Handbook of fibre rope technology

Handbook of fibre rope technology

H. A. McKenna, J. W. S. Hearle and N. O'Hear

The Textile Institute

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited
Abington Hall, Abington
Cambridge CB1 6AH, England
www.woodhead-publishing.com

Published in North America by CRC Press LLC
2000 Corporate Blvd, NW
Boca Raton FL 33431, USA

First published 2004, Woodhead Publishing Ltd and CRC Press LLC

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 1 85573 606 3
CRC Press ISBN 0-8493-2588-9
CRC Press order number: WP2588

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which have been manufactured from pulp which is processed using acid-free and elementary chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by SNP Best-set Typesetter Ltd., Hong Kong
Printed by TJ International, Padstow, Cornwall, England

Contents

Preface

Has there been an engineering manual on modern fibre rope? The answer to this oft-asked question is 'no'. As far as we know, the only comprehensive book on this subject was Himmelfarb's (1957) *The Technology of Cordage Fibres and Ropes*; it focused on natural fibres, barely mentioned man-made fibres and completely omitted several modern types of rope construction. In the 1980s Stanley Backer of the Massachusetts Institute of Technology was funded by the US Navy to work on failure theories and mathematical modelling of rope structures. This stimulated his interest because of the complex nature of rope structures and led to several graduate theses under his guidance, in addition to the reports made to the US Navy, but these had limited distribution. Useful books on specialised applications are those by Smith and Paget (1966), and TTI and Noble Denton (1999).

The general development of the fibre rope industry, following the wide acceptance of synthetic fibres in the mid-1950s, has been extraordinary but has not been chronicled. In addition, the last two decades has seen considerable research directed towards improving utilisation of the newer, ultra high-strength fibre materials and expanding the applications of high-performance grades of older materials. Much of this has been covered in research reports and in conference proceedings, but not consolidated into any kind of comprehensive form.

To fill what we see as a void, this handbook has been produced to update the history of fibre rope technology, to describe the properties of popular modern rope-making materials and constructions, to explain structural mechanics, to present an appreciation for usage, to suggest inspection procedures for used rope, to discuss testing, and, finally, to tell something about marketing and distribution.

We owe our thanks to the multitudes who have laboured in this unique industry over the centuries. The dramatic advances that have occurred in recent times are, in part, due to the vision and dedication of certain individuals and groups who we would like to recognise:

Chris Leech of the University of Manchester Institute of Science and Technology, who significantly advanced the mathematical modelling of rope structures.

Stephen Banfield of Tension Technology International, who has provided leadership in a variety of industry-funded research projects and has been responsible for termination designs that have made certain important rope structures viable.

Mike Parsey of Marlow Ropes and Tension Technology International who, among other contributions, pioneered new rope constructions that were important in developing interest in deepwater mooring of oil production platforms.

Gale Foster of the Cordage Institute, whose leadership has led to important standards development for North American rope products and who has led the efforts to establish global harmonisation in the industry. Also, special thanks are extended to him for encouragement and review relating to this book.

The fibre producers and ropemakers who have expended considerable effort to improve their products and to introduce new ones.

Many other manufacturers, academics and users of ropes have funded research or conducted trials with new products which have led to important advances. They deserve our appreciation.

The staff at Woodhead Publishing Limited have been unfailingly helpful. Our particular thanks are due to commissioning editor Patricia Morrison, her successor Emma Starr and review editor John Layton.

Acknowledgements

The authors acknowledge the advice and assistance of the following colleagues:

Stephen Banfield, Chris Burgoyne, John Flory, Roger Hobbs, Chris Leech, Martin Overington, Michael Parsey, Walter Paul, Alan Ractliffe, Richard Stonor.

Martin Himmelfarb gave permission to reproduce diagrams from his father's book, *Technology of Cordage Fibres and Rope* (1957).

The following organisations and individuals have helped by supplying information and permission to reproduce material:

August Herzog Maschinenfabrik	Postfach 22 60 D-26012 Oldenburg Germany
Columbian Rope	P.O. Box 270 Guntown MS 38849 USA
Cordage Institute	994 Old Eagle School Road, Suite 1019 Wayne, PA 19087 USA
Cortland Cable Co.	P.O. Box 330 Cortland, NY 13045, USA
DSM High Performance Fibers	Eisterweg 3 6422 PN Heerlen, the Netherlands
DuPont Industrial Fibers	4501 N. Access Road Chattanooga, TN 37415 USA

Edelrid	Postfach 1165 D-88305 Isny im Allgäu Germany
Esmet (Electroline)	1406 Fifth Street Canton, OH 44702 USA
Geo. Gleistein & Sohn	Postfach 71 02 09 D-2820 Bremen 71 Germany
John Rylands University of Manchester Library	The University of Manchester Oxford Road Manchester UK
Linear Composites	Vale Mills Oakworth Keeghley West Yorkshire BD 22 OEB UK
Marlow Ropes	South Road Hailsham, East Sussex BN27 3JS UK
New England Ropes	848 Airport Road Fall River, MA 02720 USA
Noble Denton Europe Ltd	Noble House 131 Aldersgate Street London EC1A 4EB UK
Nye, Rick	Cortland Cable Co. PO Box 330 Cortland, NY 13045 USA (for review of drafts)
Paul, Walter	Woods Hole Oceanographic Institution Woods Hole MA 02543 USA (for review of drafts)
Puget Sound Rope	1012 Second St Anacortes WA 98221 USA
Roblon Engineering	Kjeldgaardsvej, 6 DK 9300 Seby Denmark

Samson Rope Technologies	2090 Thorton St Ferndale WA 98248 USA
Saurer-Allma GmbH	PO Box 258 D-87415 Kempten Germany
ScanRope	PO Box 295 N-3101 Tønsberg Norway
Southwest Ocean Services	5718 Armour Drive Houston, TX 77020 USA
Tension Technology International	36 Huggetts Lane Eastbourne, Sussex BN22 0LU UK
TMT Laboratories	3721 Research Drive Huntington Beach, CA 92649 USA
Wellington	PO Box 244 Madison GA 30650 USA
Whitehill Mfg. Co	PO Box 356 Lima, PA 19037 USA

Our knowledge of ropes results from contacts with many people and organisations in the industry but we have limited recognition to those who contributed directly to this book. We apologise for any omissions from this list.

Author contact details

Mr Henry A McKenna
Tension Technology International
35 Hubbard Road
Weston
MA 02493
USA
Tel: +1 781 235 1129
E-mail: mckenna@tensiontech.com

Professor John Hearle
The Old Vicarage
41 Church Road
Mellor
Stockport
SK6 5LX
UK
Tel: +44 (0) 161 427 1149
E-mail: johnhearle@compuserve.com

Mr Nick O'Hear
Tension Technology International
Opweg 1, 2871 NA
Schoonhoven
The Netherlands
E-mail: nick@ohear.com

Disclaimer

The information presented in this handbook is for guidance only. Before it is used, data provided here must be verified by checking with ropemakers, by review of authorative publications or standards, by actual work experience, or upon advice of a qualified person.

It is the responsibility of a user of rope, based on his experience and/or diligent research, to select a product for a particular application and to assure that it is used in a safe manner. The particular rope product must be evaluated for suitability when it is initially placed into service and throughout the life of the application. The user must alter his procedures and/or select a different rope product if there is any indication that safety is being compromised. The guidance provided by this handbook is only one facet of this process and may not be applicable to all situations.

No liability will be accepted for actual or consequential damages claimed to be caused by use of material in this handbook.

1

Introduction to fibre ropes

1.1 Ropes from ancient times to the mid-twentieth century

1.1.1 Prehistory and history

In a sense, some animals were the first to use ropes. They used the long strands of vines and other plants to climb trees and swing from one branch to another. These 'ropes' are oriented assemblies of strong fibres in a softer matrix, not unlike modern pultruded composites. However, the real start of the story is the invention of manufactured ropes.

Probably at different times in different parts of the world, but always before recorded history, men and women discovered that they could take fibres or coarser strands found in nature, twist them together to make long, strong yarns, and then twist the yarns together to make thicker ropes. Ropes are one of the oldest human artefacts. Gilbert (1954) notes that 'a cave-painting [Fig. 1.1] in eastern Spain of Late Palaeolithic or Mesolithic date depicts a person using what appear to be ropes to climb down the face of a cliff, in order to collect wild honey'. Doubtless, ropes were made earlier in the history of mankind. However, these organic materials decay easily, unlike rock-cut drawings, stone tools, metalwork, pottery or the buildings of ancient civilisations. Natural fibre ropes only survive in water-logged or very dry conditions. Few artefacts remain. One of the earliest examples of artificial cordage is a piece of a fishing net made 10 000 years ago in Mesolithic (Middle Stone Age) times and found by archaeologists in Finland (Gilbert, 1954).

One large rope, shown in Fig. 1.2, dates from 2500 years ago. In 1942, some British troops taking time off from the war, explored the Tura Caves on the banks of the Nile. They found blocks of stone similar to those used in the pyramids, and round one of these was a rope made of papyrus in about 500 BC. The hierarchical structure was similar to a modern three-strand rope: seven fibres were twisted in the cross-sections of the yarns, 40 yarns were twisted into strands, and 3 strands were twisted together to form the rope. By a lucky coincidence, G.C. Hawkins, grandson of the founder of Hawkins and Tipson, ropemakers of Sussex in the South of England (now, as Marlow Ropes, the largest UK rope manufacturer) was an officer with the South African forces in Egypt and was given a piece of the rope.

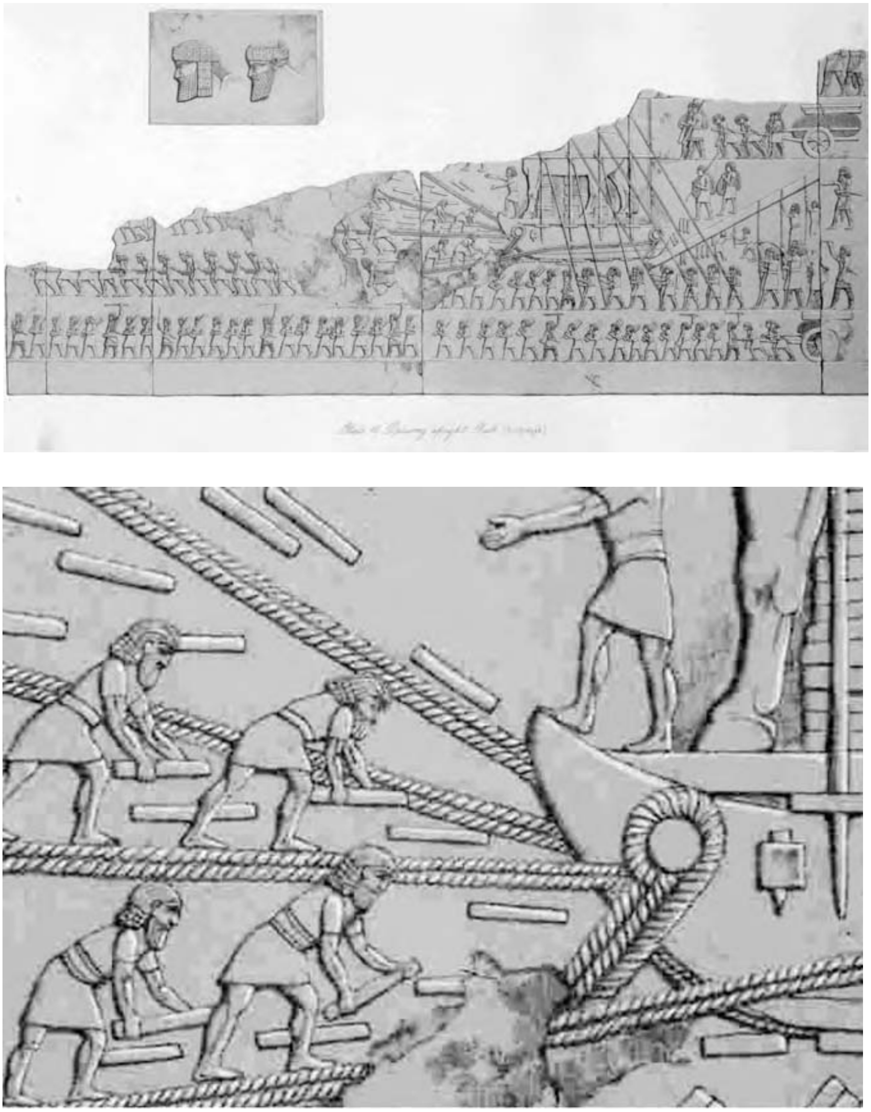
Fig. 1.1 Cave painting from eastern Spain, showing honey gatherer climbing ropes up a cliff face. From Oakley (1950) after Obermaier.

Fig. 1.2 A papyrus rope made in 500 BC. From Tyson (1966).

More information can be obtained from the pictorial and written record. A picture of an Egyptian reed boat from 2400 BC shows ropes holding up the sails. From *circa* 700 BC, the excavations of Nineveh in Mesopotamia (modern Iraq) by Layard in the nineteenth century uncovered many pictures of colossi being pulled along by ropes. The drawing of a bas-relief, Fig. 1.3(a), from the Palace of Sennacherib shows a huge statue of a bull being pulled along by scores of men using ropes as thick as a human wrist. The stranded construction of the rope can be clearly seen, Fig. 1.3(b).

As Gilbert (1954) wrote in Volume 1 of the OUP *History of Technology* 'The manufacture of ropes was of the greatest importance in the ancient empires, for man was the chief source of motive power, and it was only by means of ropes that the gangs of slaves could apply their combined strengths to move the huge stones used in the construction of the pyramids and other monuments'.

Herodotus records that, when Xerxes wanted to cross the Hellespont in 480 BC, he built a bridge of boats lashed to six cables, two of flax and four of papyrus. The Colosseum in Rome, *circa* AD 80, was covered for performances by awnings that



(a)

(b)

Fig. 1.3 (a) A bull colossus being pulled along by ropes, *circa* 700 BC; bas-relief from the Palace at Sennacherib in Nineveh. From a drawing made on the spot by A.H. Layard, during his second expedition to Assyria. From Layard (1853). (b) Detail of the ropes. Reproduced by courtesy of the Director and Librarian, the John Rylands University Library of Manchester, England.

took 300 men of the imperial fleet 4 days to erect. A modern analysis indicates that the hemp cables used to support the canvas had a diameter of 50 mm, a weight of 3 kg/m, a failure stress of 30–40 Mpa, and a modulus of 300–400 MPa (Croci *et al*., 1994).

The earliest record of the process of making ropes is on a tomb in Thebes from the Egyptian Fifth Dynasty, nearly 5000 years ago, which has the inscription 'twisting the ropes for boat-building' (Gilbert, 1954). More detail is shown in Fig. 1.4, a

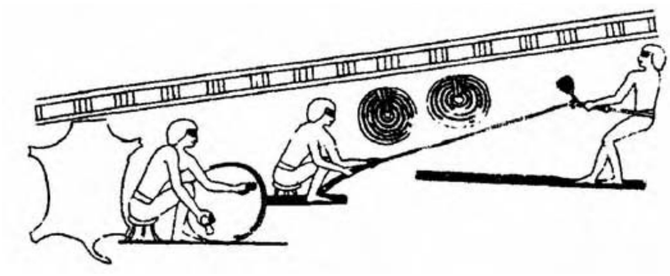


Fig. 1.4 Leather rope makers from a tomb in Thebes, *circa* 1450 BC. From Gilbert (1954).

painting of ropemakers from the tomb of Rekhmire in Thebes, *circa* 1450 BC, using methods that still persist today. The technology established by ancient civilisations hardly changed until the middle of the twentieth century. Interestingly, the later volumes of the *History of Technology* published in the 1950s make no mention of ropes.

Through the centuries, ropes have been used for many purposes: in shipping, in farming and fishing, in bridges, in climbing, as barriers, as hoists, as clothes-lines, to tie people up and to hang them – the list is endless.

1.1.2 Rope materials

Every sort of flexible strand has been used to make ropes in some place at some time. The ropemakers in Thebes, shown in Fig. 1.4, were using strips of leather. In the Orkney Islands, ropes were made of heather. We have noted the stems of papyrus, which are a metre or so long. Silk ropes may be used in luxury furnishings. The choice among an endless list depends on the balance between (a) the performance requirements for a particular end-use, typically strength, durability, flexibility and softness or hardness, and (b) availability and economics. However, the natural plant fibres, composed of cellulose, dominated rope production in historic times.

In temperate climates, the bast or soft vegetable fibre, hemp (*Cannabis sativa*), extracted from the stem of the plant, was most widely used, with some use of flax. Hemp is a widely applied word: the last edition of *Matthews' Textile Fibers*, published in the 1950s, lists 49 different fibre types called hemp. One of these was manila hemp, more properly called abaca (*Musa textilis*). In the nineteenth century, manila hemp, sisal and other hard vegetable fibres, which were extracted from the leaves of tropical plants, were imported into Europe and USA and used in the industrial production of ropes. Cotton was used for cheaper, soft ropes, where strength and durability were less important. A braided cotton cord that was developed in the late nineteenth century became almost universally accepted to hang windows; examples exist today of rope still in service after over 50 years.

The distribution of consumption among these fibres in 1951 is illustrated in Table 1.1.

1.1.3 Rope construction

Vegetable fibres are all short (staple) fibres. Cotton is typically around 3 cm long; the others are much longer. In the bale, they are irregularly arranged and must be

Table 1.1 Consumption of traditional cordage fibres in USA in 1951. From Himmelfarb (1957)

Fibre	Consumption in million pounds per annum
Hard fibres	
sisal (agave)	121
manila hemp (abaca)	94
henequen (agave)	57
Soft fibres	
jute	45
cotton	13
flax and hemp	13
istle	1
TOTAL	344

carded or combed to straighten out the fibres. Twist is then needed to hold the fibres together in a yarn. As the fibres wrap round each other, they press inwards and grip each other. With sufficient twist, there is a self-locking structure: the greater the tension, the tighter the fibres are gripped. By the various methods of hand-spinning, natural fibres were converted into yarns. This is essentially a continuous process, limited only by the length of several kilometres that can be wound onto a bobbin. The remaining stages of ropemaking – twisting a number of yarns into strands and then strands into ropes – were carried out discontinuously, most commonly in ropewalks, which were found in many ports and country towns. Illustrations of ropemaking from Diderot's *Encyclopaedia of Science, Arts and Trades* are shown in Fig. 1.5. It is interesting to note in Fig. 1.5(c) that Diderot appreciated the problems of the packing geometry of ropes. Often ropemaking was carried on outdoors (Fig. 1.6). A large dockyard ropewalk, such as that at Chatham, Fig. 1.7(a), might be over 300 metres long. At one end, there is the jack, Fig. 1.7(b), which has three hooks that can be rotated. At the other end there is a carriage with a single, rotatable hook. A commercial ropewalk that was operating into the second half of the twentieth century is shown in Fig. 1.8. Some ropewalks continue to make ropes for sale today, though this is mostly in a museum context.

The essential principles of the traditional way of making a three-strand rope, either on a ropewalk or on simpler hand-held equipment, are shown in Fig. 1.9. In Stage 1, three sets of yarns are pulled off bobbins and are held along the length of the ropewalk. In Stage 2, an assistant turns the crank handle of the jack so that the yarns are twisted into strands by the rotation of the three hooks on the jack. Twist causes the lengths to contract, so that the carriage has to move along the ropewalk, under the control of the ropemaker. In Stage 3, the hook on the carriage rotates in order to twist the strands into the rope.

In the usual mode of operation, the initial strand twist is made as high as possible without kinking. When the single hook on the carriage is released, the high torque in the strands causes the hook to rotate, and this, in turn, causes the three strands to twist together and form the rope. The ropemaker controls the production of the rope by continually pushing back its point of formation to give a tight structure; meanwhile, the assistant continues to rotate the crank to make up for the loss

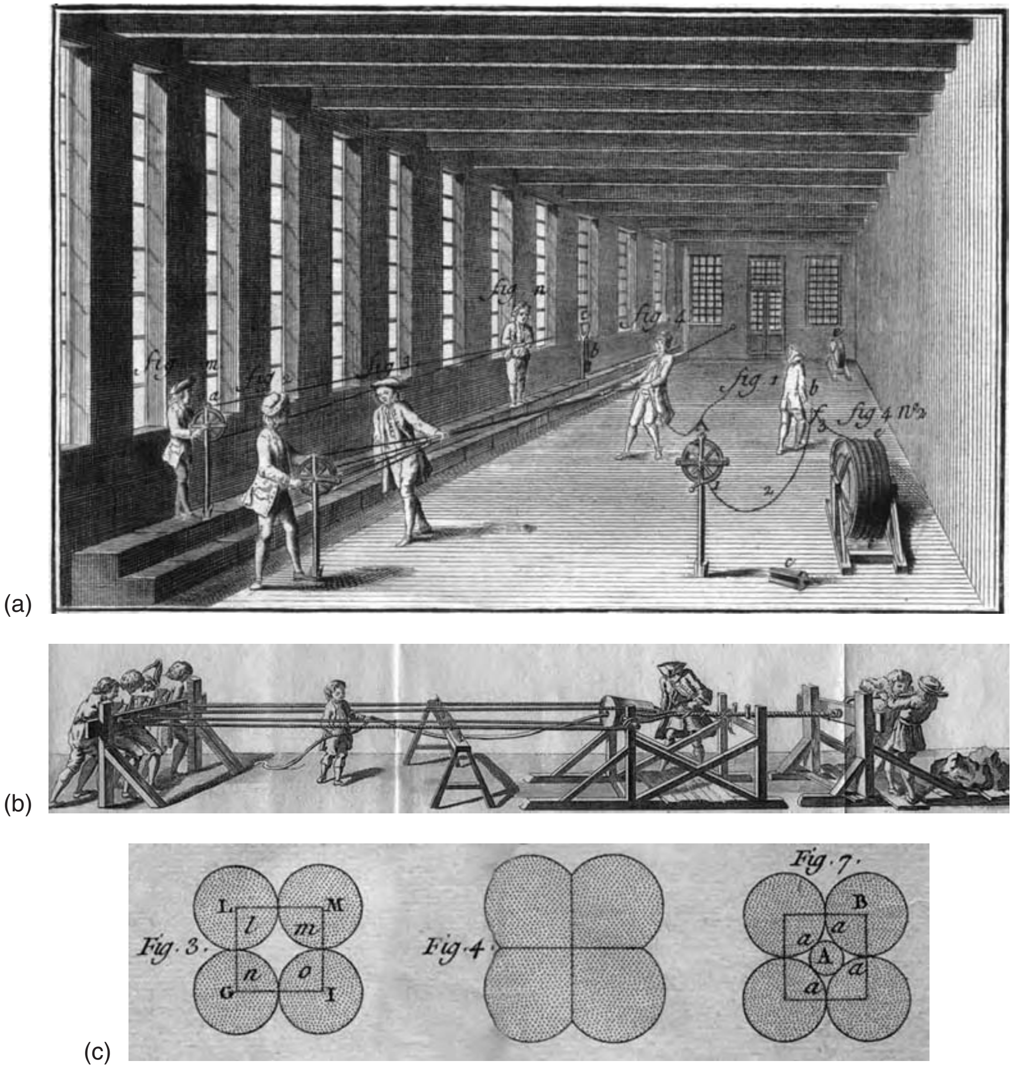


Fig. 1.5 Illustrations from the eighteenth century *L'Encyclopaedia ou Dictionnaire Raisonne des Sciences, des Arts et des Metiers* by Denis Diderot (Gillispie, 1950). (a) A rope-walk. (b) Making a four-strand rope with a smaller central core strand. (c) Geometry of a four-strand rope.

of twist in the strands. The result is a balanced rope with twist in one direction in the strands and the other direction in the yarns. Figure 1.10 illustrates the structure of three-strand ropes, taken from the authoritative mid-twentieth century book by David Himmelfarb, Master Ropemaker of the US Navy Ropewalk. Other constructions could be made by positive control of the twist levels at the two stages.

There were variants, such as two-strand cords and four-strand ropes, which might be shroud-laid with an additional central core strand, but three-strand ropes were the commonest form for thousands of years.

(a)

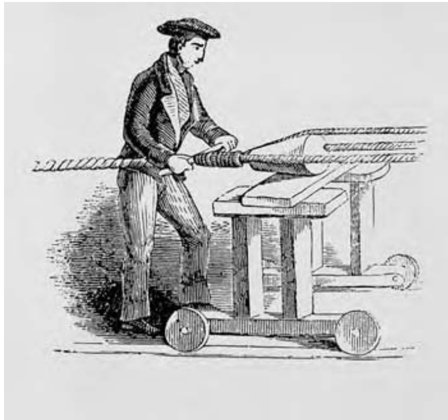
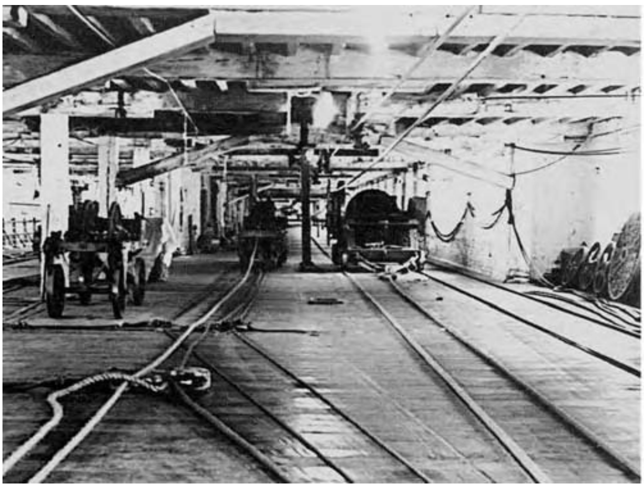


(b)

Fig. 1.6 (a) The ropewalk at Wrights of Birmingham, England, 1770. (b) Detail of forming a rope. From Tyson (1996).

(a)



(b)

Fig. 1.7 (a) The 344-metre long ropewalk at Chatham Dockyard, England. (b) A rope maker's jack.

1.1.4 The industrial revolution and steel

The Industrial Revolution, *circa* 1800, which moved textile manufacturing in Britain (and later elsewhere) from cottages to factories, changed the yarn production, including the preparatory stages of opening and cleaning, carding and drawing, from hand-spinning to machine processing. Ropewalks were made with metal fittings instead of wood. Later in the nineteenth century, as an alternative to the discontinuous action of ropewalks, machines were developed for continuous production. In one machine, rope yarns could be twisted into strands. Another type of machine, illustrated in Fig. 1.11, enabled continuous laying of three-strand ropes.

Braiding machines, as a development of hand-plaiting or the action of a maypole, were also made and braiding became a common method of making cords and some

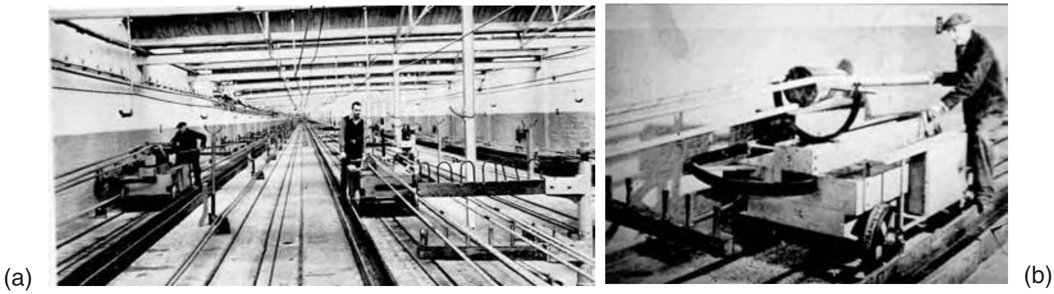


Fig. 1.8 (a) The ropewalk at British Ropes Ltd, which operated into the second half of the twentieth century. (b) Detail of laying up strands to form the finished rope. From Tyson (1966).

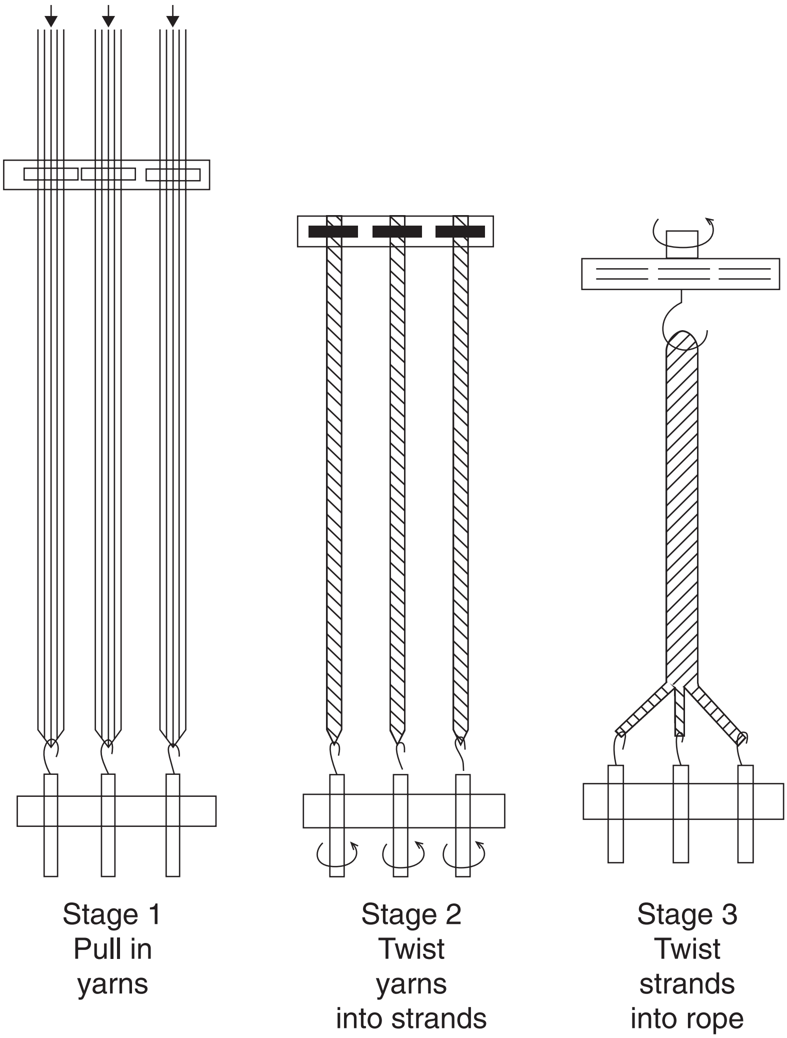


Fig. 1.9 Principles of making a three-strand rope. Note the rotation in same sense at opposite ends puts opposing directions of twist in strands and ropes.

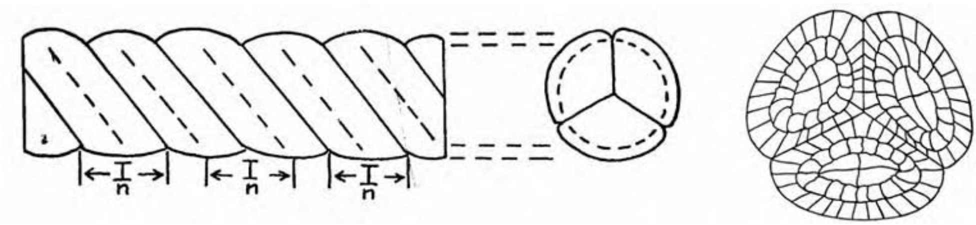


Fig. 1.10 Three-strand rope structures. From Himmelfarb (1957).

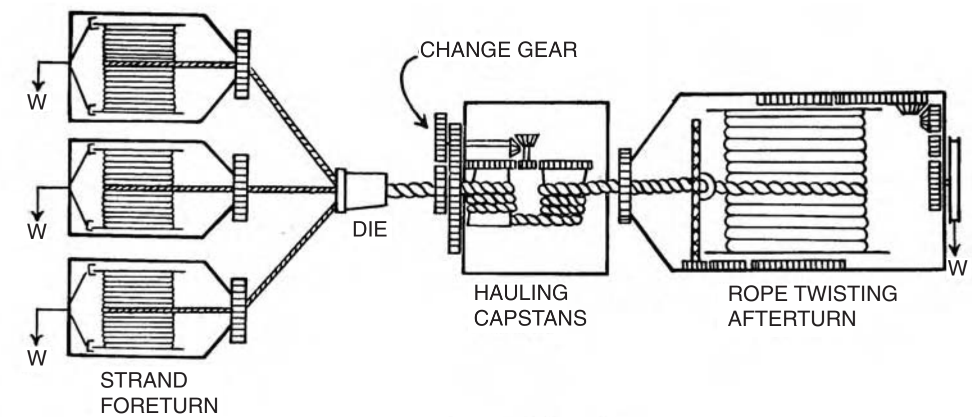


Fig. 1.11 Rope-laying machine. From Himmelfarb (1957).

small ropes. These small braids are made directly from yarns, without a strand-production stage. In the simplest circular braid, two sets of bobbins on carriers follow circular paths in opposite directions, alternately crossing one another on the inside and the outside, to give a structure like a plain weave. Plaits or braids made with a small number of carriers fill space, but with more carriers the braids are hollow and can be filled with yarns fed through the centre of the machine. Other braids have different interlacing patterns. In so-called 'solid braids', the carriers rotate in the same direction, but interlace as they move from an inside to an outside track. Yarns on the surface are then nearly parallel, crossing at small angles instead of the larger angles from crossing in opposite directions. Braids of this type are typical for uses such as clothes lines. Another example, made of coloured yarns, is used for decorative barriers in theatres and elsewhere.

The change from hand-craft to factory production did little to alter fibre ropes themselves. The most important consequence of the Industrial Revolution for the rope industry resulted not from machinery, but from the invention of steels that could be made into steel wires. These could be assembled into wire ropes and cables. Since the wires were continuous lengths, high twist was not essential, as it is for short fibre yarns, but some twist is needed to hold the wires together in a compact structure and provide flexibility. The usual construction is to wrap successive layers on top of one another, with alternating twist directions. Wire ropes came to dominate the newer engineering applications, such as bridge-cables, mine-hoists, elevators, cranes, as well as the heavier-duty cables for traditional uses, such as shipping and forestry. In many areas, fibre ropes were replaced by wire ropes, and their much greater performance supported the engineering advances of this time.

1.2 Advances since 1950

1.2.1 Synthetic fibres

Although strong *rayon* fibres, which were regenerated from natural cellulose, became available in the 1930s, their influence on the rope industry was negligible (though they did become important as an alternative to cotton in tyre-cords and related products). What led to major change in fibre ropes was the invention by Wallace Carothers of the polyamide, *nylon 66*. This was a new polymer synthesised from chemicals in coal or oil. Commercial production by DuPont started in 1939, and nylon cordage began to be used in the Second World War. By 1950, larger three-strand nylon ropes were being made. In 1951, Himmelfarb (1957) reports that 0.6 million pounds of nylon were used in cordage in USA, or 0.16% of the total cordage consumption of 344 million pounds. The middle of the twentieth century marks the start of the first major change in rope fibres since ancient times. Now, synthetic fibres dominate the rope industry, though natural fibres remain important in some uses such as sisal baler twine. For many years, nylon remained the premium rope fibre, because of its strength, extensibility and toughness.

The next synthetic fibres to come strongly into rope production were the *polyolefins*, polyethylene (polythene) and polypropylene, which replaced natural fibres in the cheaper, commodity rope market. Although the *polyester*, polyethylene terephthalate, was produced before polypropylene, its use in ropes mostly followed later, after the development of strong, industrial yarns, primarily for tyre-cords. Now, polyester has overtaken nylon in high-performance ropes, except where a lower modulus (less resistance to extension) or good recovery from high stresses, such as in fall arrest, is required. This group of first-generation synthetic fibres had moderately high strength and breaking extension, which means that their moduli (tensile stiffness or resistance to extension) were not high. Strength and durability have improved over the last 25 or so years and ropes made of fibre specifically formulated for the purpose give excellent performance.

The second generation of synthetic polymer fibres consists of high-modulus fibres with strengths more than twice that of nylon and polyester and low break extensions. A driving force was the demand for advanced composites with high strength and stiffness. Carbon fibres were the first to be made, but were too brittle in bending to be useful in ropes, except possibly as pultruded composite rods, which act like steel wires. The first high-modulus, high-tenacity (HM-HT) synthetic polymer fibre, which became available in the 1970s, was the (*para-*) *aramid* fibre, *Kevlar*, from DuPont. Because they are made from linear polymers, aramids yield in compression, which is a limitation, but has the advantage for ropes that the fibres can be severely bent without breaking. The aramids were followed in the 1980s by the high-modulus polyethylene (HMPE) fibre, *Spectra*, from Allied Fibres. Other companies are now also producing aramid and HMPE fibres. The first new fibre of the twenty-first century was *Zylon*, made from polybenzoxazole (PBO) by Toyobo. Research continues and other HM-HT fibres are being developed. The HM-HT fibres are used where their high strength and stiffness justify a high price. However, it is notable that, for a major engineering use, deepwater moorings, which became important as the twentieth century came to an end, polyester has proved to be the best material, both technically and economically.

Detail on fibre properties will be found in Chapter 2.

1.2.2 Rope constructions

The particular arrangement of the strands that makes up the structure of the rope is called the *construction*; this term will be used in this book and is commonly used in the rope industry. Nylon was first used in the traditional three-strand construction, Fig. 1.10, with which ropemakers were familiar. This is still a common rope type, but new rope constructions were introduced in the second half of the twentieth century. Because synthetic fibres are continuous filaments of effectively infinite length (it is always possible to wind one more turn on a package!), twist is not strictly needed. In principle, a collection of parallel filaments could act as a tension member. In practice, they would spread out, might become entangled and would be susceptible to breakage of individual filaments by abrasion. Some coherence must be given to the bundle to make a useful rope. The introduction of new fibres led to increased research and development by ropemakers, and their suppliers, namely machinery manufacturers and fibre producers, and, later, to studies of performance by major users. The principal modern rope types are illustrated in Fig. 1.12.

The first development beyond three-strand rope was associated with the production of large braiding machines. Himmelfarb (1957) refers to braids only in the context of cords up to 1 cm in diameter with break loads of 250 kg, but by the 1960s large braided ropes were being made. A modern catalogue would typically go to the 10 cm diameter, 250-tonne break load category for single-braid ropes. In 8-strand ropes, Fig. 1.12(a), pairs of strands cross under and over each other; two sets go clockwise (right lay or Z-) and two go counter-clockwise (left lay or S-); the centre is crossed by the strands. In 12-strand ropes, Fig. 1.12(b), strands interlace in single circular braiding patterns. With more carriers, circular braids have hollow centres and would flatten if not filled. This led to double-braid ropes, Fig. 1.12(c), in which an outer cover surrounds an 8, 12 or 16-strand core (depending on rope size), giving the technical advantage that the core is the main strength and stiffness member with the cover adding some strength and resisting surface wear. Double-braid ropes, also called braid-on-braid, are made in larger sizes up to around 20 cm diameter and 1000 tonne break load.

If fibres lie at an angle to the rope axis, there is inevitably a loss of strength and stiffness, compared to the fibre values. The reduction factor is roughly the mean value of $\cos^4\theta$, where θ is the helix angle of lay. In order to overcome this problem, ICI developed *Parafil* ropes in the 1960s. An assembly of parallel yarns was enclosed within a plastic jacket, Fig. 1.12(d). With their high strength conversion efficiency, parallel-yarn ropes are good for some applications, such as antenna stays, but their high bending stiffness limits their uses. Rope manufacturers looked instead for low-twist constructions.

If θ is kept below 10°, the simple expression indicates that the strength loss should be less than about 5%. This level of interaction gives coherence to fibre assemblies, but allows some freedom in bending. Still, the softness of such rope limits the appli-

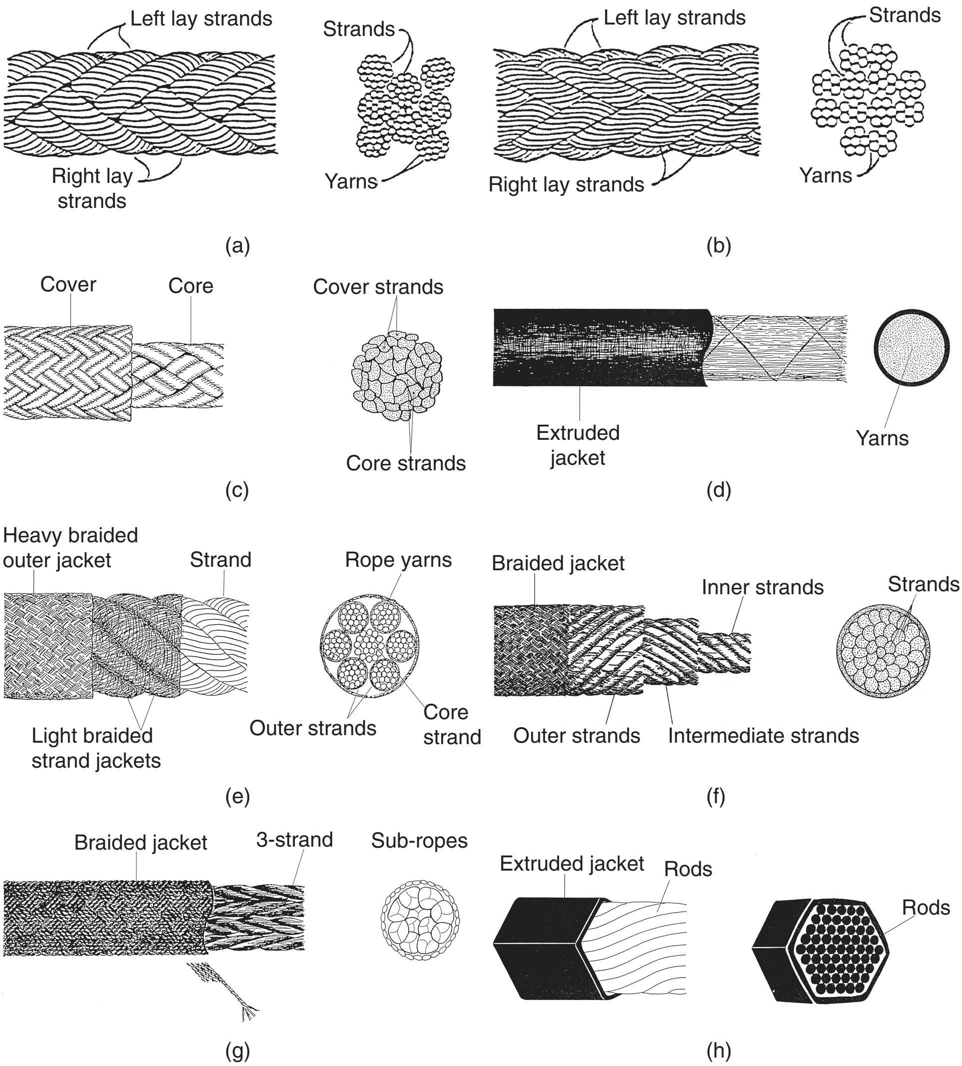


Fig. 1.12 Modern rope types. (a) 8-strand braided. (b) 12-strand braided. (c) Double braid or braid-on-braid. (d) Parallel yarn. (e) 6-round-1 wire-rope construction. (f) 36-strand wire-rope construction (18 + 12 + 6 + 1). (g) Parallel strand. (h) Pultruded rod.

cations to those that require constant tension, and experience only limited handling when slack.

In the 1980s, wire-rope constructions were adopted for fibre ropes. Common constructions are six strands helically wound around a centre strand (6 around 1), Fig. 1.12(e), or 36-strand, Fig. 1.12(f). Counter-directional layers may be wound on top of one another. All have long lay lengths. Later in the 1980s, parallel strand ropes, Fig. 1.12(g), were introduced by Marlow Ropes. A core, consisting of a number of low-twist, three-strand sub-ropes, was enclosed within a braided jacket. A later variant from Quintas and Quintas used long-lay braided sub-ropes in the core. These are the types of ropes used for the deepwater moorings of oil rigs, with diameters in polyester up to more than 20 cm for strengths of 1500 tonnes.

In another construction from the 1970s, filament yarns were pultruded with a resin binder, so that they made composite 'wires', which could be assembled within an extruded jacket, Fig. 1.12(h). This technique can be used with polymer fibres, but its main potential is that it gives a way of making glass, carbon or even ceramic fibre ropes.

Details of rope constructions are given in Chapter 3.

1.2.3 Ropemaking machinery

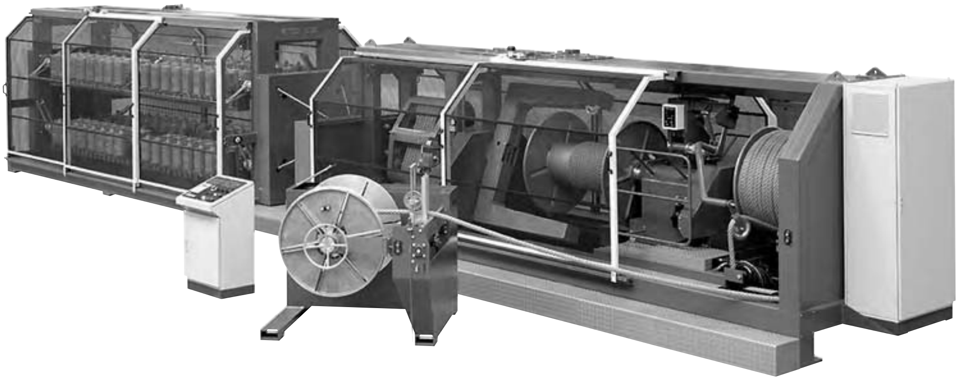
Since 1950, rope-making machinery has been influenced by the major advances in textile machinery, which give increased speeds and efficiency and reduced labour input. Individual drives by electric motors, modern electronics and control engineering, and computer-controlled operation have been introduced. Continuity of production has been enhanced by linking strand formation and rope laying into a single machine, such as that shown in Fig. 1.13(a). Operations in a moderm rope-making factory are shown in Fig. 1.13(b).

1.2.4 Rope uses

The familiar uses of ropes, which have been around for hundreds and thousands of years, continue today in the sales of industrial suppliers, hardware stores, ships' chandlers, and yachting and climbing shops. A major change in the last quarter of the twentieth century was a move into more demanding engineering applications. This was triggered by the high strength of the second generation of synthetic fibres, which were appreciably stronger than steel on an area basis and vastly stronger on a weight basis, especially when submerged in mooring applications. Joint industry studies were set up to evaluate ropes for deepwater moorings, which led to the conclusion that the modulus of polyester matched the needs better for this huge and growing market. The fibre cost alone for a single oil-rig mooring is $1 000 000 and more, depending on water depth. The HM-HT fibres are expected to find use in deepwater mooring as depths increase. However, they find important applications in more specialised markets, where very high stiffness is needed.

For deepwater moorings, weight is the critical factor. Historically, steel cables were used for catenary moorings, but as depths go beyond 500 metres an increasing fraction of the rope tension is needed to support the weight of the steel itself. There is a critical length, the breaking length, under which a material will break under its own weight. For polyester in air, this length is three times greater than for steel and in water it is more than ten times greater. Although the use of improved steels, and measures such as expensive flotation, which is difficult to handle and maintain, have enabled steel moorings to go to greater depths, polyester moorings are increasingly preferred beyond 1000 metres.

The use of fibre ropes in demanding engineering applications has led to a change of culture, which contrasts with the age-old basis of craft experience and trial-and-error. For the first time in the history of textiles, manufacturers have had to adopt an engineering-design approach, which expects calculations to be done and quantitative design data to be specified and predicted. Rope experts have had to work with marine consulting engineers to conduct research to accurately predict fibre rope performance in order to provide inputs to mooring analysis computer programs.



(a)

(b)

Fig. 1.13 (a) A modern rope-making machine from Roblon. (b) A modern rope-making factory.

In more traditional uses, such as towing and docking, fibre ropes are replacing steel because their light weight and softness make for easier and safer handling. This is not only welcomed by crews, but also proves economic for owners. In marine applications, the advantages of fibre ropes over steel are now well recognised. This is not true of land-based civil engineering. Potential benefits can be shown – for example, Cook *et al*. (1994) showed that, for a large-span structure, cable weights in aramid would be a quarter of those in steel, with considerable overall cost-benefit improvement – but conservatism prevails. Once a material has been proven by trial and error, engineers are reluctant to try a new material until someone else has used it successfully, but no one wants to be first.

1.3 Rope issues

1.3.1 What is rope?

It is implicit in the above account of the history of ropes that everyone knows what a rope is. Precise definitions are more difficult. The primary definition in the *Shorter Oxford English Dictionary* (1956) opens with two other obscure terms, *line* and *cordage*:

> **Rope** . . . A length of strong and stout line or cordage, usually made of twisted strands of hemp, flax, or other fibrous material, but also of strips of hide, pliant twigs, metal wire etc.

The entry in *Textile Terms and Definitions* (Denton and Daniels, 2002), reproduced as Table 1.2, is instructive but selective on different types of rope.

The authoritative rope glossary from the American Society of Civil Engineers (ASCE, 1993) is briefer, and *cordage* is defined both narrowly and generally:

Rope:

1) A long, flexible assembly of fibers, laid, braided, or bundled together, to serve as a tensile strength member.
2) By tradition and some US Government regulations, cordage greater than 3/16 in. diameter (see Cordage).
3) By British Standard, cordage greater than 4 mm diameter.

Cordage:

1) The product formed by twisting or braiding fibers into an essentially circular cross-section, which is capable of sustaining load. Usually applied to smaller products.
2) Traditionally and by some US Government regulations, under 2/32 in. diameter = twine, to 3/16 in. = cordage and above = rope.
3) The collective term for rope, line and cord.

A recent draft standard (ISO, 2001), which is presumably intended to replace an earlier (ISO, 1973) standard, would exclude parallel yarn ropes:

> 4.1.34 **Rope**: product obtained when three or more strands are twisted or braided or paralleled together to provide a composite cordage article larger than 4 mm in diameter.

A modern engineering definition of rope would be a *flexible tension member*. Flexibility reflects the ease of handling. Tension member reflects the fact that ropes are only useful in tension. Three limitations would be accepted:

a rope has a substructure of long elements, commonly fibres, but also tapes, monofilaments, and other thick components – a solid rubber rod is a tension element, but not a rope,

a rope is, at least roughly, circular, though some braided ropes are more like rounded squares – flat belts are tension members, but not ropes, though much of the technology is similar,

Table 1.2 The entry for rope in *Textile Terms and Definitions*, Denton and Daniels (2002). (The cross-references are to other entries in the book.)

rope
An article of **cordage**, more than approximately 4 mm in diameter, obtained when: (i) three or more **strands** are laid (see **lay** 3) or plaited (see **braiding**) together; or (ii) a core is covered by a braided or plastic film sheath. Types of rope are:

braided rope; sennit rope; sinnet rope
A rope formed by **braiding** or plaiting the **strands** together.

cable laid rope
A rope formed by three or more ropes twisted to form a helix around the same central axis. The ropes that become the secondary strands are '**S**' lay and the finished cable is '**Z**' lay, or *vice versa*.

combined rope
A rope in which the **strand** centres are made of steel and in which the outer portions of each strand are made from fibrous material.

double braided rope
A rope in which a number of **strands** are plaited to form a **core** and around which are plaited further strands to form a sheath The core lies coaxially within the sheath.

8-strand plaited rope
A rope normally composed of 4 pairs of **strands** plaited in a double 4-strand round sennit.

hard laid rope
A rope in which the length of lay of the **strands** and/or the rope is shorter than usual, resulting in a stiffer and less flexible rope.

hawser laid rope
A rope of three **strands** which are twisted to form helixes around the same central axis.

laid rope
A rope in which 3 or more **strands** are twisted to form helixes around the same central axis. (See also **ordinary lay**.)

shroud laid rope
A 4-strand rope with or without a core with the **strands** twisted to form a helix round the central axis.

soft laid rope
A rope in which the length of lay of the **strands** and/or the rope is longer than usual resulting in a more flexible rope which is easily deformed.

spring lay rope
A rope made with 6 **strands** over a main core, each strand of which has alternating wire and fibre components laid over a fibre core.

ropes are relatively thick – 10 g/m or 4 mm diameter are typical dividing lines between ropes and finer cords and twines.

1.3.2 Principal properties of ropes

Ropes made of natural fibres are attractive because of their ease of handling, good gripping surface, knot retention and relatively low recoil energy when they break. They are non-melting, which may be important in some applications. The cost can be relatively low on a size basis but may not be so for strength and longevity. A disadvantage is deterioration from biological and environmental exposure. Natural fibre ropes are widely used throughout the world – in some places they are the only easily available ropes – but their tensile properties are significantly inferior to those constructed of synthetic fibres.

Ropes of synthetic fibre are mainly attractive because of their high strength compared to weight. The metallic alternatives, such as wire rope, chain, and rod, are much heavier for the same strength. When submerged in water, fibre ropes lose much of their weight, and some are even buoyant, so the difference becomes much more pronounced. Table 1.3 demonstrates the weight advantages of fibre rope.

Two other properties nearly equal in importance to the low strength to weight ratio are flexibility and ease of handling. Laid, plaited and braided fibre ropes are very flexible. Jacketed fibre ropes often have higher strengths than conventional constructions but are less flexible and generally not used in situations that require frequent handling. However, compared to wire rope of equal strength, almost all fibre ropes can be bent and coiled much more easily.

The ability to stretch under load can be a beneficial property. Many situations occur where shock loading may occur and the elasticity of the rope reduces the peak forces; for example, fall protection in mountaineering. Objects secured by ropes may move, such as a vessel moored to a quay, and the stretch in the rope accommodates limited movement without developing large forces, though it is also important to prevent movement in order to avoid the build-up of momentum. When ropes are used in parallel, extensibility provides better load sharing. By varying the fibre material or rope construction, a wide range of tensile properties are available, from behaviour near that of wire rope (very stiff) to that of nylon, which may stretch over 20% of its length before breaking.

One disadvantage is that stretch can be dangerous in a rope with good elastic recovery, because of the energy stored in an elongated rope. If it should break, or the anchorage fail, the recoil can be deadly.

Clearly, fibre ropes are not as resistant to abrasion or cutting as wire rope or chain. This does limit their use in many applications. Problems can be overcome with special gear or procedures, but these may be impractical.

In general, most man-made fibre ropes are resistant to degradation from the environment in which they are normally used. With the wide variety of fibre materials that are available, or with the use of special treatments, chemical, bacterial, fungal and ultraviolet stability can be found for almost any application. This can be an essential property if longevity is important or when replacing metal strength members that are subject to severe corrosion.

Braided, plaited and most jacketed rope with a core strength member are free of torque and will not rotate when suspending a load. This can be a useful property. Laid ropes will rotate.

A few fibre materials are subject to creep. This is undesirable for long-term sustained loading, but may not be a problem in many applications. However, an appropriate assessment must be made before using materials subject to creep.

Table 1.3 Rope weights and sizes – typical values for 1000-tonne break load

	Nylon	Polyester	Aramid	HMPE	Steel
Weight in air (kg/m)	25	23	12	8.4	58
Weight in water (kg/m)	2.5	5.9	3.3	Buoyant	49
Overall diameter (mm)	200	175	120	125	110
Rope size number (inches)	25	22	15	15.5	14

1.3.3 Quantities and units

The nature of ropes and the meeting of textile technology with physics and engineering, not to mention preferences for Imperial (once British, but now lasting mainly in USA) or metric sytems, lead to great variety in the way of specifying rope dimensions and mechanical properties. A list of useful formulae and conversion factors are given in Appendix I.

The definitive way of characterising the size of a rope is by its linear density, namely its weight per unit length (more correctly, mass per unit length). The strict SI unit of kg/m is the right size unit for ropes, and fits conveniently with the unit of *tex* (g/km) used for fibres and yarns, since 1 kg/m = 1 Mtex.

The long history of ropes has produced a variety of other ways to identify fibre rope size. In the past, ropes over 25 mm diameter were mostly found on vessels and the circumference of the rope in inches (determined by wrapping a string or tape around the rope) was used to specify the size. Smaller ropes were measured the same way, but the size designation was diameter, determined by dividing the circumference by three (rounding of π). The trend today is away from this procedure, although it will be found in many rope producers' catalogues and other documents.

All ropes have voids that can vary in volume, depending on size and type of rope construction. A packing factor, namely the fraction of the space occupied by fibre, can be defined, and, together with fibre density, gives the effective density of a rope. This provides the link to area, circumference and diameter. International standards have been published that specify a narrow range (in order of ± 5%) of linear density that corresponds to a diameter and/or circumference. Small differences may be found between standards developed for metric sizes compared to inch sizes, but efforts to harmonise are underway. Thus, a rope size, listed by diameter or circumference, must correspond to a specific linear density. Test methods for determining linear density are published (see Section 10.9.3).

Because of its popularity in the marine industry, the circumference in inches of large ropes is now called the *rope number* in metric-based rope literature for those who wish to retain it as an additional nominal size reference.

For mechanical properties, it is clearest to normalise forces as *specific stresses*, namely force divided by mass per unit length, with Newtons/tex (N/tex) being the preferred unit. However, there is widespread use of gram/denier (g/den) based on the old silk unit of denier, which is grams per 9000 metres. Division of specific stress by density (mass/volume) gives a conventional stress, which is force/area. For a density of 1 g/cm^3, which is approximately the density of many ropes, 1 N/tex = 1 GPa. For the reasons explained in Appendix I, a great many other units are in use. One fibre producer expresses strength in inches!

1.4 Diversity and choice

The above brief account of the development of rope technology and the greater detail in Chapters 2 and 3 show that there is a vast range of rope types. Even for a given size or strength of a rope intended for a given use, there are options in the fibres, their possible mixing, and the rope structures. If all the combinations are included, it has been estimated that this leads to 500 000 possibilities for the ropemaker and rope user to choose from. As an aid to the industrial experience, an engineering approach to prediction of performance, based on fibre properties and rope geometry, is needed for the demanding applications that are becoming current.

In order to illustrate the diversity of ways in which rope is used, old and new, demanding engineering and everyday consumption, functional and decorative, serious and trivial, a miscellany of pictures is presented in Figs. 1.14 to 1.45.

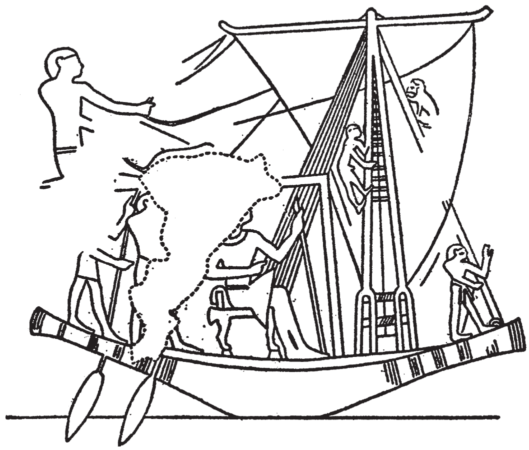


Fig. 1.14 Ropes on an Egyptian reed sailing boat. From a tomb at Deir el-Gebrazi, Egypt, *circa* 2400 BC. From Gilbert (1954).

Fig. 1.15 Ropes on a modern yacht. Reproduced by courtesy of Gleistein.

Fig. 1.16 Dockside mooring ropes.

Fig. 1.17 Promoting advanced fibre ropes for moorings. Reproduced by courtesy of Whitehill Manufacturing Corp.

Fig. 1.18 Towing an oil-rig out to its sea station.

Fig. 1.19 Towing an iceberg.

Fig. 1.20 On-board ropes (1).

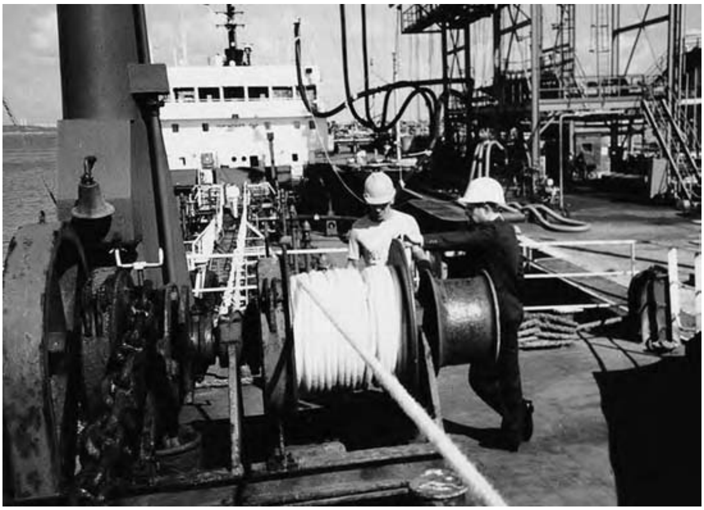


Fig. 1.21 On-board ropes (2).

Fig. 1.22 Traditional rope store near the docks at Istanbul, Turkey.

Fig. 1.23 A 25-cm thick *Spectra* HMPE rope used on the *Lindsey Foss*, 'the world's largest and most powerful tugboat'. From *Seattle Times*, April 17, 1994.

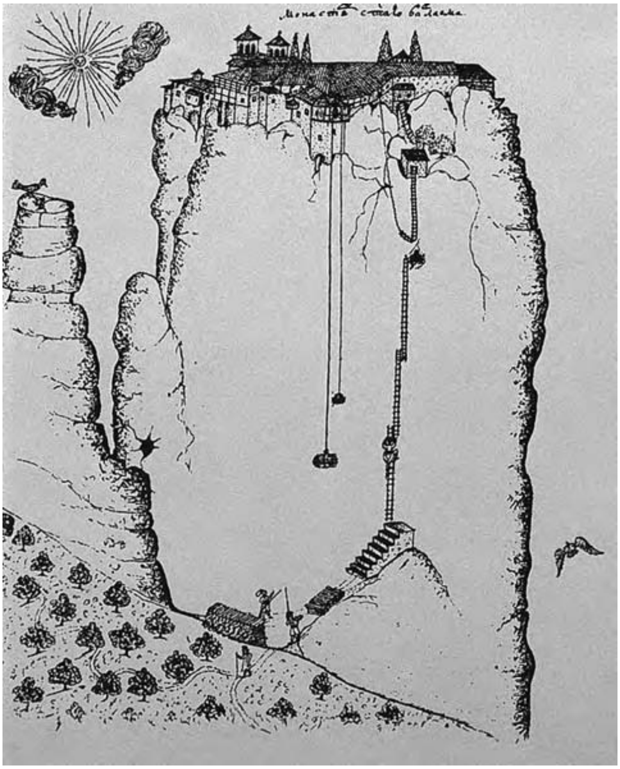


Fig. 1.24 Hoisting supplies to a monastery in Meteora, Greece. Drawn by B. Barkskij in 1745.

Fig. 1.25 Lifting 770-tonne steel foundation into place at a construction site with slings made of high modulus fibre.

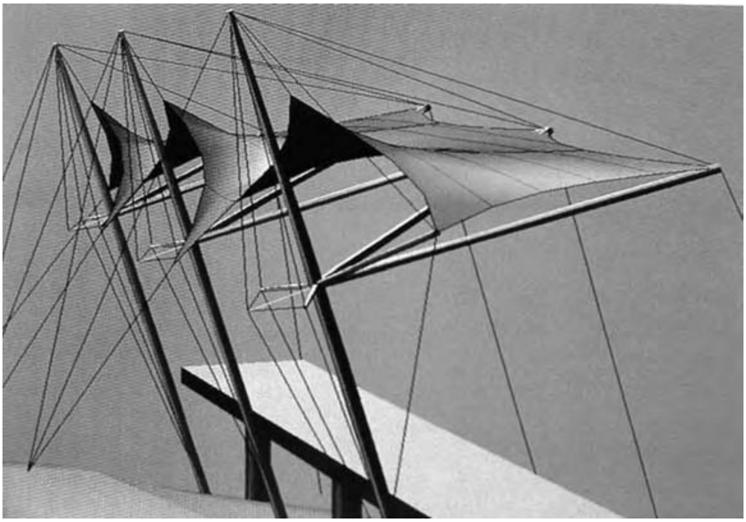


Fig. 1.26 Most architectural structures still use steel cables, as in this picture.

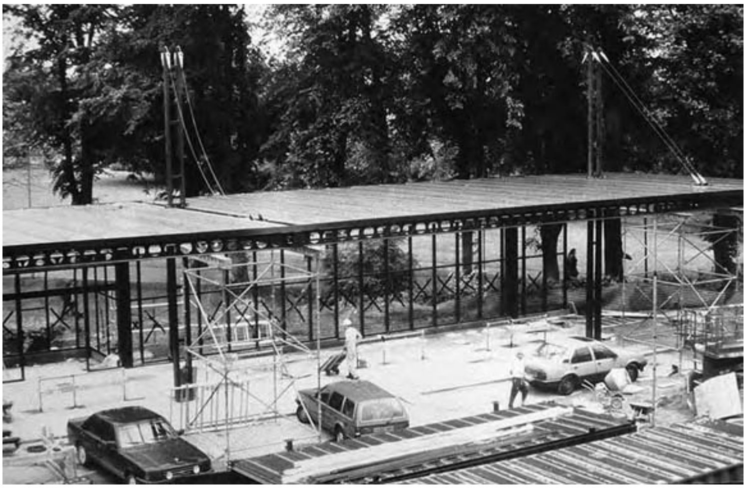


Fig. 1.27 A bus station in Cambridge, England, uses *Parafil* fibre ropes.

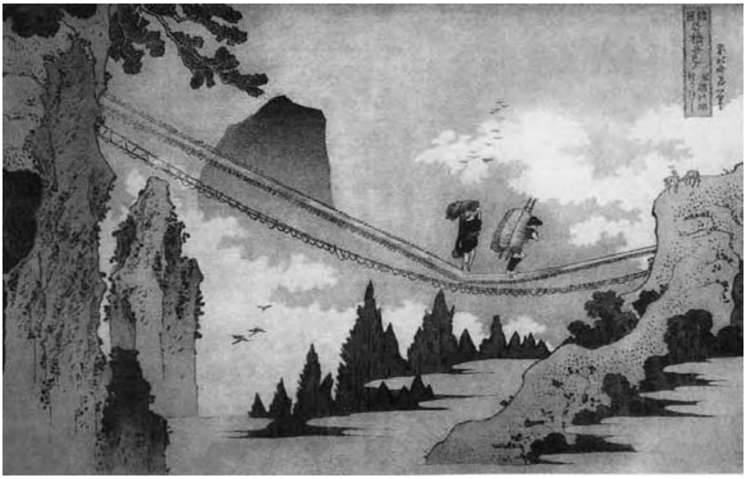


Fig. 1.28 An old rope bridge between two provinces in Japan.

Fig. 1.29 A modern bridge with steel cables, between the islands of Honshu and Shikoku in Japan.

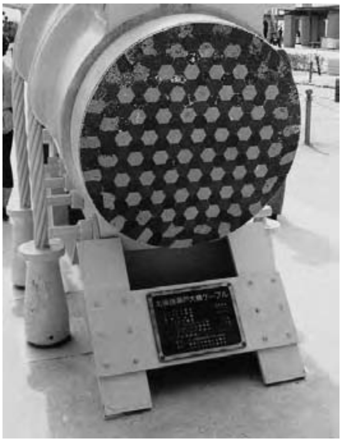


Fig. 1.30 Exhibit of the steel cables of the bridge in Fig. 1.29, at the visitor centre on an intermediate island.

Fig. 1.31 The first railway suspension bridge, built by Jonathan Roebling across the Niagara Gorge in 1855. The bridge is supported by steel wire cables. From Wittfoht (1986).

Fig. 1.32 A traditional rope bridge still in use. The climber, Peter Boardman, crossing the Kenabu River in New Guinea.

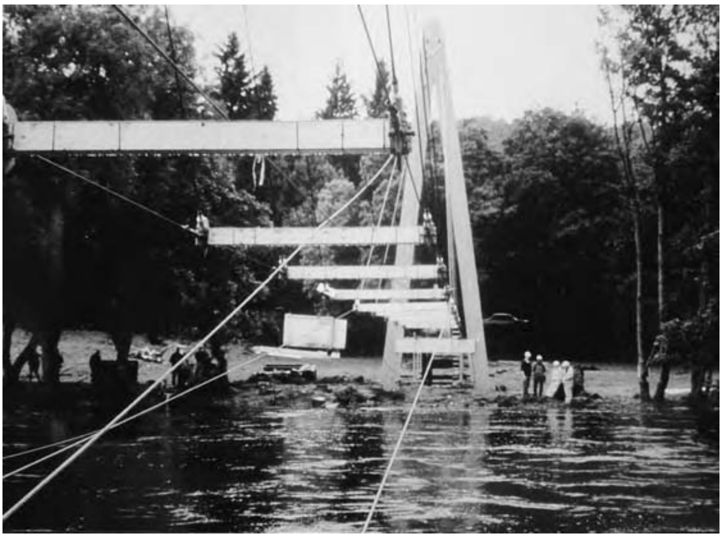


Fig. 1.33 Erecting a footbridge supported by *Parafil* ropes, across the River Tay in Scotland.

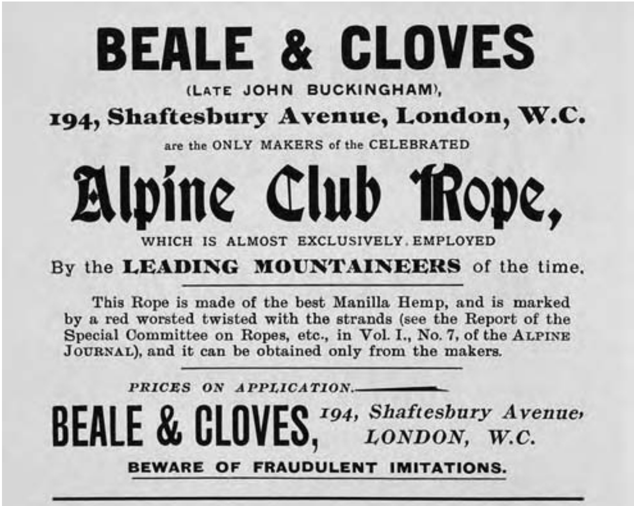


Fig. 1.34 An old advertisement for ropes.

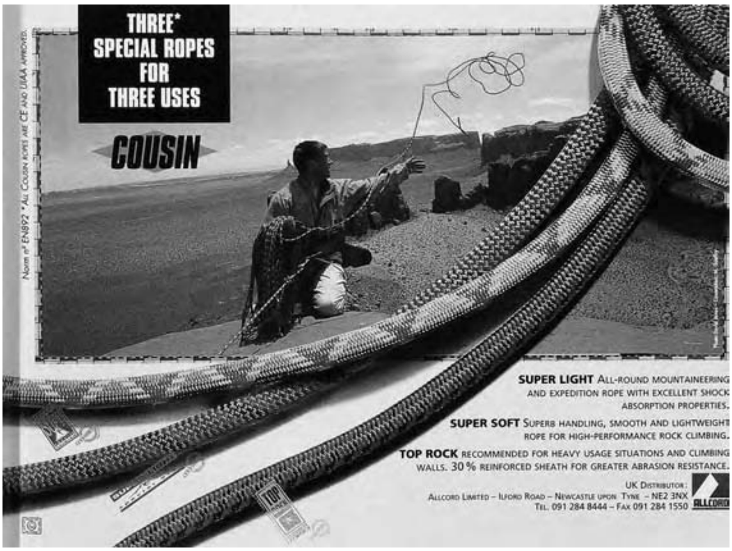


Fig. 1.35 A modern advertisement for ropes.

Fig. 1.36 A fatal rope-break following the first ascent of the Matterhorn in 1865. Whymper and the guide, Taugwalder, were joined by a large rope, but the connection to Lord Francis Douglas and three others was by a sash cord, which broke. Four climbers died. From *Scrambles Amongst the Alps* by Whymper, 1871.

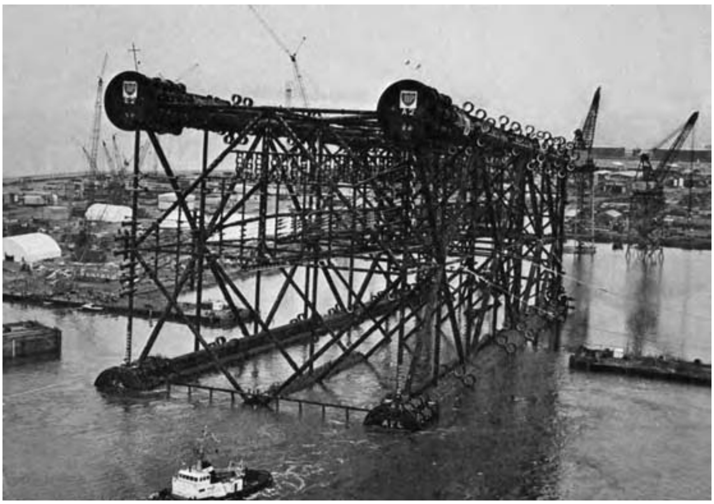


Fig. 1.37 A controlled rope-break – *Highland Fabricators* float-out ropes. Polyester superline ropes hold platform against quayside until tugs are ready to pull out. Then the ropes are blown apart by explosive charges.

Fig. 1.38 A climber at the end of the nineteenth century. From *Rock Climbing in the English Lake District* by Owen Glynne Jones, 1973.

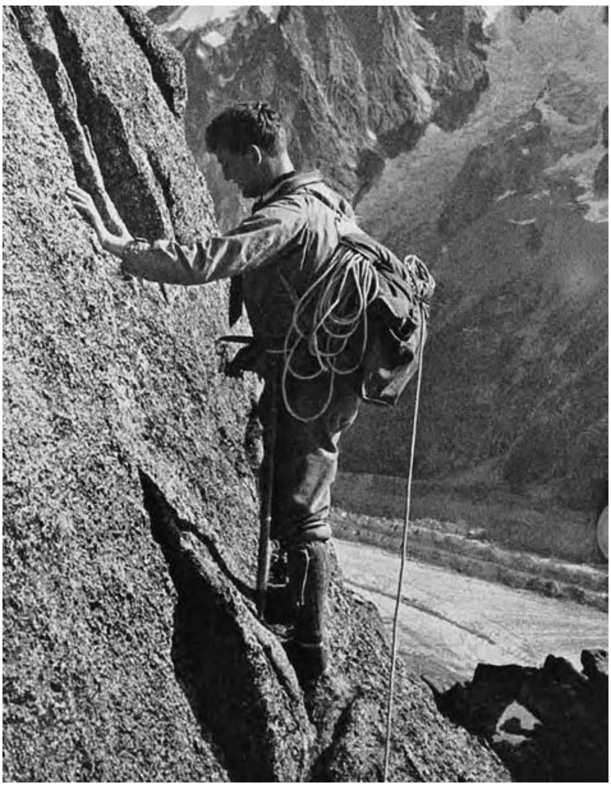


Fig. 1.39 Little had changed by the 1930s; a climber in Chamonix.

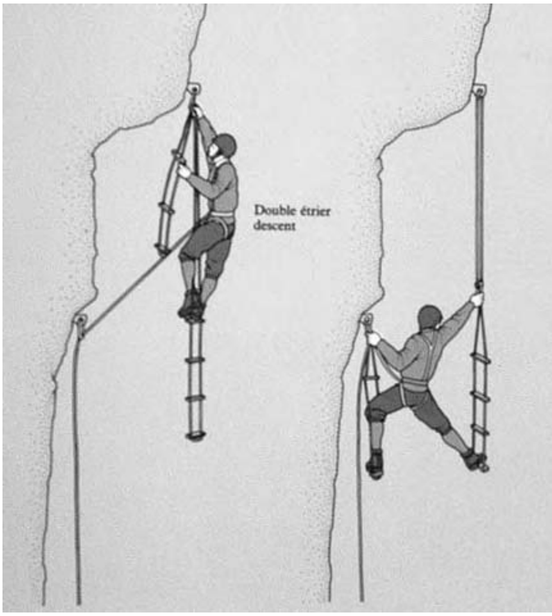


Fig. 1.40 Etriers and other devices aid climbers in the second half of the twentieth century.

Fig. 1.41 Modern rock-climbing.

Fig. 1.42 Rope as a decoration on a temple in Nara, Japan.

Fig. 1.43 Rope as a decoration in a shop-window display.

Fig. 1.44 A gruesome use for rope. From *Stabbed with a Bridport Dagger* by J B Smith in *The Dorset Year Book*. A Bridport dagger is a colloquial term for a hangman's rope, such as was made from *the best Hemp growing about Brydport* (Thomas Fuller, 1608–1661).

Fig. 1.45 A joyful use for rope: bungee jumping in New Zealand.

2

Ropemaking materials

2.1 Range of materials

The primary materials used for making ropes from natural or synthetic organic products are fibres, but, as mentioned in Section 1.1.2, almost every form of long, flexible material has been used in some place at some time or other. Here, we deal only with materials that are used in industrial rope production. In addition to many types of fine fibres, this includes some thick monofils, polymer tapes and slit film. Silk and other textile fibres may be used in decorative cordage, and mineral fibres might be used where heat resistance or some other special function is required, though asbestos is no longer acceptable on health grounds, but these fibres are not covered in this book; nor is steel for wire ropes.

Secondary materials include finishes on yarns as supplied to ropemakers, fillers and lubricants incorporated during ropemaking, and plastic jackets on some ropes.

2.2 Natural fibres

2.2.1 Traditional cordage fibres

Himmelfarb (1957) lists the seven fibres in Table 2.1 as *primary* [cordage] *fibres in international trade*. He goes on to list ten more as *secondary fibres* and 21 as *of minor importance*. In a more comprehensive list, sourced from ASTM Standard D123-52, he includes one seed fibre (cotton), 48 bast (soft) fibres, 30 leaf (hard) fibres and three palm and miscellaneous fibres. Only a minute fraction of the cotton crop goes into cordage, and there is now probably little hemp, flax or jute used, except in some small cords or in local use. Sisal and henequen are still extensively used, particularly in binder twine, where lack of biodegradability is an impediment to polyolefins in the market. Abaca (manila) is used for higher-quality ropes, when consumers want a traditional product or where the impact of synthetic fibres is weaker.

The hard fibres come from the leaves of plants and Fig. 2.1(a, b) shows how the fibre bundles reinforce the structure. The soft bast fibres, Fig. 2.1(c), stiffen the stems

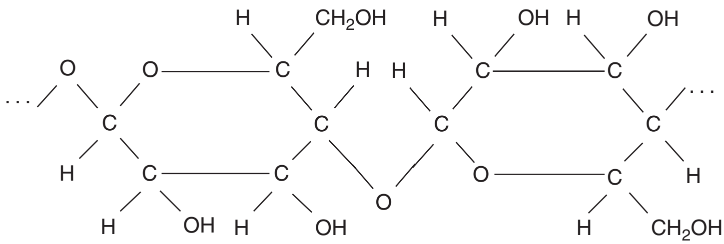
Table 2.1 Principle vegetable fibres for cordage, as listed by Himmelfarb (1957), together with world production in 2000

Fibre	Botanical name	Location in plant	Production in 2000 (million tonnes p.a.)
Abaca (Manila)	*Musa textilis*	leaf	0.1
Sisal	*Agave sisalana*	leaf	0.4
Henequen	*Agave fourcroydes*	leaf	
Jute	*Corchorus*	stem	3.5
Hemp	*Cannabis sativa*	stem	0.1
Flax	*Linum usitatissimum*	stem	0.6
Cotton	*Gossypium*	attached to seed	19

of plants. More information on vegetable fibres, other than cotton, is given by Franck (in press).

2.2.2 Cotton

Cotton, which is grown in most countries in latitudes from Greece to Australia, accounts for about half the total world fibre production. The fibres are single plant cells, which grow in large numbers on the seeds within the cotton boll (typically 150 000 fibres on 75 seeds). When the fibres reach maturity, the boll bursts open to show the soft wad of fine fibres ready for picking. Apart from absorbed water, cotton is almost pure cellulose, with only 2% of other substances, mostly fats, waxes and pectins in outer layers and mineral salts in the lumen. Cellulose is a natural polymer molecule with the formula:



Each molecule, which is about 5 μm long, comparable to the fibre diameter, has a length-to-width ratio of 10 000 : 1. The many – OH groups are important because they form hydrogen bonds to neighbouring molecules or to water molecules. The molecule is ribbon-like, but has some flexibility, particularly for bending in one plane and twisting. The cellulose is synthesised from glucose at enzyme complexes within the cells. Each complex generates about 30 chains that crystallise into ribbon-like fibrils, which form the cell walls. Absorbed water lies between the fibrils. A primary wall forms first, to the external dimensions of the fibre, but most of the cellulose is laid down inside the primary wall in daily growth rings as a secondary wall. The fibrils follow helices with an angle of about 21°, which alternate from right-handed to left-handed at intervals along the fibre. The mature fibre is circular with a hollow

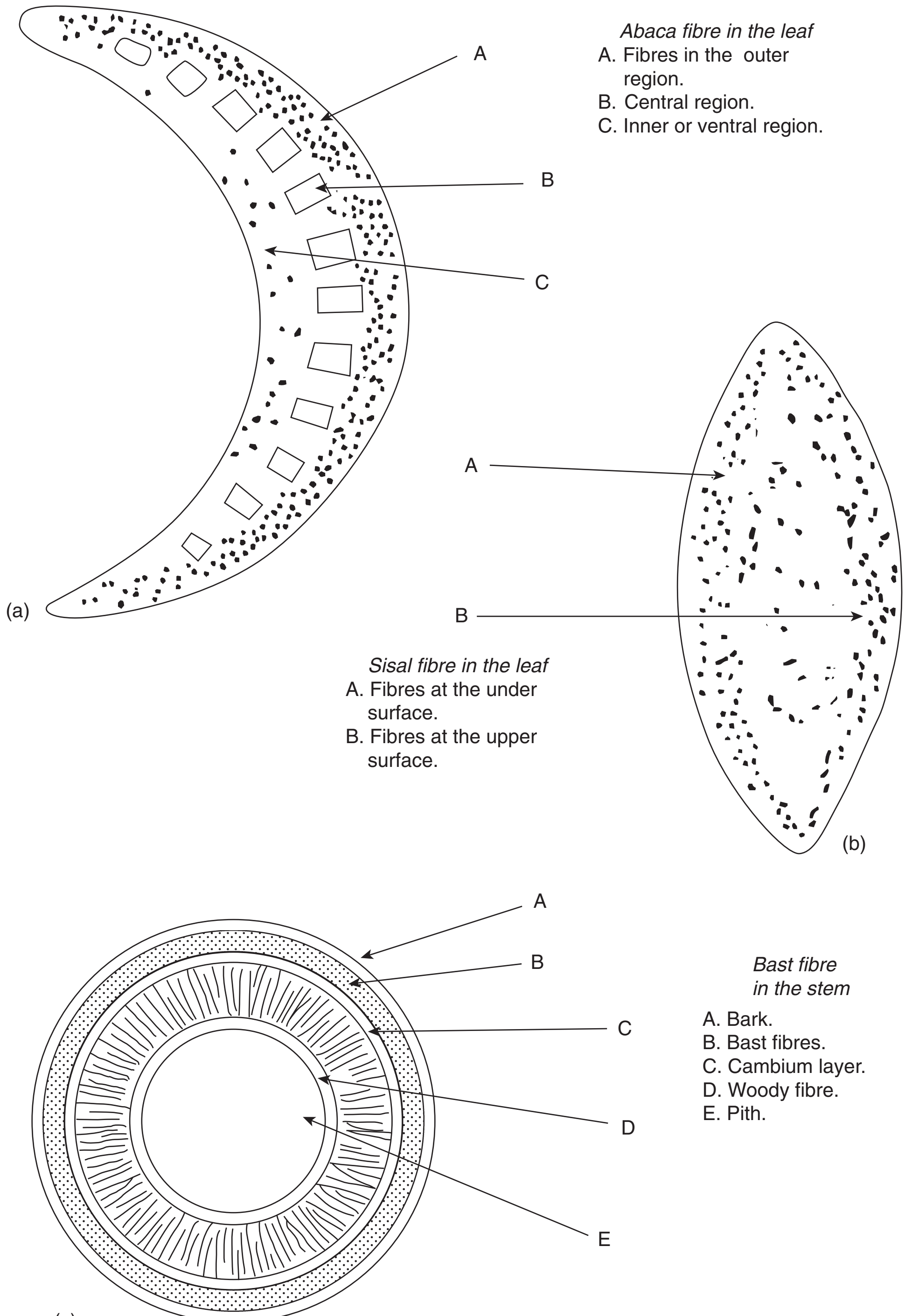


Fig. 2.1 Location of reinforcing fibres in plants. (a) In abaca (manila) leaf. (b) In sisal leaf. (c) In the stem of a bast fibre plant. From Himmelfarb (1957).

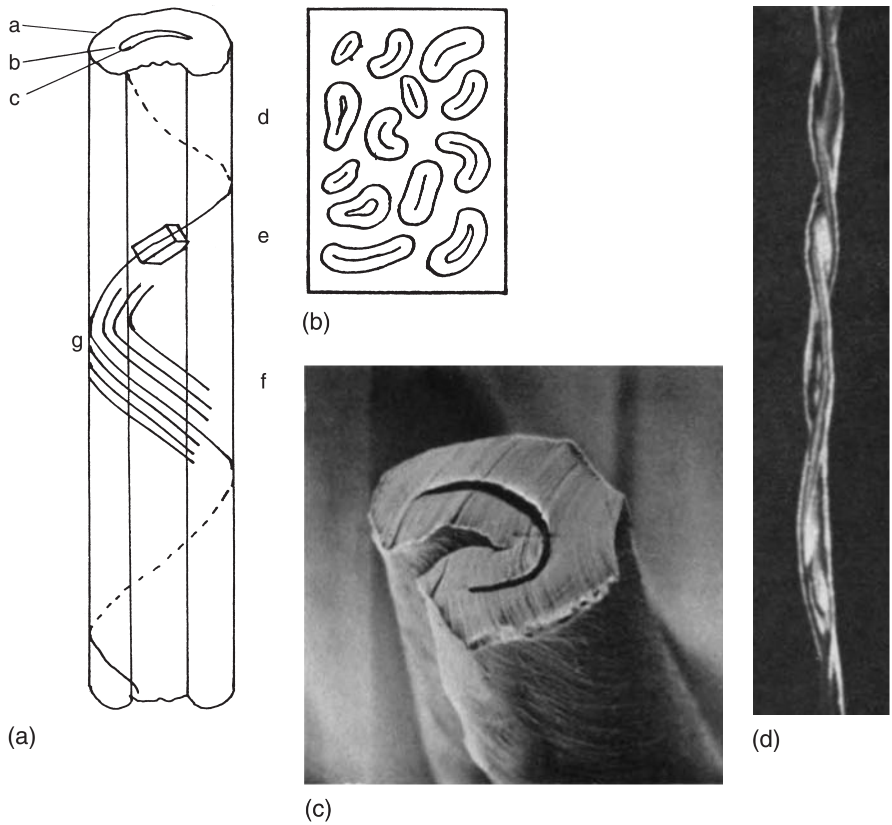


Fig. 2.2 Features of cotton fibres. (a) Schematic view: a – primary wall; b – secondary wall; c – lumen; d – molecule; e – crystal lattice; f – fibrils; g – reversal. (b) Typical cross-sections of mature fibres. (c) Scanning electron microscope view of cross-section of cotton fibre. (d) Convolutions in cotton fibre.

lumen at the centre, but, on drying, this collapses into a convoluted ribbon. Figure 2.2 illustrates features of cotton fibres. Different varieties of cotton fibres range from 10 to 30 dtex in linear density, 3 to 6 μm in diameter.

The extension of cotton fibres is determined by deformation of the crystal, but their extensibility is increased by their convoluted, reversing, helical form. The ease of extensibility and the fineness cause the softness of cotton fibres. Cotton is a moderately strong fibre. Cotton fibres are naturally slightly off-white, but can be bleached to greater whiteness. The irregular shape of the fibres gives a matt appearance. These characteristics lead to the soft handle, dull white appearance, and moderate strength and extensibility of cotton ropes. The fibre flexibility made cotton ropes suitable for uses where there is considerable bending, for example around pulleys for drive ropes, for which manila ropes would be too stiff.

2.2.3 Hard fibres

The hard cordage fibres constitute the stiffening components of the long, narrow leaves of some plants – abaca is sheath-like and the agaves are spiky. As shown in

Fig. 2.3, the 'fibres' are bundles of many cells running the length of the leaves, which in sisal are a metre or more long and in abaca may be as much as 7 metres. The individual fibre cells are 1–7.5 mm long by 7–50 μm wide in sisal and 2.5–12.5 mm long by 14–50 μm wide in abaca. After harvesting, the fibre strands are stripped mechanically from the leaves and dried.

There are major differences from cotton fibres:

- They are far from being pure cellulose. As shown in Table 2.2, they contain appreciable amounts of lignin (a woody material), gummy pectic substances, and hemicelluloses. This makes the material stiffer and gives a yellowish to brown colour to the fibres.
- The helix angle in mature fibre cells is lower, typically 7 to 10°. This increases the tensile modulus of the fibres.

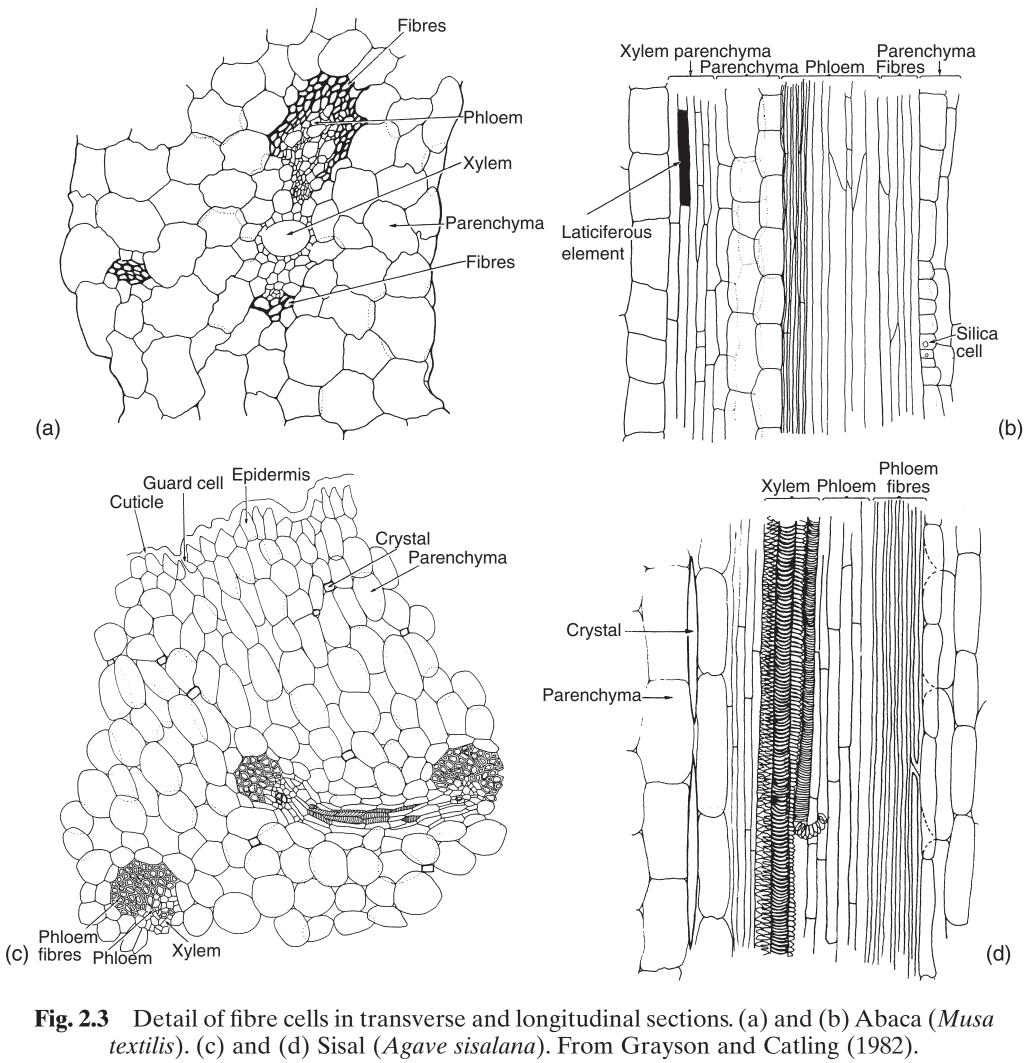


Fig. 2.3 Detail of fibre cells in transverse and longitudinal sections. (a) and (b) Abaca (*Musa textilis*). (c) and (d) Sisal (*Agave sisalana*). From Grayson and Catling (1982).

Table 2.2 Chemical analysis of vegetable fibres. From Himmelfarb (1957)

Fibre	Cellulose (%)	Water (%)	Ash (%)	Lignin etc. (%)	Extractives (%)
Abaca (Manila)	64	12	1.0	22	1.6
Sisal	77	6.2	1.0	15	1.1
Henequen	78	4.6	1.1	13	3.6
Jute	63	9.9	0.7	24	1.4
Hemp	77	8.8	0.8	9.3	4.0
Flax	76	9.0	1.0	10	3.5
Cotton	90	8.0	1.0	0.5	0.8

- The fibres, as extracted from the leaves and used, are much coarser. Himmelfarb (1957) quotes linear densities of 225–450 dtex for sisal and 150–300 dtex for abaca. However, the fibre strands are about one meter long in sisal and may be several metres long in abaca, so that the length-to-width ratio, which is a determinant of reduction in tension due to slip at fibre ends in twisted yarns and ropes, is comparable to cotton. The coarseness of the fibres makes them unsuitable for thin cordage.

Abaca fibre cells have a large lumen, which makes the fibres more flexible than sisal and gives some natural buoyancy.

Henequen is another of the agave family, yielding fibres similar to sisal. Himmelfarb (1957) also describes the following hard cordage fibres: cantala (maguey), another agave; caroa, from a plant of the pineapple family; coir from the husks of coconuts; esparto, a grass fibre; istle, from plants growing wild in Mexico; Maritius 'hemp'; phormium, New Zealand flax; and sansevieria.

2.2.4 Soft fibres

The soft cordage fibres, also known as bast fibres, stiffen the stems of plants. They are muticellular, with individual fibre cells similar in size to those of the hard fibres. However, the strands are extracted down to much finer fibres for use in textile products. The separation of the fibres follows 'retting', a process of degradation during immersion in ponds, tanks, or being laid out to collect dew. The mechanical action of processing further reduces the fibre size.

Flax, which is mainly used to make linen fabrics, and hemp, which is having a 'green' revival, are high-quality fibres. As shown in Table 2.2, they contain more non-cellulosic substances than cotton, which gives them a strong, off-white colour. The linear density of the fibres as used is in the range of 2.5–3.5 dtex, slightly coarser than cotton, and they can be several centimetres in length. The helix angle is around 10°, so that they have a higher tensile modulus and strength than cotton. The fibre fineness and the mechanical properties makes these the most suitable natural fibres for strong, fine cordage.

Jute is a lower-quality fibre. Its lignin content gives it a brown colour and, as used, the fibres have an intermediate linear density of 20 to 30 dtex.

2.2.5 Processing into yarns

Natural fibres are supplied to the textile industry in tightly packed bales. The conversion into yarns varies somewhat according to the type of fibre, but the typical

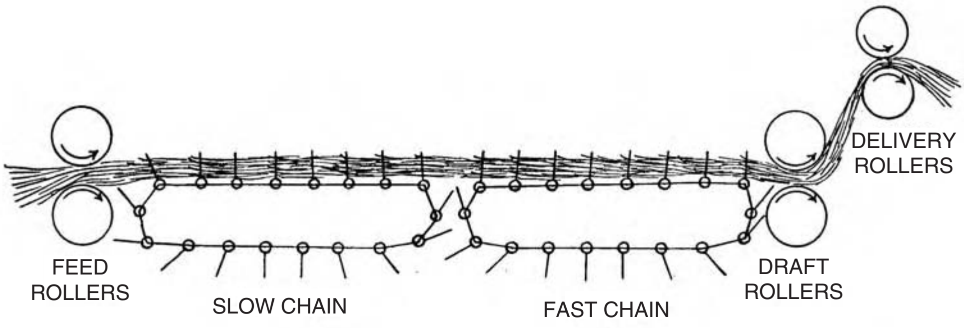


Fig. 2.4 Diagrammatic arrangement of John Good's machine. From Himmelfarb (1957).

steps for fine or intermediate fibres, such as cotton, flax and jute, are as follows. After opening the bales, the fibres are tipped into hoppers and fed into opening machines, which do an initial separation and cleaning action. Flax, hemp and jute may be subjected to a coarse combing operation, known as hackling, in order to break the fibres down into the required size. The next stage is carding, when the fibres pass through counter-rotating rollers covered with projecting wires. This completes the separation of the fibres. The material is doffed from the last roller as a web, which is then condensed into a thick, circular card sliver. In the sliver, the fibres are still imperfectly oriented and are folded back on themselves in leading and trailing hooks. A number of slivers are fed together into a drawing machine and stretched several times in length. There are usually two drawing stages, to pull out both leading and trailing hooks, and then another drawing with insertion of a small amount of twist on a roving frame. This provides the input to ring-spinning when there is attenuation down to the required yarn size and the insertion of sufficient twist to give a strong, self-locking structure. In this traditional method, as in most hand-spinning, twist is inserted by rotation of the take-up package without a break in the yarn path. In the last 50 years, several alternative methods of open-end spinning have been introduced, in which twist is inserted at a break in the path as the yarn is formed. This avoids the need to rotate heavy packages at high speed.

The long, coarse, hard fibres are prepared for spinning by repeated combing, which is also used in some long, soft fibre processing lines. The first machine, which removes much extraneous material, is known as a hackler. This is followed by a breaker, which combs, drafts and converts the fibre bundles into continuous slivers. The spreader is similar but includes doubling, as well as combing and drafting. Figure 2.4 illustrates the breaker and spreader machines patented by John Good in 1869. The slivers of coarse fibres can be fed directly into spinning machines, but those of finer fibres are first passed through a roving frame.

Yarns wound on suitable packages are supplied by spinners to ropemakers.

2.3 General-purpose synthetic polymers

2.3.1 Manufactured forms

Until 1900, the only available fibres were those found in nature. Then cellulose was dissolved and extruded to form 'artificial silk'. Rayon and acetate fibres were well established by 1930, but had no impact on ropemaking, though high-tenacity rayon found a market in tyre cords. The 1920s saw an important scientific breakthrough. It was recognised that the natural fibres, as well as rubbers and resins, were polymers, also called macromolecules, consisting of thousands of monomer units joined in long chains. Chemists started to synthesise new polymers, initially by the splitting open of vinyl compounds, $CH_2{=}CHX$, and converting them into chains $(–CH_2–CHX–)_n$, but these materials had only limited success as fibres. Polyvinyl alcohol $(–CH_2–CH(OH)–)_n$ fibres in their insoluble form have been extensively made in Japan and China, and as *Kuralon,* were widely used in Eastern Asia in fishing ropes and nets.

The break-through that transformed the fibre industry was the invention of nylon 6.6 by Carothers and his colleagues at DuPont in 1935. Commercial production was well underway in 1939, had moved from ‘silk’ stockings to parachute cords by 1945, and then into larger ropes by 1950. Nylon was followed in ropes by polyester and the polyolefins (polyethylene* and polypropylene). These polymers are extruded from the melt and oriented by drawing to provide the ‘textile yarns’, which are the starting material for rope production.

There are several different forms:

- Multifilament yarns, consisting of many continuous filaments with diameters in the order of 10 μm.
- Staple fibres of limited length, which give a hairy surface to a rope, resembling a natural fibre rope and preferred for handling in some applications.
- Thicker monofilaments, used singly as the ‘textile yarns’.
- Extruded tapes.
- Slit film that is fibrillated in processing.

There may also be a mixing of polymers, as described in Section 2.3.6.

2.3.2 Nylons

Chemically, nylon 6.6 is a polyamide, poly(hexamethylene-adipamide), with the formula:

$$[–NH–CH_2–CH_2–CH_2–CH_2–CH_2–CH_2–NH–CO–CH_2–CH_2–CH_2–CH_2–CO–]_n$$

Soon after the invention of nylon 6.6, another polyamide, nylon 6, was invented in Germany. Chemically, nylon 6 is poly(caprolactam) and two repeats of its basic formula are:

$$[(–NH–CH_2–CH_2–CH_2–CH_2–CH_2–CO–)(–NH–CH_2–CH_2–CH_2–CH_2–CH_2–CO–)]_{n/2}$$

It will be seen that the differences between nylon 6 and 6.6 are: (1) that the repeat length in nylon 6 is half that in nylon 6.6, and (2) that nylon 6 has a direction in the molecule –NH . . CO–NH . . CO– . . . , whereas nylon 6.6 looks the same from either direction. These differences cause small differences in the properties of nylon 6 and 6.6, most notably that nylon 6 melts at a lower temperature than nylon 6.6. The

* High-performance polyethylene fibres, see Section 2.4.4, are a later and different development.

numbering terminology of nylons relates to the numbers of carbon atoms in the monomer units. Some other nylons are in production as plastics and some have been tried for fibres, but none are cited as used in ropes.

What makes the nylon molecule, and also polyester, successful as a fibre material is the alternation of two types of unit along the chains, as indicated in Fig. 2.5. The $-CH_2-$ sequences provide flexibility, since above about $-100°C$ there is free

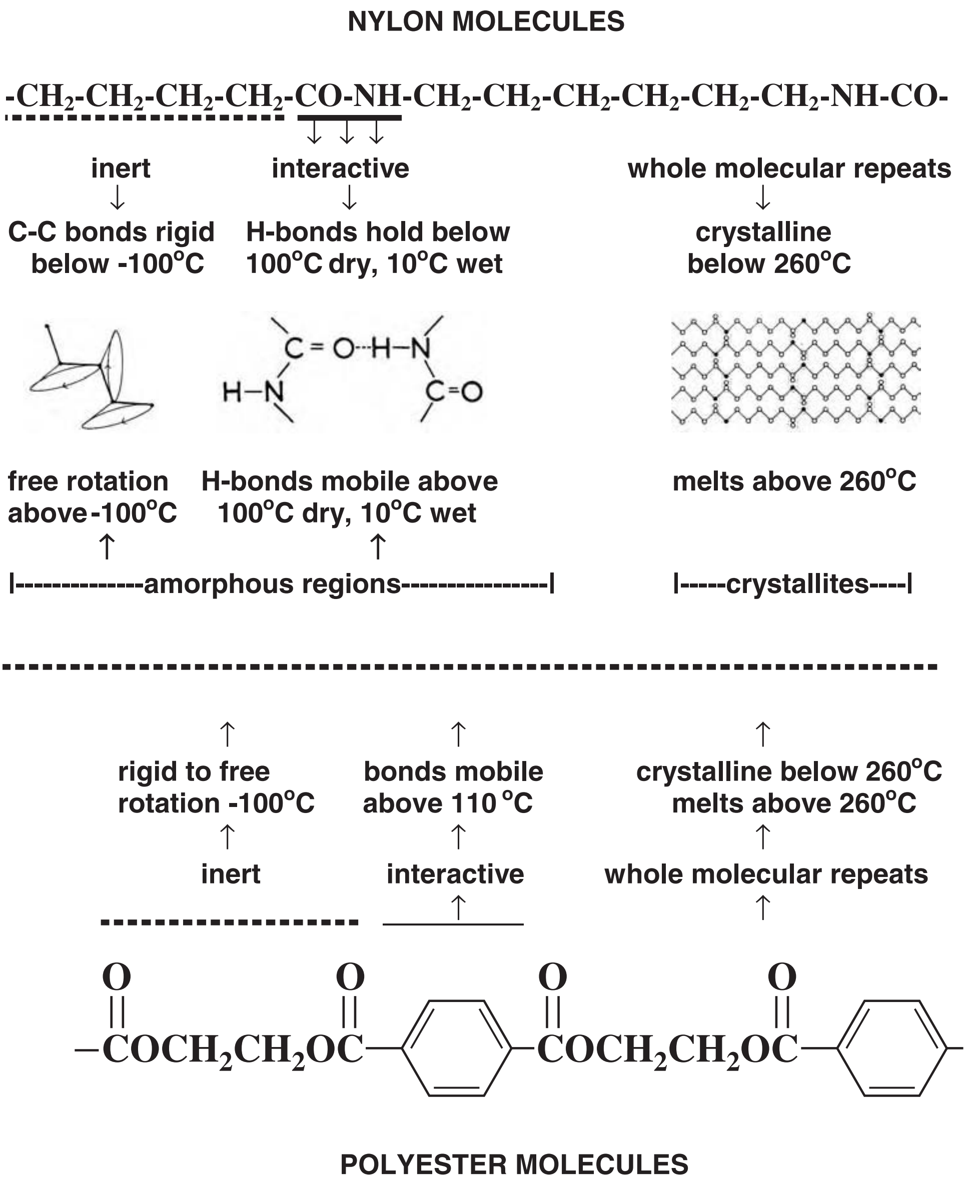


Fig. 2.5 Thermo-mechanical responses of nylon and polyester molecules, showing effect of alternating inert and interactive chemical groups. Transition temperatures, which may vary with test conditions, are indicative values. The polyamide molecule is nylon 6.6: nylon 6 melts at a lower temperature.

rotation around the C–C bonds. The –CO–NH– groups attract one another with hydrogen bonds, which are intermediate in strength between the covalent bonds of main chains and the weak van der Waals' forces between most other molecular groups. In the dry state, the hydrogen bonds become mobile around 100°C. However, absorbed water gives mobility at lower temperatures. The molecules also crystallise, with a melting point of about 260°C in nylon 6.6.

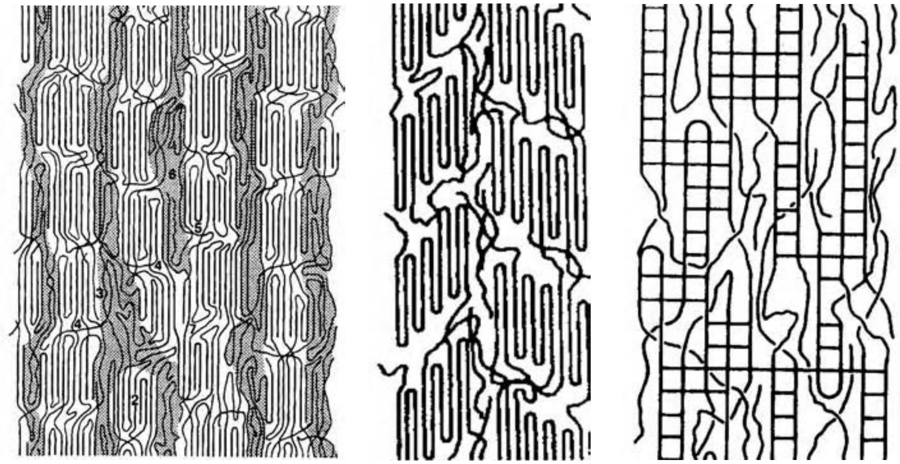
The stages in the manufacture of high-tenacity, industrial nylon yarns are as follows:

- polymerisation of nylon 6 or 6.6 from intermediate chemicals derived from oil;
- in continuous processing, feeding of molten polymer to fibre production; in discontinuous processing, solidification of granules as feedstock for fibre production;
- extrusion of the molten polymer through spinnerets, which typically contain 100 to 300 holes; attenuation and cooling of the molten thread line; application of spin finish; wind-up of undrawn yarn, or in a continuous process feed to drawing;
- drawing of the yarn by a draw ratio of around 4:1 and further thermo-mechanical processing to optimise properties; wind-up of drawn yarn.

The purpose of drawing is to promote orientation of the molecules parallel to the fibre axis, thus increasing strength and modulus and decreasing break extension. Production speeds are between 1000 and 5000 metres per minute. Specifications vary with fibre manufacturer, but typically, 1000–2000 dtex yarns with 150–300 filaments of around 7 dtex, would be supplied on 10 kg packages, each containing 100 to 50 km of yarn. Until the 1970s, a small amount of twist, about 1 turn/cm, was inserted during drawing to hold the fibres together. Now, the usual method is to pass the yarn through an interlacing jet, which provides enough entanglement to give yarn cohesion.

Nylon molecules pack into a regular crystalline lattice, and, under special laboratory conditions, single crystals can be grown. However, many techniques show that nylon fibres can be regarded as around 50% crystalline. For example, the fibre density is midway beteen the density in the crystal lattice and the density of disordered, amorphous material. The details of the fine structure are still poorly understood, but an impression is given by Fig. 2.6(a). Simpler working models of the structure, such as Fig. 2.6(b), are often drawn. Characteristic features are brick-like crystals of dimensions in the order of 5 nm, with some chains folding back at the ends of the crystallites and others fringing off as tie-molecules, which pass through disordered regions to join other crystallites. The detailed structure will vary with the thermo-mechanical history of the fibres, and, in some circumstances, the order/disorder is more uniformly distributed, as suggested by Fig. 2.6(c).

In this 'modified fringed-micelle' structure, the amorphous regions act like a rubber to give extensibility to nylon fibres, while the crystallites hold the structure together and limit the extensibility. In wet fibres or in dry fibres at higher temperatures, there is freedom for tie-molecules to be extended, limited only by the connections to the crystallites, but, in dry fibres, hydrogen bonds between –CO–NH– groups cross-link the chains and stiffen the elastomer. The shape of the initial part of the stress–strain curve depends on how and where the hydrogen bonds are formed. Increasing the degree of orientation increases the strength of nylon fibres, but there is a limit to how much draw can be applied without breaking the fibres. As seen in Fig. 2.6, there is considerable folding back of molecules, both at the ends



(a) (b) (c)

Fig. 2.6 Views of fine structure of nylon fibres. (a) Based on measurements on nylon 6. From Murthy *et al.* (1990). (b) and (c) Schematic views. From Hearle and Greer (1970a, b).

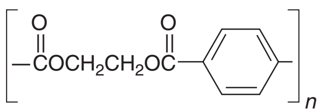
of crystallites and in amorphous regions; there are also molecular entanglements in amorphous regions, which eventually block further orientation; both of these effects limit the strength that can be achieved.

High-tenacity nylon was primarily developed for the tyre-cord market, and second-grade product was often sold to ropemakers. With increasing quality requirements for more demanding marine uses of ropes, premium grades have been introduced, with properties and finishes matched to market needs. In addition to multifilament yarns, nylon monofilaments are used in ropes, particularly where high resistance to surface abrasion is required. An advantage of nylon is its high elastic energy absorption, but a weakness, particularly for marine ropes, is its poor resistance to abrasion when wet.

2.3.3 Polyester (PET)

About ten years after the invention of nylon, a polyester, poly(ethylene-terephthalate), was synthesised and made into fibres, which were commercialised as *Terylene* by ICI and as *Dacron* by DuPont. Although these are trade-names, they have sometimes been misused as generic descriptions. Now that there are many manufacturers, *polyester* is the term to use, with PET or 2GT added when it is necessary to refer specifically to poly(ethylene-terephthalate). (Note that there is another class of polyesters, which contain latent additional functionality and which later *cross-link* to give thermoset resins used as matrices in glass-fibre and other composites.)

The chemical formula of PET is:



As in nylon, there are two sorts of units in the chains, The aliphatic sequences, –CO–O–CH_2–CH_2–O–CO–, provide flexibility, and the benzene rings provide molecular interaction. The two main differences from nylons are that: (1) the rings stiffen the structure in the amorphous regions, particularly as they associate in pairs; (2) there is no attraction for water molecules, so that the increased mobility of the benzene ring bonding is due only to temperature.

High-tenacity polyester yarns are melt-spun and drawn in the same way as nylon. The fine structure is similar, though there must be some differences that are not understood. The thermal transitions are analogous, as shown in Fig. 2.5, though they are not affected by water. The main property difference is that the stiffening effect of the benzene rings shows up as a higher initial fibre modulus. Polyester fibres do not suffer from the poor abrasion resistance shown by wet nylon, though in dry conditions nylon shows the better performance.

2.3.4 Other polyesters

There are other types of polyester fibres. Poly(trimethylene-terephthalate), 3GT, and poly(butylene-terephthalate), 4GT, contain three and four CH_2 groups in the monomer, instead of the two in PET (2GT). This gives greater flexibility to the chains and makes the properties more like those of nylon. It seems unlikely that these materials will be optimised for rope production.

In the 1990s, monomers from which poly(ethylene-naphthalate), PEN, can be synthesised, became available on a commercial scale. In PEN, the single benzene ring of PET is replaced by a double (naphthalene) ring. The double ring further stiffens the polymer chains, and increases the melting temperature and the fibre modulus. PEN yarns are being evaluated for ropes.

2.3.5 Polyolefins

Polyethylene (polythene), PE, is one of the simplest polymer chains: $[–CH_2–]_n$. Terminology can be confusing. The forms of PE synthesised in the 1930s, which had considerable chain branching, are known as *low-density polyethylene*. New catalysts in the 1950s, avoided chain branching and the product is known as *high-density polyethylene*; this is the form used in commodity PE ropes. There are premium grades of polymer known as UHMWPE, *ultra-high molecular weight polyethylene*, used in higher-performance plastics and in the HMPE or HPPE fibres described later. The other polyolefin used in ropes is polypropylene, PP, $[–CH_2–CH(CH_3)–]_n$. This differs from PE in having a –CH_3 side-group attached to alternate main-chain carbon atoms.

Being hydrocarbons, the polyolefins have weak molecular interactions. Yarns are produced by melt-spinning and drawing, but the temperatures are lower and the processes easier than for nylon or polyester. The resulting fibres are semi-crystalline. Polymer granules are easily available and many ropemakers have their own small-scale production units. Tapes and slit films can also be produced and used to make ropes. The films may be fibrillated by mechanical action, in order to increase flexibility.

Some coarse polypropylene is cut into long lengths and spun into yarns in the same way as for a natural fibre. This gives ropes that simulate the appearance and handle of sisal or manila ropes.

2.3.6 Copolymers, mixed polymers and mixed fibres

There are four ways in which two or more polymer types can be combined in ropes: copolymerisation; co-extrusion; bicomponent fibres; mixed fibres.

In copolymers, which have been little, if at all, used so far in ropes, different monomers are polymerised together. Monomers A and B can be made into the following types of copolymer:

- random copolymer:
  –AAABAABBBABBAAAABABBBAABABBBAABAAA–
- block copolymer:
  –AAAAAAAAAABBBBBBBBBBBBBAAAAAAAAAAA–
- graft copolymer:

```
–AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA–
     |                  |
     BBBBBBBBB          BBBBBBBBB
```

In co-extrusion, two or more different polymers can be blended in the melt and extruded together*. An important application in ropes is the co-extrusion of polyethylene and polypropylene to give ropes that are stronger than polypropylene ropes. The *American Group* claim that their *Ultra Blue* ropes made in this way have a 30 to 35% higher strength than equivalent polypropylene ropes and a wear life up to three times greater. Although detailed information on fibre structure is not available, it is likely that the included polyethylene, probably UHMWPE, becomes highly oriented and somewhat more chain-extended, as the fibres are drawn.

In bicomponent fibres, which have been little, if at all, used so far in ropes, the individual polymers are fed separately to skin and core or to opposite sides of spinneret holes.

Finally, different fibres may be combined together in ropes. This could be achieved by blending, in staple fibre spinning, or by co-mingling multifilament yarns, but the usual way is to combine different textile yarns in rope yarns. For example, a mixed polyester and polypropylene rope will stand severe heating in use. The polypropylene melts first, and its latent heat prevents the temperature rising to a value where the polyester would melt. The Cordage Institute refers to these as *combination, duplex or blended fibers.*

At the coarser level of rope construction, strands may be made of different fibres. For example, the core strand of a wire rope construction may be different to the others, and it is very common for a rope jacket to differ from the rope core.

2.4 High-modulus, high-tenacity (HM-HT) fibres

2.4.1 Maximising strength and stiffness

It was recognised by the early 1930s that, for maximum strength and stiffness, a polymer fibre should have the structure shown in Fig. 2.7. Long molecules, fully

* Note that the Cordage Institute describes co-extruded polymer fibres used in ropes in the following way, which does <u>not</u> accord with the general usage of the term *copolymer*:
Copolymer Fibers: Copolymers is the industry term for the melt combination of olefin polymer(s) (polypropylene/polyethylene) together or with other polymer(s) such as polyester. In most cases, copolymer combinations are based on proprietary formulas.

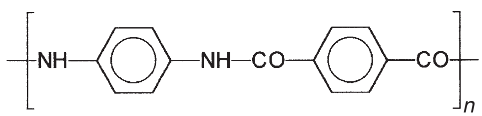
Fig. 2.7 Ideal polymer fibre structure. From Staudinger, 1932.

extended and highly oriented, are needed. The problem was how to make such structures. Two routes have been found. The first uses new, rigid, interactive polymer molecules that form liquid crystals, which can be oriented during fibre production. The second uses a flexible, inert polymer molecule, polyethylene, which can be super-drawn into the required form. No way has been found to get the required structure with nylon or PET, though this would be economical and valuable if it could be achieved.

Detailed accounts of HM-HT fibres are included in Hearle (2001).

2.4.2 Aramids

The first HM-HT fibre to be commercialised was the para-aramid fibre, *Kevlar*, from DuPont. Chemically, the polymer is poly(para-phenylene-terephthalamide), PPTA, which is a polyamide, like nylon, but with –CO–NH– groups linked by benzene rings, instead of $-CH_2-$ groups*. *Twaron* is another PPTA fibre, similar to *Kevlar*. The formula of PPTA is:



The polymer is expensive to make and to spin. It decomposes at around 450°C before it melts, and there are few solvents. Following polymerisation, PPTA is dissolved in concentrated sulphuric acid and then extruded through an air gap into a coagulating bath in a process known as dry-jet wet-spinning. PPTA molecules are relatively stiff and are attracted strongly to one another both by hydrogen bonding of –CO–NH– groups and phenylene (benzene ring) interactions. In solution, they form liquid crystal domains, which, on passing through the spinneret and being stretched in the air gap, become highly oriented. The resulting fibre has a fibrillar texture, but has the necessary highly crystalline, highly oriented, chain extended structure to give high modulus and high tenacity.

Figure 2.8(a) shows an impression of the fine structure. Certain viewing conditions in optical and electron microscopy show up regular bands with periodicities

* Note that the *meta-aramid* fibre, *Nomex*, which is thermally resistant but not high strength, has the chain linked to next-but-one carbon atoms on the benzene ring. The molecular shape does not lead to liquid crystal formation.

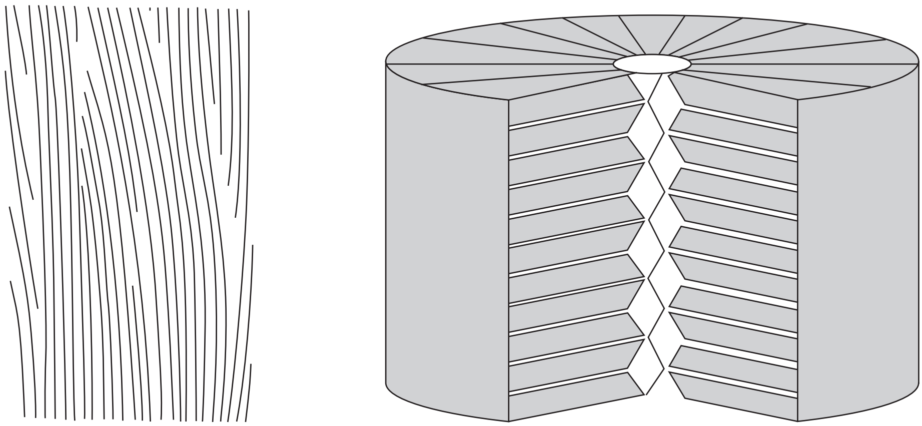
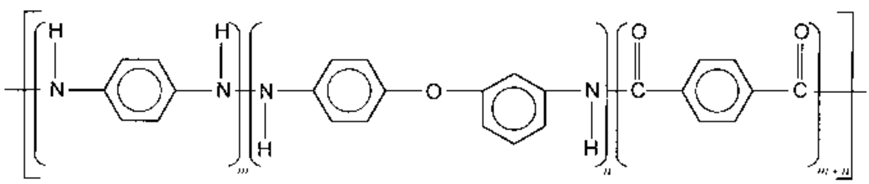


Fig. 2.8 (a) A view of the fine structure of an aramid (PPTA) fibre. (b) A pleated structure at a coarser scale. From Rebouillat (2001).

of 250 and 500 nm, which are interpreted as a pleated structure, shown in Fig. 2.8(b). Increasing orientation by straightening the pleats is a cause of creep under low tensions. Additional processing under tension at elevated temperature straightens the chains and yields higher modulus forms of PPTA fibres (see Table 2.4 in Section 2.5.3).

The molecules of PPTA are like flat ribbons. Along the chains, there are strong covalent bonds. Between molecules in the plane of the ribbons, there is moderately strong hydrogen bonding, but in the perpendicular direction, there are only weak van der Waals bonds, which are easily ruptured.

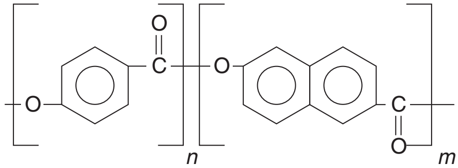
Aramid fibres are generically defined as having at least 85% of amide (–CO–NH–) groups joined directly to two aromatic rings. *Technora*, which is a fibre developed by Teijin 'after a remarkable scientific interpretation of the prior art' (quoted from Rebouillat, 2001), falls within this definition, but differs in several ways from PPTA fibres such as *Kevlar* and *Twaron*. It is a copolymer with the chemical structure:



However, as explained by Ozawa and Matsuda (1989), it is the physics of fibre formation and not the chemistry *per se*, that gives *Technora* its superior properties. The copolymer forms an isotropic and not a liquid-crystal solution. The highly-oriented and chain-extended structure results from the drawing and heat treatment after extrusion. The manufacturing process is relatively simple, since an organic solvent is used and coagulation is in an aqueous bath; strong acids are not used. Among the high modulus fibres, *Technora* has a good balance of reasonable price, low creep, high melting point, and good abrasion and flex resistance.

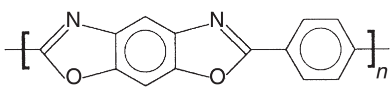
2.4.3 Other liquid-crystal fibres

Fully aromatic polyester molecules with some copolymerisation can be melted and associate in liquid crystals. They are known as liquid-crystal polymers (LCP) or, more accurately, as thermotropic liquid-crystal polymers (TLCP), though it would be more appropriate to regard the ‘P’ as standing for polyester. *Vectra* is a polymer of this type, developed by Celanese, that found use in injection moulding. Its chemical formula is:



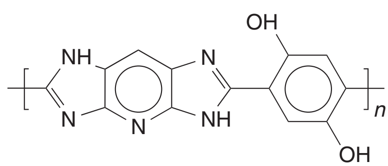
The availability of the polymer led to production of a fibre, *Vectran*, by melt-spinning. This is a cheaper process than the solution spinning of aramid fibre. However, the economic advantage is offset by the need for a long heat treatment to increase the molecular weight (chain length) by solid-state polymerisation. The scale of production has remained small and the fibre is restricted to specialised uses. Beers (2001) writes: ‘Ropes and cables for dynamic applications requiring fibre-to-fibre abrasion resistance and good bend-over-sheave is the largest single market for TLCP fibres. End-products include towed arrays/streamers for off-shore exploration, halyards for racing yachts, restraint lines for race cars, and long lines for tuna fishing’.

Extensive research on rigid-rod polymers in US Air Force laboratories led, *inter alia*, to poly(benzoxazole), PBO, or, more correctly, poly(para-phenylene bisoxazole). Five-membered rings attached to benzene rings give a very stiff molecule:



Following development work by DuPont and Dow, PBO fibres were finally commercialised by Toyobo as *Zylon.* Production is by methods similar to those for aramid fibres, and the structure has the same general character. It is convenient to regard PBO fibres as ‘super-aramids’.

Despite their high tensile strength, all the above HM-HT fibres have weak transverse bonding, which causes them to have poor transverse properties, namely low shear modulus and strength, and a low compressive yield stress. This has motivated Sikkema to invent a new polymer fibre, *M5*. Chemically, *M5* is poly {2,6-diimidazo(4,5-b : 4′5′-e)pyridinylene-1,4-(2,5-dihydroxy)phenylene}, or PIPD, with the formula:



The molecule is similar to PBO, but has the special feature of –OH groups that form hydrogen bonds in both transverse directions. The stronger intermolecular bonds enhance the transverse properties and this feature will be exploited in applications. Production on a semi-technical scale by a new company, Magellan, which has been set up by Sikkema, is expected in 2004.

2.4.4 High-modulus polyethylene (HMPE or HPPE)

Advantage can be taken of the long length of the molecules in ultra-high molecular weight polyethylene (UHMWPE) to make fibres with high strength and high tensile stiffness. These are known as high-modulus polyethylene fibres (HMPE) or high-performance polyethylene fibres (HPPE). In order to orient and fully extend the molecular chains, the most effective method is gel-spinning, which leads to *Spectra* from Honeywell (formerly Allied Fibers) and *Dyneema* from DSM. The polyethylene, $(–CH_2–)_n$, is dissolved in a good solvent at a fairly high concentration, extruded, and coagulated into a gel that can be super-drawn up to 100 times in length. This provides the required highly-crystalline, highly-oriented, chain-extended structure. Interaction between the molecules is very weak and, in contrast to the liquid crystal fibres, the melting point is low.

There are different grades of HMPE fibres. Producers have to balance the competing claims of properties and costs. In the single-stage process, ease of spinning and hence improved economy can be effected by choices of polymer molecular-weight distribution, solution concentration and other process parameters, but the economical choices act against superior yarn quality. *Spectra 900*, which was the first gel-spun HMPE fibre to come on the market, had poor creep properties. Later single-stage yarns were better. A second-stage process, in which yarn is subject to slow stretching close to the melting point, enhances the mechanical properties but increases costs. The choice of process also influences the fibre size, with *Dyneema* at 1 to 2 dtex and *Spectra* at 4 to 10 dtex.

An alternative method, invented by Ward in the University of Leeds, is to melt-spin polyethylene and then super-draw the solid fibre. The process is cheaper to run, but the strength is about half that of gel-spun HMPE and creep is greater. Celanese produced a yarn of this type called *Certran*, which was used in ropes, but it failed to be competitive when more *Spectra* and *Dyneema* became available.

Another solid-state extrusion process, developed by Nippon and now being produced in USA as *Tensylon*, involves compressing UHMWPE powder, followed by rolling and ultra-drawing. The strength of *Tensylon* is about 70% of gel-spun yarn, but its conversion efficiency is reported to be better. Weedon (2001) estimates that its selling price might be half that of gel-spun yarn.

2.4.5 Carbon and glass fibres

High-strength carbon and glass fibres are extensively used in advanced composites, but are too brittle in bending to be used as independent fibres in ropes. However, there is a potential for them to be used in the form of pultruded composite rods with diameters of a millimeter or less, in the same way as steel wires.

2.5 Fibre mechanical properties

2.5.1 Comparative properties

Table 2.3 lists typical comparative properties of the major rope fibres. It must be noted that there will be differences in actual properties of fibres from different sources and in different grades. Some of these variations are noted below, but, for accurate and current values, users should check with suppliers or test sample yarns. Textile grades of nylon, polyester and polypropylene have lower strength and higher extension. Explanations of the precise meanings of the property terms are given below.

2.5.2 Tensile testing

Together with rope construction, the fibre tensile stress–strain behaviour is the controlling factor of the most important properties of ropes. These include not only rope tensile properties, namely extensibility, and its complement, extensional stiffness, recovery from loading, creep and other time-dependent effects, energy absorption on impact loading, energy dissipation (which causes heating) break load, and break elongation, but also bending and torsional stiffness.

The measurement of stress–strain relations is a straightforward process. A fibre or yarn specimen is clamped in the jaws of an *Instron* or other test machine. The crosshead moves according to a controlled pattern – for example at a constant rate of extension up to break or in a more complicated sequence of cyclic loading. The tension is monitored by a load cell. In modern machines, test control and data recording are carried out on a PC. Because of the high ratio of length to diameter of the specimen, errors due to extension in the jaw region are negligible for most fibres. However, care must be taken with high-modulus fibres, where the elongation of the specimen is small and any deformation associated with end-effects will give too high an apparent elongation. For natural fibres of limited length, tests must be carried out on single fibres or carefully prepared bundles of fibres. For synthetic fibres, continuous filament yarns, as produced, are bundles of parallel or nearly parallel fibres, and so yarn tests give fibre properties. The response of high-twist yarns will be influenced by the twist.

Sufficient tests must be carried out to give a standard deviation of the mean that is small enough to show up relevant significant differences. Averaging of stress–strain curves blurs sharp changes in slope. In single fibre tests, the end-point at break is clear. In a yarn, the break will vary with the form of the test specimen. If there is no or very little twist or interlacing, the break of the individual fibres will be picked up over a range of elongations from the first break to the last, with the highest load occurring after a few fibres have broken. If a small amount of twist is inserted, e.g. to a twist angle of about 7°, the effect of obliquity on the stress at a given strain is negligible, but the break occurs sharply as a cooperative effect in the yarn. The peak load will be slightly higher than for a zero-twist yarn. Testing in this way is most relevant to the behaviour of fibres in ropes. Specimens break at their weakest point. Hence, measured strength reduces with increase of test length due to the greater probability of finding a very weak place (see Section 5.6.2 for a more detailed discussion of the effect in ropes).

The following factors should be controlled and specified in making tensile tests: specimen length; rate of extension (or some equivalent factor, such as time-to-break

Table 2.3 Properties of major rope fibres, based on Cordage Institute Charts, TTI and Noble Denton (1999), and Morton and Hearle (1993). Note that these are typical values, but the actual properties cover a range of values depending on the particular variant of each type of fibre

	Cotton	**Abaca**	**Sisal**	**Flax**	**Hemp**	**Jute**	**Nylon**	**PET**	**PE**	**PP**	**Aramid**	**TLCP**	**PBO**	**HMPE**	**Steel**
Density (g/cm^3)	1.54	1.32	1.32	1.54	1.5	1.5	1.14	1.38	0.95	0.91	1.45	1.40	1.55	0.97	7.85
Melting point (°C)	– – – – – – – – – – char at *ca*150 – – – – – – – – –						258*	258	140	165	decom 500	330	decom 650	150	1600
Moisture (%) 65% rh, 20°C	7.5	7.5	7.5	7	8	12	5	<1	0	0	1 to 7	0	0	0	0
Tenacity (mN/tex)	300	530	440	540	470	310	840**	820	530	620	2000	2200	3700	3500	330
Strength (MPa)	460	700	580	810	705	465	960	1130	500	560	2900	3100	5700	3400	2600
Break extension (%)	7	3	3	3	1.8	2.2	20	12	20	20	3.5	3.5	3	3.5	yld at 2
Modulus (N/tex)	5	20	20	18	21.7	17.2	7**	11	4	7	60	55	180	100	20
Modulus (GPa)	8	30	30	27	32.6	25.8	8**	15	4	6	90	80	280	100	160
Rupture work (mN/tex)	5	5	5	8	5.3	2.7	80	50	50	60	35	40	55	60	yld

* Nylon 6.6–218°C for nylon 6.
** Less when wet.

or frequency of cyclic loading); temperature; relative humidity for moisture-absorbing fibres.

In order to characterise material properties, the direct measures of load and elongation must be normalised to take account of specimen dimensions. The terminology is described in the following paragraphs, with additional information in Appendix I.

Strain = (increase in length) / (test length). Although usage varies, *strain* is preferably defined as a fraction; *extension* as a percentage; and *elongation* as an absolute increase in length.

Stress = (force) / (area) in conventional physics and engineering. However, for fibres, area is rarely measured directly but is calculated from linear density (i.e. mass per unit length) divided by density. For yarns and ropes, area is an ill-defined concept because of the spaces between fibres. It is therefore better to use *specific stress* = (force) / (linear density) = (stress) / (density), though, if the context is clear from the units or otherwise, 'specific' is often omitted.

Modulus and *specific modulus* characterise the slope of the stress–strain curve. The term can be used for *initial modulus* at the start of the stress–strain curve, *tangent modulus* at any point on the curve, *secant modulus* for a line joining the origin to a point on the curve (see Section 2.5.5 for definitions of dynamic moduli).

The specific stress at break is termed *specific strength* or *tenacity*. Another measure of specific strength is *breaking length*, since, with some blurring of the difference between mass and weight, we have:

$$\begin{aligned}&\text{length breaking under its own weight}\\&\quad=(\text{break load})/(\text{weight per unit length})\end{aligned}$$

The preferred unit for specific stress and the related quantities is Newton per tex, N/tex, where tex is linear density in g/km. The strict SI unit of linear density would be kg/m = Megatex. However, many other units are or have been in common use. In particular, g/den (grams/denier) values are often given. The link to conventional stress, modulus and strength is given by (value in GPa) = (value in N/tex)*(density in g/cm^3). Further information on units and conversions is given in Appendix I.

2.5.3 Tensile stress–strain relations

The tensile properties listed in Table 2.3 and the stress–strain curves for the fibres shown in Fig. 2.9 fall into four groups. (1) The hard vegetable fibres, abaca (manila) and sisal, have a fairly high modulus, intermediate strength and low break extension. (2) Nylon and polyester are appreciably stronger and have lower moduli and higher break extension. The main difference between the stress–strain curves of nylon and PET is the lower modulus of nylon. Polyolefins (PE and PP) are in the same group, but with somewhat weaker performance. (3) Cotton is a low strength and low modulus fibre, with a fairly low break extension. (4) The HM-HT fibres are the fourth group with strengths from 3 to 5 times greater than nylon/polyester, high moduli and low break extensions. PBO has the highest modulus and strength, but, when commercialised, the manufacturers expect *M5* to have a substantially higher strength than PBO. On a weight basis, steel performs poorly in comparison with all the fibres, but on an area basis has a strength between nylon/polyester and the HM-HT fibres.

It is important to note that the information in Table 2.3 and Fig. 2.9 is only roughly indicative of fibre properties. Actual values vary considerably with the particular

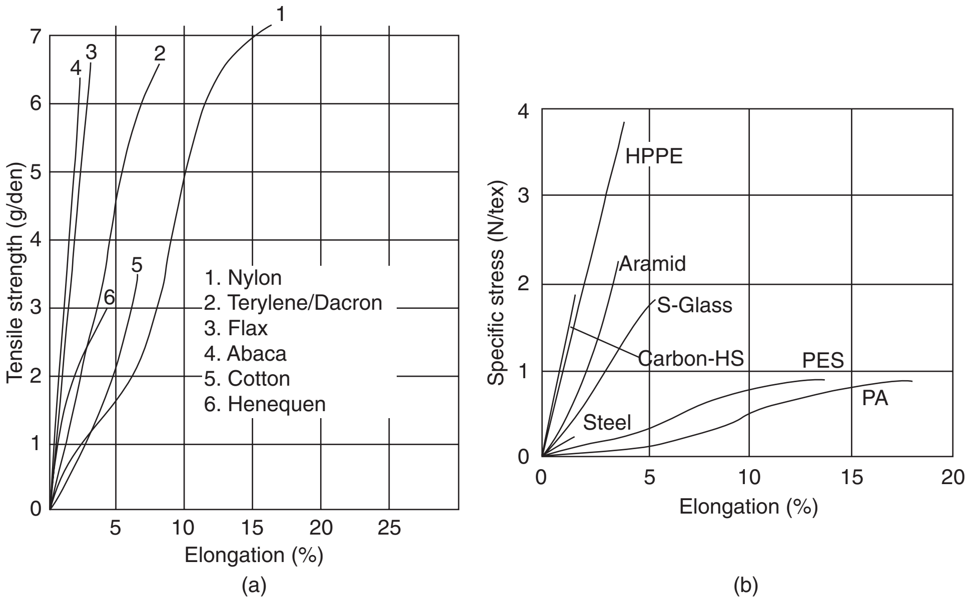


Fig. 2.9 Fibre stress–strain curves. (a) *Terylene* and *Dacron* are polyester fibres. Sisal is not included but would be similar to henequen, going to a higher strength. From Himmelfarb (1957). (b) HPPE = gel-spun HMPE, PES = polyester, PA = polyamide (nylon), HS = high strength. From van Dingenen (2001).
Note: The maximum of 7 g/den in (a) equals 0.6 N/tex, which is in the lowest quarter of (b). The current nylon (PA) and polyester (PES) in (b) are about 30% stronger than the corresponding materials of 1957 in (a). The traditional natural rope fibres in (a) would fall lower still if plotted in (b).

sample of natural fibres and the processing history of synthetic fibres. Increasing the degree of orientation imposed in melt-spun fibres has a major effect on increasing strength and modulus and reducing break extension, as shown by Fig. 2.10(a) for polyester. Industrial yarns used in ropes are high-orientation types. The lower part of the stress–strain curve is affected by the thermo–mechanical history, as illustrated in Fig. 2.10(b). With a different heat treatment in fibre manufacture, yarn as received may have stress–strain curves similar to [b] in Fig. 2.10(b). A typical plot of tangent modulus against strain is shown in Fig. 2.11. The modulus in cyclic loading is higher than that on the stress–strain curve, as shown by Fig. 2.12. In modelling rope performance, it is necessary to match the modulus as closely as possible to that corresponding to the prior and current conditions.

Table 2.4 shows the range of values for different types of aramid and HMPE fibres. The lower modulus of *Kevlar 29* is a consequence of the pleated structure shown in Fig. 2.8(b). The stress–strain curve turns upwards to give a greater modulus at higher stress, as the pleats are pulled out. Additional processing increases the modulus of the other aramid fibres. HMPE fibres are stronger and stiffer.

The mechanical properties of the natural fibres, and of nylon and, to a lesser extent, *Kevlar* are affected by absorption of water. Nylon is about 15% lower in strength and stiffness when wet than at 65% r.h., but the break extension is hardly altered. Within the likely range of temperatures in ropes, there will be little change

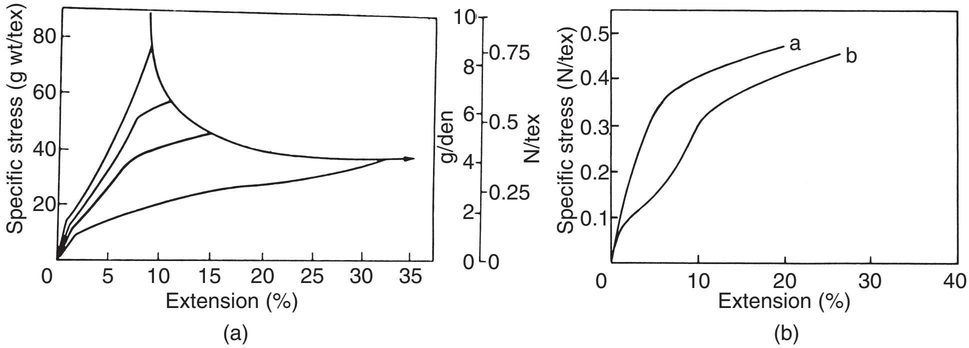


Fig. 2.10 Variations in polyester stress–strain curves. From Morton and Hearle (1993). (a) Effect of orientation, high to left, low to right. (b) Effect of heat treatment, a – as received, (b) – after immersion in water at 95°C.

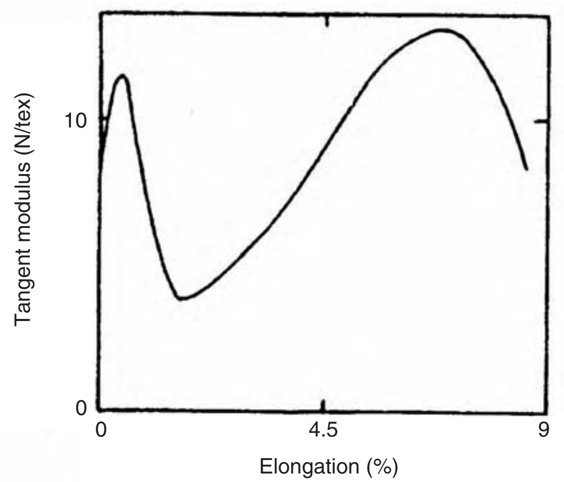


Fig. 2.11 Variation of polyester tangent modulus with strain. From van Miltenburg (1991).

in the properties of the natural plant fibres and the liquid-crystal HM-HT fibres. The strengths of nylon and polyester fall by 30 to 40% between 20°C and 100°C, with an increase of 70% in break extension and a fall of 60% in modulus. Polyolefin fibres (PE and PP) will have larger changes. HMPE fibres are also greatly weakened by increase in temperature, though, as shown by Fig. 2.13, this is related to rate effects.

To varying extents, polymeric fibres show hysteresis and imperfect recovery from extension, but measured values are dependent on rate of loading, time under load and recovery time.

2.5.4 Creep, stress relaxation and rate of loading

The time-dependence of tensile properties is shown by creep (elongation under constant load), stress relaxation (stress reduction at constant strain) and effect of rate

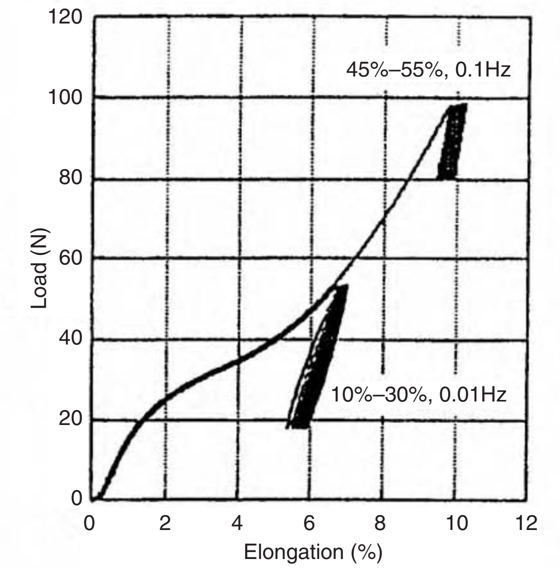


Fig. 2.12 Stress–strain response of a polyester rope yarn (AKZO *Diolen 855T*) in initial extension and repeated cycling. % values are percentages of break load. The steeper lines are overlapping hysteresis cycles, which move progressively to the right due to creep. From Bosman (1996).

Table 2.4 Range of properties of aramid and HMPE fibres. From Rebouillat (2001) and van Dingenen (2001)

Type	Tenacity (N/tex)	Modulus (N/tex)	Break extension (%)
Kevlar 29	2.03	48	3.6
Kevlar 49	2.08	78	2.4
Kevlar 149	1.68	115	1.3
Twaron	2.1	60	3.6
Twaron HM	2.1	75	2.6
Technora	2.2	50	4.4
Dyneema SK 60	2.8	91	3.5
Dyneema SK 65	3.1	97	3.6
Dyneema SK 75	3.5	110	3.8
Dyneema SK 76	3.7	120	3.8
Spectra 900	2.6	75	3.6
Spectra 1000	3.2	110	3.3
Spectra 2000	3.4	120	2.9

on stress–strain curves. Real-use situations may combine change of length and tension. Creep can be measured over long times by hanging fixed weights on yarns and noting the length at intervals. An estimate of stress relaxation is given by (creep)∗(modulus), since it is only easily measured over short times. Primary creep, which occurs at lower stresses, is recoverable in time under low or zero load, and the same mechanisms lead to inverse stress relaxation. Secondary creep, at higher stresses, is not recoverable. Creep rupture relates to the time to fail under a given load.

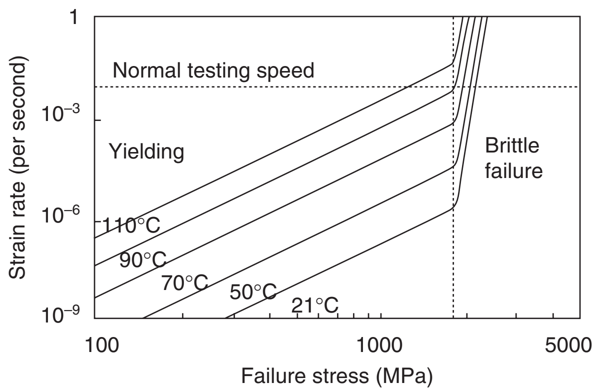


Fig. 2.13 Effect of temperature and strain rate on strength of *Dyneema*. Brittle failure indicates a sharp end to the stress–strain curve, whereas yielding is continuing elongation. ('Brittle' here does not imply the form of break found in materials such as glass.)

Table 2.5 Creep in one decade of log-time, as quoted in *Engineer's Design Guide to Deepwater Moorings*. From TTI and Noble Denton (1999)

	15% break load		**30% break load**	
	1–10 days	**10–100 days**	**1–10 days**	**10–100 days**
Polyester				
Diolen 855TN	0.240%	0.166%	0.093%	0.034%
Trevira 785	0.119%	0.069%	0.165%	0.009%
Aramid				
Kevlar 29	0.023%	0.066%	0.046%	0.021%
Kevlar 49	0.011%	0.030%	0.041%	0.009%
HMPE				
Spectra 900	1.7% 7/182 days*	13%	broken 0.7/4 days*	broken
Spectra 1000	1.1% 11/321 days*	6.3%	8% 1/28 days*	broken
Dyneema SK60	0.16% 70/>354 days*	0.47%	0.98% 7/123 days*	8%

* The figures in days for HMPE fibres are (time to start of rapid creep)/(time to break).

The molecular mechanisms of creep fall into two categories. The major effect at low stresses is a progressive straightening of molecules, often with a change in the links between molecular segments; this is usually recoverable and does not affect strength. At high stresses, whole molecules slide past one another and this leads, eventually, to rupture.

Table 2.5 gives a selection of creep data for fibres studied in the Fibre Tethers 2000 Joint Industry Project (TTI and Noble Denton, 1999). The creep of polyester yarns is small, but, augmented by realignment of the rope structure, is sufficient to require occasional tensioning of fixed lines. Nylon has a greater amount of primary

Table 2.6 Creep rupture. The measured strength–time coefficient k for nylon is 0.08 (Meredith, 1953). The available evidence indicates that k is less than 0.05 for aramid fibres and slightly more than 0.05 for polyester fibres

k	Time to fail at percent of 1-minute break load			
	20%	30%	50%	80%
0.05	2×10^{10} yrs	2×10^{8} yrs	2×10^{5} yrs	200 hrs
0.08	2×10^{4} yrs	1000 yrs	3 yrs	5 hrs
0.1	200 yrs	19 yrs	60 days	100 mins

creep. Aramid fibres creep to a small extent at low stresses as the pleated structure is extended.

Creep is potentially a more serious problem in HMPE fibres. As shown in Table 2.5, creep was very severe in *Spectra 900*, which makes it unsuitable for long-term loading, though it would be suitable for ballistic impact protection. *Spectra 1000* and *Dyneema SK60* have reduced creep, and later HMPE fibres have still less creep. When plotted against many decades of log(time), creep follows sigmoidal curves. For most fibres under typical test conditions, creep is in the region of constant or reducing slope, as shown by the polyester and aramid data in Table 2.5. However, HMPE fibres fall in the initial part of the sigmoid. Creep starts at a low rate, but then sharply increases after a certain time. For example, *Spectra 1000* at 15% of break load showed less than 1% creep in the three decades from 1 to 1000 minutes, but began to creep faster on a log(time) scale and had reached 25% in another 2.7 decades (one year). Above a certain load and time, HMPE creep becomes constant at a plateau rate, which is the top of the sigmoid. The rate of creep is strongly affected by temperature. For example, the plateau creep rate is 50 times faster at 20°C than at 0°C.

For most fibres, creep rupture is given by the following equation:

$$S = S_g[1 - k\log(t/t_g)] \qquad [2.1]$$

where t is the time-to-break under a load S and t_g under S_g, or, put another way, S is the strength at time t compared to test conditions, S_g, t_g.

The only available relevant values for the strength–time coefficient k are 0.080 for nylon, 0.088 for cotton and 0.079 for flax (Meredith, 1953). Aramid and other liquid-crystal fibres would be less than 0.05 and polyester slightly more than 0.05. Table 2.6 shows the effect on time-to-break at different loads.

HMPE fibres do not follow equation [2.1], but Table 2.5 shows that they can fail in times much less than those corresponding to $k = 0.1$. Later HMPE fibres will last for longer times. Time-to-break is very sensitive to temperature. Because of the wide range of incidence of creep, the creep potential of HMPE fibres needs to be checked in terms of the particular HMPE fibre and the conditions of test or use. For any fibre type, there will be a set of values of load, temperature and time below which creep is negligible, but above which it starts to become serious.

2.5.5 Dynamic testing, glass transition and hysteresis heating

Polymer fibres are inelastic: some of the energy of elongation is stored as strain energy and some is dissipated as heat. The simplest way of describing the behaviour in cyclic loading is by the parallel spring-and-dashpot model shown in Fig. 2.14(a). The elastic element gives an in-phase component of stress f in imposed cycling of strain e and the viscous component gives an out-of-phase component. This idealised model is strictly applicable only to the linear viscoelasticity with a single time constant. The total behaviour of real nonlinear materials with a spectrum of time constants is more complicated. However, for cycling at a small constant amplitude, the response is close to the idealised model. Even for more complex responses, the parameters derived from the idealised model can usefully be used.

Experimental results can be expressed in various ways, which are summarised in Table 2.7. In practice, as shown in Figs. 2.15, the width of the hysteresis loop will be smaller than in Fig. 2.14(c). The most commonly quoted quantities, indicated in Fig. 2.14(b), are the modulus E, which is the slope of the major axis, and the dissipation factor $\tan\delta$, where δ is the phase difference between stress and strain. However, readers may come across other quantities included in Table 2.7. Heating of ropes in

Table 2.7 Representations of cyclic testing

Quantity or notation	Basic relations	Other parameters
Imposed strain e	$e = e_m \sin(\omega t)$ t = time	$\omega = 2\pi f$ = angular frequency f = frequency in Hz
Stress f *Fig. 2.14*	$f = f_m \sin(\omega t + \delta)$ $= f_m [\cos\delta \sin(\omega t) + \sin\delta \cos(\omega t)]$ in-phase out-of-phase $= E_p e + \eta_p \, de/dt$	$E = f_m \cos\delta / e_m$ = in-phase modulus δ = phase angle or loss angle $\tan\delta$ = dissipation factor = $\eta_p \omega / E_p$ $\sin\delta = \cos\varphi$ ~ electrical power factor
Complex notation	$\mathbf{f} = \mathbf{E}\mathbf{e} = (E' + iE'')\, e_m \exp(i\omega t)$	real modulus = $E' = E_p = E$ imaginary modulus = $E'' = \eta_p \omega = E' \tan\delta$
Energy per cycle	stored = $2Ee_m^2$ (area of triangle) dissipated = $(2\pi)^1/_2 f_m e_m \tan\delta$ $= (2\pi)^1/_2 E\, e_m^2 \tan\delta$	$\tan\delta = (2/\pi)$ (dissipated/stored) ~$(2/\pi)$ (dissipated/total) for small δ specific damping capacity = ψ = (dissipated/stored) = $(\pi/2)\tan\delta$

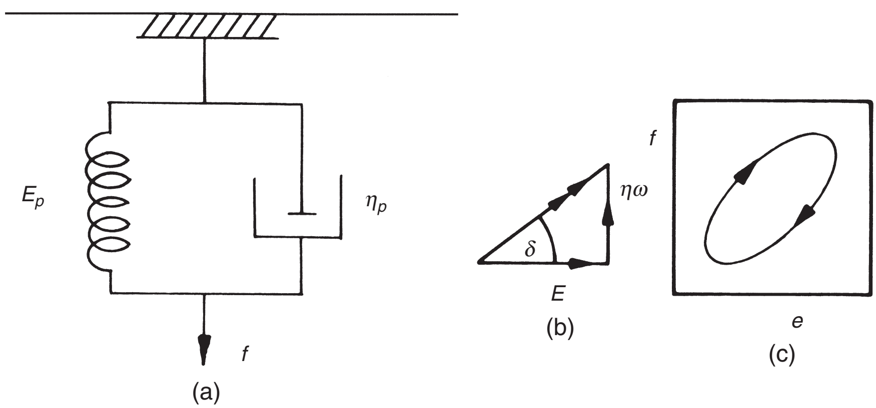


Fig. 2.14 (a) Parallel spring-and-dashpot model. (b) Vector diagram. (c) Response. (a) and (b) are from Morton and Hearle (1993).

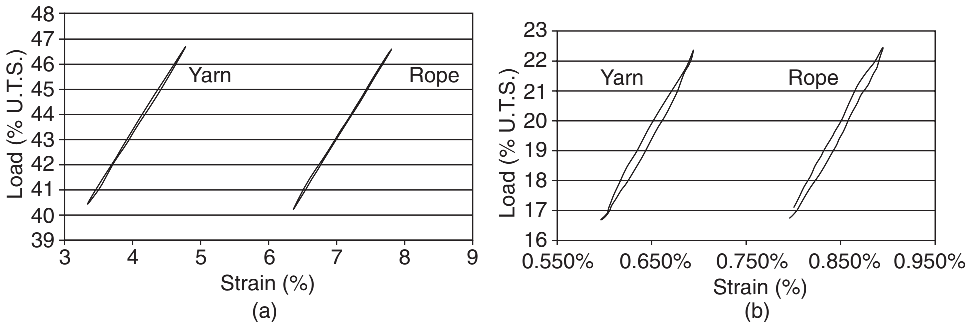


Fig. 2.15 Hysteresis loops for (a) polyester yarn and rope, (b) HMPE yarn and rope. The ropes had been worked in by prior cyclic loading. Experimental data from tests at Leeds University, England. (UTS = ultimate tensile strength.)

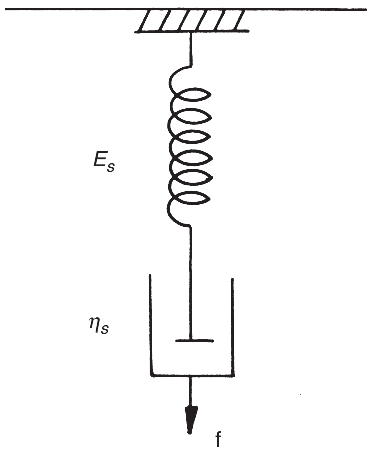


Fig. 2.16 Series spring-and-dashpot model. From Morton and Hearle (1993).

cyclic loading comes from the energy loss per cycle, which is given by the area within the loop and equals $(2\pi)*(^1/_2 E e_m^2 \tan\delta)$. Tanδ is referred to as the dissipation factor, but it should be noted that another quantity, $\psi = (\pi/2)\tan\delta$, which has been called the specific damping capacity, equals (dissipated energy)/(stored energy).

Although the model in Fig. 2.14(a) is adequate as a representation of what happens in any single cycle, the elastic constant E_p and the viscous constant η_p are not constants for changes in frequency, mean load, or large cyclic amplitudes, and may change progressively with successive cycles. There may also be non-recoverable deformation, which can be represented by a series spring and dashpot model (Fig. 2.16). Plastic deformation that is not time-dependent can be included as a friction element. Theoretical treatments of these complications, insofar as they exist, are complicated and difficult to apply to practical problems. A semi-empirical approach to relevant experimental data, with the parallel spring-and-dashpot model providing a framework, is the best option for describing individual cycles, but combinations of parallel and series models may be used to add in the creep in long-term loading.

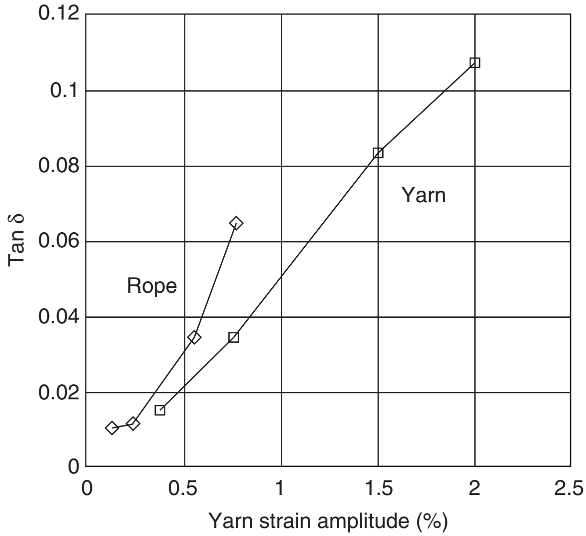


Fig. 2.17 Variation of tanδ with strain amplitude in a polyester yarn (*Diolen 855T*) and in a 17 mm 3-strand rope. From Bosman (1996).

From experimental data of the type shown in Fig. 2.12, Bosman (1996) discovered that the value of tanδ increases with strain amplitude, as shown in Fig. 2.17. This is a result that is not found in the polymer literature, where tanδ is usually regarded as a constant. The energy loss per cycle will thus be small for small strain amplitudes, but will be appreciable for large strain amplitudes. Heating in ropes is thus usually small at small cyclic amplitudes, but becomes appreciable at large amplitudes (see Sections 4.5.5 and 5.7.3). Data on other fibre types is lacking.

Figure 2.18 shows the variation of modulus and tanδ for polyester and nylon yarns. Although these are textile yarns, the general behaviour will be similar for rope yarns. In polyester, the modulus falls and tanδ rises to a peak at the glass transition temperature around 130°C, with only a small lowering for wet yarn. In nylon, moisture plays a large part and the glass transition falls from 100°C when dry to near 0°C when wet. A consequence of the rise in tanδ is that if heat starts to build up in a rope in cyclic loading, it then increases rapidly.

2.5.6 Fibre bending and torsion

When rods are bent, the outer surface extends and the inner surface contracts, with a neutral plane, which is central in linear elastic materials. This leads to the dependence of bending stiffness on *EI*, where *E* is the modulus and *I* is the area moment of inertia about the neutral plane. Bending moment *M* is given by *EI/R*, where *R* is the radius of curvature. For a circular rod, this becomes in terms of fibre radius *r*:

$$M = \pi E r^4 / 64R \qquad [2.2]$$

This relation applies to fibres for small curvatures, but, because of the oriented assembly of long molecules, polymer fibres have a low yield stress in compression.

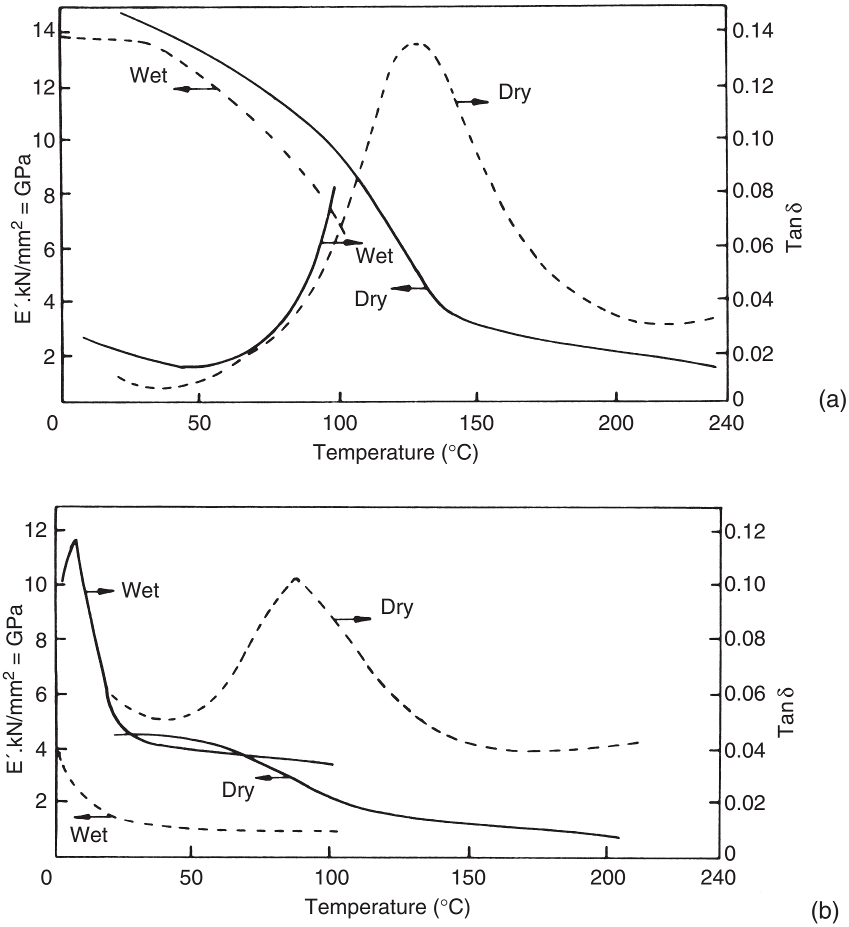


Fig. 2.18 Variation of modulus and tanδ with temperature and moisture. (a) Polyester. (b) Nylon. From van der Meer (1970).

Once the inner surface starts to yield, the neutral plane moves out because the resistance is higher on the tension side than on the compression side. The yielding is commonly, but not always, localised in kinkbands, which can be seen in polarised-light microscopy.

Because most ropes are composed of a very large number of fine fibres, the fibre radius r is very small in relation to any radius of curvature R associated with a rope. Bending can be ignored, except when localised kinking of fibres occurs. However, in ropes made of a smaller number of coarse monofilaments, bending deformations might be significant.

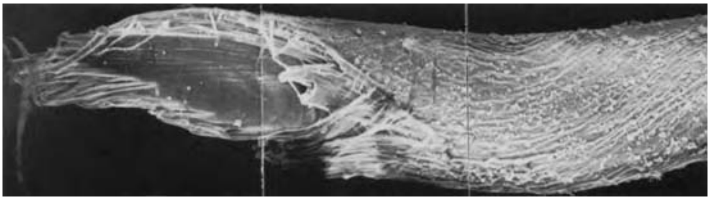
Similar arguments apply to fibre torsion, in which twisting moment depend on shear modulus and polar moment of inertia, but effects will be negligible for fine fibres. For coarse monofilaments, where they might be significant, the dependence on shear is valid for small twists, but, for large twists, the increase in length towards the surface of the fibre becomes dominant.

2.5.7 Tensile fibre fracture

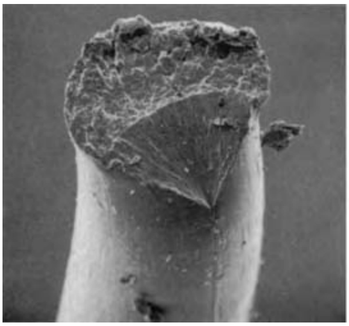
The forms of fibre fracture have been described by Hearle *et al*. (1998). In tensile tests, the natural plant fibres break in forms dependent on their helical fine structure. In cotton, Fig. 2.19(a), break is associated with the structural features shown in Fig. 2.2. There is splitting between fibrils and tearing down the collapsed region. In wet cotton, fibrils break individually.

At normal testing speeds, the melt-spun synthetic fibres fail by ductile crack propagation, Fig. 2.19(b), in which a V-notch opens and grows until it covers up to half the fibre area when the remainder fails catastrophically. At high rates, adiabatic heating causes the material to soften and rupture; snapback then collapses the material into a mushroom head, Fig. 2.19(c).

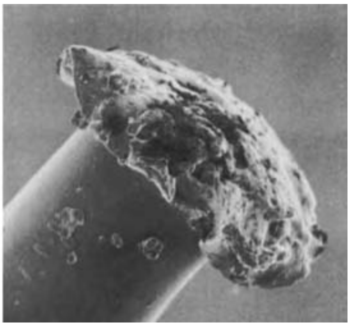
(a)



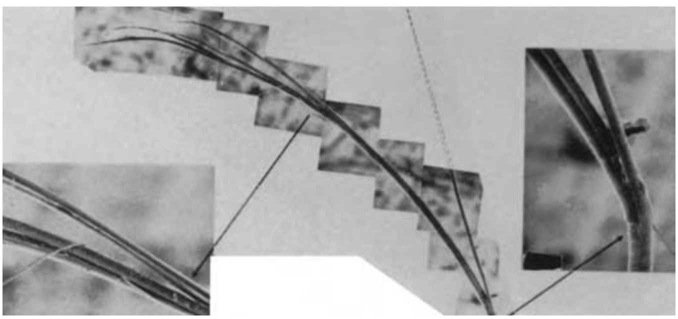
(b)



(c)



(d)



(e)

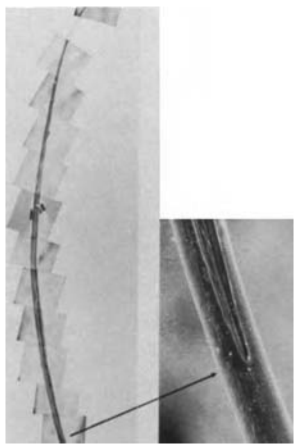


Fig. 2.19 Tensile fracture of fibres. (a) Cotton. (b) Ductile fracture and (c) high-speed fracture of nylon; these forms are also shown by polyester and other melt-spun fibres. (d) and (e) Opposite ends of fracture of aramid fibre. From Hearle *et al*. (1998).

The highly-oriented HM-HT fibres fail by multiple splitting, Fig. 2.19(d)(e), over a large number of fibre diameters. Often, as a consequence of the geometry of crack propagation, one end has a single split and the other has multiple splits. In an isolated fibre, this is complete rupture, but, within an assembly such as a rope, the long fibrillar splits can pick up load.

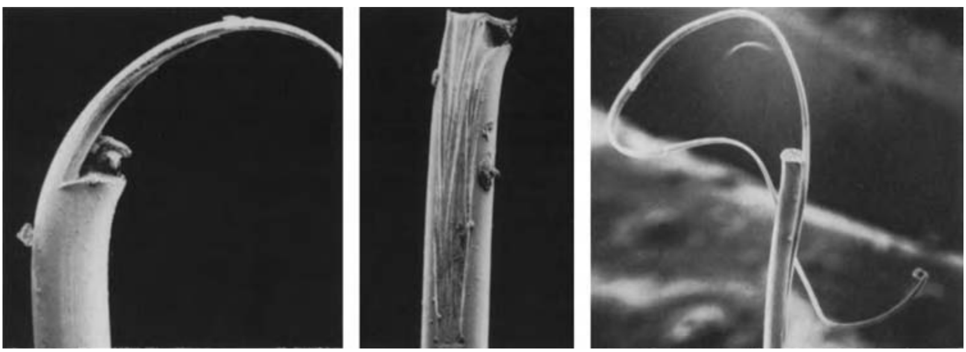
2.5.8 Fibre fatigue

Polymer fibres do not show the crack propagation that occurs in metal fatigue, but cyclic loading can lead to other forms of failure. Creep rupture is sometimes referred to as static fatigue and has been covered in Section 2.5.4. Heating due to cyclic loading, which reduces fibre strength has been covered in Section 2.5.5.

When cycled from a positive minimum load to a peak load, the break of nylon and polyester fibres has the same form as in a tensile test and the time-to-break is similar. However, when cycling from a minimum load of zero (or, for some fibres, a small positive value) to a maximum of three-quarters to half of break load, failure can occur after 10 000 to 1 000 000 cycles, with a different form of break. Break starts from a small transverse crack, but then turns and runs along and across the fibre until the unbroken part fails in tension. One broken end shows a tail, which is stripped off the other end. In nylon, Fig. 2.20(a)(b), the angle of the crack is about 10° to the fibre axis, so that the tail is about 5 fibre diameters in length. In polyester, Fig. 2.20(c), the crack runs almost parallel to the fibre axis, and very long tails are found.

The axial cracks result from shear stress at the tip of the transverse crack. A more important effect in ropes comes from the direct effect of shear stresses due to inter-fibre abrasion. This results in a progressive wearing away of fibre surfaces due to shear splitting. This property of rope fibres can be evaluated by the yarn-on-yarn abrasion tester shown in Fig. 2.21. Two portions of yarn, which are twisted together, rub against one another under controlled tension due to the cyclic motion imposed by rotation of the crank. A modified form of the instrument can be used to measure abrasion against external surfaces.

An extensive study of yarn-on-yarn abrasion of rope yarns was carried out by Goksoy (1986); see also Flory *et al.* (1988), and Goksoy and Hearle (1988a,b). Test



(a) (b) (c)

Fig. 2.20 Tensile fatigue failures when cycling from a minimum load of zero. (a) and (b) Opposite ends of break of high-tenacity nylon. (c) Polyester. From Hearle *et al.* (1998).

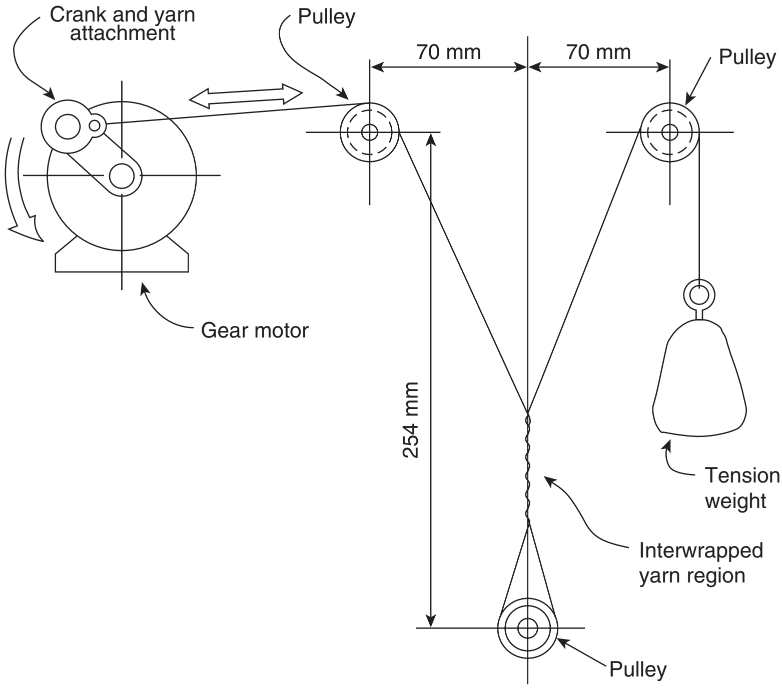


Fig. 2.21 Yarn-on-yarn abrasion tester.

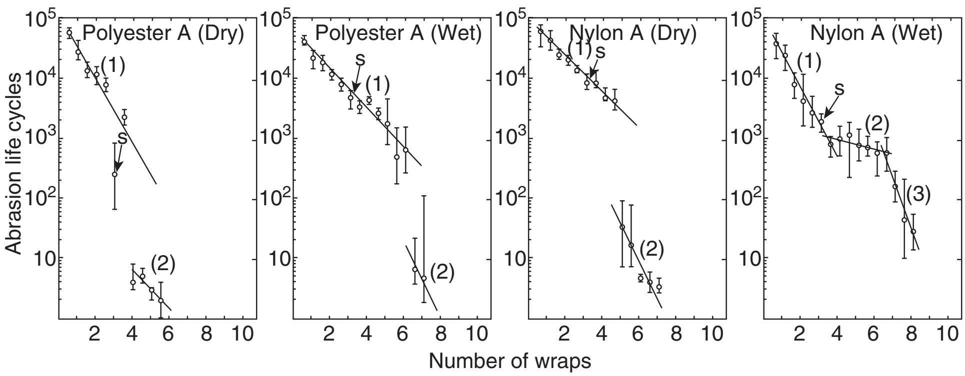
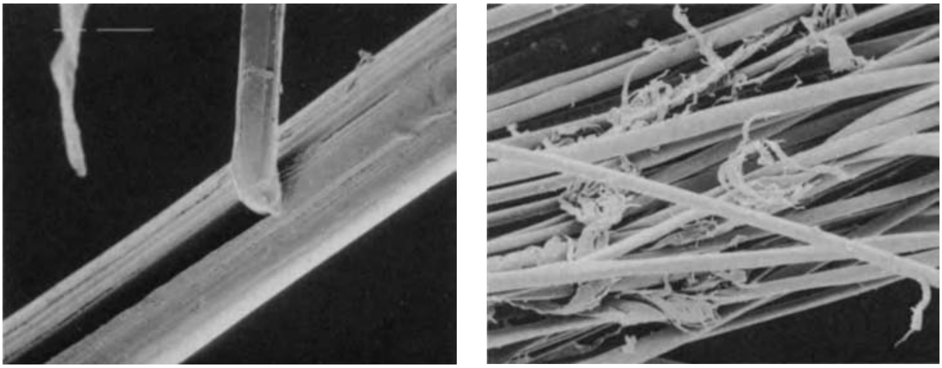


Fig. 2.22 Effect of increasing number of wraps on abrasion life. Interlacing angle = 35°; cyclic stroke = 50 mm; cyclic speed = 52 cycles/min; tensioning weight = 400 gf for polyester, 500 gf for nylon. (a) Polyester, dry. (b) Polyester, wet. (c) Nylon, dry. (d) Nylon, wet. (These are the 'A' fibres with marine finish from Table 2.8.) From Goksoy and Hearle (1988a).

results showed three modes as the severity of the test increased, as illustrated in Fig. 2.22 for an increasing number of wraps. Under gentle wear conditions, there were lives of more than 1000 cycles; under severe conditions, lives were less than 100 cycles; between these two regions, there was a sharp transition region with high variability in lengths of lives. The peeling and splitting, which results from inter-fibre abrasion, are illustrated in Fig. 2.23.



(a) (b)

Fig. 2.23 Fibre damage in yarn-on-yarn abrasion testing. (a) Nylon. (b) Polyester. From Hearle *et al*. (1998).

Table 2.8 Comparative yarn-on-yarn abrasion tests. From Goksoy (1986)

Median cycles to failure, 3 wraps, 35° angle, 200 g tension, 50 mm stroke, 52 c/s							
Polyester				**Nylon**			
A. With marine finish		**B. Without marine finish**		**A. With marine finish**		**B. Without marine finish**	
dry	**wet**	**dry**	**wet**	**dry**	**wet**	**dry**	**wet**
11 268	13 829	18 169	2 873	53 776	9 681	34 514	968

Table 2.8 shows typical results for two polyester and two nylon yarns. Polyester B presumably has a finish that is effective in reducing dry abrasion, but is washed off by water, whereas polyester A is more easily abraded when dry, but the effect of the finish is enhanced when wet. Poor abrasion when wet is characteristic of nylon, and makes it less suitable than polyester for use in a marine environment. Substituting a sodium chloride solution or synthetic sea-water for tap or distilled water made little difference to the abrasion lives. However, drying out with salt present had a dramatic effect: in one set of tests, polyester dried from tap water lasted for 4590 cycles, but from sea-water only 16 cycles, and for nylon the drop was from 28 000 cycles to 76 cycles.

Table 2.9 shows results of wet yarn-on-yarn abrasion tests in the Fibre Tethers 2000 Project (Noble Denton and National Engineering Laboratory, 1995). The difference between the two *Kevlar 29* yarns is due to differences in finish, and this is probably the main factor in the polyesters, though there may be differences in the underlying yarns from different manufacturers. Generally, aramid yarns have poor abrasion resistance; *Vectran* and HMPE are ten times better, and polyester a hundred times better.

Flex fatigue occurs when fibres are repeatedly bent. A single bend typically causes the formation of kinkbands due to internal buckling of the oriented molecular structure. Kinkbands are visible in polarised light as shown in Fig. 2.24(a). After

Table 2.9 Comparative wet yarn-on-yarn abrasion tests at two tension levels. From Noble Denton and National Engineering Laboratory (1995)

	Cycles to failure at:			
	1% of yarn break load		3% of yarn break load	
	mean	**cv**	**mean**	**cv**
Aramid				
Kevlar 29 (961)	854	14%	64	46%
Kevlar 29 (960)	4097	24%	196	22%
Twaron 1020	3922	12%	830	14%
Technora HM50	2129	11%	111	8%
LCP				
Vectran	39789	11%	6734	38%
HMPE				
Spectra 900	12078	6%	2253	12%
Spectra 1000	28823	38%	4300	9%
Dyneema SK60	31781	12%	5793	13%
Polyester				
Diolen 855TN	170473	28%	45646	25%
Trevira 785	>300000	–	63556	33%
Seagard IW81	174286	25%	35770	22%

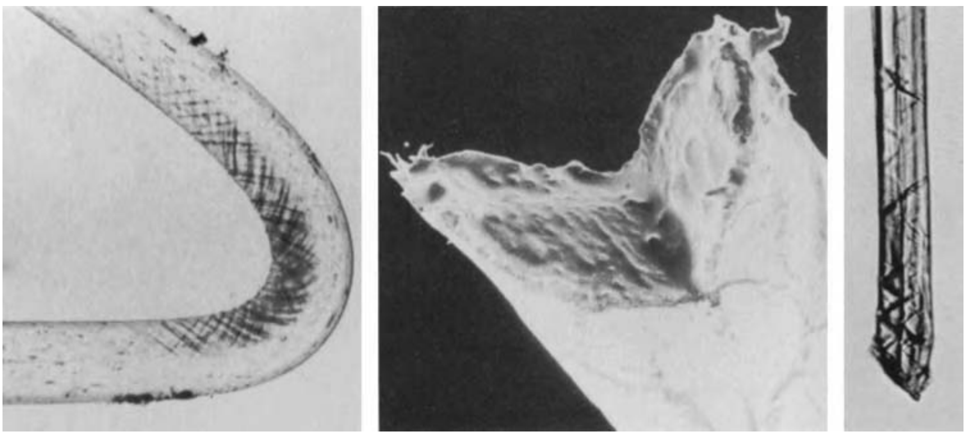


Fig. 2.24 (a) Kinkbands in bent polyester fibre viewed in polarised light. (b) Polyester failure after repeated flexing over a pin. (c) Aramid fibre showing kinkbands and angular break after axial compression fatigue in a rope. From Hearle *et al*. (1998).

a number of cycles, splits develop along the kinkbands and break occurs with the angular form shown in Fig. 2.24(b). In ropes, flex fatigue manifests itself in axial compression fatigue, when some yarns within a rope buckle even though the rope is under tension (see Sections 4.5.7 and 5.7.6). Kinkband formation and an angular break are also shown in Fig. 2.24(c).

The susceptibility of fibres to axial compression fatigue can be estimated by a buckling test shown in Fig. 2.25. The initial rounded buckling of the fibres changes

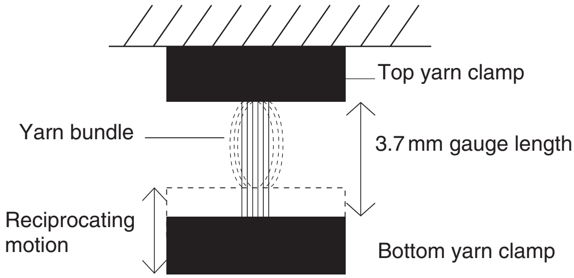


Fig. 2.25 Yarn buckling test.

Table 2.10 Examples of unrestrained yarn buckling test results. From Noble Denton and National Engineering Laboratory (1995)

	Percent retained yarn strength at cycles:		
	22 000	**55 000**	**110 000**
Aramid			
Kevlar 29 (961)	46.0	29.7	25.2
Kevlar 29 (960)	32.2	21.4	31.1
Twaron 1020	73.1	50.1	19.5
Technora HM50	65.1	62.1	60.5
LCP			
Vectran	60.8	54.8	48.5
HMPE			
Spectra 900	91.3	90.5	88.6
Spectra 1000	92.4	90.5	88.6
Dyneema SK60	91.1	88.2	81.5
Polyester			
Diolen 855TN	89.9	89.4	91.2
Trevira 785	93.8	95.7	96.6
Seagard IW81	98.3	100.5	97.0

Table 2.11 Restrained yarn buckling conclusions. From Noble Denton and National Engineering Laboratory (1995)

	Number of cycles for:	
	detectable strength loss	**severe strength loss**
Aramid	1 000	20 000
HMPE	20 000	200 000
Polyester	50 000	1 000 000

to a sharp kink. Table 2.10 gives a selection of results of residual yarn strength after increasing numbers of cycles. The kinking, which is what occurs in ropes at low tension, can be intensified by encasing the yarn in a plastic shrink-tube. This method is considered to be more reliable and the conclusions are shown in Table 2.11. Fatigue is rapid in aramids, slower in HMPE and slower still in polyester.

2.6 Other fibre properties

2.6.1 Friction

Friction of a rope during handling or running over external surfaces is a factor in operability. Between fibres within a rope, friction contributes to the forces in extension, bending and twisting, but the major effect of increasing friction is to increase the forces between fibres as they slip over one another, which leads to more severe abrasion. The classical laws of friction can be represented by two equations:

$$F = \mu N \qquad T_2 = T_1 \exp(\mu\theta) \tag{2.3}$$

where F is the frictional force under a normal load N, and T_2 is the outgoing tension when a yarn, or some other form of 'string', is pulled over a surface through an angle θ with an ingoing tension T_1.

However, the coefficient of friction μ is not a constant, except under limited circumstances, but varies with normal load, rate and environmental factors. For fibres, in any particular test conditions, the coefficient of friction will be highly dependent on the state of the fibre surface. Finishes, which are applied by the manufacturers of synthetic yarns, have a major influence. Oils may be applied in the spinning of natural fibres or in rope-making. In order to obtain information relevant to rope performance, tests need to be made on the actual yarns used and with appropriate test conditions.

In Fibre Tethers 2000 (1995), tests were carried out on a modification of the instrument shown in Fig. 2.21. The cyclic drive is replaced by a winch to pull yarn through the twist zone, and the tension weight is replaced by a chain resting on the base, thus causing the tension to rise as the yarn is wound up. Load cells measure T_1 and T_2. Table 2.12 gives some results. The differences among the aramid and among the polyester yarns are almost certainly due to differences in finish. The low friction of HMPE yarns is characteristic of the material.

Table 2.12 Yarn-on-yarn friction results. From Noble Denton and National Engineering Laboratory (1995)

	Load range (g)	Coefficient of friction, μ		
		Mean sliding	**Mean static**	**Maximum**
Aramid				
Kevlar 29 (961)	100–1600		0.157	0.167
Kevlar 29 (960)	100–1500		0.137	0.150
Twaron 1000	100–1200		0.165	0.180
Twaron 1020	100–2500		0.131	0.138
Technora	100–2200	0.117		
LCP				
Vectran	100–2700		0.144	0.151
HMPE				
Spectra 1000	200–4500	0.058		0.063
Dyneema SK60	2000–6000	0.061		0.064
Polyester				
Diolen 855TN	100–1500		0.092	0.099
Trevira 785	100–2500		0.060	0.064
Seagard IW81	100–1900		0.092	0.096

Table 2.13 Typical values of thermal properties of fibres. From Morton and Hearle (1993)

	Specific heat ($J\ g^{-1}\ K^{-1}$)	Conductivity ($mW\ m^{-1}\ K^{-1}$)
Nylon	1.47	250
Polyester	1.34	140

2.6.2 Thermal properties

The melting points of fibres are included in Table 2.3. The polyolefins, PE, HMPE and PP, melt below 200°C, but nylon and polyester at over 200°C. Above the glass transition temperature, as discussed in Section 2.5.5, the materials become more extensible. Cellulose fibres start to char below 200°C before they melt, and aramids decompose above 500°C.

When hysteresis heating occurs, the rise in temperature in ropes depends on the specific heat and thermal conductivity. In water, the external temperature can be treated as constant, but, in air, the emissivity must be taken into account, and if the fibres absorb moisture, cooling due to evaporation will occur. Table 2.13 gives some typical values of thermal properties, but conductivity of fibre assemblies will depend on how closely they are packed together.

2.6.3 Moisture absorption and swelling

There is appreciable moisture absorption in cellulose, nylon and aramid fibres, and the effect on mechanical properties has been mentioned above. The uptake of water is accompanied by swelling of the fibres. Initially, the increase in volume is slightly less than the volume of the absorbed water, but then volume increase becomes additive. In cellulose fibres, the swelling predominantly appears as an increase in diameter, which leads to a contraction in length of twisted ropes. The same would be expected for highly oriented aramids. In nylon, the micellar form, shown in Fig. 2.6, results in most of the swelling being axial; the fibres increase in length.

2.6.4 Electrical properties

Polymeric fibres are insulators, though in moisture-absorbing fibres, the resistivity falls rapidly with increase in relative humidity. In cellulose, the specific resistance ranges from 10^{13} ohm-cm when dry to 100 ohm-cm at high humidity. The synthetic polymer fibres typically have specific resistances in excess of 10^{12} ohm-cm, though the values are mainly determined by the finish. Anti-static agents are used to increase conductivity.

The electrical properties of fibres have little relevance to rope performance. In some critical applications, the risk of sparks causing fires or explosions might be a problem. This could be avoided by incorporating conducting fibres in the rope yarns, as is done to eliminate static electricity in carpets. Antenna stays are an application where the electrical properties of fibre ropes are beneficial (see Section 12.6).

Table 2.14 Environmental degredation, based on Cordage Institute data sheets

	Microbial resistance	Sunlight resistance	Chemicals causing degradation or solution			
			Acids	Alkalis	Organic solvents	Other
Cotton	poor	very good	high conc.	no	yes	sea-water
Abaca	poor	very good	high conc.	yes	no	
Sisal	poor	very good	high conc.	no	no	sea-water
Nylon	excellent	very good	if strong	no	no	phenols, formic acid
Polyester	excellent	very good	strong H_2SO_4	# yes	no	phenols
Polyethylene	excellent	fair	no	no	no	chlorinated hydrocarbons
Polypropylene	excellent	fair	no	no	no	chlorinated hydrocarbons
Aramid	excellent	fair	# strong	# strong	no	
HMPE	excellent	fair	mostly no	mostly no	mostly no	
Vectran	excellent	fair	if strong	if strong	no	
PBO	excellent	fair	# strong	no	no	

at high temperature

2.6.5 Environmental effects

Materials can be degraded by heat, chemicals, micro-organisms and radiation. Except in fires, thermal degradation of rope fibres is not a problem. Table 2.14 gives a guide to the response of rope fibres to the other sources of degradation, but full information on all possible effects would require an encyclopaedia. For some synthetic fibres, UV resistance is increased by the inclusion of stabilising additives.

2.6.6 Fibre prices and production

Although commodity fibres are priced competitively at US$3/kg or less, this is not true for more specialised fibres, where producers may be recouping development costs. Hearle (2001) in *High-performance Fibres* comments as follows:

> Production costs are naturally the proprietary information of manufacturers. Prices must be disclosed to customers, but, even so, it is difficult to find generally available information. In addition to the fact that different deniers of fibre and yarn and different grades of a generic type will be priced differently, prices will be lowered when a manufacturer is keen to develop a particular market and will be higher when demand outstrips manufacturing capacity. Sources for most of the [high-performance] fibre types are limited, so that there is no open competitive

Table 2.15 Fibre prices (from various sources). Values given are typical starting prices for coarse yarns or rovings; finer deniers and special grades will be more expensive. Edited extract from Hearle (2001)

Fibre	US$/kg
Typical commodity fibre	
Polyester	3
High-modulus polymer fibres	
para-aramid	25
HMPE	25
Vectran	47
Zylon (PBO)	130
Tensylon (solid-state extruded PE)	22–70
Carbon	
PAN based	14–17
pitch based–general purpose	15
–highest modulus	2200

market. This leads to reports of a wide range of prices: one source quotes prices for carbon fibres from 18 US$/kg for low-grade heavy tow to 1000 US$/kg for high-grade fine tow. [Table 2.15], which contains information from a variety of sources, gives a general indication of the relative prices of high-performance fibres.

Accurate estimates of the production of high-performance fibres are difficult to obtain. The general-purpose polyester fibre for textile and technical uses has global production in tens of millions of tonnes per year. Glass fibre is also produced in large volume with world capacity approaching three million tonnes per year. The other more widely used high-performance fibres will reach only tens of thousands of tonnes per year, and the newer or more specialised fibres, hundreds of tonnes per year or less.

2.7 Other rope components

2.7.1 Finishes, lubricants and fillers

Fibre finishes can be divided into two categories; the spin finish put on after extrusion but before drawing by the fibre manufacturer and the overlay finish added either by the fibre manufacturer or by the rope manufacturer.

The spin finishes applied to synthetic yarns are intended to reduce static electrification and to improve performance by optimising frictional properties for processing and use. They are tailored to meet the needs of particular applications. The provision of finishes is often referred to as a ‘black art’; there is little information in the open literature. Companies maintain confidentiality, and the spin finish formulations are generally proprietary to the fibre manufacturer, although advice can be obtained from companies supplying finishes. The finishes can be quite traditional, sometimes based on vegetable or mineral oils. Uniqema announced a new finish in 1999, *Cirrasol© PP1801*, based on an alcohol ethoxylate. The function of these finishes is to lower the coefficient of friction and to give antistatic protection so as to improve processability and downstream production speeds.

Table 2.16 Typical properties of plastics used in extruded jackets

		High density polyethylene	Polyurethane	Nylon 6	Polyester elastomer
Density	(g/cm^3)	0.95	1.12	1.13	1.19
Hardness	(Shore A)		82 A	60 M	55 D
Tensile stress at 100% elongation	(N/mm^2)		5.40		
Tensile strength	(N/mm^2)	20.0	40.0	78.0	42.0
Break elongation	(%)	400	510	200	500

Overlay finishes are added to improve performance in use. In particular, special marine finishes are applied to fibres for ropes in order to improve abrasion resistance, as discussed in Section 2.5.8. For polyester a popular marine finish is Honeywell's *Seagard*, which is based on a polysiloxane. Other polyester producers also have special marine finishes. Rope manufacturers are looking for two main properties; lower inter-fibre friction and improved external abrasion resistance. Low inter-fibre friction allows the rope to settle during cyclic loading or break testing and improves the break strength by improving load sharing. Clearly, for marine use, the finish must not be easily washed off in the sea.

Aramid manufacturers supply *Kevlar* and *Twaron* with a paraffin wax finish to improve abrasion resistance. It is interesting to note that the paraffin wax finish is quite sticky and there is a significant loss of strength (circa 10%) in both yarn and rope.

Heat-conducting lubricants may be included in ropes to reduce friction hot spots, and fillers such as oils and waxes can be used to prevent ingress of particles that cause internal abrasion.

2.7.2 Plastic jackets

Extruded plastic jackets are usual for large parallel-yarn ropes. Polyethylene is the most commonly used material; it is cheap and relatively tough. However, it is quite stiff and inflexible. This is not disadvantageous for antenna guys, which is the main application for parallel yarn ropes, and the good electrical insulating properties of polyethylene are an advantage.

Polyurethane extruded jackets have been used on a few parallel-yarn ropes, as well as on some wire rope constructions. They are elastomeric and have low modulus at low loads up to 100% elongation.

Among a wide variety of polymers that could be used to meet particular needs, nylon 6 and 6.6, polyester, ethylene/vinyl acetate, and polyester elastomer have been used. Properties of some of these materials are given in Table 2.16. An alternative to extrusion is coating. Two-component polyurethane systems are used extensively to toughen the jackets of large marine ropes such as buoy-mooring hawsers and the ropes for riser protection nets.

Jackets may have additives to protect the underlying rope fibres from UV degradation.

3

Rope structures

3.1 Introduction to rope structures

Ropes are structures made of textile fibres. They are defined as approximately cylindrical textile bodies whose cross-sections are small compared to their lengths and they are used as tension members. The rope structure contains, and must control, large numbers of synthetic or natural fibres in coherent, compact, and flexible configurations, usually to produce a selected breaking strength and extensibility with a minimum amount of fibres.

For most common ropes, the fibres are arranged in helical structures whose axes form helices in larger structures, the process continuing in stages until a rope is complete. Either laying (twisting) or interlacing (braiding) techniques are used to arrange and contain the rope elements.

Unstructured ropes, or those with very small helix angles, may require enclosure techniques of braided or extruded jackets to contain the elements.

Rope structures can be divided into two general categories. These are:

1 Laid and braided* ropes with fairly high twist or braid angles; these are the most common structures for general purpose use. They are found in industrial, marine, recreation and general utility service. They cover everything from small cords used to tie-up packages, to large hawsers for mooring tankers, and include clothes-lines, yachting ropes, haul lines for fishing nets, lifting slings, and a host of other applications.

   Laid and braided ropes for general purpose uses are:
   - Three-strand, four-strand and six-strand laid
   - Eight-strand plaited
   - Hollow braid, eight and twelve strand (also called 'single' braid)

* The words *braided* and *plaited* are used differently by different authors. Plaited ropes can be regarded as a sub-set of braids, which produce a distinct form of rope by different rope-making operations to other braided ropes. See Appendix II for further comment.

- Double braid (also called 'braid-on-braid' and '2-in-1' braid)
- Solid braid* (also called 'parallel braid')

2 Low twist rope structures, used for specialised and demanding applications where high strength to weight ratios and low extensibility are essential. This would include tethers for astronauts, guys for tall masts, deep sea salvage recovery ropes, mooring lines for floating oil platforms, and hoist cables for deep mines.
   Low twist ropes for specialised uses, often large, are:
   - Braided rope with jacket
   - Parallel strand, jacketed. (If the strands that make up the rope are small ropes themselves, the construction is sometimes called 'parallel sub-rope')
   - Parallel yarn (or filament), jacketed
   - Kernmantle rope. (Very similar to parallel strand, jacketed or parallel yarn, jacketed but with thin, coloured braided jackets.)
   - Wire rope type, exterior jacketed
   - Wire rope type, each strand jacketed

There are wide variations within each type of rope structure. The appearance and behaviour of the structure are influenced by many factors, some of which are:

- Type and size of fibre material (textile yarns) used
- Dual or blended fibre materials
- Amount of twist at each stage of production
- Size and number of sub-components at each stage of production
- Tension on sub-components during production
- Post-production heat and other treatments

Individual companies have evolved their own technology and rope designs into more of a skill than a science. Personal preference and company history are subjective factors that influence the choice of rope structure, but an important objective factor is the availability of production machinery. Ropes get tweaked this way and that, but in the end, for good performing general-purpose ropes, the range of design variations within any one type of construction is fairly small. Occasionally, a ropemaker may change the design considerably from the common version to meet a particular need. Names for different rope structures vary throughout the world and there is a confusing abundance of trade names.

In this chapter the rope structures will be described and features that make them suitable for particular applications will be mentioned. Chapter 4 will cover rope properties in detail.

By noting the above, and recognising the variety of fibre types, it can be seen that the number of possible constructions and permutations is nearly endless. This is an interesting aspect of the fibre rope industry.

* A special form of braiding in which all carriers rotate in the same direction. Alternate *hollow* braid carriers move in opposite directions and leave a 'hollow' in the centre; with a limited number of strands and tight braid structures, these ropes become geometrically solid, but they are not what are referred to here as 'solid braids'.

3.2 Formation of rope structures

3.2.1 Starting yarn material

A rope structure begins with the filament or staple fibre material which is commonly called 'textile yarn'. Its type and size sets the starting point of any rope structure. These materials may be produced by a chemical company, a firm specialising in textile fibre production, a staple yarn spinner or, mostly for monofilament or split film polypropylene, the ropemaker himself. The various types of textile yarns are described in detail in Chapter 2.

Multifilament yarns are very small, in the order of one millimetre or less and may contain up to several hundred tiny filaments of 10 to 50 μm diameter. This type of material is usual for nylon, polyester, aramid, HMPE, LCP and PBO. Some polypropylene is used in rope in multifilament form.

In order to give some coherence to the textile yarn structure, the filaments are lightly interlaced or twisted. Staple fibre yarns, made from natural fibres or chopped synthetic fibres, will be more highly twisted.

For monofilaments, the individual filaments are large, in the order of 0.2 mm to 0.5 mm diameter. Split film is very thin and cut lengthways two or more millimetres wide. Polypropylene fibre for rope is normally used in one of these forms. Very large nylon mono-filaments, in the order of 3 mm diameter, also find their way into rope where they are used in conjunction with multifilament nylon fibre in a wire-rope-like construction (commonly known as *Atlas*).

3.2.2 Rope yarns

The small textile yarn elements described in the previous section must be twisted into larger rope yarns. Depending on the manufacturer's preference, this may be carried out in one or two stages. The rope size, type (laid, plaited or braid), and available twisting machinery are the determinants of the selected sequence.

In a one-stage process, a large number of textile yarns are twisted together in one operation.

A typical first stage twist in a two-stage process is shown in Fig. 3.1. The structure can vary considerably from only a few yarn ends to many more, as seen in the figure. As sizes become larger, more twist stages are required. Traditional three-strand laid and eight-strand plaited ropes are made from rope yarns that are twisted from three first-twist yarns. If the individual yarns are S twist, Z twist is used for plying them together (shown in Fig. 3.2 for three-ply rope yarn). This arrangement can vary, however, as is shown in Fig. 3.3, where there are five first-twist yarns in the rope yarn. In this picture there is a 1000 denier basic textile yarn on the right. Four ends of the 1000 denier yarn have been used to produce the first twist. Five of these have been laid together to produce the rope yarn.

For braided ropes, rope yarns are usually made by keeping individual ply twist the same as rope yarn twist. This gives a smooth strand surface that blends the rope yarns together. Occasionally, a ropemaker will build up strands for braids from rope yarns of the type used for laid ropes which will give the strands a different appearance.

For small rope sizes, the rope yarn may serve as the strand, especially in braided ropes. Some suppliers of multi-filament textile yarns have the facility to supply lightly twisted textile yarns in the range of 20 000 to 40 000 denier. In braided ropes, the strands may be built up by twisting a large number of yarns rather than

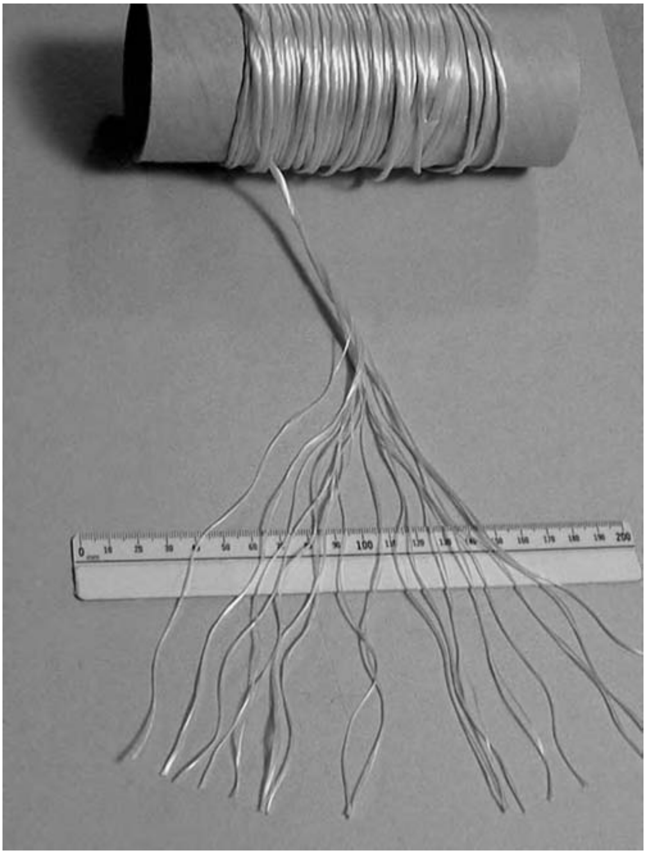


Fig. 3.1 Textile yarns separated for viewing after first stage of plying (first twist).

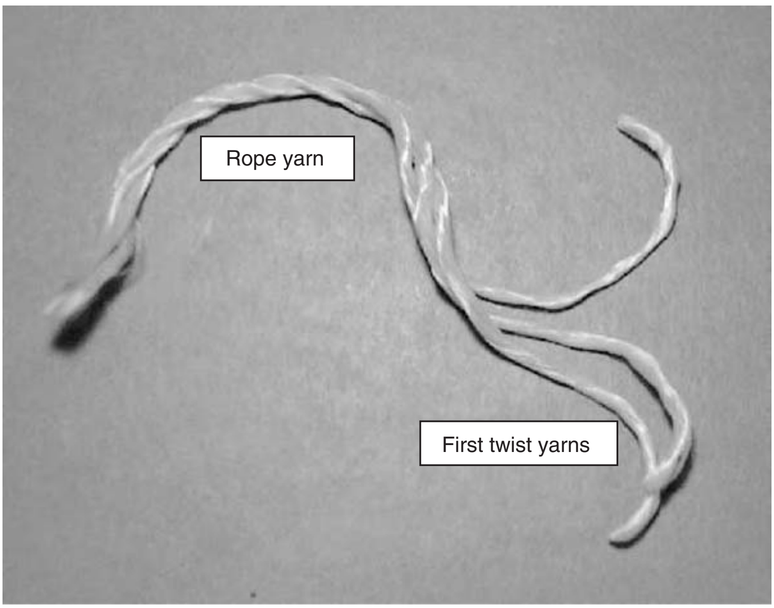


Fig. 3.2 Rope yarn produced from three first twist yarns; polypropylene split film.

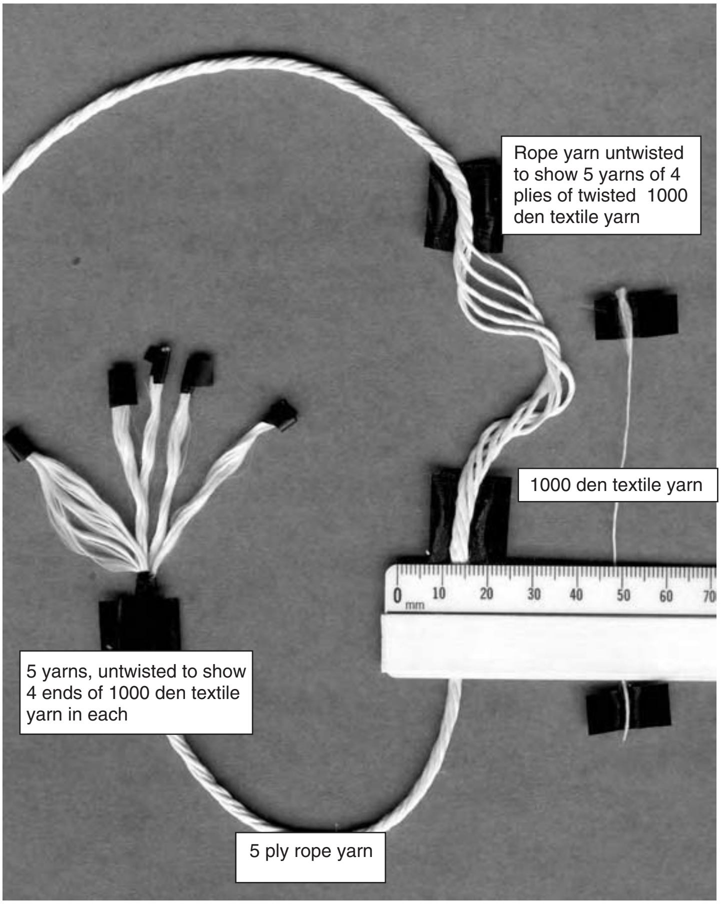


Fig. 3.3 Evolution of basic textile yarn to rope yarn.

creating the intermediate rope yarn and plying them in a second stage. Very large diameter braids will require two or more stages of plying.

Rope yarns are the basic building blocks for building the strands for larger laid and plaited ropes, and occasionally for hollow braided ropes.

There are ambiguities in terms, due to the fact that there is great diversity in the way different manufacturers identify and carry out the essential steps of *textile yarn* → *rope yarn* → *strand*. The final stage, *strand* → *rope*, is better defined for the different rope types.

3.2.3 Strands

The final building block of any rope is the strand. The formation of the strand in relation to a finished three-strand laid rope is shown in Fig. 3.4. The labelling in the figure shows the various elements of a strand of the rope.

The concept is further explained in Fig. 3.5. A strand, which has been removed from a rope, is shown at the top. The strand is turned back in the lower part of the photo to cause the rope yarns to open up. One rope yarn has been pulled out and turned back to show the filament yarns. This figure illustrates the lack of structural stability of strands that are not confined in a rope.

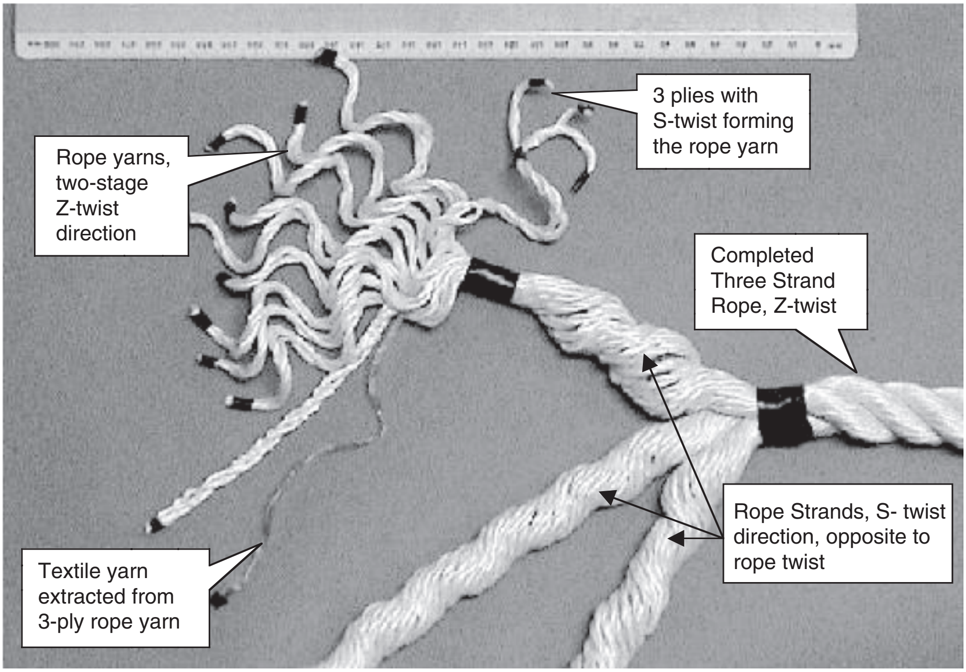


Fig. 3.4 Three-strand rope broken down into sub elements.

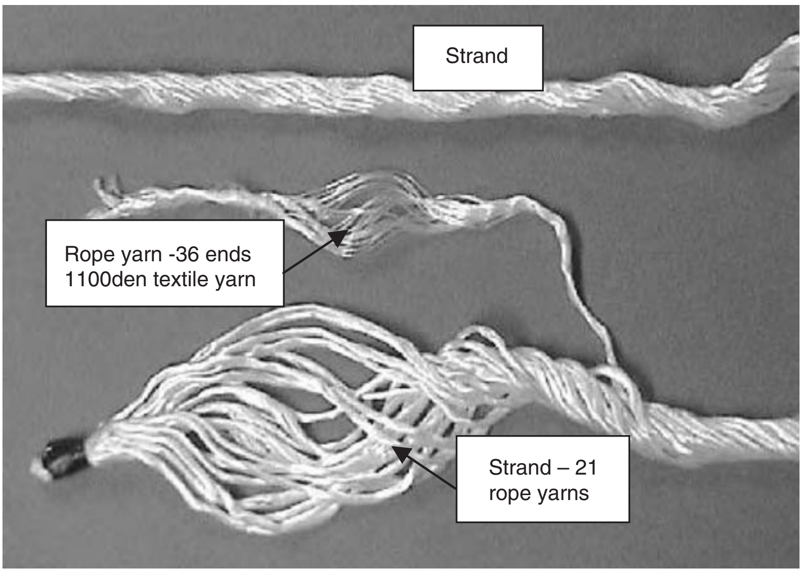


Fig. 3.5 Progression from 1100 denier basic textile yarn to a strand.

For laid and plaited rope, strands can be very large, up to 50 mm in diameter. The more yarns that are combined in a rope strand, the softer its cross-section appears, unless more twist is used to form an acceptable firm textile structure. There is a practical upper limit for the number of rope yarns that can be combined into a rope strand, above which the rope strand is a very soft structure with decreasing strength efficiency compared to the yarns utilised. The need for added twist in large strands partially explains the gradual reduction in strength as ropes increase in size. If the outer limit of strand size is reached, alternative rope constructions, such as cable laid, double braid or parallel strand, must be used.

Different rope fibre materials respond differently to variations in rope lay and strand twist in three-strand ropes (Paul, 1967). Ropes from polyester increase their strength significantly with a decrease in strand twist, but are strength insensitive to changes in the rope lay length. In nylon ropes, changes in the rope lay have a minor effect on the rope strength and the strength is not affected by changes in the strand twist. In manila, polyethylene, and polypropylene ropes, both strand twist and rope twist changes alter the rope strength.

3.3 Laid rope

3.3.1 Three-strand laid construction

The oldest and still the most widely-used fibre rope structure consists of three strands laid together by a twisting process. A typical rope is shown in Fig. 3.6. Since the rope twist is opposite to the strand twist, the strand twist loses nearly one full turn for the strand length which is needed to form one full 360° turn as they are laid around the rope axis. This would open the strand structure and result in a limp rope. To prevent this, additional fore-turn is added to the strands by the rope-laying machine or ropewalk. This process over-twists the strand structures as they are entering the rope-closing die. The fore-turn twist leaves the finished rope with about the same originally produced firmness and twist level of its rope strands. It is seen that the lay of the strands is in the opposite direction to the lay of the rope yarns that make up the strands.

Figure 3.7 is a view of the cut end of a three-strand rope that has been tightly taped to simulate the appearance of the cross-section when under tension.

3.3.2 Features of three-strand laid rope

Three-strand laid rope is one of the simplest and most versatile of rope structures. It can be made with a long lay length (soft lay) to increase strength and to decrease elongation, but this makes it prone to snagging and difficult to handle because it is so soft. When made very tight (hard lay), the tendency to snag is reduced and abrasion resistance is improved, strength will be decreased and elongation increased, and it will be easier to handle. Medium lay is most common.

Three-strand rope is made from natural fibres, multifilament yarn, monofilament yarn, slit film, and monofilament staple (chopped synthetic fibres). Different fibre types may be combined; for example, the centre of each strand may be made with polypropylene and yarns of polyester or polyester/propylene blend wrapped around the outside. This has the benefits of the abrasion resistance of polyester on the outside and the lightweight and lower cost of polypropylene on the inside. When

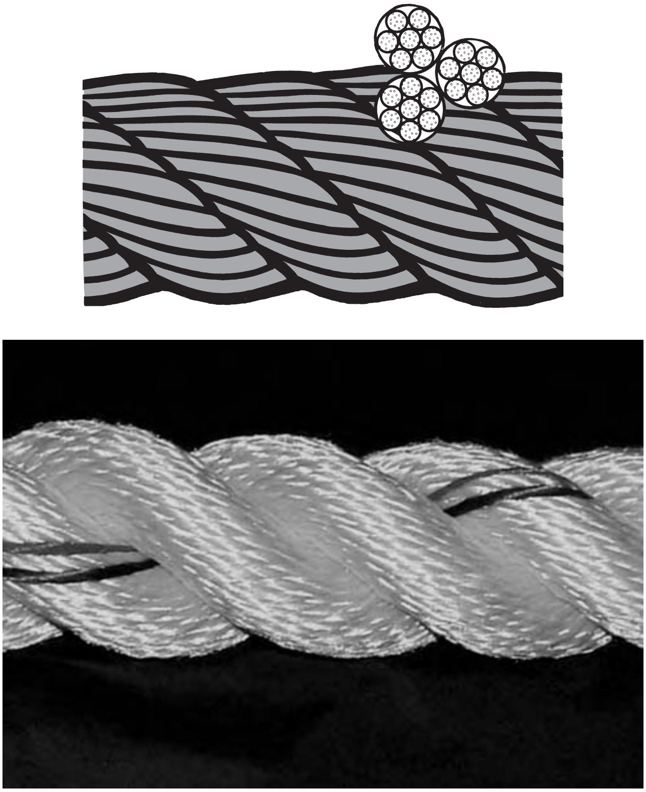


Fig. 3.6 Three-strand laid rope with coloured marker yarns for manufacturer's identification. Note the compact rope structure and smooth surface.

made of nylon, this construction is often pre-shrunk in steam to a desired level of firmness; this makes it stable in wet and storage environments, tightens the structure and makes the rope more extensible.

Rope sizes in this construction cover a wide range, from the smallest to size 18 marine ropes (144 mm diameter) and sometimes larger. (For size definition of marine ropes, see Table I.1 in Appendix I.)

This type of rope is easily spliced, which is one reason for its popularity.

Note that, because of the opposite direction of twist in strand and rope, the rope yarns on the outer surface are nearly aligned with the axis of the rope. This is the optimum orientation for best external wear resistance. This is true for outer surfaces on all rope types (Refer to Section 3.4.1 and Fig. 3.9 where twist direction is illustrated relative to plaited rope).

In their commonest form, three-strand laid ropes have somewhat lower strength and greater elongation compared to braided ropes of the same size and material. However, they have virtually identical strength/elongation properties as eight-strand plaited ropes.

For medium and high twist levels, this rope structure does not achieve good conversion of fibre strength to rope strength when using high-modulus fibre materials, especially in large sizes, becoming noticeable at about 25 mm. Due to the large strand size relative to rope diameter and the high twist levels required for a

Fig. 3.7 End view of cut three-strand rope, taped to simulate shape when under tension. Individual strands and the rope yarns can be seen.

functional rope, the structure prevents good load-sharing because of the very low extensibility of the components. Any applied torque (see below) also works against good load-sharing. Therefore, three-strand rope is rarely made with aramid, HMPE or similar high modulus fibres. Exceptions are the long-lay, three-strand sub-ropes, each a small diameter, which do have good strength conversion, and are used as components of parallel-strand ropes.

Three strand laid ropes are not torque free. This means that if a weight is suspended vertically, it will rotate and tend to unwind the rope structure. Similarly, if attached to a freely turning swivel, the rope will unlay when loaded and try to return to its original shape when unloaded. This is an undesirable consequence of its structure. In addition to load-handling difficulties, strength is reduced when the structure is permanently altered by rotation. This is not a problem if the rope is secured at both ends (see Paul, 1970 for a detailed discussion of torque in three-strand ropes).

If a three-strand rope is twisted opposite to the lay, and then tensioned, with both ends restrained, the load distribution among the rope yarns will change and weaken the rope. The more turns of twist, the worse it becomes. A similar situation occurs if one strand breaks – the remaining strands unlay and become much weaker than they were when the rope was intact.

Also, because of the helical structure, three-strand rope tends to form loops when under no tension (as seen in a garden hose). Loops that are then pulled under tension can reverse twist the rope at the top of the loop and completely unlay a short section of rope. A common term for this is a 'hockle' and it will permanently damage the rope (see Fig. 9.22). It is possible to produce laid ropes that are less prone to hockle, but it complicates manufacturing and is rarely done.

3.3.3 Four-strand laid rope

A very similar rope to three-strand laid is made in a four-strand version and it is generally used in the same way. It is not a popular form.

3.3.4 Six-strand laid rope

This structure is made by tightly laying six strands around a centre strand. Its main application is in sizes 50 to 80 mm for use on mooring winches for large vessels. It is similar to wire rope construction (Section 3.12.1) but is made by a slightly different process, and, due to the tight lay, it does not require a jacket to hold it together when slack.

3.3.5 Cable laid rope

Historically, when it was necessary to produce natural fibre ropes that were larger than practical for a single operation, a cable laid rope was produced. Here, three or four ropes were laid together with the ropes acting as the strands. Normally, the sub-ropes were of three strand construction but could be otherswise.

3.4 Plaited rope

3.4.1 Eight-strand plaited construction

An eight-strand plaited rope is shown in Fig. 3.8. The eight-strand plaited construction is a torque-balanced rope that is made by a braiding technique called plaiting. Although truly a braid, it is slightly different from hollow braids (Section 3.5) and significantly different from solid braids (Section 3.8)*.

This construction can be made from the full range of low and high modulus fibre materials. For high modulus materials it is necessary to use a relatively long braid pitch which can result in a very soft rope Coatings can mitigate the negative effect of softness.

In plaiting, the braider has eight carriers, with four operating in each direction of rotation. Note, however, that the carriers move in pairs so that the rope is like a braid of four twin strands. Each pair travels through the centre of the rope which means that it does not have a hollow centre. The four crowns of each pair of strands are very pronounced. Due to the geometric form created by the four pairs of stands, it is often referred to as a ‘square braid’.

Referring to Fig. 3.9, the upper rope was *incorrectly* made, with the same direction of rope twist in the strands of the rope as in the rope strands themselves. Note that the rope yarns at the rope surface are inclined by nearly 45 degrees to the rope axis; this increases snagging and surface abrasion in service. The lower rope is made correctly. The directions of twist of the strands in the rope and the rope strands themselves are opposite, the rope yarns at the rope surface are essentially parallel to the rope axis. This rope is also much firmer.

* See also comments in Appendix II.

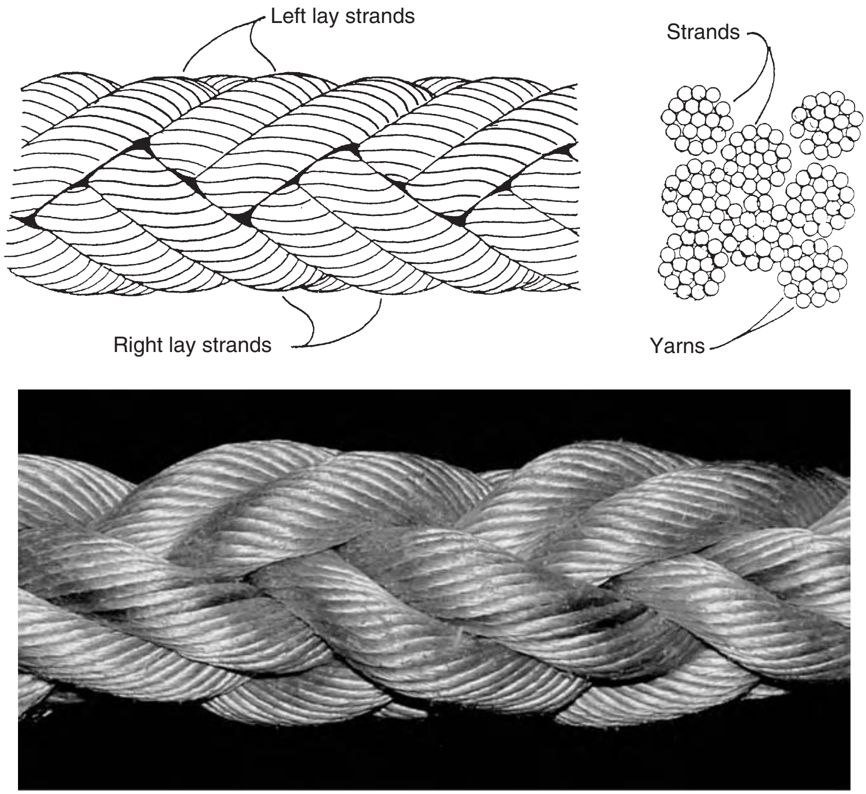


Fig. 3.8 Eight-strand plaited rope. Note the firmness of the strand surfaces due to the additional twisting of the rope strands while being plaited into the rope structure.

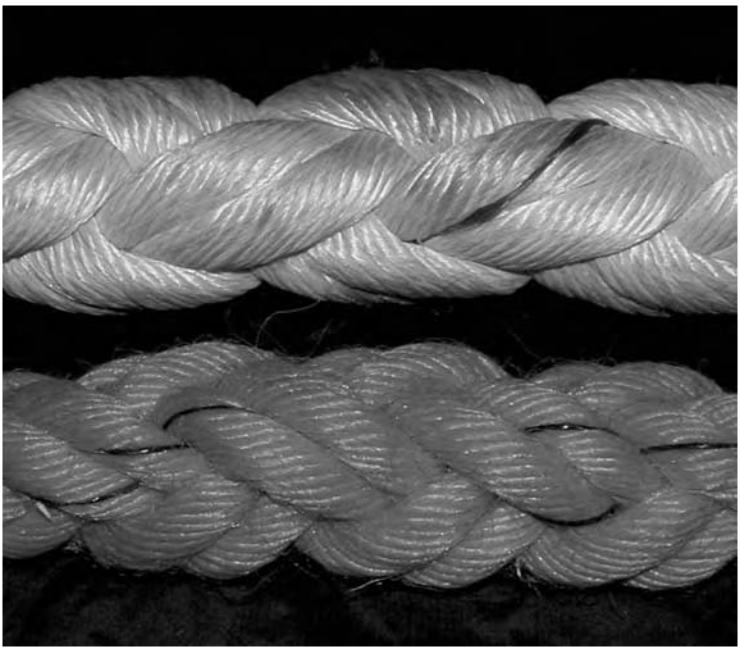


Fig. 3.9 Eight-strand plaited rope. Upper rope is made with rope yarns going across the rope (wrongly, as seen with yarn that has been painted black) instead of aligned axially in lower figure (as seen by black marker yarn that had been incorporated during production).

3.4.2 Features of eight-strand plaited rope

Eight-strand plaited ropes are used for general purposes much as is three-strand. In Europe they are very popular in small sizes whereas in North America hollow braids are more widely used up to about 48 mm diameter. The eight-strand plaited construction is found in sizes to number 20 for large marine ropes (160 mm diameter).

The eight-strand plaited construction, when made from the identical rope yarns as three-strand laid ropes, has nearly identical strength and elongation properties. For low modulus fibres and general service, strength and weight specifications are often listed as the same in some published rope standards.

Eight-strand plaited rope is balanced. A freely suspended load will not rotate. It does not hockle.

This structure has good abrasion resistance. Because of the way the crowns stand above the rope, rubbing is concentrated here. This can be seen in Figures 9.3 and 9.4. However, pressure and wear at these points tend to flatten the crowns and distribute the wear without excessive loss of fibre. The damage is often less than the appearance would indicate, as seen in Fig. 9.6.

Splicing is straightforward and well known for this construction.

Up to moderate sizes, if a long cycle length is used, this construction achieves good strength conversion efficiency when made from high modulus fibre materials such as, aramid and HMPE. Although the plaited form gives more cohesion to the rope than a laid rope with the same lay length, a long lay length will leave the rope very loose and prone to snagging unless firmed up by dipping to create an adherent coating or encasing with a braided or extruded jacket.

3.5 Hollow braid rope

3.5.1 Hollow single-braid construction

Hollow braids are made in a maypole fashion, with half the carriers on the braider moving the strands clockwise and half moving them anti-clockwise, while they also move in and out. They are distinguished by having a hole down the centre, though in eight and twelve strand braids under tension the hole collapses to a size no greater than that elsewhere between strands (see Fig. 3.10). In eight-strand braided ropes, the carriers run singly, in contrast to running in pairs as in eight-strand plaited ropes.

This construction can be made from the full range of low and high modulus fibre materials. For high modulus materials it is necessary to use a relatively long braid pitch length, which can result in a very soft rope. Coatings can mitigate the negative effect of softness.

For cords and small ropes up to about 8 mm diameter, an eight-strand braided construction is the most popular, but twelve-strand is also found. From 12 mm to 96 mm diameter, twelve-strand construction is used. Above about 96 mm diameter, the strands become too large for effective strength conversion and the structure is too loose, making it difficult to handle. Careful attention to construction design and precise production techniques have produced effective ropes to 120 mm diameter, however. A 96 mm-diameter 12-strand single braid is shown in Fig. 3.10; it is a blend of polypropylene (grey) and polyester (white) fibres. The polyester offers good abrasion resistance while the polypropylene reduces weight and cost. The colour combination is a non-technical aspect that was used to set it apart from competing products. Note that the outer yarns are oriented in the direction of the rope axis.

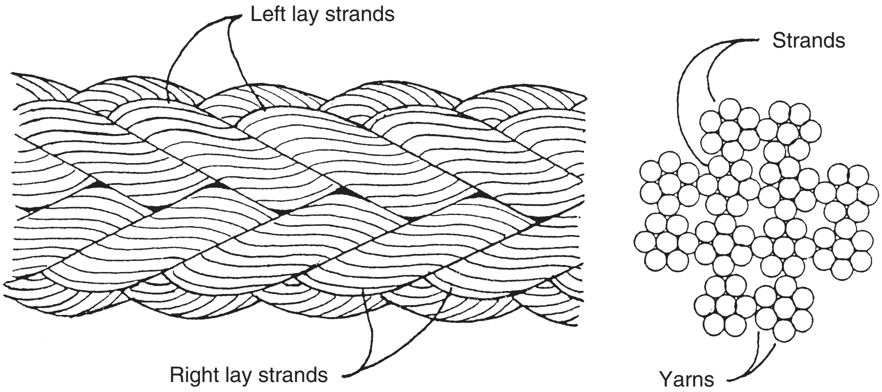


Fig. 3.10 A 12-strand single-braid, mixed polyester/polypropylene fibre, 96 mm diameter rope. Note the yarns running parallel to the axis.

Hollow single braids of 16 strands or more have a larger space in the centre and tend to collapse into a flat instead of a round form unless they have a very long braid cycle length. However, this then makes them too soft, so that the strands tend to open up during handling, and they become prone to snagging.

Figure 3.11 shows two single braids with different pitch lengths. Both ropes are the same size and the photos are to the same scale, so the difference in pitch length is easily seen by comparing the length between the coloured marker yarns. Referring to the figure, the upper rope is very tightly braided with a helix angle of about 40°. Pushing on this particular rope opens virtually no hole in the centre. For larger helix angles there is no room for any opening at all in the centre as the strands are jammed.*

* The totally jammed limit is at 45°. Higher angles are the axially compressed states of braids with a lower angle when tension is applied.

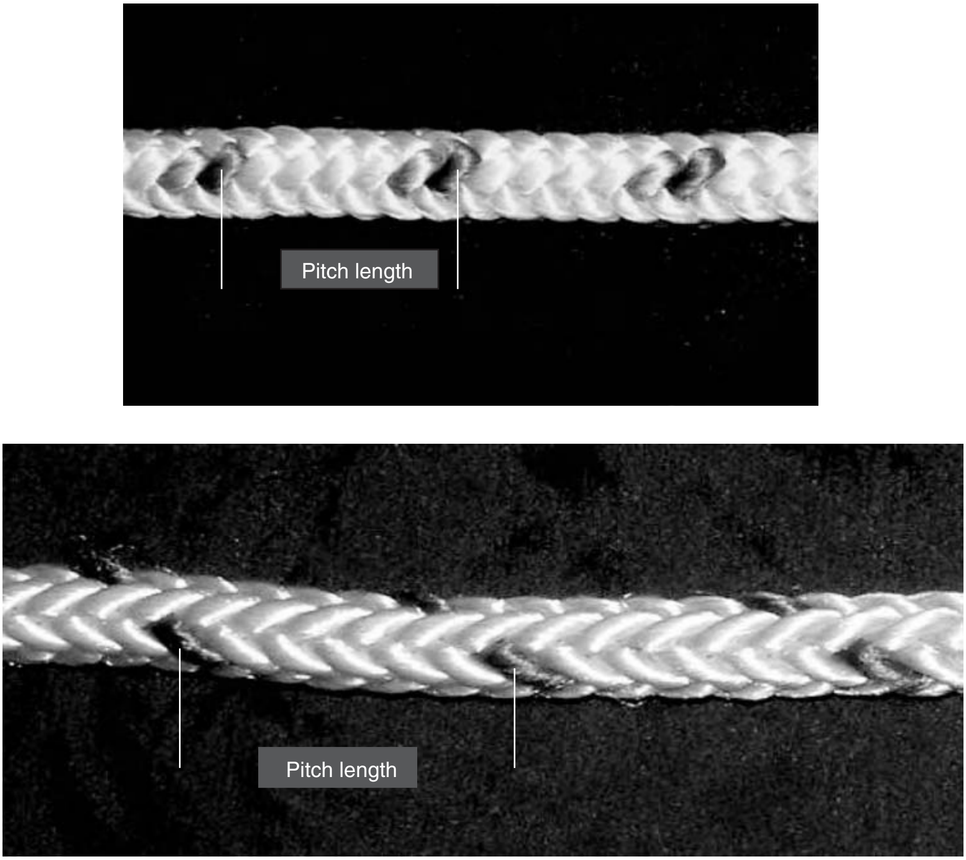


Fig. 3.11 Hollow braid, 12-strand ropes, with different braid pitches. Rope size and scale are approximately the same size in both photos. The upper rope is so tight that it is virtually solid; the lower one yields a hollow centre if compressed.

The lower rope of Fig. 3.11 has a much longer pitch with a helix angle of about 20°. Under tension, this rope becomes solid and round. However, pushing on it opens a centre hole large enough to insert the rope back into itself for splicing. This is shown in Fig. 3.12. This is in contrast to a plait in which the strands cross the centre and they all separate from one another, instead of opening the centre when the rope is compressed.

For the two ropes in Fig. 3.11, the tightly braided rope is hard and firm, which helps avoid snagging. This rope cannot be spliced by the ordinary methods for braids and is usually terminated with knots; however, a tuck splice may be possible. It is popular for tree service work where the firmness is preferred. The long pitch rope is stronger, is soft and pliable, and can be spliced. This rope is used in many commercial applications where high strength, reduced elongation and spliceability are important.

More than one strand may be braided from the same carrier on the braiding machinery. This can be seen in Fig. 3.13. The upper rope has one strand per carrier and the lower one has two. The braider itself has 12 carriers, so the upper rope has 12 strands and the lower one has 24 strands (12 pairs). More strands produce a

Fig. 3.12 A 12-strand, hollow braid, compressed to open the braid. The hole has been made by a fid so that the tail can be inserted into the centre and pushed well down the rope to effect an eye splice.

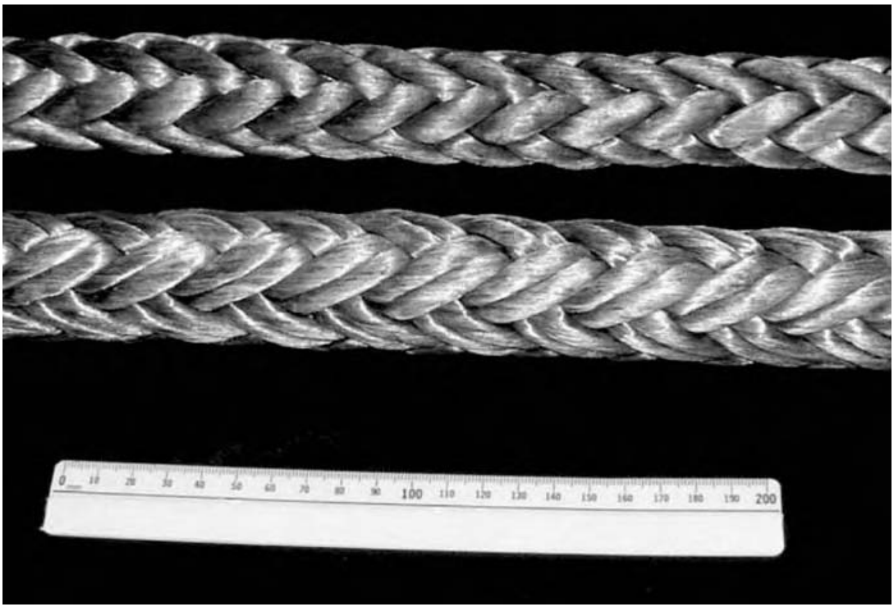


Fig. 3.13 HMPE braids of 32 mm diameter with one (above) and two (below) strands per carrier. Note the smaller strands and less bumpy shape of the lower rope.

smoother rope with more smaller crowns on the outside to distribute wear. Slightly higher strength is suggested with more fibre in the cross-section; however, it can be difficult to keep uniform tension during braiding, which is essential for optimising strength. From a production standpoint, smaller strands may be more suited to available machinery.

Hollow braids may be made in either a plain or twill braid pattern. In plain braid, one strand goes over one strand and under the next strand, which has been moving in the opposite direction during the braiding operation. In twill braids, each strand goes over two and under two strands travelling in the opposite direction, with a step between neighbouring interlacings. Twill braids are the most popular and are seen in Figures 3.10–3.13. Another possible braid structures is two over and two under in register.

3.5.2 Features of hollow single-braid rope

The distinguishing feature of this structure is its round shape. Wear occurs on the crowns of the strands but, because there are more of them and due to the roundness, it is not as pronounced as in eight-strand plait. These rope structures have somewhat higher strength and less stretch, in general, than laid and plaited ropes. On the other hand, they can experience more internal fibre damage and strength loss due to severe loading and unloading.

Hollow single-braid rope is balanced. A freely suspended load will not rotate. It does not hockle.

Except when they are too tightly braided, these ropes are easily spliced and by methods similar to eight-strand plait, except there are twelve strands to tuck instead of eight. A simple bury splice is also used whereby the rope is simply inserted back into its hollow centre to make an eye (refer to Section 7.2.3).

It is possible to make almost unlimited length with the hollow braid construction. The carriers in the braider can be loaded with varying lengths of strand. When a carrier is near empty, it is removed and replaced with a full one. The tail of the original strand is laid next to a leading length of the new strand so that they overlap. The braider is restarted and the overlapping portion is buried in the centre of the rope. This can be continued indefinitely from strand to strand, with the strand splices spaced apart along the length.

Due to the lateral pressure created by the braid when the rope is under tension, friction transmits the tension from the old to the new strand. Only a few braid pitch cycles are required so the necessary length for the overlap is short. Full strength is maintained. In a 12-strand braid, the cross-sectional fibre area is increased by one-twelfth (8.3%) in the overlap area, but the circumference is increased only by about 4.1%.

For maximum reliability when dynamic cycling or flexing is involved, 12-strand braids with single strands per carrier may have the strands end-to-end spliced instead of just overlapping them.

3.6 Double-braid (braid-on-braid) rope

3.6.1 Double-braid construction

Double braid is made by braiding a cover rope (sheath) over a braided core (see Fig. 3.14). The tension in the rope is shared by both core and cover. Most double braids are made of either all nylon or all polyester fibre but combinations of these and polypropylene may be found. High modulus fibres in cover and core result in inefficient load sharing between them and are rarely encountered.

The outer braid structure is produced by a braiding machine with a relatively large number of carriers. Without the core rope, it would be a relatively flat braid

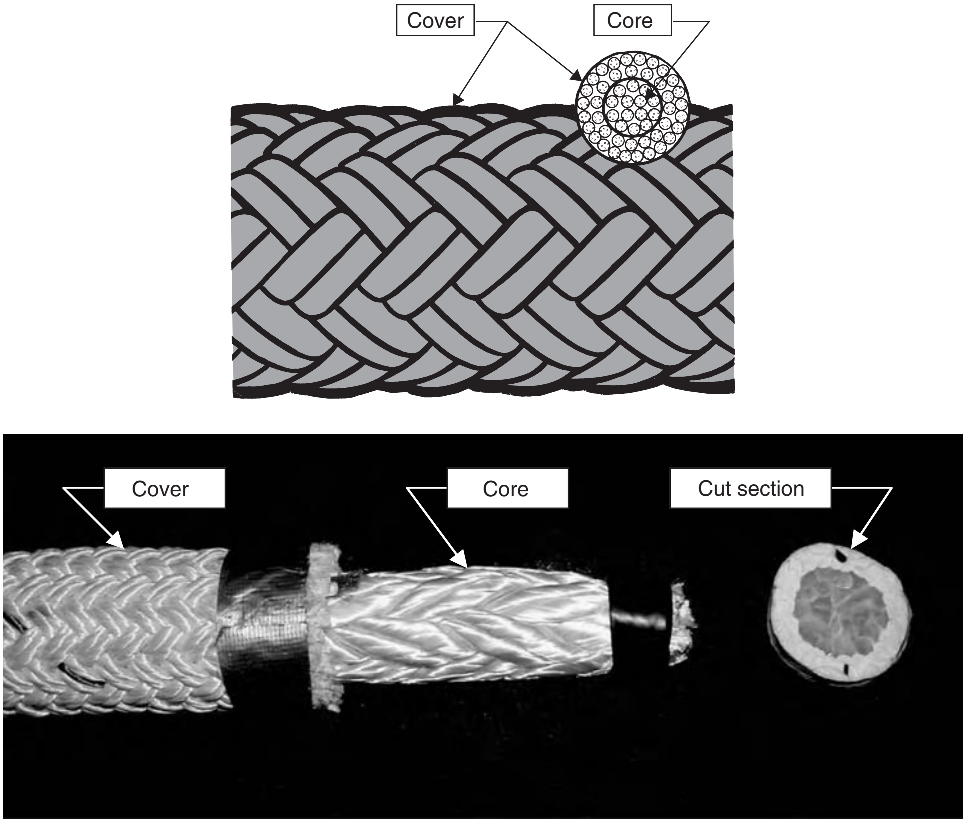


Fig. 3.14 Double braid rope. The cover is polyester and the core nylon in this design.

because of a large central hole. The number of carriers depends on the size of the rope; a typical 12 mm diameter rope may have a cover made by a braider with 16 carriers and with two or three strands per carrier (24 to 36 total strands). Large ropes, in the order of 96 mm and more, will have the cover produced from 32 carriers with at least two strands per carrier (64 total strands).

The core braids are usually made with eight carriers for small sizes and 12 carriers for larger ropes above about 40 mm diameter. One very large braider used for double-braid cores is known to have 16 carriers, but it does not improve the performance. Multiple strands per carrier, up to four, are employed on the cores of very large ropes.

The core structure is produced with a long braid pitch. This provides high strength but relatively low extensibility compared to the cover. Because the core is internal, firmness and snag resistance are not a consideration. However, the opposite applies to the cover. Firmness and snag resistance are essential, plus, to completely close over the core, the cover must have a shorter braid pitch. Thus, the core picks up tension faster than the cover. This phenomenon is exacerbated by the fact that the core diameter decreases with tension so the cover must elongate mechanically to make up the difference, which slows its ability to pickup load. The result is that the core may provide about 60% of the strength of a double braid even if the total fibre linear density is 50% for each. Some rope makers see an incremental increase in total rope strength if they put about 55% of the fibre in the core and 45% in the cover.

Since the cover is subject to external abrasion and more prone to fibre-to-fibre abrasion due to the high helix angle, having the internal core carry more load is desirable. Although cover strength is essential for splicing this type of rope, note that each leg of the splice carries only half the load; testing of properly made splices of ropes with 55% fibre in the core has verified that the strength is adequate.

A somewhat higher strength hybrid can be made with double braid construction by putting nylon in the core structure and polyester in the cover. The greater relative extensibility of the nylon allows the cover to pickup a greater share of the tension in the rope. Resistance to internal fibre-to-fibre abrasion and external abrasion when wet can be improved if a superior marine-grade of polyester fibre is used in the cover, especially if it is designed to carry a greater share of the load. Because the nylon core will shorten due to shrinkage when wet, the original balance between core and cover will change, thus making the in-service properties somewhat questionable.

Another version of double braid uses polypropylene in the core and polyester in the cover. Both fibres have about the same extension properties so initial load sharing is good. However, polypropylene will creep under high and/or sustained loads, thus creating the possibility of shifting more load to the cover. A benefit of this design is that the rope is just about neutrally buoyant and will appear to 'swim' in seawater and will float for a time with entrained air. Again, as with the polyester/nylon hybrid, the properties in the used condition are uncertain. This construction is no longer popular.

To maximise strength, the rope designer carefully balances the core/cover weight ratio, the pitch length in both cover and core braids, and the number of strands per carrier. This is a fairly complicated process but, over many years of trial and error and testing, patterns that produce good results have been verified and have found their way into computer models that speed up the design effort.

Jackets of low modulus fibre that do not support any load are often braided over a braided core of high modulus fibre to provide abrasion protection. Although they have the appearance of double braid, they are not considered as such (see Section 3.7).

3.6.2 Features of double-braid rope

Double-braid ropes compete in most of the same markets as laid, plaited and single braids. Historical perceptions indicate that among traditional ropes, double braid is stronger (20% to 30%) than laid or plaited ropes and (5% to 10%) stronger than single braids of the same materials on a diameter basis (but less on a weight basis). However, considerable development has occurred in more recent times and so many variables are involved that generalisations need to be qualified. Still, braid-on-braid is often selected because of its reputation for higher strength and less extensibility.

The firm and very round shape of these ropes make them one of the most popular lines for running rigging on sail boats. They are easily differentiated with one or more coloured yarns in the cover to aid deckhands in sorting out the right line to pull.

While laid ropes and single braids are limited to about 120 mm-diameter (size 15) and plaited ropes to about 160 mm (size 20), double braid can be made to

240 mm (size 30). Such ropes are often found mooring oil tankers to buoys in the open sea where a single line or pair of lines are used (see Fig. 8.19).

Braider splices
Long lengths of double braid rope can be produced by utilising braider splices (see Section 3.5.2).

3.7 Braided rope with jacket

3.7.1 Braided rope with jacket construction

An offshoot of double braid is a rope in which a hollow braided or plaited core is used to carry the load, and a braided jacket is used to protect it from external abrasion. The core rope would be made from a high strength, high modulus material such as aramid or HMPE. The jacket is usually of polyester fibre and may be relatively thick when superior abrasion and cut resistance are required. Such a rope is seen in Fig. 3.15. Standard sizes for general commercial applications usually do not exceed 30 mm, but much larger sizes can be made.

3.7.2 Features of braided ropes with jackets

This rope design fits a unique niche. It has high strength for its diameter, has low stretch, the load-carrying core is protected and it is especially rugged. It is popular for electrical utility service because it is unlikely to conduct electricity, unless wet. It winds well on winches as used on electrical service vehicles, and, because of its small diameter, does not require a large drum on the winch. The low elongation improves load handling.

Problems of damaging kinks in the core have been observed when the jacket is very tight, the core braid pitch is long, and the bend radius of a winch drum or pulleys is too small. Frequent flexing, even at relatively light loads, can weaken the core (see Sections 2.58, 4.5.6, 4.5.7).

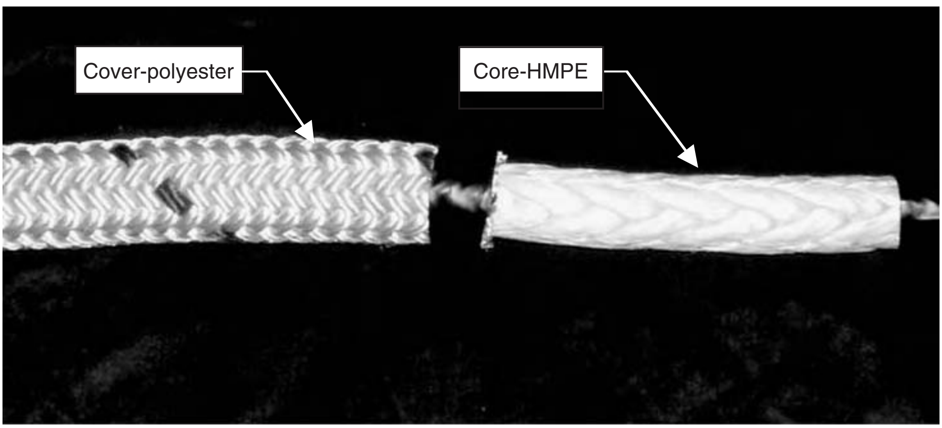


Fig. 3.15 Braided rope with heavy, non-load bearing jacket.

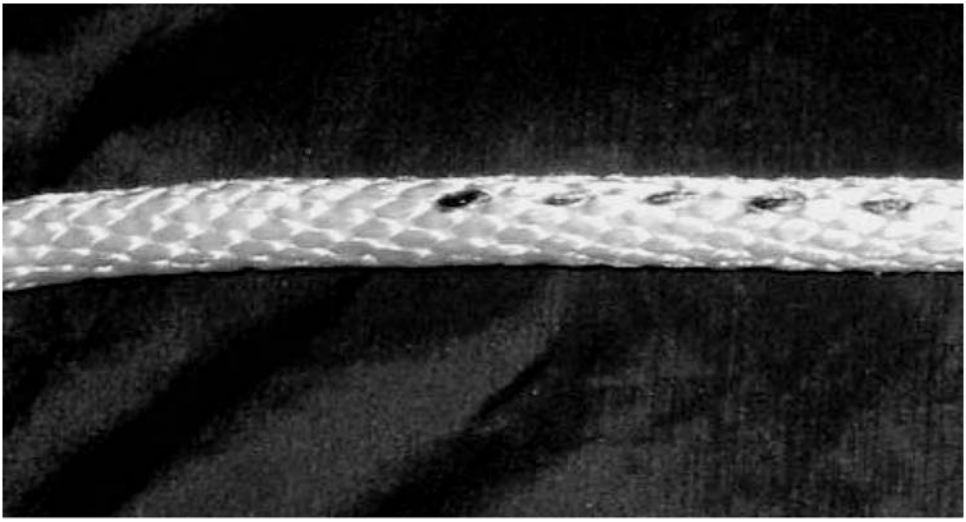


Fig. 3.16 Solid braid rope. On the surface, as indicated by the marks, the strands all appear to be aligned in the direction of the axis.

3.8 Solid braid rope

3.8.1 Solid braid construction

Of all machine-made ropes, solid braid is perhaps the oldest*. Rope walks for three strand and hand-made braids preceded it, but it is a child of the Industrial Revolution. One of the early applications was cotton sash cord for window weights. These are still made today on machines of the same basic design.

In solid braid, all the carriers on the braider move in the same direction. A strand moves under another, moves to the side in the interior of the rope, comes back to the surface and goes under again. All the strands on the surface appear aligned with the axis. Below the surface, they are crossing over to one side, always in the same direction. An example of a solid braid rope is shown in Fig. 3.16.

Cotton remains popular in this construction, often reinforced with a nylon core. Other materials are nylon, polyester and multi-filament polypropylene.

Attractive patterns can be developed by using strands of different colours, making them popular for decorative applications.

3.8.2 Features of solid braid rope

Solid braids have modest fibre strength conversion efficiency. Due to the sharp cross-over angles below the surface, they have relatively large mechanical extensibility. Of all rope structures, this is the most springy.

If one strand is broken, the rope can unravel.

They can be chosen because of their very round and appealing surface rather than their mechanical performance. They are often found in theatres for people control. Colourful halter cords for horses are both attractive and functional.

* *Solid braid* is a specific term for this type of rope. As mentioned in Section 3.5.1, hollow single braids with a limited number of strands are effectively solid. See Glossary for additional comment.

Industrial applications are limited. Typical uses are tie-downs, clothes-lines, flag halyards, and awning lines.

3.9 Parallel strand rope

3.9.1 Parallel strand construction

Parallel strand ropes, together with parallel yarn ropes and wire rope constructions, are low-twist ropes that have been developed to give high strength conversion efficiency and to minimise extensibility. Parallel strand ropes have a centre strength member made up of many individual elements which are held together by a braided jacket; these are either small ropes (called sub-ropes) or twisted yarn bundles. An example is shown in Fig. 3.17. The cores are usually constructed in one of the following ways:

- Three-strand laid ropes with a long lay length, half S and half Z lay
- Braided ropes with a long braid pitch
- Multiple ply, twisted yarns, half S and half Z twist

Long lengths can be produced, since the sub-ropes, being small in diameter, can be made very long on machinery of modest size. Stacks of reels, each containing what could be miles of these small lines, feed into the jacketing process that completes the assembly.

For ropes made from laid or braided sub-ropes, splicing is possible by splicing the individual sub-ropes. For twisted yarns, more specialised splicing techniques can be used as explained in Chapter 7.

3.9.2 Features of parallel strand rope

Because the sub-ropes can be made with low twist or low braid angles, parallel strand ropes provide excellent strength conversion from fibre strength to rope strength in large sizes if all the elements are tensioned equally and the termination is efficient. Compared to older traditional constructions and depending on jacket weight and rope size, the ability to convert yarn strength to rope strength may be in the range of 80–85% efficiency, compared with 45–60% for the conventional laid, plaited or braided constructions.

When properly terminated, fatigue life under cyclic tensile loading is excellent, exceeding conventional constructions and even wire rope, especially in a marine environment.

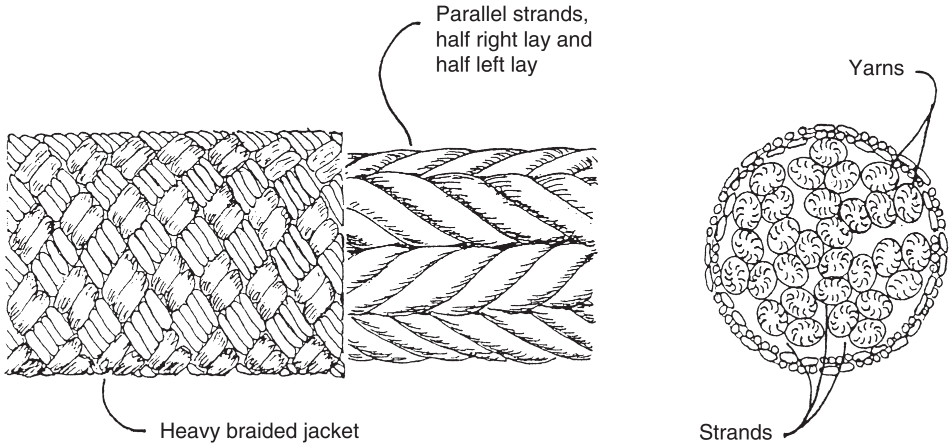
This rope construction is not well suited for flexing around radii unless they are very large. However, data is limited in this regard and other constructions that are better suited are suggested.

Very large rope sizes, to 1500 tonnes strength, have been successfully tested.

3.10 Kernmantle rope

3.10.1 Kernmantle construction

Kernmantle rope is similar to parallel strand rope or parallel yarn rope but is made in smaller sizes and is discussed separately because its construction and its applications are unique. It consists of a core or ‘kern’, which may be parallel textile yarns, multiple S and Z twisted yarns, multiple S and Z laid sub-ropes, or multiple long



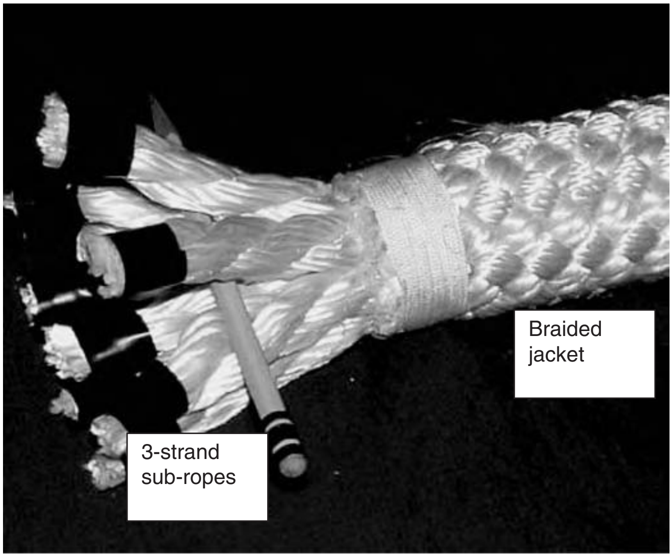


Fig. 3.17 Parallel strand rope. Three strand sub-ropes are used in this design, half S and half Z lay. Braids or twisted yarns are options.

pitch braids. This core is covered by a braided jacket (mantle), which is very thin and whose many strands are made of small twisted textile yarns. These are usually multicoloured (see photograph in Fig. 3.18). In this figure, the core has been exposed and the cover unbraided to show the number of strands (32 carrier braider with two strands per carrier for a total of 64 strands).

Kernmantle ropes are generally classified as either 'static' or 'dynamic'. The static version has relatively low extensibility. When new, the elongation at 10% of breaking strength is 5% or less. It is used for rescue work and applications that do not require high energy absorption. Dynamic kernmantle is used for fall arrest, as would be experienced in mountaineering. To qualify under what is known as the UIAA classification, the rope must survive the stated number of arrests of a falling weight; for example a 7-fall or a 10-fall rope. A drop of 80 kg for 2.5 m will result in an elon-

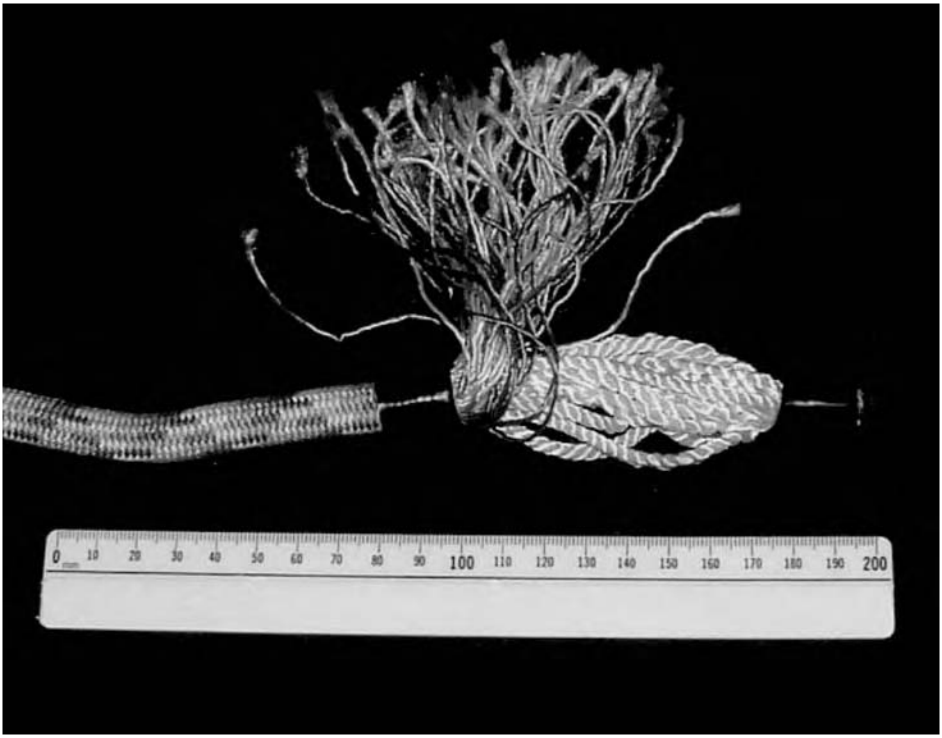


Fig. 3.18 Kermantle rope. The core is three-ply rope yarns, an equal number of S and Z lay. The jacket is tightly braided with many, very lightly twisted, multi-coloured textile yarns.

gation of 6.5% to 7.5%, but this may be higher in some ropes. Dynamic kernmantle is made of nylon and the core is usually shrunk and stabilised by steam to increase the elongation under load and to eliminate changes after becoming wet. It is usually retired after experiencing a fall arrest.

Typical sizes of static and dynamic kernmantle ropes range from 8 to 11 mm diameter. Accessory cords for use in rescue work and mountaineering are also made in kernmantle construction and range in size from 4 to 8 mm diameter.

3.10.2 Features of kernmantle rope

Kernmantle is a very round and firm rope. It is usually terminated by knotting, but certain fittings are designed to grip the rope with clamps and/or multiple wraps.

The light weight and ease of handling make this construction very popular with sportsmen and rescue workers.

The thin jacket is not very abrasion resistant but wear is usually visible and acts as a warning that the load-bearing core may be damaged. Experienced users are aware of abrasion possibilities and properly used ropes give good service. If too much of the jacket is worn away and it separates, it will slide down the rope, a dangerous situation for a person holding below that point or when a fitting has been applied there.

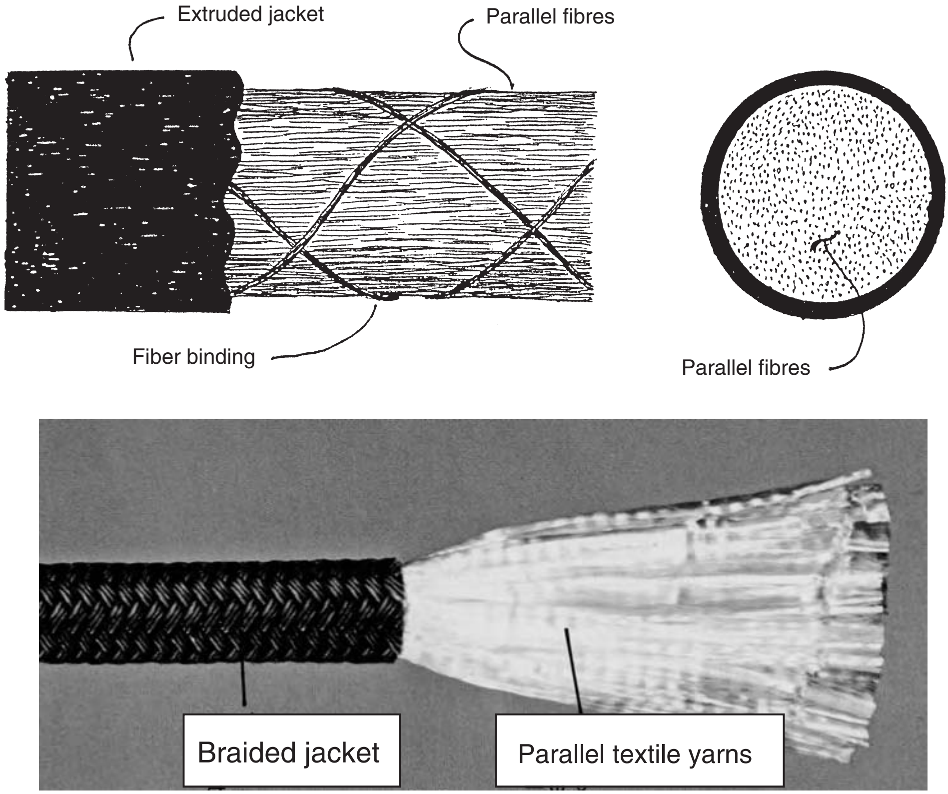


Fig. 3.19 Parallel fibre rope with braided jacket below and extruded jacket above.

3.11 Parallel yarn rope

3.11.1 *Parafil*-type ropes

The ultimate in low-twist construction is the zero-twist construction of the *Parafil* ropes, first made by ICI and now marketed by Linear Composites. These are often described as a collection of parallel filaments in a jacket, but the usual form is a large number of parallel textile yarns, which are enclosed in an extruded plastic jacket. A binding may proceed extrusion to hold the bundle together during handling (see Fig. 3.19).

Splicing is possible, but specialised skills and careful attention to exacting procedures are required. Special barrel-and-spike terminations were developed for this type of rope. Potted sockets are also used, especially in small sizes (see Chapter 7).

This construction, if carefully made and properly terminated, has very good strength conversion efficiency, in the same order of magnitude as parallel strand and wire rope constructions. With high modulus fibres, and because of lack of twist or a helical construction, it is more difficult to achieve good load distribution among the fibres unless accurately controlled tension is maintained on all yarns as they are bundled into the rope.

Parallel fibre ropes do not perform well in flexing under load unless the radius is very large.

The extruded jacket limits the range of applications for this construction. Static applications, such as guy wires for masts, are some of the most successful.

3.11.2 Other parallel yarn constructions

One type of the smaller kernmantle ropes (see Section 3.10.1) does contain parallel yarns. In addition, there is a fairly substantial production of cheap, general-purpose ropes in which parallel yarns are included within a braided, or sometimes a plastic, jacket.

3.12 Wire-rope type construction

3.12.1 Wire-rope construction

This very specialised construction of fibre ropes is produced on planetary stranders or tube stranders of the same type as are used to produce wire rope. Also, each strand is normally of wire-rope type construction. A 'six-strand' (six strands that are closed around a centre strand) is shown in Fig. 3.20. This is the most common construction but more elaborate designs have been made, such as the 18-strand rope shown in Fig. 3.21. The single central strand that is always required may be of a different material or construction from the other strands, since it tends to pick up load first. Each additional layer in a wire-rope construction has six more strands than the layer below. In the 18 strand rope of Fig. 3.21, note the difference in diameter of alternate outer strands, so that nesting provides optimum fibre density. The next largest rope is thus a 36-strand in 18-12-6-1 construction.

The wire-rope construction was developed for fibre ropes because it achieved good fibre-to-rope strength conversion with high modulus fibres such as aramid. Later it was found to work well with low modulus fibres, especially polyester.

Wire-rope construction has low twist levels and a long strand cycle length in order to achieve its very high strength. This means that the rope is very loose when slack and would be difficult to handle. A jacket, usually braided, is required; this also provides abrasion and snag protection. Note the difference with six-strand laid construction. (Section 3.3.4).

Length is limited by the strand length that can be put onto the bobbins in the closing machine. However, some extremely large machines designed for wire rope are available and lengths in large sizes are measured in kilometres.

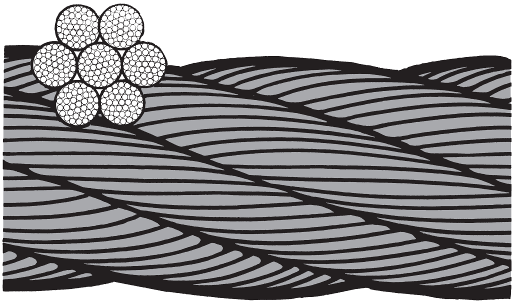
Splicing is straightforward, using basically the same procedures as with wire rope.

3.12.2 Features of wire-rope type construction

This construction provides excellent fibre strength conversion efficiency. For six-strand, in sizes of 12 to 50 mm diameter, it can reach 85%. The six-strand construction is the most common and very large sizes have been produced and tested, to 1000 tonne strength.

Six and eighteen strand constructions are not torque free. A freely-suspended load will rotate. If fibre rope is to be joined with wire rope in series, an advantage of this construction is that it is possible to match the torques with an appropriate rope design. Thirty-six strand constructions can be made that are very close to being torque free.

Wire-rope construction provides excellent tension–tension fatigue resistance. It also performs well in flex fatigue, especially if the strands are jacketed as seen in Fig. 3.21.



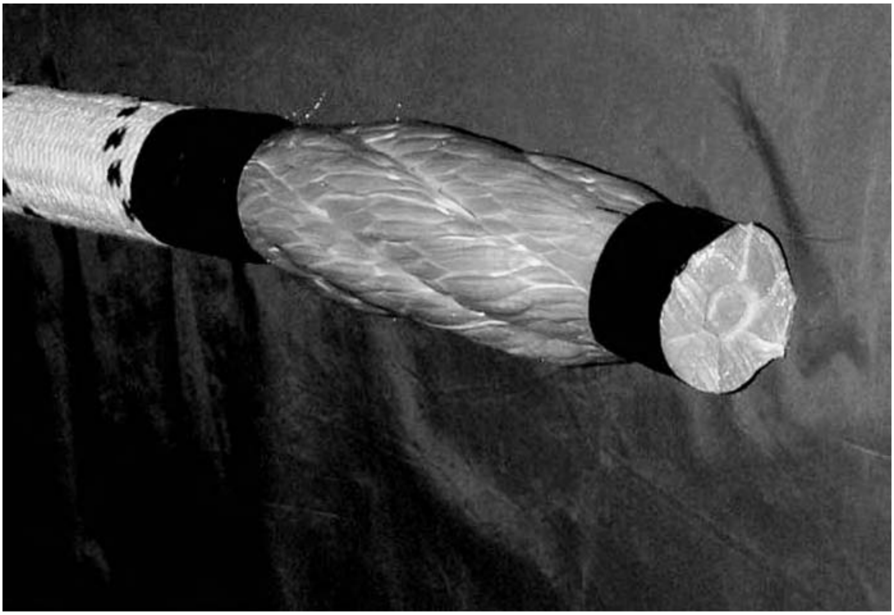


Fig. 3.20 Jacketed six strand wire rope construction (six around one) Braided jacket has been cut back to reveal six-strand core. Tightness of the tapes simulates effect of tension on the strands as seen on the end. Rope yarns that make up the core strands are visible on surface. Jacket is braided with black marker strands.

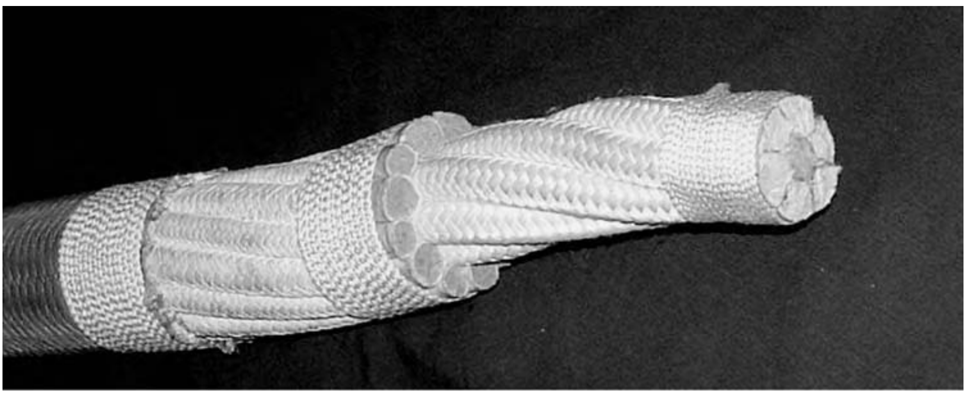


Fig. 3.21 Eighteen-strand aramid wire rope construction, all strands laid in the same direction. Inner strand layer is 6 around 1, outer layer is 12 around 6. Note nesting of outer layer with small and larger strands. Each strand has a braided jacket, and the whole rope has a braided jacket.

4

Properties of rope

4.1 Rope dimensions

In order to discuss properties of rope, definition of rope size should be recognised as an appropriate starting point.

A diameter of approximately 4 mm (3/16 inch) is usually taken as the lower limit, which differentiates ropes from small cords, and the largest ropes now made approach 300 mm (12 inches). The range is thus from the first few divisions of a typical school ruler to its whole width. However, diameter is an uncertain measure of rope size, because of the irregular boundaries of ropes and the variable spaces between fibres, yarns and strands.

Rope size is best expressed in terms of its linear density (often called 'rope weight'), i.e. mass per unit length. For more detail, see Section 1.3.3 and Appendix I.

The following equation is a useful reference:

$$\begin{aligned}&\text{rope linear density in kg/m}\\&\quad = 10^{-6} \times \text{number of textile yarns in rope}\\&\qquad \times \text{linear density of textile yarns in tex}\\&\qquad \times \text{contraction factor due to twisting or braiding}\end{aligned} \tag{4.1a}$$

If linear density is wanted in lbs/100 ft and yarn is specified in denier, the equation becomes:

$$\begin{aligned}&\text{rope linear density in lbs/100 ft}\\&\quad = 7.5 \times 10^{-6} \times \text{number of textile yarns in rope}\\&\qquad \times \text{linear density of textile yarns in denier}\\&\qquad \times \text{contraction factor due to twisting or braiding}\end{aligned} \tag{4.1b}$$

The contraction factor (Section 5.1.2) is a measure of the reduction in length as the yarns follow helical paths in the rope. It equals the ratio of the mean length along the yarn path to the axial length of a section of rope and is given by the mean value of $\sec\theta$, where θ is the angle between the yarn direction and the axis of the rope. If the rope linear density is known (by test or specification), the contraction factor can be calculated from these equations when the other parameters are known.

For some rope constructions, it may be necessary to modify these relations to allow for the weight of a jacket or other structural complications.

Linear density is easily determined by cutting off a length of rope and weighing it. Published procedures such as CI 1500 or ASTM D 4268, should be used. The relations to other dimensions are:

$$\text{rope density (kg/m}^3\text{)} = \text{rope linear density (kg/m)/rope area (m}^2\text{)} \qquad [4.2]$$

Rope area is determined from nominal diameter or circumference as listed in specifications or by measurement done by wrapping a narrow tape around the irregular outer surface (at reference tension), designating the value as the circumference of the rope and calculating the area or diameter as if it were a circle. (Differentiate between rope area and fibre area, equation [4.6]; the latter is used to determine area-based stress.)

$$\text{packing factor} = \text{rope density (kg/m}^3\text{)/fibre density (kg/m}^3\text{)} \qquad [4.3]$$

where the packing factor is the fraction of the rope's nominal cross-section area occupied by fibre.

The mass of a length of rope is determined from equation [4.4]

$$\text{total rope mass (kg)} = \text{rope linear density (kg/m)} \times \text{rope length (m)} \qquad [4.4]$$

4.2 Strength and weight

4.2.1 General

Strength comes to mind first when considering rope properties but fibre ropes would not be nearly so useful if were not for their light weight. Fibre rope engineering normally normalises strength in terms of weight, so that strength and weight should be considered together, as is done below.

4.2.2 Important relationships

For a rope in use, the important mechanical quantity is breaking load, commonly expressed in kilogram-force, kiloNewtons (102 kgf), tonnes (1000 kgf) or pounds force. The properties are best expressed in terms of linear density, but engineers also like to see values in Pascals, pounds force per square inch or other conventional stress units which are normalised by area.

The relevant quantities are:

$$\text{breaking stress} = \text{break load/fibre area, typically in MPa, but also in units such as lb/in}^2 \text{ (psi).} \qquad [4.5]$$

$$\text{fibre area (m}^2\text{)} = \text{rope linear density (kg/m)/fibre density (kg/m}^3\text{)} \qquad [4.6]$$

$$\text{specific strength (rope tenacity) in N/tex}$$
$$= \text{break load (N)/linear density (tex)} \qquad [4.7]$$
$$= \text{break load (MN)/linear density (kg/m)} \qquad [4.8]$$

These definitions lead to the following relation:

$$\text{rope break load in MN (100 tonne)} = \text{linear density (kg/m)} \times \text{tenacity in MN/(kg/m) or N/tex} \times \text{strength conversion efficiency (decimal)} \quad [4.9]$$

Strength conversion efficiency is a measure of the rope's ability to convert yarn strength into rope strength. It is determined from equation [4.9] when a rope's break load or rated strength is known. Strength conversion efficiencies may be found listed in various publications; or, for instance, a statement that a certain type of rope is '55% efficient'. They are not tabulated here as too many variables are involved, including termination efficiency, but typically can vary between 50 and 85%.

Another quantity, which was popular in the past, is the breaking length. This can be defined as the length of rope that would break under its own weight, and represents the same property as tenacity or strength-to-weight ratio. The calculation is provided should the reader encounter the term:

$$\text{breaking length (metres)} = \text{strength (kgf)}/\text{linear density (kg/m)} \quad [4.10]$$

Units and conversions for quantities mentioned in this section are included in Appendix I.

4.2.3 Strength and weight comparative data

Tables 4.1, 4.2 and 4.3 have been prepared for a variety of rope products to illustrate the linked properties of strength and weight. Steel wire rope, Table 4.4, has been added for comparison purposes; the values are for general-purpose industrial wire rope with steel core.

The strength values have been determined by examining published data by rope manufacturers or test data that is privy to the authors. Representative values have been selected simply for purposes of comparison. So many variables enter into a particular rope design, and consequent strength, that higher or lower values can be expected without any question of quality. In addition, more than one version of a particular fibre type with different tenacity might be available.

There are many other rope types that are produced and the list could be nearly endless. These tables are intended to be representative of ropes found today in general commerce. Wide variations exist in products of the same type and changes occur frequently due to improvements in the strength of fibres, introduction of new fibres, and development or upgrading of methods of production. Some comments along this line are provided below:

- Nylon and polyester ropes in three-strand laid, eight-strand plait and various braids are produced for demanding service with strengths about 15% higher than those shown.
- Nylon rope swells and becomes shorter when saturated with water; inappropriately, this is usually referred to as shrinkage because the rope gets shorter, but actually, the swelling of the fibre causes the structure to contract. The strengths shown in the tables are for the dry condition. Wet values should be reduced by at least 10% to account for 'shrinkage' (actual value depends on the degree of wetness). Nylon ropes will recover strength if aggressively cycled between low and high tensions, even if continually wet, and full recovery can be achieved if cycled dry.

Table 4.1 Typical strength and weight properties for various low-modulus fibre ropes in conventional constructions

Size diameter (mm)	Material	Construction	Breaking strength (kgf)	Breaking strength (kN)	Linear density in air (kg/m)	Linear density in water (kg/m)	Strength-to-weight ratio [kgf/(kg/m)]
12	Manila (dry)	3-strand laid and 8-strand plait	1085	10.6	0.11	–	9.80×10^3
24			3680	36.1	0.40	–	9.20×10^3
96			43 000	421.0	6.40	–	6.71×10^3
12	Nylon (dry)	3-strand laid and 8-strand plait	2580	25.3	0.094	0.011	27.4×10^3
24			10 100	99.0	0.375	0.045	26.9×10^3
96			147 000	1440.0	6.00	0.718	24.6×10^3
12	Nylon (dry)	Double braid and 12-strand single braid	3300	32.3	0.098	0.012	33.7×10^3
24			13 300	129.0	0.390	0.047	33.7×10^3
96			185 000	1810.0	6.200	0.762	29.8×10^3
12	Polyester	3-strand laid and 8-strand plait	2600	25.4	0.116	0.032	22.4×10^3
24			10 000	98.0	0.460	0.129	21.7×10^3
96			154 000	1510	7.360	2.060	20.9×10^3
12	Polyester	Double braid and 12-strand single braid	4000	39.2	0.132	0.037	30.3×10^3
24			14 000	137.0	0.530	0.148	26.4×10^3
96			183 000	1800.0	7.520	2.110	24.2×10^3
12	Polypropylene	3-strand laid and 8-strand plait	1880	18.4	0.069	floats	27.2×10^3
24	monofilament	(values for standard strength fibre –	6400	62.7	0.260	floats	24.6×10^3
96	or slit film	add 20+% for higher strength fibre)	86 000	843.0	4.080	floats	21.1×10^3
12	Polypropylene	8-strand braid	2900	28.4	0.090	floats	32.2×10^3
24		12-strand braid	9450	92.6	0.290	floats	32.5×10^3
96		(values for higher strength fibre)	120 000	1180.0	4.200	floats	28.5×10^3
48	Nylon	Wire rope type, 7 strand (Atlas)	50 000	490	1.48	0.18	33.8×10^3
96	monofilament	(very large monofilaments)	190 000	1860	5.90	0.71	32.2×10^3

Table 4.2 Typical strength and weight properties for various high-modulus fibre ropes and special-construction low-modulus ropes

Size diameter (mm)	Material	Construction	Breaking strength (kgf)	Breaking strength (kN)	Linear density in air (kg/m)	Linear density in water (kg/m)	Strength-to-weight ratio [kgf/(kg/m)]
12	Aramid	Wire rope type laid	11 400	107	0.133	0.041	85.4×10^3
24		(may be 6, 12, or 36 strand)	45 000	441	0.520	0.162	86.5×10^3
96			477 000	4670	6.000	1.830	79.0×10^3
12	HMPE	Wire rope type laid	12 900	126	0.095	floats	136×10^3
24		(may be 6, 12, or 36 strand)	54 000	529	0.390	floats	138×10^3
96			550 000	5400	4.060	floats	135×10^3
12	HMPE	12-strand braid and 8-strand plait	10 200	100	0.095	floats	107.0×10^3
12	HMPE treated	(second figure for post production treatment)	14 000	137			147.0×10^3
24	HMPE		32 600	320	0.349	floats	93.4×10^3
24	HMPE treated		49 900	490			143.0×10^3
96	HMPE		408 000	4000	5.800	floats	70.3×10^3
96	HMPE treated		690 000	6760			132.0×10^3
12	LCP	12-strand braid	14 000	137	0.137	0.040	102.0×10^3
24			49 000	480	0.504	0.145	97.2×10^3
96			690 000	6760	8.470	2.430	81.5×10^3
48	Polyester	Wire rope type, 7 strand, jacketed	65 000	637	1.580	0.435	41.1×10^3
96			276 000	2700	6.500	1.790	42.4×10^3
160			700 000	6860	16.000	4.400	43.7×10^3
48	Nylon (dry)	Parallel strand, jacketed	58 000	568	1.280	0.157	45.3×10^3
96			231 000	2260	5.300	0.652	43.5×10^3
160			590 000	5780	14.500	1.740	40.7×10^3
48	Polyester	Parallel strand, jacketed	69 000	676	1.650	0.450	41.8×10^3
96			283 000	2773	6.500	1.780	42.8×10^3
160			710 000	6000	17.000	4.670	41.8×10^3

Table 4.3 Typical strength and weight properties for various low-modulus fibre ropes in solid braid constructions

Size diameter (mm)	Material	Construction	Breaking strength (kgf)	(kN)	Linear density in air (kg/m)	Linear density in water (kg/m)	Strength-to-weight ratio [kgf/(kg/m)]
6	Cotton/Nylon	Solid braid, cotton cover with nylon core	365	3.58	0.018	–	20.0×10^3
12			1200	11.8	0.079	–	15.2×10^3
6	Nylon (dry)	Solid braid	570	5.6	0.023	–	24.8×10^3
12			1820	17.8	0.095	–	19.2×10^3
6	Polyester	Solid braid	475	4.7	0.024	–	19.8×10^3
12			1660	16.3	0.095	–	17.5×10^3
6	Polypropylene	Solid braid, multifilament fibre	360	3.5	0.019	–	18.9×10^3
12			1250	12.3	0.076	–	16.4×10^3

Table 4.4 Typical strength and weight properties for steel wire rope

Size diameter (mm)	Material	Construction	Breaking strength (kgf)	(kN)	Linear density in air (kg/m)	Linear density in water (kg/m)	Strength-to-weight ratio [kgf/(kg/m)]
12	Steel	Wire rope 6 × 19 IWRC	10 450		0.69	0.60	15.1×10^3
24		Wire rope 6 × 19 IWRC	40 800		2.76	2.40	14.8×10^3
96		Wire rope 6 × 37 IWRC	570 000		44.10	38.40	12.9×10^3

- Polypropylene, co-extruded polyolefins and polyester / polypropylene blends are being produced with as much as 30% higher strength than those listed and usually demonstrate improved abrasion resistance.
- HMPE ropes can be tensioned by a unique process following rope production to improve load distribution between rope components. This is particularly effective for braided constructions and both types are shown in Table 4.2 for purposes of comparison.
- The parallel-strand and wire-rope constructions can have non-load bearing jackets of varying weights depending on thickness; this affects linear density of the whole rope which can make comparisons somewhat confusing.
- Parallel-yarn ropes were not listed due to a limited number of applications, but well-made ropes, properly terminated, will have strengths close to those of parallel strand ropes.

4.2.4 Minimum strength

The breaking load values in the tables are for minimum strengths. This is defined in some standards as two standard deviations below the mean of a statistically significant number of break-test results (see CI 2002 for a typical procedure for determining minimum break strength). Average strengths or just 'strength' are reported by some ropemakers and the person reviewing published data should be careful to determine the basis that was used. Typically, for general-purpose industrial and marine ropes, average strengths are 10% to 15% higher than minimum strengths.

4.2.5 Termination strength

In use, rope is only as strong as the means used to hold or anchor it at its ends; this is called the 'termination'. The disturbance of the rope structure to make a splice or the interface with the fitting inevitably weakens a rope at the termination. The minimum strengths reported in Tables 4.1 and 4.2 are based on ropes with efficient spliced terminations. This is considered the most realistic approach as most ropes that can be spliced are used with eyes that have been produced on the ends to secure the line. Some standards allow for an increase in the actual breaking load if the specimen has been tested with a splice and it breaks in the splice; this will give an unrealistically higher values for the product if breakage during a test or in service normally occurs in the splice, which is most often the case.

4.2.6 Strength-to-weight ratio

The strength-to-weight ratios for the various rope products have been included in Tables 4.1 to 4.4. This is a measure of rope tenacity (equation [4.7]) and provides a quick view of weight relative to strength for comparison between various products. Some interesting insights can be gained from examining this property as explained below when reviewing data in Tables 4.1, 4.2 and 4.4:

- Wire rope has a lower strength-to-weight ratio by a factor of nearly two or more when compared with any synthetic fibre rope. For rope made of very high tenacity fibres, the factor can be over eight.
- The man-made fibre ropes listed in Table 4.1 represent the more conventional industrial products. In general, it can be seen that the strength-to-weight ratios are fairly closely grouped.

- Note that braided ropes, for the same diameter, are stronger than three-strand laid or eight-strand plaited ropes (about 35%) but braided pack more fibre into the same size and are therefore heavier, bringing the strength-to-weight ratios closer (about 20%).
- Strength-to-weight ratios decrease as rope size increases. This is especially true of high modulus ropes in a braided construction. Looking at HMPE 12-strand braid in Table 4.2, the usual version has a 35% decrease in strength-to-weight ratio from 12 mm diameter to 96 mm. However, a post rope production tensioning process, as noted previously, has been developed that produces better load sharing among the rope components and, when employed, this cuts this difference to about 10%.

4.2.7 Submerged weight

The effective linear density for ropes submerged in water has also been included in Tables 4.1, 4.2 and 4.4. To determine the linear density in fresh or sea water, the following relationship is used:

$$\text{submerged linear density} = (\text{fibre density} - \text{water density}) / \text{fibre density} \qquad [4.11]$$

where water density = 1.00 for fresh water and 1.04 for seawater (g/cm^3).

Using polyester parallel strand construction and wire rope (both 96 mm diameter) for comparison, it is seen that the wire rope is very nearly twice as strong, but its submerged weight is 20 times as great. Therefore, on a strength-to-weight basis, the polyester is 10 times better. This is significant for applications such as deepwater mooring where the submerged weight of wire rope becomes very difficult to manage.

4.2.8 Service conditions

The strength values shown in Table 4.1 must be interpreted in the light of conditions in service. As some ropes may degrade faster than others, the safety margin might have to be increased for a very high strength line, as compared to one of lower strength which may have a much longer life at a larger diameter. Although everyone tends to look at strength first, the selection must view all aspects of the application.

Chapter 8 is devoted to uses of rope, and such considerations as the above are covered in more detail.

4.3 Elongation

4.3.1 Elongation observed

All ropes, including wire rope, elongate when loaded. The next most important mechanical property of ropes after strength and low weight is the extent to which they stretch. Himmelfarb (1957) has a set of plots for three-strand ropes. These are mainly traditional manila ropes, but they demonstrate features that apply to all ropes. Note that percent of break load is plotted against percent elongation, which

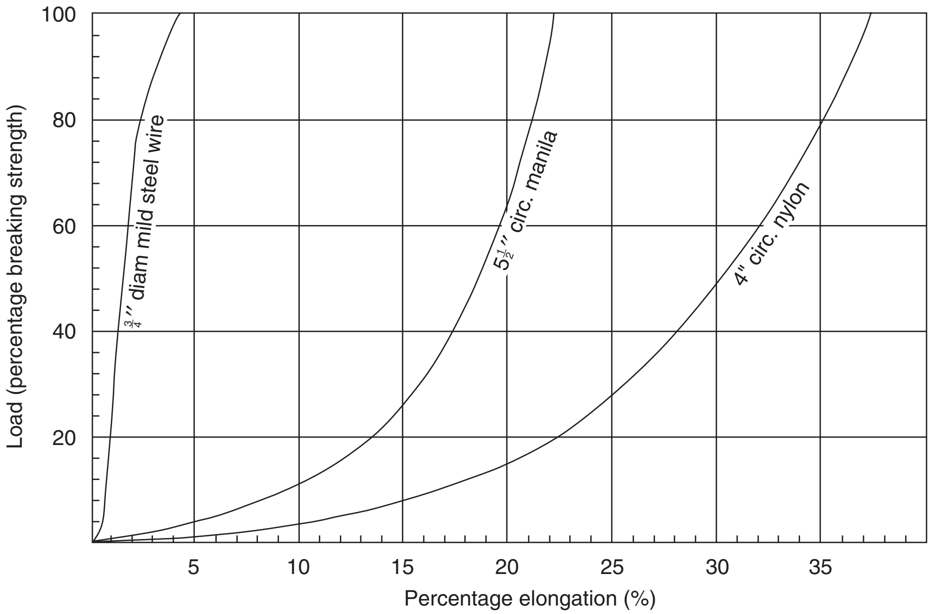


Fig. 4.1 Load–elongation curves for three ropes. From Himmelfarb (1957).

is a convenient way of normalising data. More common engineering procedures would plot absolute values of tension against elongation, or normalise by plotting stress or specific stress against strain (fractional) or percent elongation

Figure 4.1 shows that manila rope is much more extensible than a steel wire rope, and nylon is still more extensible. Accompanying the stretch, there is a reduction in diameter, as shown in Fig. 4.2. A 30% reduction in diameter, as seen with nylon at high load, is very noticeable when working in the field and is a powerful warning to stand clear.

Figure 4.3 shows the influence of rope construction: a soft-laid rope with low twist is less extensible than a tightly twisted hard-laid rope. The soft lay will have higher strength but it will also be very soft, prone to snagging and difficult to handle.

Comparing three-strand ropes A and B in Fig. 4.4, extensibility increases slightly as the diameter increases. The four-strand version of size A is C and is seen to stretch more. Cable laid ropes (Section 3.3.5) are structures made by laying smaller ropes together to make larger ropes; these are seen in Fig. 4.4 as being even more extensible, both when made of manila (D) or nylon (F).

A large amount of the elongation of a new rope is due to a compacting of the rope structure, as demonstrated by Fig. 4.5. If a relatively large pre-load is applied, most of this initial elongation is taken out and the elongation is reduced when compared to curve E. As explained in Chapter 10 on testing, a small preload, called 'reference tension', is required by various standards as an initial tension to establish a 'zero' point for measuring elongation properties.

Figure 4.6 shows that weathering (moisture saturation and shrinkage) of a manila rope, which will reduce its break load, also makes it more extensible. Finally,

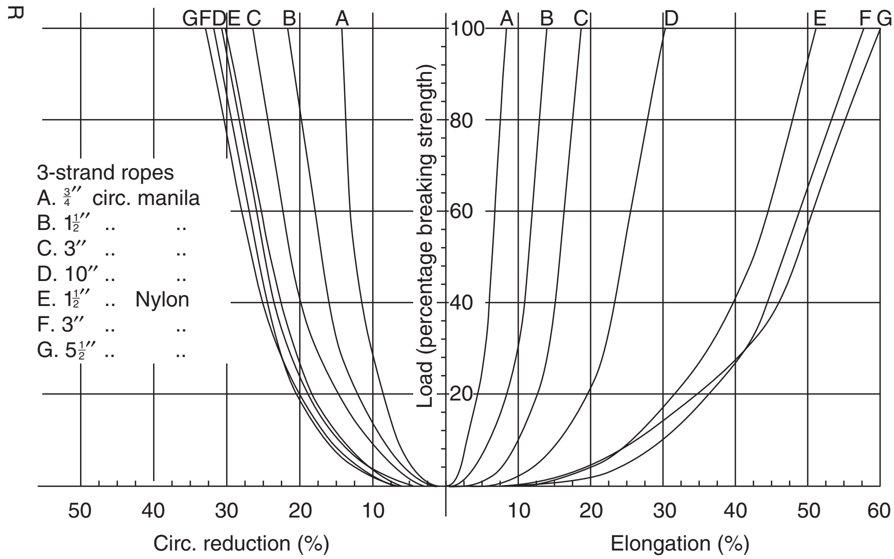


Fig. 4.2 Load–elongation and circumference reduction (= diameter reduction) for various sizes of ropes made from two different fibres. From Himmelfarb (1957).

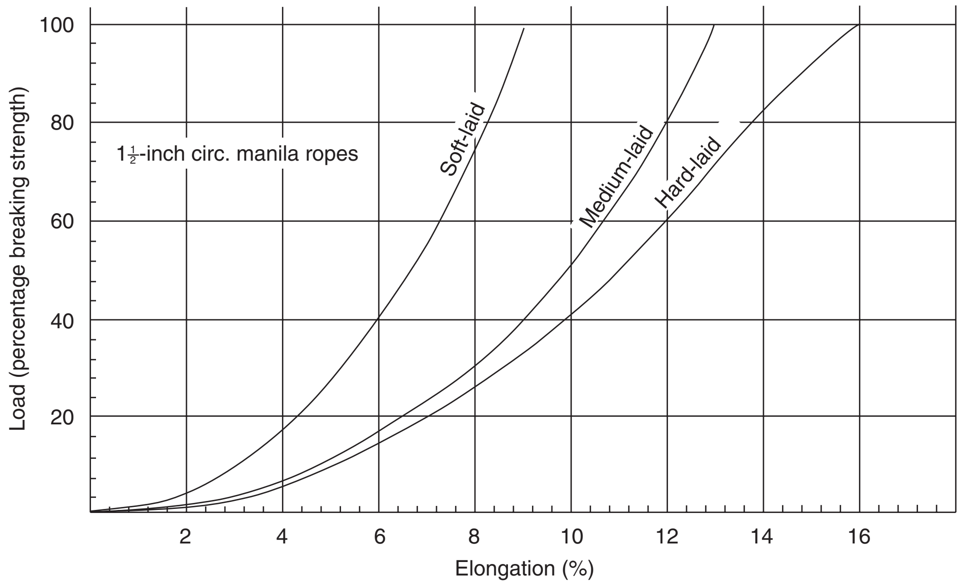


Fig. 4.3 Effect of tightness of twist and lay on load–elongation curves. From Himmelfarb (1957).

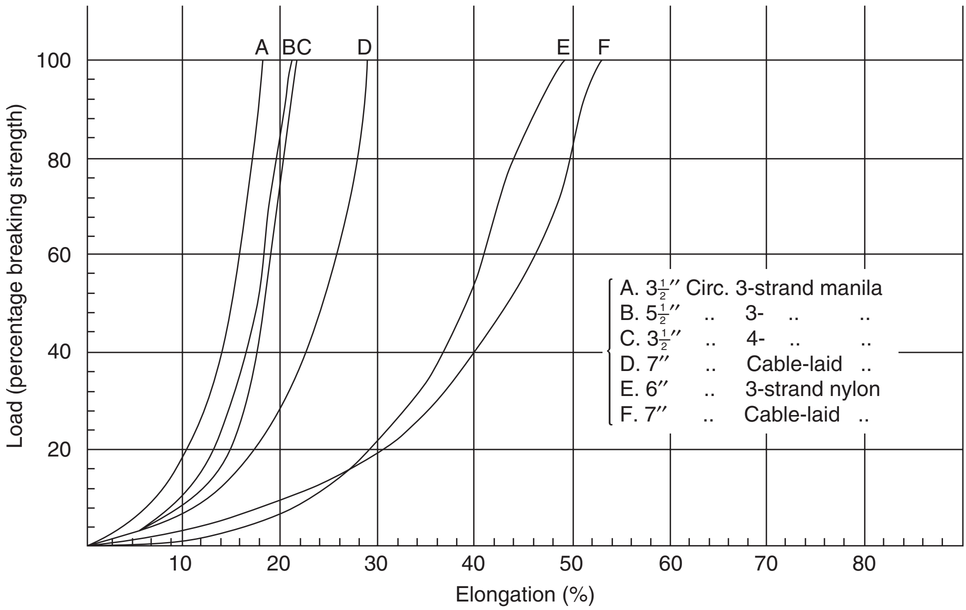


Fig. 4.4 Effect of size and construction on load–elongation curves. From Himmelfarb (1957).

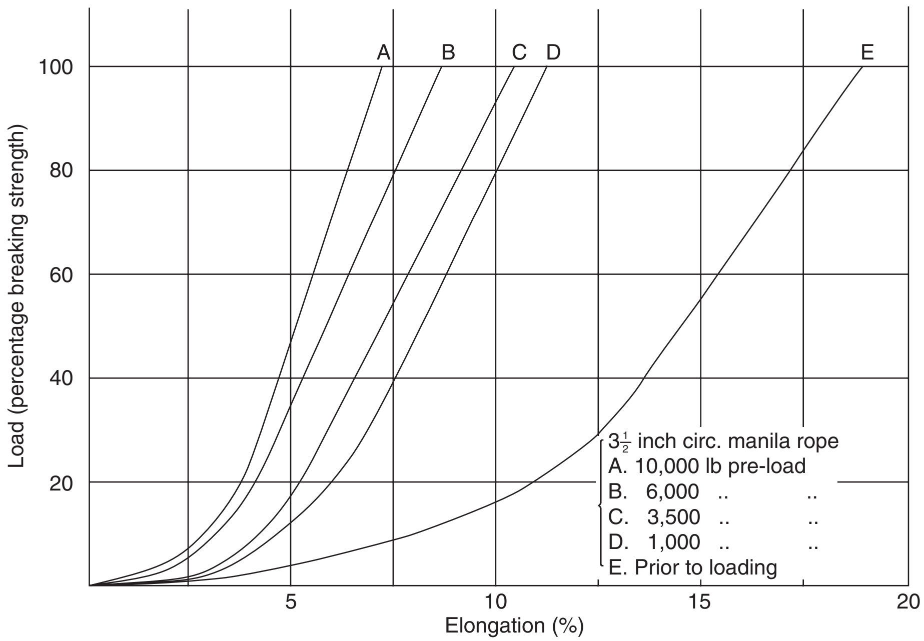


Fig. 4.5 Effect of pre-loading on load–elongation curves of manila rope. From Himmelfarb (1957).

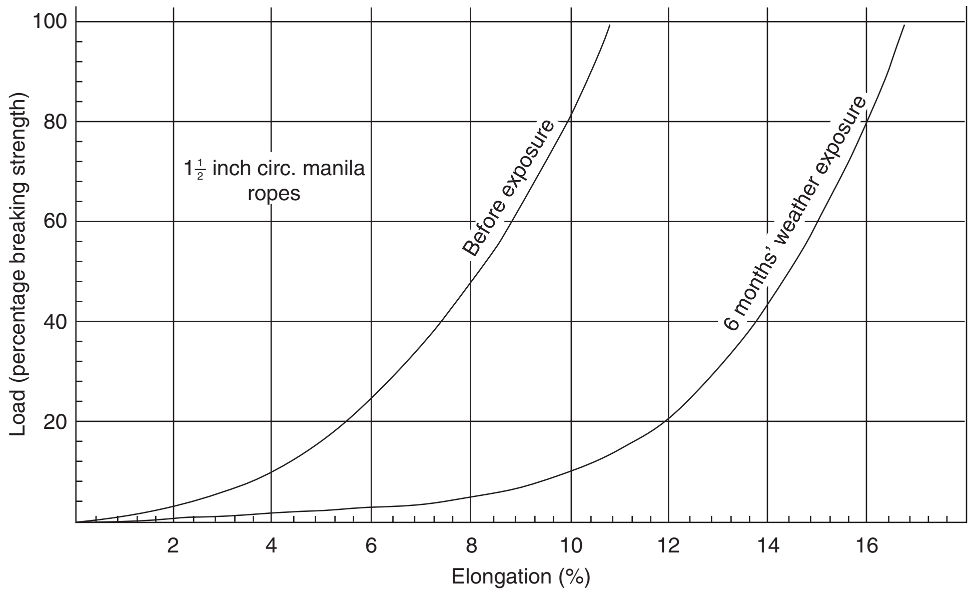


Fig. 4.6 Effect of weathering (moisture saturation) on load–elongation curves of manila rope. From Himmelfarb (1957).

Fig. 4.7 shows that nylon ropes are more extensible when wet (fully saturated by soaking). Other man-made fibres do not share this trait.

Repeated cycling of the load has a pronounced affect on elongation response. Nylon, because of the difference in behaviour between dry and wet is particularly interesting; Figure 4.8 shows the load–elongation curves after cyclic loading of the same rope as in Figure 4.7. At the 25% load level, the percent elongation of the dry specimen was reduced from 12.5 to 8.0% after cycling of the load, and the wet specimen from 21 to 14%.

A typical response profile to cyclic loading of most man-made fibre ropes is shown in Fig. 4.9. A new rope is tensioned from A to B. It is unloaded and arrives at point C which is significantly to the right of A. The next cycle takes the tension to D and unloading puts the elongation at point E, only slightly to the right of C. By the fifth cycle the loops fall nearly on top of one another. By the tenth cycle, loop G–F, the rope is fairly well stabilised. The effect of a single pre-loading is also shown in Fig. 4.5

Ropes will gradually increase in axial stiffness as tension cycling progresses. The effect is difficult to forecast as it depends on many factors: fibre material, construction, load level, number of cycles, loading rates, creep, internal fibre breakage, contamination, and external abrasion. However, if a rope is used prudently, under consistent conditions, and retired in a reasonable time, the elongation of a fibre rope should remain close to that found after a short breaking-in period.

4.3.2 Axial stiffness and modulus

Strict usage determines modulus from the slope of a stress–strain curve with units such as GPa (or, for specific modulus, N/tex) and axial stiffness as tensile strain.

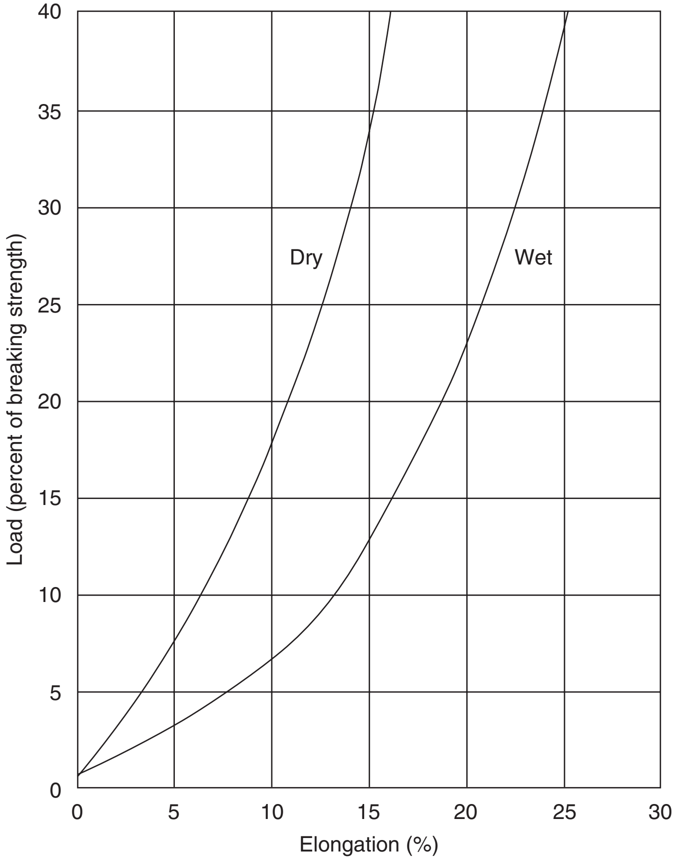


Fig. 4.7 Effect of change from dry to wet on extensibility of stabilised nylon double braid – single loading after complete relaxation. From Samson Ocean Systems (1979).

Many engineers will prefer to work in this way. Alternatively, the slope of plots of percent of break load against percent elongation may be used, as is done in Fig. 4.10. Decimals work as well as percentages and some plots will be presented this way. The nonlinearity of the plots needs to be taken into account.

For hand calculations, the best approach is to read the data directly from the graph. Methods to calculate elongation for a particular rope of a specific length are given in Section 4.3.8.

For computer or general mathematical models, the axial stiffness at any load can be quantified by the slope of curves. All lengths should be measured from a reference tension indicated by the dashed line in Fig. 4.10. Straight line approximations may be used where there is reasonable linearity. The tangent modulus is the slope at any point, such as B. The secant modulus is the slope of lines such as AB or BC.

Tangent (B) would be dc/ac. The slope of secant (AB) would be Bb/Ab. Other approximations could be made to cover a specific working load range. Curve-matching could be used for a non-linear analysis. For computer modelling, the curve can be represented by a polynomial with specified coefficients.

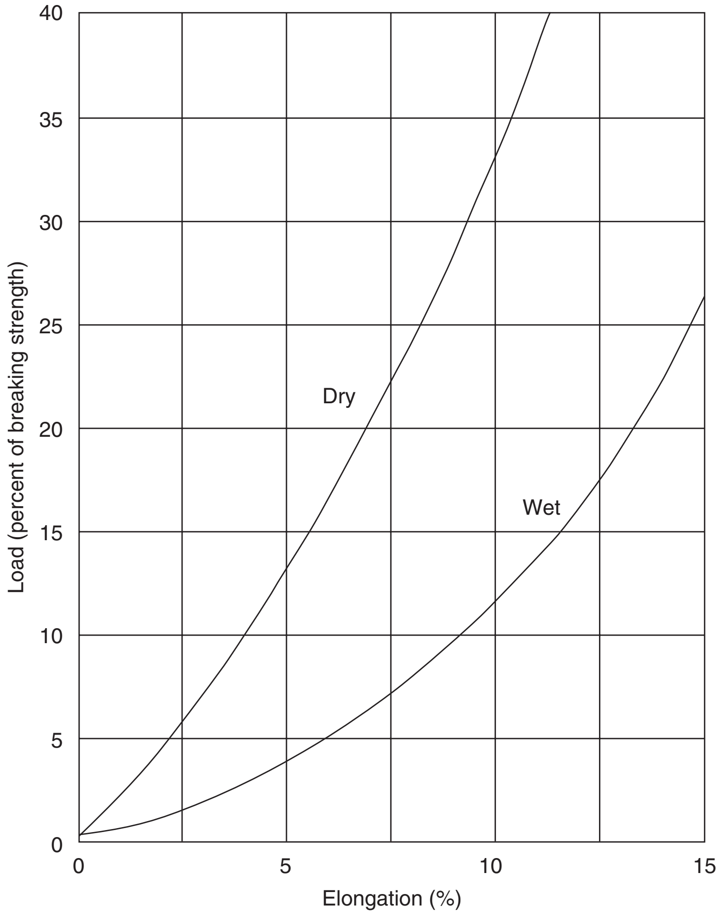


Fig. 4.8 Effect of bedding-in (permanent elongation) and relaxation (recoverable elongation) on *stabilised* nylon double braid after rest. Compare with Fig. 4.7 but note change of elongation scale. From Samson Ocean Systems (1979).

4.3.3 Elements of elongation

There are three elements to fibre rope elongation when load is first applied to a previously untensioned rope, then released and then followed by repeated loading. This procedure represents a breaking-in process by which permanent elongation is removed; it is called stabilisation. See Fig. 4.11 for a schematic representation of the process.

The elements of elongation are:

- Elastic – recovered immediately when load is released.
- Recoverable – a small amount of elongation that comes back gradually over time
- Permanent – non-recoverable elongation that occurs due to bedding-in of the structure and possible plastic elongation of fibres

In Fig. 4.11, when the rope is unloaded after the tenth cycle, it returns to reference tension immediately. The elongation on the tenth loading cycle will be designated

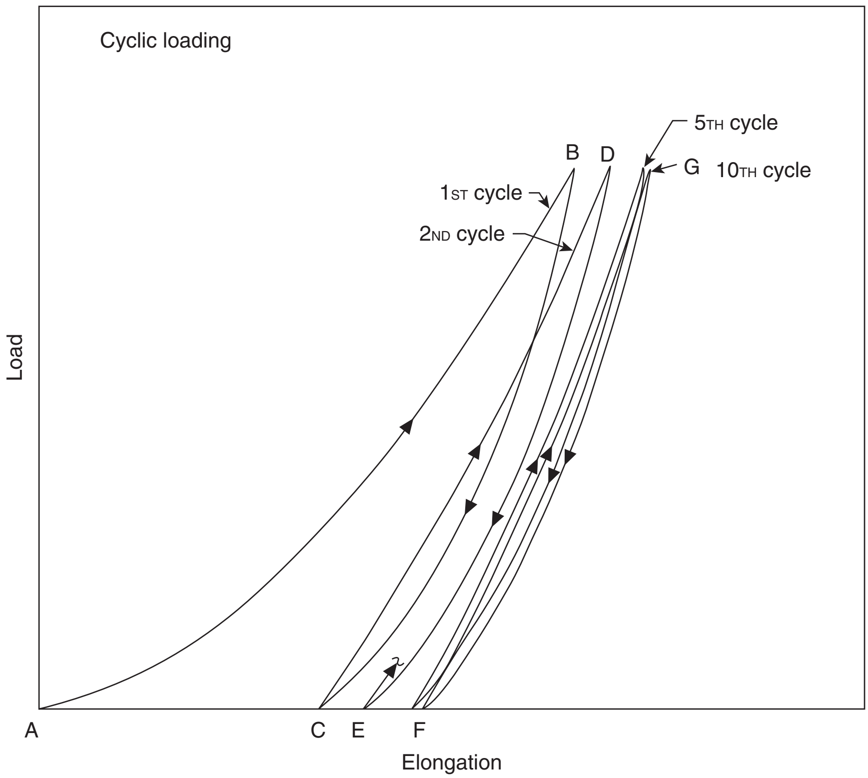


Fig. 4.9 Typical stabilisation profile for new rope through 10 cycles.

the elastic elongation, from which values of elastic stiffness and elastic modulus can be determined as shown in Fig. 4.10.

If a previously tensioned rope is allowed to rest unloaded, it will continue to contract until equilibrium is reached after a few hours, or in some cases up to a day. This elongation is designated herein as 'recoverable' elongation; however, other names will be found in the literature, including viscoelastic elongation, which is appropriate, and hysteresis (see Section 4.3.5), which is not.

The remaining elongation will not recover. It is due to compacting of the rope structure and plastic elongation of the fibres. It is designated 'permanent elongation'.

A stabilised and fully-relaxed rope on the first loading cycle displays a modulus that is initially lower than the elastic modulus, but it will approach it rapidly as loading is repeated. In Fig. 4.11, the starting point for the first cycle would be at the left end of recoverable elongation. This is dependant on the load and the tension that was involved in stabilisation.

4.3.4 Stabilisation

In standard CI 1500, stabilisation procedures are suggested and these are covered in Chapter 10. Briefly, ten load cycles to either 20% or 50% of breaking strength are to be applied. The 20% load level is used for general-purpose ropes as it is

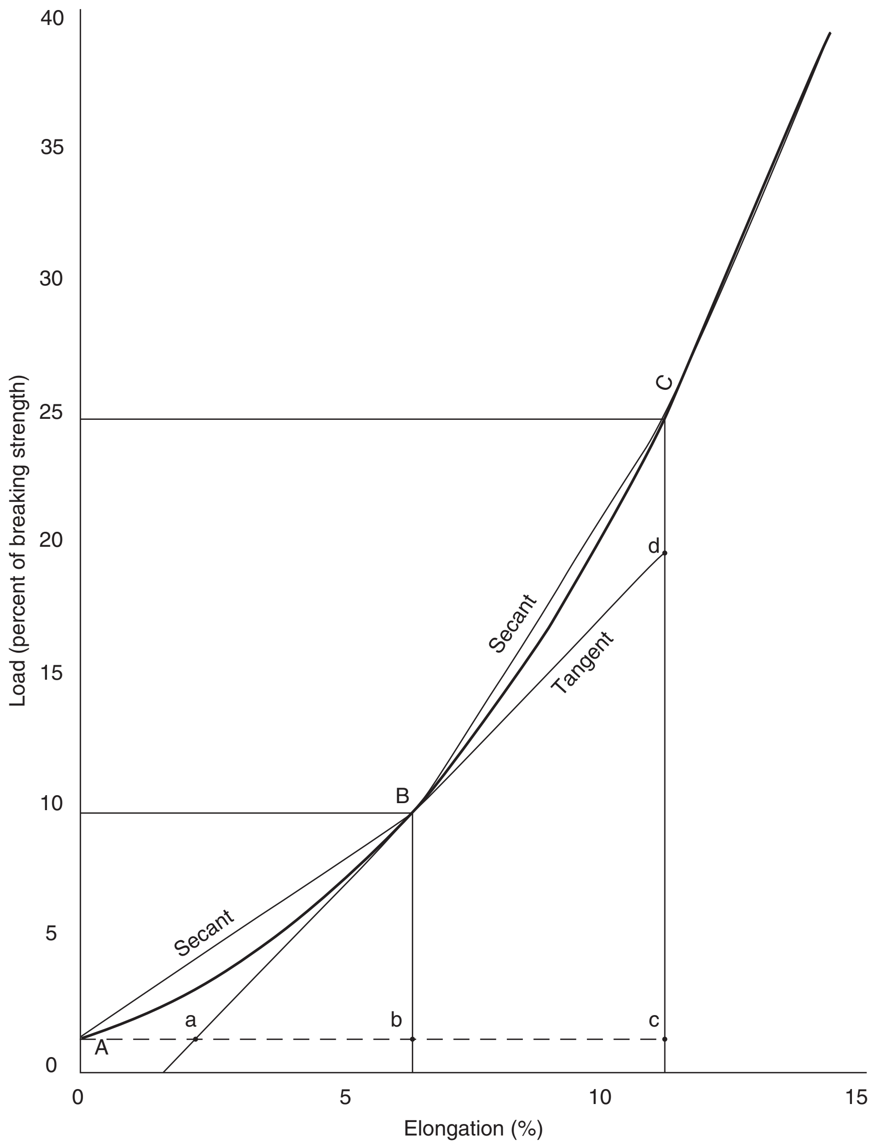


Fig. 4.10 Methods of approximating modulus. Point A is at reference tension.

expected that working loads should not exceed this level. The 50% load level is for maximum stabilisation. Experience has shown that ten cycles is usually sufficient, but some specifications advocate more extensive loadings.

4.3.5 Hysteresis

The unloading curves as seen in Fig. 4.11 do not follow the loading curve, best seen by looking at the tenth cycle. The area between the two curves represents the energy that is lost in the form of heat. Examples from cycling between loads are shown in

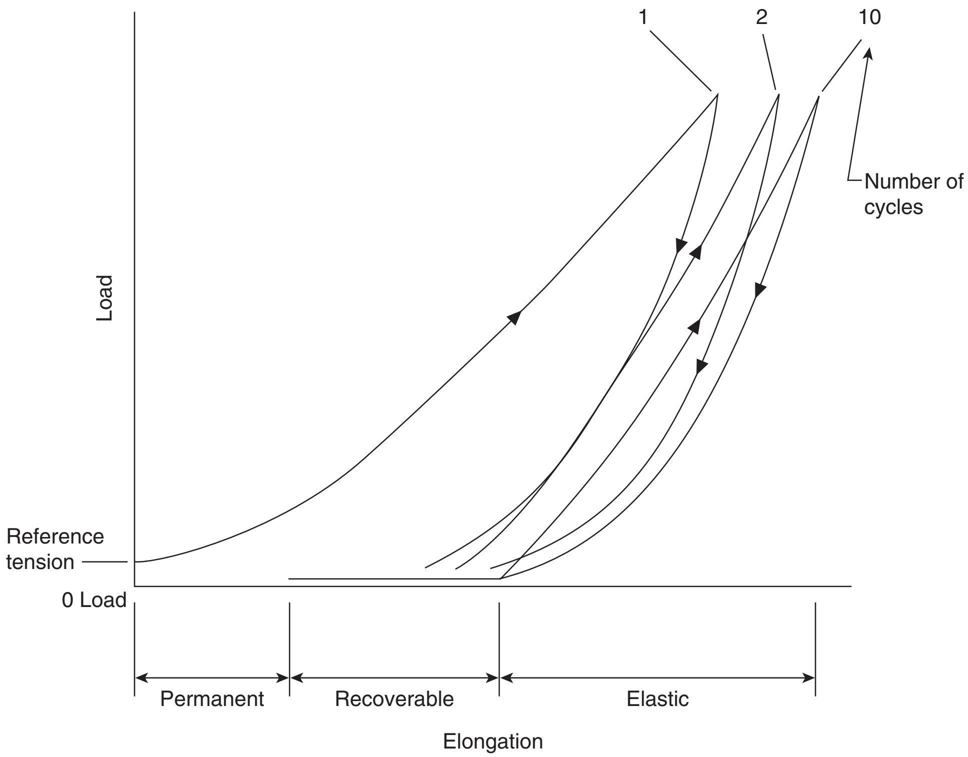


Fig. 4.11 Stabilisation of low modulus braided rope – elements of elongation defined.

Fig. 2.15. Although not usually a problem with general-purpose industrial ropes, heating can be significant in certain applications, particularly those involving relatively fast load cycling over a wide range of tension. This is covered in more detail in Section 2.5.5.

4.3.6 Definitions

Some useful terms related to elongation properties are:

- Tension (load) – the actual force applied, e.g. in Newtons or pounds force
- Percent of break strength – tension/break load × 100
- Stress – tension/fibre area
- Specific stress – tension/linear density

For axial stretch, the various terms can be confusing and are not always consistently used. Some common ones are:

- Stretch – the ability to elongate
- Elasticity – the ability to immediately recover any elongation when unloaded
- Elongation – the actual amount of elongation at some tension
- Percent elongation – the percent increase in length (elongation/test length × 100)
- Strain – the fractional increase in length at some tension (elastic elongation/test length)

- Axial stiffness – tension/strain, which is tension/(elastic elongation/test length)
- Modulus (area) – axial stiffness/fibre area, which also is stress/strain
- Specific modulus (weight) – specific stress/strain
- Elastic modulus – axial stiffness of a stabilised rope while undergoing cyclic loading

Refer to Chapter 5, *Rope Mechanics*, for information on how to use other terms for defining elongation properties. Many of these terms appear in the literature or are used to report analysis from specialised test programmes. It is important to ascertain precisely the basis for the term and its units.

4.3.7 Elongation of fibre rope

Figure 4.12 is representative of the load–elongation properties of some typical stabilised ropes for a single loading cycle from a relaxed condition. From Fig. 4.12, at

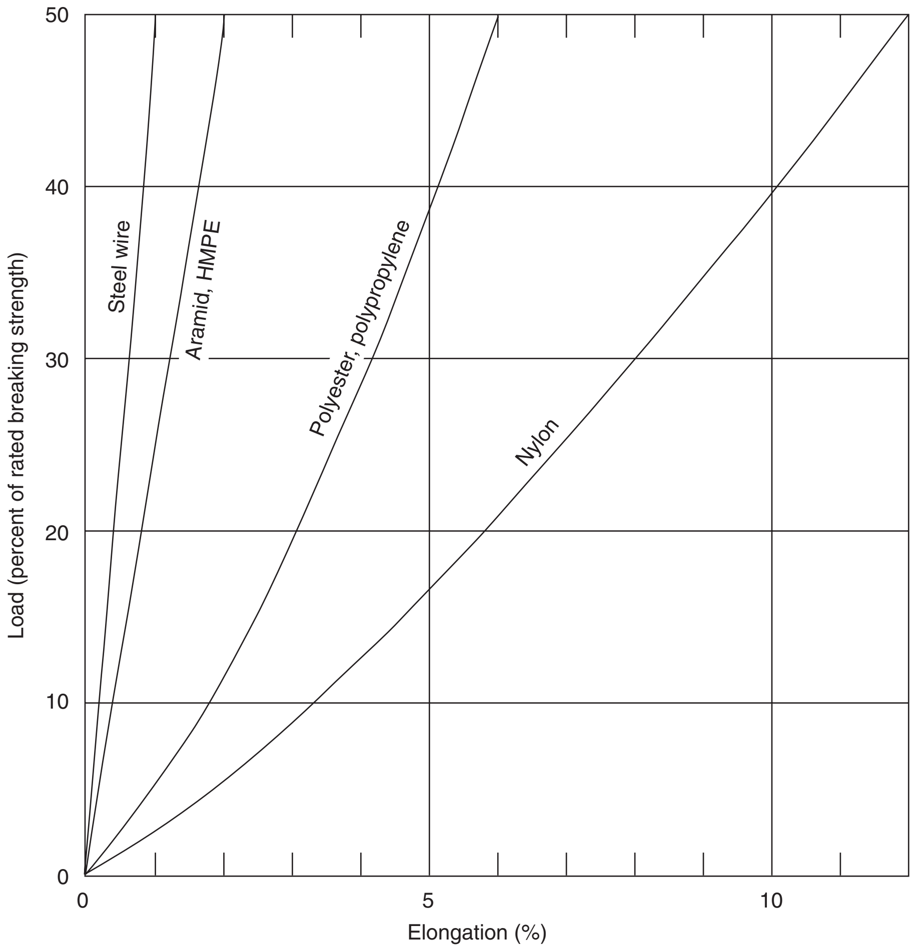


Fig. 4.12 Typical load–elongation profiles for various ropes from zero to 50% of breaking strength.

50% of estimated breaking strength it can be seen that aramid and HMPE ropes have about twice the elongation of wire rope, polyester is about twice as extensible as aramid and HMPE, and nylon is about twice as extensible as polyester. Comparing wire rope and nylon, the difference is about 12 to one. This gives a considerable range of capabilities for users of fibre rope when stretch is an important parameter in the application.

The elongation at breaking load would be about twice that shown in Fig. 4.12. In practical reality, loads above 50% of breaking strength should rarely be used, except as with climbing ropes, for example, when a rope is discarded after use in a fall.

Some ropemakers are now reporting data in their literature for stabilised (used) ropes at some percentage of breaking strength, such as '20%' or '30%'. Most commonly, however, only the breaking elongation is reported in ropemakers' literature and that is often for new rope; this may not be very helpful. Elongation data at other loads is usually available on request. Determination of the required stroke of a test machine that will be used to break a specimen is one situation where elongation at the breaking load is needed.

Because of non-linearity and viscoelasticity, the modulus for stabilised rope is not constant. For exacting applications where modulus is an important parameter, definitive data that is representative of operating conditions must be obtained. Section 5.1.2 covers the mechanics of axial stiffness. For example, Figures 5.2(a) and (b) provide elongation response data for deep sea mooring ropes that have been extensively tested to accurately define modulus under specific conditions.

4.3.8 Calculating break load and elongation

Assume that a typical plot of percent breaking strength versus percent elongation for stabilised rope is available for a particular product of a specific size. This can be used to estimate values for other sizes (see Fig. 4.12).

If a working load (from assessment of the service conditions) of a particular rope can be determined and a design (safety) factor is selected, the required breaking load can be calculated.

$$\text{Required breaking load} = \text{working load} \times \text{design factor} \tag{4.12}$$

$$\%\ \text{break strength at working load} = 100/\text{design factor} \tag{4.13}$$

$$\%\ \text{elongation — read from graph at \% break strength} \tag{4.14}$$

$$\text{Total elongation} = \%\ \text{elongation} \times \text{length of rope}/100 \tag{4.15}$$

If elongation over a particular load range (upper and lower loads) is required, the following calculations will determine the length:

$$\%\ \text{elongation upper — read from graph at upper load}$$

$$\%\ \text{elongation lower — read from graph at lower load}$$

$$\text{Length} = \text{elongation} \times 100/(\%\ \text{elongation upper} - \%\ \text{elongation lower}) \tag{4.16}$$

4.3.9 Effect of construction on elongation

The behaviour of ropes of different construction relative to elongation can be illustrated by the example of Fig. 4.13. Double-braided nylon rope is compared to eight-

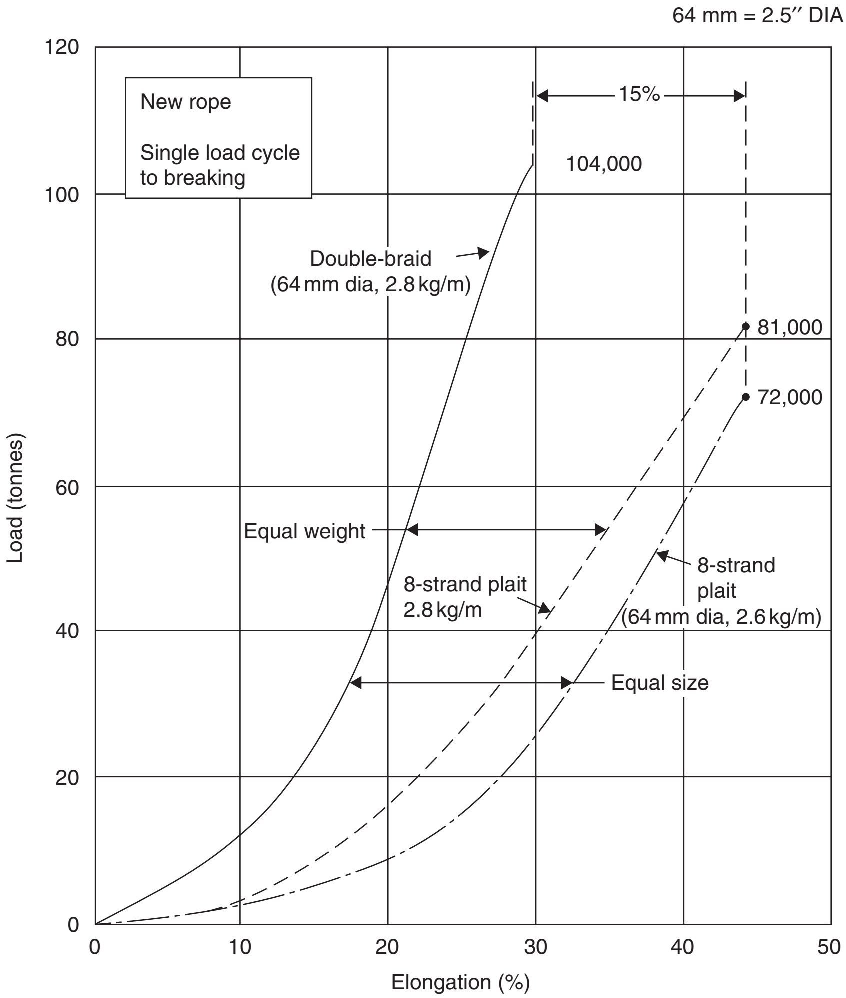


Fig. 4.13 Effect of construction on strength and weight of *new* nylon rope – 64 mm diameter double braid and 8-strand plaited ropes compared. From Wong (1981).

strand plaited nylon rope. Both are typical ropes produced for general service and are nominally 64 mm diameter. A 64 mm double-braided nylon has a linear density of 2.8 kg/m, whereas standard 64 mm eight-strand plaited rope has a linear density of 2.6 kg/m due to less fibre compaction. For this evaluation, a second specimen of the eight-strand plait was produced to have the same weight as the 64 mm double braid.

Greater density, less twist in the strands and lower helix angles makes the double braid less extensible at the same load.

Figure 4.13 shows the test results for unstabilised specimens to be:

Strength on equal size	Double braid – 104 000 kgf	Eight-plait – 72 000 kgf
Strength on equal weight	Double braid – 104 000 kgf	Eight-plait – 81 000 kgf
Elongation equal size	Double braid – 30%	Eight-plait – 45%
Elongation equal weight	Double braid – 30%	Eight-plait – 45%

Elongation difference, plaited over double braid, is about 15% absolute (45 – 30) and 50% relative (15/30). Note, however, that most of the difference occurs at low load.

Figure 4.14 shows the test results for stabilised specimens to be:

Strength on equal size	Double braid – 104 000 kgf	Eight-plait – 72 000 kgf
Strength on equal weight	Double braid – 104 000 kgf	Eight-plait – 81 000 kgf
Elongation equal size	Double braid – 25%	Eight-plait – 36%
Elongation equal weight	Double braid – 25%	Eight-plait – 33%

Elongation difference on an equal weight basis has been reduced from 15% to 8% absolute (33 – 25) and from 50% to 32% relative (8/25).

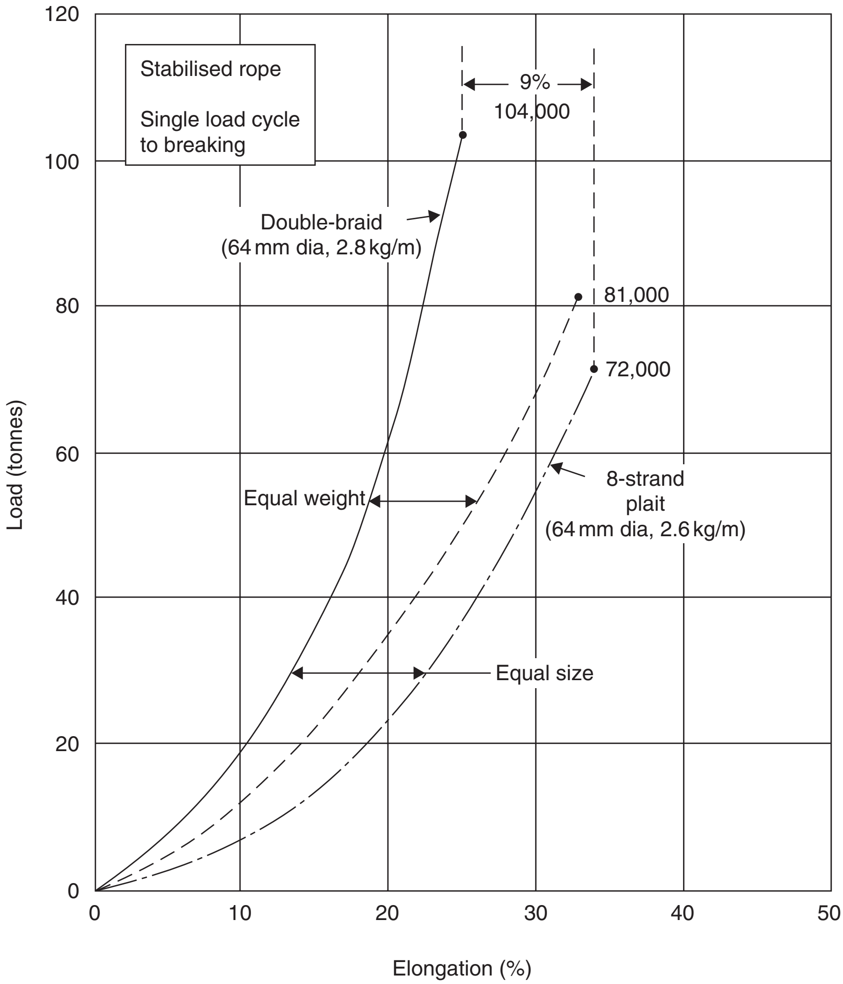


Fig. 4.14 Effect of construction on strength and weight of *stabilised* nylon rope – 64 mm diameter double braid and 8-strand plaited ropes compared. From Wong (1981).

4.3.10 Comparative data

Elongation properties for various common commercial rope types are tabulated in Table 4.5. Similar data for high-modulus ropes and special constructions for nylon and polyester ropes are given in Table 4.6.

As can be seen in these tables, data is provided for both 'new' and 'broken in' (stabilised) rope at the breaking load and at 30% of the breaking load after full relaxation. These values are only approximate and are targeted at the higher end of a range. The performance of a particular rope depends on many factors. As an example, reference tension is critical since much elongation occurs at low loads as pulling begins. 'Breaking in' is also difficult to define; CI 1500 requires 10 cycles to 20% of breaking strength but 50% is commonly used.

Definitive values for modulus, especially when measured to the breaking load, cannot be provided because:

- There are many fibre materials and a number of blended products used in commercial ropes. This covers too much ground to try to tabulate.
- Modulus varies with twist levels, lay and braid angles.
- Modulus will change with time in service and load levels encountered
- Rate of loading affects modulus
- The modulus is usually non-linear

Many rope makers have reliable and comprehensive stiffness data under static and dynamic conditions. For critical applications, simulated laboratory or field tests may be necessary.

4.4 Energy absorption

Ropes that stretch absorb energy. This can be a useful property. Fall-arrest ropes for mountaineers is a good example. The work that is done is the energy absorbed and can be measured by the area under the load–elongation curve.

The same example as in Figures 4.13 and 4.14 are plotted together in Fig. 4.15 to show energy absorbed. The graphs compare unstabilised 64 mm diameter double braid and eight strand plaited nylon ropes taken to the breaking load. The results are:

On an equal size basis:

Nylon double braid 10.4 ton-m/m   Eight-strand plait 9.2 ton-m/m

On an equal weight basis: (by increasing the eight-strand energy by the weight ratio)

Nylon double braid 10.4 ton-m/m   Eight-strand plait 10.0 ton-m/m

A conclusion can be drawn that the energy absorption capacity of a rope primarily depends on its linear density and the fibre type, not on its construction. Double braid stretches less but is stronger; eight-strand plait is less strong but stretches more. It is intuitive that it is the fibre that absorbs most of the energy and, if the same type and mass of fibre is the same in two reasonably made ropes of the same linear density, they will absorb about the same amount of energy, although one may stretch more than the other.

Table 4.5 Typical elongation properties for various low-modulus fibre ropes in conventional constructions

Material	Construction	Breaking elongation (%). New	Breaking elongation (%). Broken in	Elongation (%) at 30% break load. New	Elongation (%) at 30% break load. Broken in
Manila	3-strand laid & 8-strand plait – soft lay	9	–	5.5	–
	3-strand laid & 8-strand plait – hard lay	16	6	8	3.5
Nylon (dry)	3-strand laid & 8-strand plait	40	30	22	15
Nylon (dry)	Double braid and 12-strand single braid	35	27	18	14
Polyester	3-strand laid & 8-strand plait	24	17	15	9
Polyester	Double braid and 12-strand single braid	20	15	11	7
Polypropylene	3-strand laid & 8-strand plait (standard fibre)	18	12	8	5
Polypropylene	12-strand braid (high strength fibre)	18	12	7	4
Nylon (dry)	Wire rope type, 7 strand (Atlas)	29	20	17	11

Table 4.6 Typical elongation properties for various high-modulus fibre ropes and special construction low-modulus fibre ropes

Material	Construction	Breaking elongation (%). New	Breaking elongation (%). Broken in	Elongation (%) at 30% break load. New	Elongation (%) at 30% break load. Broken in
Aramid	Wire rope laid, parallel strand	4.5	2.0	1.7	0.7
HMPE	Wire rope laid, parallel strand	4.5	2.2	2.0	0.8
HMPE	12-strand braid and 8-strand plait	6	4	2	3
HMPE treated	12-strand braid	5	4	2	1.5
LCP	12-strand braid	5	4	2	1.2
Polyester	Wire rope type, 7 strand, jacketed	15	11	5	3.5
Nylon (dry)	Parallel strand, jacketed	30	25	14	12
Polyester	Parallel strand, jacketed	14	12	7	4.5

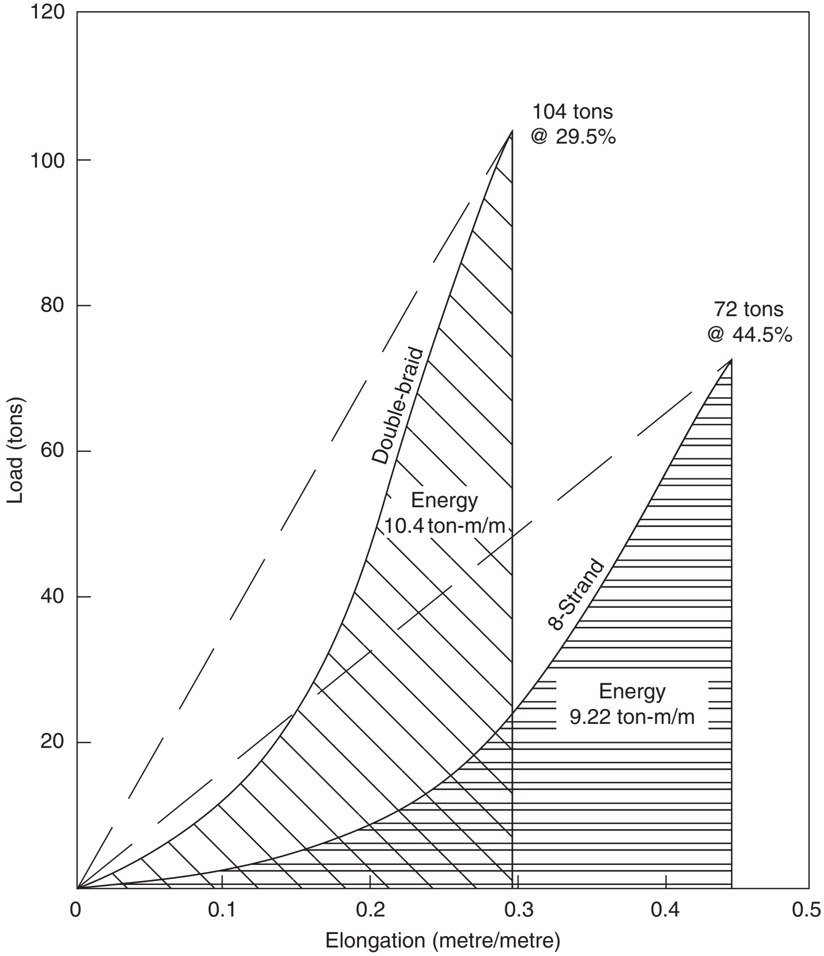


Fig. 4.15 Energy compared for new double braid and 8-strand plaited nylon ropes – 64 mm diameter, pulled to breaking. From Wong (1981).

If rope load–elongation performance is reported as % break strength versus % elongation (Fig. 4.12), the energy absorbing capacity of a length of rope can be calculated as follows:

$$\text{energy (tonne-m)} = \text{area under curve} \times \text{breaking strength (tonne)} \times \text{length (m)} \times 10^{-4} \qquad [4.17]$$

where area under curve is measured graphically or from curve matching (use % values to calculate area not decimals).

4.5 Fatigue

4.5.1 General

The ability to resist progressive damage from cyclic loading or long term static loading is an important rope property for many applications. This is generalised under the term 'fatigue'. Fatigue results in loss of strength and possibly an increase in axial stiffness that will compromise the performance required for a particular application.

The following forms of fatigue can be identified as liable to occur in fibre ropes.

- tensile fatigue
- creep rupture
- hysteresis heating
- flex fatigue
- axial compression fatigue
- structural fatigue

Damage from external mechanisms outside the rope structure is not considered fatigue. These would include: external abrasion, cutting, abrasive wear in terminations, heat from sources outside the rope, chemical attack, and overloading.

It must be stressed that fibre fatigue differs from metal fatigue, which has been widely studied by engineers and scientists for over a hundred years. Cyclic stress can introduce inter-crystalline cracks on the metal surface that can propagate across a section until failure occurs, but this is not a mechanism that operates in natural or synthetic polymer ropes. As described in Sections 2.5.4, 2.5.5 and 2.5.8, other fatigue mechanisms occur in fibres, and the discontinuities between fibres, yarns and strands in ropes means that degradation is distributed in more complex ways over rope components.

4.5.2 Tensile fatigue

Ropes that are cycled under load are subject to tensile fatigue. When used at reasonable maximum working loads, ropes will deteriorate primarily due to internal fibre abrasion. For general-purpose ropes, maximum working loads should not exceed 20% of breaking strength, which usually is well below the point where other forms of fatigue begin to enter the picture. Higher load levels are used in specialised applications when operating conditions are carefully controlled and all damage mechanisms are at least somewhat predictable. An example is deep-sea moorings where the mean tension may be 40% of breaking strength and, as the vessel surges back and forth due to environmental conditions, the load range around the mean may be ±10% of breaking strength. Extensive testing has given reasonable assurance of a viable working life (see Section 12.3).

For the purposes of the discussion here, tensile fatigue is defined as repeated loading and unloading that results in inter-fibre abrasion and filament breakage leading to loss of strength. As a rope is elongated, its helix angle changes. If, as in Fig 4.16(a), two adjacent components move to the position on the right without slipping, shear is introduced and probably causes little damage. If the components slip with respect to each other, as in Fig. 4.16(b), with a back and forth motion, the filaments will abrade over time. In braided structures where strands cross over each other, there is a scissoring action that can advance relatively rapidly compared to laid structures where the components are parallel.

When nylon fibres rub against each other, surface cracks develop in the filaments and propagate at about a 10° angle, which can quickly sever the fibre. Surface cracks on polyester filaments on the other hand form less readily and tend to travel along the axis resulting in little damage. Figure 4.17 shows a nylon rope that had broken

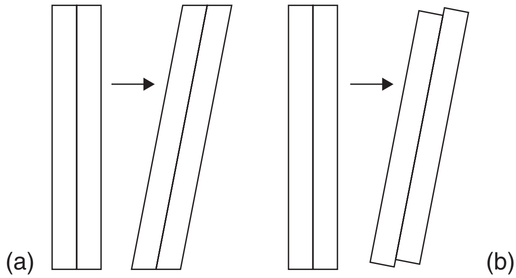


Fig. 4.16 Two modes of shear. (a) With no slip, shear in material. (b) With slip between components.

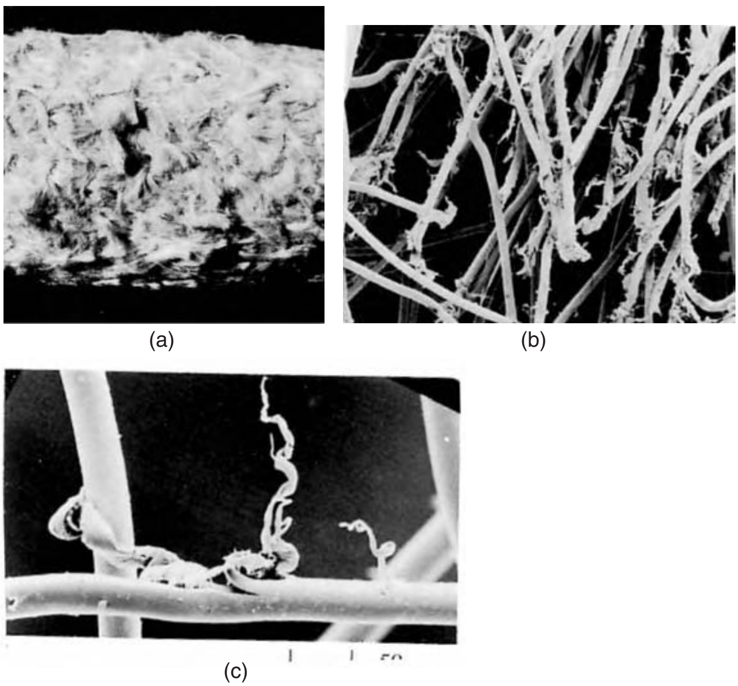


Fig. 4.17 Internal abrasion in a large nylon rope cycled wet up to 50% break load. (a) Broken fibres appearing on the surface of the rope. (b) Broken fibres from the interior of the rope. (c) Progress damage in a fibre. From Hearle *et al.* (1998).

after 970 tension cycles wet, between a low load and 50% of breaking strength. The continuous filaments have broken into short lengths, which has reduced the strength to that of a short-fibre structure. The cracks and splits can be seen in the scanning electron micrographs. A polyester rope would have lasted millions of cycles under these conditions. Contamination can accelerate fibre degradation which can lead to tensile fatigue. After drying, salt crystals are known to cause internal damage under cyclic or flex loading. Figure 4.18 is an example of fibre damage under such conditions.

Rope performance for tensile fatigue is definitely related to fibre properties. Table 2.9 shows that aramid fibres suffer severe abrasion damage, but HMPE and

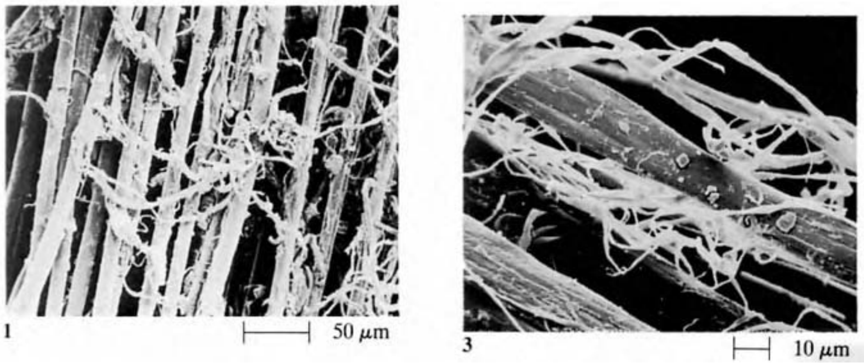


Fig. 4.18 Fibrillation due to salt crystals in a *Kevlar* aramid rope used as a Genoa sheet. From Hearle *et al.* (1998).

Vectran last about 10 times longer and polyester 100 times longer. However, the incidence of internal abrasion in ropes is strongly affected by the finish applied to the yarns. Marine finishes lead to much less abrasion damage.

Degradation due to tensile fatigue is dependant on many variables. It would be impossible to try to quantify the performance of all the various rope types under different operating conditions. Instead, the following notes are provided for guidance in assessing the potential performance:

- Dry nylon ropes for traditional commercial applications give good results at modest load levels. Wet performance can be poor unless a water-resistant lubricant (marine finish) is used. Dry performance is also enhanced by such lubricants.
- Dry polyester ropes for traditional commercial applications give good results at modest load levels and possibly somewhat higher than nylon. Wet performance can give mixed results depending on the finish, but a water-resistant finish can give excellent life.
- Common polypropylene ropes give a lower performance level compared to dry nylon and polyester at similar loads. However, newer versions of the fibre give better results; there are claims that they are superior to polyester but independent verification is not currently available. Wet and dry performance of polypropylene ropes is similar. As far as is known, special finishes are not available.
- Braided structures experiencing extensive tensile load cycling can show internal fibre abrasion. However, service life for braids can be more than adequate and damage can be easily observed (see Chapter 9).
- The rate of strength loss is highly dependant on load levels and the range of loading. The worst condition is complete or nearly complete unloading (0% to 5% of breaking strength) of a rope in each tension cycle.

A wet test of a 50 mm diameter polyester double braid, with water-resistant fibre lubricant, was tensioned between 15% and 30% of break strength, and, after 200 000 cycles, revealed a 10% increase in strength over a control specimen; no significant evidence of filament breakage was observed (McKenna, 1983). The same rope was tested at 1% to 30% break strength; at 200 000 cycles there was clear evidence of filament breakage; at 1 000 000 cycles, the fuzzy surface coating of broken filaments nearly obscured the braided structure. At this point the test was stopped; the residual strength was 65% of breaking and the elongation was about 40% less than what would be expected for stabilised rope after a few cycles.

Testing to determine tensile fatigue performance is limited. What exists is difficult to quantify as test conditions vary considerably within reported data. Often, ropes broke due to abrasion in the termination but this was reported as a rope breakage; protection in the eye or a better termination would have given a considerably different result.

By way of example, Fig. 4.19 shows some data that was collected from a selection of tests of wet nylon and wet polyester ropes of double braid and eight-strand plaited constructions by McKenna (1983). Similar data is provided in Fig. 4.20.

Polyester ropes in parallel strand or wire rope construction, specifically designed for deep mooring of floating oil production platforms are compared to steel wire for tensile fatigue in Figures 4.21 and 4.22. The performance of the polyester is seen to be very superior to the steel wire.

Residual strength testing of heavily used ropes or those tension cycled on test machines with sufficient duration to cause internal filament breakage (tensile fatigue) can be misleading. Ropes can maintain what appears to be respectable strength based on residual strength tests after some period but it has been found that failure can occur quickly after little additional tension cycling. This is because loss of fibre places more stress on the remaining fibres; the structure becomes unbalanced; tensile and creep rupture failure of now overloaded components occurs. Degradation can accelerate past a certain point with a very rapid falloff in strength.

Descriptions and associated pictures of ropes that have experienced tensile fatigue and have incurred significant loss of strength (fatigue) due to inter-strand abrasion can be found in Section 9.7.4.

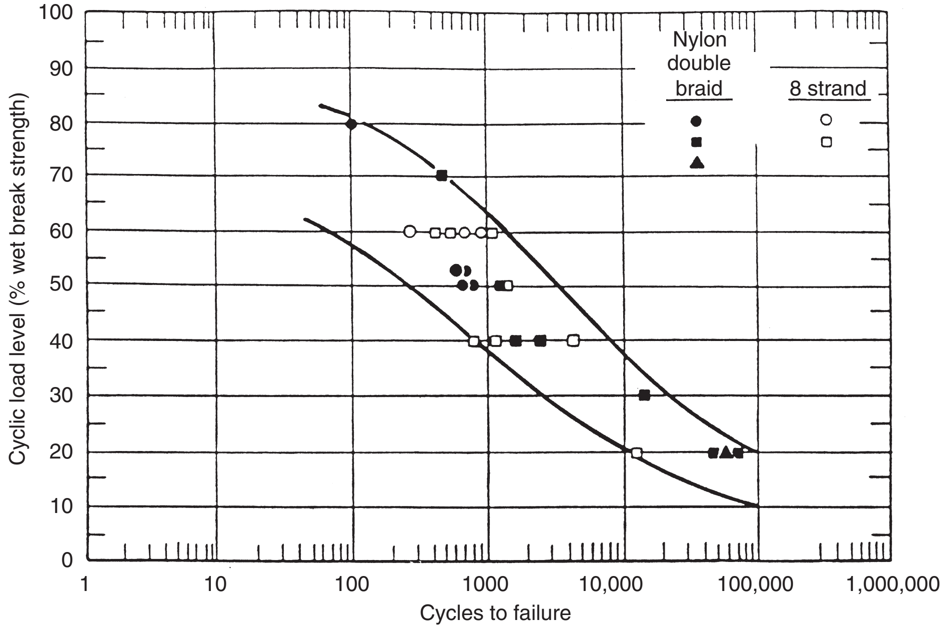
4.5.3 Creep and creep rupture

Creep of fibres may be either recoverable (primary creep) or non-recoverable (secondary creep). It is the latter that is relevant to fatigue failure of fibre ropes. Tests by Mandell (1987) (Section 5.7.2) indicate that for cyclic loading, the creep effect is the same as if the peak load had been applied continuously. Creep rupture occurs when the creep limit of the fibre material is reached.

Loading that induces creep at a slow rate causes an initial increase in strength as load distribution among yarns and strands improves. If the load is constant, this also reduces the creep rate as more fibre elements pick up a greater share of the load. The opposite effect occurs as rope elements begin to break; strength remains relatively high until this happens but progressive failure can occur rapidly as load is shifted to the remaining material, thus increasing the creep rate. Creep eventually leads to breakage. Figure 4.23 has data for creep rupture of wet nylon fibre and yarn. Nylon can fail in less than a day at the 50% load level. Nylon 6 fibre exhibits lower creep rates than nylon 6.6.

Creep is accompanied by a reduction in the elongation at the breaking strength. A rope near the point of creep rupture will elongate very little when tested to breaking, even though the ultimate load may be relatively high.

The propensity for a rope to creep is mostly dependent on the fibre properties, although a rope will creep at a lower rate compared to the fibre at the same



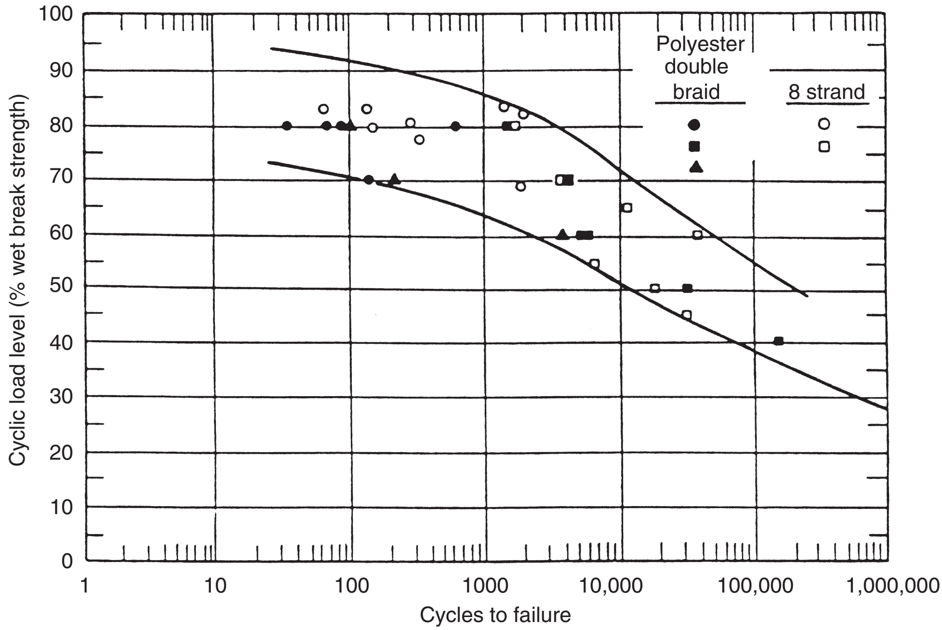


Fig. 4.19 Tension cyclic loading to failure of wet nylon (upper) and polyester (lower) ropes of various constructions. From McKenna (1983).

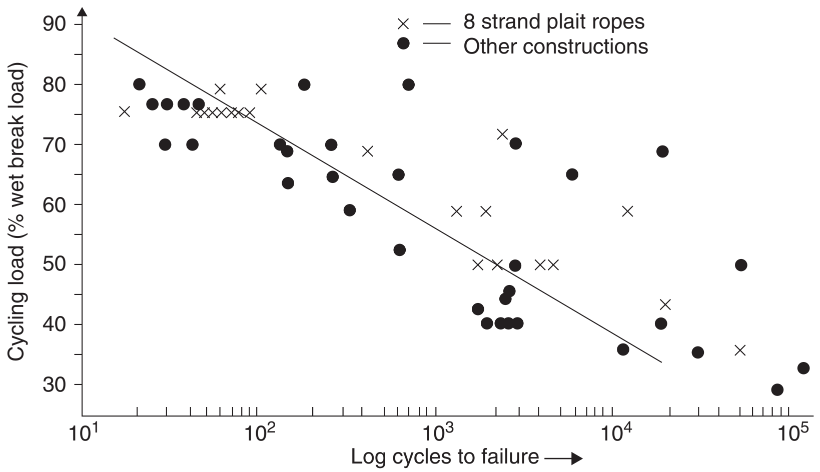


Fig. 4.20 Data collected by M R Parsey on life of wet nylon ropes subject to varying cyclic load levels. Data below 50% of break load is dominated by tensile fatigue; above 50% break load, creep rupture comes into play and time becomes a factor, in addition to internal fibre abrasion.

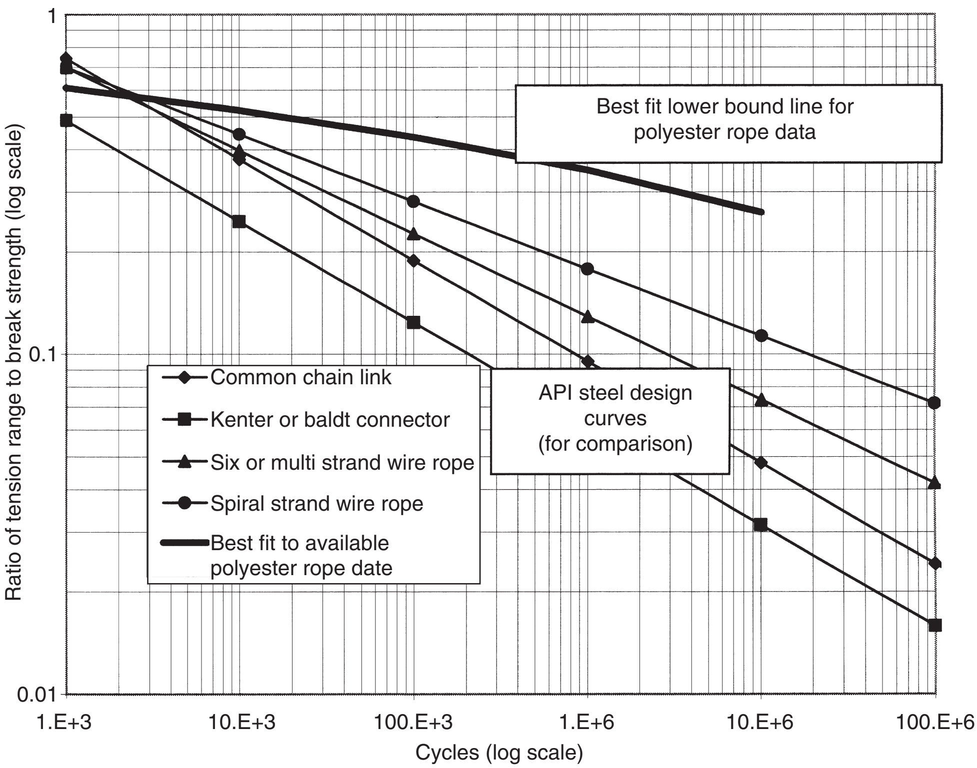


Fig. 4.21 Plots of tension–tension range against cycles to failure. Comparison of lower bound of collected polyester rope data with American Petroleum Institute (API) guidance for steel chain and rope. From TTI and Noble Denton (1999).

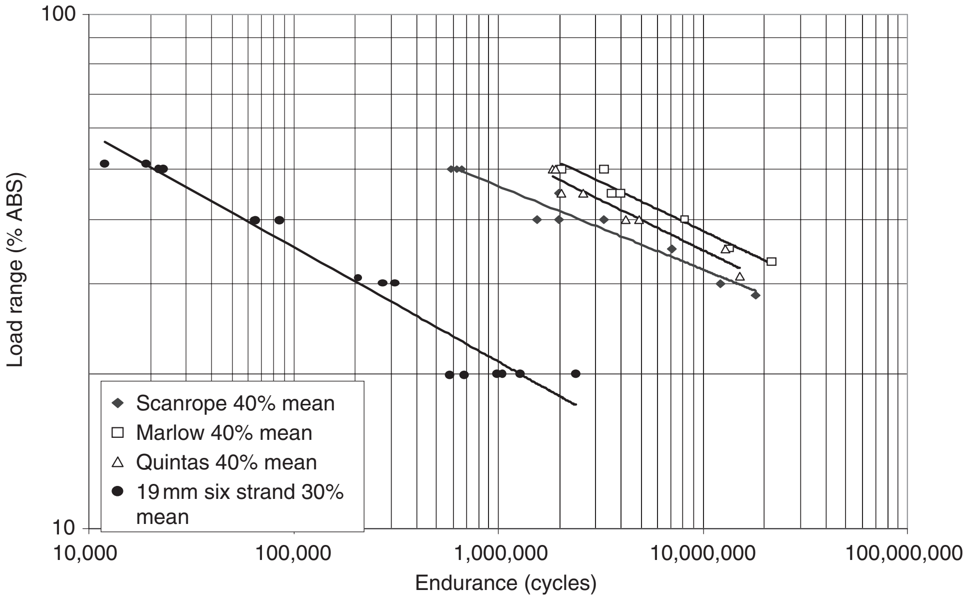


Fig. 4.22 Comparative tests showing cycles to failure of polyester and 19 mm six-strand steel wire ropes for a range of cyclic loadings as percentage of actual break strengths (ABS) at 40% mean load for polyester and 30% mean load for steel. Scanrope is a wire rope construction, Marlow is parallel strand with three-strand sub-ropes, and Quintas is parallel-strand with braided sub-ropes. Reproduced by courtesy of Neil Casey, NEL.

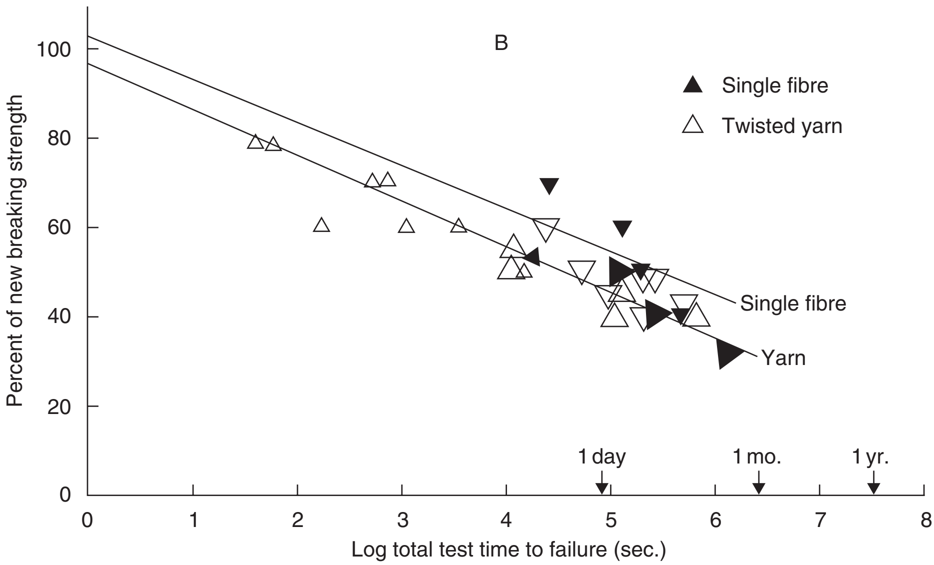


Fig. 4.23 Plot of percent breaking strength against log-time for creep rupture of wet nylon single fibre and twisted yarn. From Mandell, 1987.

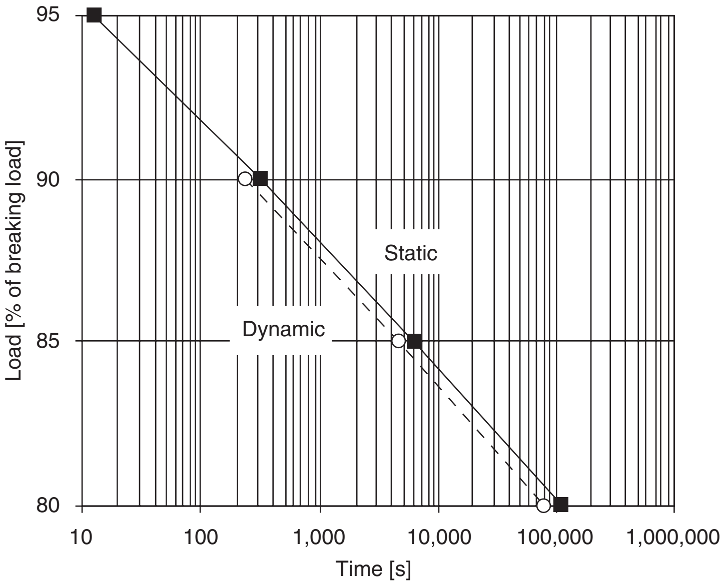


Fig. 4.24 Time to break under static and dynamic loading (±2.5% of breaking load) at 80 to 90% of breaking load for *Diolen 855TN* 2200dtex high-tenacity polyester yarns. From Bosman (2001).

percentage of their ultimate strength. Some data on fibre creep is provided in Section 2.5.4 and Tables 2.5 and 2.6.

Polyester, aramid and LCP fibre ropes have very low levels of creep. All creep very little up to and beyond 50% of breaking strength, which is well above maximum service loads for all but the most unusual applications. Polyester is known to stabilise after an initial creep in the order of 1–2% at 10–20% of breaking strength when the tension is kept constant. Times to break under high loads for both polyester and aramid ropes are shown in Figures 4.24 and 4.25, respectively.

Polypropylene is also subject to creep and should not be held at high tension (excess of 20% of breaking strength) for long periods of time.

HMPE fibre ropes are subject to creep and this can be a very important consideration in selection of load level and duration. These ropes are usually selected for high performance applications and are expensive, but they must not be overloaded for long periods. Specific creep data is difficult to quantify due to various grades of fibre and the particular rope construction. Fibre data is the best place to start as creep in a rope will always be less than that of the fibre.

Permanent elongation due to settling of the rope structure is not considered as creep (Section 4.3.3 and Fig. 4.11).

4.5.4 Relaxation

A complement to creep is tension relaxation. If a rope is loaded to a level where creep is induced and the length is held constant, the tension will gradually decrease. As the tension decreases the rate of relaxation will decrease. An understanding of

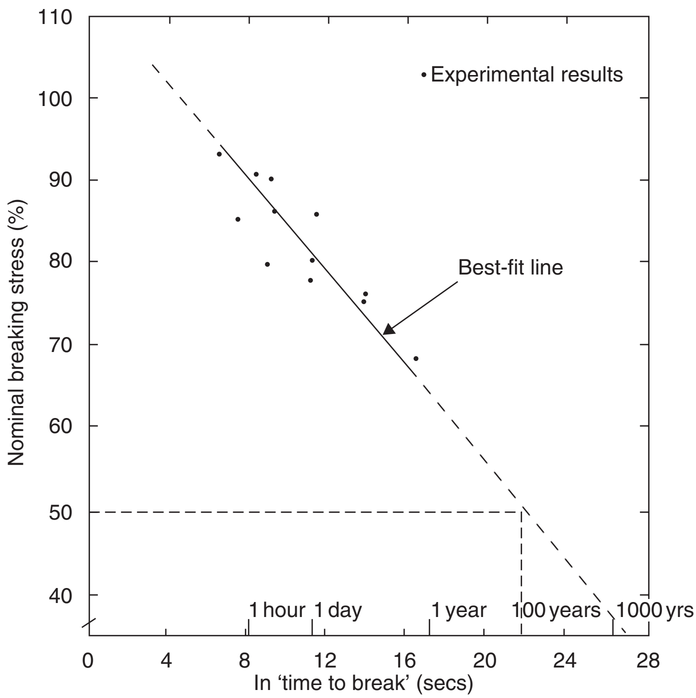


Fig. 4.25 Data from tests on aramid (*Kevlar 49*) parallel yarn ropes, *Parafil Type G*. From Chambers (1988).

this concept is necessary in static applications where a rope has been tensioned between two fixed points.

4.5.5 Hysteresis heating

Under relatively high tensions and frequent cycling of the load, ropes will raise in temperature due to hysteresis (Sections 2.5.5 and 5.7.3). Data from a test of 90 mm diameter parallel strand polyester rope is presented in Fig. 4.26.

There may also be heat generation from friction due to slip between fibres (Section 4.5.2 and Fig. 4.16) which would be difficult to differentiate from internal fibre energy loss.

Any heat generated from hysteresis will be distributed throughout the rope. Higher loaded elements are usually those in the centre of the strands, which will result in slightly higher temperatures at those locations. The larger the rope, the more difficult it is for the heat to escape. Wet ropes will conduct heat away better than dry ones. If submerged, the surface temperature will be held to that of the surrounding water. However, it is known that water has been turned to steam within a rope, even fully submerged, which caused thermal conductivity to decrease. In air, heat is not so easily lost from the surface and the emissivity must be taken into account.

Large diameter fibre ropes that have been used in ocean towing applications have failed due to heating when storm conditions have caused tension cycling. Studies

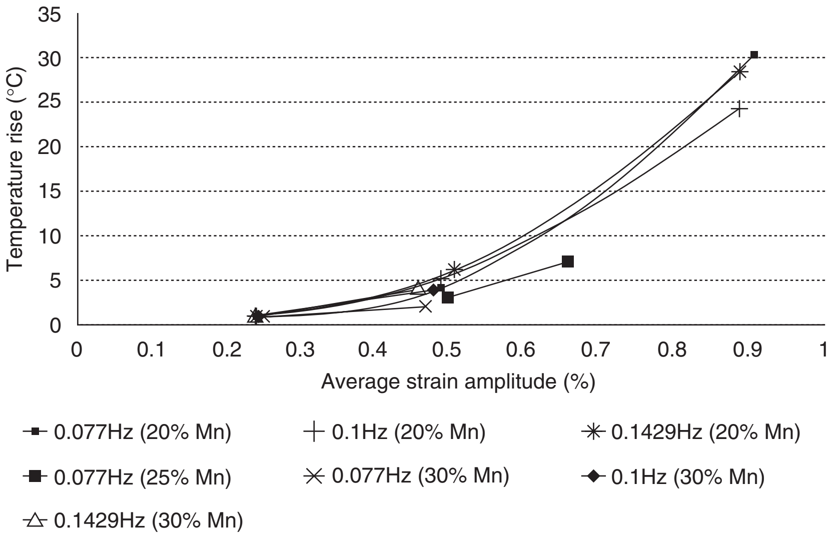


Fig. 4.26 Maximum temperature difference from surface temperature for 2.5 MN break load, 90 mm diameter polyester parallel strand rope, cycled as indicated with mean load (Mn) of ×% of break load. From Banfield and Hearle (1998).

related to deep sea mooring have found that polyester ropes must remain within a definite strain range when being tensioned by the cyclic motion of a floating oil production platform.

4.5.6 Flex fatigue

Flex fatigue can be caused by varied circumstances. Some are:

- Running over pulleys
- Winding and unwinding on fixed surfaces, such as fairleads, chocks or pins
- Continuous flexing at low loads, such as a mooring line on a buoy which rides on waves.

The effect on the rope structure when bent is discussed in Section 5.5 and illustrated in Fig. 5.19. Compression, and possible kinking, can occur on the inside radius of a bend and tension on the outside (Himmelfarb, 1957).

Especially with small D/d ratios (fixed surface diameter to rope diameter), running over a pulley can cause slip between rope elements that results in internal fibre abrasion as well as frictional heat. Both can be damaging. Figure 9.16 is an example.

A skirt on a hovercraft had been secured by polyester rope which had been satisfactory. The polyester was replaced with nylon with the result shown in Fig. 12.27. The environment is wet, which is not good for nylon. Although the loads are relatively low, the motion of the skirt causes constant flexing of the line.

There is no easy way to quantify what D/d ratio for a pulley should be used for long life. Certainly, make it as large as possible. The performance will depend on: rope material, fibre finish, rope construction, load, speed, frequency, surface material and pulley shape. Some helpful rules are:

- Avoid parallel strand and parallel fibre constructions
- Polyester (when using a suitable grade) is superior to nylon and polypropylene
- A good finish is helpful
- Nylon or polyethylene pulley surfaces are much superior to metal; although other polymer-based materials could well be suitable.
- A ratio of 8 to 1 for three-strand, braids and wire rope constructions is probably about the minimum for moderate service. Assessment by trials or simulations is the best approach.

Flexing is a common source of fatigue and is often wrongly ignored if tensions are relatively low.

4.5.7 Axial compression fatigue

There are circumstances where elements within a rope, such as fibres, yarns or strands, will buckle. Two plastic hinges are created that results in a Z shaped kink in the element. These kinks are usually flat and very short, less than one centimetre, and are commonly called 'kinkbands' (see Fig. 4.27). These usually form at low loads even if the rope is under some tension. Twisting or very tight jackets are common sources of kinkbands. The body of splices has been a source of kinking.

If loading or handling conditions cause the hinges in the kink to flex frequently, the fibre may fail at the kink. This can appear as a square cut, neatly severed and is axial compression fatigue. An example is a winch line with a very tight, non-

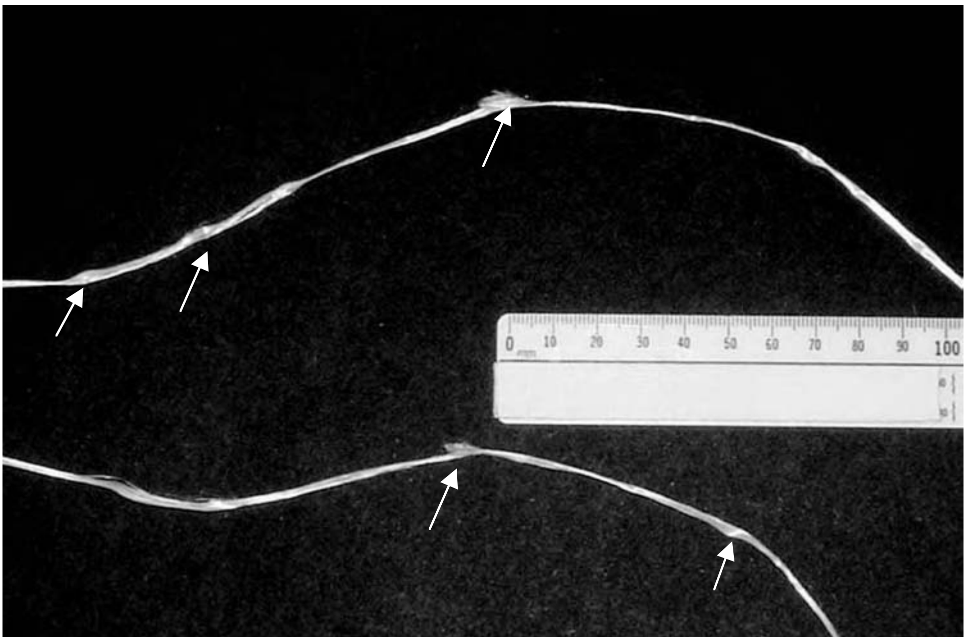


Fig. 4.27 Compression fatigue in strands from failed aramid rope. Kinkbands and bands with broken filaments can be seen.

loadbearing, braided jacket over a braided HMPE strength member. The line would be unwound with only the weight of fittings, a heavy load would be lifted and secured, and the line rewound onto the winch drum. Each duty cycle caused flexing in the kinks and they began to sever. The line failed and a subsequent detailed examination of rope conponents revealed many kinks on a uniform and repetitive cycle length.

Aramid fibres fail rapidly when kinks flex. HMPE is much better and polyester is very resistant to failure.

The mechanics of axial compression are covered in Section 5.7.6.

4.6 External abrasion resistance

Obviously, the ability to resist damage from abrasion due to rubbing on exterior surfaces is an important property. It depends upon:

- The fibre material
- Wet or dry conditions
- Finish on the fibre
- The rope construction
- Nature of the abrasive surface
- Tension in the rope and pressure on the abrasive surface
- Speed of sliding over the surface

As far as is known, there is no standard for quantifying abrasion resistance. Data is developed empirically from use. Through trial and error, it is determined that one rope works better than another and that is usually the way abrasion resistance is reported.

Some generalisations can provide guidance (partly from CI 2003):

- Polyester, especially if treated with a good marine finish, resists abrasion well.
- Nylon is good dry, poor wet, unless treated with a marine finish which provides improvement.
- Aramid is a poor performer, wet or dry, but lubricants and marine finishes give better performance.
- HMPE is very abrasion and cut resistant but, due to low melting point, it can give poor performance if the combination of pressure and speed creates heat.
- Polypropylene is fair to good depending on type and filament size. Low melting point is a disadvantage. Blends with polyester perform much better.
- LCP has very good abrasion resistance.
- Manila is fair but degrades with age.
- Surface yarns and strands should approximately align with the axis of the rope.

4.7 Friction

The coefficient of friction between ropes and other surfaces is an important consideration in many applications. There are conflicting requirements. Avoidance of build-up of tension and external abrasion benefit from low friction, but holding a rope, for example on a capstan winch as seen in Fig. 4.28, benefits from high friction. Frictional heat can cause fibres with low melting points (HMPE and polypropylene) to melt, which can lubricate the friction surface, reduce the coefficient to near zero and create a dangerous situation.

Fig. 4.28 Friction is used to haul a double braid polyester line on a sailing yacht. This also exemplifies the need for good abrasion resistance. Reproduced by coutesy of Samson Ocean Systems.

Friction is also essential to make a splice work. Here it is fibre-to-fibre friction.

Friction coefficients are variable, difficult to quantify and are usually stated as a range. The variables are:

- Fibre material
- Surface material
- Surface condition – smooth, variable by design, damaged by wear, corroded
- Finish on rope fibre – most reduce friction but coatings on HMPE ropes are intended to increase it.
- Pressure against a surface – a function of the tension, the surface radius and any tendency for the rope to flatten
- Wet or dry – friction coefficient usually increases if the rope is wet
- Static or dynamic

Some typical values are provided in Table 4.7.

Table 4.7 Typical friction coefficient ranges for ropes of various materials sliding on smooth steel surfaces

Rope material	Friction coefficient – static	
	Dry	Wet
Nylon	0.1–0.12	0.12–0.15
Polyester	0.12–0.15	0.15–0.17
Polypropylene	0.08–0.11	0.08–0.11
Aramid	0.12–0.15	0.15–0.17
HMPE	0.08–0.11	0.08–0.11

4.8 Ultra-violet exposure

Ultra-violet exposure mainly comes from sunlight, but problems with small polypropylene ropes indoors and exposed to fluorescent lighting have been observed. This property is related to the fibre material and data can be found in Table 2.14.

Ultra-violet inhibitors are used in most synthetic fibres designed for use in rope. This is especially important for nylon, polyester, aramid and polypropylene. Pigments, especially black and dark colours, are very helpful for polypropylene.

Small ropes are affected much more than large ones. Ultra-violet only penetrates to a small depth, but at a diameter of 50 µm or so this can have a large effect on a filament. Damage is limited, however, to the filaments on the surface, which form a very small percentage of the fibre in a large rope. Rope sizes over 24 mm probably see minimal effects unless used in sub-tropical deserts for excessive periods of time. Open constructions such as eight-strand plait are affected more than compact double braid.

The strength of ropes with jackets and load bearing inner cores is not affected except that the jacket can see reduced abrasion resistance.

4.9 Temperature

4.9.1 Limiting temperatures

The melting or decomposition points of some fibres are given in Table 2.3. However, ropes cannot be used anywhere near these values. Nylon and polyester should be limited to 90°C (194°F) and polypropylene to 60°C (140°F) (ASME B30.9). Higher temperatures are acceptable for aramid. HMPE should not exceed 50°C (120°F) because of creep considerations.

4.9.2 Long-term exposure

Most fibres degrade if maintained at elevated temperatures for long periods of time. Temperatures less than those listed above can cause loss of strength, but this depends on the time and temperature. Nylon 6 fibre, for example, retains 84% of its strength after soaking at 95°C (200°F) for 4000 hours. For polyester, due to hydrolysis, maintaining even moderately elevated temperatures in water or steam for an extended time can lead to gradual strength loss.

If long-term use or storage at elevated temperatures cannot be avoided, check with the fibre supplier before proceeding.

4.10 Chemical and biological attack

Natural fibre ropes degrade relatively quickly in damp conditions, and are attacked by micro-organisms. However, synthetic fibre ropes are resistant to attack by most chemicals, unless they are highly corrosive and/or at elevated temperatures. Some guidance is given in Table 2.14, but if exposure to unusual chemicals is expected, specific checks should be made. Synthetic fibre ropes are not attacked by common micro-organisms.

For nylon, avoid acids and contamination with rust when wet. For polyester avoid dilute alkalis at elevated temperatures and concentrated alkalis. For polypropylene avoid volatile hydrocarbon solvents.

4.11 Shrinkage

Nylon ropes can be 'shrunk' by processing the rope through steam. The swelling of the fibre expands the diameter, shortens the rope and increases the extensibility. The effects are shown in Figures 4.7 and 4.8 for ropes that become wet while in use. The steam process carries this further and makes the rope very firm and resistant to further 'shrinkage'. As a property, this is preferred by some users.

Polyester fibre can be shrunk by heating. At the higher end of working loads, it will give a rope more elongation on the first few cycles but this soon disappears due to the shrink effect being permanently removed (a form of creep). In double braid, a core made of heat-treated polyester will permanently elongate as the rope is loaded to high tension, thus transferring more load to the cover (see Section 3.6.1); a modest increase in break strength can be attained compared with producing the entire rope out of untreated fibre. This shrink effect may also have application where higher extensibility is required for one time use.

4.12 Spliceability

The ability to be spliced with relative ease can be an important property of any rope. For may applications, the capability to form an eye in the end of the rope as a termination is essential. To be truly spliceable, the procedure should be standardised for the general-purpose uses and carried out with a modest amount of training, skills and tools.

Some used ropes, although spliceable when new, cannot be spliced after considerable use or shrinkage, or the splices, if made, can be very weak. Nylon braids that have shrunk fall into this category.

Almost any rope can be spliced, but specialist skills and tedious procedures are often required. Unless tested, efficiency and reliability may be questionable.

4.13 Knot retention

Knot retention can be an important property for certain applications. Tree service operators, rescue crews, mountain climbers and homeowners trying to secure a ladder use knots. No one wants them to slip. Some ropes hold better than others. Some comments:

- Manila fibre ropes – excellent
- Eight-stand plaited ropes that are tightly twisted and plaited – good
- Polypropylene staple ropes – good
- Nylon three-strand and braids – poor
- Polyester continuous filament braids – fair
- Polyester with staple (fuzz) on the surface – good
- Polypropylene monofilament three-strand and braids – poor

Handbooks on knots and manuals on special rope use skills give information on appropriate knots to use. There is always knot that will hold. Some information on knots is given in Section 7.10.

4.14 Hardness

Three-strand laid ropes may be produced in hard, medium or soft lay. Tightly twisted strands and a short lay length will produce a hard rope which is very firm, not very flexible and more snag resistant than the other versions. Soft lay rope is stronger and floppy. Medium lay is most common. Plaited ropes are sometimes specified with a hardness requirement. A test method is described in Section 10.15.

5

Rope mechanics

5.1 Introduction

5.1.1 The issues

Ropes, which may contain millions of fibres in their cross-sections, are extremely complicated structures. Correct and detailed analysis of the mechanics is not easy to develop. The purpose of this chapter is to introduce readers to what has been done. Hopefully, this will give readers an insight into the complexity of the physics and mathematics and increase their understanding of rope performance characteristics. This knowledge will inform designers of the parameters affecting the strength, extensibility and durability of ropes, so as to avoid pitfalls. More detailed information on the mechanics and the modelling can be found in the cited references.

Himmelfarb's (1957) account of the mechanical properties of ropes is almost entirely qualitative, including only five simple equations, and reflects the centuries of practical experience. This was the state of the art. There were only isolated analyses of the mechanics of textile materials before Walter Hamburger, who had been a founder of Fabric Research Laboratories in Boston, published in 1948 the first of a series of papers on *Mechanics of Elastic Performance of Textile Materials*. Joined by Milton Platt, the research included *Factors Influencing the Efficiency of Cordage* for the US Office of Naval Research. Since then, there have been continuous advances in academic research on the mechanics of fibre assemblies, though, with the coming of synthetic continuous filament yarns, little more on traditional cordage.

Most of the textile industry still relies on the traditional empirical approach, but, in the last decade, this has begun to change for ropes to be used in demanding applications, such as deepwater moorings. In other branches of engineering there has been a creative interchange for two centuries between theory and practice. For example, the engineering design of a bridge is based on well-defined properties of steel, a well-defined geometry, finite-element software for calculating forces and deformations, and means to determine stress concentrations and their effects. For ropes, not only is software only just becoming available, but the situation is complicated by the ephemeral nature of the fibre properties and the rope geometry.

Fibre modulus depends on prior history as well as on current loading and the geometry changes as ropes bed-in during cyclic loading.

What information is needed by the designer of a total system, such as a deepwater mooring, a riser protection net, or, in future as a replacement for the current use of steel, an elevator hoist or a cable-supported fabric building? And how can a ropemaker develop an optimum rope design to meet these needs, and, without impossibly expensive testing of very large ropes, show the systems engineer that valid design procedures have been followed?

Rope strength is the most obvious requirement and is quoted as a primary specification. Rope break load must be greater than the maximum expected applied tension by a specified 'safety factor'. Rope stiffness is as important, since, in stress-driven systems, this limits displacements, and, in strain-driven systems, determines tensions that develop. Torque development, or preferably its absence, is relevant, because torque can lead to twisting of ropes against terminations or connecting links, with damaging consequences. 'Fatigue', better described as predicted length of life before failure under imposed conditions, must be within safe limits. Bending stiffness is relevant to many applications, particularly when ropes are pulled over sheaves or round bollards.

Much research on rope mechanics is a development of earlier work on the mechanics of twisted yarns, which has been described by Hearle *et al*. (1969), Hearle and Konopasek (1975) and Hearle (1989).

5.1.2 Rope size and mechanical properties

The break load and resistance to elongation (axial stiffness) of a rope clearly increase with increasing size of rope. In order to compare the performance of different fibres and different rope constructions, normalisation is needed. However, the quantitative expression of the relations is not as simple as with solid materials. Because of the uncertain definition of area of ropes, which have irregular boundaries and internal space between fibres, yarns and strands, rope size is best expressed in terms of linear density, i.e. mass per unit length in kg/m. This leads to the use of *specific stress*, which is (force)/(linear density), instead of the conventional *stress*, which is (force)/(area). The relations between various relevant parameters are shown in Table 5.1 and in Appendix I, which includes unit conversions.

A first approximation to the linear density of a rope would be to multiply the number of fibres by the fibre linear density – or equivalent calculations for yarns or strands. However, there is a contraction in length during rope formation, because the components lie at an angle to the rope axis due to the twisting or braiding. As can be seen from Fig. 5.1, a component with linear density c at an angle θ to the rope axis will contribute a mass $cL\sec\theta$ to the length L of rope. Hence:

$$\begin{aligned}\text{linear density of rope} &= \text{number of components (fibres, yarns or strands) in rope}\\ &\quad\times \text{linear density of components}\\ &\quad\times \text{mean value of } \sec\theta \text{ for components}\end{aligned}$$

A convenient parameter to use is the contraction factor, given by:

$$\begin{aligned}\text{contraction factor} &= (\text{mean length of components})/(\text{length of rope})\\ &= (\text{linear density of rope})/(\text{sum of linear density of components})\\ &= \text{mean value of } \sec\theta \text{ for components}\end{aligned}$$

Table 5.1 Expressions for rope dimensions and tensile properties

The following relations apply:

rope area = rope linear density/rope density [5.1]

rope density = fibre density × packing factor [5.2]

where packing factor = fraction of rope cross-section occupied by fibre

rope linear density = (number of yarns in rope) × (yarn linear density)
× (contraction on rope formation) [5.3]

total rope mass ('weight') = rope linear density × rope length [5.4]

The normalised properties are best expressed in terms of rope linear density, sometimes called 'rope weight', i.e. mass per unit length in kg/m, but engineers also like to see values in Pascals or other units, which are conventionally normalised by area. The relevant quantities are:

strength = break load/area, typically in Mpa

specific strength = force/(mass/length), with MN/(kg/m) equal to N/tex

modulus = axial stiffness/area, in MPa or GPa

specific modulus = axial stiffness/(mass/length), in N/tex or MN/tex

These definitions lead to the following relations:

rope break load in MN (~100 tonne)

= rope linear density in kg/m × specific strength in MN/(kg/m) or N/tex

= rope linear density in kg/m

× fibre tenacity in N/tex

× strength conversion efficiency (fractional) [5.5]

There are analogous relations for stiffness.

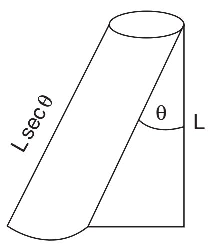


Fig. 5.1 A rope component lying at an angle θ to the rope axis.

For a twisted single yarn (as shown in Fig. 5.5), the geometry is easily defined. The mean value of $\sec\theta$ is calculated to be $^1/_2(1 + \sec\alpha)$, where α is the helix angle at the surface (see Hearle *et al.* 1969). For ropes, the geometry is more complicated because of the multiple twist levels or braid forms, but computer programs can be used to evaluate the geometry and compute the necessary quantities. The values in Table 5.2 show that contraction becomes appreciable when lay angles are much more than 10°.

For a length of rope in use, the important mechanical quantities, both having units of force, are:

Table 5.2 Values of sec θ

θ	**0**	**10**	**20**	**30**	**40**	**50**
Sec θ	1.000	1.015	1.054	1.155	1.305	1.556

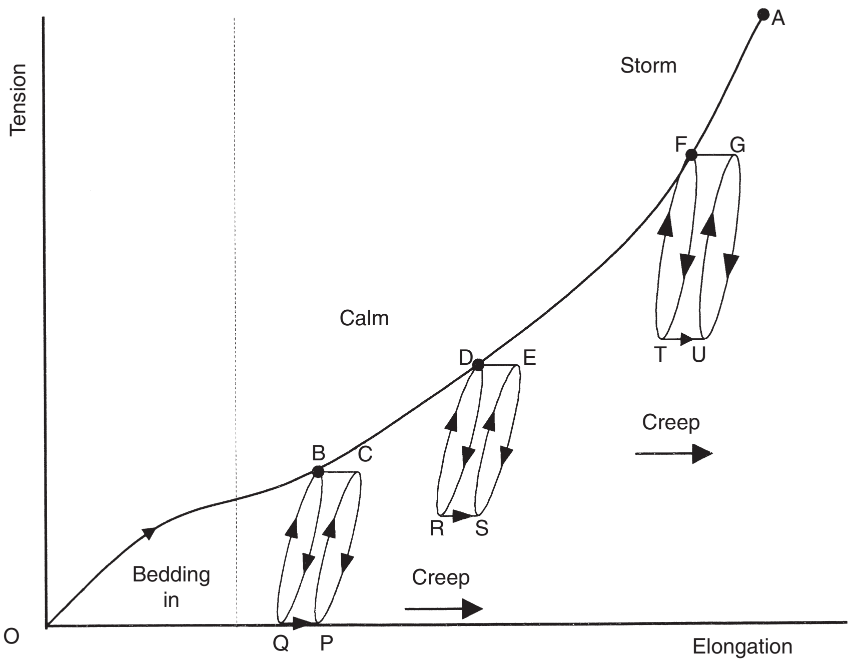


Fig. 5.2 Schematic representation of a typical rope response to tension loading. Post-installation stiffness corresponds to BQ, and storm stiffness to FT.

- rope break load in MN (≈100 tonne) = rope linear density in kg/m × fibre tenacity in N/tex × strength conversion efficiency (fractional)
- axial stiffness in MN = tension/strain = tension/(elongation/initial length) = rope linear density in kg/m × fibre modulus in N/tex × stiffness conversion efficiency (fractional)

The axial stiffness is also called the spring constant, and, in engineering, referred to as AE, where A = area and E = modulus, or KL, where K = elastic spring coefficient (force per unit length extension) and L = length of spring.

Because of fibre viscoelasticity and changes in geometry as ropes bed-in or are subsequently disturbed, stiffness values are dependent on prior history and current loading pattern. Figure 5.2 shows a typical response of polyester and similar ropes to tension loading. A schematic representation, which has been used to define two rope stiffnesses for use in mooring analyses, is shown in Fig. 12.11.

There are four major factors that influence the tensile properties of ropes, namely (i) obliquity, (ii) slip at fibre ends, (iii) variability, load sharing and weak places, and (iv) changes in rope structure, bedding-in.

5.1.3 Obliquity

The translation of fibre properties into rope properties is largely controlled by the angle at which the fibres lie to the rope axis. On a simplified model, Fig. 5.3, the contribution to rope stress of a fibre lying at an angle θ to the rope axis is reduced by $\cos^4\theta$ for the following reasons. (i) The fibre elongation is less than the rope elongation by $\cos\theta$. (ii) The fibre length is greater than the corresponding rope length by $\sec\theta$. Hence strain is reduced by $\cos^2\theta$. (iii) The component of fibre tension acting along the rope axis is given by $\cos\theta$. (iv) The rope stress acts on a larger area than the fibre stress by a factor $\sec\theta$. Hence stress is reduced by $\cos^2\theta$. To a first approximation, we therefore have:

$$\text{rope specific stress at a given strain} \\ = \text{fibre specific stress at same strain} \times \text{mean value of } \cos^4\theta \qquad [5.6]$$

A fibre parallel to the rope axis with θ = 0 is most highly extended, and, on the simplest model with strong interaction between fibres, would break first and trigger a sharp rope break at the same extension as the fibre. The mean value of $\cos^4\theta$ factor would thus also apply to rope strength. If there are weak interactions within the

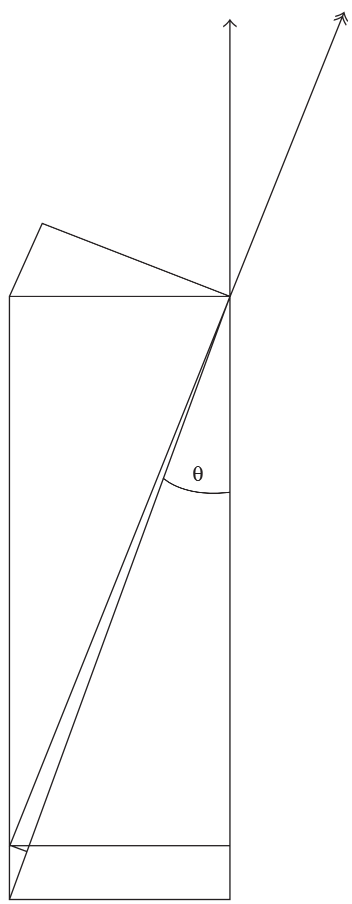


Fig. 5.3 Inter-relation of rope and fibre stress and strain.

structure, the break may be spread over a range of extensions as individual components break, but the peak load will usually also be close to or less than that given by the mean value of $\cos^4\theta$. There are many simplifications in the above derivation, notably the neglect of lateral contraction and transverse forces. More exact analyses are given below.

In a single twisted yarn with the same twist period at all radii, the helix angle θ increases from zero on the central axis to α at the surface of the yarn. The mean value of $\cos^4\theta$ is $\cos^2\alpha$. In ropes with several twist levels, computer modelling of the geometry would enable the values of θ and the mean value of $\cos^4\theta$ to be determined. An alternative procedure is described in Section 5.4.

5.1.4 Slip at fibre ends

In ropes made of discontinuous fibres, it is necessary to take account of slip from fibre ends. In twisted structures, the fibres, yarns and strands wrap round one another, and generate transverse forces that grip the fibres. At the end of a fibre, as shown in Fig. 5.4(a), there will be zero tension, but tension builds up along the fibre due to the frictional resistance to slip, until it reaches the level at which the fibre is fully gripped and the tension is that due to the imposed strain. For a singles yarn, the effect of twist for a given extension is shown in Fig. 5.4(b). At high twist, the no-slip tension is considerably reduced due to obliquity, but the slip length is small. As twist is reduced, the reduction due to obliquity decreases but that due to twist increases. There is an optimum twist level for maximum tension. Just beyond the low-twist level in Fig. 5.4(b), the structure becomes unstable. The fibre is nowhere fully gripped. This is the boundary between a fibre assembly that can be drafted as fibres slide over one another and one that is self-locking.

In a singles yarn, where fibres follow concentric helices, twist by itself is not enough. Fibres on the outside will not be gripped and will not transmit grip to lower layers. In some spinning systems, fibre migration, change of radial position along a fibre path, means that all fibres are gripped when they are in the interior of the yarn. However, in multi-ply structures, such as cords and ropes, migration is not essential because the wrapping of yarns and strands round one another serves to grip the fibres on the surfaces of the yarns.

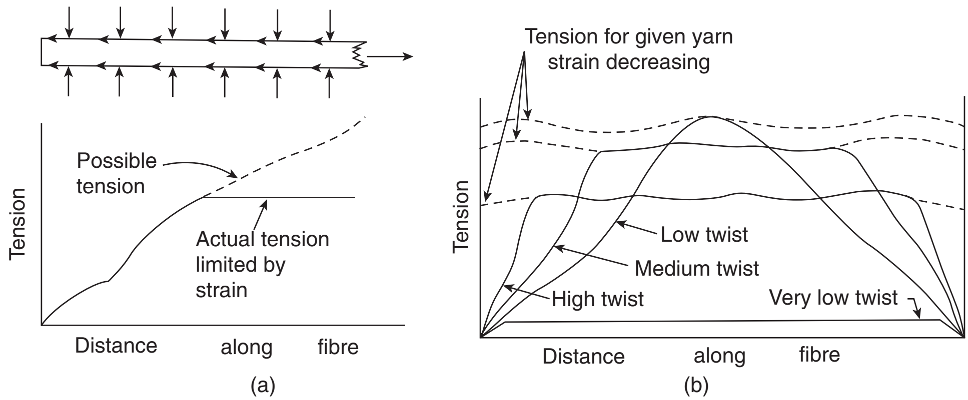


Fig. 5.4 (a) Build-up of tension along a gripped fibre. (b) Effect of twist level. From Hearle *et al.* (1969).

A simple treatment of the mechanics of fibre slip in ropes is as follows. At the point where the tension due to friction equals that due to strain without slip, we have:

$$\pi a^2 f = 2\pi a \mu g s \qquad [5.7]$$

where a = fibre radius, f = tensile stress, μ = coefficient of friction, g = transverse stress and s = slip length.

The slip factor SF is related to the fibre length L by:

$$\begin{aligned} SF &= \text{tension with slip}/\text{tension without slip} \\ &= (L - s)/L = 1 - \tfrac{1}{2} af/\mu gL \\ &= 1 - \tfrac{1}{2}(a/L)/\mu\mathcal{T} \end{aligned} \qquad [5.8]$$

The dependence on the aspect ratio is obvious. Long, fine fibres will be more effectively gripped than short, coarse fibres. Similarly, high friction will reduce slip. The factor $\mathcal{T}$ is an operator that converts applied tensile stress into transverse gripping forces. The higher the twist levels and the greater the interaction of yarns and strands, the greater will be the value of $\mathcal{T}$ and the less the slip. Its calculation would be complicated, and, in practice, ropemakers choose structures which give effective gripping. An indication of order of magnitude is given by an analysis that shows that the transverse stress at the centre of a continuous filament yarn with a twist angle of 30° would be 1/8 of the tensile stress.

The theory of slip at fibre ends is relevant but is rarely used in rope design, even though it would predict a minimum staple length for a specific rope geometry and forecast strength when a friction value is known.

The evaluation of natural fibre ropes, with their short staple, developed over centuries and was based on experience and simple testing. The work on cordage mentioned in Section 5.1.1 was an exceptional theoretical analysis. The reduced production of natural fibre ropes means that the effects of slip in ropes have not been modelled in more detail. A popular type of modern polypropylene rope uses continuous filaments chopped into staple, but the long lengths means that the effect of slip will be small. Later research has concentrated on continuous filament structures, in which slip from fibre ends does not play a part.

5.1.5 Variability, load sharing and weak places

The third major factor is variability between and along components of rope. It is not difficult to average values of stress at a given strain to give modulus values. The effects on break are greater because failure depends on extreme value statistics. If yarns or strands are put into ropes at different lengths, or if their properties are different, load will be unevenly shared. If there are weak places along the length, this is where breaks will occur. However, both of these effects are influenced by the transfer of stress from one fibre to another. There will be an effective slip length over which components act independently. This length will be long in parallel yarn ropes and short in ropes with high twist which generates transverse forces.

5.1.6 Change in rope structure; bedding-in

The final factor is the indeterminacy of rope structures. When first made, there are large spaces, particularly between strands and to some extent between smaller components. One theoretical limit would be a close packing of circular cylinders, but the packing may not be as good as this. When the rope is put under tension, the strands can be compressed into a wedge shape, as shown, for example, in Figures 1.5(c) and 3.7. The change in geometry affects the mechanical properties. However, this is not just a result of a single application of tension. The rope structure progressively becomes more compact with successive applications of tension. Bedding-in of ropes, which is a necessary preliminary to rope testing, requires many cycles. There may also be some evening-out of variability in the structure.

5.2 Tension, torque, elongation and twist

5.2.1 Twisted yarn mechanics

The remainder of this Chapter is directed primarily towards synthetic continuous filament ropes, and we first look at the tensile and torsional relations in the simpler case of twisted singles yarns. Even when torque is not deliberately applied, the application of tension to a twisted rope structure will generate torque, which, unless fully resisted at the termination, will cause the rope to twist so as to relieve the torque. The twisting, or untwisting, will contribute to rope elongation in addition to the direct effect of tension. Tension, torque, elongation and twist are thus inextricably linked.

Although some analyses of the mechanics of fibre assemblies have been based on the equilibrium of forces and moments, energy methods have proved much more useful. For a system subject to a force P_L, conservation of energy for an increment of elongation dS_L gives:

$$\text{work done} = P_L dS_L = \text{fibre strain energy} = \Sigma dE_f \qquad [5.9]$$

If the fibre load–elongation relation is given by a function $P_f = f(S_f)$, $dE_f = P_f dS_f$. We can then separate the fibre-property term from the geometrical term:

$$P_L = \Sigma(\partial E_f/\partial S_f)(\partial S_f/\partial S_L) = \Sigma P_f(\partial S_f/\partial S_L) \qquad [5.10]$$

When normalised in terms of fibre specific stress f_f and strain e_f, this is given as a sum over elements of fibre mass m_f as:

$$f_f = \Sigma m_f f_f(\partial e_f/\partial e_L)/\Sigma m_f \qquad [5.11]$$

The application to singles twisted yarn is given by Hearle and Konopasek (1975). The idealised geometry is shown in Fig. 5.5(a). Each filament follows a helical path of constant pitch h and radius r, with the helix angle θ increasing from 0 at $r = 0$ to α at $r = R$. In one turn, the filament length is l, equal to L at the surface. The geometry is defined by the triangles in the opened-out diagrams, Fig. 5.5(b),(c). The mean value of $\cos^4\theta$ is $\cos^2\alpha$, which is the approximate factor for reduction of modulus and strength.

In a full treatment of combined extension and twist, as shown in Fig. 5.6, equations [5.10] and [5.11] must be modified to include both a tension P_L and a torque M_L on a length of yarn, which elongates by dS_L and rotates by $d\phi_L$ radians. The work done, which is $(P_L dS_L + M_L d\phi_L)$, must equal the strain energy ΣdE_f due to fibre extension. By partial differentiation, we can separate the tension and torque terms. After normalising, the summation in equation [5.11] is replaced by an integration over the whole yarn cross-section. The specific tensile stress and specific torque are then given by equations [5.12] and [5.13] in Table 5.3 in terms of the following input

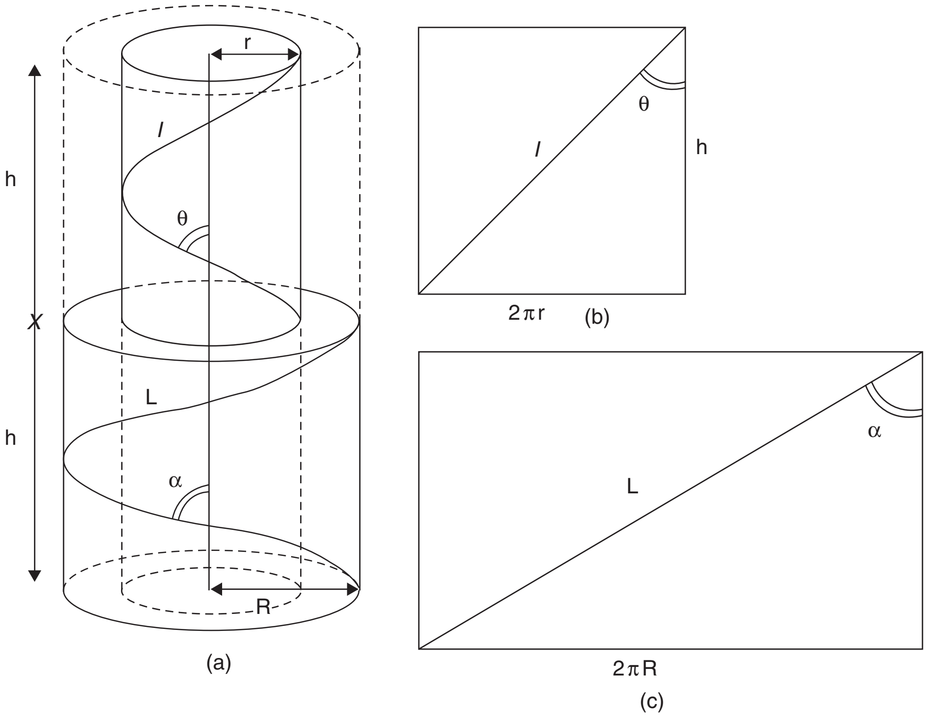


Fig. 5.5 (a) Idealised twisted yarn geometry. (b) and (c) Opened-out diagrams at intermediate and surface radii.

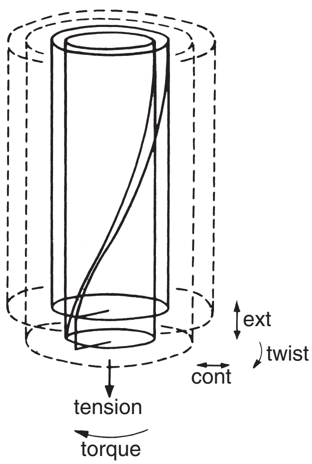


Fig. 5.6 Combined extension and twist. From Hearle and Konopasek (1975).

quantities: the yarn extension e_f and twist T; the fibre stress–strain curve, $f_f = f(e_f)$; Poisson's ratio v, which for constant volume deformation equals 0.5; the initial yarn radius R_0, which can be calculated from linear density, fibre density and packing factor; and initial twist T_0, which is related to surface twist angle α_0.

Table 5.3 Tension and torque in an idealised twisted yarn subject to extension and twist

specific tensile stress $= f_y = 2\int_0^1 f_f(\partial e_f/\partial e_L)xdx$	[5.12]
specific torque $= m_y = 2\int_0^1 f_f(\partial e_f/\partial T)xdx$	[5.13]
$(1+e_f)^2 = (1+e_L)^2\cos^2\theta_0 + \left[1 - ve_L(1+T/T_0) + T/T_0\right]^2$	[5.14]
$\tan\theta_0 = x\tan\alpha_0$	[5.15]
$\tan\alpha_0 = 2\pi\, R_0 T_0$	[5.16]

See text for explanation of symbols. Suffix $_0$ indicates initial values.

In order to determine fibre strain e_f it is necessary to take account of four effects: (i) yarn extension e_L; (ii) lateral contraction, defined by a Poisson's ratio v, which reduces fibre extension; (iii) twist from an initial value T_0 to a final value T per unit length, which if positive will increase fibre extension; (iv) the correct form for large strains. This leads to equation [5.14] in Table 5.3.

Hearle and Konopasek (1975) showed that the analysis could be modified to cover extension, without twisting, when the idealised concentric helical geometry of Fig. 5.5 was not applicable, as in ply yarns, cords and ropes. The angle θ is taken as the angle between the fibre axis and the cord axis. Application of Fig. 5.3 and the more exact form with large strains and lateral contraction are still valid. The resulting equations are:

$$f_L = \Sigma_c f_f(\partial e_f/\partial e_L)\delta c_0/c_o \qquad [5.17]$$

$$f_f = \mathrm{f}(e_f),\ \text{fibre stress–strain curve} \qquad [5.18]$$

$$(1+e_f)^2 = \left[(1+e_L)^2\cos^2\theta + (1-\nu e_L)^2\sin^2\theta\right] \qquad [5.19]$$

The summation Σ_c is taken over all linear density elements δc_0, which are equal to area elements, in the initial state of the cord with a linear density c_0. This analysis has not been applied to ropes but would be appropriate in highly twisted ropes with multiple levels if the hierarchical method in the next section were in error. It would be necessary to model the cord geometry in order to associate the elements δc_0 with the orientation angle θ.

5.2.2 Twisted yarn behaviour

Because they are simpler and cheaper to make, there have been more detailed measurements of the tensile properties of twisted yarns than of ropes. However, the effects of increasing singles twist serve to illustrate qualitatively the behaviour of ropes as multiple twist levels are increased.

Figure 5.7 shows load–elongation curves of nylon yarn. There is a general decrease in yarn stiffness with increasing twist. At low twist, there is little interaction between neighbouring filaments, each of which breaks independently. But at higher twists, stress transfer causes the first break to lead to break of the whole yarn. Figure 5.8(a) shows that there is good agreement between experiment and theory except for a slightly larger than predicted extension at low stress. This is because the yarn structure is not ideal but has some buckling of central fibres, which develop less stress than if they followed the ideal straight path. If a small stress is applied

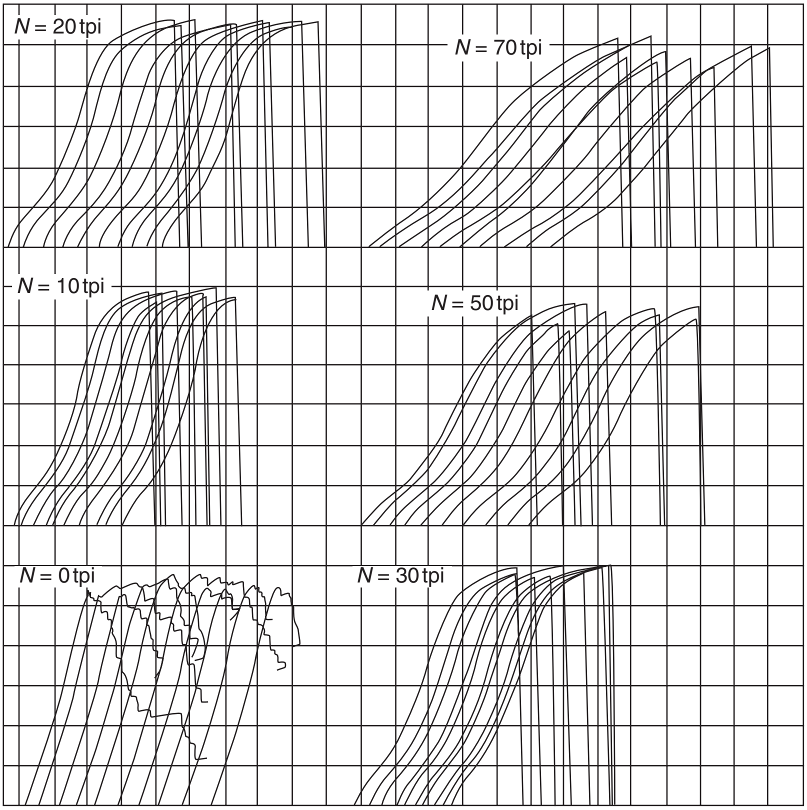


Fig. 5.7 Load–elongation curves of 100 denier nylon yarn at increasing levels of twist (tpi = turns per inch). From Hearle *et al.* (1969).

and the dynamic modulus is measured, Fig 5.8(b) shows perfect agreement between experiment and exact theory. The approximate $\cos^2\alpha$ relation is a guide to the right trend, but is slightly higher.

Figure 5.9 shows that although theory predicts a continuous decrease in strength with twist, experiment shows an initial rise, which results from the mutual support of neighbouring fibres. Weak places in a fibre are prevented from breaking when they are gripped by neighbouring fibres. This is a minor manifestation of the gripping of short fibres, which could be regarded as continuous filaments with occasional locations of zero strength. Peak strengths occur at surface twist angles of about 7°.

5.3 Predicting rope properties

5.3.1 Fibre rope modelling

Under a contract from the US Navy, Tension Technology International (TTI) developed the mechanics of twisted yarns methodology to apply to the more complicated geometry of twisted ropes with a multiplicity of helices at different levels (Leech *et al.*, 1993). The resulting software is currently being enhanced to make it easier

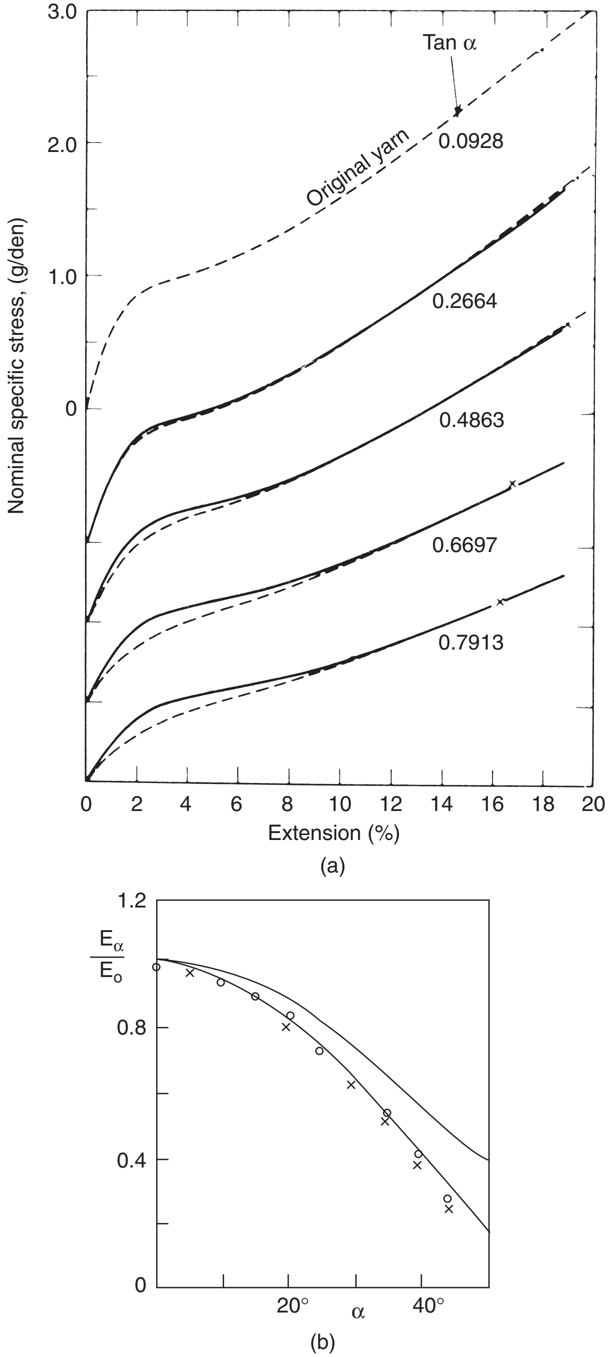


Fig. 5.8 (a) Comparison of predictions of energy-based theory (full lines) with experimental measurements (dotted lines) for a rayon yarn for increasing twist angle α. From Hearle *et al*. (1969) after Treloar and Riding (1963). (b) Variation of experimental values of relative dynamic moduli of nylon (circles) and polyester (crosses) yarns under a stress of 2.7 mN/tex with twist angle α. The upper line is the approximate $\cos^2\alpha$ relation; the lower line is for the exact theory. From Hearle (1989) after Zorowski and Murayama (1967).

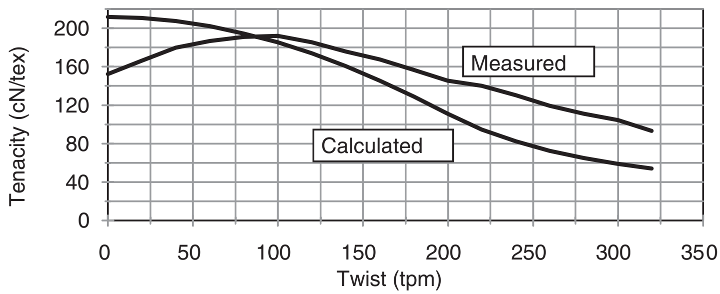


Fig. 5.9 Change of strength of 1670 dtex aramid yarn with twist.

to use and to cover a wider range of effects. In addition, because of their importance in rope fatigue, as described in Section 5.7, the internal forces were also included.

The method is hierarchical, which mirrors the manufacturing process. The model is defined by a computer program in which the response at each level becomes the input to the next highest level. The full sequence depends on the rope construction, but is typically as follows:

fibre → textile yarn → **rope yarn** → **strand** →(sub-rope) → **rope**

The commonest computation is shown in bold. The load–elongation curve for the rope yarns, which are composed of many textile yarns, is taken as the starting point, if known, but, if not, the textile yarn is used. The sub-rope is only present in parallel-strand ropes. Different yarns can be incorporated in different parts of the rope structure. The input yarns are specified by the following parameters: linear density (mass/length); density (or fibre density and packing factor), which determines yarn diameter; tensile stress–strain curve, defined by the coefficients of a fourth-order polynomial; and coefficient of friction.

The first action is to establish the twist geometry. At the lowest level, this will be the geometry of Fig. 5.5, in which fibres follow concentric helical paths. At the next level, the twisted yarns take the place of the fibres in Fig. 5.5, and so on. Account must be taken of the change of twist in lower-level components, when they are twisted together at higher levels (see Section 6.1.3). The strain and energy equations then apply in a way analogous to that described above, with the stress–strain properties being computed at each level. A basic assumption is that planes perpendicular to the axis of each component remain planar and perpendicular to the axis. The planes move farther apart, rotate due to twist, and reduce in area, either to keep the volume constant or to allow for compression. Differential geometry keeps track of the deformations throughout each level of structure.

Three options for packing of components are shown in Fig. 5.10. In 'packing' geometry, the components are in circular layers with contact forces acting radially towards the central axis. In 'wire-rope' geometry, the layers are self-supported by circumferential contact forces. In 'wedge' geometry, the spaces between the components are eliminated, or partially eliminated, and contact forces act both radially and circumferentially. For each geometry, there is a packing factor in the initial state, which may be reduced by lateral pressures when the rope is tensioned.

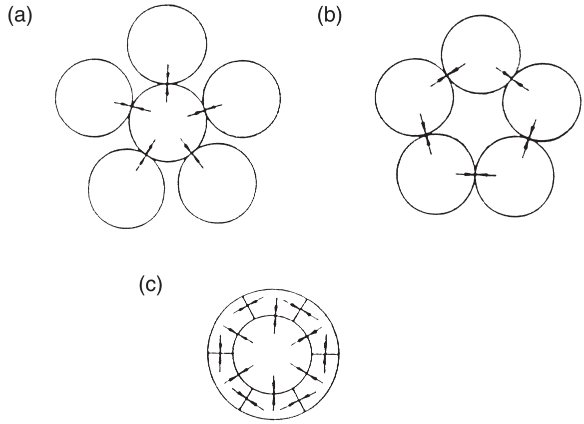


Fig. 5.10 Packing of components. (a) 'Packing' geometry. (b) 'Wire-rope' geometry. (c) 'Wedge' geometry. From Leech *et al.* (1993).

Friction is introduced by slip at contact points, with magnitudes determined by differential geometry. There are many modes, as shown in Fig. 5.11. Modes 1 and 2 involve axial sliding between components due to stretching and twisting. Mode 3, rotational slip, is an end-effect. Modes 4 and 5 are scissoring and sawing at crossovers. Mode 6 is due to bulk compression or dilation. Component distortion was not explicitly included, but is implicit in the change of packing geometry.

In order to include derivation of the internal forces, which requires virtual displacements, the analysis is based on the Principle of Virtual Work expressed as:

$$P\,\delta S + M\,\delta T = \delta E \qquad [5.20]$$

where, for each component level, P is tension, S is elongation, M is torque, T is twist and E is strain energy, based on the stress–strain curve of the next lowest level. Because of fibre fineness, only elongation energy from integration of tensile stress–strain properties from yarns in extension and recovery needs to be taken into account.

Application of virtual displacements then gives the tension and torque:

$$P = \Sigma P_c l_{0c}(\partial e_c/\partial S) \qquad M = \Sigma P_c l_{0c}(\partial e_c/\partial T) \qquad [5.21]$$

where P_c is the axial load in the component as a function of strain e_c, which depends on S and T for the component from the differential geometry, and l_{0c} is the reference length of the component.

In order to determine internal forces, a virtual change in the helix radius r is introduced. The contact force is then given by expressions similar to equation [5.21] involving $(\partial e_c/\partial r)$. The frictional force is given by multiplying the contact force by the coefficient of friction. The additional energy term is the product of friction force and displacement at contact points, given by the differential geometry.

Implementation of the program involves the following steps:

- Definition of rope structure: number of components, twist and packing at each level, which is a lengthy but straightforward procedure.
- Definition of input yarn properties: dimensions, polynomial coefficients of stress–strain curve and coefficient of friction.

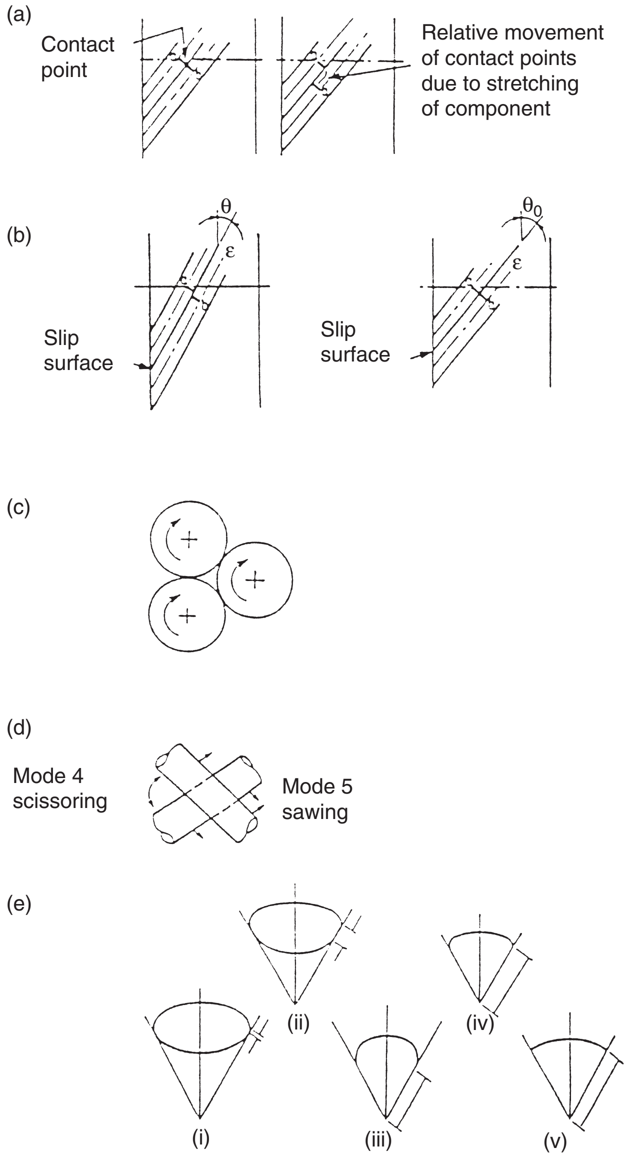


Fig. 5.11 Modes of slip. (a) Mode 1 Stretching. (b) Mode 2 Twisting. (c) Mode 3 Rotating. (d) Mode 4 Scissoring and Mode 5 Sawing. (e) Mode 6 Distortion progressing from (i) to (v). From Leech *et al*. (1993).

- Loading pattern: elongation to break, cyclic loading between limits, etc.
- Graphical or numerical interrogation of predicted responses at each level.

Figure 5.12 shows the good agreement between experiment and theory for three levels of a parallel-strand polyester rope. Measured break loads are usually slightly less than predicted values, due to effects of variability, not all of which are included in the model. Figure 5.13 is for an aramid wire-rope construction. The computation indicated that the first rope as made was not to specification; there was good agree-

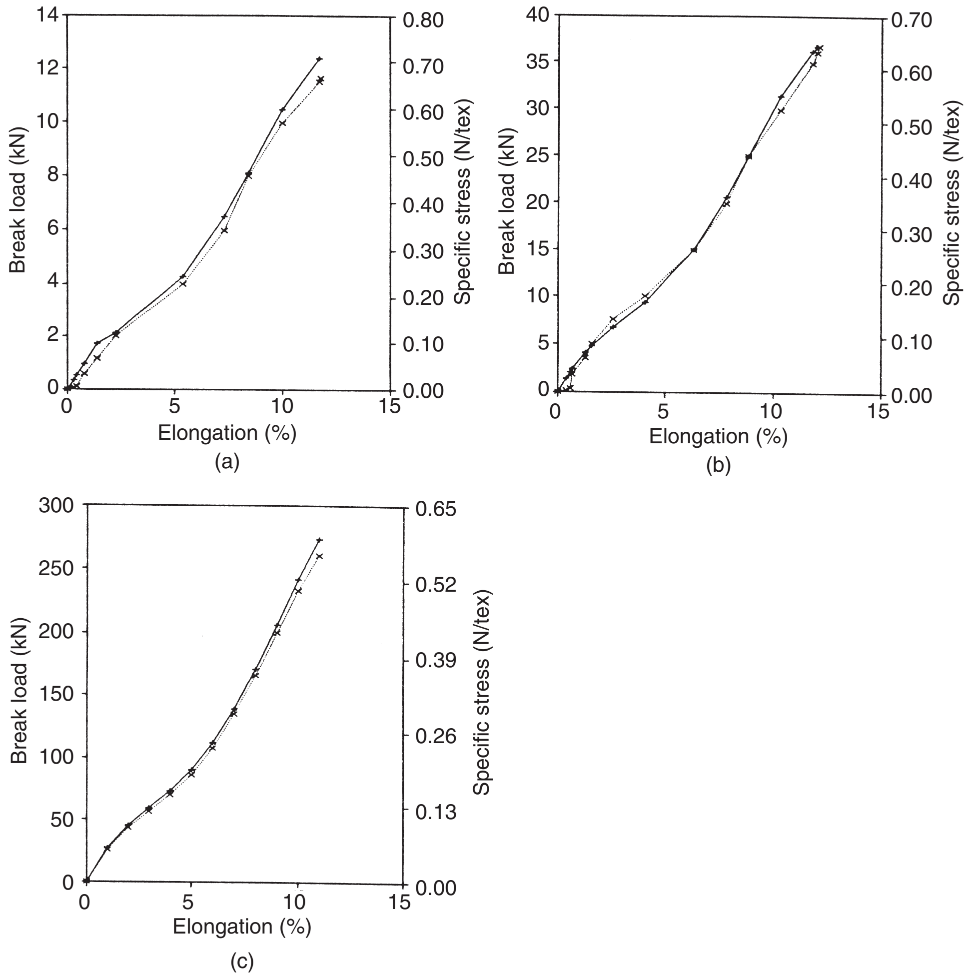


Fig. 5.12 Theoretical predictions (dots) and experimental measurements (crosses) of load–elongation properties of a polyester parallel-strand rope. (a) Strand. (b) Sub-rope. (c) Rope. From Leech *et al.* (1993).

ment when the rope was remade. Figure 5.14 shows measurements of the torque–twist response of a parallel-strand polyester rope, with bedding-in on the first twisting. The predicted slope of the torque–twist relation agrees with experiment.

The program can be used for parametric studies. Figure 5.15 shows a 10% decrease in modulus at 3% extension in an aramid wire-rope construction, when the twist in the outer layer is increased from 2.5 to 4.5 turns per metre. Changes in break strain and peak load are also found. The computation allows each level to break independently, but, in practice, energy stored in the remainder of the rope length would likely lead to the first break triggering total rupture. Figure 5.16 shows the effect of changing from aramid to polyester in the same rope construction. The difference between torque generated by elongation in balanced and unbalanced structures is shown in Fig. 5.17, and a prediction of hysteresis in Fig. 5.18.

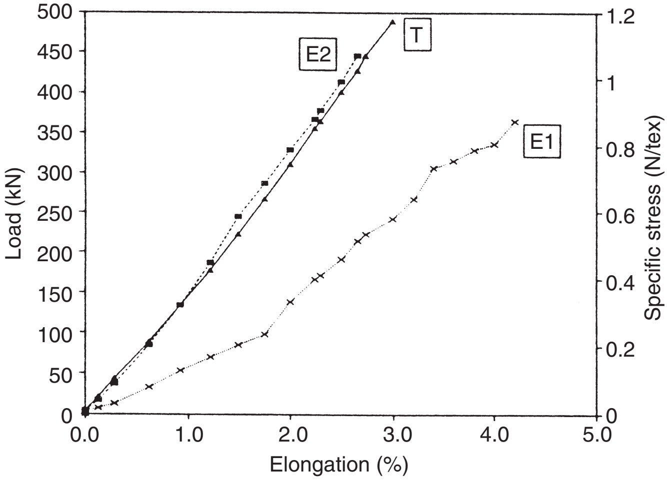


Fig. 5.13 Load–elongation of a 7-strand aramid rope. T is the theoretical prediction. E1 is an experimental measurement, but, on examination, the rope was found to be not to specification. E2 is the measurement on a correctly-made rope. From Leech *et al.* (1993).

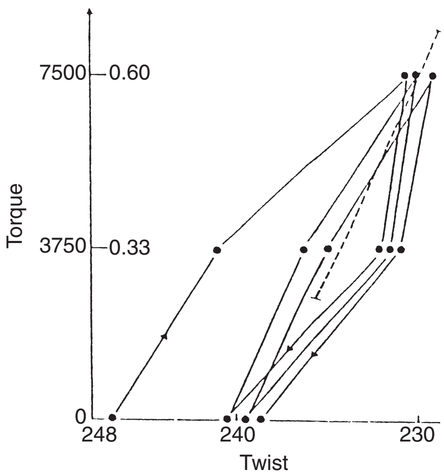


Fig. 5.14 Torque–twist relations for a strand (component of a sub-rope) of parallel-strand polyester rope. Full line: experimental. Dotted line: mean theoretical prediction. The units are arbitrary values related to the dimensions of the test specimen. From Leech *et al.* (1993).

The only significant effect of friction on load–elongation predictions came from the sliding modes 1 and 2. Even this was small. A change from $\mu = 0.1$ to 1.0 caused a barely detectable difference in the load–elongation curves of a parallel-strand polyester rope. Friction does have a major role in long-term life under cyclic loading, as discussed in the following.

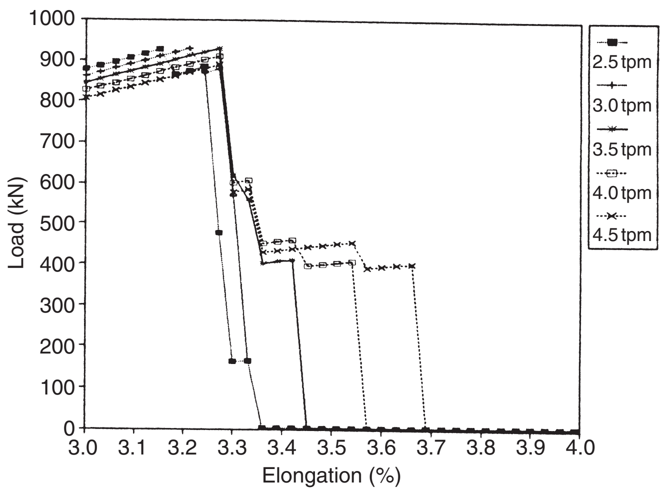


Fig. 5.15 Effect of outer layer twist on breakage of a 36-strand aramid rope. From Leech *et al.* (1993).

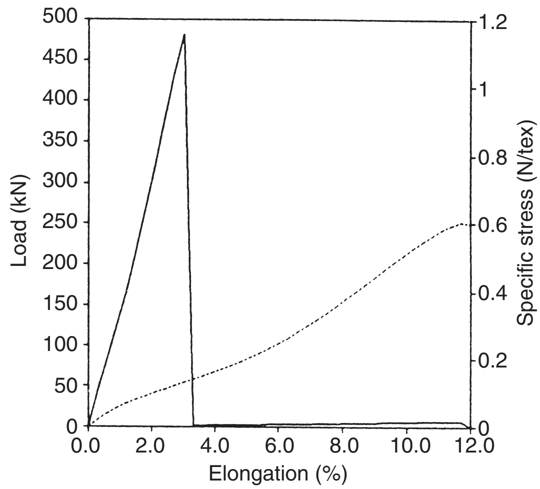


Fig. 5.16 Effect of constituent material on a 7-strand rope with the same construction in aramid (full line) and polyester (dotted line). From Leech *et al.* (1993).

5.3.2 Braided ropes and splices

Braided ropes and splices have an interlacing geometry. From textile yarns to strands, the helical geometry as described above will be applicable, but, at strand level, the angle to the rope axis will depend partly on the circumferential helical path and partly on the radial translation as strands pass under and over one another. The differential geometry will be different to that of twisted ropes and the scissoring frictional mode will be more important. However, the model described in Section 5.3.1 can be adapted to predict braid responses. Leech (2003) has published an analysis of the mechanics of splices.

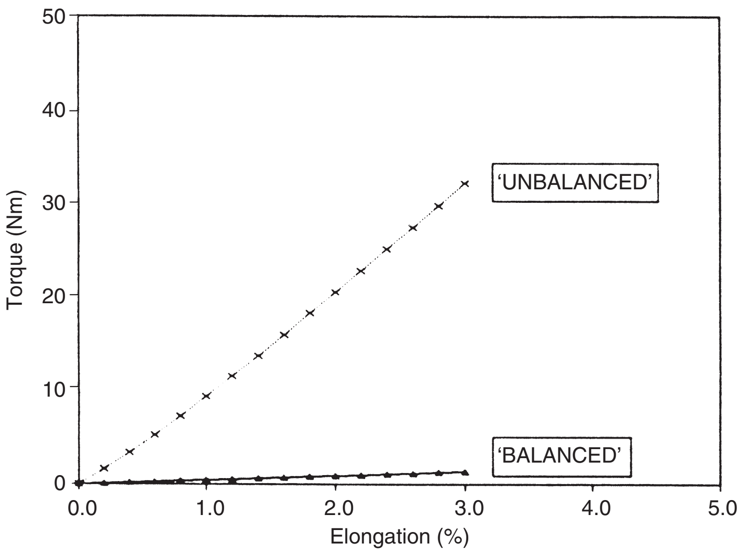


Fig. 5.17 Predicted generation of torque in an aramid wire-rope construction, with and without attention to torque balance. From Leech *et al.* (1993).

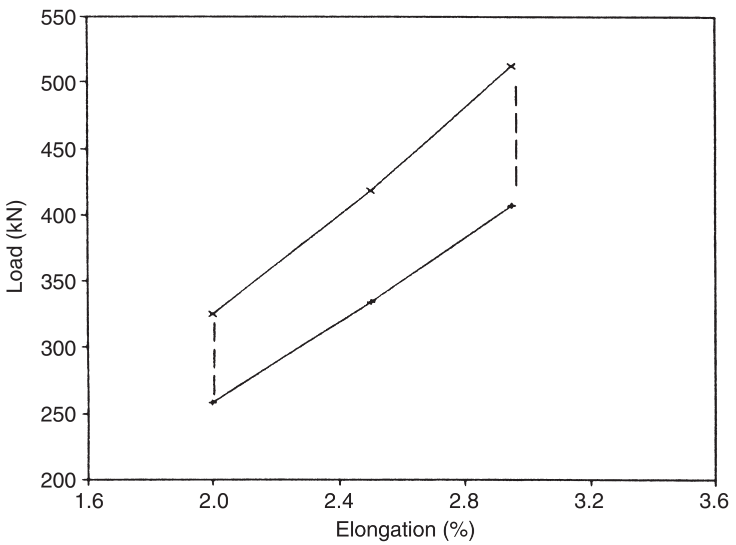


Fig. 5.18 Predicted hysteresis due to load cycling in a 7-strand aramid rope. From Leech *et al.* (1993).

The method of equations [5.17] to [5.19] will be applicable with θ defined as the angle between fibre directions and the rope axis, but this would need detailed computation of the differential geometry. Alternatively, equations [5.22] or [5.23] could be used, with appropriate modifications of the definition of θ at the strand level.

5.4 An alternative approach

5.4.1 Prediction of modulus

An alternative to the detailed modelling in the last section has been provided by O'Hear (2000), who has modified the simplistic analysis in Section 5.1.3 by taking into account lateral contraction and other effects. This leads to the equations below, in which the power of $\cos\theta$ is changed from $\cos^4\theta$. For a single level of twisting, e.g. from rope yarns to strand, the equation is:

$$\text{strand modulus} = \text{rope yarn modulus} * \cos^{4.75}\theta \quad [5.22]$$

If there are several layers of twist in the rope:

$$\text{rope modulus} = \text{yarn modulus} \times (\cos^{4.75}\theta_1 * \cos^{4.75}\theta_2 * \ldots\ldots * \cos^{4.75}\theta_n) \quad [5.23]$$

where n is one less than the number of structural levels in the rope (e.g. $n = 3$ for textile yarn, rope yarn, strand and rope). The helix angles θ_1 to θ_n are for the path followed by the axis of the component.

Equations [5.22, 5.23] take account of the increase in linear density due to contraction on twisting. Quite often, however, the change in area and weight due to the helix angle is ignored. If this is the case then $\cos^{3.75}\theta$ should be used.

5.4.2 Strength

The simplest argument is that a straight yarn ($\theta = 0$) has the same elongation as the rope, and that when this yarn reaches its break elongation, it will trigger the break of the rope. In this case the strength should decrease in the same way as the modulus. In fact, predictions using equation [5.23] overestimate strength. In one test on twisted aramid strands, a good fit was to $\cos^9\theta$. There are a number of reasons why strengths may be lower than the idealised prediction; particularly the effects of variability on load sharing. The effects can be expected to be more severe for fibres, such as aramid, with low break elongations. An efficiency factor can be used as an empirical correction to modify equation [5.23] for strength prediction.

Another factor that gave a good fit over a limited range was $(-0.067 + 1.97\cot\theta)$. This relation was based on an assumption that the lateral pressure on fibres, a squeeze factor, reduced their strength. However, little work has been done on the details of strength translation. The extension due to lateral pressure is automatically taken into account in the theory of Sections 5.2.1 and 5.3.1, and it is possible to argue that lateral pressure would increase resistance to tensile failure.

5.5 Bending stiffness

As described in Section 2.5.6, the bending stiffness B of a solid rod depends on EI, where E is the modulus and I is the area moment of inertia. The bending moment $M = Bc$, where c is the curvature, namely the reciprocal of the radius of curvature. The bending stiffness of a rope must lie between two extremes. With strong interaction between components, the rope could act as a solid rod, with a bending stiffness B_s, or alternatively, the fibres could be free to bend independently, with a total bending stiffness B_f. For circular cross-sections these values would be

$$B_s = \pi ED^4/1024 \qquad B_f = N\pi Ed^4/1024 = (\pi ED^2d^2/1024) \quad [5.24]$$

where, in a rope of diameter D with fibres of diameter d, N is the number of fibres, equal to $(D/d)^2$.

Hence, the ratio of the stiffest to the most flexible model is $(D/d)^2$. Since fibre diameters are of the order of 10 μm and rope diameters are 10 to 100 mm, this ratio is 10^6 to 10^8. The choice of rope construction means that ropes can either act almost like rigid rods, for which a considerable free length could be held horizontal without bending appreciably, or could be extremely flexible, bending back on themselves with negligible resistance. Detailed modelling would depend on the difficult question of the degree of interaction between fibres in the rope.

Loose, low-twist ropes will come close to the flexible limit, unless they are enclosed in a tight jacket. In high-twist ropes, the interaction between fibres is much stronger, but various factors will keep the stiffness below the rigid limit. In contrast to a solid rod, components on the inside of a bend may be free to buckle and thus reduce the compressive stresses. This is a large-scale version of the molecular buckling in fibres described in Section 2.5.6. Furthermore, in a twisted or braided structure, components pass from the outside of a bend, where they are under tension, to the inside of a bend, where they are in compression. Slippage along the components will partially relieve these stresses and reduce bending stiffness. Finally, the rope may be free to flatten, thus reducing the effective diameter. A diagram by Himmelfarb (1957), Fig. 5.19, indicates how there will be pressure points in a bent rope, through which sliding may occur and lead to abrasion.

Parallel yarn ropes demonstrate the extremes. Without a jacket, the collection of yarns would be loose and flexible. In order to control the structure, a tight plastic jacket is applied. Because there is no twist, yarns on the outside of a bend must suffer the full extension and those on the inside be compressed axially with little room in which to buckle. Parallel yarn ropes are thus extremely stiff. The stiffness is reduced somewhat because the ropes flatten during bending; an elliptical cross-section gives a lower bending stiffness than a circular cross-section of the same area.

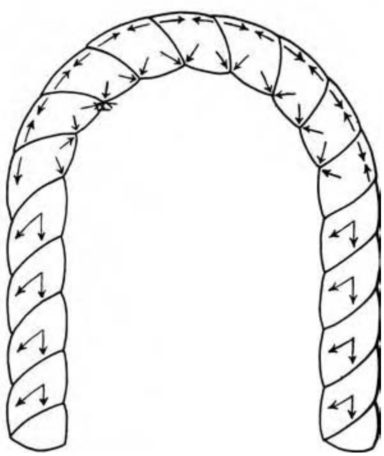


Fig. 5.19 Forces in a bent rope. From Himmelfarb (1957).

5.6 Variability

5.6.1 Two factors

Variability comes into rope mechanics through differences in fibre properties and effects in rope construction. Because fibres, yarns, strands and ropes are long linear forms, three effects are involved: the *weak-link effect*, which acts along linear elements; *strain differences in bundles* with elements of varying length; *load transfer in bundles*, which acts between linear elements. The statistical approach is discussed by Phoenix (1980). Variability in fibre modulus also has an effect.

5.6.2 Weak-link effect

For an isolated linear element, the weak-link effect is easy to deal with theoretically, but involves considerable statistical difficulties in practice. Consider a chain made up of links in which the probability of a link having a strength between S and $(S + \mathrm{d}S)$ is $\mathrm{P}(S)\mathrm{d}S$. A chain of n links will break at the weakest link. The probability $\mathrm{P}_n(S)\mathrm{d}S$ that this gives a strength between S and $(S + \mathrm{d}S)$ requires that one of the n links has this strength and that all the others are stronger. Hence:

$$\mathrm{P}_n(S)\mathrm{d}S = n\mathrm{P}(S)\mathrm{d}S\left[\int_{\mathrm{P}}^{\infty}(S)\mathrm{d}S\right]^{n-1} \qquad [5.25]$$

For continuous lengths, a similar relation applies, with $\mathrm{P}(S)$ replaced by $\mathrm{P}_L(S)$ and $\mathrm{P}_n(S)$ by $\mathrm{P}_{NL}(S)$, where L is a test length and NL is some other length. Figure 5.20 illustrates how strength decreases with length, and, starting with a normal distribution, the distribution becomes skewed. Peirce (1926) derived the following approximate relation between the mean strengths $\bar{S}_L$ and $\bar{S}_{NL}$ in terms of the percentage coefficient of variation cv:

$$\bar{S}_{NL}/\bar{S}_L = 1 - 4.2(1 - N^{-1/5})(\mathrm{cv}/100) \qquad [5.26]$$

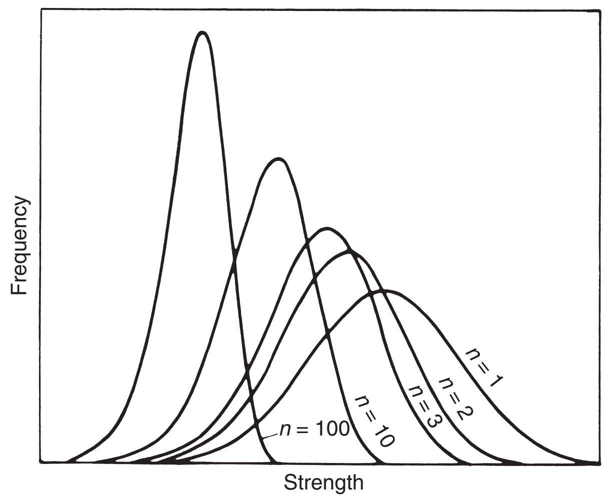


Fig. 5.20 Change of strength distributions with nL, from a normal distribution at $n = 1$. From Morton and Hearle (1993).

For equation [5.26] to be valid, the length L must be long enough not to affect the break load. For example, in a strand of short fibres, there will be a change when the length is short enough for individual fibres to be gripped in two places. A correction is also needed when there is correlation between the strength of neighbouring elements.

Meredith (1952) found that the tenacity of cotton fibres decreased from a mean value of 0.59 N/tex at 0.1 mm to 0.31 N/tex at 10 mm. Even though manufactured fibres are more regular (and may be better now than in 1952), nylon fibres showed a 15% reduction from 0.54 N/tex to 0.47 N/tex.

It is rare to find more than two or three strength tests carried out on a given rope, so that statistical information is limited. Figure 5.21 shows the cumulative distribution for 18 breaks of an aramid parallel-yarn rope at a length $L = 500$ mm (Amaniampong, 1992). If we assume that a longer length of rope was made up of a random sequence of these 18 pieces, the distribution would change as shown in Fig. 5.21. At $100L$, there is a negligible probability that the fibre will break at a strength greater than the weakest of the 18 test values. In reality, of course, there would likely be even lower values in the larger group.

The last comment demonstrates the practical statistical difficulty. Break depends on extreme value statistics. But what are the extreme values? The best that can be done is to fit a set of measured values to some frequency distribution and extrapolate. In real situations, it may be necessary to go from test lengths of metres to use lengths of kilometres, and, even if enough data was available to give the test distribution, it is questionable whether extrapolation would be valid to a probability of 1 in 1000.

Data on strength and fatigue, which follow extreme value statistics, often follow the Weibull distribution:

$$P(S) = 1 - \exp\left[-(S/S_o)^{\rho}\right] \qquad [5.27]$$

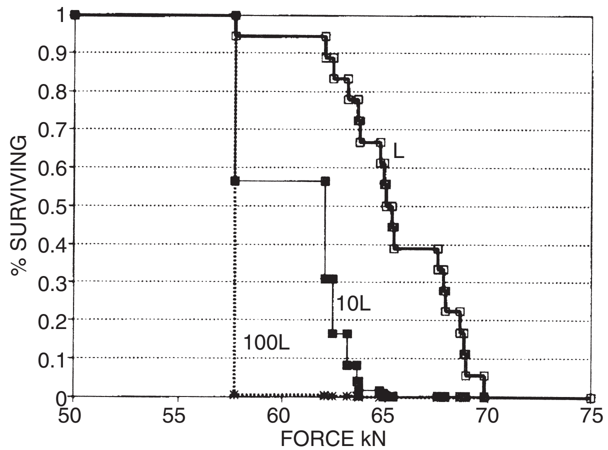


Fig. 5.21 Statistics of failure of an aramid parallel-yarn rope. Points on line L are the experimental values for 18 tests on a length of 500 mm. Points on lines 10 L and 100 L are the hypothetical results with a random selection of specimens from L. From Hearle *et al.* (1992) from data of Amaniampong (1992).

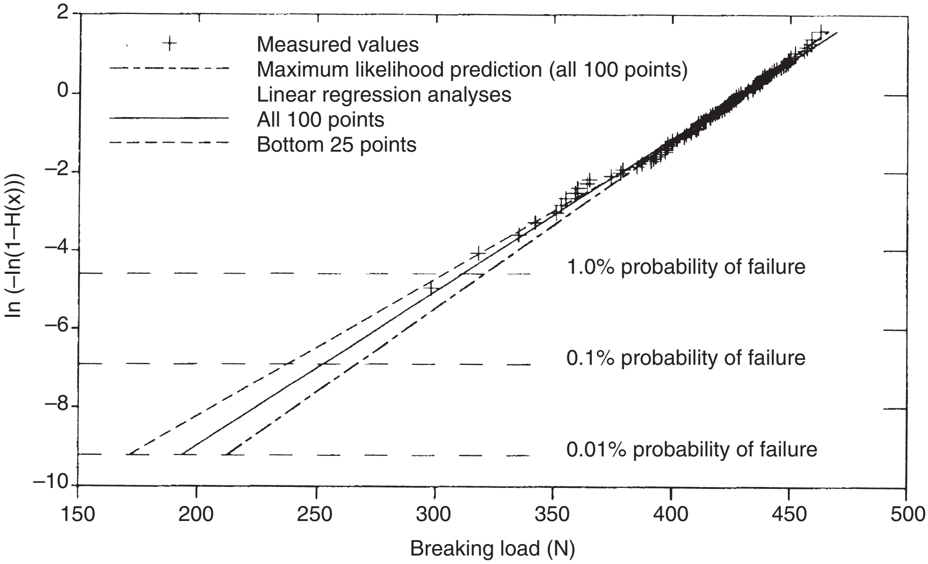


Fig. 5.22 Plot by Amaniampong (1992) of his data on 100 aramid yarn tests in the form of a cumulative Weibull distribution. From Hearle *et al.* (1992).

The Weibull scale parameter S_0 is close to the mean value and the shape parameter ρ varies inversely with the coefficient of variation. This distribution has the advantage that the form is unchanged when the length changes:

$$P_n(S) = 1 - \exp\left[-n(S/S_o)^{\rho}\right] \qquad [5.28]$$

Figure 5.22 shows a plot by Amaniampong (1992) of data on 100 tests of an aramid yarn, *Kevlar 49*, against a function of a cumulative distribution H(x), which would give a straight line if the Weibull distribution is applicable. Except for the very strongest values, the top 75 points fit the Weibull distribution well, but the line diverges for the lower strength values. Depending on the choice of extrapolation, the weakest of 1000 specimens is predicted to be anywhere between 240 and 270 N, which is a considerable uncertainty, compared to a mean value for the 100 specimens of over 400 N.

5.6.3 Strain differences and load sharing

The components in a rope follow paths of different lengths. Ideally, the lengths should be matched so that the components are all at zero tension in the same stress-free state of the rope. In practice, there may be differences either between neighbours following the same paths, as indicated schematically in Fig. 5.23, or in mismatch of different helical paths, so that some fibres will be strained more than others. With zero tension on the rope, some components will be under compression and some will be under tension. The initial resistance to extension will be less than expected for a perfect structure until all components are under tension. Those components that are shorter or less extensible than their neighbours will reach their breaking extension first. Strength will be less than if all fibres were contributing

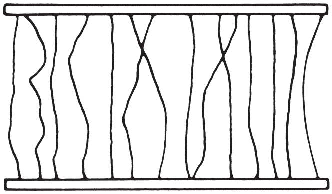


Fig. 5.23 Schematic view of differences in path length. From Morton and Hearle (1993).

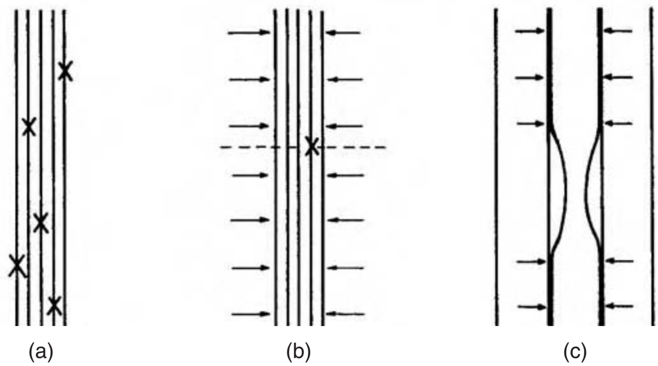


Fig. 5.24 Load sharing in fibre bundles. (a) Independent break of fibres with no load sharing. (b) Break at weakest place of whole bundle, with load sharing. (c) Support of a weak place. From Hearle *et al.* (1969).

equally. This is equivalent to the effects of different component strengths discussed in the next section.

A special case of tension difference in a rope is the action of a tight braided jacket. The circumferential component of yarn tension in the braid causes the tightness. There is also an axial component, which for zero tension on the rope as a whole must be balanced by axial compression of the core.

Compensation for length differences occurs due to creep in HMPE ropes. A taut fibre which is initially taking most of the load, will creep, but slack fibres will not. Consequently, the length differences will effectively be reduced and the load will become more evenly shared.

5.6.4 Load transfer in fibre bundles

The effect of load transfer in bundles of fibres is illustrated in Fig. 5.24, and its consequence was demonstrated practically in Fig. 5.7. With no load transfer, Fig. 5.24(a), as in the zero-twist nylon yarn of Fig. 5.7, each filament is free to break independently. But with load transfer, Fig. 5.24 (b), as in the twisted yarns of Fig. 5.7, weak places are protected, Fig. 5.24(c), and the bundle breaks at its overall weakest place.

The effects without load transfer are shown schematically in Fig. 5.25. Fibres with the same linear stress–strain relation fail at a range of positions along the line, characterised by a distribution of break loads and extensions. After the break of the weakest fibre, the stress falls below the line and the peak load is appreciably less

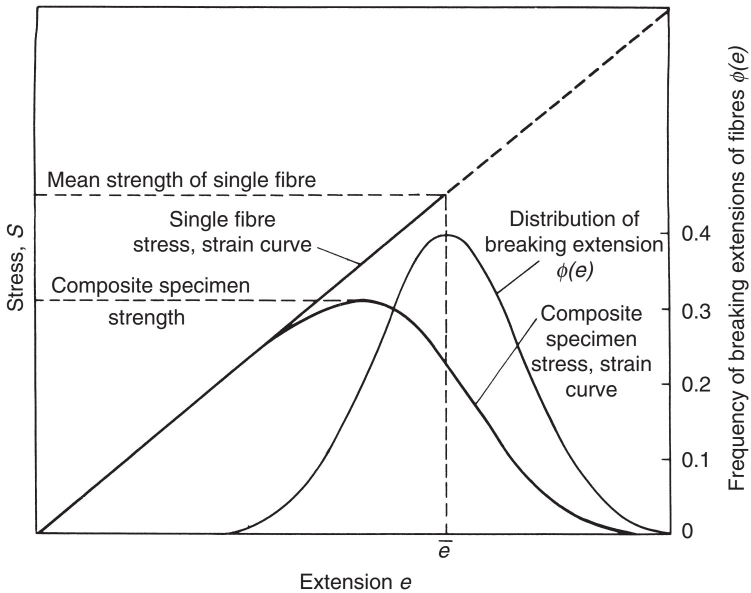


Fig. 5.25 Schematic view of response of an assembly of fibres with the same linear stress–strain relation, but a distribution of strengths and break extensions. From Morton and Hearle (1993).

than the mean fibre strength. Although the lines would look different, the principles would be the same for a nonlinear fibre stress–strain curve of fibres with different moduli. If the initial lengths were different, there would be a decrimping region at the start of the curve, and the length differences would be added to the break extension distribution.

With sufficient interaction between fibres, a weak place, as in Fig. 5.24(c) will not be able to extend locally, but will follow the extension of the whole bundle. Eventually, at some cross-section, a fibre will reach its break extension and fail with a transfer of stress to the neighbours. The load transfer will cause a neighbouring fibre to break next before any more remote fibre. In a short specimen, local extension in the break region may allow the tension to drop after the first break and an increase of load is needed to continue the break process. In a long specimen, there is considerable strain energy stored in the remainder of the specimen, and its tension acts on the break region to cause a catastrophic failure.

The basic principles are clear. The problem, which has led to an extensive mathematical literature, is to understand the load-sharing rules and their detailed consequences. There is an interaction with the weak link effect, because the length of an element that is free to act independently depends on the strength of the gripping forces. Depending on how much slippage can occur, the stress transfer takes place at a reducing level over a finite length. The second fibre break will occur where the increased tension coincides with a weak enough place. A cumulative process of break follows. Unfortunately, because of inevitable idealisation, the theoretical modelling is not easily applicable to the complexities of real ropes.

The above discussion has been presented in terms of fibre bundles, but analogous arguments will apply to variability in any of the sets of components in ropes, such as yarns and strands.

Figure 5.9 showed how, before decreasing in strength due to obliquity, measured yarn strength initially increases with the insertion of twist, due to stress transfer causing the yarn to break at its single weakest place instead of picking the weakest place in each fibre. Similarly, in well-made twisted and braided ropes, the load transfer eliminates the worst effects of variability and measured strengths are only slightly less than the predicted strengths for a uniform structure.

5.6.5 Parallel-yarn ropes

Parallel-yarn ropes do not experience reduction in stress at a given strain due to obliquity. However, their conversion efficiency from yarn to rope is comparable to that of twisted ropes. The problem is variability and lack of stress transfer.

The only source of a transverse gripping force comes in pressure from the jacket and that does not increase with increase in rope tension. Each yarn is free to break at its weakest place, so that the weak link effect is a major effect. For example, for a yarn with a coefficient of variation of 10%, going from a yarn test length of 10 cm to a length of 10 m in a rope test would reduce the mean yarn strength by 17%, according to equation [5.26]. In addition, because of the long slip length, a broken yarn will cease to contribute appreciably to rope strength over a long length. The reduction in peak load below mean break load, as shown in Fig. 5.25, will cause a further reduction in rope strength, which will be made still greater if there are any length differences between yarns in the rope.

5.7 Fatigue and durability

5.7.1 Modelling long-term life

The ultimate failure mode for a rope under load is creep rupture, which is sometimes called static fatigue. However, static design loads in any system intended for long-term use should be such that this might take millions of years. Cyclic loading brings in other forms of damage as described below. The computer program produced by TTI for the US Navy, as described in Section 5.3.1, was extended to cover long-term strength reduction (Hearle *et al*., 1993). The predictions are qualitatively indicative of trends, but many aspects of quantitative prediction are limited by lack of input data on fibre properties.

The basic program will model the response in cyclic loading for a given range and mean load, and, in principle, could assess the damage occurring in a cycle. However, to take a practical example, a 20-year life for a mooring at a wave period of 7 seconds, would cover 100 million cycles. It is clearly impossible to compute what happens in every cycle. The procedure adopted, as shown in Fig. 5.26, is to model a cycle, assume a similar amount of change occurs for a succeeding batch of *n* cycles, and then modify the model before running another cycle. The following sections describe how the various damage modes are included in the program.

5.7.2 Creep rupture

Creep rupture is included in terms of equation [2.1], which is:

$$S = S_g[1 - k\log(t/t_g)] \qquad [5.29]$$

where t is the time-to-break under a load S and t_g under S_g.

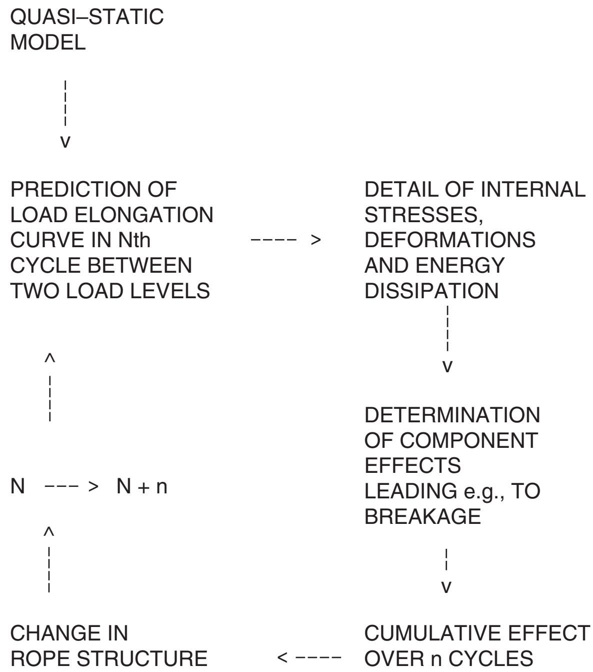


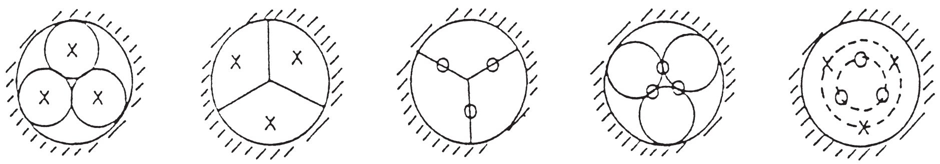
Fig. 5.26 Computing procedure for long-term life. From Hearle *et al.* (1993).

The direct effects of this for a constant load on fibres are shown in Table 2.6, and, by the program described in Section 5.3.1, could be adapted to cover the range of loads on rope components. However, interaction with other modes of failure, which changes the loads on components, requires a more detailed procedure.

Yarn data relates tension to time-to-break, which gives a scaling factor for break load in terms of time under load t_g. A set of modified load–elongation curves, which are scaled by this factor, is produced and used in the cyclic modelling. The polynomial coefficients are unchanged, since the input is normalised by the break load. Experimental data by Mandell (1987) indicates that time-to-break in cycling is the same as if the peak load P had been applied continuously. For a cycling frequency f, $t_g = 1/f$ and the appropriate scaling factor is used for the first cycle, which is assumed to cover the response for the next $(n - 1)$ cycles. For cycle $N = n$, the program puts $t_g = (N/f)$ and a new scaling factor is used. This continues as N increases in each round of computing. Fibre breakage is introduced by checking the loads on components. If any elements experience loads greater than their break load adjusted for elapsed time, their contribution is put to zero, which increases the load on other elements. The consequence is a rapid cumulative loss of strength in the final stages before total rupture. The reduction to zero of the contribution of a broken element is a conservative assumption, since the element will continue to contribute at some distance from the break as described in Section 5.6.4.

5.7.3 Hysteresis heating

The basic program generates the energy loss due to hysteresis in cyclic loading of fibres, based on an input value of tanδ (Section 2.5.5) and losses due to friction.



(a) (b) (c) (d) (e)

Fig. 5.27 Heat generation in a rope during cycling. From Hearle *et al*. (1993).

Figure 5.27 indicates schematically how heat sources are located for modelling in a three-strand rope. Fibre hysteresis losses are treated as single sources at the centroids of components, Fig. 5.27(a),(b). Frictional losses are treated as single sources at contact points or the mid-points of contact lines, Fig. 5.27(c),(d). The combined effect is thus treated as coming from two rings of heat sources, Fig. 5.27(e). The distribution of heat sources would follow the appropriate geometry for other rope constructions.

The movement of heat with time depends on the thermal diffusivity, which equals (density × specific heat/thermal conductivity). If this is taken as constant in a circular rope, Green's functions, which are listed in the literature, can be used to find the change of temperature with time for any location of a point heat source. The effects are additive, so that the contributions from all the point sources can be included. For marine use, it is assumed that the rope surface temperature is equal to the water temperature and that all spaces within the rope are flooded, so that simple averaging gives the thermal diffusivity. For dry ropes, the spaces can be regarded as insulating, and the effective conductivity will depend on the contact paths through fibres. In air, the surface emissivity would have to be introduced to allow for change in the surface temperature.

Rise in temperature alters the load–elongation properties of the yarns and so changes the input to the basic model. The way to introduce this depends on the availability of experimental information on fibre stress–strain curves. In many cases, two parameters can be used to define a linear reduction in break load and increase in break extension, with unchanged polynomial coefficients.

Unless loading conditions are so severe as to melt fibres, increase in temperature is not in itself a source of damage to fibres. However, it interacts with other factors by reducing fibre strength, increasing creep (particularly in HMPE fibres) and so on. Heating can always be reduced by replacing a large rope with more than one smaller ropes. Modelling can be a useful design tool in these circumstances.

5.7.4 Abrasion damage

Internal abrasion has been shown to be a serious problem in highly structured, wet nylon ropes (see Section 4.5.2). Table 2.9 shows that it is a potential problem in aramid ropes, but less so in HMPE or polyester ropes. It is also less severe in low-twist ropes. However, provided axial compression fatigue, external abrasion and structural disturbance are avoided, internal abrasion is the only identified form of damage in cycling over long periods of time.

The wearing away of fibre surfaces or the development of cracks running across fibres results from cyclic shear stresses generated between fibres. In principle, the rate of wear per cycle for a given fibre type is determined by a function of contact pressure, coefficient of friction, magnitude, angle and rate of slip, temperature and moisture content. In practice, such information is not available and an empirical approach is adopted.

A rate-of-wear parameter F is defined for a given contact as the fraction of a fibre lost per cycle under given test or use conditions. In N cycles NF fibres will be lost and will cease to contribute to stress but are assumed to continue to occupy space and to transmit transverse forces. Tensions borne by other fibres are increased. The modelling allows for values of F to be allocated to all contact types.

A simpler global treatment assumes that the overall rate of wear of the rope depends only on maximum tension and tension range, expressed as a function of break load. This enables data from rope fatigue tests to be used. For a given mean load, the cycles to failure N are related to load range X as a percentage of break load by the equation:

$$\log N = a + bX \qquad [5.30]$$

where a and b are constants for a particular rope construction and material.

External abrasion has not been included in the modelling, but the principles and the programming would be similar to those for internal abrasion.

5.7.5 Model predictions

Figure 5.28 is a predicted fatigue plot for a seven-strand aramid rope cycled with a period of 6 seconds between 16% and 45% of its predicted break load when new. The creep rupture and hysteresis heating parameters are estimated from experi-

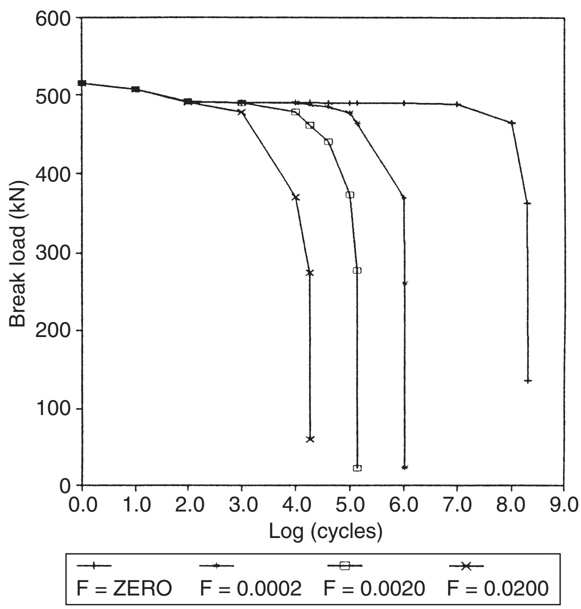


Fig. 5.28 Predicted change in residual strength of a 7-strand aramid rope, taking account of creep rupture, heating, and internal abrasion. From Hearle *et al.* (1993).

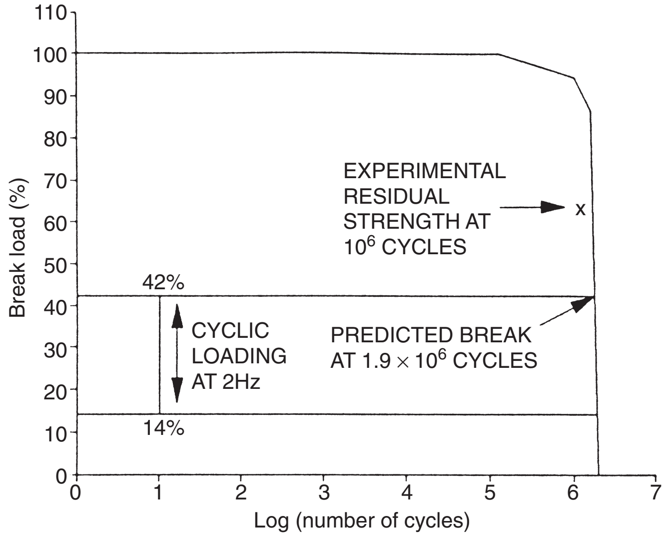


Fig. 5.29 Predicted change in residual strength for a 5-tonne aramid rope, using global abrasion parameters. From Hearle *et al.* (1993).

mental data. Four values for the abrasion parameter F are shown. The decrease in residual strength in the first 100 cycles is due to rise in temperature, which becomes close to constant asymptotic values in about 10 minutes. The predicted equilibrium temperatures are 72°C in the core strand and 32°C in the outer strand. In the absence of internal abrasion ($F = 0$), there is very little change between 100 and 10^7 cycles. Creep rupture then starts for the most highly loaded fibres and increases rapidly as the tensions in the remaining fibres increase. Failure would occur in 1.6 $\times\ 10^8$ cycles or 30 years. As internal abrasion is introduced, with F at 0.0002 (0.02% of fibres at contact points lost per second or 5000 cycles to lose a fibre), 0.002 and 0.02, the decrease in residual strength starts earlier. The final rapid drop is characteristic of fatigue failure and means that it is not possible to extrapolate to failure times from measurements of residual strength by more than about a decade of log cycles. Pathological investigation to observe actual damage may be more useful.

The use of the global abrasion model, with a = 10.009 and b = –0.197, is shown in Fig. 5.29. This matches the experimental observation.

5.7.6 Axial compression fatigue

At low rope tensions, it is possible for some yarns to go into axial compression while the tension is taken by other yarns. Local buckling of the yarns then occurs. This was observed during the extensive fatigue testing in the Fibre Tethers 2000 Joint Industry Study (Noble Denton and National Engineering Laboratory, 1995) in ropes that were cycled to low minimum loads. Close observation of the tests showed two causes. The first cause is rope twisting. In ropes that were not torque-balanced, the test length of rope rotated against the splice, which had a lower torsional resistance than the rope itself. Even with a rigid potted termination, variability in the rope caused local rotations. The second cause was non-uniform loading of rope components, which results from the component lengths put into the rope in manufacturing.

As described in Section 2.5.8, axial compression causes molecular buckling within fibres, which is visible as kinkbands that are most severe on the inside of the places where the fibres have buckled as a whole into sharp kinks. After repeated cycling the fibre fails. Figure 5.30(a)(b) shows that the breaks occur in groups of about 1 cm lengths separated by unbroken regions. Details of the breaks are shown in Fig. 5.30(c)(d). Whole-fibre kinks in fibres and molecular kinks within the fibre are shown in Fig. 5.30(e)(f).

Since the publication by Hearle *et al.* (1993), the computer model has been extended to cover axial compression fatigue (Hearle *et al.*, 1995). The theoretical basis is given in an analysis of the mechanics of buckling of yarns in ropes under axial compression (Hobbs et al., 2000). Earlier studies (Hobbs, 1984; Hobbs and Liang, 1989) had covered the buckling of heated pipelines on the seabed. The tendency to thermal expansion generates an axial compressive force and the pipes buckle elastically against friction on the sea-bed. Two examples, modes 1 and 4, of the many solutions of the differential equations are shown in Fig. 5.31(a),(b). The buckled zones are separated by straight sections, with the excess length in the buckle coming from axial slip. Other solutions have different numbers of buckles in a zone, and the limiting infinite mode is shown in Fig. 5.31(c).

Forces that determine buckling of a yarn in a rope are shown in Fig. 5.31(d). The axial compressive force is P, which pushes a straight portion of yarn into a buckle against a frictional resistance $p\mu\pi d$, where p is the lateral pressure, μ is coefficient of friction and d is yarn diameter. The resistance to buckling comes from the direct

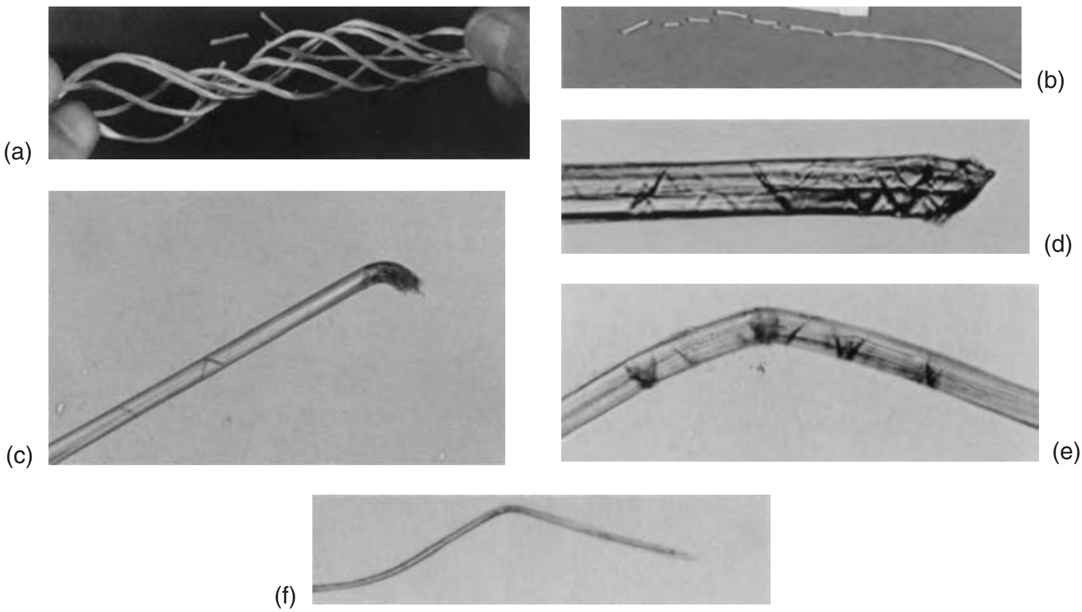


Fig. 5.30 (a)–(d) Centre yarn of core strand in a 5-tonne aramid (*Kevlar 129*) 6-round-1 wire-rope construction after 1 000 000 cycles between 10 and 50% of break load. (a) and (b) Yarn rupture in short lengths. (c) and (d) Fibre breaks. (e) and (f) Internal kinkbands and whole-fibre kink and break from a 5-tonne aramid (*Twaron 1000*) rope after 1 000 000 cycles between 20 and 60% of break load. From Hearle *et al.* (1998).

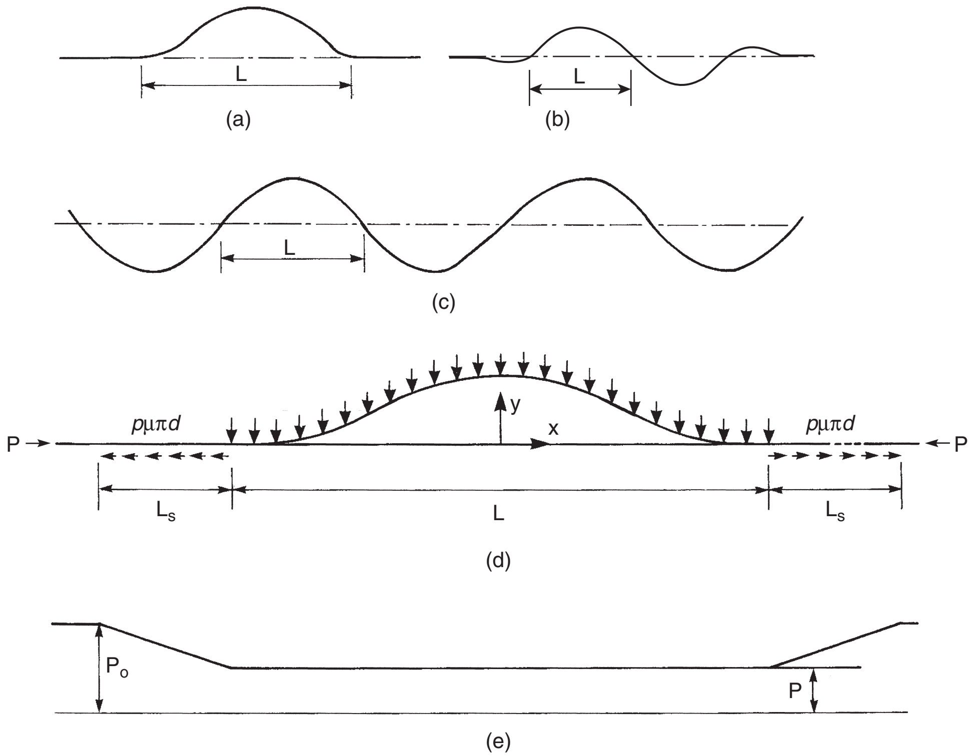


Fig. 5.31 Restrained elastic buckling in axial compression. (a) Mode 1. (b) Mode 4. (c) Infinite mode. (d) Restraining forces. (e) Axial compressive force. From Hobbs *et al.* (2000).

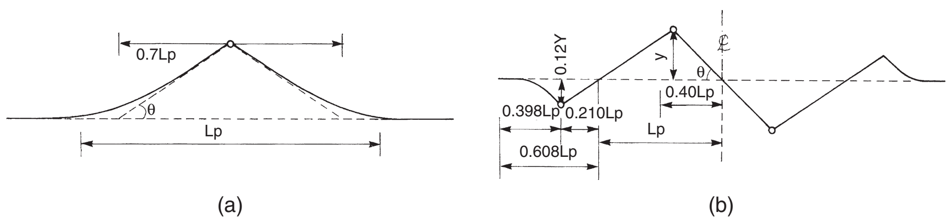


Fig. 5.32 Plastic buckling. (a) Mode 1. (b) Mode 4. From Hobbs *et al.* (2000).

action of the lateral pressure, shown by the vertical arrows. The change in compressive force along the yarn is shown in Fig. 5.31(e).

Because of the nonlinear bending resistance of yarns, the smooth curves of the elastic solutions form a plastic hinge when the position of maximum curvature reaches the yield point in bending. The predicted sharp kinks, shown in Fig. 5.32, resemble those found in ropes that have suffered from axial compression fatigue, as shown in Fig. 5.30. The detailed solution starts with elastic buckling, which leads to the full line ABC in Fig. 5.33 for the variation of buckling amplitude with compressive force. A decreasing region is unstable, so that the solution would snap from A to C. In an ideal case of perfectly straight parallel yarns, it is not clear how the

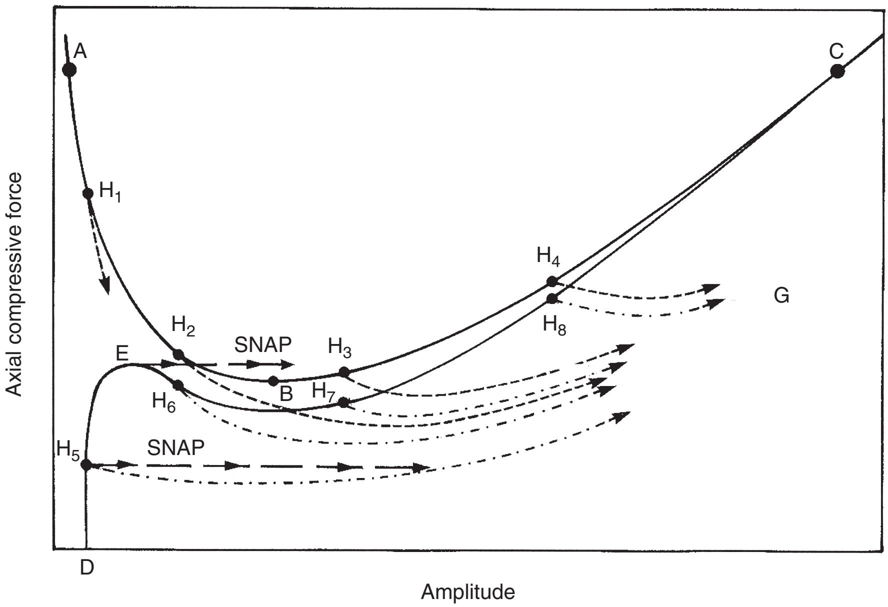


Fig. 5.33 Variation of buckling amplitude with axial compressive force. ABC is for ideal plastic buckling. DEC is for elastic buckling with starting irregularities. The dotted lines are for peeling off of plastic buckles. From Hobbs *et al.* (2000).

initial small buckles at A would form. In reality, there are likely to be some irregularities in yarn paths which provide incipient buckling. Depending on the size of the irregularities, the curve will start from a point such as D and follow DEC. When the severity of buckling reaches the yield point, the plastic solution peels off the full lines of the elastic solution and follows the dotted lines.

Experimental observations indicate that the fibres in a yarn buckle cooperatively. The theory developed by Hobbs *et al.* (2000) was applied to the core yarn of a 6-round-1 aramid wire-rope. This rope had been tested in tension–tension cycling at 38 ± 24% of break load, and found to suffer axial compression fatigue probably due to twisting. The fibres were 1.7 dtex; seven rope yarns, each consisting of seven 1700 dtex textile yarns, made up the core strand. Yarn modulus was taken as 52.3 GPa; its compressive yield stress, which determines the bending yield point, as 0.355 GPa; and the coefficient of friction as 0.15. The radial pressure on the core yarn, which can be calculated from the rope modelling program, was taken as 0.1 GPa for the minimum tensile stress of 0.16 GPa. There is a problem in estimating the bending stiffness of the yarn, which, for the reasons given in Section 5.5, can lie anywhere between 6276 Nmm^2 for the solid rod model with a yield moment of 257 Nmm, and 0.606 Nmm^2 and 2.53 Nmm for the free sliding model. Table 5.4 shows values calculated on the assumptions that the plastic solution peels off at the elastic minimum and at higher and lower values. Although the values cover too wide a range to be useful as quantitative predictions, they are comparable to observed forms and so confirm the basic theory.

For practical utility, it is not necessary to know the detailed form of buckling but just the conditions that lead to axial compression. If yarns go into axial compression, then they will eventually fail, so that the occurrence of axial compression is

Table 5.4 Predictions of axial buckling in an aramid rope assuming that the core yarn goes into compression. From Hobbs *et al.* (2000)

	Solid-rod			Free-sliding		
EI=	6276 Nmm^2			0.606 Nmm^2		
M_P=	257 Nmm			2.53 Nmm		
Half-wavelength (mm)	7.5	8.75*	10	0.25	0.296*	0.35
Buckle amplitude (mm)	1.62	1.87	2.8	0.014	0.027	0.044
Slip length (mm)	9.52	19.7	35.5	1.84	1.84	3.55

* elastic minimum

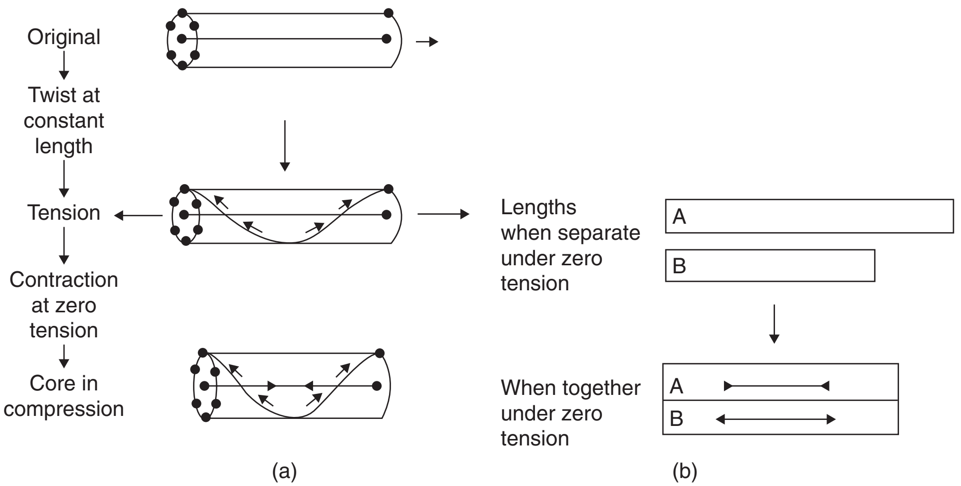


Fig. 5.34 Two causes of axial compression with positive rope tension. (a) Twist. (b) Mismatch of lengths. From Tension Technology International (1994).

the critical factor. Unless there is external restraint, it is not possible to apply a large axial compressive force to a rope because it buckles as a whole. There will be axial compression on the inside of severe bends in ropes. However, axial compression is most commonly found when a rope is under positive, but low tension. Twisting, as shown schematically in Fig. 5.34(a), is one cause. If an assembly is twisted at constant length, the outer paths are increased in length generating tension. If this tension is reduced, the core goes into compression. Starting with a twisted yarn with zero tension in all filaments, over-twisting will put the core into compression, and untwisting will put the outer layers into compression. For more complicated rope structures, the effects will depend on the combination of twists at different levels, but some components will always go into compression. Mismatch of fibre lengths, as shown in Fig. 5.34(b), is another cause. Under zero tension, the longer component will be in compression and the shorter one in tension. A particular manifestation of this is a tightly braided jacket: the axial component of braid yarn tension forces the rope core into compression.

The rope model described in Section 5.3.1 enables axial compression to be detected. Figure 5.35(a) shows the tension–compression boundary for an aramid wire-rope construction for ranges of twist and tension. Note that over-twisting the

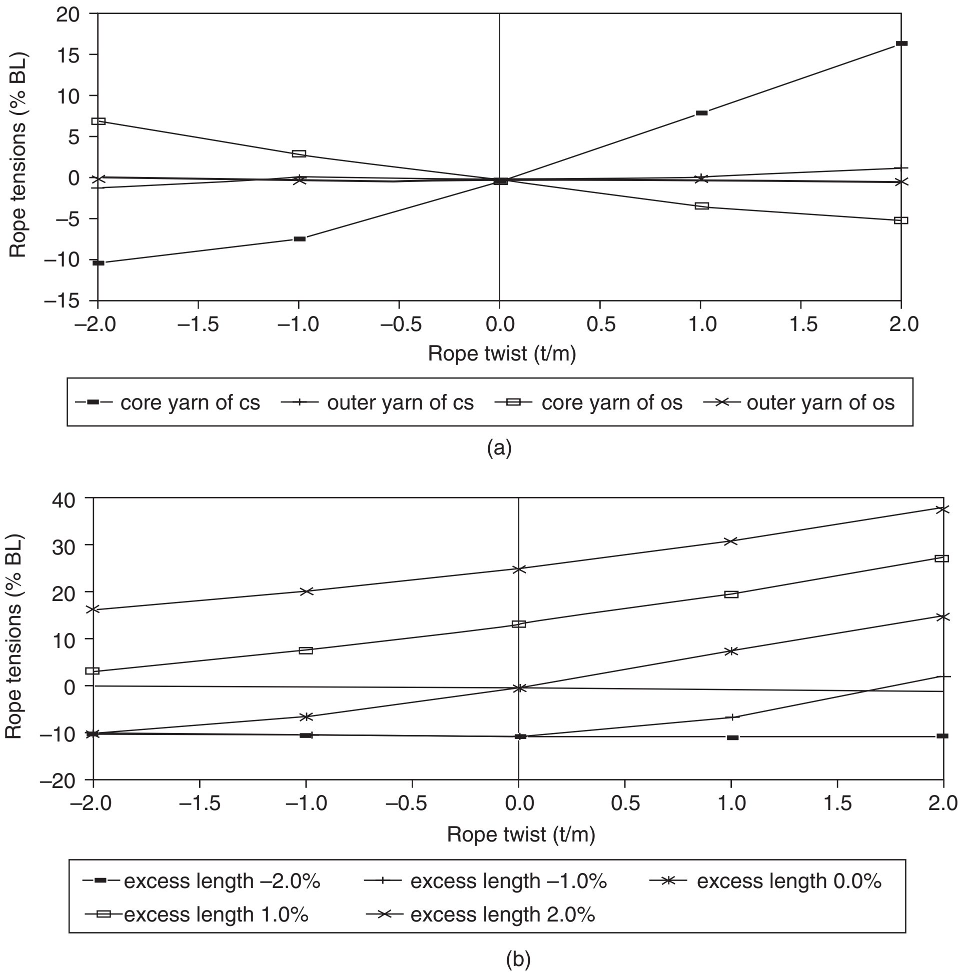


Fig. 5.35 Tension–compression boundary. (a) Aramid 6-round-1 wire-rope construction. Core yarns and outer yarns of core strands (cs) and outer strands (os). (b) Polyester 6-round-1 wire-rope construction, core yarn of core strand. From Hearle *et al*. (1995).

rope means that the core yarn of the core strand will be in compression unless substantial tension is applied. Conversely, untwisting will put the core yarn of the outer strand into compression. The combination of yarn and strand twist means that the boundary for outer yarns remains close to zero rope tension for all twists. Figure 5.35(b) includes the effects of both twist and mismatch of lengths for the core yarn of a core strand of a polyester wire-rope construction. If the yarn has a length 2% greater than the correct length, it will require substantial rope tension to eliminate compression at all twist levels shown. If it is 2% shorter, considerable twist is needed for compression, even at zero tension.

The data in Tables 2.10 and 2.11 show that axial compression fatigue is most severe in aramid fibres, less so in HMPE, and still less in polyester. Figure 5.36 shows kinks in HMPE ropes after cycling to low tensions. Polyester showed minimal kinkbanding, even after 1 000 000 cycles. Well-made ropes, which avoid inequalities

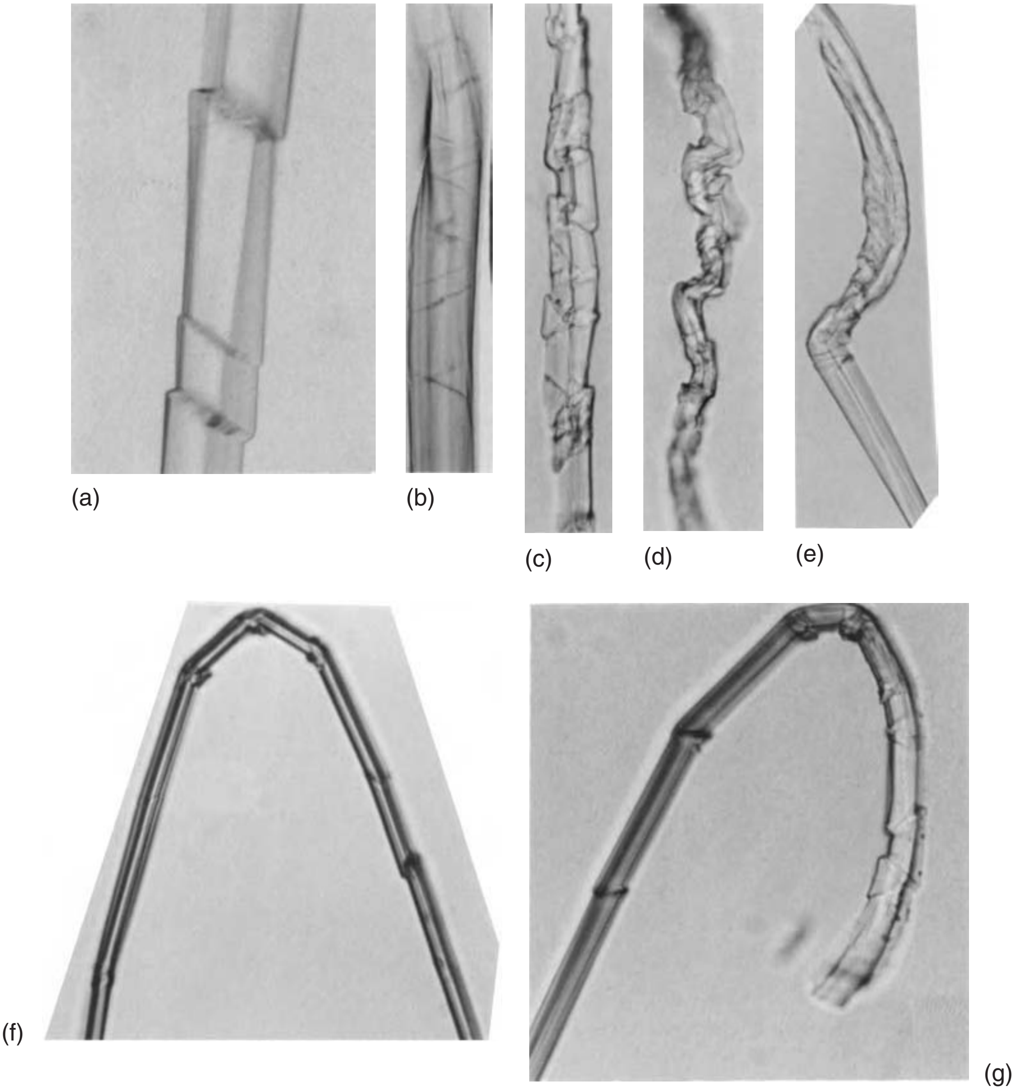


Fig. 5.36 (a) and (b) Kinks due to axial compression in HMPE *Spectra 900* wire-rope construction after 1 000 000 cycles between 25 and 50% of break load. (c)–(g) Kinks in HMPE *Dyneema* wire-rope construction after 1080 cycles between 10 and 70% of break load. From Hearle *et al.* (1998).

in tension, and care in use to avoid twisting, will give a lower incidence of axial compression fatigue. This can then be avoided by maintaining a high enough rope tension and ensuring that ropes are not cycled to low tension for more than a limited number of cycles.

5.8 Hockling and snarling

When a rubber rod is twisted, tension is needed to hold it straight. If it is released, it buckles into a snarl, usually as shown in Fig. 5.37(a), though at high twist levels a

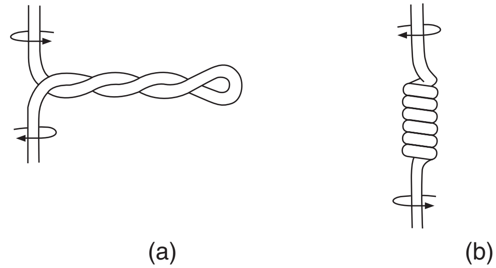


Fig. 5.37 (a) Normal snarling of a twisted rod. (b) Cylindrical snarling at very high twist. From Hearle *et al.* (1998).

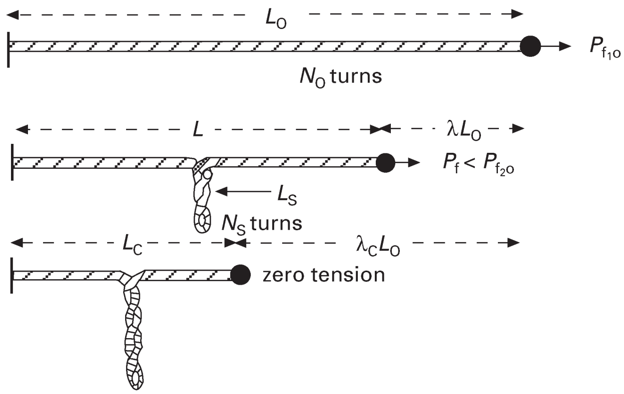


Fig. 5.38 Snarling in a twisted rod at reducing tension. λ is extension ratio. From Hearle *et al.* (1998).

cylindrical snarl, Fig. 5.37(b), forms. If the twist imparted in making a rope, or its components, is not balanced, it will be twist-lively and may buckle into a snarl like Fig. 5.37(a). More commonly, this occurs when a rope is twisted during handling and the normal snarl is called a 'hockle'.

The mechanics of snarling has been worked out in connection with stretch yarns made by twisting, setting and untwisting (Hearle *et al.*, 2001). Figure 5.38 shows the change from the straight rod to the full snarl under zero tension. Each turn of the snarl removes one turn of twist from each end of the rod, but because the snarl has a helix angle θ, the net effect is a reduction in twist of $2\cos\theta$ turns. The twisting energy is reduced, but acts against an increase of the potential energy of the applied tension and the development of bending energy in the snarl. The relation between tension and reduction in length (twice the length of rod in the snarl) is given by minimising the total energy U, where:

$$
\begin{aligned}
U &= \text{potential energy} + \text{twist energy} + \text{bending energy} \\
&= P_f(L_0 - L) + U_T + U_B
\end{aligned}
$$

The symbols are shown in Fig. 5.38. Details of the energy minimisation and the predicted changes are given by Hearle (1966) and Hearle and Yegin (1972a,b, 1973).

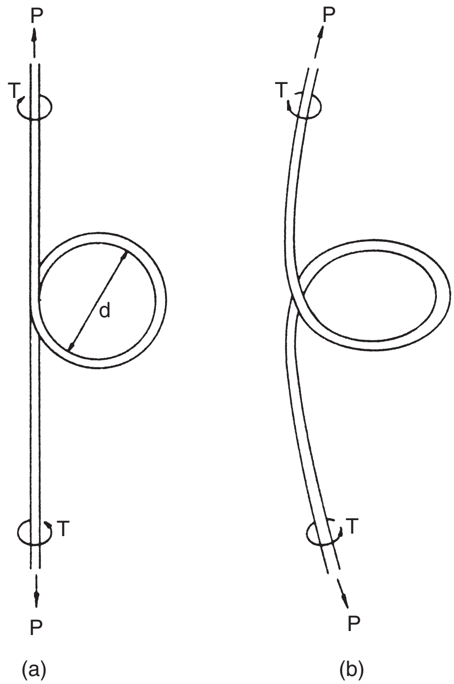


Fig. 5.39 Kinking of a twisted cable. (a) Loop shape assumed for analysis. (b) Actual loop shape. From Ross (1977).

A number of studies have been made of kinking and loop formation in marine cables and umbilicals (Liu, 1975; Ross, 1977; Tan and Witz, 1992, 1993, 1995; Yabuta *et al.*, 1982). Figure 5.39 shows a theoretically assumed loop shape and an actual loop shape for the initial kink, which forms before the development of the full snarl.

5.9 System effects

5.9.1 Length effects and interaction with terminations

The mechanics of ropes themselves would be fully covered by the theoretical or experimental analysis of the total deformation response of a representative test length, taking account of time and environmental effects. Other aspects of mechanics involve the whole rope system and the interactions between ropes and other components. Some aspects of system mechanics are covered in the following sections.

Figure 5.40 is an illustration used by DSM to show the superiority of fibre ropes over steel; much longer lengths can be used without the rope breaking under its own weight. In practical situations the external load will reduce the maximum length, which will also be influenced by system geometry. The maximum span of a suspension bridge with steel cables is believed to be about 2.5 km, but fibre cables could be used for much longer spans. The effects are much greater in water, where polyolefin ropes, including HMPE, are buoyant, and other ropes will have effective densities of less than 0.5 g/cm^3, which would at least treble the break length.

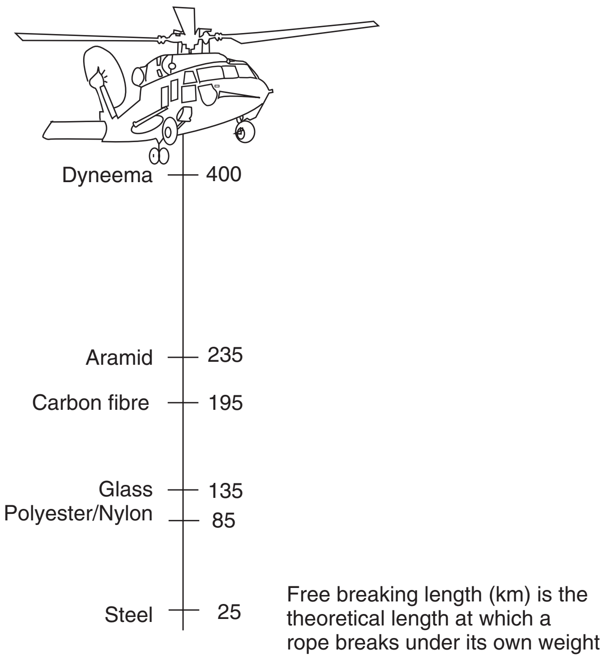


Fig. 5.40 Breaking of ropes under their own weight. From van Dingenen (2001).

Buoyancy forces, based on Archimedes' Principle, serve to reduce the effect of weight on freely hanging ropes, including catenaries. However, the situation is different for a taut rope anchored to the sea-bed. The equations are simplest for a vertical rope, as shown in Fig. 5.41, but would apply with modifications to angled moorings. An element dh of the rope under a tension T will be subject to a net vertical force dT, a weight mgdh, where m is the linear density of the rope, and a tranverse hydrostatic pressure ρgh, where ρ is the density of water. In the vertical direction:

$$\mathrm{d}T = -mg\mathrm{d}h \qquad T = T_1 - mgh \qquad T_1 - T_0 = mgH \qquad [5.31]$$

where T_1 = tension at surface, T_0 = tension at sea-bed, and H = total length.

There is a difference mgH between the tension at the top and bottom of the rope, just as there would be in a rope hanging freely in air. For a 1000-tonne break load, 23 kg/m, polyester rope, this would contribute 2.3% of break load per 1000 metres. At 1000 m depth, the hydrostatic pressure is 100 Mpa, which is about 10% of the strength of nylon and polyester yarns, so that there is not likely to be any appreciable change in fibre properties. However, there will be a Poisson's ratio effect. Since the transverse force acts in two perpendicular directions, the contribution to axial strain will be $2\sigma(\rho gh/E)$, where σ and E are the Poisson's ratio and modulus in the transverse direction, respectively.

The problems of estimating the reduction in strength in long rope lengths due to the weak link effect have been discussed in Section 5.6.2. In a system, it is necessary to consider the rope plus the termination. It is common in testing, for failure to occur at a termination. This does not make the test useless as a measure of rope strength because it does provide a lower bound. However, the situation is different

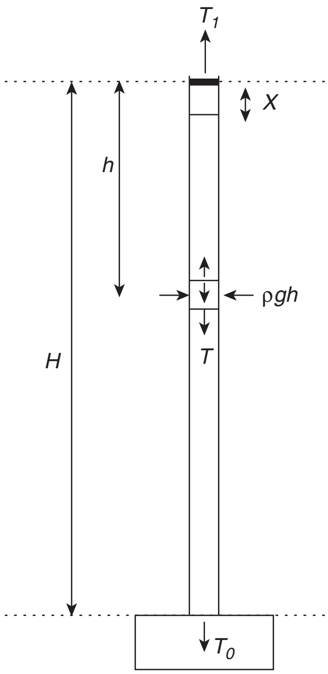


Fig. 5.41 Forces on a taut rope anchored to the sea bed. From Hearle and Parsey (1997).

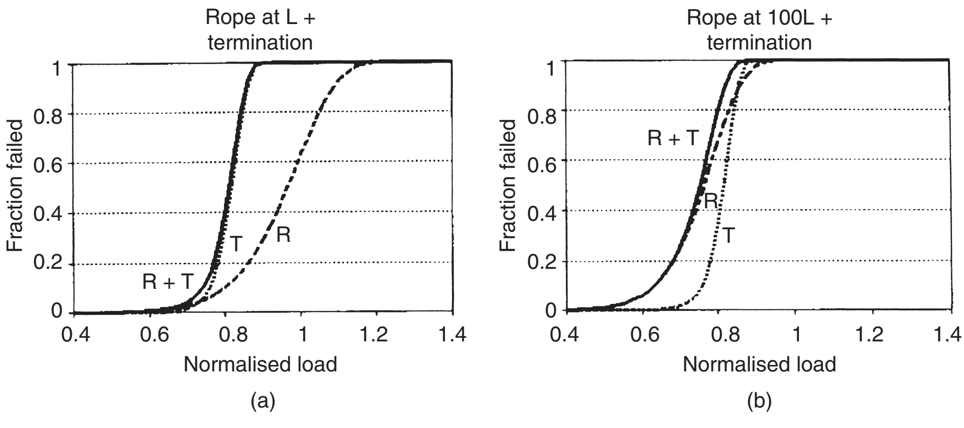


Fig. 5.42 Combination of distributions of strength in rope and termination. (a) For length L. (b) For length $100L$. From Hearle *et al.* (1992).

for long lengths in use. Figure 5.42(a) shows hypothetical distributions of strengths in a rope of test length L and a termination. Only for a combination of an uncommonly high termination strength with an uncommonly weak rope specimen would failure occur in the rope. The combined distribution closely follows that for the termination. However, for a rope length of $100L$, Fig. 5.42(b), the position is reversed. The weak-link effect reduces the strength distribution and rope failure becomes dominant.

5.9.2 Torque and twist in systems

If a rope is tensioned between grips that are not free to rotate, the development of torque is not an important effect. However, unless there is torque balance, there will be twisting if the rope is in series with other components, such as chain or wire rope, or if the termination is free to rotate.

A linear model of two components of lengths L_1 and L_2 in series, Fig. 5.43(a), can be defined by treating the tension and twist effects as independent:

- contribution of tension T to torque = k_1T_1 and k_2T_2
- contribution of twist n in turns per unit length to torque = K_1n_1 and K_2n_2, with right-handed (S) twist taken as positive.

Suppose that the lack of torque balance causes the junction of the two components to rotate by N turns in the positive direction for L_2. For equilibrium, $T_1 = T_2 = T$, and equality of torque gives:

$$k_1T_1 - K_1 N/L_1 = k_2T_2 + K_2N/L_2 \quad [5.32]$$

Hence:

$$N = (k_1 - k_2)/[(K_1/L_1) + (K_2/L_2)] \quad [5.33]$$

$$n_1 = -(k_1 - k_2)/[K_1 + (K_2L_1/L_2)] \quad [5.34]$$

$$n_2 = (k_1 - k_2)/[(K_1L_2/L_1) + K_2] \quad [5.35]$$

The twist, which is a potential source of damage, increases with the difference in the torque/tension response of the two components of the system and decreases with increased resistance to twisting.

For a rope plus a soft termination, Fig. 5.43(b), the termination length is constant, so that we can put $(K_2/L_2) = K_3$, the torque/twist response of the termination. This gives:

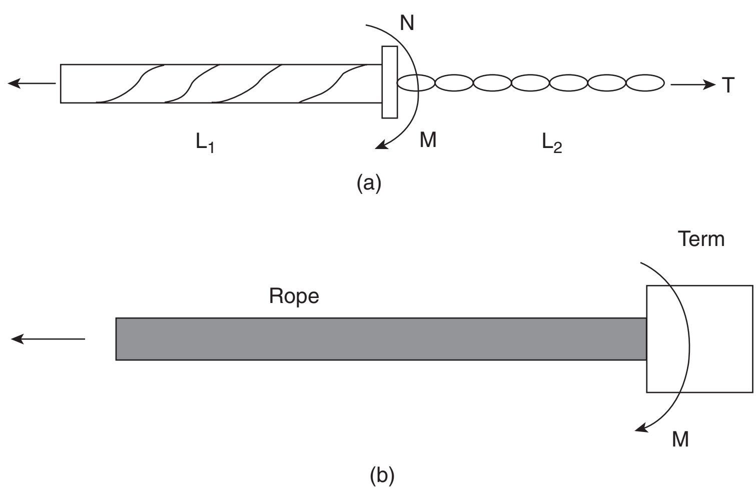


Fig. 5.43 (a) Two components in series with unbalanced torque relations. (b) Rope plus termination. Note that this may be regarded as a half-length with two identical terminations; or as a full length with a rigid opposite termination; or as a full length with lumped parameters.

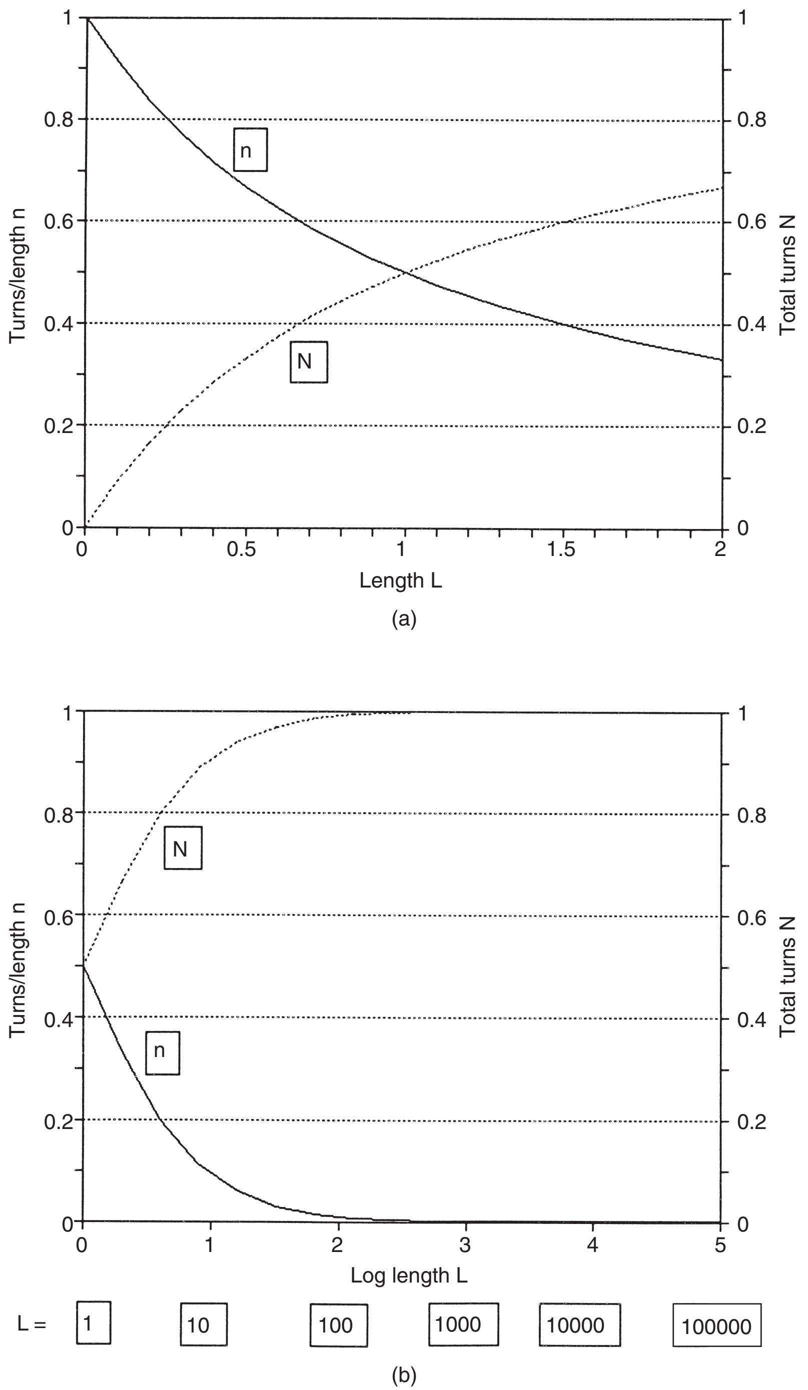


Fig. 5.44 Predicted total turns N and turns per unit length n for a rope plus termination with unit values for parameters. From Noble Denton and National Engineering Laboratory (1995).

$$N = (k_1 - k_2)/[(K_1/L_1) + K_3] \tag{5.36}$$

$$n_1 = -(k_1 - k_2)/[K_1 + K_3 L_1] \tag{5.37}$$

Figure 5.44 shows a normalised calculation of turns and twist. As the rope length increases, the total number of turns increases, but the twist in the rope decreases asymptotically to zero. This means that the effect in the rope will be more severe in short test lengths than in long lengths in use.

A more complete analysis of these effects, which includes axial strain e, would be based on the full interaction of tension, torque, extension and twist:

$$T = a_1 e + b_1 N \qquad M = a_2 e + b_2 N \tag{5.38}$$

More generality still would come from replacing the linear terms by nonlinear functions, $T(e,N)$ and $M(e,N)$, which include cross-terms.

6

Rope production

6.1 Introduction

6.1.1 The sequence of rope production

At its very simplest, making a rope consists of plying yarns, often by twisting, and re-twisting the plied yarns together to make sub-structures such as strands. These in turn are assembled and twisted or braided into ropes. Finally, in some ropes an external jacket is provided, generally by braiding, but occasionally with an extruded plastic jacket or even a combination of both. The basic steps in making a rope can thus be listed as follows:

- Yarn manufacture ('textile yarns' or other starting material)
- Plied yarn assembly ('rope yarns')
- Strand manufacture
- Rope manufacture.

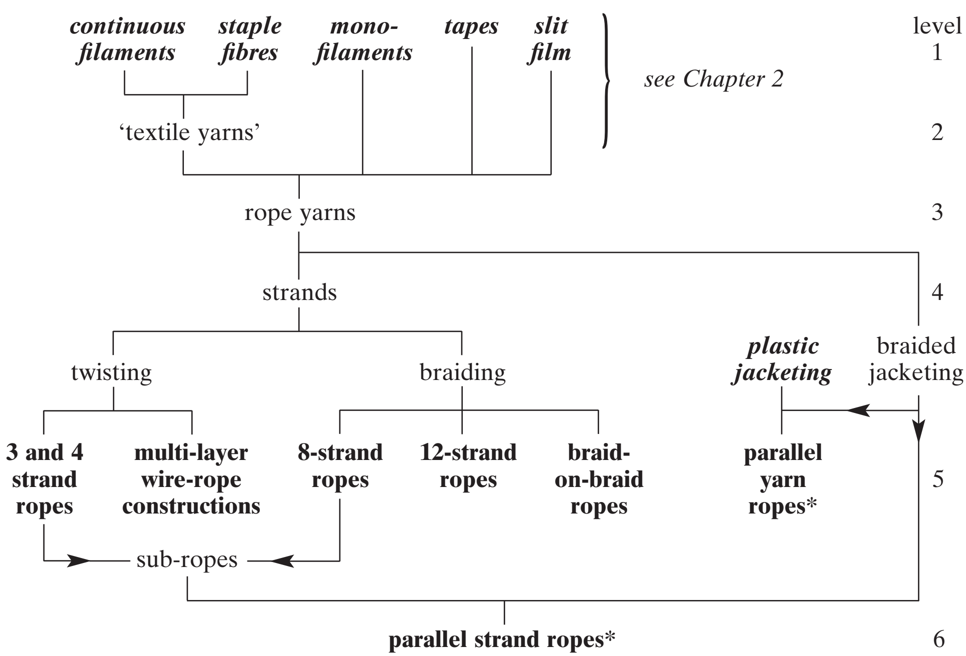
There are variants for different rope types, and Table 6.1 shows the routes to the principal modern ropes, whose construction is described in Chapter 3.

6.1.2 Starting materials

The starting materials for rope production, which were described in Chapter 2, are yarns (usually called textile yarns in the rope industry), monofilaments, tapes or slit film. Most of the yarns used by the rope industry are multifilament yarns, which are composed of synthetic fibres in the form of continuous filaments. There is still some use of traditionally spun textile yarns, which are made by assembling short natural fibres (staple fibres), with some use of synthetic staple, which is converted into yarns in a manner similar to spinning natural fibre yarns (Section 2.2.5).

The start of production is dictated by the form of packaging of the fibre material. Most commonly, major fibre suppliers wind yarns onto single-end, cross-wound packages, 20 kg being typical, and these may or may not be on tubes. The single-end packages must be set up on racks (creels) to feed the twisters. Alternatively,

Table 6.1 Principal production routes for modern ropes. (***Bold italic*** are starting materials; **bold** are final ropes)



* jacketing essential to rope construction; optional for other rope types.

multiple-end beams with 144 or more yarns are supplied; a beam may weigh 700 kg. If polypropylene is produced from an in-house extruder, it may either be wound on packages or fed directly into rope-yarn twisting.

6.1.3 Twisting theory and practice

Surprisingly the theory of rope manufacturing is not simple. There are a number of issues related to twisting, of which the most vexed question is that of backtwist. The principles are described in this section, ahead of their applications in rope manufacturing.

Twist can be either left-handed or right-handed. In the textile industry, these are referred to as S or Z twist, as illustrated in Fig. 6.1. Most commonly, successive twisting operations alternate twist directions. Ropemaking involves twisting textile yarns into rope yarns, rope yarns into strands, and strands into ropes. These operations can be carried out either by up-twisting, in which the supply is rotated, or down-twisting, in which the take-up is rotated.

Figure 6.2(a) shows ring-spinning as it is used in the production of cotton and other staple fibre yarns (see Section 2.2.5). The front drafting rollers feed the supply roving into the system. Twist is inserted by rotation of the bobbin at high speed. To a first approximation, one turn of the bobbin inserts one turn of twist into the yarn. However, in order to wind the yarn onto the bobbin, the traveller rotation lags behind the rotation of the bobbin. The twist inserted is therefore slightly less than that given by (bobbin rotation in r/min)/(yarn speed in m/min). When ring spinning

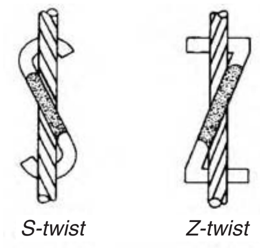


Fig. 6.1 Left-handed S and right-handed Z twist. From Denton and Daniels (2002).

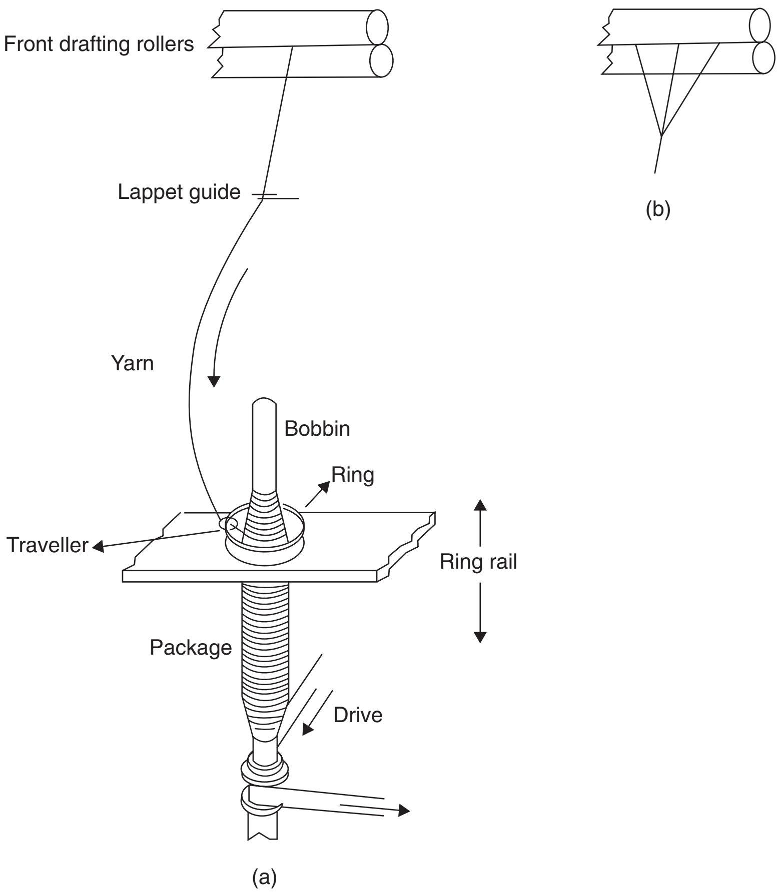


Fig. 6.2 (a) Ring-spinning for staple fibre yarns. From Grosberg and Iype (1999). (b) Feed when twisting yarns together.

is used to assemble textile yarns into a rope yarn, the several ends will be fed together into the system, as shown in Fig. 6.2(b). The rotation of the wind-up package then not only twists the yarns together but also twists the yarns themselves. If the rope yarn twist is in the opposite sense, the textile yarn twist within the rope yarn will be reduced from its supply value; conversely, if the twists are in the same sense, it will be increased.

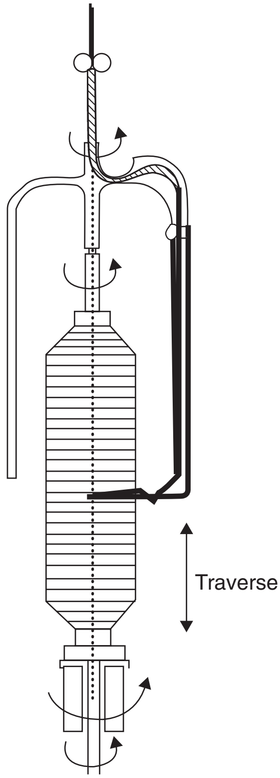


Fig. 6.3 Flyer spinning. From Grosberg and Iype (1999).

A variant of ring-twisting is flyer-twisting, Fig. 6.3. The incoming yarns are fed through a guide in a rotating flyer. It is the flyer that is driven, so that the twist is correctly given by (flyer rotation in r/min)/(yarn speed in m/min). The take-up package rotates at a slower speed, either controlled directly or held back by a friction brake, in order to wind up the rope yarn or strand. As with ring-spinning, twist in the incoming yarn is changed.

The above methods are forms of down-twisting, in which the take-up package is rotated. In uptwisting, the supply package is rotated; the basic principle for a singles yarn is shown in Fig. 6.4. The supply bobbin is rotated and the twisted yarn is fed to a simple wind-up package. In order to twist together a number of yarns or strands, the supply packages are mounted on frames or in cages that are rotated, as shown in later pictures of rope-making machinery. Each rotation of the supply system inserts one turn of twist.

A major advance in the twentieth century was the invention of two-for-one twisting. This is illustrated in Fig. 6.5. The two-for-one operation is described by Grosberg and Iype (1999) in the following way:

> The supply packages are maintained in a stationary position. The supply yarns pass through guides mounted on freely rotating arms and through the hollow rotating spindle, at the base of which they pass through an eyelet and onto the winding head. Each rotation of the spindle inserts one turn of twist in the length

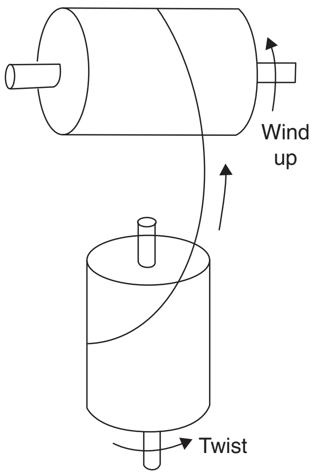


Fig. 6.4 Uptwisting.

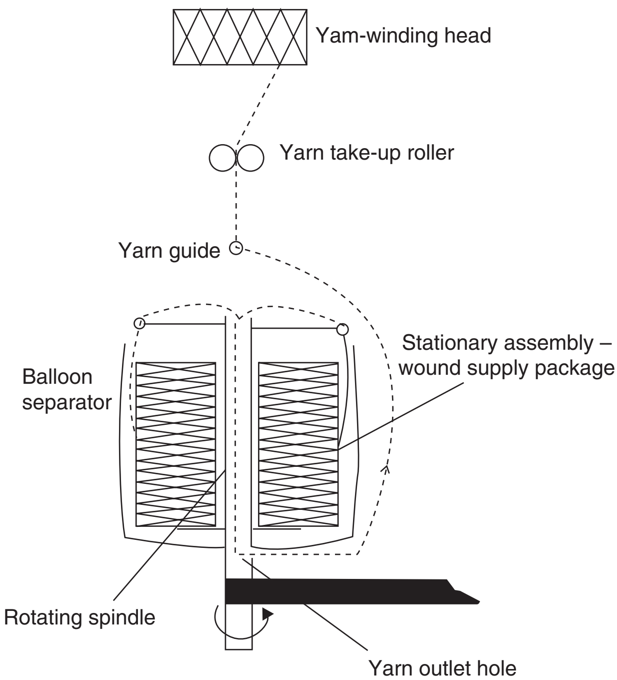


Fig. 6.5 Two-for-one twisting. From Grosberg and Iype (1999), slightly modified.

of yarn within the spindle. The rotating eyelet on the spindle also inserts one turn of twist simultaneously on the length of yarn leading to the take-up rollers by forming a balloon. Thus two turns of twist are inserted for every spindle revolution.

As described above, the simple action of twisting a number of components together also puts twist into the components themselves. This added component twist is usually undesirable, so machines have been developed that avoid it. Backtwist is the process that removes the added twist. The supply package is rotated in such a way as to neutralise what would otherwise be the added twist.

In rope making there are two basic types of machine: those that give backtwist and those that do not. The difference is shown schematically in Fig. 6.6 for the notional twisting of two yarns together, Real examples are stranders, such as those shown later in Figs. 6.12 and 6.13. The bobbins could be either fixed on a stationary base as in Fig. 6.6(a) or, alternatively, rotated by gearing to the main twisting head, as shown in Fig. 6.6(b). Without backtwist, approximately one turn is applied to the yarns (or whatever is on the bobbins) for each turn of the cage. This will add or subtract from the twist already present in the yarns. If, as is usual, the yarns are twisted in the opposite direction, they will be untwisted by this step. With backtwist, the added twist, which would result from stranding, is more or less eliminated. Failure to provide backtwist means that the filaments in the yarns will not share load properly. If the product on the bobbins is a 3 or 4 strand cord, then the untwisting will bear equally on each of the strands. There will, of course, be some slight untwisting of each of the strands, and, if these are concentrically twisted yarns, then there will be some small reduction in load sharing. Clearly, the lower the elongation at break the greater is the impact of the absence of backtwist.

The precise amount of backtwist required is dependent on the helix angle in this operation. Its calculation requires an understanding of the geometry of multiple helices, which is not simple. A mathematical treatment of back-twist is given in Appendix IV.

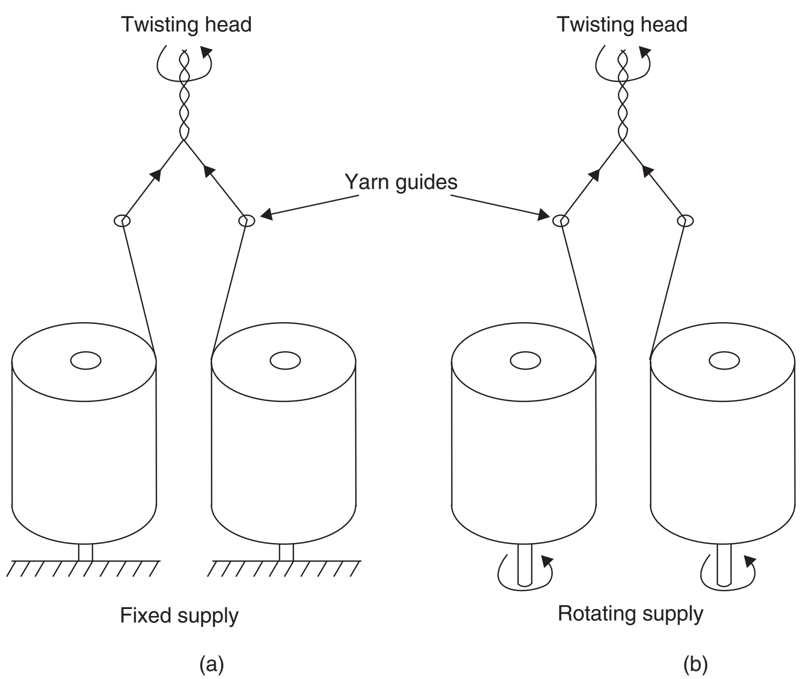


Fig. 6.6 Notional twisting of two yarns. (a) Without backtwist. (b) With backtwist.

A final complication to note about twisting is the effect in winding and unwinding. This is important not only in rope production, but also in rope handling. If the yarn, strand or rope is wound on or off axially with rotation of the package, as shown for unwinding in Fig. 6.7(a), there is no change of twist. However, if it is pulled off or fed to a rotating wind-up over end, as in Fig. 6.7(b), one turn of twist will be inserted for every turn on the package. Similarly, twist may or may not be inserted in coiling ropes.

6.2 Production of rope yarns

6.2.1 Assembling textile yarns

Whether the textile yarn is continuous filament or produced from staple, its size is too small for most rope manufacture. Rope yarns can be assembled either by twisting or by winding the yarns together to form a parallel roving. As a general rule, twisting is better since it gives the assembled rope yarn some structural integrity and preserves its strength. The outer helix angle of the rope yarn is generally around 5° to 10°, as shown in Fig. 6.8. Most commonly, the whole set of textile yarns is combined into a rope yarn in a single operation. However, sometimes it is carried out in two stages, first and second twist. For example, rope yarns for three-strand laid and eight-strand plaited ropes may be made by plying three first twist yarns together in a fly twister.

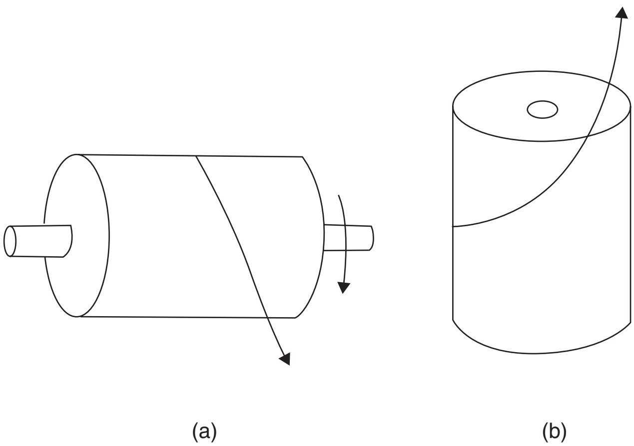


Fig. 6.7 (a) Unwinding straight off a rotating package. (b) Pulling off over end from a stationary package.

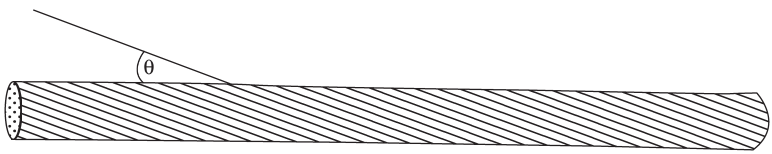


Fig. 6.8 Rope yarn showing outer helix angle.

6.2.2 Ring twisting

A few textile yarns can be plied together into rope yarns on a ring twister, Fig. 6.9 (also see Fig. 6.2). This machine is very suitable for the twist in making small cords for applications as diverse as tyre reinforcement to trawler nets. It is also commonly used to produce the first twist for small braided ropes, for larger ones that have a large number of small strands, or for braided jackets that often have small strands.

A ring twister has no backtwist and feeds all the yarns in at the same length. These machines are fast. Even old machines run at 3000 r/min and modern machines at twice that speed. Ring twisters have a bank of stations, up to 40 or 50 on each

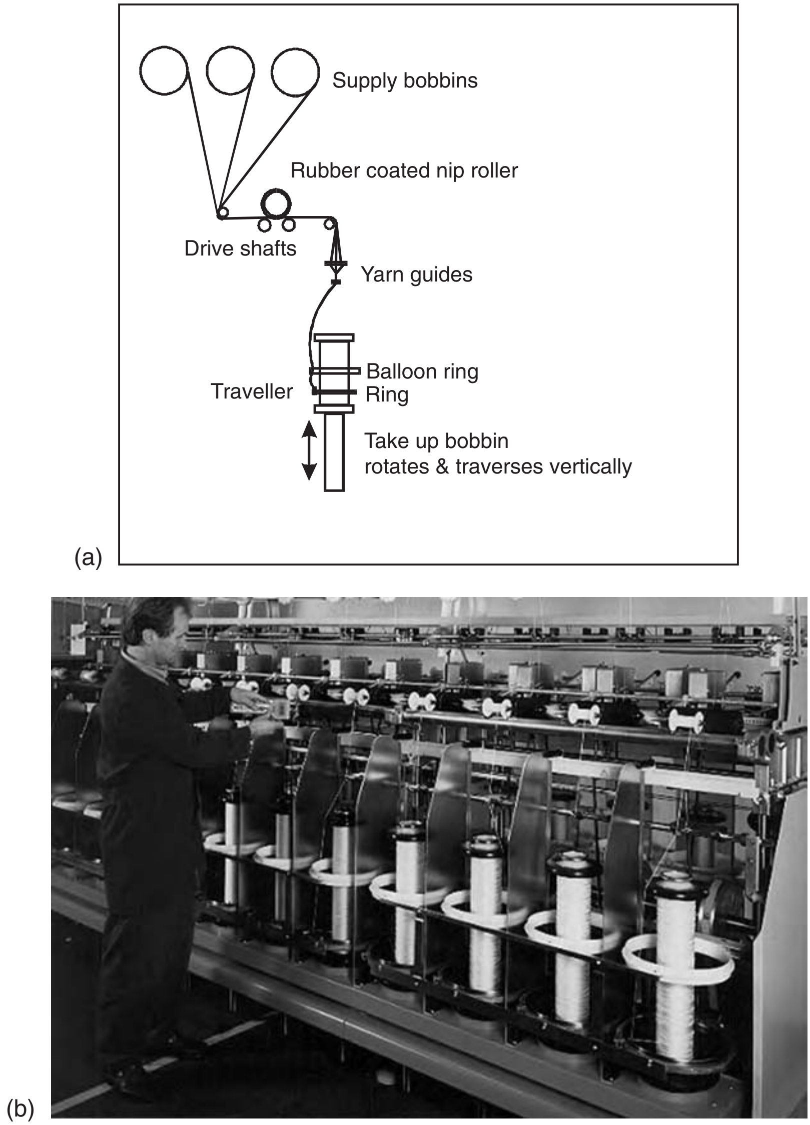


Fig. 6.9 Ring twister. (a) Schematic arrangement. (b) Typical commercial machine. Reproduced by courtesy of Saurer-Allma.

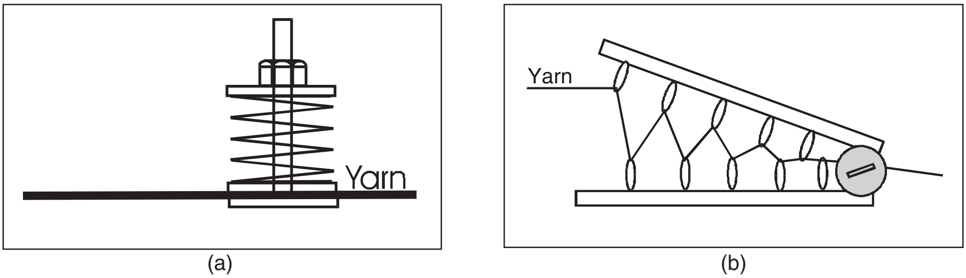


Fig. 6.10 (a) Disc-and-post yarn tensioner. (b) Spring-loaded ring capstan tensioner.

side, and are good for plying several yarns together at each station. The machine works by rotating the take-up bobbin and feeding the yarns at a metered rate. This gives the twist level. For example, if the machine is rotating at 3600 r/min and the yarn is fed in at 60 m/min, then the twist will be 60 turns per metre. In fact, the twist will be slightly less than this because a few turns per metre are required to wind the yarn up on the take-up bobbin. The complete absence of backtwist means that twist will be introduced into the individual textile yarns and this helps if it is required to separate the yarns later, for example, for strength testing.

Because of the creel size and yarn routing, it is generally not very practical to twist many more than a few yarns together on a ring twister and even this may involve using only alternate twisting stations. Nevertheless, it is an extremely fast and very economical method of yarn assembly.

Generally, ring twisters are used to twist from 2 to 4 yarns together. The fact that all the yarns are fed into the machine with the same length means that the assembled yarn loses strength if the structure has more than one layer, which would occur, for example, if a manufacturer needed to assemble nine textile yarns into a rope yarn. This is because the yarns in an outer layer have a longer path and would need to be longer to share load evenly. In practice, the yarns in all the layers are the same length, so that, as load is applied, the outer layers pick up load first whilst the inner layers are still slack. Twisting more yarns together pushes one or more of the yarns into a separate layer, although migration can cause an interchange of position. The simple analysis is based on the assembled yarns forming a round structure. If the twist is kept low, under load the assembly forms into a twisted ribbon rather than a round rod. This mitigates the effect of all the yarns having the same length.

An important detail is the yarn tensioning. There are several different kinds of tensioner including even a magnetically-braked sheave. The standard disc-and-post tensioner works well, provided that excessive yarn deposits from finish or residue are not allowed to build up and that the yarn tensions are checked to ensure that they are reasonably even. A very good arrangement is to pretension the yarn with the disc-and-post tensioner, Fig. 6.10(a), and then to give the final tension with the ring capstan, Fig. 6.10(b). Each station on the ring twister requires separate tensioners.

6.2.3 The flyer twister

Many yarns can be twisted together on a flyer twister (see Fig. 6.3). This machine has no backtwist, but draws off yarns to the required length and, because of this, can be used to twist many yarns at higher helix angles without losing as much strength as with a ring twister. Flyer twisters, like ring twisters, can also be arranged in a bank of multiple stations with a single drive. Yarns are fed to a flyer twister from a creel which should use individual yarn tensioners. It is generally better to ensure that the yarns are guided over small rotating plastic pulleys rather than stationary guide rods. This cuts down yarn abrasion and reduces yarn deposits. It is quite reasonable to assemble 50 to 100 yarns with a suitable size flyer twister. Depending on its size, the speed of rotation could be around 2000 r/min. The principle of operation of the flyer twister is very similar to that of the ring twister. For each rotation of the flyer there is one yarn twist. Unlike with the ring twister, the take-up bobbin does not rotate and the assembled yarn is wound up by the action of the flyer.

6.2.4 The two-for-one or double twister

As a general rule, the two-for-one or double twister is preferred to the flyer twister. It has twice the productivity, because the yarn receives two twists for each rotation of the bow. The principle of two-for-one twisting was described in Section 6.1.3, with Fig. 6.5 showing it in uptwisting mode with the supply rotating, The double twister shown in Fig. 6.11 is in downtwisting mode with the take-up rotating. The yarns are fed through eyelets attached to the bow. The bow rotates and this puts twist in the yarn. Each rotation of the bow imparts two turns of twist to the yarn. The first twist occurs at the first pulley before the yarn runs round the bow and the second twist occurs on the first pulley of the capstan after the yarn leaves the bow and before it is wound on the package.

The problem with the two-for-one twister is that the yarn lengths are determined by the first twist, and the second twist simply over-twists the yarns. One way out of this is to install a pre-twister in front of the two-for-one twister. This is essentially a pair of pulleys that rotate at twice the speed of the bow. The yarns are then fully twisted before they enter the two-for-one twister and each yarn is the correct length for its position in the twisted assembly. When the yarns go on to their first twisting point in the two-for-one twister, they are actually half untwisted and remain so until they reach the second twisting point at the other side of the bow. At this point they are fully twisted once again and the resulting product is a very well-balanced yarn assembly.

The bow acts as a guide for the yarn, but it is not essential to the operation of a two-for-one twister. The yarn will behave in much the same way as a skipping rope between two children. The pulleys act as the hands and the yarn is allowed to form its own 'balloon'. The principle remains the same as that described in the preceding paragraph.

6.3 Strand manufacture

6.3.1 Strand twisting

For most rope constructions (see Table 6.1), strand manufacture is the final step before completing the ropemaking process. For small braids, the 'strands' may be only first twist yarns, but for larger ropes they may consist of multiple layers of yarns that produce a strand nearly the size of a person's arm.

In strand manufacture, a number of rope yarns are twisted together to form a strand. This may be carried out on either large flyer twisters or two-for-one twisters. The direction of twist is usually opposite to that of the rope yarn. Neither of these

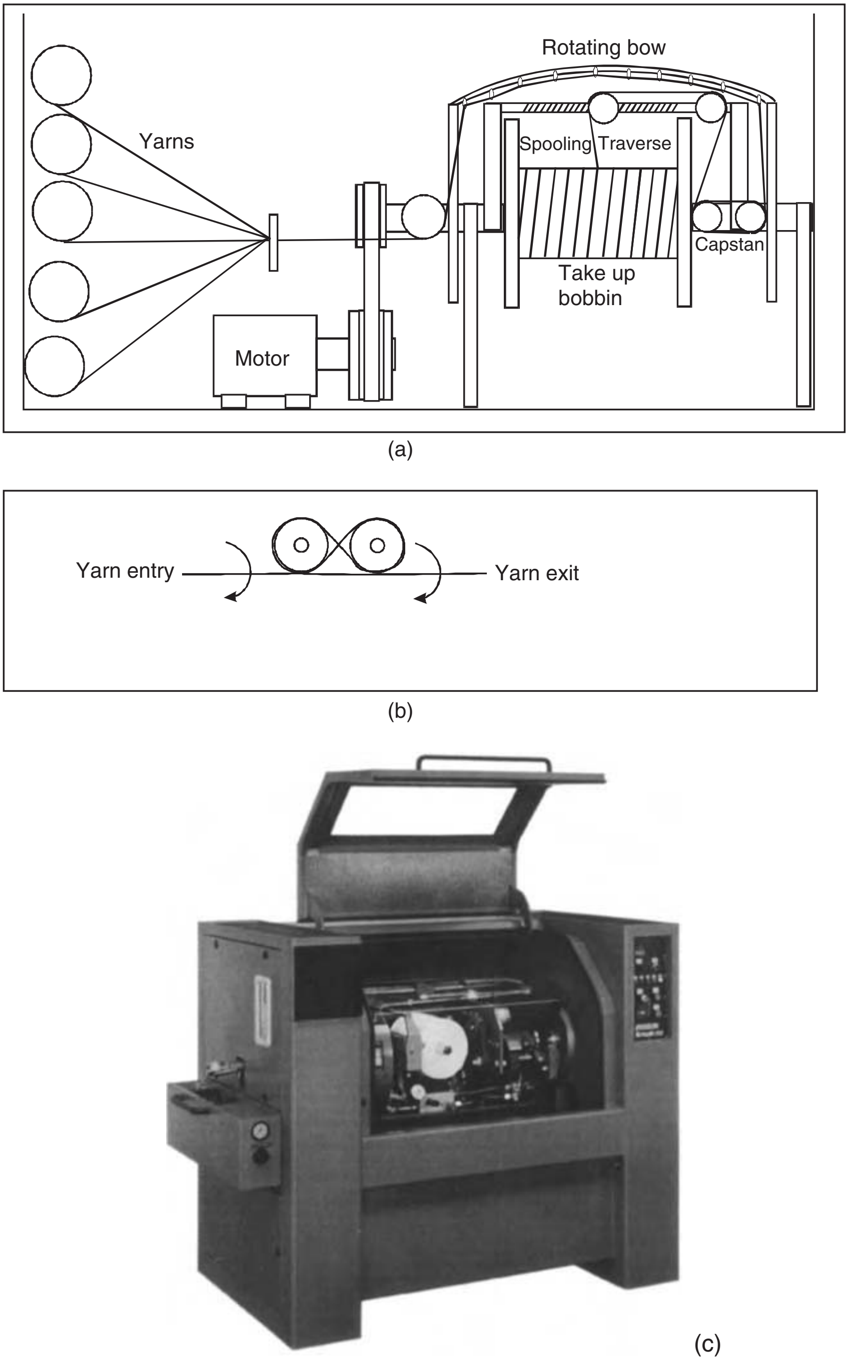


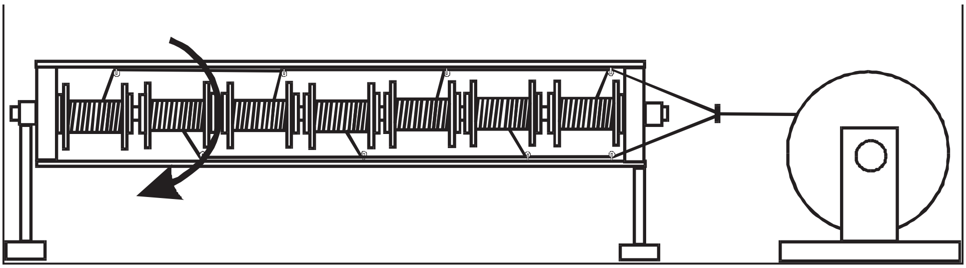
Fig. 6.11 Two-for-one twister. (a) Schematic arrangement. (b) Pre-twister. (c) Commercial machine: *Roblon Tornado* 300 heavy-duty twister.

machines has backtwist, so that, for each twist of the strand, approximately one twist is removed from the rope yarn if the twist is in the opposite direction, or added if (unusually) it is in the same direction. The main effect of the lack of backtwist is to make the yarn lengths uneven, thereby upsetting load sharing. If the fibre has reasonably high elongation this may not matter too much, but for high modulus fibres such as aramid, there may be a noticeable loss of strength. The full theory of backtwist is given in Appendix IV.

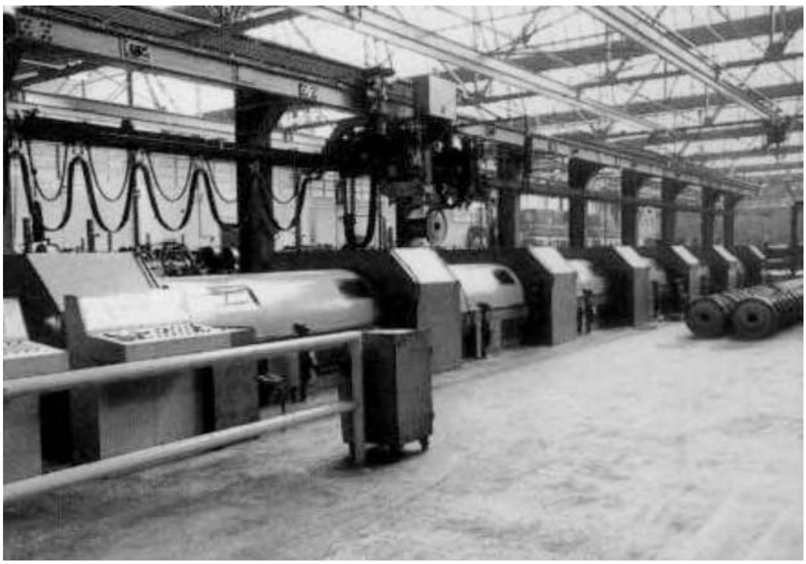
Alternatively, strands may be made on tubular or planetary standers, both of which provide backtwist. These standers are now commonly incorporated in integral ropemaking machines as described in the next section.

6.3.2 The tubular strander

The tubular strander, Fig. 6.12, consists of a rotating outer cage which encloses the bobbins. These do not rotate with the outer cage, but sit in floating cradles as illustrated. They are free to turn as the yarn is paid off and they are also provided with



(a)



(b)

Fig. 6.12 Tubular strander. (a) Schematic arrangement. (b) Commercial machine: OM Lesmo's tubular strander.

individual brakes, which give the yarns their tension. This machine gives 100% backtwist. The yarns are guided over pulleys or guide posts along the cage.

Tubular stranders can hold many bobbins; 19 is very common. However, it is difficult to hold the yarn tensions even. This is because the yarn at the rear runs over many more guides than the yarn at the front. On the other hand, tubular stranders are much faster than planetary stranders, running at speeds of 500 or 1000 r/min depending on size.

6.3.3 The planetary strander

In a planetary strander, Fig. 6.13, the bobbins are geared to the cage and make one rotation back for each rotation of the cage. Planetary stranders rotate at the slow speeds of 10 to 100 r/min depending on size. The bobbins are individually braked. The brakes can be anything from magnetic braking to a simple rope brake. Magnetic brakes are designed to maintain uniform tension irrespective of how much rope yarn or strand there is on the bobbin. With a simple rope brake operating on the flange of the bobbin, the degree to which the bobbin is full affects the yarn tension (see Fig. 6.13(b)). This generally does not matter too much as the bobbins are usually filled with the same amount of yarn and run out of yarn at the same rate.

6.4 Production of three- and four-strand rope

6.4.1 From ropewalks to integral machines

Three-strand ropes are traditionally the commonest form of rope and are still used in large quantities. The outer helix angle is typically 20° to 30°. Lower helix angles can be used if the strand is to be used as a sub-rope in a parallel strand construction. The helix angle then would be around 15°. There are a number of decorative cords where the helix angle is around 45°. The production methods for four-strand ropes, which are less common, are similar to those of three-strand ropes. In order to avoid undue repetition, 'four' is usually omitted in the following account, but can be substituted for three. A brief description of the historical method of making three-strand ropes on ropewalks was included in Section 1.1.3. Some ropewalks are still in use making ropes for sale, though mostly in a craft museum context.

The early machine shown in Fig. 1.11 laid up ropes continuously from strands. Modern practice links strand formation and rope laying in a single machine, such as that shown in Fig. 1.13, which produces rope directly from rope yarns as shown in Fig. 6.14. The strand twist and the rope lay length are controlled by the speeds of rotation and the speed of the capstan. The relative speeds are set by changing the gears. This machine does not have backtwist. This means that, for every turn of the drum, one twist is removed from the strands. Consequently, the outer yarns become too long and there is a reduction in strength in the strand. There is a tendency for the added twist to run back from the drum to the cradle. This helps to correct the yarn lengths and the loss of strength is not as severe as might be thought. Clearly the machine should be designed to have as little friction as possible so as to promote the untwisting to run back to the strand closing point.

Utilisation of the two-for-one principle (see Sections 6.1.3 and 6.2.4) for both strand and rope twisting makes it possible to avoid rotation of heavy parts. It is the bow, usually referred to in this context as a flyer, that rotates.

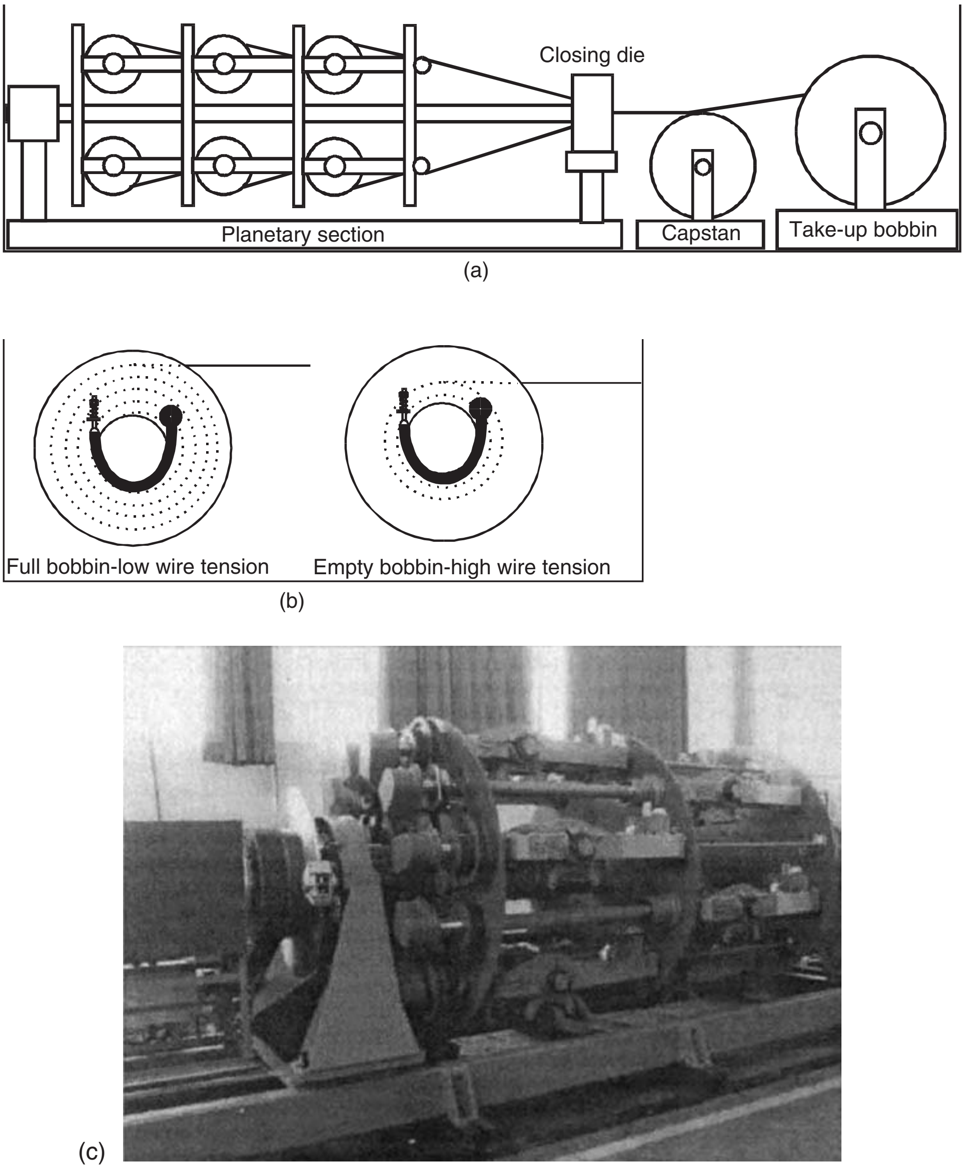


Fig. 6.13 Planetary strander. (a) Schematic arrangement. (b) Rope brake. (c) Commercial machine: OM Lesmo's planetary strander.

6.4.2 An integral rope-making machine

Figure 6.15 shows an integral rope-making machine. The left-hand part is a two-for-one strander and the right-hand part is a two-for-one rope-laying, or closing, section. The machine shown in Fig. 1.13a and in more schematic detail in Fig. 6.16 has the added feature of automatic coiling, as described later.

Roblon describe the action of the machine in the following way:

> The stranding section consists of three (or four) creels on which the pay-off bobbins are placed. These may either be flanged spools or cross-wound bobbins

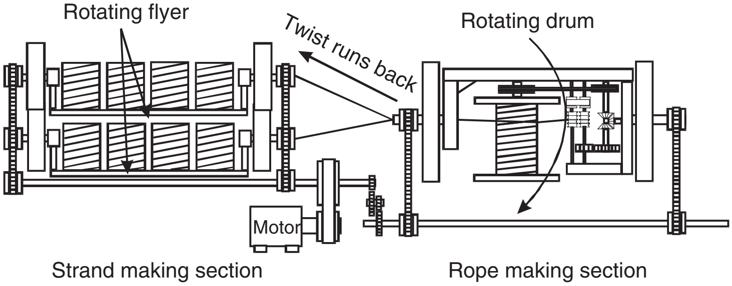
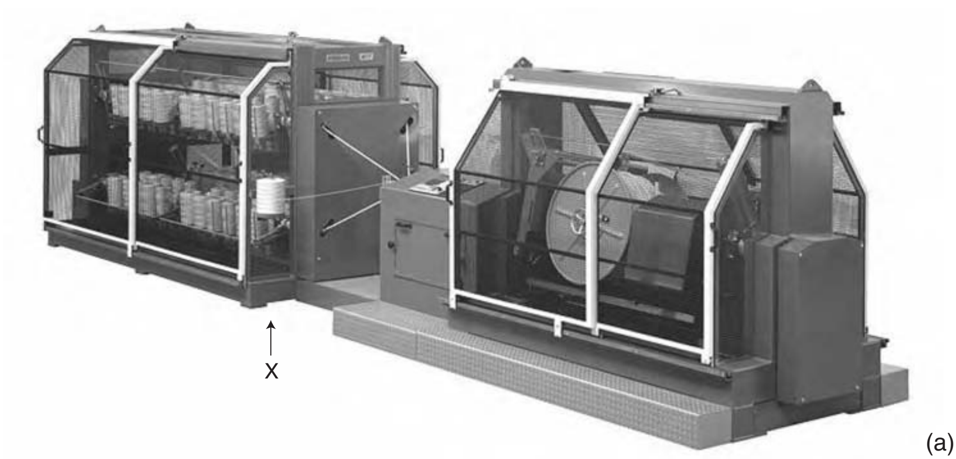


Fig. 6.14 Schematic of an integral rope-making machine.



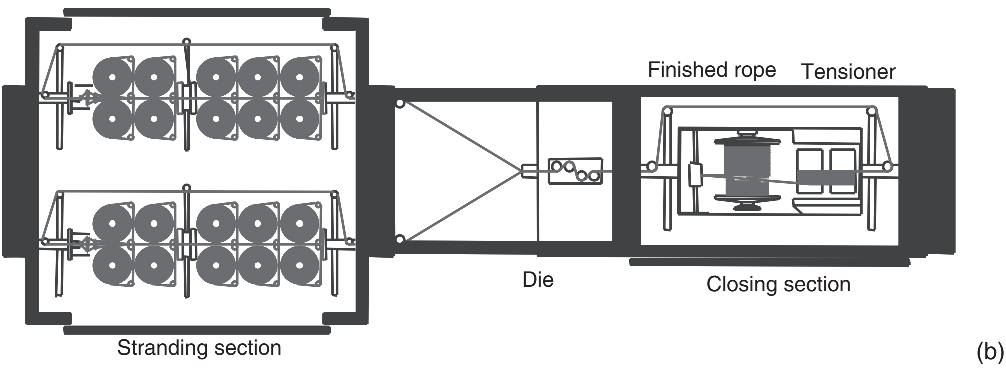


Fig. 6.15 (a) Integral rope-making machine. (b) Schematic of machine. Reproduced by courtesy of Roblon.

(on tubes or tubeless). The pay-off bobbins may also come directly from the extruder winders*. The yarn from each pay-off bobbin is led through to the flyer arms, which are positioned on either end of each creel. Once the flyers are set in motion they provide the yarns with the first two [strand] twists per revolution – thereby producing the actual strand. On their way from the stranding section and

* Polypropylene (and some other fibres) are produced by the rope maker and may be fed directly to form rope yarns on extruder winders.

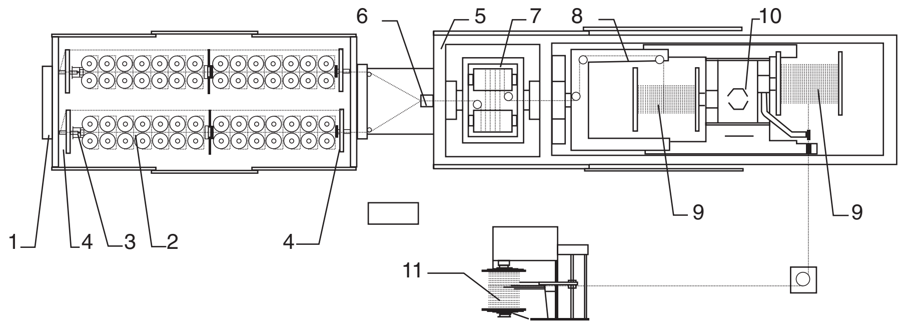


Fig. 6.16 Schematic of the machine shown in Fig. 1.13a. 1 – Strand section. 2 – Pay-off packages. 3 – Strand die. 4 – Strand flyer arm. 5 – Rope section. 6 – Rope die arrangement. 7 – Capstan. 8 – Rope flyer arm. 9 – Take-up reel. 10 – Turntable system. 11 – Coiling machine. Reproduced by courtesy of Roblon.

into the closing section, the strands pass through the rope die, which helps form the finished rope.

The closing section consists of a cradle in which the capstans and the coiling arrangement are placed. The rope flyers, which are placed on each side of the cradle, provide the finished rope with the last two [rope] twists. Please note that the direction of these twists is opposite the twist direction found in the stranding section.

Figures 6.17–6.21 show more details of the machine. The creel in Fig. 6.17 is for a small machine that can accommodate three yarn bobbins per strand. Larger machines will take up to 32 bobbins. Figure 6.18 shows detail of the take-off and tensioning of yarns. The strand die, which, together with the rope die, controls the geometry of rope assembly, is shown in Fig. 6.19. For quality rope production, it is necessary to choose the correct sizes of dies and to have an even distribution of rope yarns in the strand die. The additional package shown above X in Fig. 6.15(a) is an optional addition to add in a marker yarn or yarn in the core of the rope. Figure 6.20 shows the take-up capstan.

In Fig 6.16, there are two rope take-up reels. The one on the left, nearest the entrance to the closing section, is the active take-up. When this is full, the turntable rotates and an empty take-up replaces the full take-up. The finished length of rope is then unwound from the full take-up and wound on the coiler, which is shown in Fig. 6.21. The wheel at the end enables the flange to be removed, so that the wound-up rope package can be slid off the coiler ready for packaging.

6.5 Production of braided rope

6.5.1 Basic principles

Braiding* is a process that can be used to make anything from tiny lines of 1 mm diameter to extremely large mooring hawsers of 200 mm diameter or more. The basic action in circular braiding is like a maypole, and is similar to that of traditional

* *Braiding* and *plaiting* are similar terms. See Appendix II for details of terminology.

Fig. 6.17 Creel on a small machine. Reproduced by courtesy of Roblon.

Fig. 6.18 Detail of take-off from package. Reproduced by courtesy of Roblon.

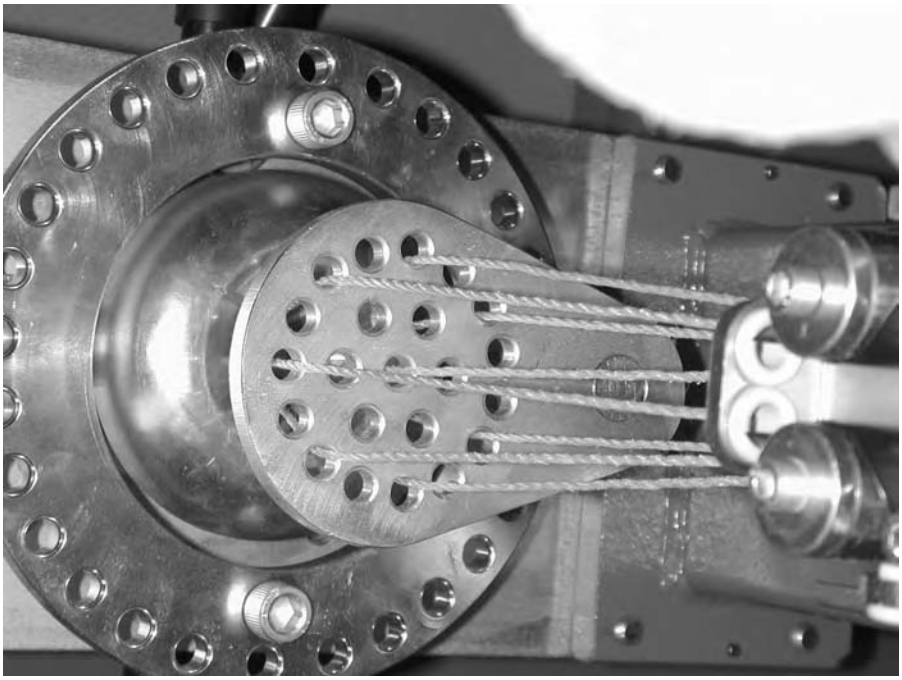


Fig. 6.19 Die, set up to make a 3-strand rope with three rope yarns per strand. Reproduced by courtesy of Roblon.

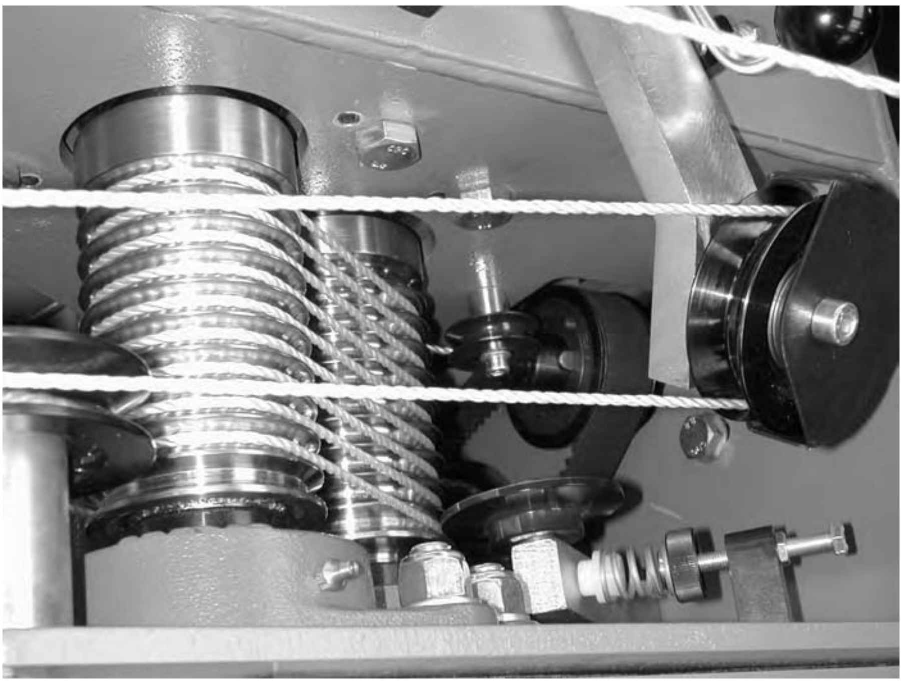


Fig. 6.20 Take-up capstan. Reproduced by courtesy of Roblon.

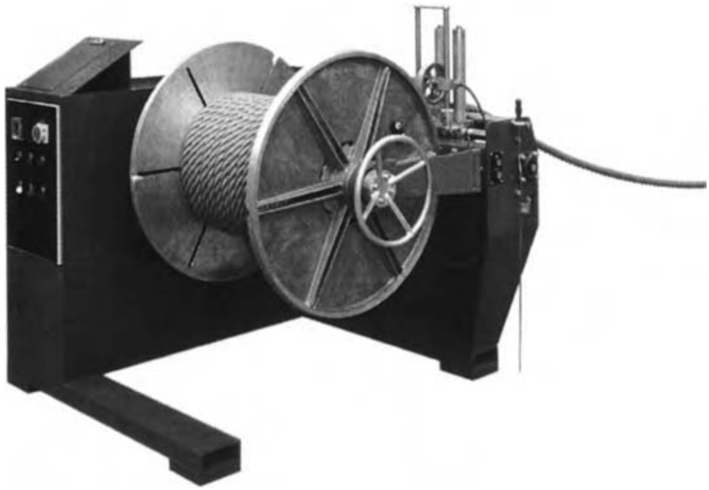


Fig. 6.21 Coiler. Reproduced by courtesy of Roblon.

Morris Dancers. A small braiding machine is shown in Fig. 6.22. The bobbins are mounted on carriers which travel on rotating horn gears, passing from one horn gear to the next. The horn gear is that part of the machine which provides the rotating and interleaving motion shown in the braider set-up diagram, Fig. 6.23.

Braided ropes have helix angles of generally between 20° and 30°. Lower helix angles are used if the braid is for the sub-rope of a parallel strand rope. This is because lower helix angles yield higher strengths and the structural integrity and robustness associated with a tighter braid is not required. Often the angle is just enough to ensure that the strand hangs together during production and is spliceable. This is around 10° to 15°.

In flat braiding, the carriers interleave along a linear path, with reversals in direction at the end. These machine are used to make flat webbings, which are competitive with ropes in some uses.

For rope making, all braids are circular braids. Many interlacing patterns are theoretically possible. Two forms are common in commercial rope manufacture. In a *plain braid*, the yarns alternate under and over at each crossover, as shown in Figures 6.23(a) and 6.24(a). In a 2-by-2 *twill braid*, Figures 6.23(b) and 6.24(b), the yarns go under two and over two in a staggered arrangement. The twill braid has greater structural integrity, and is most commonly used in ropes. Other forms, such as a *hopsack*, in which yarns go under two and over two in register, may be produced.

With very few carriers, the yarns cross at the centre of the braid to give a braid that is a rounded square in cross-section. With a large number of carriers, the interlaced yarns make up a hollow circular braid, which, in the absence of a core would collapse into a ribbon. With an intermediate number of carriers, the hollow at the centre may disappear under tension to give a cross-section of tightly packed strands; if ends are pushed together, a central hole opens along the axis of the braid. If the strands remain circular, no more than about 12 strands can be accommodated without having a sizeable central hole. If the strands distort in shape, more can pack into towards the centre.

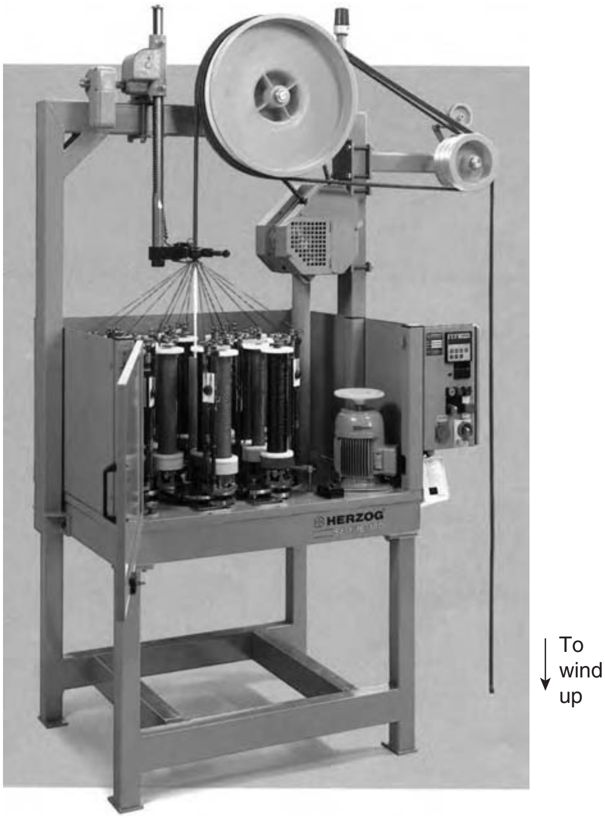


Fig. 6.22 A small braiding machine. Reproduced by courtesy of Herzog.

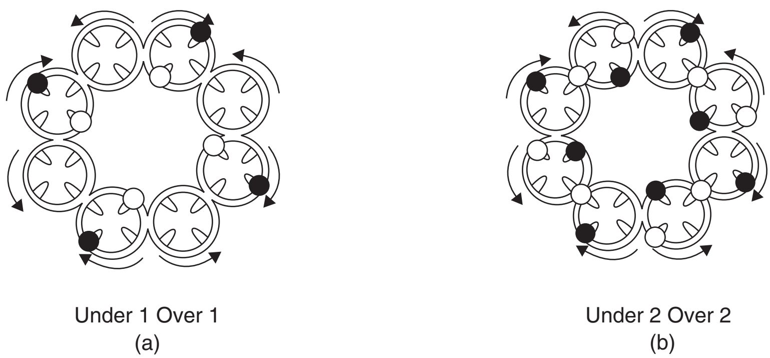


Fig. 6.23 Examples of braider set-ups. (a) For plain or diamond braid. (b) For twill braid.

Braids may be produced with more than one strand per carrier. Thus, strands are braided into the rope in pairs, triples or even quadruples. Single braided ropes may have one or two strands per carrier. Cores for braid-on-braid ropes may have up to four strands per carrier, increasing in number as rope size increases. Braided jackets usually have at least two, and sometimes several, strands per carrier. Production

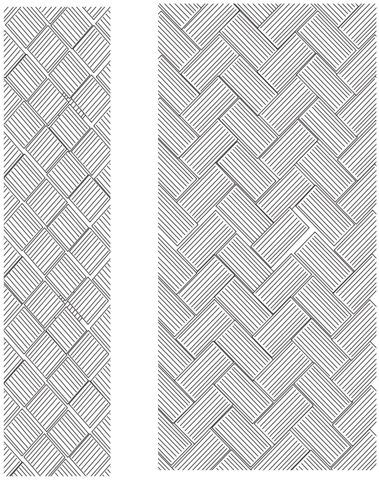


Fig. 6.24 (a) Plain braid. (b) Twill braid; note that under two + over two is stepped.

facilities often dictate the choice of design as one large strand per carrier will, in mass and volume, equal two smaller strands per carrier, yet the ropes may be comparable in performance; the braid design is influenced by the availability of machinery.

The combinations for production of braid-on-braid ropes to produce ropes of similar performance are nearly endless. The parameters are: basic fibre size, core/sheath mass ratio, number of strands in core, number of strands in sheath, strands per carrier in core, strands per carrier in sheath, and finally, helix angles and twist ratios, which have an influence on all of the above. Computers have reduced a typical design effort for braid-on-braid design from the order of a day to less than 30 minutes, and minimised the need to build and test so many specimens.

The above comments show that a great variety of braided rope constructions could be made. Those of most commercial importance are mentioned in following sections.

6.5.2 Rewinding

It is usually necessary to rewind the strands from the bobbins used in the take-up for strand production onto the carrier bobbins used in the braider. This operation can take place at high speed and is increasingly automated. For smaller rope sizes, the stranding bobbins may fit directly onto the braider carriers. Rewinding is necessary when there are more than one strand per braider carrier. Uniform winding under controlled tension is necessary to achieve maximum rope quality and performance.

6.5.3 Braider splices

Unlimited length can be produced for circular braids, both single and braid-on-braid. To make a braider splice, the strand length on each carrier bobbin is varied;

the variation may be spread evenly over the length to empty the fullest carrier bobbin, or the spacing may be concentrated over some minimum length that allows a fairly rapid sequencing of splicing before resuming normal operation. Once the spacing is established, subsequent braider splices will occur at the same spacing.

To perform a braider splice, the braider is stopped when a bobbin nears empty and the remaining strand is stripped off and cut to an appropriate length. The bobbin is removed and a full one is inserted. Some strand is pulled off and laid adjacent to the length of the other strand. The overlap length should be at least one full braid cycle. The two ends, leading and trailing, are taped or otherwise secured together and the braider is restarted. This pulls the new strand into the braid where it is quickly locked into place by the compression of the braided structure of the rope. Spacing between braider splices must be long enough so that one braider splice does not run into the next, plus a reasonable contingency of a few cycle lengths.

The rope is slightly larger in diameter over the length where the two strands occupy the same space. This increase would be approximately 6% in the case of a twelve-strand single braid and would be unnoticeable for most applications. The effect is less for braid-on-braid as core and sheath are unlikely to have braider splices that occur opposite each other.

6.5.4 Eight-strand plaited rope

A very popular type of braid is called eight-strand plait. It is made from a braider with eight carriers, which cross in pairs. The motion of the carriers through the braider is such that the strands appear to be positioned next to each other in pairs; thus the structure appears as four pairs. Each of the strands alternately passes through the centre on each braid cycle. Thus, the plaited rope is not truly a circular braid. In cross-section, it appears as a rounded square on the outside with the centre closed by the interior strands, hence its common name of 'square braid'.

Eight-strand ropes are often made on small braiding machines, but for large eight-strand ropes, machinery may be as much as 3 or 4 metres in diameter and 4 metres high. An example is shown in Fig. 6.25.

6.5.5 Twelve-strand and other hollow braid rope

As described in Section 3.5, hollow braids (which nevertheless collapse into a compact form with only a notional hole in the centre) may be made with various numbers of carriers. Twelve-strand ropes are the most common, but eight and sixteen are also made. The machines must be set up with the appropriate numbers of yarn packages on the carriers and the correct carrier paths. Figure 6.22 is typical of braiders used to make small ropes and cords. Figure 6.26 shows a large braider for twelve-strand rope.

6.5.6 Braid-on-braid rope

For braid-on-braid or double-braid ropes, a core braid is first made as described above. This is usually an eight-strand or twelve-strand construction depending on size, and the helix angle is low. It is then fed into the centre of a second braiding machine with a large enough number of carriers to form a hollow braid around the core, as seen in Fig. 6.27. A small double-braid machine is shown in Fig. 6.28.

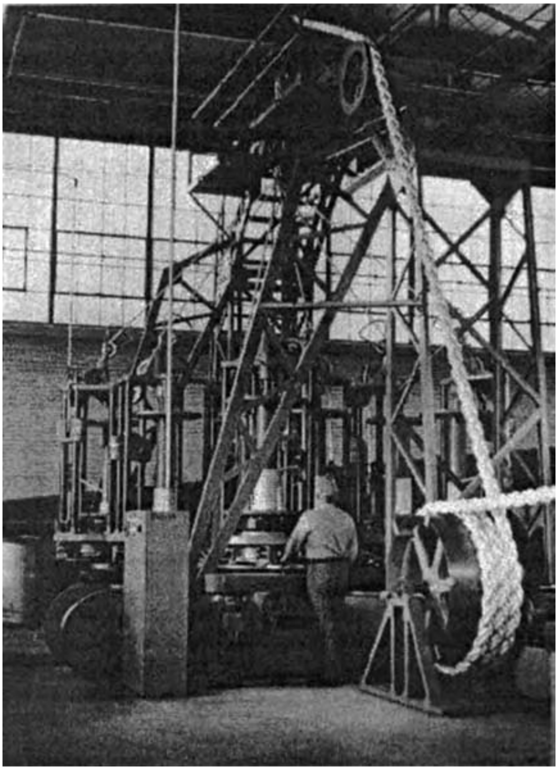


Fig. 6.25 A large braiding machine for 8-strand plaited rope. Reproduced by courtesy of Wall Industries.

6.5.7 'Solid' braid rope

In the production of so-called solid braids, the two sets of carriers unusually rotate in the same direction. Interlacing at an acute angle occurs as the carriers switch between an inner and an outer track. The common forms are 9-strand and 20-strand. Solid braids are commonly used for small cords, as utilised for example in window sash cords. Note that although these are called solid braids, they may be braided around a core that will fill the centre.

6.6 Production of low-twist rope

6.6.1 Parallel-strand rope

In order to optimise strength and stiffness, low-twist constructions for fibre ropes have been developed. The parallel-strand rope* has a rope core, consisting of a number of parallel sub-ropes, within a tough braided jacket. The rope structure relies entirely on the jacket for its structural integrity. The sub-ropes may be either low-twist three-strand ropes or long-pitch braided ropes, which are produced as described previously.

* The term is confusing, since the rope consists of parallel sub-ropes (not strands), which themselves contain strands.

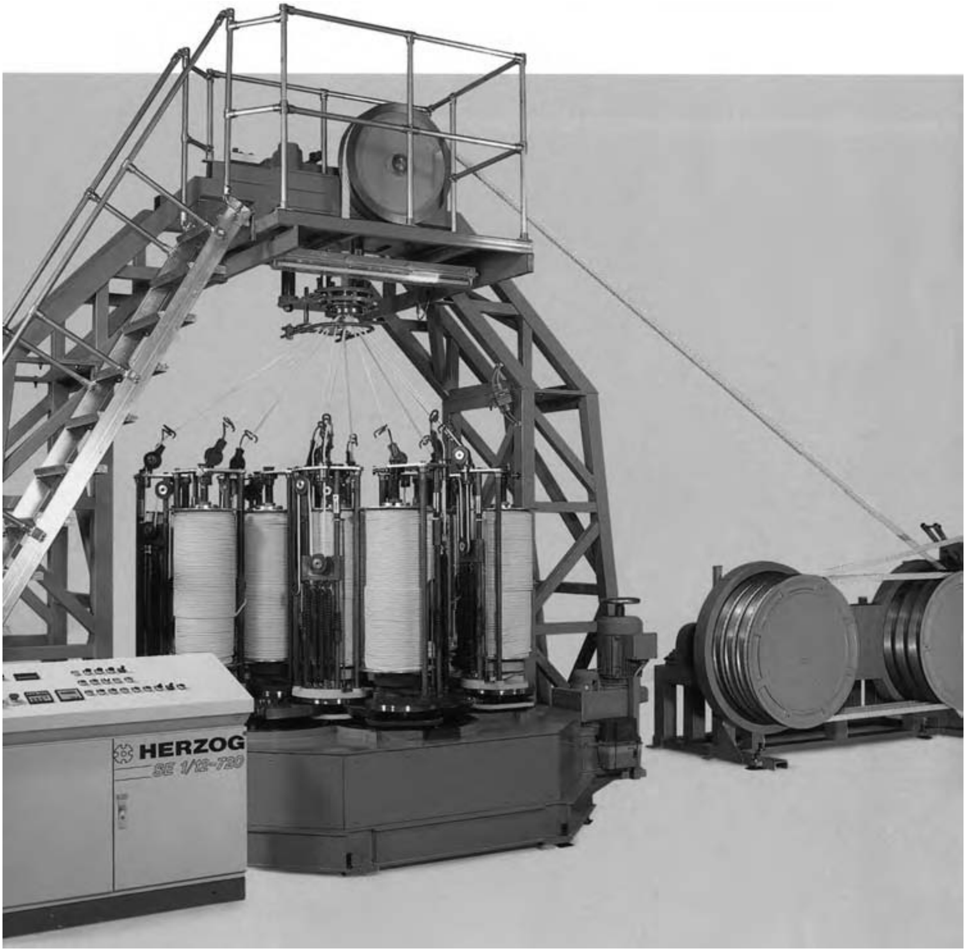


Fig. 6.26 A large braiding machine for 12-strand rope. Reproduced by courtesy of Herzog.

Each of the strands or sub-ropes is fed from its own bobbin into a very large circular braider. This braider will usually have between 32 and 48 bobbins. It is important that the strands are fed into the machine under even tension to ensure that they all have the same length in the rope.

The number of sub-ropes can vary. There may be as few as 4 or as many as 100. More, smaller strands make the rope more efficient in strength but harder to splice. The parallel strand construction should be torque-free. This occurs naturally if the sub-ropes are braided. If the sub-ropes are three-strand, there should be an even number with half laid in one direction and half in the other.

6.6.2 Wire-rope constructions for fibre ropes

In fibre ropes made with a wire-rope construction, the rope yarns correspond to the wires in steel wire ropes. The production methods and machines are similar. In these constructions, twisted strands are arranged in one or more concentric rings around

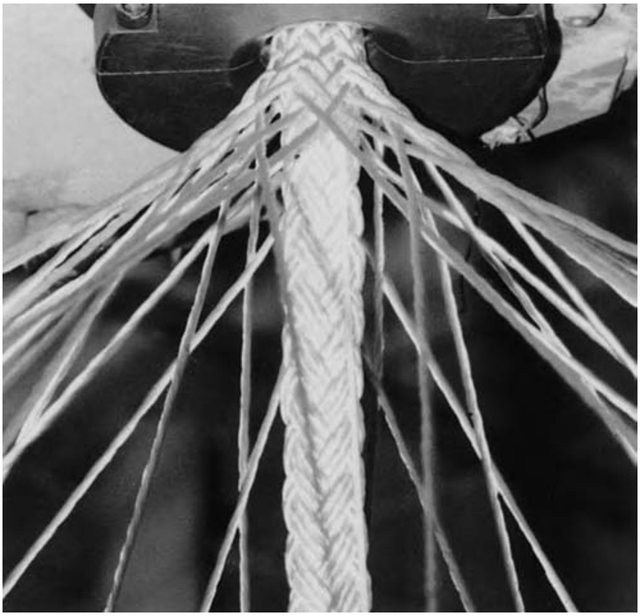


Fig. 6.27 Formation of a braid-on-braid rope. Reproduced by courtesy of Samson Rope Technologies.

a central core strand, as in constructing steel wire rope. The core strand may or may not be designed to carry load. Common constructions are 6 + 1 (six strands around the core); 12 + 6 + 1 (twelve strands around six strands); and 18 + 12 + 6 + 1. Most wire rope construction fibre ropes are supplied with a braided polyester or nylon jacket. Extrusions and polyurethane coatings have also been used. A braid impregnated with polyurethane makes an extremely tough jacket.

Torque balance can be achieved by designing the rope in two concentric layers. The inner layer is stranded in one direction and the outer layer in the opposite direction. The rope is designed so that the torques produced in each layer are equal in magnitude but opposite in direction. The individual strands are often jacketed with a thin cover. This holds the fibre yarns together during production but can also be a factor in providing optimum performance when flexing over pulleys, particularly for aramids.

These ropes are generally made with an outer jacket and this suffers the same problems described for parallel strand rope jackets; looseness and a tendency to pick up load over pulleys and on traction winches. One solution for wire rope constructions is to dispense with the outer jacket and to jacket the strands individually; braided polyester or nylon jackets work well. The jackets are integrated into the rope construction by squeeze between the strands under load. Structural integrity is achieved as with three-strand laid ropes.

There are various strand or rope constructions possible, as shown in Fig. 6.29. If all strand wires are the same size, simple hexagonal packing is possible. There are two wire rope constructions which get over the shape problem if all the strand wires are not the same diameter. These are Warrington and Warrington Seale. These more

Fig. 6.28 A small braid-on-braid machine. Note the core braid going up between the yarns from the carriers. Reproduced by courtesy of Herzog.

complicated constructions keep the strand round in steel wire ropes and avoid the high wire contact pressures on pulley grooves inevitable with equal wire diameter constructions. This enhances the rope lifetime in cycling over sheaves. Warrington Seale is a particularly good arrangement. It combines roundness and flexibility with reasonably robust outer wires. The utility of these constructions is more doubtful with fibre ropes since the strands flatten out and the rope becomes round

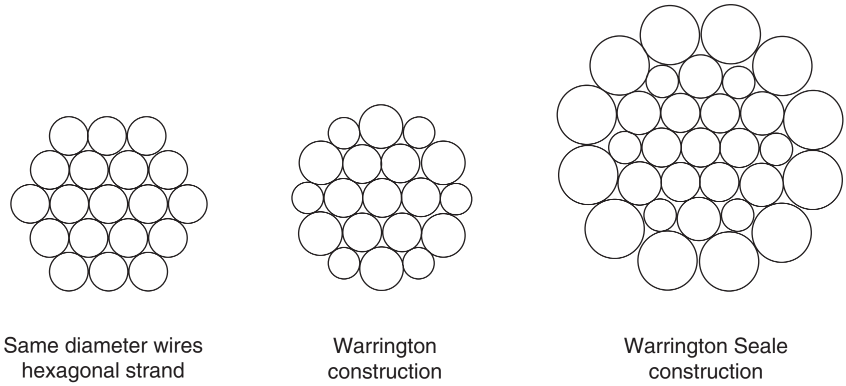


Fig. 6.29 Wire-rope strand constructions.

anyway. However, a very good Warrington aramid construction has been made commercially.

The strands of a wire rope construction fibre rope can be made as described in Section 6.3, ideally on a planetary or tubular strander. The rope is then closed on a planetary rope closer. The use of backtwist machines for both production steps ensures the highest possible rope quality.

6.7 Production of parallel-yarn rope

6.7.1 Braided constructions

It is an old-established practice to feed parallel textile yarns into the core of either a conventional braider that is producing a hollow braid or a braider producing a hollow 'solid braid'. The parallelism of the core yarns gives high strength and stiffness. Typically, spun cotton yarns would have been used in the core. Today, the core can consist of high-performance filament yarns. Medium-sized ropes are made by this method for some yachting and other applications.

6.7.2 Kernmantle

This rope is a specialised offshoot of braided constructions and is mentioned separately due to its unique name and popularity for mountaineering, fall arrest and rescue applications. The core is usually parallel fibre yarns but multiple twisted yarns with half twisted on one direction and half opposite are used; also multiple subropes of long pitch braid may be found. The rope has a thin braided jacket to hold the core together. For fall arrest in mountaineering, the nylon fibre used in the core is treated with steam to shrink it and improve energy absorption; a fall arrest may pull out the shrink and alter the properties.

6.7.3 *Parafil* rope

In another type of parallel-yarn rope, pioneered with the name *Parafil*, a bundle of parallel textile or rope yarns is fed into the centre of an extruder, which coats the core in a plastic jacket. Small parallel yarn ropes can be made with entirely untwisted textile yarns fed from a creel into the extruder, but as the size increases this becomes impractical and would require an enormous creel. The textile yarns are assembled into rope yarns twisted alternately in opposite directions. This has a useful benefit since the twisted rope yarns are easier to separate and handle when making the termination. The jacket is generally high density polyethylene, but nylon can be used to increase the jacket stiffness or polyurethane for better flexibility.

6.8 Post-production treatments

6.8.1 External jackets

In parallel-strand and parallel-yarn ropes, the jacket is essential to the integrity of the rope. For other ropes, braided jackets are often put on in order to give improved structural integrity, to improve handling characteristics, to increase friction, and to reduce surface wear. Braided jackets made from spun yarns are fuzzy and have a very good feel for applications such as yacht ropes. Polyester yarns have better abrasion resistance than high-modulus yarns. The most common applications use jackets to cover high modulus fibre ropes, which are the strength member.

The ropes described above are fed into the core of a braiding machine, which is supplied with bobbins of the required jacketing yarns. The helix angle of a braided jacket is often around 30°.

Occasionally, plastic jackets are applied, typically polyurethanes. These can be applied by feeding the rope into the core of an extruder. Alternatively, the polyurethane can be sprayed on lengths of rope stretched out on a frame, as shown in Fig. 6.30.

6.8.2 Stretching and heat-setting

HMPE ropes develop their full strength after a short period of use. This gain of around 20% can also be achieved by heat stretching the ropes or the strands before rope closing. Since it is much easier to heat smaller members, it is preferable to perform this operation on the strands. The load required is a few gf/dtex, depending on the temperature, which should be around 120°C. Some experimentation is required to establish the exact conditions. Overheating will cause the molecule to lose its crystal structure and most of the fibre's strength.

6.9 Quality considerations

Most manufacturers are very focused on strength and this clearly is a vital consideration, but the rope also has to perform well in the application and this means that it must be made exactly according to the design, particularly with respect to helix angles. Reducing the helix angle may well improve the strength but the cycling-over-sheaves performance is likely to suffer.

The design of the rope should specify the yarn type and size, the number of components, and the direction and amount of twist at each manufacturing step. The role of quality control is to ensure that these parameters are adhered to and that they are achieving the required strength.

For each rope, a record of required production data should be made and kept. These should include:

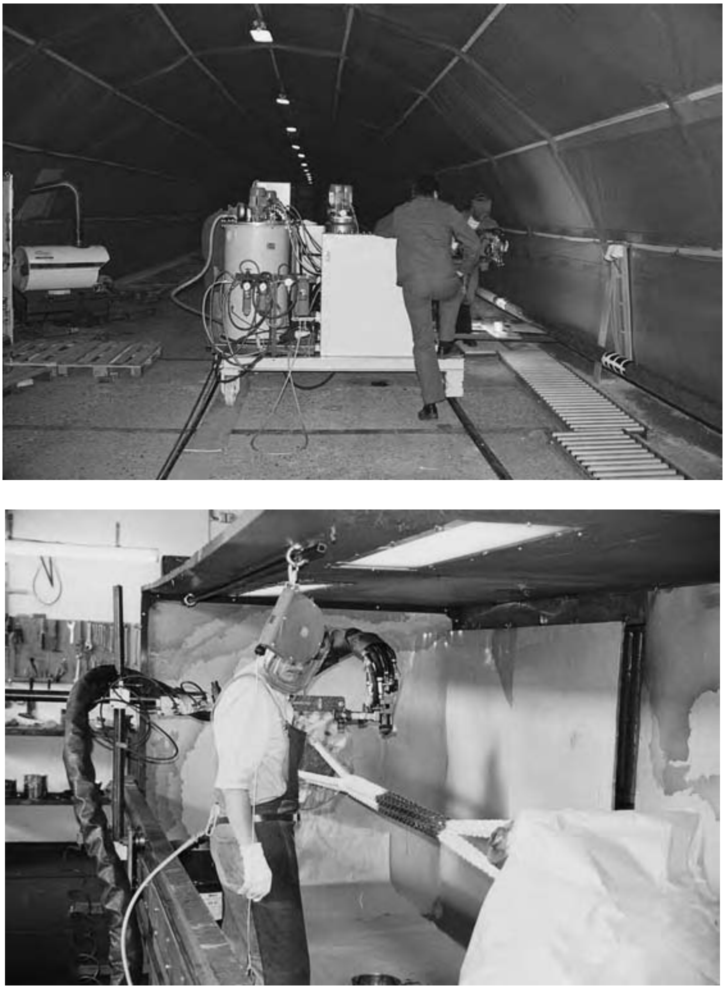


Fig. 6.30 Spraying-on a polyurethane coating.

- Yarn type by unique designation; i.e., manufacturer's name, chemical name, manufacturer's designation number, yarn size, filament count, finish (if not covered by foregoing)
- Number of yarns, rope yarns, or plies at various stages of production
- Twist levels, lay lengths, braid pitch as appropriate for each stage
- Tension settings or designated tensioning device
- Gear settings for all machines
- Die size, configuration and height above carriers for braids
- Linear density of finished product

The incoming yarn should be supplied with a certificate of strength and elongation at break. If not, 10 strength/elongation measurements should be made on a yarn tensile test machine from randomly selected specimens.

Before starting to twist the rope yarn, the tension on each incoming yarn should be checked – they should be reasonably even, within ±10% of each other. This is most important for the high modulus yarns. During twisting, deposits on the tensioners and other sliding surfaces should be removed before they become excessive. If a pretwister is required, it should be verified that it is installed.

The rope yarn should be checked for the direction and number of twists per metre, or lay length for each production run that has required a gear change. At least three determinations are recommended over the first few metres of production. The rope yarn should be round and even in appearance. There should be no loose or looped out yarns.

For each machine set-up, the strand should be checked to ensure that it has the required number of rope yarns, the right direction of twist and the specified lay length.

Occasionally it is a good idea to check the strand's strength. This can be done on a tensile testing machine over suitable bollards.

The rope core should be checked for the number of strands, the direction of twist and the lay length. If it is a torque-balanced core, then different strands should have been made for the different layers; their direction of twist as well as the direction of twist of the layer should be checked.

Yarns for braiding should be wound onto the carrier under carefully controlled conditions so that they are under even tension and they are all the same length. If they are twisted, half should be twisted in one direction and the other half twisted in the opposite direction, and they should be mounted on carriers travelling in opposite directions on the braiding machine.

Spring tension on braider carriers should be checked periodically.

The rope jacket should be tight on the rope but not overtight. As a general rule this means that the rope jacket should not slough up when pushed along the rope but the rope should be flexible enough to drape. Different applications call for different jacket tightness. For example, a mountaineering rope needs to be quite supple, whereas a winching line needs to be as compact as possible and draping is unimportant. The rope jacket should be also checked to have the specified number of strands per carrier, yarns of the right linear density (decitex) and braid with the correct number of carriers. The jacket should be even in appearance, with no looped out or loose yarns.

7

Terminations

7.1 Fibre rope terminations

For a rope to transmit force it needs a termination, whether it be a permanent attachment, such as a splice, socket or mechanical grip, or a temporary fix, such as a knot or wraps around a post. An effective termination is essential to almost every application that puts a rope under tension. An eye-splice, Fig. 7.1, is the most widely used and usually the most efficient permanent termination, and should be used wherever possible.

A fibre rope is only as strong as its weakest link, and this is often the termination. Local disturbance of the rope structure in the area of the termination can cause a reduction in strength. Also, under cyclic tension, abrasion, slippage or kinking may occur in the termination and this can lead to a gradual loss of strength and failure.

An important aspect of the mechanics of terminations is that, for a given stress or percent of break load, the tension increases as the area of cross-section increases (second power of diameter) but the grip on the rope surface increases as the circumference increases (first power of diameter). This means that, unless the grip can be spread through internal components of the rope, it is more difficult to make effective terminations on large ropes than on small ropes.

7.2 Splicing

7.2.1 Introduction to splicing

Splicing can be used in three ways. An eye-splice puts a loop in the end of a rope. An end-to-end splice can either join two ropes together or, finally, join two ends of the same rope to make a circular grommet.

Fibre rope splicing is a skill that must be learned. The simpler splices can be produced by carefully following a manual. However, small practices that are learned from experience or by testing of the splices are often needed to produce the best results. A well-practiced expert can make splices that match rope strength.

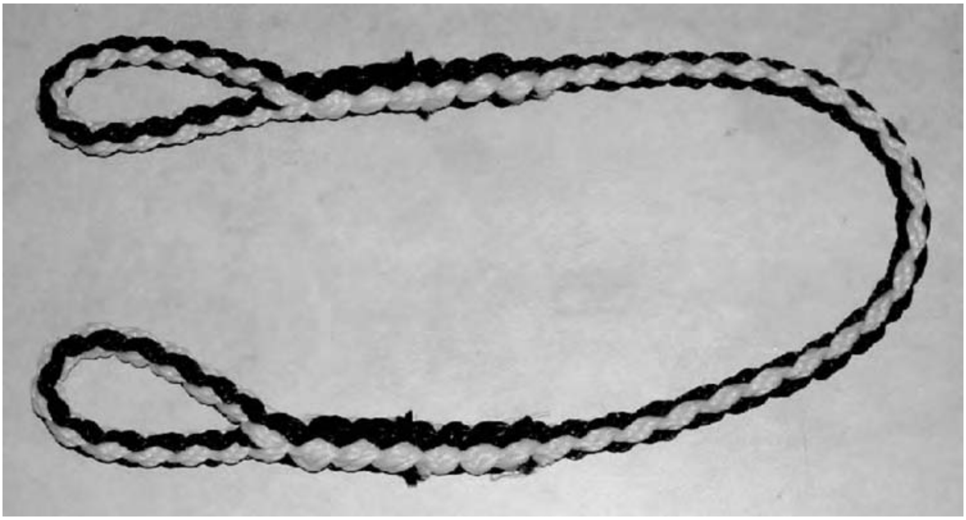


Fig. 7.1 Eight-strand 18 mm plaited polypropylene monofilament rope, with eye splice in each end. Splice made with four full tucks and three tapered tucks.

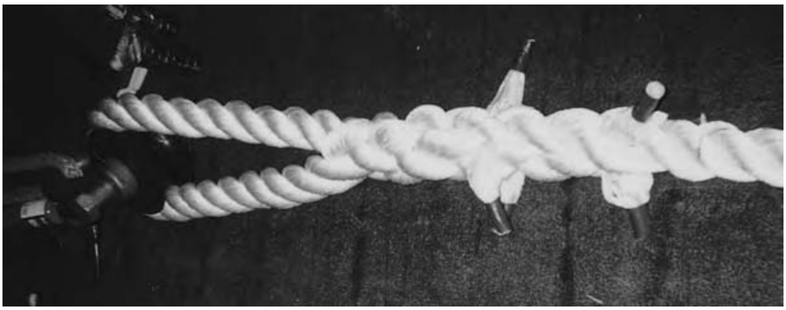


Fig. 7.2 Eye splice in 3-strand nylon rope under tension. Note the spool in the eye, which is used as a thimble.

The most common and one of the most dependable methods of termination of fibre ropes is an eye splice, which can be placed round a suitable fitting. Figure 7.1 shows an eight-strand plaited rope with an eye splice in each end; Fig. 7.2 is of a three-strand rope set up in a testing machine and anchored with an eye splice. These splices are made by separating the strands at the ends of the rope from the structure, Fig 7.3, bending the rope into a loop and tucking the separated strands into the body of the rope. Another approach is to separate the strands, create an eye, and then braid them over the exterior of the rope; this over-braid will tighten and grip as tension is applied at the eye. An intermediate stage of tucking the strands in an eight-strand plaited rope is seen in Fig. 7.4. There is enough grip on the tucked strands to hold considerable tension, usually to the maximum breaking strength of the rope.

It is beyond the scope of this book to cover the details of splicing and to explain all the nuances. Detailed information, including instructions on making splices, is

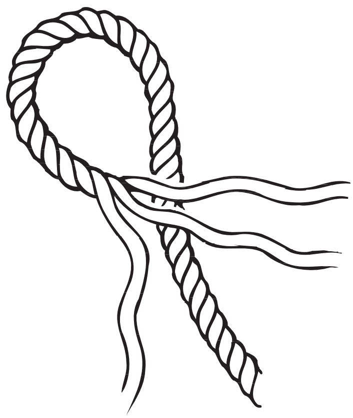


Fig. 7.3 Start of 3-strand eye splice. Reproduced by courtesy of Gleistein.

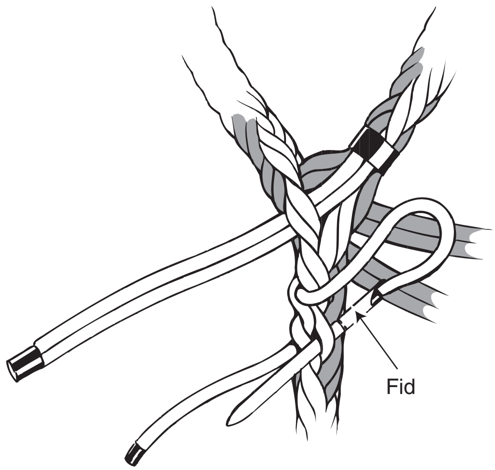


Fig. 7.4 Intermediate tucks in 8-strand plaited rope eye splice. The fid is a metal tube, used to push strands through rope and under body strands. Reproduced by courtesy of Gleistein.

given by Merry (2000). Some ropemakers, notably Gleistein (2000), publish informative manuals. For specialised or critical applications, especially with high-strength, high-modulus materials or very large ropes, the assistance of a qualified person is advised.

7.2.2 Laid and plaited ropes

The splice procedure is very similar for three-strand and four-strand laid ropes and eight-strand plaited ropes. Both are produced by separating the strands and tucking them into the body of the rope. Eight-strand rope can use four pairs of strands for tucking, but other procedures tuck all eight strands individually; both are satisfactory. For three-strand and four-strand ropes, the tuck direction must be opposite to the lay of the rope.

Splice strength efficiency can be increased if tapered tucks are added after the full tucks.

End-to-end splicing is used to join two ropes together in series or to splice a rope back into itself to produce a grommet. The splice is similar to an eye-splice, except that two sets of separated strands are spliced into the opposing ends. For eight-strand plaited and laid ropes, there are two variations for end-to-end splices.

(i) *Short splice.* This is made with two series of tucks on each side of the middle and is identical to the normal eye splice. There are two rope diameters in the middle of the splice and the circumference is increased by about 60%. Strength may be assumed to be 95 to 100%. (Columbian Rope Co., 1986)

(ii) *Long splice.* The full lengths of the strands are tapered in order to reduce the cross-sectional area at the middle. More tucks further apart are used. This method has about 85 to 90% of rope strength in three-strand rope and 70 to 80% in eight-strand rope. The increase in diameter is 25% on three-strand rope and none on eight-strand plaited rope. For three-strand rope, this splice can be modified to reduce the diameter increase to nil, but strength is reduced to 50 to 60%. (Columbian Rope Co., 1986)

7.2.3 Hollow single braids

Hollow single-braid ropes may be spliced by three methods. Small ropes may be eight strands whereas small and large sizes can be twelve strands. The procedures are the same in both constructions.

(i) *Tucking the rope through itself*

Many hollow braids have a long braid pitch, which makes a soft rope that can be opened to allow the rope to be inserted through itself. This is shown in Fig. 7.5. A number of passes through the rope (tucks) is required.

This splice is easy to make but may not be the most suitable for long-term cyclic loading. It cannot be used on tightly braided ropes.

(ii) *Burying the rope in the hollow centre*

Alternatively for a rope with a long pitch length (soft braid), the end of the rope may be buried well down into the body of the rope (see Fig. 7.6). This works well with the slippery nature of HMPE ropes as the bury length can be as long as necessary to hold securely. It is essential to taper the ends of the buried strands for maximum strength.

This is the most common splice for eight-strand hollow braided ropes and is used extensively with twelve-strand hollow braids. It can be a very reliable splice for cyclic loading if the included angle of the eye is small (see Section 7.3.2). Lockstitching should be employed; see splicing manual.

(iii) *Tuck splice*

This is a very efficient splice and can be used on twelve-strand ropes that are too tightly braided for the methods described above. It works like an eight-strand plaited splice except that there are six pairs of strands; thus it is somewhat more arduous. See Fig 7.7 for a description of the splice.

End-to-end splices can be made by any of the above procedures.

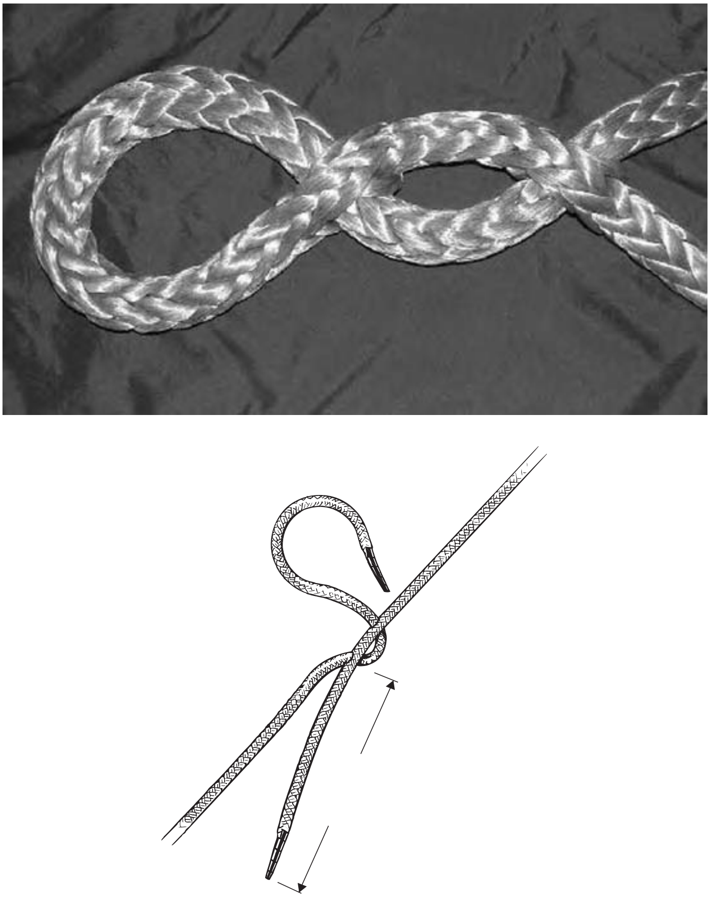


Fig. 7.5 Splicing 12-strand hollow braid by tucking whole rope through body of rope. More tucks than shown would be required. Tucks are called 'brummels'. Lower figure reproduced by courtesy of Gleistein.

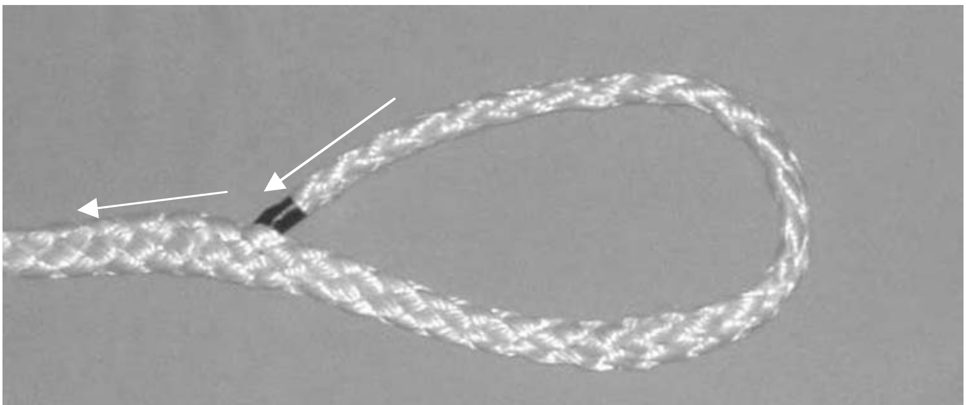


Fig. 7.6 Eye splice made by burying the rope into the hollow centre of the body. Rope is 12-strand HMPE with four strands per carrier.

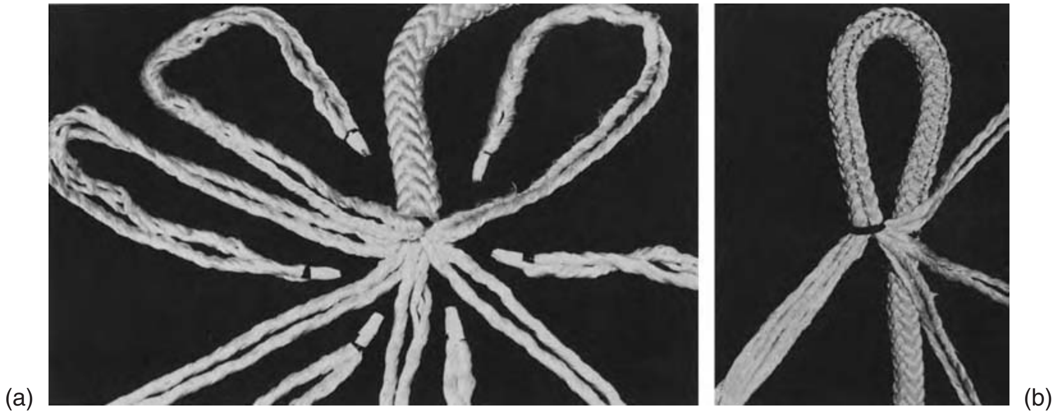


Fig. 7.7 (a) Start and (b) stage two of 12-strand hollow braid eye tuck splice. Reproduced by courtesy of Samson Rope Technologies.

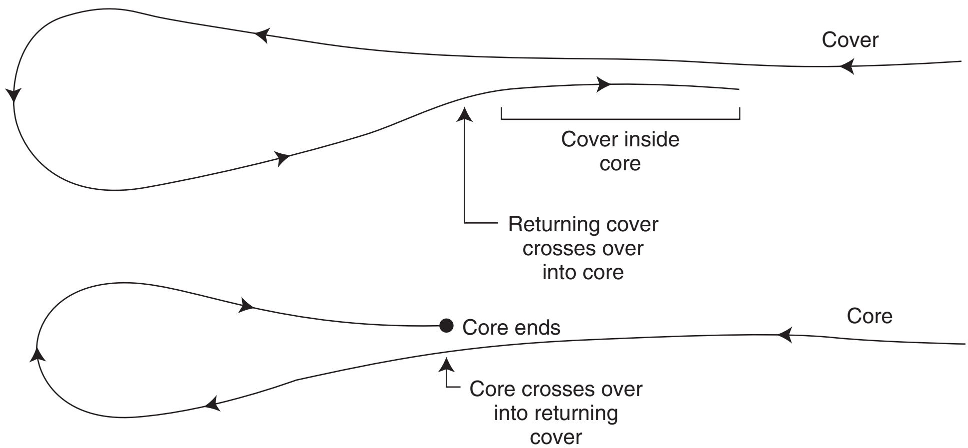


Fig. 7.8 Schematic of double braid splice. (Top) The cover goes around the eye, and the tapered end of the cover crosses over the core and then goes inside the core, beyond the crotch. (Bottom) Core crosses over to inside of cover, goes around eye and ends next to crossover point. (See also Fig. 7.9).

7.2.4 Double braids (braid-on-braid)

The very popular double-braid rope construction did not find a place in the rope market until a splicing method was developed. This splice is the most complex for standard rope types, and skill in performing it without the manual is considered admirable. Its wide use as rigging on sail boats has led to an army of qualified splicers.

In making the splice, the core and cover are first separated over a length somewhat greater than the length required in the eye. The core is then shortened by a length, which equals the length of the cover that will finally be embedded within the rope. The core and cover are then recombined, but cross over to follow the

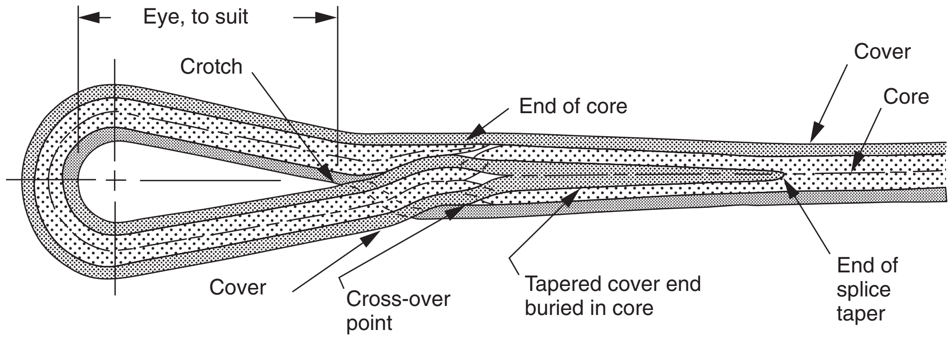


Fig. 7.9 Final configuration of double braid splice. Reproduced by courtesy of Samson Rope Technologies.

opposing directions, shown schematically in Fig. 7.8. A cross-section of the finished splice is seen in Fig. 7.9. Some points to note are:

- The cross-over point is where the core enters the returning cover, and it must be buried a specific distance from the crotch.
- A short, tapered length of core is buried next to the cross-over point. This is important for maximum splice strength. If terminated at the crotch or above it, strength is diminished and a hollow depression will appear in the cover just above the crotch. This was the procedure early in the development, but failures led to this improvement.
- The cover must bury a specific distance and must be tapered.

Double-braid splices can come undone during handling before the rope has seen sufficient use to set the splice. To avoid this, lock stitching, in which a small cord is stitched through the rope where the cover tail is located, is recommended. This is usually described in splicing manuals.

7.2.5 Jacketed high-modulus ropes

Many ropes have a high-strength, high-modulus core rope made of a very soft eight-strand plait or a twelve-strand hollow braid, and a braided jacket that protects the core but does not carry any load. An eye splice is produced in the core and the cover is then worked back over the eye and anchored at the crotch, usually by whipping with twine (see Fig. 7.10). This is the same rope as in Fig. 3.15, where core and cover can be seen.

7.2.6 Rope-to-wire rope splice

It is possible to perform an end-to-end splice that will join fibre rope to wire rope. This normally is only done on small sizes and with lines of nearly equal size. The fibre rope will be the weaker of the two and its full strength is rarely achieved. For critical applications, the efficiency of the splice should be evaluated by destructive prototype testing. Fatigue may be a problem if long-term cyclic loading is involved.

For procedures refer to a splicing manual.

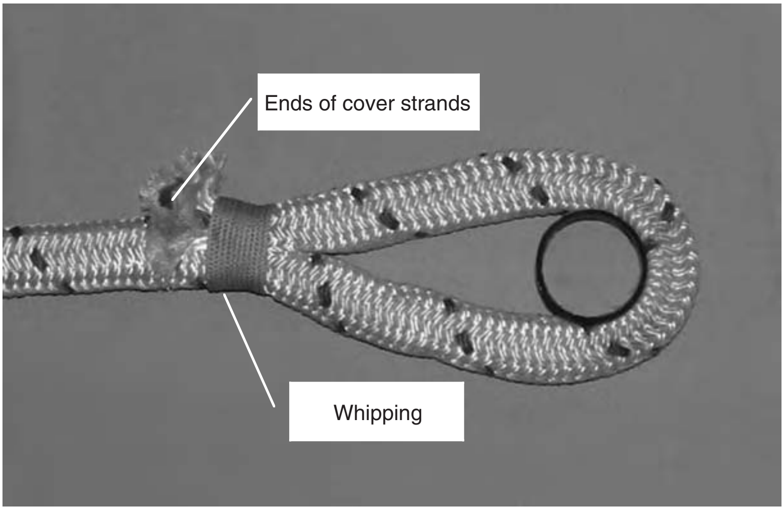


Fig. 7.10 HMPE 12-strand core rope that has been spliced by method (ii) of Section 7.2.3. The braided jacket has been pushed back for splicing of the core, and then moved over the eye and anchored by whipping.

7.2.7 Other splices

Other splices for less conventional ropes are described below. The ropes associated with these splices are normally for specialised applications.

- *Parallel-strand (sub-ropes).* Parallel strand rope made with small sub-ropes are terminated by splicing an eye into each of the sub-ropes. The splices are all produced carefully to an appropriate length. These are then bundled and covered to produce a single eye.
- *Parallel-yarn ropes* The parallel yarn core bundle is separated into a number of smaller bundles. These are then braided back over the core body, half right-hand and half left-hand. Considerable length down the body of the core is required to develop the necessary grip. Some means of compressing this braid against the rope is necessary, usually with a very tight whipping.
- *Wire-rope constructions.* The same splices used with steel wire rope are employed but modifications are sometimes necessary for optimum results. Basically, tucks are inserted under the strands in the body of the rope in a direction opposite to the lay of the rope. The simplest is for six-strand rope (six around one) but 12, 18 and 36 strand ropes may be spliced.

All the above ropes are jacketed and a means to retain continuity between the jacket on the rope and the covering on the eye is almost always necessary.

7.2.8 Extruded jackets and splicing

For parallel-yarn or other ropes with extruded jackets, care must be taken at the jacket end where it has been cut away to expose the underlying rope for splicing. Most extruded jackets have relatively high bending and torsional stiffness and the core is relatively flexible. The splice at the transition must be stiffened and joined to the jacket to prevent local damage from bending and twisting.

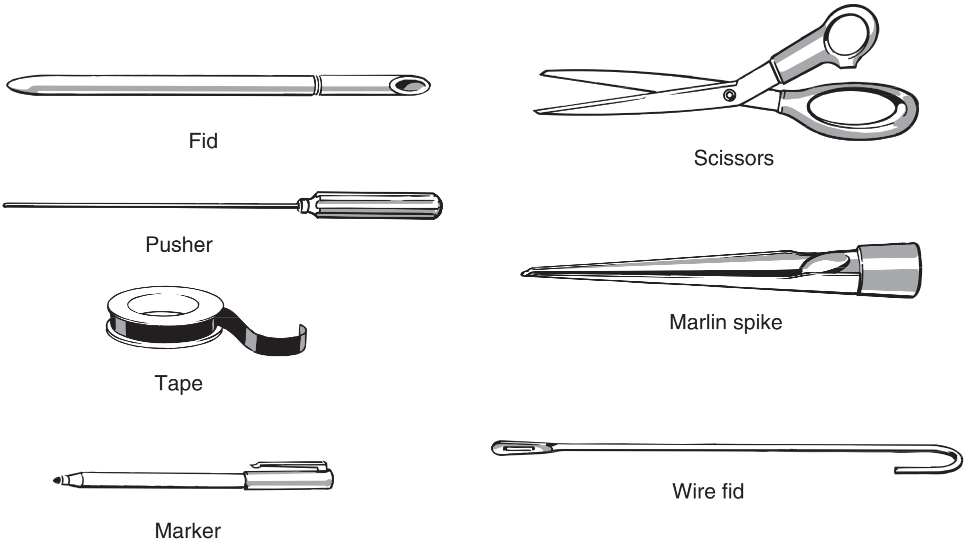


Fig. 7.11 Splicing tools. Reproduced by courtesy of Gleistein.

7.2.9 Splicing tools

Typical splicing tools are shown in Fig. 7.11. Tubular fids are not practical for large rope sizes and wire fids are used. A pair of hooked wires are engaged into the strands or other rope components and are used for threading.

7.3 Splice mechanics

7.3.1 Friction in splices

All fibre rope splices depend on friction. For most splices, tucking or burying of strands into the body of the rope is employed. The helical structure of laid and braided ropes creates lateral pressure that enables friction to hold the strands that have been inserted into the main body of the rope. In Fig. 7.4, the strands at the end of the rope have been un-braided and the figure shows the beginning of the process of tucking these into the rope. The lateral pressure (squeeze) created by the strands of the rope body will grip the strands when tension is applied. Note that, for the construction and fibre in Fig 7.2, only three full tucks are required to generate enough frictional grip to secure the splice (normally there would be additional tapered tucks to make the transition at the body of rope more gradual and optimise strength).

Predicting the holding capability of a splice is very complicated and depends on several variables. However, modelling based on fibre data and splice geometry has been successfully demonstrated and is undergoing continued development and verification. This is highly specialised and a detailed analysis is beyond the scope of this book.

7.3.2 Loading of eye splices

In an eye splice under ideal conditions, each leg of an eye sees half the axial component of the tension T_R in the rope below the splice. Thus, the tucked strands have to hold a force that is significantly less than the tension in the rope (see calculation below). Refer to Fig. 7.12, where θ is the included angle.

The tension T_L in each leg is determined from the following formula:

$$T_L = \tfrac{1}{2} T_R / \cos(\theta/2) \qquad [7.1]$$

The values above only tell part of the story, however. There is a lateral component acting at the crotch of the eye that wants to tear the splice apart. There are only a few strands working at that location, most likely at unfavourable angles, to resist this force. This lateral tearing force T_T is given by:

$$T_T = \tfrac{1}{2} T_R * \tan(\theta/2) \qquad [7.2]$$

The lateral force value can be used to calculate stresses in thimbles (Fig 7.13) as they often collapse due to this compression. This is especially true when used during testing of ropes to the breaking tension.

If the pin diameter d is known, a convenient method of preparing an eye splice

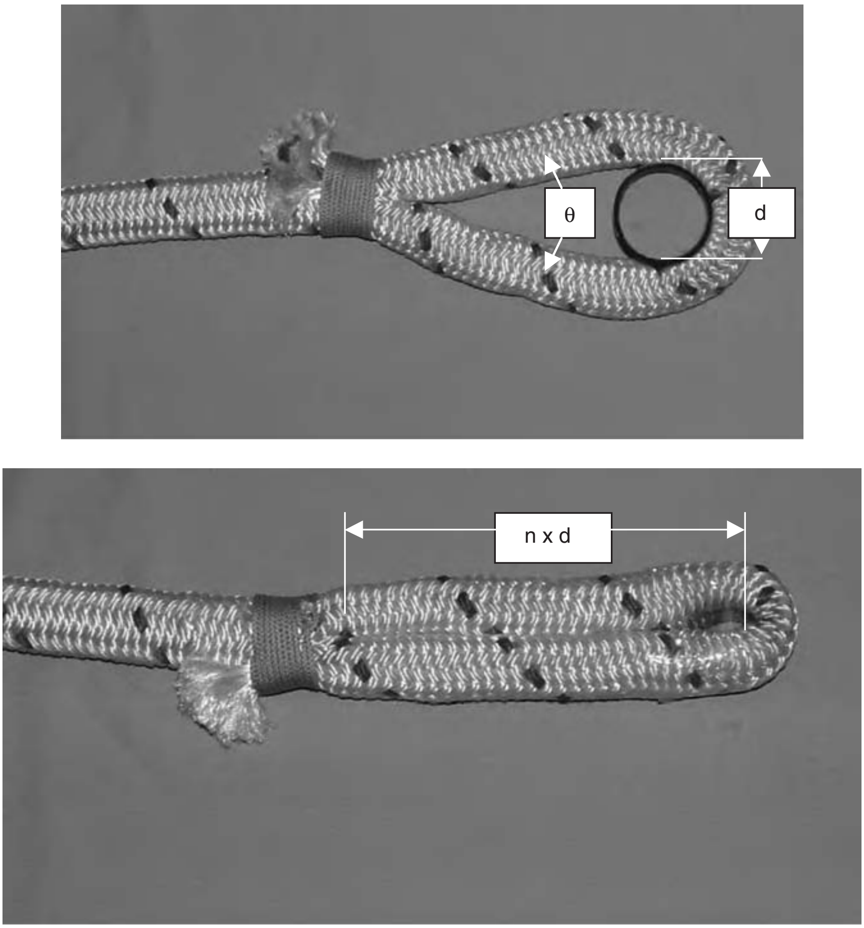


Fig. 7.12 (Top) An angle θ is designated for pin diameter d. (Bottom) The length when the eye is flattened (n × d) is used to measure when starting the splice. Eq [7.3].

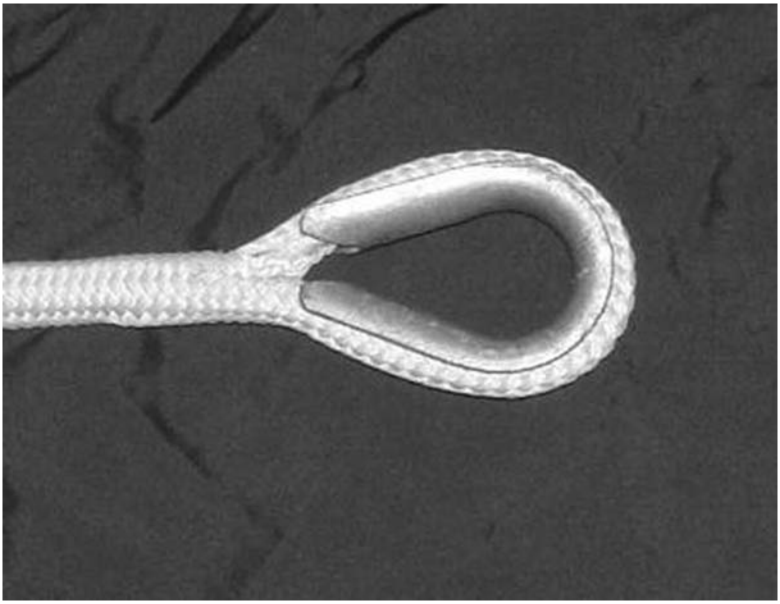


Fig. 7.13 Heavy-duty wire rope steel thimble, closely fitted into eye of a double braided rope. Included angle between legs is about 40°.

Table 7.1 Leg tension T_L and tearing force T_T in eye splice for rope tension T_R of 1000 kgf (1 tonne)

n	θ (degrees)	T_L (kgf)	T_T (kgf)
2	49	549	226
3	26	513	116
4	18	506	79
5	14	504	60

for a particular included angle between the legs is to mark the length of the legs in n multiples of the diameter d before starting the splice (legs of the splice pressed together, see Fig 7.12). The following can be used as a guide when the leg length is nd, and where d is the pin diameter

$$n = 0.5 \times [1/(\tan \theta/2) + 1.57] \quad [7.3]$$

Table 7.1 relates n and θ to values of leg tension and tearing force. The preferred minimum value of n is 3, with 5 or more being best.

If an eye is closely fitted to a standard heavy duty wire rope thimble that is sized to fit the diameter of the fibre rope, the included angle typically is about 40° (see Fig. 7.13).

It is well documented that large included angles cause damage at the crotch of an eye splice and the calculations above provide an explanation. Varying tension causes movement between rope components at the crotch, and hence cyclic loading can cause rapid abrasion in this area of an eye splice where the included angle is large, even if a single loading to ultimate strength may give good results. See Fig. 9.19 for an example of eye damage in the crotch after cyclic loading.

7.3.3 Load distribution in eye splices

Most thimbles or pins that might be used to secure the eye have frictional resistance to rotation. This can cause unequal loading of the legs of the eye. Normally the resistance to rotation is small, but there are exceptions, such as very rough bollards. The unbalance may be caused by poor initial set-up, rotation of the far end of the rope, or slippage of the inserted leg in the splice as load is applied.

7.3.4 Pressure on anchors

Eye splices and grommets are usually anchored to fittings that have a round surface. The pressure between the rope and the fitting can be an important consideration. Damage to the rope is usually evaluated by test or experience, as there is little theory available for determining maximum fibre pressure under varying conditions. Damage to the fibre is almost always caused by cyclic loading at high interface pressures rather than from the compressive failure of the fibre.

Pressure on the fitting itself should also be considered. If polymer-based materials are used as thimbles, the maximum compressive strength of the material can be exceeded. Care should be exercised when testing such fittings; they may be satisfactory at working loads but may fail catastrophically if used during break testing of the rope. Metal fittings normally do not have any problem with pressure at the interface.

All fibre ropes flatten to some degree so the area for calculating pressure can only be estimated. Testing is required to determine the degree of flattening. Once a value for the width after flattening on a pin had been determined, a triangular load distribution from the centre outward would give a conservative value for the maximum pressure at the centre of a pin or thimble (see below). This load distribution can also be used for calculating bending stresses in the pin.

$$\text{Max. pressure-centre of rope} = 2 \times \text{tension}/(\text{width of flattened rope} \times \text{pin diameter})$$

7.3.5 Lateral forces at anchor points

Flattening under load can generate very large lateral forces if constrained on the sides by a thimble, pulley or parallel plates. Polymer thimbles and pulleys with semicircular grooves equal in width to the rope diameter have been split, or flanges broken, by these pressures. Under cyclic loading, wear can be rapid on the rope at the sides of the groove due to lateral pressure when groove width equals rope diameter. Making the side restraints wide enough to allow for flattening does not appear to decrease breaking strength for most rope constructions. Wire rope constructions may be an exception under certain loading conditions and should be evaluated by simulation of the application.

7.4 Mechanical terminations

7.4.1 Description of mechanical terminations

Mechanical terminations use pressure and friction on the rope which is created by an internal conically tapered body (barrel) an internal conical in conjunction with

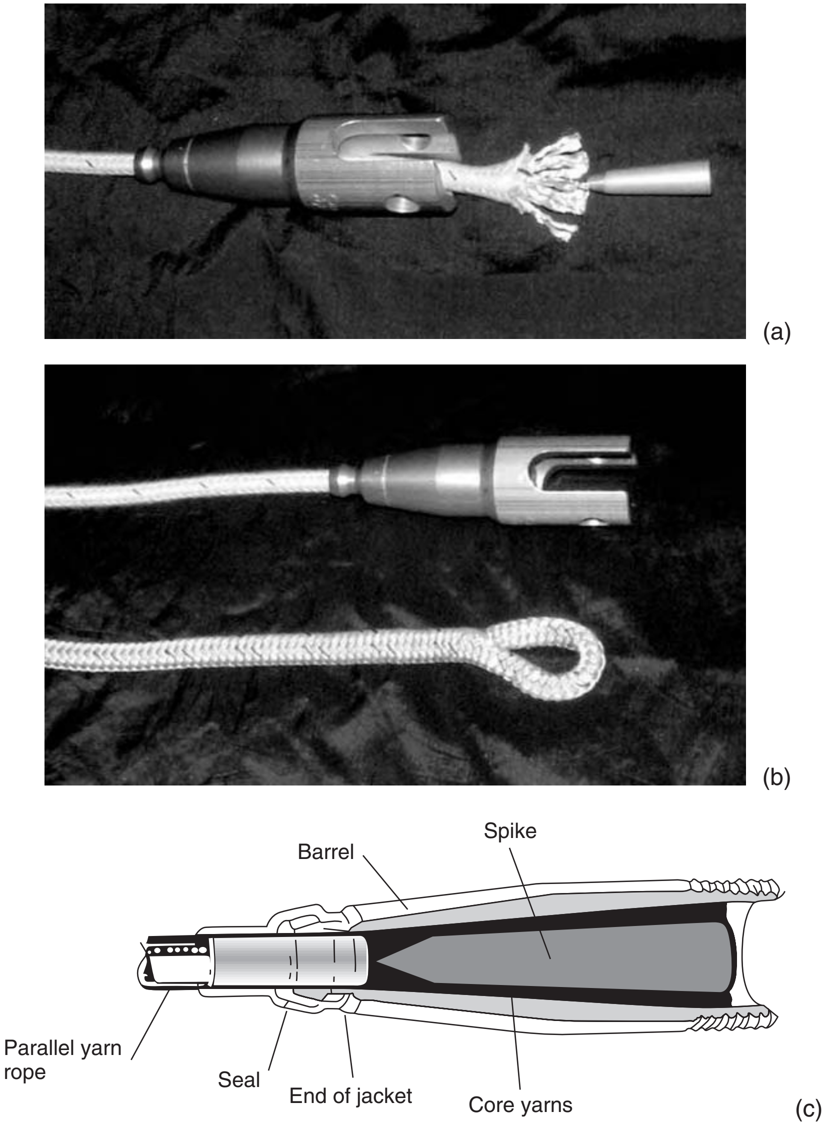


Fig. 7.14 Barrel and spike termination for 10mm rope. (a) Ready for assembly. (b) Finished, with eye splice of similar size braid alongside for comparison. (c) Schematic for parallel yarn rope with extruded jacket. The clevis end is integral in (a) and (b) but it would be a separate piece that screws on in the schematic.

wedge (spike) or collet that increases the pressure as tension is applied. Examples are shown in Figures 7.14 and 7.15. Some initial tightening is required so that the wedge or collet will seat and move on the taper as tension is applied, in order to develop a continuing increase in pressure. Friction between the fibre and fitting, the angle of the taper and its length are the determining factors in the design. It is known that shallow tapers are required. Circumferential grooves or teeth are sometimes added to create a mechanical locking effect with the fibre or to create additional localised pressure to increase the grip.

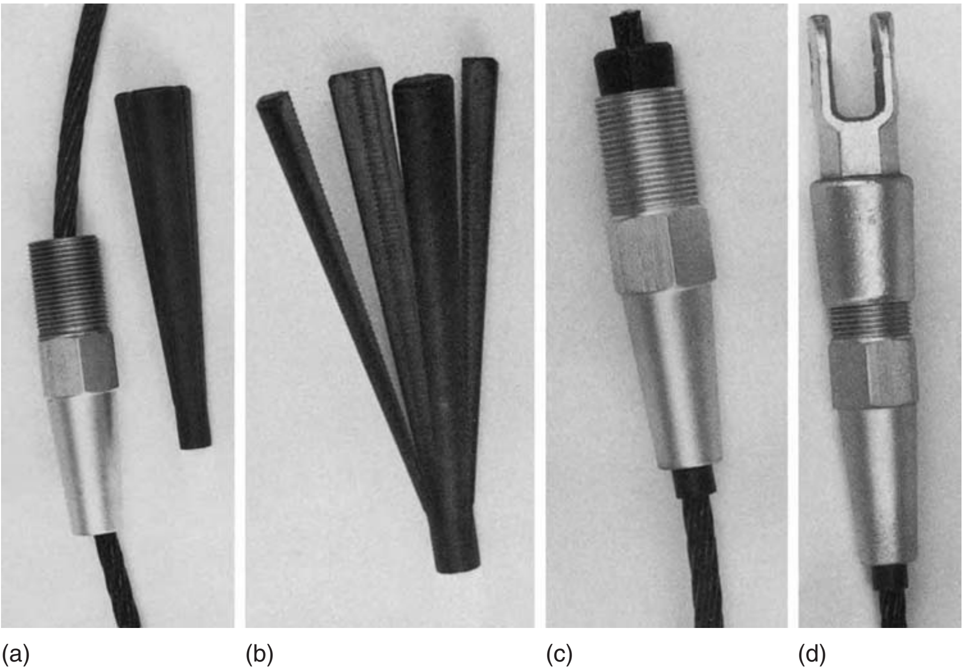


Fig. 7.15 Mechanical termination with segmented collet to grip rope. (a) Socket and split sleeve before assembly. (b) Split sleeve opened. (c) Sleeve around rope inserted into socket. (d) End cap screwed on tightly to press sleeve into socket. Reproduced by courtesy of Electroline.

7.4.2 Performance of mechanical terminations

Designs for mechanical terminations have been developed almost entirely by trial and error as far as gripping ability and fatigue resistance is concerned. Suppliers have conducted testing that shows high strength for certain rope materials and constructions. Some tests on single pulls to break, show rope failures away from the fitting. Limited fatigue tests have shown good results in the range of 10^5 cycles on some terminations, but a few other tests at greater numbers have shown fibre abrasion at the nose of the fitting. Because so many variables are involved between termination design and the rope (material and structure), a potential user is advised to verify the suitability of his application with the supplier of the fitting.

Good results with fittings with segmented collets, Fig. 7.15, have been reported with firm rope constructions of aramid fibre that have a solid extruded jacket such as polyamide (nylon). Due to cold flow under the pressures involved, polyethylene did not perform well as a jacket extrusion material.

Rope strength increases approximately as the square of the diameter while the gripping circumference increases as the first power. Therefore, to maintain the same gripping area and pressure as loads become larger, the length must increase in proportion to the diameter. The result is that, due to the shallow taper angle, fittings become very long. Also, the internal pressure is high, so wall thickness of the tapered body (barrel) has significant weight.

Mechanical fittings tend to be longer in length than an eye splice and thimble combination (see Fig. 7.14(b)). However, they offer more convenient options for interfacing with other fittings or anchor points, they can be installed quickly without special skills, and most are reusable. They are the standard terminations for *Parafil* (parallel fibre) ropes.

7.5 Socketed terminations

7.5.1 Description

Socketed terminations are produced by separating the strands, spreading out the yarns and distributing them inside a conical socket. A resin, usually a 2-part polyester or epoxy, is then introduced and it encapsulates the filaments (see Fig. 7.16).

7.5.2 Mechanics of socketed terminations

The mechanics of this design are difficult to analyse. The modulus of the fibre and the modulus of the encapsulating resin are known to be related to performance. However, performance prediction by analytical means remain elusive.

It is interesting to note that only a few millimetres of length are needed to grip a single filament of 50 μ diameter (typical filament size) with sufficient adhesion to break it. However, if a rope is 24 mm diameter, a socket that is only a few millimetres thick would be like a thin wafer and not strong enough. So the socket must be made longer, but only the first few millimetres provide the adhesion.

As a practical matter, socketing is mostly done with no tension in the rope so the diameter as it enters the encapsulation is fixed at the zero tension level. However, when it is loaded the rope diameter decreases but the socketing resin is incompressible and does not move. This phenomenon causes an abrupt lateral step at the rope/resin junction around the circumference. This lateral displacement increases in magnitude as size increases. It is essential that the unlaying of the rope, separating

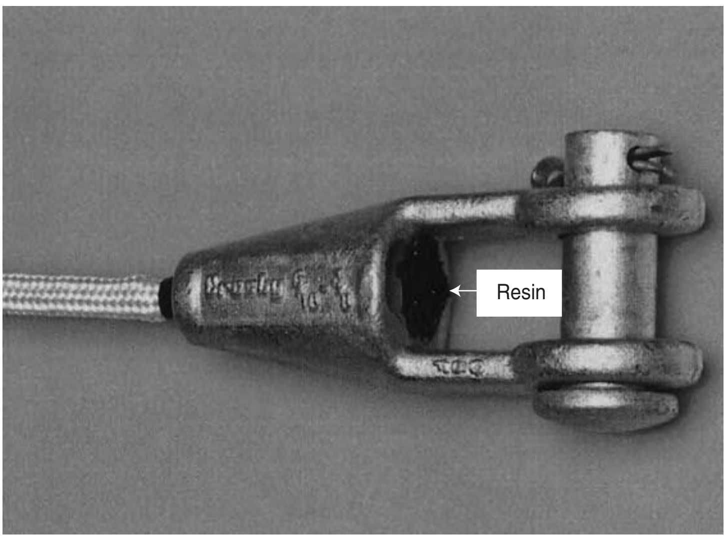


Fig. 7.16 Socketed termination. Socketing resin can be seen at the top of the cone.

the yarns and spacing between the end of the rope structure and the face of the socket resin, take this into account. A suggested solution for large ropes is to separate the yarn bundle into segments (McKenna, 1996; Flory, 1997).

7.5.3 Socketed termination performance

Producing a socketed termination that will achieve good and predictable results is not an easy process. Any socketed fitting used for a critical application should be done by a procedure that is proven or verified by prototype testing.

Small sizes in the range of 12 to 24 mm have shown more success than larger sizes. Very large size (over about 60 mm) lack a good record.

Socketed terminations are commonly used for steel wire ropes, originally made with molten metal but now with resins. Consequently, many potential users of large ropes who wish to replace steel wire rope, like to use socketed terminations. They see the socketing process as much easier and they have people familiar with it. But even if a reliable socketing design were available, the fittings would be very large and heavy, and comparable to a spliced eye with a thimble. At this point in time, for large ropes in critical applications, it appears that the proven reliability of spliced eyes should be considered first.

7.6 Thimbles and pins

7.6.1 Introduction

For an eye splice or a grommet, the rope must be placed over a smooth curved surface. Metal thimbles, Figures 7.13 and 7.17, are the most common devices. Polymer spools, Fig. 7.18, and other approaches could be used and would follow the general rules for thimbles provided below.

Sections 7.3.2 to 7.3.5 cover forces and other parameters related to fibre ropes under tension that pertain to the strength and configuration of thimbles and pins.

7.6.2 Thimbles

Some rules and guidelines for thimbles:

- The semicircular groove for the rope should allow room for it to flatten
- The surface must be smooth; galvanising is desirable.
- Thimbles designed for synthetic rope should be used (Fig. 7.17). These have ears that prevent the thimble from falling out of an eye or from turning.
- For wire rope thimbles, Fig. 7.13 thimbles should be retained by whipping or other means to prevent turning or falling out. Spliced eyes will enlarge with use so that a thimble can become loose.
- Cyclic loading will cause abrasion on the metal surface. A covering of polyester or HMPE fabric will extend the life considerably.
- Spools made of nylon or other plastic materials have been found to significantly reduce surface abrasion under cyclic load conditions (see Fig. 7.18). The variety of materials that might be used is extensive, so verify suitability. Be certain to check the rated capacity and analyse specially-designed spools for adequate strength.
- Thimbles designed for conventional ropes should be used with caution for high modulus, high strength ropes.

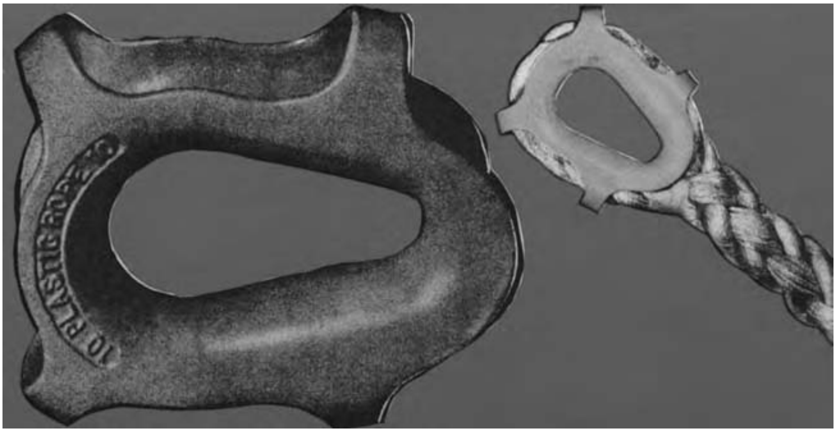


Fig. 7.17 Fibre-rope thimble. From Lowery Brothers Product Catalogue, New Orleans, 1983.

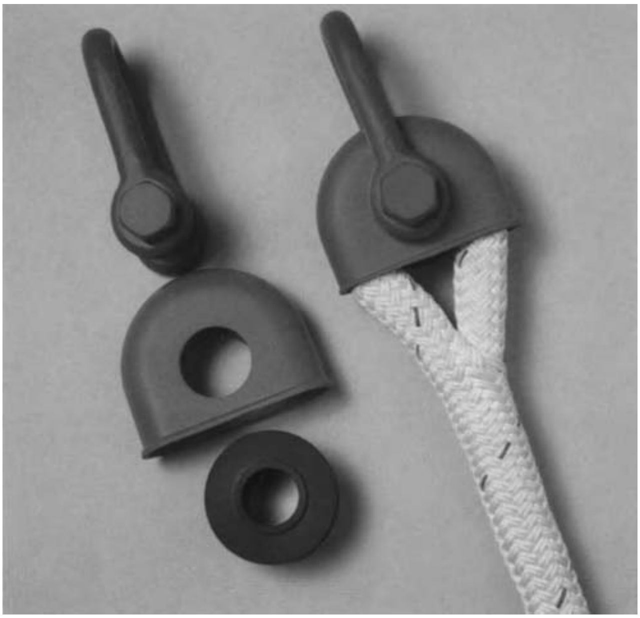


Fig. 7.18 Nylon spool thimble with flexible cap and matching shackle.

7.6.3 Links

Special links can be very useful in providing a removable link or to eliminate the need for a thimble/shackle combination which are heavy and cumbersome. They can be used to connect two fibre ropes or a fibre rope to a wire rope. The Tønsberg link and Mandal shackle are nearly identical, as seen in Fig. 7.19. Another specially-designed fitting is seen in Fig. 7.20. They provide a more favourable radius than if the rope were bearing directly on a shackle without a thimble.

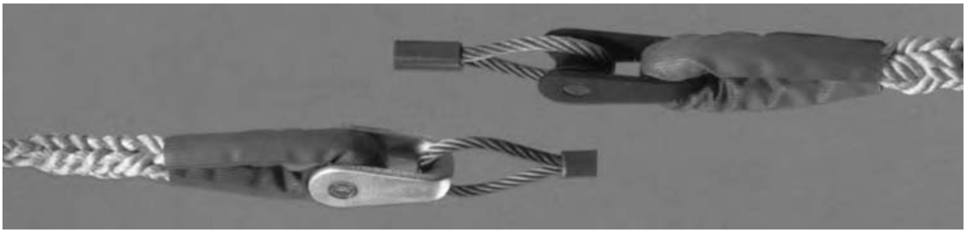


Fig. 7.19 (Upper) Mandal shackle. (Lower) Tønsberg mooring link. Reproduced by courtesy of ScanRope.

Fig. 7.20 Custom-made thimble adds function of shackle into one fitting. When pin is taken out, the rope eye can be inserted or removed. Reproduced by courtesy of Samson Rope Technologies.

7.6.4 Pins

For pins, diameter is the main consideration. The following points are made for making pin selection.

- For conventional ropes with eye splices, a pin diameter equal to the rope diameter will give a high break strength as a percentage of what is normally expected. It will not work well under long-term cyclic loading.
- A pin diameter of two times the rope diameter, for conventional ropes, gives good results but wear will occur under long-term cyclic loading. Going to three times the rope diameter may not reduce the wear. Inspect the

rope under the pin on a regular basis and retire it as appropriate (see Chapter 9).
- For grommets (two legs working), a greater pin diameter is needed. At two times the rope diameter, a grommet may only provide about 65% the strength that two working legs would provide. Reasons for this disparity are the pin size and difficulty in equalising the load in each leg.

7.6.5 Boating and sailing

A large selection of terminations has been developed for boating and sailing. The variety makes it impractical to cover them. However, the principles of use are the same as for other fittings.

7.7 Wire rope clips and swaged sleeves

External pressure is one way of gripping the free end of a rope, as it is when a rope is held by hand. Wire rope clips and swaged sleeves (which form an eye) work in the same manner. They create sufficient friction from pressure to prevent the clamped end from slipping along the body of the rope. This requires considerable pressure (see Fig. 7.21). Tension reduces the diameter of the rope so that some clamping ability is lost.

In the figure, three swaged sleeves are employed. This would be a minimum but these are heavy sleeves and tightly clamped. Clips are more difficult to tighten and more are required There are many variables involved in the use of these devices so hard rules are difficult to come by.

Rope strength should be reduced by at least 50% before calculating a working load. Even this may be too little if the clips or sleeves are not applied in sufficient number and tightness. For critical applications, testing should be performed and strict assembly procedures applied; the working load limit should be based on the termination strength.

7.8 Cleats, bitts and bollards

Traditional cleats, bitts (two posts) and bollards (single posts, more often used as the anchor for an eye) use friction from wraps of rope around the devices. This is a common way of securing ropes (refer to Fig. 7.22). Some guidelines for use are given in Section 8.4.10. The rope tension reduces with the angle of wrap according to the well-known exponential capstan relation (see Section 8.4.6). This means that only a small tension, or even the weight of the free end, is needed to hold a large rope tension.

In yachts, it is usual to use various forms of cleats whereby a rope is gripped by friction combined with pressure created by wedging action, usually between teeth formed into the fitting. Clam and V-cleats utilise a fixed V-shaped channel. Cam cleats are rollers that rotate off-centre to increase the pressure on the line as tension increases. These devices are designed for quick engagement and release but cannot come close to holding the full strength of the rope; parts may fail on cam cleats, and the rope may slip and possibly be damaged on all of them.

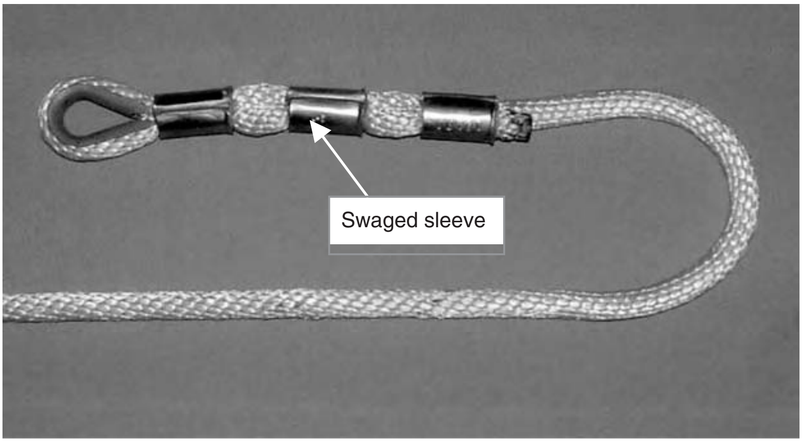


Fig. 7.21 Wire rope clip (above) and swaged sleeve on 12 mm nylon solid braid (below). Clips work the same as the sleeves except that they are tightened by bolts.

7.9 Stoppers

Stoppers are used to hold tension on the body of a rope by lacing another rope around it. This relieves tension on one end so that some kind of operation may take place (see Fig. 7.23).

7.10 Knots, bends and hitches

Knots, bends and hitches* are a convenient way of terminating any flexible rope construction; however, they become impractical for large sizes (over about 24 mm).

* Terminology is variable. *Knot* is commonly used to cover all interlacings of ropes and cords, but is sometimes limited to interlacings, such as a thumb knot, in the middle of a rope. *Bends* refer to joining of two ropes. *Hitches*, used for example to fix a rope to a post, fall apart if allowed to be free.

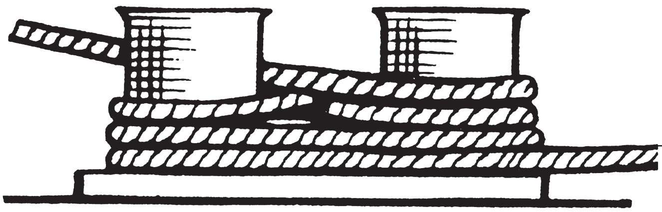


Fig. 7.22 Mooring line terminated on a set of bitts (above) and cleat (below). Reproduced by courtesy of Samson Rope Technologies.

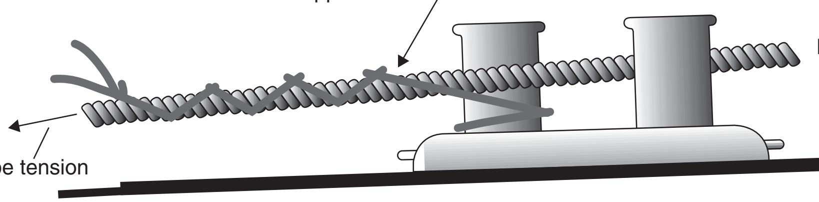


Fig. 7.23 Fibre rope stopper. A rope wrapped around the main rope to hold tension.

Figure 7.24 shows a knot used to secure a rope that is not spliceable to a shackle. Note the rounded shape of the shackle, which optimises performance.

Friction, pressure, adverse angles and sharp turns weaken ropes at knots. The percent of rated breaking strength ranges from 80–90% for an anchor bend to 43–47% for a square (reef) knot (Columbian Rope Co., 1986; Dunn, 1977). The grip-

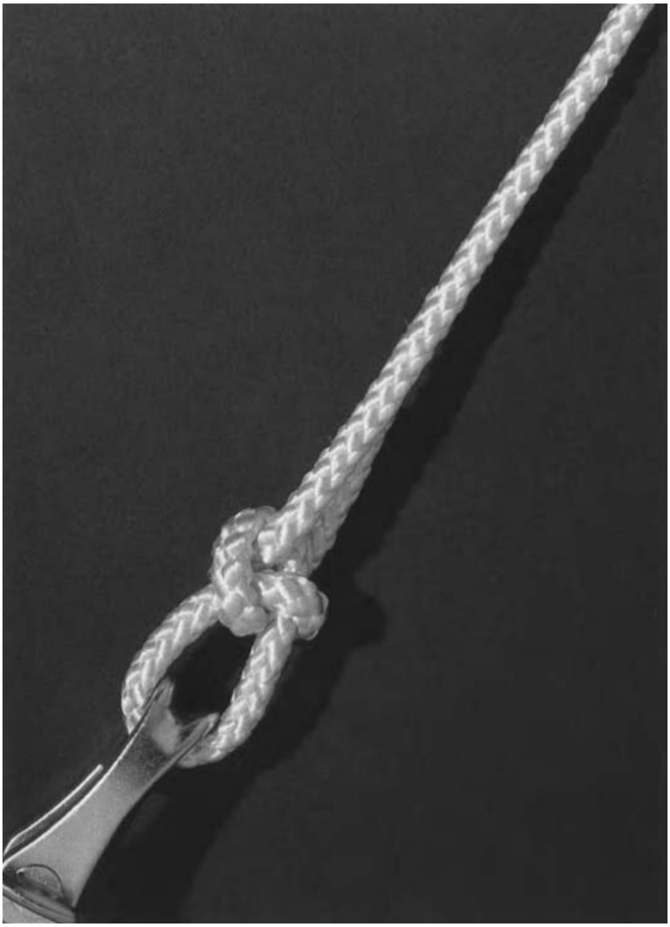


Fig. 7.24 Knot used on sail boat with non-spliceable braided rope. Note generous radius on fitting. Reproduced by courtesy of Samson Rope Technologies.

ping force depends on rope friction and bending stiffness, as well as on the type of knot. For example, a square (reef) knot can only be used to join identical ropes; it slips with different ropes. A bowline knot is one of the most efficient and can be untied; it should be used whenever it is appropriate.

Jarman (1986) is a general reference on knots. Smith and Padgett (1996) contains a great deal of information on the use of knots in climbing.

8

Use of rope

8.1 Introduction

History and the obvious place of rope in modern society and industry demonstrate the value of fibre rope. Obviously, the service life is paramount. Whether it is successfully arresting a fall of a rock climber or providing years of service as a mooring line on an ocean-going vessel, the operator must choose the right rope and use it properly. This chapter will discuss the use of rope for many representative applications. From these descriptions, the reader should be able to relate to his own situation. More details of selected special cases are given in Chapter 12.

An important fact to keep in mind when using rope is that although ropes are frequently overloaded and break, most rope failures are caused by severe localised damage or an accumulation of wear that weaken them to the point that they break at ordinary working loads. External abrasion and cutting are probably the most common causes of damage. Also, constant use for long periods of time, perhaps at excessive loads, causes internal damage due to fibre-on-fibre abrasion and consequent loss of strength. In many cases, the rope is kept in service well beyond a reasonable life and not considered for retirement until it is literally falling apart. See Chapter 9 on inspection and retirement, which are important components of rope usage.

In many situations rope can be dangerous. The recoil that occurs when a rope breaks at high tension can be lethal, even in sizes as small as 12 mm. People can also become entangled in a rope leading to loss of a limb or death. Lifelines and rescue ropes must not fail when arresting a fall or when supporting a person. Therefore, suitable selection and proper use can be essential in protecting life and property.

In this chapter, safe use guidelines will be presented first. This will be followed by a list of applications that will briefly describe an activity, name the common fibre materials and rope constructions that might be used, mention the important properties at work, and provide notes on use.

8.2 Safe use guidelines

8.2.1 Estimating the load

Always attempt to estimate the maximum load that might be applied to the rope. Some suggestions:

- If lifting a weight, make an effort to estimate the mass. If necessary, find someone who can do this as the methods are well known. Handbooks providing the density or specific gravity of materials are readily available and the weights of many objects are in catalogues or data sheets.
- Weigh a single item and multiply by the number of items. Limit the number of items so as not to exceed the maximum load.
- Base an estimate on experience. For instance, in tree service activities, workers have learned how to estimate the weight of limbs based on diameter, length and type of wood; they cut smaller pieces if the estimate is over the limit.
- Ropes that are used regularly for the same service can have the load measured with a tension meter during initial operations or continuously.
- History may have shown what has worked well in the past. Check with knowledgeable persons or use personal experience and estimate the load accordingly.
- Ropes in good condition may be breaking for no apparent reason other than overloading. This can be a clue as to the load if the rated strength of the rope is known.
- If dynamic loads are involved, estimate the acceleration and apply a multiplier. A factor of two is likely to cover all but the most severe cases.

Estimating the tension in a rope by looking at it, kicking it or listening to it is not reliable. Do not be deceived by anyone who says he has this capability.

8.2.2 Working load limit

Never use a rope at a load near its rated breaking strength (the minimum expected terminated strength – Section 4.2.4). This seems obvious, but it happens too often, sometimes with disastrous consequences. Establish a working load limit (WLL) that should not be exceeded.

Determine a design factor (often called safety factor). The working load limit is determined as follows:

$$\text{WWL} = \text{Rope rated strength}/\text{design factor} \tag{8.1}$$

The rated strength of a rope used in this calculation should be the minimum expected terminated strength (see Section 4.2.5).

Design factors less than five are rarely used for fibre rope applications. If risk is high, loads difficult to estimate and usage not controlled, design factors of 12 or higher may be appropriate.

In some documentation, the load limit is expressed as a percentage of the break load. Thus a design factor of 5 would correspond to a maximum allowable load (WLL) equal to 20% of rated breaking strength.

Consider the following when selecting a design factor:

- Seriousness of the consequences if the rope should fail.
- How accurately can the loads be estimated? Factors well above five should be selected if reasonable estimates cannot be made of the maximum tension.

- In high risk situations, can a stronger rope be used if the extra size and weight will not encumber the operations? If so, choose a design factor higher than a minimum that might be considered.
- How long will the rope be used and will it be inspected? If a person selecting a rope knows that it will not be retired until it is frayed, has broken strands, is contaminated with dirt, and shows other signs of damage, then a very high design factor should be selected.
- Are dynamic or shock loads anticipated (see Glossary)? Use a higher factor to cover dynamic loading if not allowed for in load estimation and an even higher value for shock loading.
- Are knots being used? If so, reduce the rated strength value of the rope by the strength efficiency (see Section 7.10) before calculating the WLL; if strength efficiency is not known, use 50%.
- How well-trained are the operators or those who will inspect the rope? Are safe operating procedures in place and being followed?
- Can the rope be damaged by unusual circumstances that may not be avoidable? Examples: slipping that may cause localised melting, sharp corners or bends, being left under load for long periods of time, constant flexing.
- Design factors less than five may be used if the operation is defined, conducted under well-controlled procedures, the loads have been accurately predicted, and appropriate inspection and retirement criteria have been established. Design factors less than five should be established by a qualified person.

One problem is that if the application is displacement driven, for example by the rise and fall of a vessel due to waves, selecting a stronger rope also increases the rope stiffness. Consequently, the peak tension will increase if the displacement remains fixed. The use of a stronger rope may not solve the problem and could overload fittings and anchors. Extensibility is controlled by the rope's material, construction, length, or a combination of these.

It may not be possible to predict the maximum load that may be placed on a rope and operational factors may prevent the selection of a larger and/or stronger rope; at the same time, it is essential that a fibre rope be used for the particular application. In this case the operating procedures must take into account the dangers associated with a rope parting under high tension and all appropriate precautions must be taken.

8.2.3 Recoil

Any rope will recoil when it breaks under tension. Some research with nylon and polyester ropes in the order of 50 mm have measured speeds in the order of 180 m/sec (650 km/hr, 600 ft/sec, 400 mph), about half the speed of sound when severed near the maximum rated strength. Loading was done by taking up on a slack line with a massive armoured military vehicle travelling at modest speed. It should be obvious that there is virtually no time for a person to react to the danger after a rope breaks. In most such accidents, the person does not even see the line that hits him.

Ropes that are in a straight line between load and anchorage or tensioning device will recoil mostly in a straight line. The dockhand in Fig. 8.1 should not be standing where he is, especially since a well known break point occurs when mooring lines are bent over a fairlead or chock. The rope will develop a zigzag pattern that is not very wide, no more than a metre or two depending on rope type, size and length, as shown in Fig. 8.2(a). The rope will fly past where it is secured to a distance no

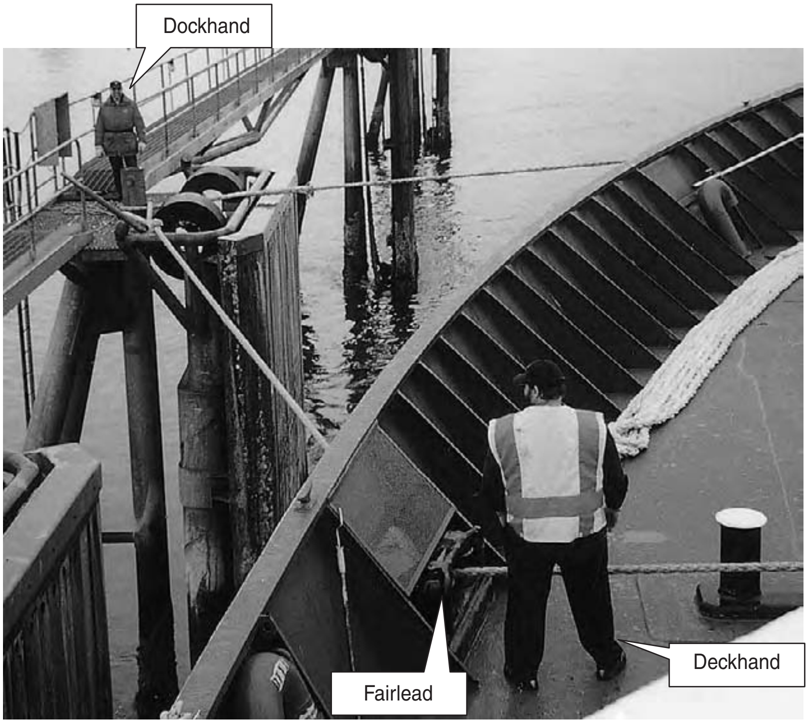


Fig. 8.1 Do not stand in line with a rope under tension. The dockhand is in danger: The deckhand is safe if the line parts at the fairlead, and fairly safe if it breaks to his right.

more than the length to the break point. However, it can strike and bounce off an object or anchorage point and move to the side.

Ropes are often wrapped around some type of structure or vertical winch. If the line breaks beyond such a structure, it will recoil and swing around it and sweep a wide path. A common example is a bollard or fairlead on the deck of a ship where a mooring line is led from a winch, around a fairlead or post, across the deck to a chock and then to the shore. A point of break at a chock is most likely if the mooring line is overloaded; the recoiling end will sweep around the fairlead across the deck as shown in Fig. 8.2(b).

Anchorages are often not as strong as the rope secured to it. The anchor fitting can break or be torn off its mounting. The energy stored in the rope will cause the device to fly through the air, pulling the rope with it. A similarly dangerous situation occurs when wire rope or chain is used to secure an auxiliary fitting through which the rope is led. The following is a sad example. A size eight (64 mm) polypropylene mooring line (strength 36 tonnes) was run through a turning pulley with a 45° wrap and tensioned with a winch rated at 15 tonnes. The pulley was secured by a 10 mm wire rope (strength 7.5 tonnes). The wire broke; the pulley was projected across the deck and struck a deckhand, killing him.

8.2.4 Bending and slippage

Rope that is bent over a small diameter can break unexpectedly. Rapid failure is often caused when a rope slides over a tight radius while under high tension;

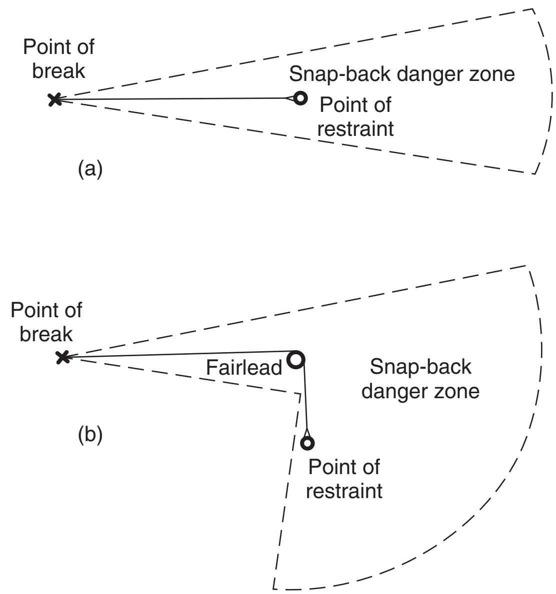


Fig. 8.2 Snap-back danger zones (a) for break of a rope in a straight line, and (b) for break where rope direction changes. If the break is at the fairlead, the danger zone is reduced.

friction causes localised melting which weakens the rope considerably at that point. Sliding can be caused by the stretch in the rope as tension is applied. It can occur when a load shifts. These effects may also happen when a rope is bent over itself or another rope. The sharp radius and any sliding that may occur can create a potential for breakage.

8.2.5 Guidelines for safe usage

A list of guidelines for safe usage of rope is provided below. In spite of the length of the list, every possible circumstance may not be covered. Operators must be aware of their own particular circumstances of operation and develop safe usage practices.

- Specify a working load limit. Do not overload ropes.
- Never stand in line with or next to a line under tension (see Fig. 8.1.) Identify recoil danger zones for all potential break points of lines that are wrapped around objects (see Fig. 8.2). Identify recoil danger zones if an anchorage or auxiliary fitting should fail.
- Never stand under a load.
- Make allowance for dynamic or shock loading if these are a possibility.
- Avoid sharp bends on a rope.
- Provide padding of effective thickness for sharp bends or when slippage is a possibility.
- Do not bend lines over themselves or other ropes when under tension. Use appropriate fittings, such as chocker hooks on slings, to provide a smooth radius.
- Verify that elevated temperatures or use near chemicals will not damage the rope.

- Avoid contamination by grit. Bottom sediment in marine environments can be damaging. Seawater that has dried leaving salt crystals is a known source of internal fibre abrasion. For these situations, tension cycling leads to progressive deterioration.
- Do not use knots unless required, and make allowance for strength reduction.
- Use a proper knot. Some knots tend to slip, especially with nylon and polypropylene.
- Do not allow laid ropes to twist by using them with swivels or attached to freely suspended loads.
- Wire rope that is not torque balanced can be damaged when used in series with fibre rope of torque-free construction. The fibre rope acts like a swivel and the wire rope will unlay as load is applied; the consequent twist introduced into the fibre rope may weaken it.
- Do not drag ropes over rough surfaces or pull them from under a load.
- Do not use ropes on winches or capstans that have the capacity to severely overload them; change to a stronger rope.
- Inspect ropes frequently, ideally with every use (see Chapter 9).
- Establish retirement criteria (see Chapter 9).
- Establish safe operating procedures and train operators.

8.2.6 Standards for safe use

Many standards and publications are available that provide guidance for safe use and good operating practices. Some are:

- Life Safety Rope, Harnesses and Hardware, ANSI/NFPA 1983–2001
- Pruning, Trimming, Repairing, Maintaining and Removing Trees – Safety Requirements, ANSI Z133.1 – 1994
- Safety Requirements for Window Cleaning, ASME A39.1 – 1995
- Safety belts, lifelines and lanyards, OSHA – 26 CFR 1926.104
- Fall protection systems, criteria and practices, OSHA – 26 CFR 1910.502
- Fall protection, OSHA – 26 CFR 1926.760
- Slings, OSHA – 26 CFR 1910.184 (ASME B30.9 is more up-to-date)
- Slings, ASME B30.9, Chapter 4
- Rigging Manual, Construction Safety Association of Ontario, 1975
- ISO 9554, Fibre Ropes – General Specification

8.3 Rope uses

Table 8.1 gives a long list of rope uses that demonstrates the utility and versatility of fibre rope.

There is going to be disagreement on whether a particular fibre and construction is the best for any application that is cited in the list. Rope users can be very opinionated, but understandably, as there is so much variety in rope types and how they are used. The list reflects what is known to be popular and the intent is to associate a use with rope properties.

Sizes listed are approximate and are intended to be typical of most applications.

Many uses have been omitted. Do not select a rope solely on the basis of this list. See Section 8.2 for guidance on rope selection.

Table 8.1 Summary of uses for rope

Use	Typical rope	Important properties	Notes
Arborist rope – climbing	Polyester/Polypropylene blend 12-strand hollow braid. About 12 mm	Mandated strength 24 kN (USA), abrasion resistance, firm, low stretch	Used for climbing, support while working, and as life-line in case of a fall. Usually not spliceable Other rope types also used. See Fig 8.15
Arborist rope – load handling	Polyester/Polypropylene blend 12-strand hollow braid. 18 mm to 32 mm	Strength, abrasion resistance, firm, low stretch	Used for lowering cuttings, dragging. Must absorb impact as cut tree parts often fall before rope picks up load. Usually not spliceable. See Fig. 8.15
Barging – US inland waterways – facing lines	HMPE 12-strand hollow braid. 24 mm to 40 mm	Low stretch, high strength, abrasion resistance, flex fatigue resistance	Replaces steel wire rope. Lines tensioned by winches hold pusher tug into barges. Runs around pulleys successfully. Creep should be monitored. See Section 12.5
Barging – US inland waterways – mooring	Polyester/polypropylene blend, 3-strand laid most popular. 48 mm mostly	Strength, moderate elongation, abrasion resistance, frictional properties	Widely used in locks to arrest motion and secure barge rafts in order of 25 000 tonnes. Stopping done by surging on bitts. Good frictional performance from polyester/polypropylene blend. See Fig. 8.16
Caving	Kernmantle, various types. 9 mm to 11 mm mostly	Similar to rescue ropes depending on conditions	For details, see Smith and Padgett (1996)
Clothes-line	Cotton, manila, nylon, polyester, polypropylene solid braids popular. 6 mm typical	Low cost, firm, round. Works well with clothes pegs	Cotton solid braid of 6 mm diameter has been the most popular but almost every type of rope is used. Commonly used for undemanding utility use at home and industry. Also see sash cord

Table 8.1 *cont'd*

Use	Typical rope	Important properties	Notes
Cranes	Aramid, HMPE, LCP – wire rope construction. 12 mm to 24 mm	High strength, very low elongation, flex fatigue resistance, corrosion resistance	For lifting and controlling boom. Mostly under study but some applications. Will most likely require polymer pulleys. Replaces wire rope
Electrical utility service, boom truck winch line	Polyester braid-on-braid. 24 mm to 32 mm	Strength, abrasion resistance, low stretch, non-conducting if dry.	Used on winch on boom to handle transformers, poles, etc. for electrical utility service work. Non-conductor of electricity is essential. See Fig. 8.17
Electrical utility service, boom truck winch line	HMPE 12-strand braid with heavy polyester braided jacket. 24 mm to 32 mm	High strength, abrasion resistance from heavy jacket, very low stretch, non-conducting if dry.	Same service as above. HMPE gives smaller line for same strength or stronger line for same diameter. Low stretch is extra benefit in this service. Higher cost than all polyester. See Fig. 8.17
Elevators for tall buildings, deep mines.	LCP, aramid, HMPE	High strength, very low elongation, flex fatigue resistance	Under study to replace wire rope at same diameter. Attractive for deep mines and very tall buildings due to greatly reduced weight
Fishing – trawl net recovery line	HMPE 12-strand braid, 8-strand plait. About 48 mm	High strength, abrasion resistance	Successfully replaced heavy wire ropes used to recover massive nets with 50 tonnes and more of fish onto vessel
Fishing – lead line	Polyester or nylon hollow braids	Moderate strength, abrasion resistance	Rope is tightly braided over a lead core. Used to weight bottom of fishing nets
Fishing – purse seining	Polyester braid-on-braid About 18 mm	Strength, abrasion resistance, smooth/round surface, low stretch	Line runs through metal rings to close net. Must run smoothly and resist wear from rings. Marine finish greatly improves abrasion resistance

Guy lines	Aramid – wire rope and parallel fibre, parallel strand.	Very high strength, very low elongation, non-interference with radio and micro-wave, non-conducting	Used on tall radio and micro-wave towers. Light weight a benefit. Usually covered with extruded jacket. Mechanical terminations are common
Lariat rope	Nylon, 3-strand laid. 10 mm	Hard lay	Wax-like coating makes line smooth and stiff in bending. Used by professional cowboys to rope animals in competitions. Fig. 8.18
Life lines, safety lanyards, fall arrest lines	Polyester or nylon, braids and 3-strand laid. Typical 10 mm to 14 mm	Mandated strength of 22.2 kN (USA).	Manila not allowed in USA
Messenger lines, heaving lines, fore runner lines	Polypropylene, nylon braid and laid. 6 mm typical	Low cost, light weight	Used to pull mooring lines to shore, and similar applications to pull-in other ropes or cables
Mooring – deep-sea oil platforms	Polyester primarily, Parallel strand and wire rope construction. 120 mm to 200 mm	High strength to 1500 tonnes. Well defined elongation properties, spliceable	New application that replaces wire rope for deep-sea mooring of oil production and drilling platforms for very deep water. See Section 12.3
Mooring – offshore oil loading buoys	Nylon and polyester braids, 8-strand plait, parallel strand. 120 mm to 240 mm	Very high strength, energy absorption capacity, fatigue resistance	Once the leading market for the world's largest ropes. See Fig. 8.19
Mooring lines – commercial vessels	Polypropylene 8-strand. 36 mm to 72 mm	Moderate strength, modest elongation, modest abrasion resistance, floats	The most popular mooring line. Low cost. Laid ropes also popular. These lines give good service and reasonable life. Buoyancy is a principal benefit
Mooring lines – commercial vessels	Polyester 8-strand, braids and laid 36 mm to 72 mm	Good strength, modest elongation, good abrasion resistance, does not float.	These lines give good service and life. Moderate cost. Selected for longevity and ability to withstand damage from overloading. Weight a negative

Table 8.1 *cont'd*

Use	**Typical rope**	**Important properties**	**Notes**
Mooring lines – commercial vessels	Nylon 8-strand plait, braids and 3-strand laid 36 mm to 72 mm	Good strength, high elongation, modest abrasion resistance.	Good energy absorption and ability to accommodate draft and tide changes. Moderate cost. Not as rugged as polyester but slightly less weight
Mooring lines – commercial vessels	Nylon mono-filament and multi-filament 6-strand laid. 36 mm to 72 mm	Good strength, hard and stiff in bending, moderate elongation, mono-filament has good abrasion resistance	Good energy absorption and ability to accommodate draft and tide changes. Moderate cost. Winds well on winch drums, should have large radius chocks and fairleads
Mooring lines – reduced recoil	Aramid + nylon 4-strand laid. Each strand jacketed. 24 mm to 36 mm	Strength, reduced recoil if line breaks, needs good frictional characteristics on capstans and bitts.	Developed to improve mooring safety on military vessels. Nylon component breaks after aramid, absorbing some of the energy. See Fig. 8.20
Mooring lines – high performance commercial vessels	HMPE 8-strand plait and 12-strand braid. 24 mm to 60 mm	Very high strength, lightweight, floats, very low elongation, low friction	The strength and light weight are desirable. However, low elongation requires frequent tending due to tide and draft changes. Low friction makes them difficult to work on capstans and bitts. Most are used on drum winches. Very high cost but can reduce crew size
Mountaineering	Kernmantle, dynamic rope, nylon. 9 mm to 11 mm popular	Strength, high elongation, energy absorption capacity	For details, see Smith and Padgett (1996) and case study Section 12.10
Power line stringing, pulling line	Polyester braids, parallel strand and parallel fibre. 22 mm to 36 mm	High strength, moderate elongation	Long lengths (several kilometres) are used to pull wire rope through towers that are then used to pull high-voltage electrical conductor
Power line stringing, pulling line	HMPE, aramid parallel strand and parallel fibre	High strength, low elongation	Long lengths (several kilometres) are used to pull high voltage electrical conductor through towers

Power line stringing, pilot line	Polypropylene braid. 8 mm to 12 mm	Moderate strength, lightweight, varied colours	Long lengths (several kilometres) are used to pull pulling line through towers. Helicopters used. Colours help prevent crossing of lines between towers
Rappelling (controlled descent by climber or rescue worker using mechanical braking device)	Kernmantle – see rescue rope. 9 mm to 11 mm popular	Strength, abrasion resistance, smooth round, low stretch, good frictional characteristics	For details, see Smith and Padgett (1996)
Recreation – water ski tow rope	Polypropylene 12-strand hollow braid. 6 mm	Moderate strength, easy to splice, colourful. Strength 5.8 kN (1300 lbs) (USA Water Ski Assn.)	Similar applications – para sail tow, rope tows for skiers, traverse ropes, tent ropes
Rescue rope	Kernmatle, static rope, polyester. 9 mm to 11 mm popular	Strength, abrasion resistance, low stretch, non-rotating preferred	For details, see Smith and Padgett (1996) and Section 12.10. Other types also used
Rock climbing	Kernmantle-see mountaineering. 9 mm to 11 mm popular	See mountaineering	For details, see Smith and Padgett (1996) and Section 12.10
Salvage in deep water	Polyester, nylon, HMPE, aramid. Various types and sizes.	Strength, good flex fatigue resistance.	Must run over pulleys and wind on winches. Elongation a benefit in most cases due to heaving of salvage vessel. Wire rope too heavy and inelastic for deep sea operations
Sash cord	Cotton, cotton nylon reinforced, polyester solid braid. 6 to 8 mm	Low cost, runs well over pulleys	Cotton solid braid of 8 mm diameter has been the most popular. One of first uses for solid braid after braiding machinery invented in late nineteenth century

Table 8.1 *cont'd*

Use	Typical rope	Important properties	Notes
Ship handling lines	Polyester, some nylon, 3-strand laid or braided. 40 mm to 72 mm	Strength, moderate elongation, abrasion resistance, fatigue resistance	Used to manoeuvre ships in harbours. Severe service with large tugs in bad environmental conditions. Sizes limited to about 72 mm due to weight for crews. Surging of tugs requires moderate elongation to absorb shock. Size depends on tug pulling capacity
Ship handling lines	HMPE lines, 12-strand hollow braid or 8-strand plait. 32 mm to 60 mm	Strength, low elongation, abrasion resistance, fatigue resistance	Used to manoeuvre ships in harbours. Much lighter and easier on crews than polyester. To accommodate any surging of the tug, special procedures are required since energy absorption capacity is less than polyester. See Figures 8.21 and 8.22
Slings	Any type and size.	Strength, abrasion resistance, low elongation, spliceable	Popular industrial use for high performance, high quality ropes. ASME B30.9 and other standards apply. See Section 8.4.12
Staging, circus, aerial acts	Mostly polyester, some HMPE and aramid. Braids, plaits and laid. 6 mm to 18 mm and larger for special cases	Strength, easy to handle, reliable, flex fatigue resistant, hold knots	Replacing natural fibre ropes. Braids, 3-strand laid and plaits all popular. Aerial acts can use very customised constructions
Tie-down – for vehicle load securement	Polypropylene and polyester. Any rope type, 3-strand laid and hollow braids most common. To about 24 mm	Moderate strength, flexible, low stretch, good knot retention, moderate abrasion resistance, UV resistance	See North American Cargo Securement Standard, CI 2007 or other applicable standard. Black polypropylene monofilament with UV inhibitor often used

Towing lines and springs	Nylon and polyester lines, laid or braided. 64 mm to 150 mm	Strength, moderate to high elongation, tension fatigue resistance	Springs are series insert to add elasticity to wire rope tows. All fibre rope tows can have shorter scope, better surge modulation and less drag in the sea than all wire rope
Tug-of-war	Manila, staple wrap polyester, 3-strand laid and braids. 28 mm or larger	Easy to grip. Moderate strength, low elongation	Avoid small diameters as grip is difficult (except for small children). Low elongation is much safer. Fuzzy surface of staple wrap polyester is OK but do not use smooth braids or rough mono-filament polypropylene
Winch lines	See 'Electrical utility service'		See 'Electrical utility service'
Window cleaning	Braided polyester. Nylon occasionally. 11 mm to 18 mm	Strength, abrasion resistance, smooth round, low stretch, good frictional characteristics	The rope should be selected in accordance with the advice of the maker of the rappelling (braking) device that is employed. Also, see Smith and Padgett (1996)
Yachting – anchor lines	Nylon braids, 3-strand laid, plaited. To 36 mm	Strength, high stretch, abrasion resistance	Elasticity to absorb surges due to wind and waves. Chafing at fittings on vessels requires protective gear. Large vessels use chain
Yachting – running rigging and halyards	HMPE or LCP, braided core with polyester jacket. To 14 mm	High strength, very low stretch, abrasion resistance, flex fatigue resistance	Becoming popular for high-performance boats and yachtsmen who can afford the cost. See Section 12.11 and Fig. 8.23
Yachting – stays	Aramid, LCP. 10 mm	High strength, very low stretch and nearly zero creep	Replaces metal rods. Lightweight, non-corroding
Yachting – running rigging, halyards	Polyester braid-on-braid. To 18 mm	Strength, low stretch, abrasion resistance, flex fatigue resistance	A wide variety of ropes are used. Polyester braid-on-braid is the most popular and is made in a variety of styles. Colours are used for identification. See Section 12.11 and Fig. 8.23

8.4 Guidelines for using rope

8.4.1 Introduction

Various operations that are employed when using rope are discussed below. Chapters 4, 5, 7 and 9 also provide important information related to the use rope and should be studied carefully.

8.4.2 Removing rope from reels and coils

It is important not to introduce twist in a laid rope when removing it from reels and coils as this will cause it to kink more readily. Actually, twist is not good for any rope. Follow these rules:

- *Reels.* Set up the reel so it can rotate about the horizontal axis. Pull the rope directly off the reel while it rotates. Do not remove the rope by pulling it around a flange with the other flange sitting on the ground (see Fig. 8.3).
- *Coils.* Pull the rope from the centre of the coil unless advised differently by whoever prepared the coil.

When storing a rope for rapid deployment in the future, arrange it as a figure eight. In that way, it may be pulled out directly without twist (see Fig. 8.4).

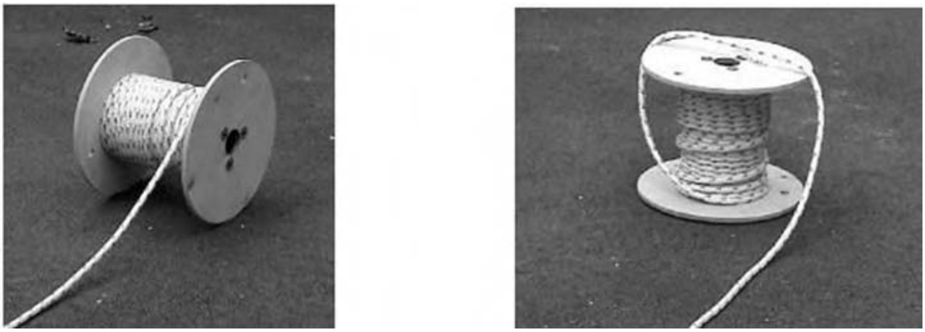


Fig. 8.3 Take rope from a reel by unwinding, as on the left. Do not pull off the rope by walking around the flange, as seen on the right.

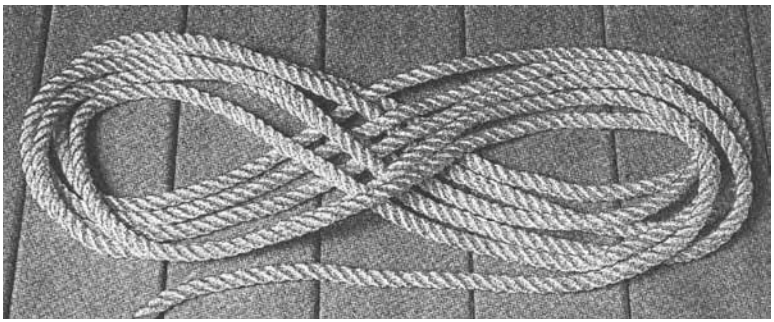


Fig. 8.4 A good way to coil a rope so that it can be pulled out without introducing a twist.

8.4.3 Box storage

To calculate the approximate box volume for a specific length of rope:

$$\begin{aligned}\text{Volume} &= K_{\text{box}}\pi(d^2/4)L \times 10^{-6}\\ &= K_{\text{box}}d^2L \times 7.85 \times 10^{-5}\end{aligned} \qquad [8.2]$$

where: Volume is in m^3
K_{box} is 1.8 for compactly faked (distributed) rope
K_{box} is 2.3 for loosely faked rope
d is rope diameter in mm
L is rope length in metres

The dimensions of the box can be calculated from the required volume.

8.4.4 Reel storage

To calculate the required approximate reel volume for a specific length of rope:

$$\begin{aligned}\text{Reel volume} &= K_{\text{reel}}\pi(d^2/4)L \times 10^{-4}\\ &= K_{\text{reel}}d^2L \times 7.85 \times 10^{-3}\end{aligned} \qquad [8.3]$$

where: Reel volume is in m^3
K_{reel} is 1.7 for tightly wound rope
K_{reel} is 2.2 for loosely wound rope
d is rope diameter in mm
L is rope length in metres

$$\begin{aligned}\text{Reel volume} &= (\pi/4) \times (B^2 - C^2) \times A\\ &= 0.785 \times (B^2 - C^2) \times A\end{aligned} \qquad [8.4]$$

where: A is the inside width between flanges on reel in metres
B is the outer diameter of rope on a full reel in metres
C is the barrel diameter (inside diameter) in metres.

From this, an appropriate combination of A, B and C can be determined if the length and diameter of the rope are known.

If a particular reel has been selected, the length in metres of a specific size that will fit onto it is:

$$\text{Length} = [10^4 \times (B^2 - C^2) \times A]/[K_{\text{reel}}d^2] \qquad [8.5]$$

Developed from Dunn (1977).

The outer flange diameter should be at least two rope diameters greater than the B diameter: even more if many layers are on the reel, especially for small ropes.

8.4.5 Reel crushing pressure

Winding multiple layers of fibre rope onto a reel or drum under tension can create very high crushing forces. Unlike steel wire rope which can support the layers above it, fibre rope has little or no resistance. The rope tension creates an internal pressure that acts on the barrel and the flanges as a fluid under pressure. Each layer adds to the pressure created by the layer under it. Winch drum barrels that were suitable for wire rope have been known to collapse when many layers of fibre rope have been used, even at lower tensions.

A single layer of rope will exert a pressure on the barrel equal to twice the rope tension divided by the projected area, namely the barrel diameter times the rope diameter. In the next layer, the effective barrel diameter has increased by two rope diameters, and so on through the layers, all of which contribute to the pressure exerted by the first layer on the barrel. Assuming that the rope is wound onto the drum at constant tension, the summation for many layers gives the following expression for the pressure on the barrel:

$$\text{Barrel pressure} = (2T/d)\left\{[D]^{-1} + [D+2d]^{-1}[D+4d]^{-1} + \ldots\ldots[D+2(n-1)d]^{-1}\right\} \quad [8.6]$$

where:	barrel pressure is in N/mm^2	(or lbf/in^2)
	T is the constant tension in N	(or lbf)
	d is the rope diameter in mm	(or inches)
	D is the barrel diameter in mm	(or inches)
	n is total number of layers.	

Stress, except at the end points, may be determined by treating the barrel as a cylinder under external pressure.

8.4.6 Reel flange forces

For the reasons cited above, multiple layers of fibre rope can create a large pressure against the flanges. The forces that are generated push the flanges outward, causing a shear stress, and create a large bending moment at the barrel. There is an additional tensile stress at the inside corner where the flange joins the barrel since the barrel has been compressed by the rope pressure (see above) but the flange, being very rigid, restrains it. This adds to the tensile bending stress. Weld failure at this corner is common.

Common design practice is to weld a disc into the inside of the barrel, under the flange, to eliminate the compression of the barrel at that point. Finite element analysis is needed to determine this stress in the barrel ends and flange interface.

The first and last elements of equation [8.6] can be used to calculate the force and centre of pressure against the flanges in order to calculate the bending stress.

8.4.7 Winch drums

Besides the high forces described above, fibre rope is generally more difficult to deal with on winch drums than wire rope. A typical use of winch drums is in mooring a ship to a dock. An excess length will be wound off the drum, fixed to a bollard, and then wound back on the drum to apply the correct tension to the rope.

Upper layers will bury between underlying wraps. Winding might continue, but when it comes time to pull line off the drum, nothing but trouble will be encountered. Some guidelines to avoid problems with multiple layers of rope on drums are:

- If possible, put the underlying layers onto the drum under tension before adding layers above under tension. The winding force should be some modest percentage of the maximum tension and should be determined experimentally.
- Level wind the rope tightly, at least the underlying layers (see Fig. 8.5).
- Use rope with a very firm structure. The six-strand laid rope made with nylon monofilaments works well on marine mooring winches. The softer the rope, the more difficult it is to work.

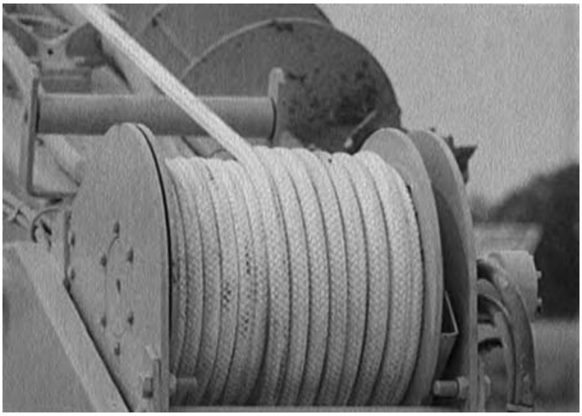


Fig. 8.5 Compact winding of braid-on-braid rope into a winch drum, as used on an electrical utility service vehicle. Reproduced by courtesy of Samson Rope Technologies.

- Use split drums. Here the drum has an intermediate flange with a split that allows the rope to pass through to the other side. Low tension storage is done on one side. In the final stages of winding the rope back on the drum, when the tension becomes high, the rope is passed through the intermediate flange and one or two layers are wound on the high tension side. Since the high tension side has only the barrel diameter or a layer more, the torque on the winch is less for a given tension than if on top of the stored volume (see Fig. 8.6).
- Use double drum traction winches and low tension storage on a separate reel (see Section 8.4.8).

Good fleeting* is more critical than with wire rope. Level winding facilities may be necessary to prevent the rope from building up in the centre of the drum or against one flange. Level winders should use rollers with a large diameter; eight times the rope diameter is suggested for laid, plaited or braided ropes. If rollers are not used, polymer guides, such as nylon or high density polyethylene, will give better service than metal.

Secure the tail of the rope tightly in the barrel or on the flange. It should hold the maximum tension expected to be applied to the rope with one wrap on the drum.

Never operate the winch with less than five full wraps on the barrel. HMPE ropes should have at least eight wraps.

See the comments about drives in Section 8.4.9. These also apply to drum winches.

8.4.8 Double drum winches

Double drum winches are traction devices that use friction to grip a rope. The rope enters at high tension and exits at low tension (see the schematic of Fig. 8.7 and the picture of Fig. 8.8). Some type of take-up device needs to apply a moderate back tension and to store the rope as it is retrieved. Usually, the take-up is a powered reel.

* Fleeting is changing the angle of approach of the rope to the drum, which should be kept as small as possible for even winding.

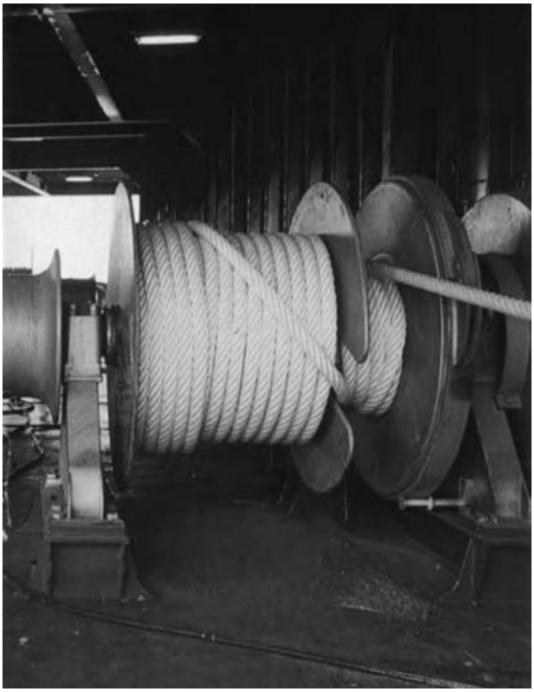


Fig. 8.6 Split drum winch with 6-strand Atlas-type rope. Storage is on the left, crossover through the flange, and high-tension on the right at the smaller diameter.

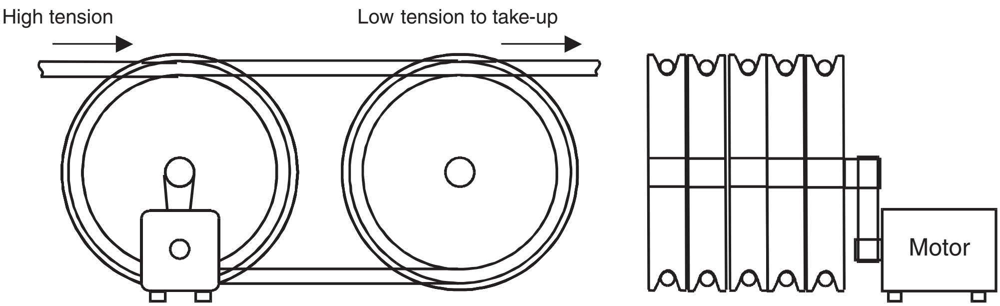


Fig. 8.7 Schematic of double-drum traction winch.

The relationship for calculating tension is:

$$\frac{T_1}{T_2} = e^{\mu\alpha} \tag{8.7}$$

where: T_1 = High tension
T_2 = Low tension
μ = Coefficient of friction
α = Wrap angle in radians

The wrap angle includes all wraps of all the grooves.

Fig. 8.8 Traction winch with 80 mm (size 10) polyester double braid for ocean towing and salvage operations.

If the groves on the drums are V shaped, the expression $e^{\mu\alpha}$ becomes $e^{\mu\alpha/\cos\theta/2}$, where θ is the total included angle of the V. However, V grooves put a higher pressure on the rope, may distort the rope structure and may cause excessive abrasion. This must be weighed against the extra grip that will result in fewer grooves and lower loads on the winch structure.

The wet coefficient of friction is higher than dry for fibre rope on metal. Calculations based on dynamic, dry values should be used for determining total grip, and static, wet for determining maximum loads on the winch structure.

The forces between drums are determined by adding all the rope tensions on both sides of every groove. These can accumulate to a very large value, several times the incoming tension. The bending stresses in the drum shafts and bearing loads must be carefully analysed.

When pulling in, the tension in the entering grooves remains at the initial tension until slipping begins. The point at which this happens is determined by the take-up tension. If the traction winch has excessive grooves, the first wraps remain at the high incoming tension; thus the loading on the shafts can be much higher than necessary. The point at which slipping begins is also determined using the wet, static friction coefficient. The wraps that involve tension reduction are calculated using the dry, dynamic friction coefficient. However, this kind of precision is usually unnecessary as the actual coefficient of friction is very difficult to estimate accurately and the necessary design allowance should cover the differences.

If take-up reels must store a large amount of line, it is likely that the full drum diameter will be several times that when nearly empty. Since most reels have a constant torque drive, the empty reel tension can be several times higher than when it

Table 8.2 Sample calculations based on a constant upper tension. The first data set compares varying friction coefficients with a fixed number of wraps, and the second data set compares the friction coefficients with the number of wraps that would result in approximately constant lower tension. The friction coefficients cover the range usually encountered with fibre rope on smooth steel; lowest for HMPE, highest for manila

Traction drum winching								
5 Wraps								
Coefficient of friction	0.05	0.06	0.08	0.1	0.12	0.14	0.16	0.18
Number of wraps	5	5	5	5	5	5	5	5
Upper tension (tonnes)	201	201	201	201	201	201	201	201
Minimum lower tension (tonnes)	41.8	30.5	16.3	8.7	4.6	2.5	1.3	0.7
Lower load < 5 tonnes								
Coefficient of friction	0.05	0.06	0.08	0.1	0.12	0.14	0.16	0.18
Number of wraps	12	10	8	6	5	5	4	4
Upper tension (tonnes)	201	201	201	201	201	201	201	201
Minimum lower tension (tonnes)	4.6	4.6	3.6	4.6	4.6	2.5	3.6	2.2

is full. This means that there will be more full tension wraps on the winch when the take-up tension is high due to a near empty reel.

When letting line out, the tension on the take-up side remains at the low take-up value until slipping begins and the rope tension within the winch begins to raise. Thus, during payout of line, there are lower loads on the winch shafts and bearings as the high tension wrap angle will be less than when pulling.

To provide against slipping and subsequent danger of loosing the line, a design margin is often applied by making the take-up capacity greater than the minimum tension. The number of wraps can then be near the minimum, which minimises forces on the winch structure. However, if the take-up device has the risk of going into free-wheel due to power loss or break down, then a backstop on the take-up end is needed to protect against uncontrolled payout.

Table 8.2 provides some sample calculations. Note the sensitivity to friction coefficient and number of wraps.

8.4.9 Capstans and gypsy heads

Ropes are commonly tensioned on capstans and gypsy heads (see Figures 8.9 and 8.10). Here friction is used as with the double drum winch. The theory is the same, except that a person usually applies the force on the low tension side by pulling on the rope. And, instead of two drums, the rope is wrapped, helically, around a single drum. Usually, four, five or six turns are used, as seen in Fig. 8.10.

The usual mode of operation is to allow the drum to turn while controlling the line from behind. The drum turns at constant speed while the line moves at the speed the operator can pull it in, slower and intermittently. The more force applied by the

Fig. 8.9 Vertical capstan winch. Using seven turns, which essentially locks the rope onto the drum, this winch is operated by switching the motor on and off, rather than letting the drum turn inside the rope.

Fig. 8.10 Controlling a line on a gypsy head driven by an anchor windlass on a large ferry. The weight of the rope on the low-tension side is enough to hold the tension. The operator can release the tension incrementally by bumping the tail, or shaking it.

operator, the greater the pulling force. A balance can be reached which will cause the line to stop moving but the drum will continue to turn, thus holding a fixed tension.

In Table 8.2, if a friction coefficient of 0.14 is used, five turns produces a ratio of back tension to pulling tension of 80:1 ($T_1/T_2 = 201/2.5 = 80$). If the operator is applying a force of 20 kgf, the line pull will be 1600 kgf (1.6 tonnes). A strong person might be able to pull 60 kgf with considerable effort, so it is unlikely that a tension of $60 \times 80 = 4800$ kgf (4.8 tonnes) can be exceeded.

Adding a sixth turn in the above example will increase the ratio to almost 200. So, a 60 kgf force by the operator can produce a tension of nearly 12 tonnes. This may be too high for the rope or may stall the winch. Note that by specifying the number of turns and by having trained operators, the maximum tension on the line can be controlled to some degree.

The operator may stand to the side or behind the winch, which may be safer, so partial turns are also possible.

Even if the drum is turning in the pull-in direction, the operator can pay out line by reducing the force on his end. Because the drum is always turning, the dynamic friction coefficient remains fairly constant and operation can be smooth and controllable.

Because of the helical wrap on the drum, the rope wants to move along the drum in the axial direction, as if it were a screw thread. Because of the flange on the end of the drum, the incoming line pushes the wraps already on the drum to the side. With the drum turning faster than the line, this sideways motion can be very smooth and the wedging action that must occur between the incoming rope, the flange and the first wrap on the drum is not excessive. It is much like removing a cork from a bottle; if it can be made to turn, it comes out much easier.

If many wraps are put onto the drum, or if the line is moving with the same speed as the drum and is static on the drum, the incoming line may climb up on top of the wraps already on the drum instead of pushing them along the circumference. This is called an overriding turn and will disrupt the operation completely. There is potential for overriding turns for the capstan in Fig. 8.9 as there are seven wraps on the drum.

With many wraps, the drive must be turned on and off to pull in or release line. The incoming rope is forced between the drum flange and the first turn under considerable pressure because it takes so much force to push the wraps along the drum; this may lead to severe abrasion. Finally, with the rope virtually fixed to the drum, there is little or no limit to the tension except switching the motor off, stalling the machinery or breaking the rope, whichever comes first.

If the drive is turned off and the drum stops (a backstop or brake must be functioning to prevent runaway), the friction coefficient goes from dynamic to static, and it takes much less force on the operator end to hold the line. An example is the gypsy in Fig. 8.10, where the weight of the rope is enough to provide the back tension with four and a half wraps. In this situation, a rising tide has caused an increase in mooring tension and the operator is letting out some line by bumping the line on the drum with his hands so that it will slip in small increments, a procedure that requires considerable training.

The operator must not stand close enough to be pulled into the drum if the line should surge suddenly. He should not stand in excess rope behind the capstan or gypsy, and be aware of places that the line might part, fittings break or anchorages fail. The safest place to stand should be located, consistent with the ability to perform the task at hand.

Gypsy heads on large vessels are often an auxiliary attachment to powerful chain windlasses or drum winches, but driven by the same machinery. The force that can be developed by the gypsy if too many turns are used may be more than the strength of the rope, or at least in excess of a safe limit. This should be checked and the number of turns limited accordingly or other procedures implemented to prevent overloading.

Electric motors can have a stall capacity more than twice their normal design rating. Electric drives can exert more force in a rope than stated in the rated design specifications for a capstan or winch. Therefore, stalling an electric drive with rope may lead to dangerous tensions.

The relief valve on hydraulic winches usually limits overloading to a small percentage of the rating, but dumping the hydraulic fluid over this valve for an extended period can severely overheat the fluid. Most direct engine drives (diesel / gasoline) will have a noticeable drop-off in speed and stall relatively rapidly if overloaded.

8.4.10 Bitts

Bitts are twin posts, as seen in Figures 8.11 and 8.12. Friction is used to hold a rope and the theory is the same as for double drum traction winches. Bitts are unpowered so cannot pull line, but they are often used as brakes to pay out line under tension. Friction will vary between static and dynamic as the operator feeds line intermittently, as he normally would do.

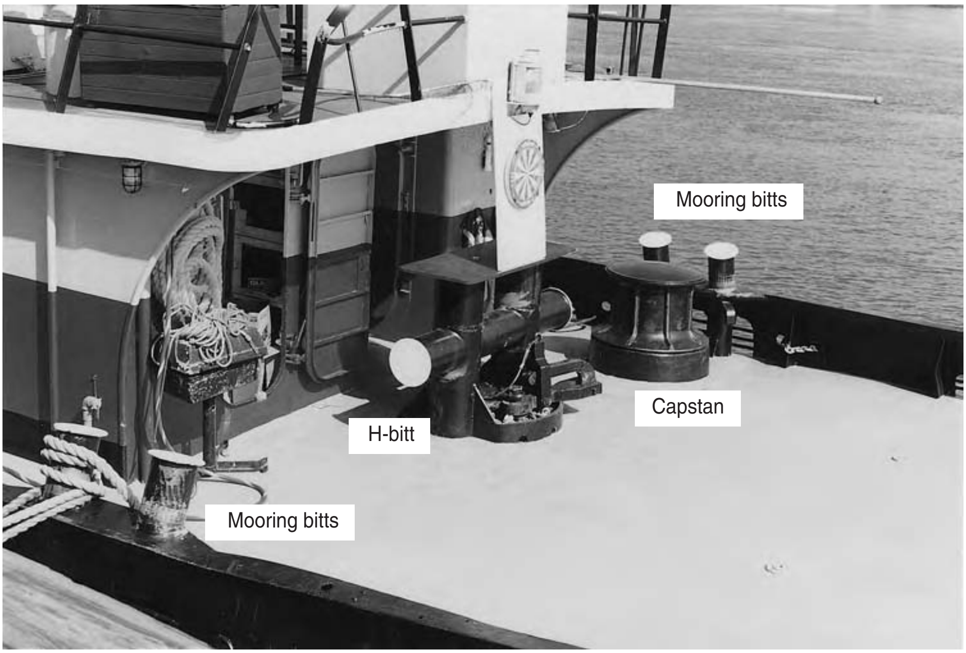


Fig. 8.11 Tug with H-bitt for towing with fibre line and vertical capstan. Bitts for quayside mooring can be seen on top of the rails.

Fig. 8.12 Working a line on bitts. The operator should have taken a full turn about the first post before starting the figure-of-eight configuration.

As with capstans, limiting the number of turns can give some control over tension. However, when the point at which slip begins is reached, the friction changes from static to dynamic. If long lines are involved, a considerable length of rope may move rapidly through the bitts before the tension falls enough for it to stop. Due to the danger of rapid slipping, extra wraps are needed for safety.

As tension increases, the operator can see the first wraps tightening on the bitts. Experience can be used to know when to feed line to the bitts to relieve tension.

The operator must always stand back far enough so that he will not be pulled into the bitts in the event of a sudden surge. He should not stand on excess rope behind the bitts and be aware of places where the line might part, fittings break or anchorages fail. The safest place to stand should be located, consistent with the ability to perform the task at hand. Remember that a recoiling line will go past the bitts and then swing around.

8.4.11 Suspended cables and guy lines

Some notes about fibre ropes that are used as a suspended cable or guyline are in order. Experience with steel wire rope should not be assumed to be the same as with fibre rope.

An excellent example of a suspended cable is one used for supporting a target that is towed between two points, as seen in Fig. 8.13. Here, an aramid rope of wire rope construction has been suspended between two mountains some miles apart. The weight and electronic interference precluded the use of wire rope for this weapons test facility.

If a permanent installation with relatively high tension and fixed anchors is involved, some things to be aware of are:

- Use a fibre material that has a low creep rate. These are likely to be aramid, LCP, PBO or polyester.

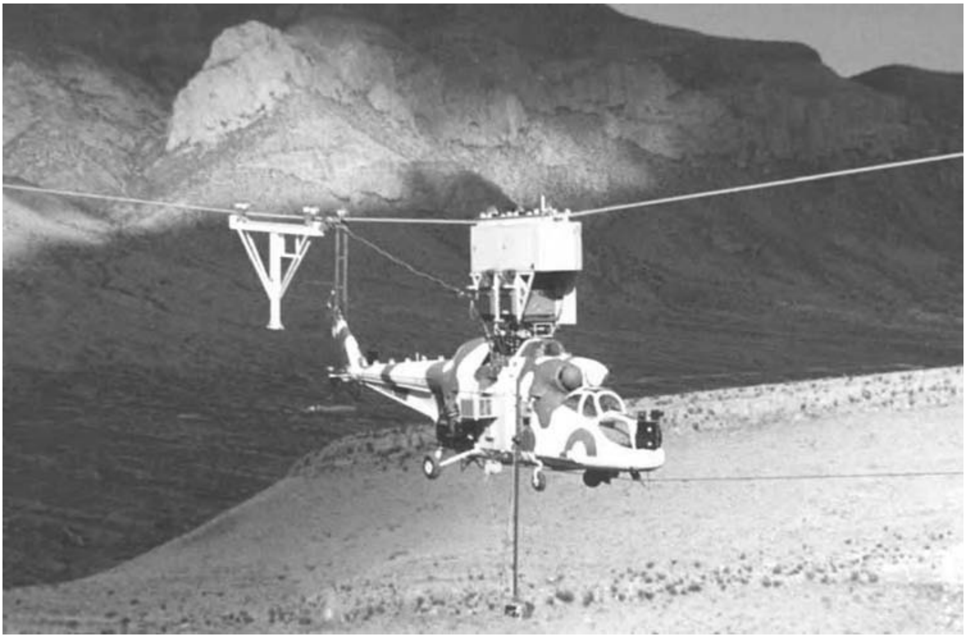


Fig. 8.13 Aramid cable in wire rope construction. The cable runs between two mountains and is used to suspend military targets for research. From Du Pont literature.

- All ropes have permanent elongation due to mechanical settling-in of the structure. The rope should be cycled above the maximum design load if possible. This is often done by using a tensioning device once the cable is installed. There are too many variables to give specific recommendations. Long cables can be 'stretched' on machinery similar to a double drum traction winch but with tapered drums. Unfortunately, the equipment is expensive, becomes massive for large ropes and may require different drums for each type of rope.
- Some creep will occur in most cases and this results in tension relaxation. Some type of retensioning facility is normally required.
- Polyester has significantly more creep than the other fibres that were mentioned, but it stabilises rapidly and will show very little creep after a short initial phase. This can vary with high tenacity polyester fibre from different suppliers so the user should check creep data carefully. Retensioning is usually required, but the length may be minimal.
- An increase in tension due to external forces (example: wind, waves) can result in a large increase in sag because the elongation of the rope results in changes in cable length. Sag in tightly suspended cables is very sensitive to changes in length: that is, a tiny change in length can result in a large change in sag. The lower the rope modulus, the greater the effect.
- Apply a pretension that is high enough so that the cable will not go slack under load variations induced by external sources. Unloading or very low tensions can be damaging if cyclic loading is involved.
- Strumming and galloping can be problems. This should be investigated. The lower modulus of fibre ropes may result in surprisingly different performance compared to steel wire rope due to tension-related sag variations.

- The mathematical relationships for defining the shape of suspended cables are available in texts on applied mechanics. By knowing the creep rate and the modulus of the rope, the performance of the system can be accurately analysed.

The light weight, high strength and corrosion resistance of fibre ropes makes them ideal candidates for modern suspension bridges, though they have only been used on one or two small bridges. Actually, man has been using such fibre rope bridges since pre-history. Their wider use is currently under investigation for vehicular traffic involving very long spans, but the engineering challenges go well beyond the cable itself and some resistance to their use may be psychological.

8.4.12 Slings

Fibre rope slings are made by splicing a section of rope into an eye-and-eye configuration or as an endless sling (grommet). They work with hooks, shackles or other fittings to connect to or go around items that are to be lifted. Because of the wide use of slings in industry and safety considerations, regulatory guidelines have been established. The advice in Section 8.2 is definitely applicable, but more detail will be found in documents such as ASME B30.9.

The working load limit (also known as rated capacity or rated load) can be calculated from the following (see Fig. 8.14 for the different sling hitch types and bend requirements):

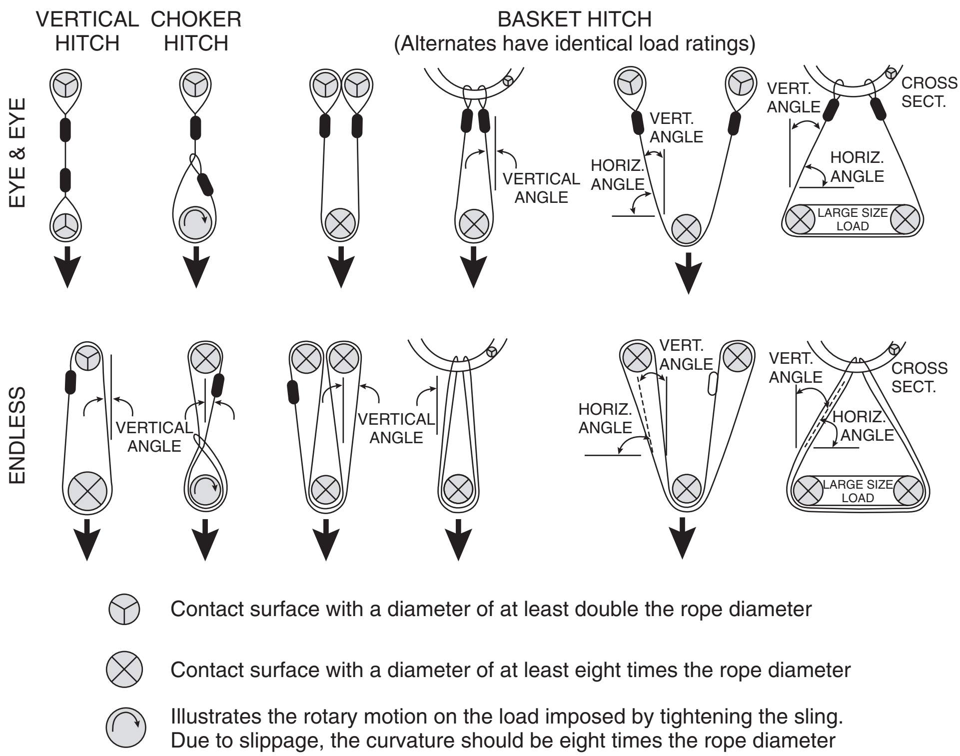


Fig. 8.14 Types of hitches for slings. Reproduced with permission from Cordage Institute Manual.

Fig. 8.15 Arborist at work.

Design factor = 5 (minimum by regulation in USA)

Eye-and-eye slings

- Vertical hitch WLL = Min. breaking strength / design factor
- Choker hitch WLL = 0.75 × Min. breaking strength / design factor
- Basket slings WLL (vertical legs) = 2 × Min. breaking strength / design factor
- Basket slings WLL (inclined legs) = 2 × Min. breaking strength × cosine (vertical angle)* / design factor

Endless slings

- Vertical hitch WLL = 1.8 × Min. breaking strength / design factor
- Choker hitch WLL = 1.34 × Min. breaking strength / design factor
- Basket slings WLL (vertical legs) = 3.6 × Min. breaking strength / design factor
- Basket slings WLL (inclined legs) = 3.6 × Min. breaking strength × cosine (vertical angle)* / design factor

* Vertical angles more than 60° must not be used. Vertical angles less than 10° may be considered vertical.

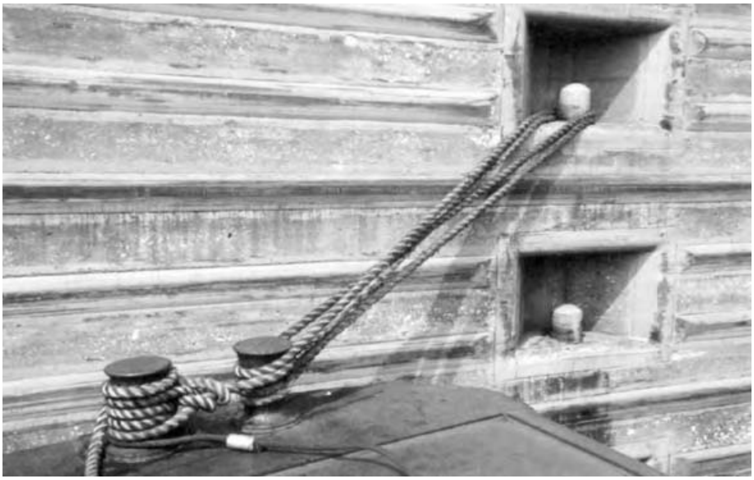


Fig. 8.16 Barging. (Upper) Tug pushing fifteen barges with a total of 25 000 tonnes of coal. (Lower) Mooring in locks with tug pushing dead slow. This line is used as a brake to stop the barges at a precise position in the lock by sliding on bitts and around pin in the lock wall.

Fig. 8.17 Electrical utilities. Fibre ropes at work. Reproduced by courtesy of New England Ropes.

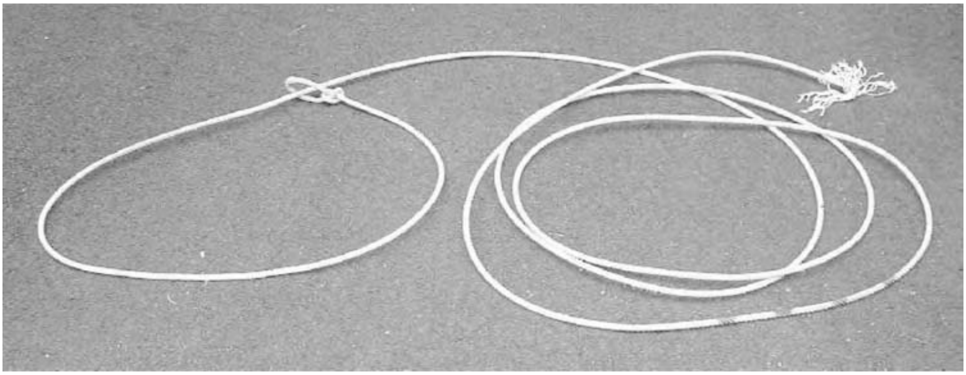


Fig. 8.18 Lariat rope. Hard lay three-strand nylon with wax coating. Note neat knot at eye.

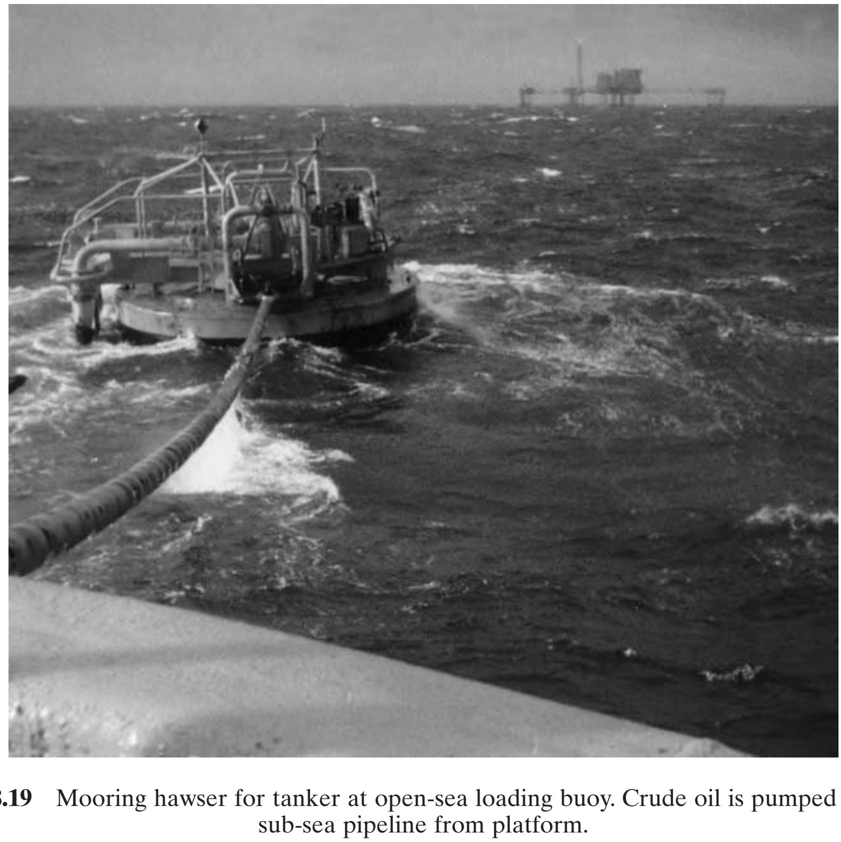


Fig. 8.19 Mooring hawser for tanker at open-sea loading buoy. Crude oil is pumped via sub-sea pipeline from platform.

Fig. 8.20 Four-strand aramid reduced-recoil ship mooring lines. Reproduced by courtesy of Whitehill.

Fig. 8.21 Ship handling line. Reproduced by courtesy of Puget.

Fig. 8.22 Pulling braided HMPE ship handling line from winch on tug. It would take at least two men to handle a polyester line or wire rope of the same strength. Reproduced by courtesy of Puget.

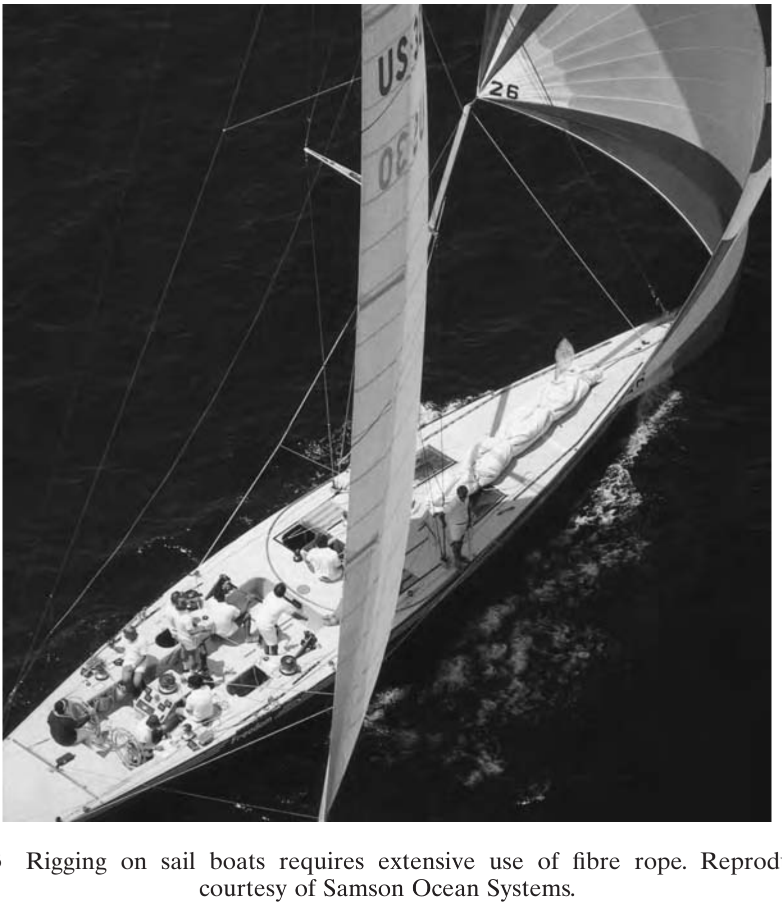


Fig. 8.23 Rigging on sail boats requires extensive use of fibre rope. Reproduced by courtesy of Samson Ocean Systems.

Choker hitches should always be used with a sliding hook, shackle or other protection at the choke point rather than rope-to-rope contact. If that is not done, reduce the capacity; by half is suggested.

If a design factor of five is used, the selection and use of the sling must conform to all regulations and safe operating practices. The sling must be retired in accordance with such standards and practices. Design factors higher than five may be required under certain circumstances (see Section 8.2.2).

(Figures 8.15–8.23 are examples of the many uses of ropes and are referred to in Table 8.1).

9

Inspection and retirement

9.1 Introduction

This chapter provides guidelines and procedures to inspect ropes and to establish criteria for evaluation leading to continuation of service, repair, downgrading or retirement. Careful and frequent inspection and evaluation of fibre rope reflects prudent safety management required to protect personnel and property.

9.2 Basis for inspection and retirement

As noted in Chapter 8, fibre ropes are employed in a large variety of applications that differ greatly in the severity of use. In some applications, ropes can serve for many years. In more severe service or under different conditions, the same rope may degrade rapidly. Also, ropes of different size, construction or material can show substantial differences in longevity in the same application. For these reasons, a basis for conducting an inspection and making an evaluation should be established by someone who is familiar with the service history of the rope. If background information is not available, the basis will be considerably different and must be much more conservative.

An inspector may have considerable resources at hand to evaluate a used rope. These may include extensive usage history, procurement specifications, ropemaker's literature, previous inspection records, comprehensive inspection facilities and access to testing laboratories. However, this is most frequently not the case. The inspection may have to be carried out on the deck of a tanker in the harbour at Anchorage, Alaska, in February. Of course, limited inspections are very worthwhile and should be carried out. This Chapter attempts to provide guidance both to organisations that have comprehensive safety and inspection programmes in place and for inspectors who must work with limited information and facilities. Items marked ► should be observed if at all possible.

► The working load limit (WLL) (Section 8.2.2) is an important criteria. This is useful if the maximum load that is anticipated is known. The WLL is determined from the published or test strength of new ropes, divided by a design (safety) factor, rarely less than five. A properly selected WLL for a rope when new does allow for strength reduction from use. Damage that is estimated to have reduced strength by 10% to 20% is usually within the range that should be acceptable. If the maximum load is not known or it is estimated that it may exceed a reasonable margin of safety, the level of damage acceptance should be very small.

► For each specific fibre rope application the user must establish a basis for retirement that considers conditions of use, experience with the application and the degree of risk present. The inspector should establish a definitive basis for the evaluation with the user. The user may be the inspector, but, even so, he should have a clear picture of how he intends to evaluate the rope.

Casual inspections occur often, however. Someone will ask, 'Is this rope any good?' Without any idea of how it was or is to be used, and, unless the rope is found to be nearly as good as new, it should not be given a stamp of approval.

► An inspector should always act conservatively when evaluating a rope and making recommendations for further use. Residual strength in a used rope can only be estimated and destructive test methods are required in order to be definitive. The visual or tactile methods described herein can only provide an estimate of rope condition. This must be considered when establishing the basis for evaluation. However, ropes that have been properly selected and used may be kept in service with some wear if inspected and evaluated in accordance with the guidelines presented in this chapter.

The person who sets the basis for evaluation should not have a strong economic incentive to keep used ropes in service; he may or may not be the inspector. The inspector himself should be an independent and experienced person who can make reasonable judgements relative to the pre-established basis for evaluation.

► Finally, a very good rule to follow when making an evaluation is: 'if it looks bad, it is bad'.

9.3 Rope materials and constructions

9.3.1 Scope

The primary focus of this chapter covers rope materials and constructions in general use. The very high-strength, high-modulus ropes are mostly used in sophisticated applications that have unique demands and are not covered specifically. However, much of the guidance for evaluating the more common ropes will apply to these as well.

Eye splices and end-to-end splices need to be evaluated as part of an inspection and are covered in this section. Improper splicing techniques or damage are common and need to be evaluated.

9.3.2 Ropes for evaluation

The following types of ropes are covered in detail for inspection and retirement evaluation.

Materials: Nylon (Polyamide)
Polyester
Polypropylene

Constructions: 3-strand laid, 4-strand laid
8-strand plaited
8- and 12-strand single braid
double braids
jacketed ropes
kernmantle (Cordage Institute, CI2005-02 (2002) for more kernmantle inspection guidelines)

9.3.3 Thimbles and other fittings

► Thimbles are an important part of many rope applications. They are used to protect the eye termination of spliced ropes and grommets and should be inspected if present. In other cases, they should be in place and, if missing, the assembly should be repaired accordingly. Thimbles and fittings are described in Chapter 7.

Other fittings, besides thimbles, are often used as fibre rope terminations. The suitability of such devices should be verified as some may not be effective (refer to Chapter 7).

9.4 Inspection and retirement programme

9.4.1 General

The user is responsible to establish a programme for inspection and retirement that considers conditions of use and degree of risk for the particular application. This programme should include:

- Assignment of supervisory responsibility
- Written procedures
- Training of inspectors
- Record keeping
- Establishment of a basis for evaluation and retirement criteria.
- Schedule for inspections

The user should assign an individual responsible for establishing the programme, supervising, updating, monitoring effectiveness, training, qualifying inspectors and preserving records.

Ropes that secure or control valuable assets or whose failure would cause serious damage, pollution, or threat to life warrant more scrutiny and detail in the programme than for ropes in non-critical use. If a fibre rope is used in a highly demanding application, with potentially critical risks, the advice of a qualified person may be necessary when developing the specific inspection and retirement programme.

Any relevant regulatory standards and guides should be reviewed and the requirements incorporated into the programme.

The user should continue to revise and refine the programme based on experience.

9.4.2 Training

Personnel assigned the responsibility for rope inspections should be properly trained to recognise rope damage, and to understand the rope inspection procedures and retirement criteria contained in this chapter. It is incumbent upon the organisation that undertakes an inspection programme to utilize trained inspectors. It may be necessary to seek the assistance of a qualified person to provide training. Rope manufacturers may also be of assistance.

9.4.3 Log and record keeping

An important tool for rope evaluation is a log of inspections, including a record of findings. This will include data on the type of rope, time in service and description of intended use.

9.5 Used rope inspection and evaluation

9.5.1 Introduction

This section describes the steps normally taken to inspect and evaluate a used rope.

Complete rope evaluation includes familiarisation with the rope's history, visual and tactile inspection, and supplemental testing if appropriate. Supplemental testing may be necessary when more quantitative assessments are required; these may include destructive strength tests. This might be done economically when one of a number of multiple lines can be taken out of service. Also, microscopic examination or chemical analysis can be performed on fibre elements that can be removed from a rope without causing any significant loss of strength.

9.5.2 Identification

- ► At the start of the inspection, identify the rope specimen by a dated tag with separate designation codes for each specimen.
- ► For easier identification, mark and number convenient intervals along the length. If the rope is very dirty, intervals could be marked by using knotted twine passed through the rope to secure tags. Tape that can be marked and is durable is also effective if wrapped tightly around the rope. Damaged areas should be marked or given a length reference.

9.5.3 Review of records and history

A general knowledge of the usage history of the rope can aid the inspection process by identifying potential types or locations of damage. Time in service, frequency of use and storage arrangements between uses can be important.

- ► Determine the conditions of use by witnessing the operation or by interviewing personnel. Attempt to estimate the maximum loads placed on the rope. Identify and quantify, if possible, unusual events that may have damaged the rope; such as, overloading, impact loading, long duration of sustained loading, sunlight or chemical exposure, and heat exposure.
- Ascertain the type and size of the rope and obtain the manufacture's or purchase specifications for strength if possible.
- If a rope log is available, examine it for rope identification, specifications and history. Try to verify that the data matches the specimen.

9.5.4 Inspection process

- Photograph the rope and specific areas if appropriate.
- ► Lay out the rope in a straight line, on a smooth surface, under hand tension. Attempt to apply enough tension to straighten the rope (in increments if space is limited). Small diameter ropes may be inspected by pulling segments hand-over-hand. For long lengths of larger ropes it is best to utilise a mechanical advantage to apply light tension on the rope while it is being inspected.
- ► Visually examine, stepwise, the entire rope length for detectable damage and deterioration; include eye splices and/or end-to-end splices.
- ► Sight the rope down its length as you would a plank or mast. Inspect for high or low strands and randomly uneven cross-sections. Look for twist in braided and plaited ropes, and corkscrewing in stranded ropes.
- ► For ropes small enough for a tactile inspection, feel for unevenness, rough spots and stiff (lacking flexibility) sections.
- Measure the rope circumference. Determine the circumference in a number of places, in particular in any damaged areas. This is most easily done with a thin whipping twine, thin metal or fabric tape measure or a pi-tape, wrapped around the rope with slight hand tension. Compare value to nominal circumference if available from historical data, noting that used ropes are often smaller than when new. Circumference measurements at any point should not vary more than 10 percent from what is found on most of the rope.
- Look for variations in the lay length (in a twisted rope) or pick length (in a braided or plaited rope). Apply a small tension to the rope and compare measurements at various locations along the rope. Note any appreciable deviations in lay or pick length that exceed ± 5 percent over the rope length. On long specimens, the tension must be high enough to minimise the effects of friction with the ground.
- ► Examine the rope for abrasion, cuts, broken yarns. Make a note of the type, location and level of damage; such as, number of broken or noticeably damaged yarns, depth and length of abrasion or wear spots, frequency and spacing of damage, if damage is one strand or multiple strands. Estimate the loss of strength by comparing abraded or cut fibres as a percentage of the rope diameter or strand diameter. Damage to several adjacent strands less than three lay lengths or three braid cycle lengths apart should be summed the same as if it were around the circumference at the same point.
- ► Open the rope and examine the interior. Turn laid rope slightly to open the interior for observation. Push on single braided or plaited ropes, or use a spike or fid (conical pin) to open the interior to view. Do the same on double braided rope to allow a hole to be opened in the cover so the inner core can be inspected. Be careful not to pull strands out of place so much that they cannot be worked back into the original position. Look for broken filaments, fuzzy areas, and kink bands.
- ► Check braided ropes for hardness. Braided ropes should be supple and bend easily. They should flatten slightly when compressed laterally. Pushing on the rope should cause the braids to open and an inability to do this implies compaction of broken filaments and serious damage.
- ► Check Kernmantle, jacketed ropes or double braids for core breaks. This is manifested by sudden reduction in diameter, is often visible when tension is applied and can be felt by running hands over the rope.

- Inspect splices around eye and in tuck area, and thimbles or other fittings.
- Occasionally, multiple specimens are available and one may be broken. Examine any such broken rope specimens in detail if it is known to have identical service to the others. A meaningful inspection should include both ends of a broken rope. Note location and nature of break. If possible, identify the conditions that caused the damage.

9.5.5 Destructive testing

- For a more definitive estimate of residual strength, a portion of the rope or its components (yarns or strands) can be removed and tested for residual strength. Such tests require destruction of the portion of the rope that is tested.*
- Small samples of fibre that would not weaken the rope can be removed for microscopic examination or chemical analysis. In some cases this could be informative.*
- Used ropes from the same or similar applications can be removed from service periodically for destructive testing for strength and elongation. Such a programme can provide important data for purposes of evaluation of ropes that remain in service.*

9.5.6 Evaluation

- As the final step in the procedure, the inspector must evaluate the condition of the rope. This will lead for a decision for disposition as covered by Sections 9.6 and 9.7.
- Record all findings.

9.6 Disposition following inspection

9.6.1 Introduction

It is expected that a rope will be left in normal service if no significant damage is identified. However, when, following an inspection, a rope is considered to be damaged, a decision must be made to repair, downgrade or retire the rope. To choose one of these options use the guidance in Sections 9.1(a) to 9.1(o) of Table 9.1. Descriptions of various types of damage are provided in Section 9.7, with the accompanying photographs, and these provide background for understanding Table 9.1.

9.6.2 Repair

The decision to repair a rope must be made very conservatively. Interpret the recommendations in Table 9.1 as follows:

- 'No' – Don't do it.
- 'Not recommended' – Unlikely to be successful.
- 'Possible' – Depends on the application.

* Used rope evaluation for strength based on rope or component testing should be done by a qualified person.

Table 9.1 Evaluation and retirement criteria

Rope type	Damage description	Sect. ref.	Fig. ref.	Repair	Downgrade	Retire
9.1(a) Initial evaluation – General						
All ropes	Rope displays moderate wear. No history of use, no records or no specifications. Time in service unknown. No severe damage. Potential personal injury or material damage exists if rope should break.	9.5.3 9.7.2	None	No	Possible	Best action
9.1(b) Excessive tension / Shock loading						
All ropes	History of excessive tension (for example, over 50% of published strength) or shock loading. No visible damage.	9.5.3 9.7.3	None	No	Possible	Best action
3-strand laid 8-strand plait All braids	Visible damage; i.e., broken strands, splice slippage, measurable creep or internal fusion. History of excessive tension or shock loading.	9.7.3	None	No	No	Yes
All ropes	Back of eye flattened and hard; cannot be softened	9.7.9	9.18	No	Possible	Yes
9.1(c) Cyclic tension wear						
All braids	Broken or seemingly cut outer filaments that are packed into the surface or protrude uniformly over working length. Fuzzy appearance uniform over length. Broken internal filaments over length. Packing of broken filaments that hardens rope giving less than normal flexibility; rope cannot be pried open for internal inspection.	9.7.4	9.1 9.2 9.3	No	Possible	Yes
3-strand laid 8-strand plait	Broken, powdered or matted filaments at strand rub areas at centre of rope visible upon twisting or compression of rope to expose interior between stands.	9.7.4	9.4 9.5	No	Possible	Yes
Jacketed kernmantle	Broken filaments on interior filaments of core rope. Fusion or hard spots on core. Powdered, broken or matted filaments at cover/core interface.	9.7.4	None	No	No	Yes

Table 9.1 *cont'd*

Rope type	Damage description	Sect. ref.	Fig. ref.	Repair	Downgrade	Retire
9.1(d) External abrasion						
3-strand 8-strand plait 12-strand braid	10% loss of fibre cross-section in whole rope or in an individual strand cross-section. Crowns of strands badly worn reducing strand diameter by more than 10%.	9.7.5	9.6 9.8	No	Possible	Best action
Double braids	Outer braid worn away by less than 10% of the circumference or 10% over one quarter of strands along the length; core not exposed significantly.	9.7.5	9.7	No.	Possible	Best action
Double braids	Outer braid worn away by more than 10% of the circumference or over one quarter of the strands along the length; core exposed.	9.7.5	None	No	No	Yes
All ropes	Localised hard or burn areas, area more than 15% of rope circumference in width; or length in excess of one half number of strands; and penetration more than 5% of rope diameter.	9.7.5	None	No	No	Yes
Jacketed kernmantle	Load bearing component (core of jacketed rope) is damaged by more than 5% of the cross sectional area.	9.7.5	None	No	Not recommended	Best action
Jacketed ropes or kernmantle – jackets	When core undamaged, non-load bearing jacket abrasion assessment depends on the criticality of coverage for a particular application. Loss of 10% of strands at one area is cause for concern but occasional breakage of jacket strands along length is probably not so critical.	9.7.5	9.9	Not recommended	Possible	Case by case
All ropes	Localised hard or burn areas, area less than 15% of rope circumference in width; penetration less than 5% of rope diameter.	9.7.5	9.10	No	Possible	Best action

9.1(e) Cuts						
Double braids	Outer braid cut by less than 5% of the circumference or 10% of diameter of one quarter of number of total strands along one cycle length; core not exposed.	9.7.6	None	No	Possible	Case by case
Double braids	Outer braid cut by more than 5% of the circumference or 10% of diameter of one quarter of number of total strands along one cycle length; core not exposed.	9.7.6	None	No	No	Yes
3-strand laid 8-strand plait 12-strand braid	10% loss of fibre cross-section in whole rope or in an individual strand cross-section	9.7.6	9.11	No	Possible	Best action
3-strand laid 8-strand plait	Over 10% loss of fibre cross-section section in whole rope or in an individual strand cross-section	9.7.6	9.11	No	No	Yes
Jacketed	Load bearing component (core of jacketed rope) is damaged by more than 5% of the cross sectional area.	9.7.6	9.12	No	Possible	Best action
Jacketed ropes – Jackets	Core undamaged. Jackets are not load bearing. Damage assessment depends on the criticality of coverage for a particular applications. Also, jackets might be repaired.	9.7.6	9.12	Possible	Possible	Case by case
9.1(f) Pulled strands and yarns						
3-strand laid 8-strand plait	Rope yarns may be pulled out from main strands. Less than 10% of rope yarns in a strand are out of place	9.7.7	9.13	Yes	No	Case by case
8-strand plait Braids	Main strands, less than 15% of number present are pulled out of position a moderate amount can be worked back into the rope to conform to the original structure	9.7.7	9.13 9.14 9.15	Yes	No	Case by case
8-strand plait Braids	Main strands are pulled out of position, more than 20% of number present or so much that they cannot be worked back into the rope to conform to the original structure	9.7.7	9.13 9.14 9.15	No	Possible	Best action
Double braids Jacketed ropes	Inner core protrudes through jacket. Rope can be massaged back into original structure without kinking.	9.7.7	None	Yes	Possible	Best action
Double braids Jacketed ropes	Inner core protrudes through jacket. Rope cannot be massaged back into original structure without kinking. Displays moderate wear	9.7.7	None	No	No	Best action

Table 9.1 *cont'd*

Rope type	Damage description	Sect. ref.	Fig. ref.	Repair	Downgrade	Retire
9.1(g) Flex fatigue – pulleys, rollers, chocks and fairleads						
All braids	Broken outer filaments that are packed into the surface with fuzzy appearance uniform over flex length. Broken internal filaments over flex length. Packing of broken filaments that hardens rope giving less than normal flexibility; rope cannot be prised open for internal inspection. Non-recoverable flattening.	9.7.8	None	No	Possible	Best action
3-strand laid 8-strand plait	Broken filaments and evidence of wear on strand crowns on surface on flex length. Broken filaments and powder at strand rub points at centre of rope. Internal fusion.	9.7.8	None	No	Possible	Best action
Jacketed	Broken filaments and evidence of wear on surface in flex length. Broken filaments on interior filaments of core rope. Fusion or hard spots on core. Powder or broken filaments at cover/core interface. (Figure shows core with jacket removed.)	9.7.8	None	No	No	Yes
9.1(h) Spliced eyes and other terminations						
All ropes	Improperly made splices. Check for correct fabrication. Refer to qualified person, manuals or published procedures. Old splice can be cut out and new one made.	9.7.9	7.2 9.17	Yes	Possible (Splices in used rope often not reliable)	Best action
All ropes	Surface abrasion or cut damage in splice eye. See Sections (d) and (e).	9.7.9	9.18	No	Possible	See (d) and (e)
3-strand laid 8-strand plait Braids	Splice has slipped. Strand tails have pulled back into rope. (Old splice can be cut out and new one made.)	9.7.9	None	Yes	Possible (Splices in used rope often not reliable)	Best action
Braids	Leg junction shows cut or ragged strands. (Old splice can be cut away and new splice made.)	9.7.9	9.19	Yes	Possible (Splices in used rope often not reliable)	Best action

All ropes	Damaged or improper splice cannot be remade with confidence that strength is not compromised.	9.7.9	None	No	No	Yes
Thimbles	Thimbles have sharp edges or corrosion. Thimble loose in eye. Rope does not fit thimble. Thimble can be replaced. Assess rope damage in accordance with Sections (d) and (e).	9.7.9	None	Yes	Possible	Case by case
No thimbles	No thimble but one should be used. Eye damage is occurring. Minor rope damage is present. Repair possible by adding thimble.	9.7.9	9.20	Yes	Possible	Case by case
Other terminations	Mechanical, potted should be verified as to strength and reliability. Splicing or replacement not possible.	9.7.9	None	No	No	Yes
9.1(i) Knots						
All ropes	A knot has been used instead of a splice and cannot be removed or replaced by a splice. No damage at knot. Assume strength has been reduced 50% and calculate working load limit on this basis – less than max. working load for application.	9.7.10	9.21	No	Possible	Best action
All ropes that can be spliced	Knot/s have been placed in body of rope between splices and cannot be removed without damage or, if they are, the length previously in the knot is abraded or kinked.	9.7.10	None	No	Possible	Yes
Ropes for use with knots, not spliceable	Working load limit is based on 50% of published breaking strength – compare to actual. Little (10% or less) fibre damage at knot.	9.7.10	9.21	No	No	Case by case
Ropes for use with knots, not spliceable	Working load limit is based on 50% of published breaking strength – compare to actual and found not acceptable or there is in excess of 10% fibre damage at knot.	9.7.10	9.21	No	Possible	Yes
9.1(j) Creep (cold flow)						
All ropes	Rope is very close to or exceeds the creep limit set by the user or rope maker. Creep is checked by procedures set by user or rope maker and found to be near limit.	9.5.3 9.7.11	None	No	No	Yes
All ropes	Rope type is subject to creep and history of use shows that it may have experienced excessive creep. Rope has been used for extended time at high loads expected to cause creep.	9.5.3 9.7.11	None	No	Possible	Best action

Table 9.1 *cont'd*

Rope type	Damage description	Sect. ref.	Fig. ref.	Repair	Downgrade	Retire
9.1(k) Axial compression and kinkbands						
Jacketed	Body of rope shows distinctive periodic bulges along its length. Internal inspection is not possible.	9.7.12	None	No	Possible	Yes
Jacketed	Internal inspection reveals distinctive Z shaped kinkbands in portions of the load-bearing core. More than 10% of the cross-section is affected. These tend to repeat in a regular pattern along the length	9.7.12 4.5.7	None 4.2.7	No	No	Yes
Splices	Splices in ropes made of high modulus fibre may exhibit kinkbands. Damage is very difficult to access without destructive testing.	9.7.12	None	No	No	Yes
9.1(l) Hockle, twist, kink or corkscrew						
3-strand laid	A loop has been pulled tight causing hockle; rope structure cannot be turned back easily without leaving the rope distorted.	9.7.13	9.22	No	No	Yes
3-strand laid	3-strand ropes display a corkscrew appearance when laid out straight and without tension. Corkscrew can be removed by twisting in opposite direction.	9.7.13	9.23	Yes	No	Case by case
3-strand laid	3-strand ropes display a corkscrew appearance when laid out straight and without tension. Corkscrew cannot be removed by twisting in opposite direction (often result of bad splice in short length, use with wire ropes or manufacturing defect).	9.7.13	9.23	No	Possible	Best action
3-strand laid	Rope is unlaid (strands do not stay together).	9.7.13	None	Not recommended	No	Yes
3-strand laid	Swivel has been used with 3-strand ropes	9.7.13	None	Not recommended	No	Yes
8-strand plait All braids	Rope has been used in series with wire rope (unless wire is non-rotating type). Wire rope probably also damaged.	9.7.13	None	Not recommended	No	Yes
Braided and plaited ropes	Discernable twist when laid out straight, even under tension. Twist can be removed by twisting in opposite direction.	9.7.13	9.24	Yes	No	Case by case
All ropes	Kinking is present. Kink will not disappear completely when slight tension is applied or springs back when tension is removed. Rope is hard and flattened at kink.	9.7.13	None	No	No	Yes

9.1(m) Sunlight degradation						
Polypropylene ropes	Polypropylene rope with many brittle and broken filaments on the surface.	9.7.14	9.25	No	No	Yes
All ropes without non-load bearing jackets	Ropes less than 1 inch diameter that are known to have had extensive exposure (year or more) to bright sunlight. Especially nylon, aramid and polypropylene.	9.7.14	None	No	Possible	Best action
All ropes with non-load bearing jackets	Jacket completely covers the rope, or can be patched to cover the rope, and is not subject to severe wear. Underlying core has been protected.	9.7.14	None	Yes	No	Case by case
All ropes with non-load bearing jackets	Jacket appears severely affected and cannot be repaired. Jacket shows signs of sunlight degradation and is subject to rough service.	9.7.14	None	No	No	Yes
9.1(n) Chemical and heat degradation						
All ropes	Examination and/or history indicates chemical or solvent exposure, agent unknown.	9.7.15 2.6.5 4.10	None	No	No	Yes
All ropes	Examination and/or history indicates chemical or solvent exposure. Agent known to be benign. Fibre specimen test indicates no or little degradation.	9.7.15 2.6.5 4.10	None	No	No	No
9.1(o) Dirt and grit						
All ropes	Ropes exhibit grit or silt deposits on the inside. Broken or powdery fibre material may be present. The grit tends to fall out when the rope is dry and it is flexed.	9.7.16	9.26	No	No	Yes
All ropes	Seawater has dried and left a salt deposit on the inside of the rope. The rope has been used extensively when dry with the salt present.	9.7.16	None	No	Possible	Yes
All ropes	Seawater has dried and left a salt deposit on the inside of the rope. No long term use when dry. Rope can be rinsed thoroughly with fresh water.	9.7.16	None	Yes	No	Case by case
All ropes	Rope has been significantly impregnated with oil or sticky substances. This material attracts and retains dirt and grit. It is not possible to clean the rope.	9.7.16	None	No	No	Yes

If the rope shows severe damage in only a few concentrated areas, it may be possible to remove the damaged sections and resplice the rope.* For end-to-end splices, assume 100% strength (i.e. the strength of the rope with eye-splice) for a short splice and 80% for a long splice (Columbian Rope Co., 1986).* After completion of new eye splices or end-to-end splices, pretension or load cycle the rope to set the splice if possible.

Based on his evaluation, an estimate of the reduced breaking strength of a repaired rope might be made. If strength loss is greater than allowable (Section 9.2), the inspector must then determine a new working load limit (WLL) based on the pre-established design factor. If the new WLL is below the anticipated maximum load for the application, the rope must be downgraded or retired.

9.6.3 Downgrade

The decision to downgrade a rope must be made very conservatively. Interpret the recommendations in the tables as follows:

- 'No' – Don't do it.
- 'Not recommended' – Condition is likely to be worse than estimated.
- 'Possible' – Depends on the application.

The residual breaking strength of a rope may be estimated by the inspector. If wear or damage exceeds what would normally be expected, the inspector or user must determine a new working load limit (WLL). If this is below the anticipated maximum application load, the rope must be downgraded or retired.

Downgrading may also apply to ropes that have been repaired by splicing as used rope splices may have questionable strength.*

The user must make certain that downgraded ropes cannot be used for the original application or at higher loads than the newly determined WLL. If this is impractical, the rope must be retired.

9.6.4 Retire

Interpret the recommendations in the tables as follows:

- 'Yes' – Retirement compulsory
- 'Best action' – Retire if there is any uncertainty
- 'Case by case' – Continued use acceptable upon positive evaluation and risk assessment

Retired ropes must be disposed of in accordance with any applicable regulations and rendered unsuitable for future use.

* **Caution**: Splicing of a heavily used rope may be impossible, or very difficult (due to shrinkage, double braided nylon rope can be particularly bad). In many cases where a splice of well used rope is attempted, there is a significant strength loss, especially if making the splice was a struggle. Care must be taken and consultation with a qualified person may be appropriate. For jacketed ropes where the core is the strength member and undamaged, it may be possible to repair the jacket with whipping, wrapping, or coating depending on the application; if uncertain on the efficacy of the repair, consult manufacturers' recommendation or a qualified person.

9.7 Types and effects of damage

9.7.1 Introduction

Each topic following refers to an item in Table 9.1 that provides guidance on the evaluation of each type of damage. The Table section number has been placed in brackets [ ] after the title of each section.

Knowing the causes and appearance of damage is essential to a good rope inspection and essential in determining retirement criteria. This section describes the most common causes of rope damage and describes the effects. The figures referenced in this chapter contain pictures illustrating these conditions.

Smaller ropes (generally less than 6 mm diameter), due to their reduced bulk, suffer a proportionately larger loss of strength than larger ropes due to cuts, abrasion, and environmental exposure. Extra attention is recommended when inspecting small diameter ropes.

9.7.2 Initial evaluation [Table 9.1(a)]

Some types of 'damage' can only be determined by rope history as they may not be apparent by visual or other examination: Shock loading or creep are examples. In this section 'damage' can refer to a lack of historical information relating to the use of the rope.

9.7.3 Excessive tension / Shock loading [Table 9.1(b)]

Overloading or shock loading a rope above a reasonable working load limit can cause significant loss of strength or durability. However, the damage may not be detectable by visual or tactile inspection. The usage history of a rope is the best method to determine if excessive tension or shock loading has occurred. Overloading and shock loading are difficult to define and the inspector must take a conservative approach when reviewing the history of the rope. Repeated overloading will result in similar damage as that caused by cyclic fatigue, as described in Section 9.7.4 Shock loading may cause internal melting of fibre especially in splice tuck or bury areas.

9.7.4 Cyclic tension wear [Table 9.1(c)]

Ropes that are cycled for long periods of time within a normal working load range will gradually lose strength. This loss of strength is accelerated if the rope is unloaded to a slack condition or near zero tension between load cycles. The subsequent damage is commonly referred to as fatigue. Although there are various mechanisms for the breakdown of synthetic fibres under cyclic tension, by far the most common is fibre-on-fibre abrasion (see Fig. 9.1 where long-term loading and unloading has caused a breakdown of yarns in the outer braid of a double braided rope). This rope was also extremely hard due to internal compaction of broken filaments while the less used rope shown above was soft and pliable.

Braided ropes develop many broken filaments at the crossover points of strands in the braid due to fibre-on-fibre abrasion. Occasionally, the broken ends of yarns may appear as if cut square (a magnifying glass may be necessary). These broken filaments give the rope a fuzzy appearance on the outside and over the entire length that was under load; this can be so bad as to obscure the underlying braid structure.

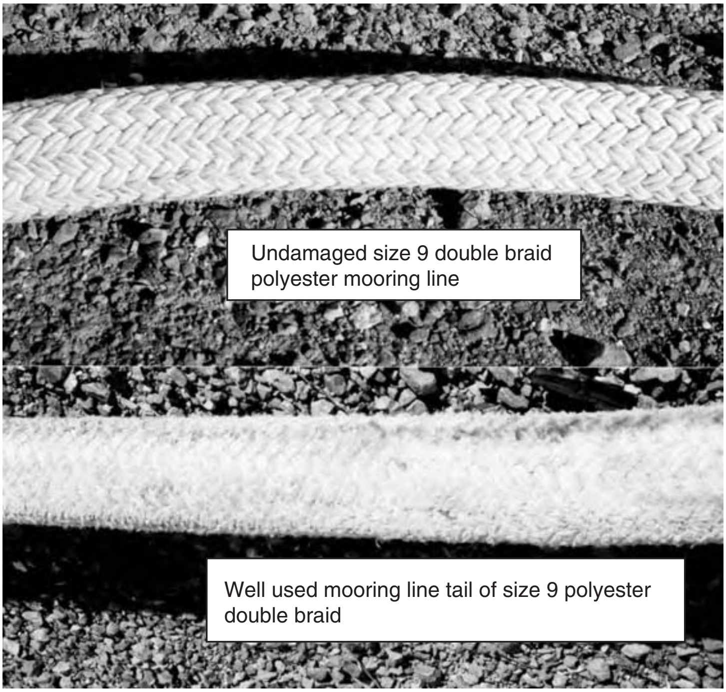


Fig. 9.1 Fibre abrasion due mostly to cyclic tension combined with grit contamination. The used rope is hard-packed and stiff.

Figure 9.2 shows an extreme example of braided rope that exhibits excessive damage from frequent loading and unloading.

For braided ropes, broken filaments within the rope can also mat, entangle and/or leave a powdery residue. Extreme internal filament breakage will make the rope very hard, lose flexibility and be noticeably larger in diameter (with a subsequent reduction in length); it may be so hard that it is impossible to pry the rope open to examine the interior structure. Again, see Fig. 9.1, where this was the case.

Matted yarn, broken and fuzzy filaments, and fibre fusion may be observed internally. See Fig. 9.3 on how to expose the inside of an 8-strand plaited structure to examine it.

For 3-strand laid and 8-strand plaited ropes, most of the wear from cyclic loading will occur on the inside of the rope where the strands rub on each other. Broken, matted filaments and a powdery residue may be observed. Figure 9.4 shows the exposed inside structure. For laid ropes, twist the rope in the opposite direction of the lay to open the rope for internal examination.

Wire lay and parallel core ropes usually have a non-load bearing jacket and the core strength member must be examined under this sheath. Broken filaments, powdery residue or fusion may be observed if the interior can be examined.

The rope in Fig. 9.5 was used to handle limbs for tree work and kept in service too long. The cyclic tension, combined with dragging over branches, has cut through the outer filaments. The strand cross-overs cut the filaments very neatly as seen in the photo. An identical new rope is shown for comparison.

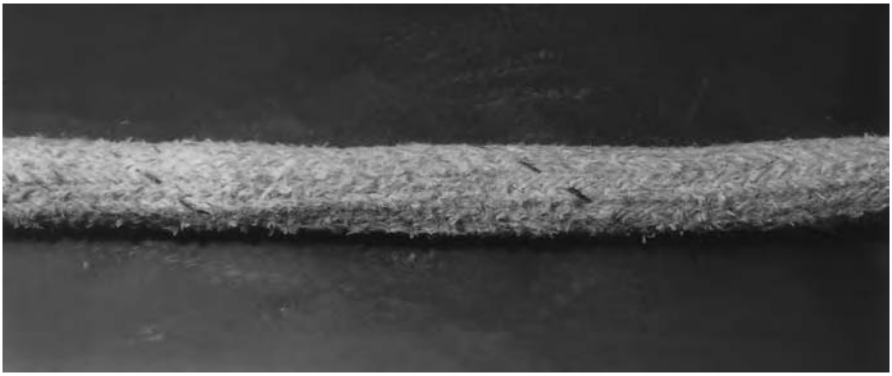


Fig. 9.2 Fibre-to-fibre abrasion from cyclic loading. Damage at surface is clearly visible. Specimen is from test of 1 million cycles from 1 to 30% of rated strength of submerged polyester double braid. Residual strength was 65% of new control specimen.

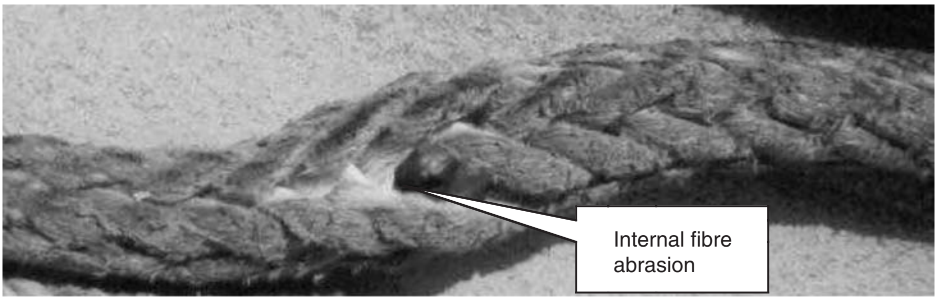


Fig. 9.3 Inspection for inter-strand abrasion on 8-strand plaited rope.

9.7.5 External abrasion [Table 9.1(d)]

Most external abrasion is localised. Gouges and strips along one side of the rope are common; these display cut fibres and are often accompanied by fusion. Damage sufficient to degrade the rope is usually obvious. More uniform abrasion may be seen in ropes that are used over fixed objects that bear along a considerable portion of its length. Also, dragging over a rough surface will show uniform abrasion. Figure 9.6 shows the effects of both external abrasion and cyclic overloading.

External abrasion can be distinguished from cyclic fatigue since the interior of the rope will not have damage and the damage is rarely uniform, as seen in Figures 9.7 to 9.9. The surface of the rope may be melted and appear black due to sliding while bent over surfaces when under high tension (see Fig. 9.10).

Jacketed ropes require inspection of the outer cover. The load-bearing core should not be exposed by a damaged jacket. Loose strands in the jacket may snag and could be a consideration in some cases (see Fig. 9.9).

9.7.6 Cuts [Table 9.1(e)]

It is usually obvious during visual inspection to see where fibres have been cut sufficiently to degrade a rope. Damage assessment includes an evaluation of the

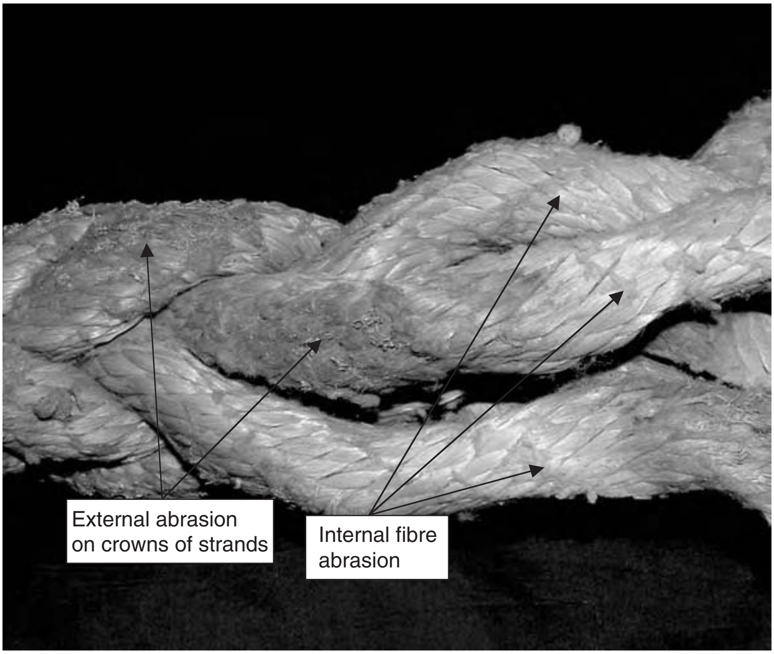


Fig. 9.4 Inter-strand abrasion seen internally (strands forced open for viewing).

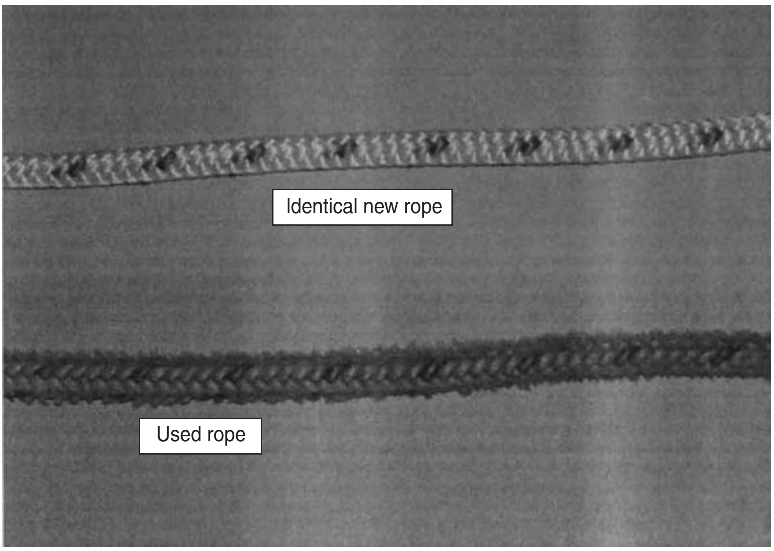


Fig. 9.5 Arborist rope, 12 mm – Note broken filaments on surface.

amount of affected fibre, and location and orientation of the cut. For multiple cuts, the space between damaged areas is important (see Fig. 9.11).

For jacketed ropes where the jacket is non-load bearing, a cut that does not damage the core will probably not affect the strength (see Figures 9.9 and 9.12).

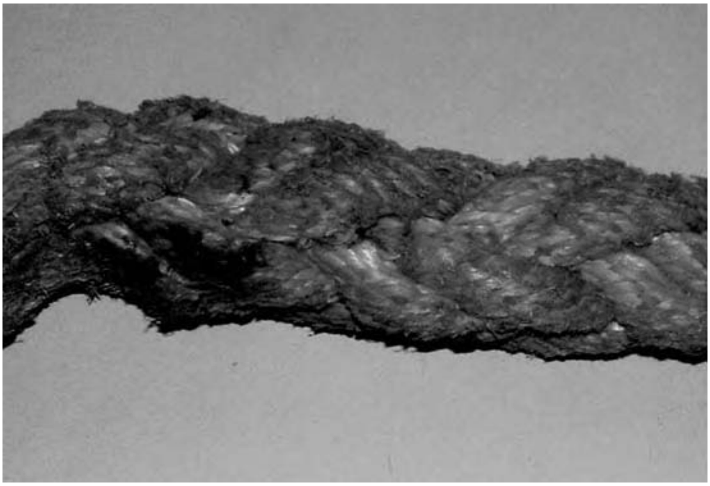


Fig. 9.6 Extensive external abrasion on 8-strand plaited mooring line. Wear is concentrated on crowns of the strands.

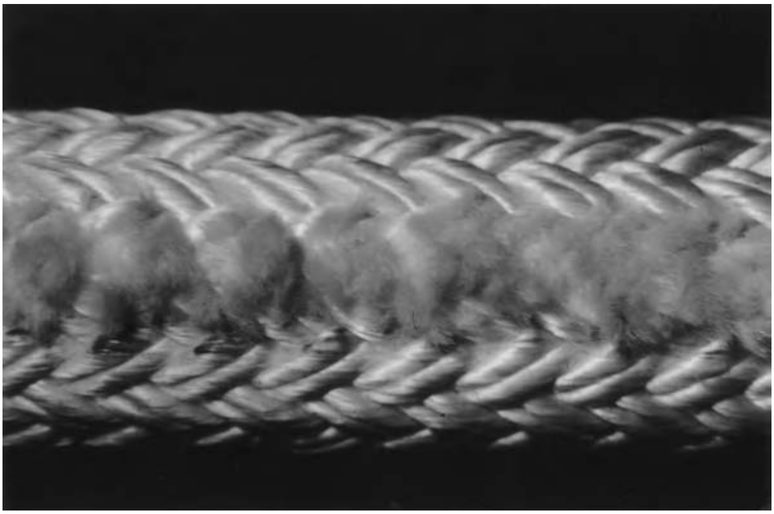


Fig. 9.7 Localised external abrasion. Loss of strength due to damage along length is cumulative. Reproduced by courtesy of Samson Rope Technologies.

Careful inspection in the vicinity of the cut should be performed to ensure integrity of the core. Core deformation or herniation of a core strand through the jacket could occur on subsequent use if the cover is not repaired. Cores can shift relative to the jacket causing slippage and wrinkles. Cuts to jackets may cause other adverse effects such as handling difficulties, snagging, inability to slide through fittings smoothly, and exposing the core to grit.

Fig. 9.8 Localised external abrasion.

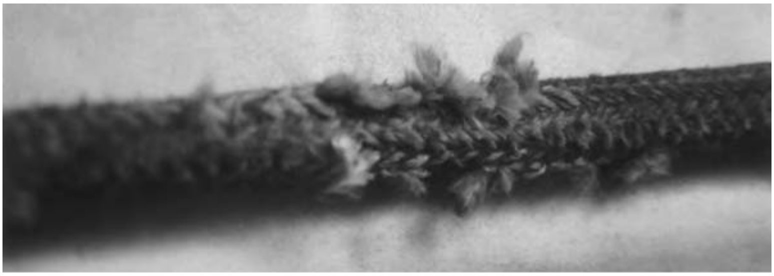


Fig. 9.9 Localised jacket wear on jacketed rope. The core strength member is undamaged.

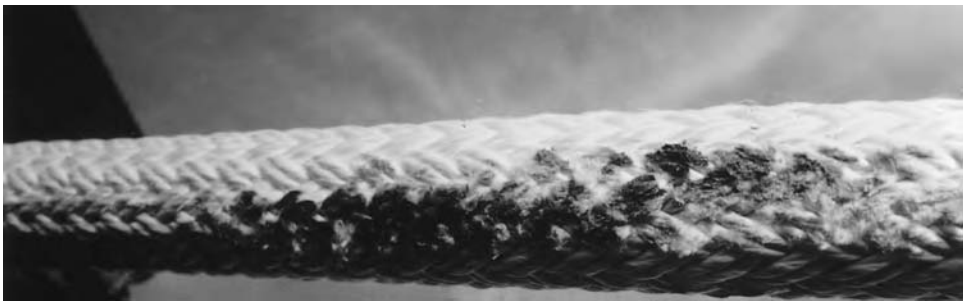


Fig. 9.10 Burning and melting from sliding over a fixed surface while under high tension. Reproduced by courtesy of Samson Rope Technologies.

9.7.7 Pulled strands and yarns [Table 9.1(f)]

Strands and rope yarns can be snagged and pulled out of the rope structure. It is often possible to work the strand back into the rope to restore the original structure. The level of damage is a function of the percentage of the rope cross-section that has been permanently lost (see Figures 9.13 to 9.15).

Fig. 9.11 Cut strand on well-used 8-strand plaited rope.

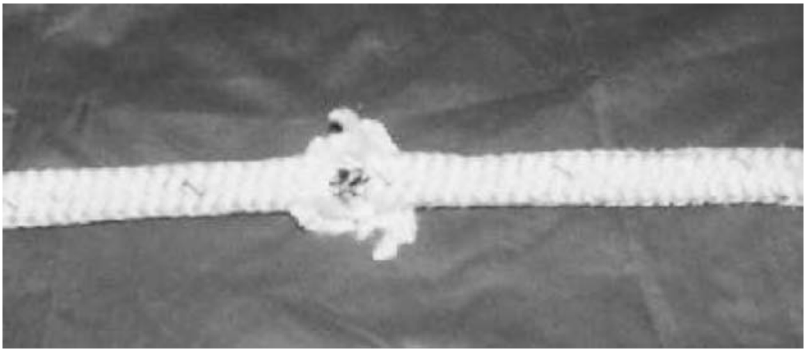


Fig. 9.12 Severe cut in jacket, exposing load-bearing core.

Fig. 9.13 Pulled strand in 8-strand plaited rope. Moderate external abrasion can be seen.

Fig. 9.14 Pulled strand on well-worn double braid. Note that wear and contamination are on the outer surface and that the interior of the strand is in a relatively good condition.

Fig. 9.15 Pulled strand in new double braid. Reproduced by courtesy of Samson Rope Technologies.

9.7.8 Flex fatigue – pulleys, rollers, chocks, fairleads [Table 9.1(g)]

Constant bending of any type of rope causes internal and external fibre abrasion. This is frequently caused by running on pulleys. But, other types of flexing such as frequent bending over a small radius surface can also cause flex fatigue damage. Flexing over fixed surfaces is often accompanied by surface wear, especially if sliding action is also present. Wear will appear on the surface of the contact area. The fibres will become matted on the surface and/or glazed from heat build-up, especially with ropes using polypropylene fibres. Broken filaments and fusion will be found inside the rope over the bending zone but not elsewhere in the rope. Figure 9.16 is of the

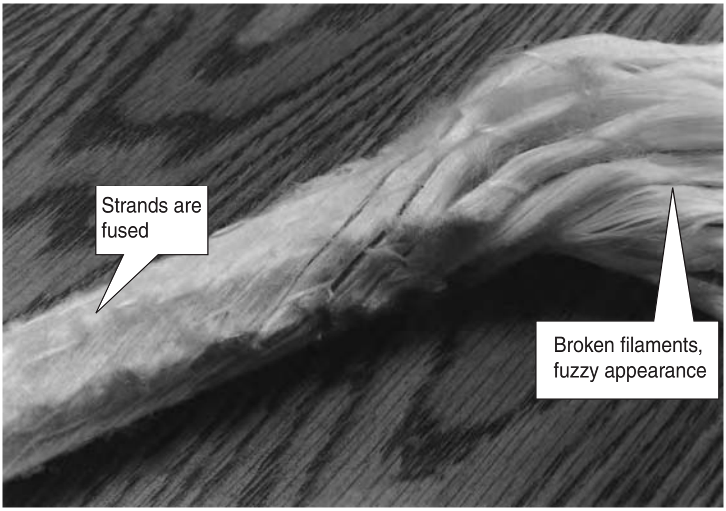


Fig. 9.16 Jacketed rope shows internal damage from running over pulley at high tension. The jacket has been removed to show core. Reproduced by courtesy of Tension Member Technology.

core of a jacketed rope that had been cycled over a pulley; the portion that was on the pulley was fused and the portion just beyond that showed considerable fibre abrasion.

9.7.9 Spliced eyes and other terminations [Table 9.1(h)]

The following should be noted when inspecting splices:

- Check for properly made eye and end-to-end splices; splices should always be based on the manufacturer's instructions or other reliable sources (see Chapter 7). A long splice for end-to-end is about 80% efficient: consider this when establishing a WLL. A properly made 3-strand eye splice is shown in Fig. 7.2 and a poor quality splice in Fig. 9.17.
- Damage is common at splices (see Figures 9.18 and 9.19). These areas always need to be examined closely. Look for broken strands at the leg junction, as in Fig. 9.19. Other points to look for are surface wear in the back of the eye, flattening where the rope bears on pins or bollards, slippage of tucks in stranded or twisted ropes and displacement of core/cover for braided rope with buried splices.
- Eye splices used on small pins are likely to have internal and external damage at the back of the eye. Figure 9.20 shows a rope directly on the body of a shackle that is about the same diameter as the rope. This can lead to rapid wear unless the application is static. Thimbles improve the situation considerably. Use the discussion in Section 7.6 for guidance in evaluation.
- Tucks in three-strand and eight-strand splices, and in single braid tuck splices may have slipped in the splice. The buried leg in single and double ropes may have slipped. Freshly exposed fibre in tucks or buried legs will look clean or have a slightly different appearance where fibres have pulled out of the body of the rope.

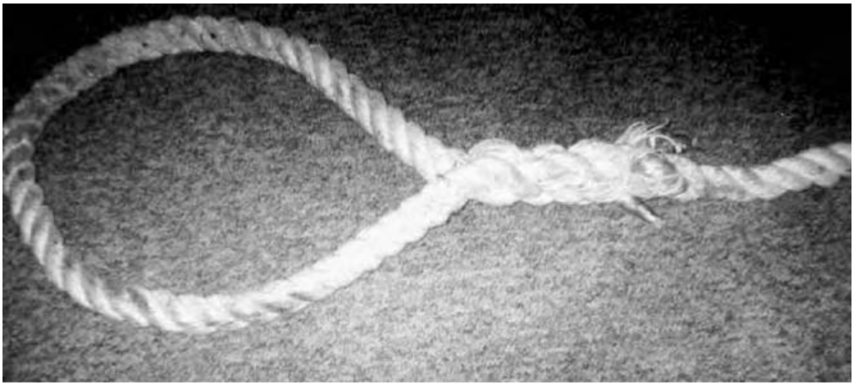


Fig. 9.17 Three-strand eye splice of poor quality.

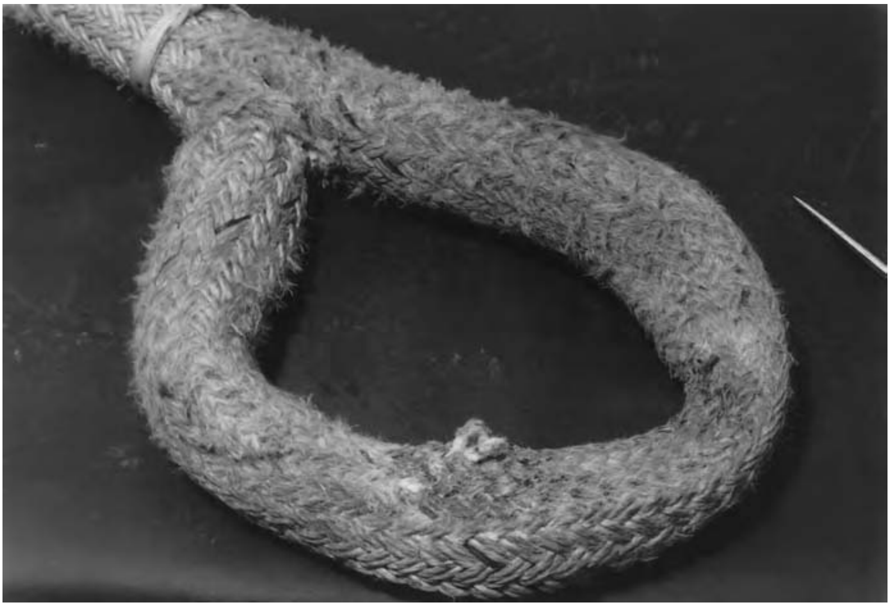


Fig. 9.18 Wear in double braid eye splice.

- Lock stitching should be used with buried splices (see Section 7.2.3(ii)) on single braid rope and should be covered by splicing instructions. Check to see if they are present. They are often found on double braided ropes (see Section 7.2.4). In both cases they should not be broken.
- To function, parallel fibre rope and some parallel strand rope splices usually require a continuous covering that applies compression to the splice body, especially to anchor the end area. This will be detailed in the rope manufacturer's splicing instructions; it is often in the form of whipping, a small cord that is wrapped tightly around the splice. Damage that allows the whipping to come loose can allow the splice to slip.

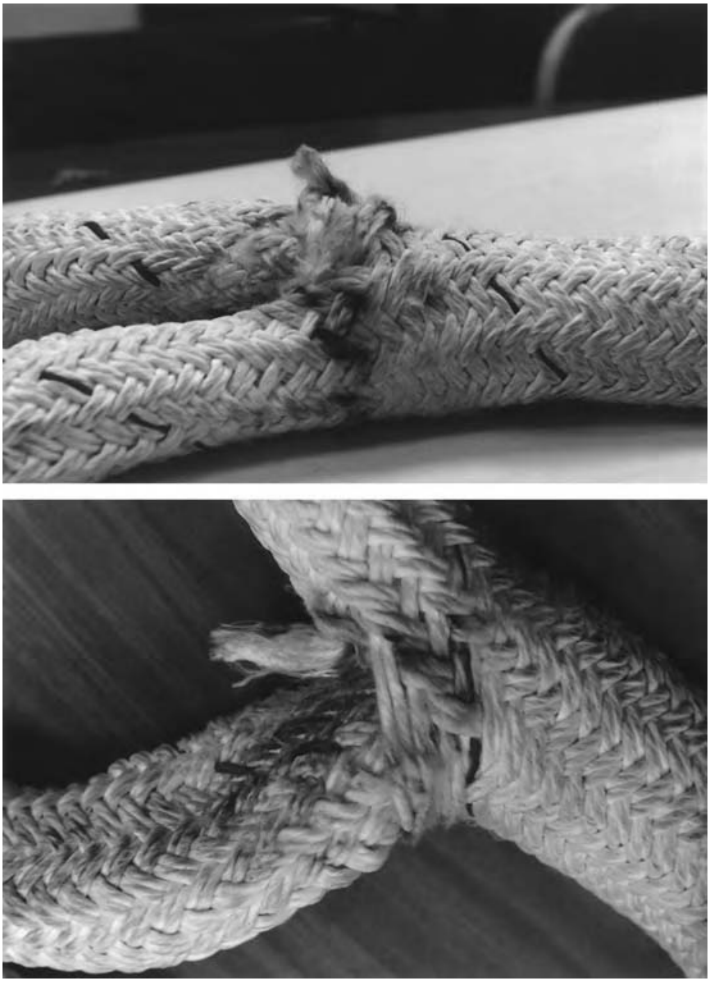


Fig. 9.19 Tearing at leg junction of eye splice in polyester double braid. This is as a result of loading for 100 cycles at 70% of breaking strength.

The following should be noted when inspecting thimbles:

- Inspect for corrosion, cracks or sharp edges that indicate weakness or the potential to cut or abrade the rope.
- Check that the groove in the thimble for the rope is slightly larger (5%–15%) than the rope when there is little or no tension.
- Check security of thimbles in the eye of a rope. Fibre rope thimbles have ears that prevent the eye from turning in the thimble or allowing the thimble to fall out. If steel wire rope thimbles are used, they should be tight in the eye or lashed to the legs of the eye to prevent turning or falling out. Adhesives have also been used successfully to secure rope in a thimble.
- Fibre rope thimbles designed for nylon, polyester or polypropylene ropes may not have sufficient strength if used with very high strength fibre ropes. Unless otherwise indicated, the ultimate strength should be assumed to be equal to the largest sized nylon rope that will fit. Heavy-duty steel wire rope thimbles are

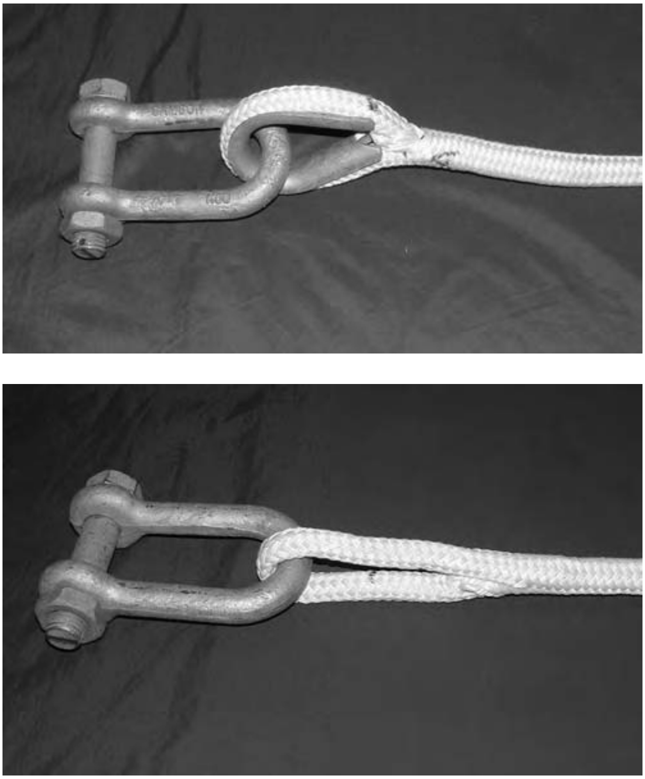


Fig. 9.20 (Above) Rope with wire rope thimble. Note tight fit in eye so that thimble is not likely to fall out. (Below) Without a thimble, the bend over the shackle is very small, about equal to the rope diameter and is not suitable for frequent loading.

often suitable for the stronger ropes when the fibre rope and wire rope size are the same. If data is available, determine strength compatibility.

- Thimble rated load must always exceed the WLL for an application. Ideally, if the breaking strength of a thimble is known, it should exceed the rope strength. Many thimble suppliers quote the design (safety) factor; therefore, the ultimate strength can be estimated by multiplying the rating by the design factor, usually four or five.

The following should be noted when inspecting other terminations:

- Mechanical, potted or other types of terminations are not common but may be used with fibre ropes if it can be verified that they have been qualified for the particular service. Verify compliance with the recommendations of the manufacturer or qualified person.
- Always inspect the interface for abrasion where the rope joins the fitting.

9.7.10 Knots [Table 9.1(i)]

Some ropes are intended to be used with knots. Examples are: rescue, climbing and arborist ropes. These ropes should be inspected for wear in the rope as it enters or exits the knot (see Fig. 9.21).

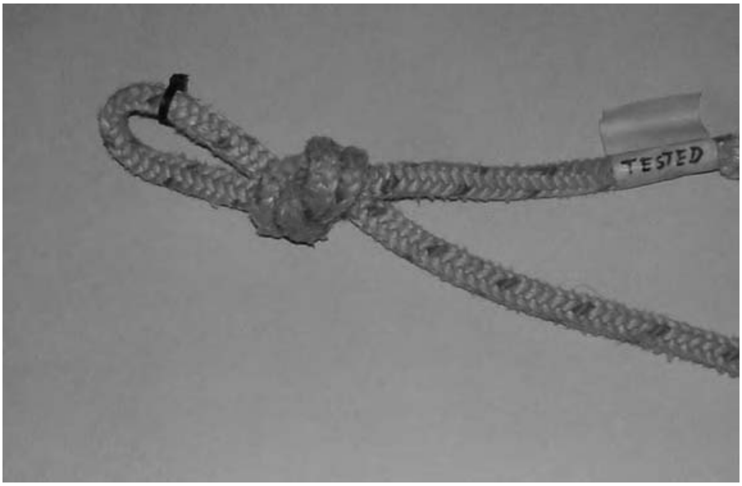


Fig. 9.21 A knot in a non-spliceable arborist rope.

Knots must not be used unless the working load is reduced by an appropriate amount (50% is a widely accepted amount). When knots are in use, the inspector should verify that the WLL has considered the strength reduction caused by the knot.

It is cause for retirement or downgrading if a knot is not called for and cannot be removed or the rope reveals structural damage due to knotting.

The inspector should endeavour to determine if a knot is called for, and if the type of knot is suitable for the application and was properly tied.

9.7.11 Creep (cold flow) [Table 9.1(j)]

Ropes made of materials that creep (Section 2.5.4) will be measurably longer if loaded continuously for long periods of time. Creep rates depend on the material, time, temperature and load relative to breaking strength. The inspector should research the loading history of the rope and determine if the fibre material is subject to significant creep at the operating conditions. Ropes made of polypropylene are particularly susceptible and nylon is somewhat susceptible.

Ropes that fail due to creep often retain relatively high strength until they are very close to failure; thus the need to check for operating conditions that may suggest excessive creep.

Creep also reduces the elongation at breaking during a strength test. Maintaining relative high stretch before failure is important in some applications. In most cases, however, loss of stretch can only be determined by a destructive test. Strength testing may not reveal the true condition of the rope unless stretch is also checked and compared to normal values.

Visual inspection for creep is only possible if the rope is cycled at moderate load a few time to set the structure when it is new; then gauge marks are placed on the rope and the length carefully measured under reference tension before it goes into service. The recorded length is then compared to the used length measured under the same reference tension.

9.7.12 Axial compression and kinkbands [Table 9.1(k)]

Ropes that have a braided or extruded jacket over an inner, load-bearing core may experience axial compression as manifested by kinkbands. This occurs mostly in ropes with a very tight jacket. In severe cases the rope will have bulges in zones where kinks are concentrated (bulges often repeat at a uniform cycle length).

If the inner core can be inspected, bands of kinked fibres or yarns that have a Z appearance may be seen. If damage is severe, the filaments at the Z points will be severed as with a knife. If the jacket cannot be opened for internal inspection, destructive inspection or testing may be the only means of evaluation (see Fig. 4.27).

Kinkbands can also appear in splices of very high strength, high modulus ropes. This is an indication that serious damage could be present. Destructive testing may be the only means of evaluation.

9.7.13 Hockle, twist, kink and corkscrew [Table 9.1(l)]

If a loop is introduced into a 3-strand rope (or other multi-strand laid rope), it will tend to hockle when tension is applied. Once set, hockles cannot be turned back to restore the rope structure and this indicates severe damage (see Fig. 9.22).

Some ropes will display a corkscrew appearance and must not be used unless restored to normal appearance (see Fig. 9.23).

Braided and plaited ropes should display little or no twist and those that do must not be used unless restored to normal appearance (see Fig. 9.24).

Kinks that are permanently set in a rope are a sign of serious damage. When tension is removed, the kink returns. The rope may be flattened from crushing and cannot be worked back to normal, which is essentially the same as a kink.

Fig. 9.22 Hockle (back turn caused by tensioning with loop in 3-strand rope). Reproduced by courtesy of Samson Rope Technologies.

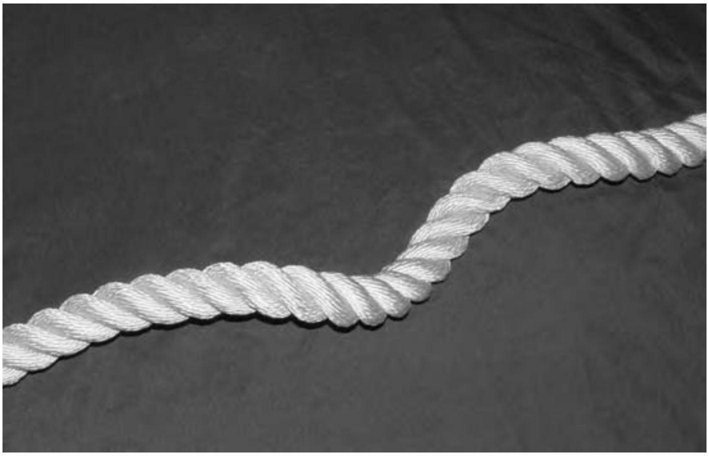


Fig. 9.23 Corkscrew due to turns introduced into rope (seen when there is no tension).

Fig. 9.24 Turns introduced into 12-strand braid. This is a common occurrence when line is used with gypsy head (upper left corner).

9.7.14 Sunlight degradation [Table 9.1(m)]

Ultra-violet (UV) radiation from direct sunlight will cause brittle and weak outer rope yarns. UV degradation is difficult to inspect visually. Discoloration and brittleness in the filaments may be observed in some cases. Strength testing of a few surface fibres or the entire rope is required for a definitive assessment. Sometimes the filaments are so brittle that they can be crushed by hand (see Fig. 9.25 and refer to Section 2.6).

The effect on the rope is much less as diameter increases. Damage to very small ropes can be rapid; ropes over 1 inch (2.5 cm) in diameter are much less affected. UV degradation is stronger in the lower latitudes and will progress with time of exposure. Assessment can be difficult and advice of a qualified person should be sought if there is potential for UV damage.

Non-load bearing jackets or coatings will protect the core rope.

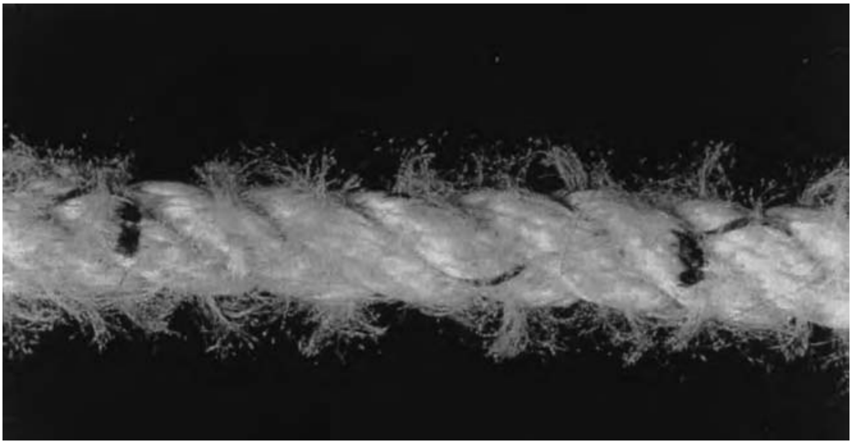


Fig. 9.25 UV (sunlight) degradation of polypropylene rope. Surface filaments have become very brittle. Reproduced by courtesy of Wellington.

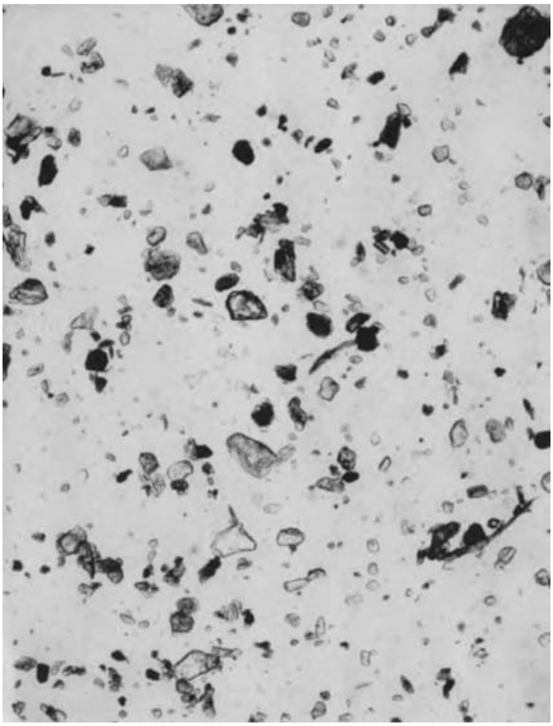


Fig. 9.26 Dirt and grit from size 9 polyester double braid mooring line tail after 12 years in service. (Revealed by 40× magnification.)

9.7.15 Chemical and heat degradation [Table 9.1(n)]

Synthetic fibre materials generally resist chemical attack and heat exposure in normal circumstances but can be weakened in certain situations. Visual inspection may reveal discoloration and brittleness of the fibres. Melting, bonding of fibres, hard spots or stickiness may be observed. However, these manifestations are not always present. The inspector should research the exposure history of the rope.

Nylon ropes, when wet, can be seriously degraded by long-term contamination with rust. This can be detected by a reddish or brown colouration.

Fibre ropes stored at even moderately high temperatures for long periods of time can be degraded without any visual indication of damage. Refer to Section 2.6.

9.7.16 Dirt and grit [Table 9.1(o)]

Dirt and grit cause internal fibre abrasion in ropes that are in regular use after contamination. Most ropes can be forced open for internal inspection. A magnifying glass may be helpful for identification of fine particles (see Fig. 9.26).

Sea water that has dried and has left a salt deposit can be damaging due to internal abrasion if the rope is continually used in the dry condition.

Oil and grease deposits, of themselves, do not damage most rope materials. However, they trap dirt and grit and may make the rope difficult or unpleasant to handle. The inspector needs to assess the effects in the light of the application.

10

Testing

10.1 Introduction

10.1.1 General

Strength evaluation dominates, by far, all the tests that might be run on fibre ropes. This seems obvious since when anyone thinks of any kind of rope, the first thing that comes to mind is, 'How strong is it?'. However, there many other tests that are conducted to measure the various properties of fibre ropes or those of the fibres from which they are made. Some of these properties may be more important than strength alone in certain applications.

The tests that are covered in this chapter are listed below.

- Strength*
- Elongation*
- Size* and weight*
- Constructional parameters*
- Length*
- Hardness
- Torque
- Fatigue — tension–tension
- Fatigue — flexing
- Abrasion (external)
- Creep
- Fibre and yarn material properties*
- Fibre identification

The most common test on fibre rope determines the tension versus elongation relationship. The strength is determined by the tension that causes the specimen to break. Size and weight are also measured frequently. Standards exist for all these

* Likely to be used in a quality assurance programme associated with rope production

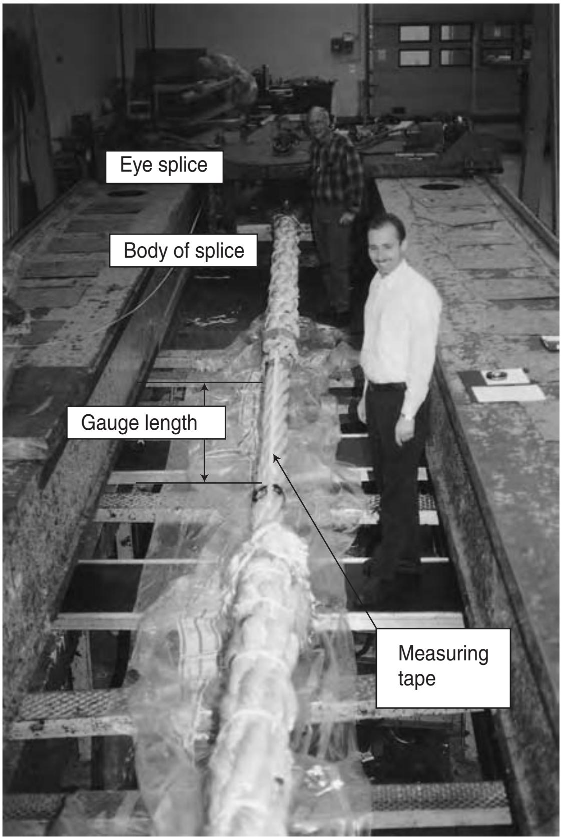


Fig. 10.1 Large 650-tonne polyester fibre rope in test machine. Reproduced by courtesy of ScanRope.

common tests and are covered by CI 1500, ASTM 4268 (now lapsed and no longer available) and ISO 2307. CI 1500 and ASTM 4268 were prepared in parallel and are, in general, in agreement. A very large rope specimen prepared for strength and elongation testing is shown in Fig. 10.1.

10.1.2 Test plan

Every rope test of any consequence should have a written test plan which includes a data reporting form. For test facilities that frequently repeat the same types of tests, a standard procedure and data reporting form should be used.

The test plan should always include a complete description of the specimen that includes the following:

- Material, size and type of construction
- A sketch of the specimen
- Condition of the specimen
- Estimated maximum breaking strength if conducting strength testing.

The following sections of this chapter should be used as a guide for developing a complete test plan.

10.2 Reasons for testing

10.2.1 Background

The reasons for conducting tests are as varied as the tests themselves. This background is useful for gaining an appreciation of the significance of testing in the development, production and use of rope. Some of the more important tests are discussed below.

10.2.2 Quality assurance

An acceptable quality assurance programme for rope production requires frequent testing of incoming materials to assure that the fibre is what has been ordered as to type, treatment (if any), performance specifications and size.

During the various stages of production, the ply count and twist levels of the rope components should be checked at some specified frequency.

The finished rope should be checked for size (linear density) and structural parameters, at least randomly. Strength and elongation testing of finished product should be done on a selected basis. If the customer has ordered a specific length, this should be checked in accordance with a standardised test.

The tests that are likely to be required in a comprehensive quality assurance programme are noted in Section 10.1.1.

10.2.3 Design and specifications

Fibre ropes often cannot be reliably designed to meet a specific strength specification without verification by testing. Unless changes from a known design are relatively small, knowledge of just the fibre properties may not be enough to accurately predict the strength of a new product. Also, strength will vary with size but not always in ratio with the amount of fibre present in the cross-section. Computer models and data bases are just becoming available but will require continual updating and verification. These will improve the prediction process. However, in general today, testing is advisable to verify strength and elongation predictions and is necessary to defend against liability claims.

If a rope manufacturer wishes to publish minimum or average strength values for a product line of multiple sizes, it is incumbent upon him to test and statistically analyse the range of sizes according to a recognised procedure, such as Cordage Institute CI 2002. Here, computer models can be used to reliably reduce the effort since testing of a few sizes will allow good extrapolation for untested sizes. Such models must be based on statistically significant sampling and include accurate data on constructional parameters.

Predicting durability at the design stage can be more difficult than predicting strength. Again, verification of predictions and performance claims by the tests described herein is usually essential. Experience has shown that a new product or design modification of an existing one that was expected to increase the life of a rope in a particular application could be the opposite or of minimal benefit.

10.2.4 Residual strength

All fibre ropes gradually lose strength and extensivity with use. Knowledge of rates of degradation is important for safety and economy. A number of tension–tension fatigue tests on large ropes have been carried out in joint industry studies sponsored by offshore oil related organisations interested in deep sea mooring. These have been useful in gaining an understanding of the behaviour of the particular ropes that were tested in this specialised application.

A considerable amount of testing is done of used ropes to determine residual strength after problems have appeared, but systematic testing of used rope by users and rope manufacturers to develop patterns leading to development of retirement practices is often neglected. If this were done, it could go a long way to blunt the frequent criticism that fibre ropes are unreliable compared to wire rope, since many users keep fibre ropes in service until they literally fall apart and then test them. Fibre ropes could be used much more efficiently if data on rates of strength loss could be tied to experience and acted upon instead of waiting for the rope to break before retiring it. This would augment the guidelines enunciated in Chapter 9, 'Inspection and Retirement'.

Testing for residual strength is often done after a rope has broken in service and injury or damage has resulted. This is often of questionable value as the weak link is gone, what is left of the specimen may not be suitable for proper testing or the test may not be able to replicate the conditions at the time of the incident.

An estimation of a rope's residual strength can be accomplished by testing the strands or yarns of a used rope. This generally requires special skills and judgement, and it is beyond the scope of this handbook to go into detail.

10.2.5 Research or special applications

Testing for various forms of fatigue and creep are usually done under research programmes to make life predictions. Sometimes a test programme will be undertaken for one specific application, such as deep sea mooring of floating oil production platforms. Other tests, not covered in this chapter, have been conducted to evaluate internal heat build up and the effects of axial compression of components on rope life during cycling to low tensions.

New designs of rope construction or the introduction of new fibre materials requires testing to verify performance. Good research tries to duplicate the conditions expected to be encountered in the field rather than measure only strength.

10.3 Safety in testing

10.3.1 General

Considerable energy is stored in fibre ropes that are taken to their breaking point. Recoil of the rope when it breaks can approach sonic velocity. Considerable potential for serious injury to personnel or damage to equipment exists. Precautions must be taken.

The danger associated with rope testing depends greatly on the strength of the specimen. For yarn testing and small cords, only safety glasses may be required. As forces become larger, the design of test equipment, maintenance, selection of fittings, operating procedures and safety facilities become increasingly important.

10.3.2 Recoil

When test specimens break, they tend to recoil along the line of their axis, so the danger zone from recoil is mostly in line with the rope. Standing in line with the rope on either end of the test equipment should not be allowed within some distance greater than the length of the specimen. On rare occasions, breakage occurs in one leg of an eye splice and the rope may whip to the side. Usually the structure of the test equipment shields the sides, but precautions must be taken if this is not the case.

Recoiling ropes can hit objects left on or under the test equipment. They can be thrown in almost any direction or can bounce off surfaces with considerable force. Never leave material in an area that can be struck by a recoiling line.

Instrumentation that may have been placed on or near the rope may be propelled by recoil of the rope. Although the components may be small, they can achieve considerable and dangerous velocity. On one occasion, a flexible metal measuring tape about 20 mm wide had been taped to the rope to measure elongation with video from a 'safe' distance. When the rope broke, the tape was shredded and a small piece broke a light fixture a few metres above.

10.3.3 Fittings and machine parts

One of the greatest dangers is the breakage of machine parts or fittings used for testing. Metal objects propelled by the rope specimen are the most dangerous and most unpredictable as to direction. Operators must be certain that the equipment has been designed with adequate safety margins relative to the maximum forces that can be exerted, with appropriate consideration for fatigue if the equipment is to be used extensively at high loads. As an example, a piece of a thimble for 50 mm diameter rope was found nearly 200 metres from an outdoor test facility when failure occurred at about 90 tonnes: a small piece hit a worker on his hard hat about 20 m away.

Fittings, such as shackles, must always be used within their rating. Custom fittings should have their rated load clearly marked. However, fittings that have been used near their rated load thousands of times, or ones that may have been severely overloaded many times, may fail catastrophically by fatigue. Fittings should be dedicated to the test facility, always used within their rating, their history monitored, inspected for cracks and retired after a reasonable period.

10.3.4 Impact against test equipment

When a rope recoils upon breaking, the structure of the test equipment must absorb the energy. Broken welds may appear in the structure so regular inspection is required. Most test frames are designed for compressive loads but recoil impact is in the opposite direction and under shock conditions. The designer may not have made suitable allowances for this eventuality.

Rope may recoil against the piston rod of a hydraulic cylinder that has been designed for straight pulling. Long slender rods have been bent when struck. This also causes an impact on the piston of the hydraulic cylinder, which creates a large spike in hydraulic pressure on the fluid behind the piston. On this side of the piston, hoses that may have been selected for low pressure have been known to rupture. Pressure gauges and valves have also been destroyed when this happens. Undesirable consequences are fire, an oil bath for personnel or a huge mess.

Test machinery damage is more likely to occur when very large or very long ropes are being tested at near the maximum capacity of the test equipment.

10.3.5 Protective barriers

Cages over the test bed are appropriate, but they must not be considered 'bullet-proof', especially for large ropes that may have strengths to as much as 1000 tonnes. Broken fittings or metal objects are the most dangerous, and although breakage is rare, they can easily tear though most cages that have been installed over test beds. The best protection is to have operators and bystanders stand well clear of the test area and remain behind a substantial barrier that has a better chance of stopping flying metal objects.

10.3.6 Working near a tensioned specimen

Finally, many times personnel wish to approach the specimen while it is under load to inspect it or to take measurements. The question is asked, what is a safe load? The easy answer is 'never at any tension' but this may not be reasonable. The following are offered as guidelines, but the person in charge is responsible for the final determination. Some of these items should be done as part of normal procedures regardless of the fact that someone will approach the specimen.

- Never approach a rope under tension exceeding 50% of a new rope's published breaking strength. Verify that the break strength value is reliable.
- Do not approach a rope at more than 50% of the test machine's rating.
- Never approach used ropes or ropes of unknown strength.
- Do not approach rope after extended cyclic testing, such as when fatigue or abrasion testing is underway, as the residual strength is unknown.
- Verify that the termination strength and rated strength of any fittings exceed the rope strength and that rope splices have been produced by a qualified person.
- Check to see that all fittings are properly installed.
- Verify that the load instrumentation is reading accurately.
- Make certain that the test equipment cannot be engaged when personnel are near the specimen.
- Do not approach the specimen if the test equipment is still moving.
- Remain next to a tensioned specimen for as little time as possible.
- Ideally, all work near the specimen should be done by one person who has prepared for the operation in advance. Besides safety, this is important as stopping a test at a high load for an extended period may adversely affect the test results.

10.3.7 Safety checklist

Each test facility should maintain a safety check list that is reviewed for every test. The checklist should be supplemented for test conditions that may not be covered by the general one. Review the guidelines above as the checklist is developed.

10.4 Terminations for strength testing

10.4.1 Introduction

A means of securing the ends of the test specimen in the test equipment is an important consideration. The test is more often one of the termination strength rather than a precise determination of the ultimate strength of the rope itself. This is also discussed in Section 4.2.5, but is worth covering here due to the influence on the interpretation of test results.

10.4.2 Standards

When the rope is in service it must be held in some fashion. It seems sensible, therefore, to test ropes with the same termination that is expected during use. CI 1500 and ASTM D 4268 require that the specimen be tested with a termination that is normally used in service.

10.4.3 Splices

Most ropes in general industrial or marine service can be spliced and are usually terminated by an eye splice. When tested or in use, ropes loaded to their ultimate strength will generally break at the end of the splice where it joins undisturbed rope. Historically, this averages about 5% to 15% less than could be achieved if the rope had reached its potential maximum independent of the termination. The results usually depend on the splice design and expertise of the splicer so variations have to be expected. Ultimate rope strength might occur when ropes are gripped by special, highly efficient devices or by the occasional 'perfect' splice that causes the rope to break away from the termination's influence.

10.4.4 Tapered wedge grips

Grips that use tapered wedges to squeeze the rope can be very efficient and can work well with ropes up to about 50 mm diameter. As size increases, the potential for slippage or rope breaks in the wedges increases. There are a variety of wedge designs in use and the history of successful use should be verified before undertaking tests. Gripping capability also varies with rope construction.

When grips are used, double braided and jacketed ropes may experience difficulties in any size as the core element may slip inside the outer braid. In some cases, when the jacket does not normally carry load, it is removed and the core rope tested independently.

10.4.5 Bollards

Bollards are described in Section 7.8. The concept of using friction on two drums to hold the rope has been adopted for strength testing. They are particularly useful for ropes that cannot be spliced. Generally they are limited to smaller sizes, in the range of up to about 75 mm diameter. The number of turns required to hold the load increases with rope strength and the size and weight of the bollards becomes unwieldy. They can give good results, especially in small sizes or with high modulus ropes. For low modulus specimens, failure often occurs prematurely on the bollard at the tangent point where the rope first contacts the drum. This is due to frictional heat generated at that point as the rope will slip on the drum surface as it tightens.

Bollards can be dangerous if the anchor on the low tension tail end of the specimen should slip. This can happen if this tail is not securely anchored, which often happens. The rope may unwind from the bollards in a violent and dangerous manner.

10.4.6 Mechanical and socketed fittings

Mechanical fittings that grip the end of the rope and poured sockets are discussed in Section 7.4. These are acceptable for testing if they are the terminations normally used in service (see Section 10.4.2). If they do not achieve a strength expected of the rope itself, the tests should be used to rate the assembly and not the rope.

Mechanical fittings, such as barrel and spike, are very large, heavy and expensive for ropes with strength in the range of 50 tonnes and such attributes all increase rapidly after that. These are not good candidates for everyday testing but may be used for evaluating specialised and specific applications that may use such fittings.

Terminations are also produced by introducing a resin into a socket (potting). These have been successful with fibre ropes with high modulus but the socket design, resin selection, methods of socketing and skill of the fabricator are extremely important to achieve optimum performance.

Sockets and, to a lesser extent mechanical fittings, are attractive, however, for testing as they are relatively short compared to eye splices. This can overcome bed length limitations of the test equipment. They should only be used if their reliability can be assured. If reliable data is not available from the manufacturer of mechanical or socketed fittings or other dependable source, a significant number of samples should be run to assure consistency and reliability, as large scatter is sometimes found in the test results when these fittings are used.

10.4.7 Knots

Some ropes cannot be spliced and are normally used with or terminated with knots. Usually, sizes are 20 mm diameter or less. However, they are often tested for strength with wedge grips or bollards that could give a much higher strength than if knots were used to terminate the test specimen. This fact is worth considering when evaluating test results in the light of the requirement that ropes should be tested with the termination used in service (Section 10.4.2).

10.5 Strength and elongation test equipment

10.5.1 General

Strength and elongation properties of rope are normally evaluated on the same type equipment. The essential features are a means of gripping a length of rope at each end, a capacity to pull or push the ends apart, and means of measuring tension and elongation. Small rope tests may be carried out on testers with mechanical motor driven gearing, but for large ropes, hydraulic cylinders are almost universal. Elongation is preferably measured by extensometers operating over a gauge length between terminations and away from rope disturbed by splices.

The requirements for testing fibre rope can be considerably different than for wire rope and chain. Although equipment for such testing is widely available and provides sufficient force capacity, it needs to be evaluated carefully for the testing of fibre rope to determine if it meets the stroke and speed requirements.

10.5.2 Bed length and stroke

The bed length must be long enough to accept a specimen that contains splices or other terminations, and with enough distance of undisturbed rope between terminations to obtain a valid test. For ropes to 16 mm diameter, this undisturbed length should be not less than 300 mm and for larger ropes should be 20 times the rope diameter (CI 1500). For very large ropes this may be impossible due to the scarcity of very long test machines and exception may have to be taken to this requirement; in this case, it should be noted in the test report and any implications covered by discussion.

A valid strength test needs to be carried out without having to readjust the specimen for inadequate stroke in the test machine (CI 1500). This means that the test equipment must have sufficient stroke to exceed the elongation of the rope up to the maximum force that is expected. This capability also must include the stroke necessary to take up the slack that is inevitably required to get the specimen into the test machine. Finally, splices will settle in during testing, which can require some small amount of additional stroke.

Some test machines are equipped with an auxiliary pulling device that can pull slack out of the specimen for mounting and even pull the rope to reference tension (see Section 10.7.1). This can reduce the stroke requirement for the main tensioning equipment and has been found to be beneficial.

10.5.3 Rate of loading

The equipment should be capable of a rate of load application that will bring the rope to 20% of its estimated breaking strength in not less than 20 seconds nor more than 200 seconds (CI 1500). The same speed need not be maintained to the breaking point. Pulling may be stopped briefly to take measurements or for some other essential test requirement but every effort should be made to meet the maximum time requirement. Ropes made of some fibres that creep can have rapid creep rates as loads go above certain levels (in the range of 50% breaking strength). When creep is a consideration, very slow loading rates may not be realistic and creep rates should be checked in advance with the rope maker or fibre supplier.

For testing a wide range of rope sizes with materials of varying elongation properties, the equipment should have variable speed capability over an appropriate range. This relates to the power of the motor installed on the machine; faster speed capability at low tension levels and slower speeds as the load approaches the breaking force. In a hydraulic apparatus, variable volume or dual pumps can be utilised, one for low pressure with high volume and another that takes over at high pressure and reduced volume.

10.5.4 Pin and clevis opening

If specimens with eye splices are tested, the pin diameter on which the eyes are placed should be at least twice the rope diameter. For grommets and ultra high strength fibre materials, larger pins, at least three times the rope diameter, generally give better results. It is ideal for certain laid and wire rope constructions if the distance around the pin at the pitch diameter of the rope is equal to an even multiple of the lay length; in this way, all the strands are of the same length.

The clevis opening (gap at the pin) for the rope should exceed the rope diameter by at least 10% when the rope is under reference tension; this is to prevent binding as most fibre ropes flatten on pins unless centring grooves are employed. Grooves in pins must not be less than the rope diameter but, ideally, should be about 10% larger. For wire rope constructions, the groove diameter may equal the rope diameter. A means to centre the rope on flat pins is necessary if the opening exceeds the rope diameter by more than about 20%.

10.6 Strength instrumentation

The only essential element of instrumentation for strength testing is a calibrated load cell. The accuracy at 20% of the maximum expected force encountered during the test and continuing to the maximum should be ±1.0% (CI 1500).

Calibration should be done by a qualified and independent authority and must be traceable to a national standard.

The certified calibration for a particular load cell should be established over a specific range. It may be necessary to start the calibration well above zero to give the accuracy required by any standard. For instance, for testing large ropes to the breaking load, it may not be practical nor necessary to maintain a high level of accuracy at 10% of the maximum force level. At some facilities, different load cells are used for different load ranges. Changing load cells during a particular test is undesirable, but may introduce little error in elongation measurements if the rope has been stabilised beforehand (Section 10.8.3).

Using the pressure in a hydraulic cylinder that provides the test tension as a load cell may not meet a high accuracy requirement. However, this technique is widely used. Here, the hydraulic pressure in a cylinder is multiplied by the area of the piston to obtain the force. The inaccuracy is due to friction effects and dependence on the accuracy of the pressure gauge and the ability to read it. Large cylinders are particularly inaccurate when used at tensions well below their maximum.

During calibration of a hydraulic cylinder as a load cell, a section of fibre rope or other elastic element should be introduced into the set-up in order to keep the piston moving while taking readings. If all metal fittings are used to install the calibration load cell, there will be little elasticity and thus little motion in the system resulting in what are essentially static readings. During a test, the difference between static and dynamic friction will introduce error; thus moving readings are more accurate than those taken when the piston is static. Taking readings while the piston is moving may be different from the standard procedure followed by official calibration agencies.

Strain gauge based load cells, are, in general, very accurate but they may be damaged by recoil when ropes break and, therefore, may not be suitable for ultimate strength testing unless a means of protection is provided.

The load instrumentation reading should stop automatically at maximum load or otherwise preserve this value.

An automatically generated plot of force versus pulling head travel should be available. This is discussed in detail in the next section.

10.7 Elongation instrumentation

10.7.1 Reference tension instrumentation

Most measurements of elongation of fibre ropes are made from a standard reference tension, not zero tension. From CI 1500 and ASTM-D-4268 the reference tension is:

$T_{Ref} = 1.38\ D^2$ where: T_{Ref} = Reference tension in Newtons
D = Diameter in millimetres

or: $T_{Ref} = 200\ D^2$ where: T_{Ref} = Reference tension in pounds force
D = Diameter in inches

Note: A different reference tension is used when determining linear density, diameter or circumference (Section 10.9.3).

To measure elongation and changes in elongation that are required to evaluate the stretch properties of fibre rope, a load cell is necessary to measure reference tension. A smaller load cell of higher accuracy at these low tensions than the one used for full strength testing is often employed.

At reference tension, which is in the order of 1% or less of the strength of common ropes, an accuracy of ±2.5% should be sufficient.

If an auxiliary load cell is used, after reaching reference tension, but before proceeding to higher loads, the position of the pulling device is accurately marked, the small load cell replaced by a larger one and the specimen returned to precisely the same extension for the start of loading to higher tension. The small load cell and a means of clearly marking the specimen position, with allowance for the different lengths of the load cells, should be considered an important part of the instrumentation.

10.7.2 Measuring elongation in a gauge length

The most reliable measurements for determining stretch properties of fibre rope are taken from a gauge length established on a section of undisturbed rope between terminations such as the ends of splices. In Fig. 10.1 the gauge length has been marked by elastic bands and a metal measuring tape has been stretched between them (white stripe on top of the rope but just visible in the figure).

Since test equipment length limitations can often dictate short gauge lengths, the accuracy of measuring and marking can be very important. High modulus ropes are particularly demanding in this regard. The instrumentation scheme should address this critically. The potential errors in each measurement should be estimated, added and divided by the gauge length; the potential maximum error, expressed as a percentage, should be included in any report.

Some suggestions for marking for visual measurements, either from proximity to the rope or from a distance via video are:

- Use elastic tape, stretched enough to remain tight on the rope as it is tensioned, to hold markers at each end of the gauge length. Note that the diameter decreases with increasing tension requiring the tape to adjust without losing tension.

- Realise that markers may rotate with the rope as it is tensioned. They may end up on the back side, out of view.
- Scribe the rope with a fine line completely around the rope. Use a contrasting colour or add a background colour that will not move on the rope.
- Weave a large thread or fine yarn, with contrasting colour, through the rope carefully around the circumference, coming to the surface at intervals.

A measuring tape may be placed on the rope for remote observation as was done in Fig. 10.1. Once the gauge length is established, secure a measuring tape at one end and pass it under an elastic strap that will not come loose as the rope is tensioned. However, the tape must be able to slide under the strap and the strap must make a clear line that defines the end of the gauge length. Observe changes in gauge length as load is applied. Use eye sight from a safe location, a scope or camera. This may be difficult if the rope tends to rotate.

Dual channel video for elongation linked to force measurement output provides a convenient record.

If visual measurements are taken from a tape, safety may limit readings to only 50% of breaking strength (see Section 10.3.6). If pulling head travel is also recorded for the entire test to break, the elongation at the breaking strength of the gauge length may be estimated by comparing the two values at 50%.

Similar arrangements using wire or high modulus cord connected to a displacement transducer has been used successfully. Linking the output to the force measuring instrumentation is necessary to obtain results. However, the transducer may be destroyed when the rope breaks. Use of low strength wire and placing a mass in the system may cause the wire to break before damage is done, but this is not guaranteed to work every time.

Lasers and photoelectric cells that can track a target on the rope have also been used. As noted above, the rope may rotate as tension is applied so a double line around the rope with a tiny gap for tracking may be used.

10.7.3 Measuring elongation in overall specimen length

It is usually simpler to measure the change in length of the entire specimen instead of a gauge length. This is done by measuring the travel of the pulling head. However, since most specimens have been produced with eye splice terminations, the two legs of each splice increase the apparent stiffness and the extra fibre volume in the splices themselves has the same effect. The included angle between the splice legs is also a consideration as a large angle (small eye) makes the splice legs shorter; this helps reduce the error, but it weakens the splice so the rope may break prematurely. Often the tucks of the two splices may be of significant length compared to the length of the specimen, so even a small eye will not help very much. Finally, splices settle in during testing which has the effect of slightly increasing the elongation measurements.

Elongation data collected by measuring pulling head travel should be considered approximate but can give meaningful information if accuracy in not a prime consideration. The results are improved if the length of undisturbed rope is in the order of five or more times the total length from the pin in each eye to the end of the splice, totalled for both splices.

Even if gauge length measurements are taken, it is a good idea to take simultaneous pulling head travel measurements as well. It provides a good cross-check on the data and can be used to evaluate the stiffening effect of the splices.

A variety of schemes have been employed to measure pulling head travel and will not be discussed here. The maximum deviation in data measurement should be estimated and recorded; this is divided by specimen length to give percentage of error and should be included in any test report.

Most designs of pulling head travel instrumentation try to protect it from rope recoil damage.

10.7.4 Reference length

If load cycling is involved, permanent elongation has almost certainly occurred in the specimen after a few cycles. This is due to settling in of the rope structure. If elongation properties are to be measured in relation to this 'settled in' condition (Section 10.8.3) rather than to the 'new' rope condition, the length at reference tension is measured after a specified initial cycling (see Section 10.8.3). The test plan must specify when and how reference length is to be determined, and the method must be described in any report.

10.8 Strength and elongation testing procedures

10.8.1 General

Strength and elongation testing are commonly done simultaneously. Strength testing may be done alone but elongation measurement is almost always combined with force measurements. The procedure below is written for a typical strength/elongation test. For strength testing alone, use only those steps that are applicable.

For more detailed instructions see CI 1500 or ASTM 4268.

For all tests, as part of the data record, a complete description of the specimen (Section 10.1.2) and test parameters should be recorded. Include the following:

- Overall length (if eye splices are used, the centre distance between pins on the test machine is usually used and taken under reference tension). A sketch is preferred
- Type of termination
- Eye size and pin diameter if eye splices are used
- Length of gauge length and rope condition when measured (new or stabilised)
- Length of undisturbed rope between splices
- Published or estimated breaking strength.
- Test speed
- Type, capacity and accuracy of load cell

10.8.2 Single pull to breaking

A single pull to break as described by this procedure can provide data to determine breaking load, elongation at the breaking point measured from reference tension, and a load/elongation curve for the specimen.

The following procedure is suggested when making a single pull to break:

- Prepare the specimen with the designated terminations (Section 10.4.2) and with appropriate markings or other facilities for elongation measurements (Sections 10.7.2 and 10.7.3).
- Verify that the test machine, auxiliary fittings and instrumentation meet the requirements of this chapter.
- Prepare the test machine and any equipment required to measure elongation.
- Place the test specimen in the test machine and complete the installation, including instrumentation.
- Perform the safety check (Section 10.3.7).
- Apply reference tension in accordance with the guidance of Section 10.7.1.
- Record the gauge length or the specimen overall length, or both as appropriate.
- Zero all instrumentation
- Begin loading. Record data in accordance with the test plan.
- Rope may not actually break completely, but broken strands or slipping in a splice probably warrants termination of the test (see Fig. 10.2).
- Note nature and location of breakage and mode of failure.

To calculate the percent elongation at the breaking load for a gauge length, use this equation:

$$E_{BS}\% = [(L_{break} - L_{ref})/L_{ref}] \times 100$$

where: $E_{BS}\%$ is percent elongation at break
L_{break} is gauge length at break load
L_{ref} is gauge length at reference load

Substitute the pin to pin dimension for gauge length if the overall length of a specimen with eye splices is used and the related elongation has been estimated.

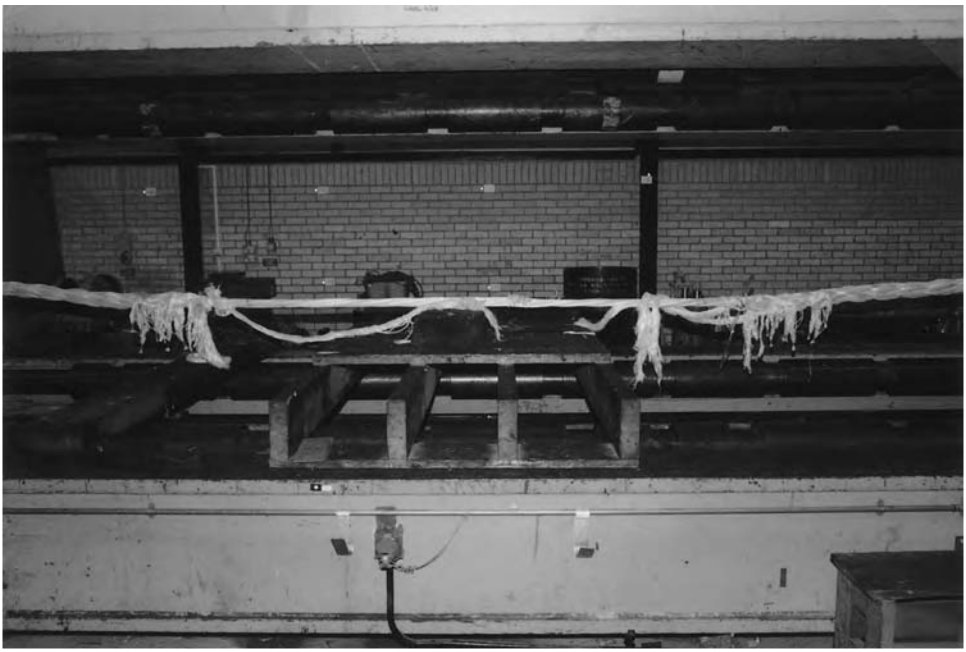


Fig. 10.2 Partial break of large rope. Such breaks are likely if there is a short distance between splices, which is usually a result of test-bed length limitations.

Typically, data is taken autographically and reduced to a graph with load on the vertical axis and elongation on the horizontal axis. This is usually converted to a graph of percent of breaking strength up to the breaking load versus percent of elongation. Figure 4.12 shows typical plots for ropes of various materials.

10.8.3 Cycling to stabilise the specimen

To stabilise a test specimen, two load levels are suggested by CI 1500 for peak cyclic load:

Ten cycles to 20% of published or anticipated break strength
Ten cycles to 50% of published or anticipated break strength

A typical autographic plot showing a stabilisation profile is shown in Fig. 4.9. This test may be used to report the elastic elongation performance of the rope after 10 cycles. This is represented by loading curve F – G in Fig. 4.9. The calculation is the same as in Section 10.8.2.

The area within the loading and unloading curves between F and G in Figure 4.9 is hysteresis and represents heat energy dissipated in that cycle. This area can be measured by various techniques and the hysteresis calculated based on the units used to record the data. The area below the loading curve is a measure of stored energy; some is recovered immediately and called elastic energy and the total is recovered after some time. Refer to Fig. 4.11.

10.8.4 Cycling prior to loading to break

Test methods CI 1500 and ASTM 4268 allow cycling prior to a break test. This may increase the breaking strength compared to a single loading to the breaking point.

If elongation measurements are not required, the cycling need not be continuous.

The data record for a break test of pre-loaded specimens should include the upper and lower load levels, or percents of break strength, and the number of cycles employed.

10.8.5 Cycling to determine elastic, permanent and recoverable elongation

As described in Section 4.3.3, the elongation from reference tension on the first cycle at the selected tension to the end of unloading on the tenth cycle contains three components. These are:

(i) Elastic elongation (recovered immediately)
(ii) Recoverable elongation (recovered over time after unloading)
(iii) Permanent elongation (mechanical settling-in of the rope structure and any splices).

These are graphically defined in Fig. 4.11.

The following test procedure is suggested for obtaining data necessary to evaluate these elongation properties. Length measurements are made at either the gauge length, overall specimen length or both, depending on the test plan. Autographic data recording is essential for accurate results.

- Follow the same procedure as in Section 10.8.3 for the first cycle.
- Continue, non-stop, to the tenth cycle (or other number as stated in the test plan), measure the elongation and return the specimen to the reference tension. There is no need to take this measurement if autographic recording is used.
- Measure the length of the gauge length and/or overall specimen length at the reference tension immediately or read from an autographic record later.
- Put the specimen in a completely slack condition. Most ropes will slowly continue to contract so provide sufficient slack; minimise any dead weight or friction that may tension the rope as it relaxes.
- Wait 24 hours. This is somewhat arbitrary as rope materials behave differently but a conservative, all inclusive rule is easiest to define. If test time is an important consideration and a high level of accuracy is not necessary, a wait of two to four hours should give a high percentage of recovery.
- Load the specimen to reference tension and measure the gauge length and/or overall specimen length.

All these properties are normally reported as a percentage of the length at the initial reference tension. However, when reporting the elongation performance of stabilised rope, the length at reference tension after cycling and relaxation is often used; this eliminates the effect of prior permanent elongation and is required by CI 1500. To avoid confusion, the selection of reference length should be stated.

An additional property is the first cycle elongation of a stabilised but relaxed rope. Refer to Section 4.3.3. Use the following procedure:

> Load the relaxed specimen to the selected load level and immediately measure the elongation of the gauge length and/or overall specimen length. Determine the percentage elongation by dividing by the reference length of the stabilised specimen. This is in accordance with CI 1500.

10.8.6 Wet testing

Strength and elongation testing may be conducted on a wet specimen. The following is taken from CI 1500.

- Soak in fresh water for 22 to 28 hours. There is no evidence that seawater will give a different result and its corrosive effects can affect test equipment; therefore, it is not recommended.
- Conduct the test within 12 hours. Cover the specimen to minimise drying if the test is not conducted within one hour. If the delay exceeds 12 hours but is less than 24 hours, the specimen may be soaked for two hours prior to the test. A more extended delay requires the initial soak to be repeated.

Note that if cyclic load testing is to be conducted wet, spraying or immersion is required and must be maintained for the test period.

10.9 Size, linear density, lay and braid cycle lengths

10.9.1 General

As explained briefly in Chapters 1 and 4, rope size is best defined by linear density. Diameter and circumference are then determined as 'nominal' from a rope standard such as those issued by the Cordage Institute. The rope size is defined as being within ± 5% of the corresponding linear density. However, diameter and circumference can also be measured directly. This chapter covers the test procedures for linear density, diameter and circumference.

10.9.2 Reference tension

Note: A different reference tension is used for size measurements from that used for elongation as specified in Section 10.7.1.

From CI 1500 and ASTM-D-268 the reference tension is:

$$T_{Ref\text{-}S} = 0.35\ D^2 \qquad \text{where: } T_{Ref\text{-}S} = \text{References tension} - \text{Newtons}$$
$$D = \text{Diameter} - \text{millimetres (nominal)}$$

or:

$$T_{Ref\text{-}S} = 50\ D^2 \qquad \text{where: } T_{Ref\text{-}S} = \text{References tension} - \text{pounds force}$$
$$D = \text{Diameter} - \text{inches (nominal)}$$

10.9.3 Linear density

The procedure for measuring linear density is given below. This is consistent with CI 1500 and ASTM D 4268.

Instrumentation:

- Weighing device with an accuracy of 0.25%.
- Measuring tape graduated to read to 1 mm.
- Tension reading gauge calibrated to an accuracy of 2% or less.

Specimen:

- Remove new rope carefully from a reel or spool by pulling off the reel perpendicular to the axis to avoid twisting; do not unwind around the flange or off the end. Mark the rope with a straight line along its length to make a record of its normal condition. If the rope is not on its original package, attempt to remove any abnormal turns; sight down braided, plaited or jacketed structures, or allow laid structures to hang free.
- Introduce pins, knots, grips or other means of holding the small reference tension well beyond the expected specimen length.
- The specimen length must be at least 300 mm for ropes of 16 mm diameter or less and 1800 mm for ropes 17 mm diameter or more.
- Keeping the axial line straight, mark the rope with two fine lines, fine coloured yarn, fine wire or other means that will provide an accurate measurement in the order of 1 mm. For ropes 16 mm diameter, the marks should be at least 250 mm apart and no closer to the holding point or end of splice affected area than 25 mm, and, for ropes 17 mm diameter and larger at least 1500 mm apart and no closer to a holding point or end of splice affected area than 150 mm. Some tension may facilitate the marking process.

Measurement procedure:

- Keeping the axial line straight, apply reference tension.
- Measure the marked length. For ropes 16 mm diameter and less the accuracy should be ±2 mm and for ropes 17 mm diameter and larger the accuracy should be ±5 mm.

- Remove the specimen from the test machine.
- Carefully cut the rope at each mark, being very careful to make the cut perpendicular to the rope axis.
- Weigh the cut length.

Calculating linear density:

$$\text{Linear density} = \text{Weight cut length}/\text{specimen length}$$

10.9.4 Diameter, circumference, size number

Linear density method:

- Obtain an accepted standard for the particular rope product that lists diameter, circumference and linear density for a range of sizes.
- Perform or obtain results from a linear density test.
- Diameter and circumference may be determined from the value for linear density. Typically, any value of linear density within 5% of that stated in the standard would correspond to the diameter or circumference.

Diameter – direct measurement:

- Apply reference tension.
- Option 1: Use a calliper to measure across the crowns of the rope or to the highest opposite points on the rope (see Fig. 10.3).
- Make several measurements and average them.
- Option 2: Wrap a pi (π) tape around the rope under slight hand tension. A pi (π) tape is a narrow, flexible metal tape graduated in units of length / π (3.14 mm for each unit). Measure the diameter at the zero mark on the tape.

Direct measurement of diameter is useful when the rope must fit through a hole of specific size.

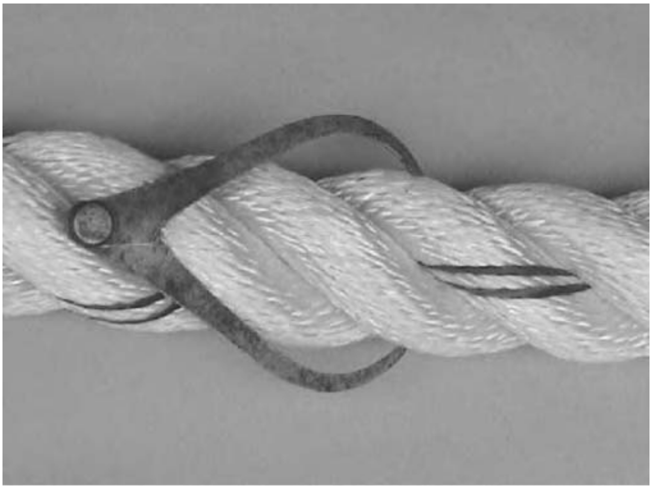
Circumference – direct measurement:

- Apply reference tension.
- Option 1: Wrap a string around the rope with light hand tension so that the string crosses itself flush against the rope. Accurately mark both sides of the string where they cross.
- Straighten out the string and measure the distance between the marks.
- Option 2: Wrap a measuring tape around the rope under slight hand tension. The tape should be a narrow, flexible, metal measuring tape. Measure the circumference. Note: it may be easier to read if the measurement is taken at unit ten on the tape since it is easier to tension the tape (therefore, a reading of 16 is a circumference of 6).

If a circumference is measured, the diameter may be determined by dividing by π (3.14).

If a diameter is measured, the circumference can be determined by multiplying by π (3.14).

In general, for large ropes over about 50 mm diameter, the circumference measurement, either directly or with a pi tape, is preferred to the use of callipers, with the diameter read off the tape or calculated. This is the usual practice in the commercial marine industry.



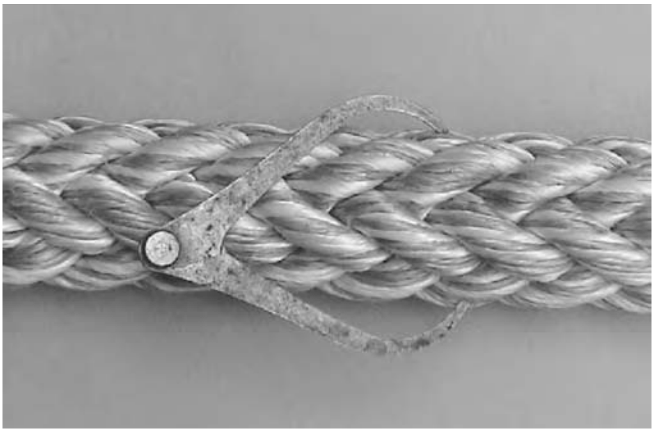


Fig. 10.3 Diameter measurement on 3-strand laid and 12-strand braided rope, at reference tension.

Size number:

Size number is the circumference of a rope in inches but is expressed as a dimensionless number. This is rarely used outside the commercial marine industry but will be found in some catalogues or publications (see Appendix I, Table I.1).

10.9.5 Lay and braid cycle lengths

The lay length of a laid or stranded rope can be measured from reference tension. Place a straight edge on top of the rope in line with the axis. Place a small mark directly in the centre of a strand next to the straight edge. Locate the centre of the same strand when it appears under the straight edge and mark its centre. The distance between marks is the lay length. For greater accuracy measure several lay length cycles and divide the measured length by the number of cycles (see Fig. 10.4).

The cycle length for braided ropes is similar to the above. In Fig. 10.5 the rope contains a coloured strand, so it is easy to see the strand when the cycle repeats. At

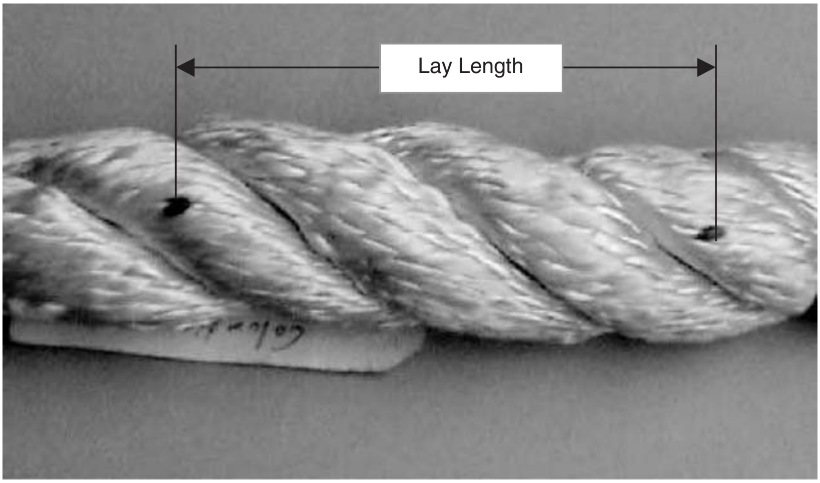


Fig. 10.4 Lay length of 3-strand laid rope. This is a soft rope with a long lay length.

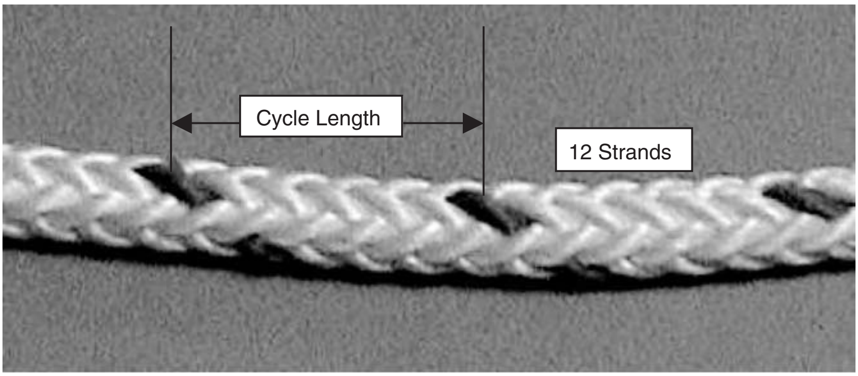


Fig. 10.5 Cycle length of a 12-strand tightly-braided rope.

reference tension, measure the distance from one location to where it reappears, making certain the axial line is straight. This rope has 12 strands, 6 in one direction and six in the other; the cycle length is the same for both.

For braids, cycle length is sometimes defined as pitch (cycle length/number of strands in one direction) or pick count (number of strands in one direction/cycle length). One is the reciprocal of the other.

Parameters such as helix angle can be determined from these measurements when the radius to the centre of a strand and the number of strands are known.

10.10 Length

There is no standard test method for determining the length of fibre rope, but its measurement can sometimes be contentious.

Many manufacturers of general-purpose fibre ropes actually sell the rope by weight, not length. Even though a buyer may order 220 metres (common length for large mooring lines for ships), he is shipped the weight equivalent of that length based on the linear density. Typically, the tolerance on linear density is ±5%, so a rope can be 5% longer or 5% shorter. However, 5% of 220 m is 11 m, a fair length.

Sometimes ropes are ordered with spliced eyes but no specification is made as to whether the length measurement is made before or after splicing. For a 60 mm diameter rope with two metre spliced eyes on each ends, the difference in cut length versus spliced length would be about 12 m.

Braided rope are easily compressed. Other ropes, depending on how tightly they are made, can also be shortened if compressed. These ropes when laid out for a measurement need tension to pull out the fluff. Since linear density is measured at reference tension (Section 10.9.2), length should be measured likewise if using linear density to measure length. However, a buyer may not know the procedure and could come up considerably short by his reckoning.

Nylon ropes will shrink when saturated with moisture, or even when exposed to high humidity. Changes in the order of 5% to 8% are common. Length measurements of wet nylon rope can create considerable discussion between buyer and seller.

Used ropes also become shorter as broken filaments on the interior expand the structure. Foreign matter may do the same. However, a user does not have much recourse to the seller if an old rope is measured a little shorter than what he thought he purchased.

10.11 Cyclic loading tests

10.11.1 Tension–tension fatigue tests

Ropes in use are exposed to regular or irregular cyclic variations in tension, which, as described in Section 4.5.2, can cause progressive damage. This gives a requirement for tension–tension fatigue testing. However, the difficulties in carrying out such a programme are considerable. There are no generally applicable standard procedures. Such testing as has been done, has been carried out for research related to particular applications. Although the situation may not be as severe in some other applications, it is convenient to describe the problem in terms of studies of tethers for deep-sea moorings.

Table 10.1 illustrates the basic difficulty. Moorings are subject to wave motions with periods of about 7 seconds and might have a projected life of 20 years, so that

Table 10.1 Time needed for fatigue tests

Frequency (Hertz)	Period (seconds)	Number of cycles					
		10^3	**10^4**	**10^5**	**10^6**	**10^7**	**10^8**
10	0.1	100 s	16 mins	2.8 hr	28 hr	12 days	115 days
1	1	16 mins	2.8 hr	28 hr	12 days	115 days	3 years
0.1	10	2.8 hr	28 hr	12 days	115 days	3 years	30 years
0.01	100	28 hr	12 days	115 days	3 years	30 years	300 yrs

the ropes would be subject to 10^8 cycles. Reproduction of use conditions, which would take 20 years for one test, is clearly not an option. What alternatives can be adopted?

- Cycle at higher rates. For full-size ropes with break loads of around 1000 tonnes, the period cannot be less than about 30 seconds without causing undue heating. To reach 10^5 cycles would take about one month and this may still not be useful to predict what happens after a thousand times more cycles.
- Use small ropes as models. At 5-tonne break load, cycling at 2 Hertz was used in the Fibre Tethers 2000 Joint Industry Study (Noble Denton and National Engineering Laboratory, 1995). This made it possible to test a range of ropes at various load ranges to about a million cycles, and to identify conditions where early failures occurred.
- Test at more severe load ranges. If the severity is much greater than the use conditions, different modes of fatigue damage, with an incidence varying with fibre type, may be activated that are different from those which would be encountered in service. Some fibres are more subject to rapid creep at high loads, some have lower fibre-to-fibre abrasion resistance and some are more prone to axial compression fatigue at low minimum rope tensions.
- Progressively increase the severity of loading. One recommended test procedure cycles from 1% of breaking strength to 50% of breaking strength for 1000 cycles, 60% for 1000 cycles and so on until the specimen breaks (OCIMF 1987). A calculation is then made that can be used to compare one rope to another. It is then assumed that the rope that gives the best value will have the best fatigue life. Because this test is so severe and not at realistic load levels, it does not assure a quantitative estimate of the life at lower loads.
- Measure residual strength after a given numbers of cycles. This is of limited value because the strength may decrease very little until a rapid drop occurs near the time of final failure.
- Make a pathological examination of ropes after a given numbers of cycles. Testing of yarn strengths shows the extent to which damage is occurring, and extrapolation indicates when this will lead to major loss of rope strength. Table 10.2 shows a typical test report. Microscopical examination shows what fatigue damage mechanisms may be taking place.

In order to be fully meaningful, a fatigue testing schedule should cover many test conditions: different mean loads and load ranges, wet and dry, different temperatures, etc. It is difficult to achieve this in a reasonable time at a reasonable cost. This has meant that there has been little or no verification of test procedures. Rope users, design engineers or producers needing to evaluate fatigue performance should consider carefully the expected use conditions. Previously reported test data should be carefully reviewed as to test conditions and methodology to determine relevancy. A decision should then be made as to what is the most reasonable test procedure that can be carried out within an available budget.

As an example of a cyclic test procedure, Table 12.2 shows the schedule suggested in the *Engineers' Design Guide* (TTI and Noble Denton, 1999) for testing for length, elongation, and stiffness properties of polyester ropes intended for deepwater moorings.

Table 10.2 Illustrative test report on yarns from 5-tonne rope after fatigue testing. From Noble Denton and National Engineering Laboratory (1995)

Rope type – Twaron 6/1 wire rope construction. – unfailed after 1.01 million cycles at 27 ± 19.5% of breaking strength. Residual strength tests on individual textile yarns and position of failure shown in table. Textile yarn was Twaron 1020 1680 dtex

OUTER STRAND OUTER YARN		OUTER STRAND CORE YARN		CORE STRAND OUTER YARN		CORE STRAND CORE YARN		CORE STRAND CORE YARN (1)	
FAILURE POSITION mm	A.B.L. KGS	FAILURE POSITION mm	A.B.L. KGS	FAILURE POSITION mm	A.B.L. KGS	FAILURE POSITION mm	A.B.L. KGS	FAILURE POSITION mm	A.B.L. KGS
all over	26.8	500	25.5	all over	18.7	834 bak	0.0	all over	17.7
400	25.3	320 bak	11.9	all over	19.4	852 bak	0.0	all over	24.2
700	19.5	620	24.9	400	24.3			400	25.1
all over	24.6	650	28.2	all over	25.0			all over	26.6
all over	21.7	580	19.3	580	20.8			580	24.1
280	21.4	all over	26.6	all over	20.5			all over	22.4
all over	26.9	660	24.5	big	23.8			big	24.8
330	21.0	all over	17.8	all over	19.4				
all over	23.5	all over	24.1	all over	22.3				
450	27.0	500	17.7	all over	19.4				
MEAN	23.8		22.0		21.4		0.0		23.5
STD.DEV	2.7		5.1		2.3		0.0		2.9
C. OF V.	11.5		23.3		10.8		0.0		12.1
% RESIDUAL STRENGTH	77.7		72.0		69.8		0.0		77.0

(1) Residual strength of remaining unbroken piece
bak = broke at kink
big = broke in grip

10.11.2 Scaling

To reduce cost when evaluating very large ropes, most fatigue testing is done on specimens of small size. This seems realistic if the specimen is a good geometric model of larger sizes. A more comprehensive approach would be to test two smaller ropes, but significantly different in size, and use the data for extrapolation to the larger size. At least one thing is reasonably certain: if the smaller specimen does poorly, a larger one will not do better.

10.11.3 Test equipment

Tension–tension fatigue test equipment is essentially the same as for load–elongation testing, provided that provision is made for cyclic changes in load over many cycles, either through tension control or displacement control. Facilities are fairly widely available for testing small ropes, but, as far as is known, there is only one facility in the world that is capable of tension–tension fatigue testing of ropes with break loads over 100 tonnes.

Tension–tension fatigue testing can lead to failure of the test equipment or test-related fittings before the work is complete. Personnel should be reminded to stay clear when fatigue testing is in progress.

One problem is abrasive wear at the terminations in the test machine. A failure here only represents a true fatigue failure of the rope if the same method of termination is used in an application. Steel pins can be very abrasive when an eye termination bears directly on the pin and failure often occurs here before the body of the rope wears out. A heavy fabric, such as polyester or HMPE sail cloth, wrapped around the eye, has been shown to be effective. Also, a nylon or high density polyethylene liner on the pin works well but the bearing pressure must be kept below the compressive strength of the liner (which is usually the case for diameters greater than 2 times the rope diameter for nylon or polyester ropes). The pressure area may be estimated by using 50 to 70% (braids flatten more than laid ropes or wire lay type ropes) of the diameter of the rope times the diameter of the liner, assuming it is flat. Grooved supports must allow the rope to flatten or lateral pressure on the groove walls can cause abrasion, or, as has happened, split the support at the root or break the flange. The test report must describe the termination and method of protecting the eyes so that similar protection would be used in an actual application.

10.11.4 Modulus and hysteresis

Cyclic loading tests also provide information on modulus and hysteresis, which are useful for modelling the response of a moored rig to the effect of wind, wave and current. A typical plot is shown in Fig. 10.6. The usually calculated quantities would be the moduli at installation (new rope), after breaking in, and storm (dynamic). The hysteresis during storm simulation testing would determine the potential for damaging heat build-up.

10.12 Flex fatigue testing

10.12.1 Flex fatigue testing – general

Flex fatigue is usually associated with running a rope over pulleys, although it can also be found in cases where a rope wraps and unwraps on a fixed surface. Both can

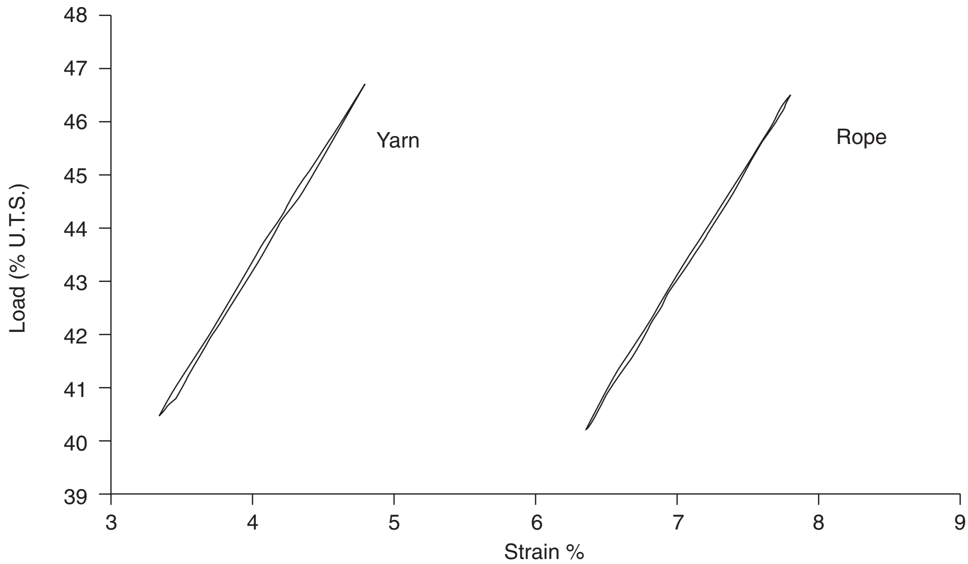


Fig. 10.6 Typical cyclic load–elongation responses for polyester yarn and rope.

be tested in the laboratory by cycling back and forth over a pulley. If sliding on the curved surface, beyond the scuffing that might normally occur, is a consideration, testing becomes more complex. Also, if tension changes while the rope is moving over the curved surface the length changes due to elasticity and can cause surface abrasion. Testing for these conditions would require special arrangements but they are noted here to make the reader aware that the test arrangement should represent the actual field conditions.

Due to the cyclic loading that may occur in flex fatigue testing, much of the information provided for tension–tension fatigue testing may apply here. See Section 10.11.

10.12.2 Mode of failure – flex fatigue

The mode of failure can take several forms which should be anticipated by the test protocol. A combination may occur. These are:

- Internal fibre-to-fibre abrasion
- Melting internally
- Exterior abrasion and/or melting
- Compression damage (kinkbanding) in jacketed ropes.

10.12.3 Scaling for flex testing

Scale models should be appropriate for most flex fatigue testing. The smaller rope must be representative of the larger one in material and geometry. The load must be at the same percentage of breaking strength and the ratio of pulley diameter to rope diameter must be the same. Finally, the pulley material must be the same. Smaller ropes will generate heat slower and dissipate it faster than large ones, so the test should check rope temperature; if marginally high, caution should be used when extending the results to much larger ropes. However, heat transfer technology may be used to estimate heat build-up at full scale if a heat transfer coefficient can be established.

Finally, if the smaller model does not perform well, the larger one will be worse.

10.12.4 Heat and accelerated testing

If the test speed is close to the anticipated operational speed and melting or overheating occurs, the test shows that the conditions are too severe. However, if in an effort to accelerate testing, a much higher speed is used in testing, melting may appear but may not be representative of performance in service.

10.12.5 Compression and kinkbanding

Compression and kinkbanding, when they occur, are mostly found in jacketed ropes that undergo flexing. Ropes that are to be used with a jacket should not be flex tested without the jacket because jacketing can be the cause of kinkbanding and fibre compression failure (see Section 4.5.7).

Kinkband damage has also been found in tuck splices ropes of wire rope construction made from high modulus fibre.

Scaling is not recommended as diameter and jacket tightness can play important roles in causing compression fatigue and these would be very difficult to model.

When the strength element is covered by a jacket, compression damage may not be detected until failure occurs. The hidden evidence appears well before failure. It may be worthwhile to run a preliminary test of short duration to check if kink bands have developed, even if the jacket is destroyed by opening it.

10.13 External abrasion resistance testing

External abrasion is difficult to quantify and there is no known industry-wide standard test. The principal reason is the reproduction of abrasion tools that are exactly alike. Also, the sources of external abrasion are so very different that test protocols would vary greatly depending on the use of the rope. Abrasion tools that have been tried are: hardened steel bars, ceramics, wire mesh, sandpaper, and, no doubt, others. Refer to Fig. 10.7.

Ropes are used at so many different loads, that several levels would be required for appropriate evaluation because of differing behaviour at different loads. Certainly, speed is important since, at some combination of load and speed, the rope will get hot enough to alter the surface properties or even melt the fibre. The angle of wrap around the abrasive tool is probably a consideration, but, as far as is known, its influence has not been quantified.

Abrasion testing is usually done by cycling the rope on an abrasion tool that is curved. This induces bending which may result in internal fibre-on-fibre abrasion as discussed in Section 10.12.2. The test operator may find it instructive to examine the specimen internally at some point.

Finally, it is known that both internal fibre abrasion and external surface abrasion resistance can be highly influenced by the presence of water. So, wet testing may be an additional necessity for a realistic evaluation.

In the final analysis, the best way to assess external abrasion resistance is to compare one rope candidate to another following identical testing. At the risk of

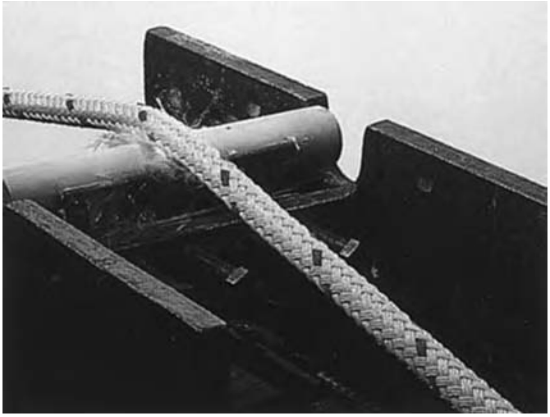


Fig. 10.7 Abrasion test. Braided rope rubbing on a hardened steel bar. Reproduced by courtesy of Samson Rope Technologies.

stating the obvious, the test should attempt to simulate actual service as closely as possible.

10.14 Creep testing

Creep testing appears to be relatively straight forward – simply hang a weight on a rope or a scale model and measure its elongation over time. However, the time for significant data may be measured in years and this may not be realistic. Using loads much higher than normal and/or elevated temperatures to accelerate the testing probably will not give representative data for time to failure. It may be helpful to determine the elongation to failure instead of time to failure. In this way, a shorter test that measures a time to what is estimated to be a safe elongation may be informative.

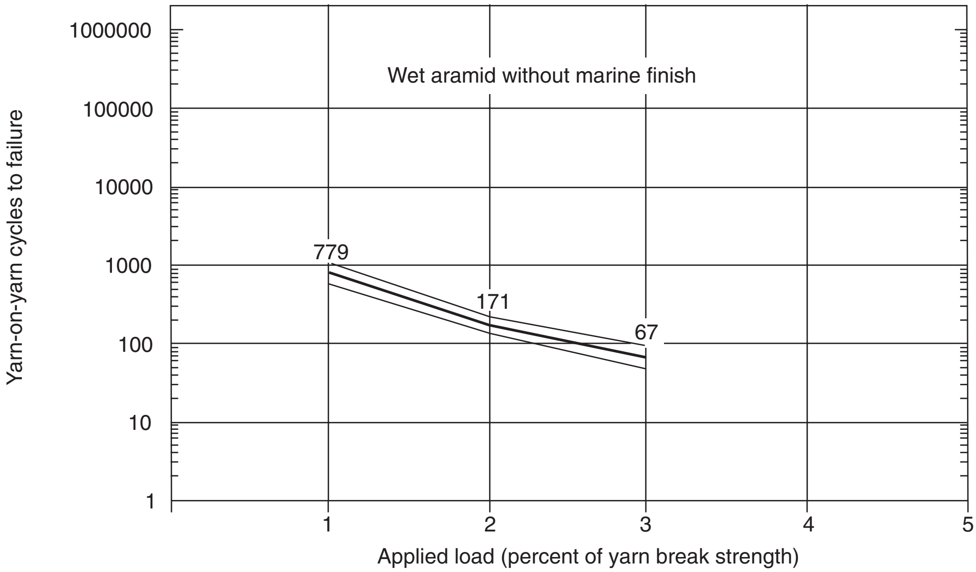
Creep data provided by a reliable fibre supplier or published rope data from reputable sources is usually the best place to start. The rope or scaled specimen may be tested for a limited time to see if the creep rate matches the fibre data. Rope, at the same percentage of break strength, creeps slower than the fibre of which they are made. Some useful extrapolation may be possible based on fibre creep behaviour.

Caution should be used if residual strength is measured following creep testing that was carried out for a limited time short of failure. Due to load redistribution between fibres and yarns, the strength may even increase initially. Further, the strength would be expected to remain high until near the time that the ultimate breaking load has been reached (Section 4.5.3).

Although strength can remain high until approaching creep rupture, the elongation to break near the end of a creep test will be significantly less than that of a new rope. The elongation in a simple break test after limited creep exposure can be compared to a specimen that has not been loaded. This would give some indication of the margin that remains after the particular creep exposure time.

10.15 Hardness testing

Three-strand laid ropes may be tested for hardness. The test procedure is given in CI 1501.



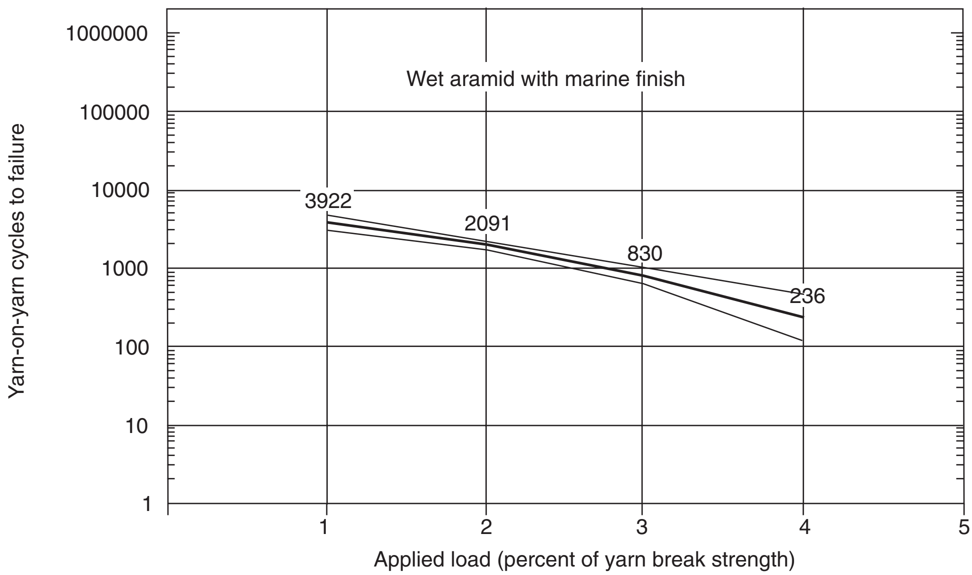


Fig. 10.8 Results of yarn-on-yarn wet abrasion test of identical aramid fibres with and without water-resistant (marine) finish. From Tension Technology International internal test data.

Briefly, a well defined, tapered, stainless steel spike is forced through a hole in a pressure plate and into a rope specimen by a compressive test machine. Specifications for the spike and pressure plate are given in CI 1501. The rope specimen and spike are set up in the test machine and the spike is forced between the strands. The rope is slack and the ends are tightly taped or wrapped. The force required to reach each of two marks on the spike is recorded.

The hardness is defined by a range of acceptable force values for each of the two readings. Test results will vary with rope size, lay length and fibre type. Rope hardness is determined from a table that lists the range, by rope size, into which the measured value must fall for 'hard', 'medium' or 'soft'.

10.16 Testing for fibre properties

10.16.1 General

It is a good policy to measure fibre properties independently whenever developing new rope products and for quality assurance on incoming yarn for regular production. However, due to equipment variations, the same test equipment and yarn grips should be used unless consistency between test machines has been verified. Fibre producers test under ideal conditions and may use slightly different equipment and procedures. Independent data, generated by the user, is the best way to evaluate yarns.

Regular and consistent testing will permit the development of a data base that will allow the establishment of reasonable tolerance ranges for acceptance of the yarn into production.

Size (linear density), strength and elongation at break are usually measured.

10.16.2 Yarn-on-yarn abrasion test

The effects of rope filaments rubbing on each other is discussed in Section 2.5.8. Figure 2.21 shows the apparatus for testing resistance to yarn-on-yarn abrasion and Fig. 2.22 shows some typical test results. The test procedure is defined by CI 1503.

Table 10.3 Fibre identification tests for low-modulus rope-making materials

TEST	Nylon	Polyester	Polypropylene
In flame	Melts and burns White smoke Yellowish drops fall	Melts and burns Blackish smoke Melted drops fall	Shrinks and melts Smell of candles Melted drops fall
Remove flame	Stops burning Small bead on end Hot bead stretches into fine thread	Stops burning Small black bead on end Hot bead stretches into fine thread	Burns rapidly Hot mass stretches into fine thread
Residue	Hard, round yellowish bead	Hard, round blackish bead	Hard, brown or blackish
Burning odour	Celery, fishy	Oily, sooty, like sealing wax	Asphalt, burning paraffin wax (candles)
Buoyancy	Sinks*	Sinks*	Floats
Colour	Usually white with bluish tint, may be dyed	Usually white with silvery tint, may be dyed	Rarely white, all range of colours
Filament size	Very fine, can barely see	Very fine, can barely see	Usually coarse if round but may be fine. Also as film strips

* Entrained air and tiny bubbles adhering to filaments must be removed by agitation while fibre is submerged.

Table 10.4 Fibre identification tests for high-modulus rope-making materials

Test	Aramid	HMPE
In flame	Does not melt White smoke if any	Shrinks and melts
Remove flame	Stops burning or burns very slowly	Burns rapidly Hot mass stretches into fine thread
Residue	Black, filaments remain visible	Hard, black
Burning odour	None	Asphalt, burning paraffin wax (candles)
Buoyancy	Sinks*	Floats
Colour	Pale gold	White
Filament size	Very fine, can barely see	Very fine, can barely see

* Entrained air and tiny bubbles adhering to filaments must be removed by agitation while fibre is submerged.

Briefly, a specimen of yarn is attached to an eccentric crank. The yarn passes around pulleys and is wrapped around itself for a designated number of turns. A weight is fixed to the free end of the yarn. In the intertwined section, the tensioned yarn rubs on itself when the crank rotates. The intertwined section may be submerged in water for wet testing.

The test provides comparative data for different fibres or fibres with different finishes. An example is shown in Fig. 10.8 where the same aramid fibre has been tested with and without a water resistant (marine) finish and the results compared. This test can also be used in a quality control programme to assure that the correct fibre finish has been delivered.

10.17 Synthetic fibre identification

10.17.1 Quick identification

Tables 10.3 and 10.4 suggest some relatively simple tests that may allow a person to determine what fibre a rope is made from without an involved chemical analysis (also see Flory, 1992). Fibres covered in the tables are:

- Nylon (6 and 6.6)
- Polyester
- Polypropylene
- Aramid
- HMPE

10.17.2 Formal fibre identification testing

A large variety of more scientific testing can be used to be more definitive (The Textile Institute, 1985).

11

Consumption, markets and liability

11.1 Introduction

Some appreciation of how much fibre rope is produced and how it finds its way from the manufacturer to the end user completes the journey through fibre rope technology that was started in Chapter 1. Until the end of the age of sail, most rope was produced in or near major ports and the maritime industry consumed the greatest volume by far. Today, modern ropemaking is far flung and extremely diverse, as are the outlets for purchasing it.

The volume of fibre rope that is produced makes it a significant business in every industrialised area. A few countries have seen the development of a rope industry primarily for export. In less developed areas, rope is still made by hand with primitive machinery, to be sold locally. This chapter will attempt to provide an overview of consumption, markets and distribution channels, mostly from a European and North American perspective. Trying to define all this globally in historic and economic terms would require a book of its own.

Liability issues will also be discussed in this chapter as this is related to overall marketing strategy. Accidents are a reality but need not happen if the product is selected and used properly. It is one of the objectives of this handbook, and of efforts by others in the rope industry, to enhance understanding and thereby improve safety.

11.2 Consumption of fibre rope

11.2.1 Fibre consumption

Virtually all fibres of nylon, polyester, aramid, HMPE, LCP and PBO are produced by large chemical companies and sold to ropemakers in the form of yarns. The volume of nylon and polyester fibre that is used in rope is very large compared to the others cited. Of all the high tenacity nylon and polyester fibre that is produced, only a small percentage (15% for nylon and 10% for polyester at most) goes into rope, but this is probably the second largest consumer of these materials after tyre cord.

Most polypropylene or other polyolefin fibres for rope are extruded from granules by the ropemakers themselves or by organisations that are closely affiliated. Usage of polypropylene fibre for rope is probably twice that of nylon and polyester combined. Polyethylene usage in rope is very limited.

Natural fibres are now less important in the industrialised world but still represent significant volume for non-critical use. Manila rope is the most common and is produced near where the fibre is harvested.

11.2.2 Estimating rope consumption

It would be presumptuous to claim that an accurate estimate of world-wide consumption of fibre rope is possible. Trade data is non-existent in many parts of the world, and where it is kept, fibre rope becomes mingled with twine, fish nets, tennis nets, decorative cords and other uses of textile fibre products. The effort is further complicated due to the use of both low strength fibre materials for cheap rope and high tenacity fibre materials specifically produced for top grade products.

Trade associations that represent ropemakers do not collect data from their members, as far as is known. Fibre producers that sell to the rope market have some feel for what they ship into the rope industry but much polypropylene is produced by the ropemakers themselves and this is the largest volume of production by far. Just identifying what to count is a challenge. So, what is presented here must be considered as highly estimated. Different assumptions will give widely differing results.

The estimates presented here were gathered from a wide variety of sources and adjusted to achieve coherence. Some data was old and needed to be modified to suit current trends.

11.2.3 Consumption of fibre rope

The greatest volume of rope is made from low modulus fibres: nylon, polyester and polyolefins (mainly polypropylene). Table 11.1 provides highly estimated data on consumption. The worldwide value of the market, exclusive of twine and small cords, is estimated to be at least \$1.5 billion, which results in an average price of about \$6.00 per kilogram. This is the revenue to rope manufacturers, exclusive of mark-ups by distributors, wholesalers and retailers.

In 1951 it was estimated that that the US produced 47 000 metric tons of manila fibre rope. Today that value is closer to the entire world wide consumption with a market value of about \$250 million.

Table 11.1 Annual volume of rope for various low modulus synthetic fibres in metric tonnes

Fibre	North America	EU	Rest Europe	Rest World	Total
Nylon	21 000	6 200	5 700	23 300	56 200
Polyester	10 000	3 000	2 700	11 100	26 800
Polyolefin	61 000	18 100	16 500	67 600	163 200
Total	92 000	27 300	24 900	102 000	246 200

Aramid fibre has not reached the levels once projected for rope and has been somewhat replaced by HMPE. Consumption is estimated at 1000 metric tonnes, with a value of about $30 million.

HMPE fibre ropes seem to be increasing in popularity and consumption has been somewhat limited by supply. It is estimated that about 30% of production goes into rope, the highest percentage of any fibre. Consumption is estimated at 1500 metric tones with a value of about $57 million.

Other fibre materials such as LCP, PBO and polyethylene are sold in insignificant quantities compared to the others and are not included in the estimates.

A variety of resources were used in preparing these estimates. Some are: Appendix III, US Department of Commerce (1999) and US Trade Commission (1994).

11.3 Markets

11.3.1 Commercial market segments

Table 11.2 is an attempt of define the various commercial segments of the fibre rope market by use. The examples given to describe each segment are only a limited selection and there is often overlap. Actually, it can seem like every application is a market of its own.

The listing is significant because it generally represents the breakdown of distribution channels which is discussed later in Section 11.4.2.

Some insight into international trade in fibre ropes can be gained by examining Appendix III, which contains data on production, imports and exports of rope products in the UK. The price differentials between imports and exports is significant.

11.3.2 Segmenting by performance, quality and price

Another way to define market segments is by performance, quality and price. A very cost conscious person may feel that 'a rope is just a rope', but be assured that is not the case. Such an attitude can lead to grief.

Generically, a fibre may be nylon, but it may have been produced for some other application, such as upholstery, and this may make it a poor choice for a rope

Table 11.2 Rope market segments by use

Commercial marine	Ocean-going vessels; tug and barge operations; canal transportation; naval vessels
Recreational marine	Sailing vessels, large and small; mooring lines; flag halyards; water ski tow ropes; sail boards
Recreational personal support	Mountain climbing, caving, rescue rope
Industrial	Electrical and communications wire and cable stringing; slings for lifting; load securement; conveyors; lumbering; agricultural; mining; civil engineering works; tree service; decent rope for window washing; life lines and safety lines
Consumer retail	Clothes-line; tie-downs; gardening; general purpose utility; decorative
Custom ropes	Speciality applications; marine salvage; deep sea mooring; space tethers; guy lines; lariat ropes

Table 11.3 Rope market segments by performance, quality, and price

Top grade	Meets or exceeds a generally recognised high performance standard or a high standard set by the buyer. Specifications are usually verifiable.
Service grade	Good performing products that are suitable for most applications for which they are promoted and may meet a recognised standard
Low grade	Looks like service grade and promoted as such, but either has lower strength or does not wear well or both.
Low cost	Rope for non-demanding applications where some strength and durability are expected but low price is the deciding factor (example: flag halyard).

product, especially for demanding applications. Overproduction of high-tenacity tyre yarn may result in its being offered for use in rope but, having been treated to bond to rubber, it can give rise to poor durability rope. In other cases, quality problems during fibre production of both rope grade and other fibre types may have resulted in failure to meet specifications for its originally intended purpose but it may be offered at a low price.

Poor rope design or shoddy production may result in poor performance. Often, design can be based on the most efficient production rather than performance. There have been cases when ropes were produced underweight for the stated size, or less expensive filler material has been added to make up the size. The objective is to keep cost low. This is not to say that low cost equals poor performance, but there is the potential to produce rope that may not meet normal industry standards. However, there are cases where the application is not all that demanding and cost can legitimately be the determining factor.

The rope market actually might be divided into four categories by performance, quality and price as shown in Table 11.3. A reasonable estimate is that 80% of rope is purchased based on price. Buyers will present a rudimentary specification, such as nylon braid, and expect to receive a good product.

To distinguish between the categories above when purchasing the better grades of rope, consider the following:

- Deal with firms with a good reputation, preferably one known to have a good quality system, ideally ISO 9000 or 9001 certified;
- Be very specific as to the product that is ordered. Request a certificate of compliance to the procurement requirements;
- Ensure that the rope has been certified as meeting a recognised standard;
- Ensure that the rope dealer has good, technically-oriented literature available for the actual product that is offered;
- Ensure that the delivery package is clearly marked with an adequate description of the product.

11.4 Distribution

11.4.1 Introduction

In general, ropes carried as standard products in a ropemaker's catalogue are not sold directly to users. These ropes are sold through distributors or other inter-

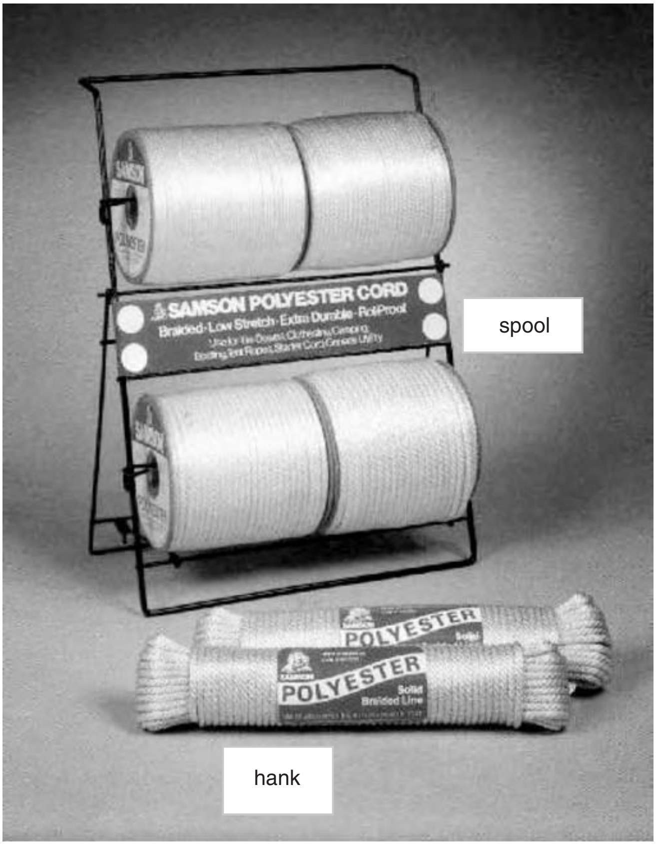


Fig. 11.1 Typical packaging for retail sales. Reproduced by courtesy of Samson Rope Technologies.

mediary outlets. Distributors usually carry an inventory of popular products. This inventory may be in bulk, such as large reels, and the rope is cut to length on order. In other cases, the rope has been pre-packaged as spools, reels, coils or hanks by the ropemaker (see Fig. 11.1).

Large users of rope, such as major shipping companies or the military, may buy directly from the manufacturer. Large retail outlets also are likely to buy direct and may have their own labels applied to the package.

Some organisations buy rope from many producers, domestically and/or by importing, and then sell to distributors or large users. They may do their own packaging with their own labels or those of the retailer.

11.4.2 Retail channels

As might be expected, retail channels generally follow the market segments of Section 11.3.1. However, considerable overlap exists.

The maritime and offshore oil industries may buy from ship chandlers, warehousing organisation that provide splicing and assembly services, or direct from a manufacturer.

Industrial organisations are likely to purchase from industrial supply houses that carry many other unrelated products. Some supply houses specialise in particular industries; for example, a firm that supplies safety nets and body harnesses will carry a line of fibre ropes.

Many steel wire rope warehouses and assembly facilities also carry fibre rope and will sell to industrial and maritime buyers. A considerable amount of fibre rope is sold to the inland waterway operators and civil engineering organisations in the United States through this channel.

Recreational users will buy climbing ropes from outdoor sports retailers, or sail boat rigging from marine supply outlets. The ropes sold by large retail chains that serve these markets would have been purchased direct, but smaller retailers are likely to use distributors that cover more than one rope market.

For domestic use, individual consumers are likely to buy from the local hardware store or one of the large home supply chains. However, they may use a marine or sport store, but this may not be economical if a speciality sport rope is purchased for an everyday use. Conversely, a rope pulled off the shelf in a hardware store should not be used as a climbing rope.

11.5 Liability

Liability for accidents during the use of rope is an unfortunate reality. Some situations are: the rope has been misused; the wrong type of rope has been selected; damage has been ignored; and, rarely, the rope itself is defective. One only has to look at the complexity of products and their myriad uses to see the possibilities for misuse. Couple this with the fact that uninformed and untrained persons have virtually unlimited access to rope and the potential for disaster can be clearly seen.

Ropemakers, sellers and users first must make all reasonable efforts to advise people with safety related information. They also need to protect themselves from unwarranted claims for damage from accidents. If a rope breaks and someone is injured, it is easy to say, ‘it broke, therefore it is defective’, end of story, pay up. However, courts are reasonable if the ropemaker can establish that he has met his obligations to produce a quality product and to have made reasonable efforts to inform the public as to its proper and safe use.

It is important to note that a ropemaker does not have to make every rope with the highest possible performance. There are many applications for rope where, for example, lower tenacity fibre, mixtures of high and low tenacity materials, or surplus from other industries are appropriate. What is important from a liability standpoint is to clearly state the specifications for the product and its intended use.

The following are suggestions for establishing a position that will help to defend against unwarranted accident liability claims.

(i) Clearly state that it is the obligation of the user to determine if a particular rope is safe for his application and to establish appropriate procedures. Emphasise that the ropemaker cannot know the details of the application nor the level of skill of the operators.

(ii) Do not make a recommendation for a particular application. Provide technical literature on products that might be used and advise the user to make the selection of the type and size. See item (i) above.

(iii) Comprehensive technical literature should be available for the product. Strength, elongation and similar technical data should be verifiable by test records;
(iv) Avoid exaggerated claims in the literature; for example, 'this rope will never wear out';
(v) Make technical literature available to distributors and users wherever feasible;
(vi) Mark packages with sufficient information to describe the product;
(vii) Rope design specifications should be on record for every product that is sold, including precise yarn specifications and complete detail for every stage of production;
(viii) A quality system* should be in place to assure, by records, that the product described in the literature was actually the product produced;
(ix) Safety related literature should be available. Some suggestions are:
   - Cite or distribute CI 1401, 'Safe Use Guidelines';
   - Reproduce CI 1401 or an abridged version in the company's literature;
   - Produce a safety guideline. This may be comprehensive or a small pamphlet which covers key factors that may be placed in each shipment and/or may be available as handouts at the point of sale (see Section 8.2.5).
(x) Staff who speak to rope users should be trained in safety and liability issues.

11.6 Conclusion

This final look at markets and consumption continue to exemplify the diversity and complexity of the rope industry, both technically and commercially. This vital product provides thousands of jobs and technical challenges, and is an indispensable tool.

Further development of the fibre rope market will see the replacement of more and more steel wire rope. This is a huge market compared to fibre rope and even small inroads would be significant. Gradually, the new ultra high strength fibre ropes, and some old ones, will take over existing applications and create new ones that will produce amazing technical advances.

* The ropemaker defines his own quality system. Procedures from order processing to shipping should be covered. Quality control inspections and product testing should be based on selective sampling and needs only to be reasonable.

12

Case studies

12.1 Diversity of ropes

As is apparent from earlier chapters of this book, particularly the miscellany at the end of Chapter 1, fibre ropes are made from a range of materials in a wide variety of constructions for a great diversity of uses, from the purely decorative to demanding engineering. It is clearly impossible to go into detail for every application. In this Chapter, we illustrate the diversity with a number of case studies.

The first two are examples where there has been strong interaction with design engineering calculations. These examples also show the importance of a total systems approach. The rope must be considered as one element in the overall structure.

Most of the others typify the traditional, craft approach, in which experience, qualitative judgment, simple calculations, and empirical trials lead to the production of ropes to meet specific needs. They include not only successes, but also some failures, which can be technically more instructive than accounts of use without problems.

12.2 Riser protection nets

12.2.1 Introduction

Risers on offshore oil production platforms can be vulnerable to impact damage from vessels that may accidentally get alongside or under the platform. This is especially true of very large platforms where the gap between columns may be as much as 65 meters. Although the probability is very low for such an occurrence, the consequences could be catastrophic. Riser protection nets (RPN) have been installed on several floating platforms to reduce the risk. One of the first of these nets, which was designed by Tension Technology International (TTI) and has performed well, was installed on the Auger platform in the Gulf of Mexico in 1992. TTI have since designed and supervised the installation of nets for the Heidrun and Åsgard fields off the coast of Norway. Auger was made by Southwest Ocean Services of Houston, Texas, Heidrun was made by JDR Cable Systems of the Netherlands and Åsgard by ScanRope in Norway. Currently TTI is designing a net for an installation in the Caspian Sea, but, because the distance between the columns and the riser is smaller, aramid ropes are being used instead of the polyester ropes in other installations.

The nets are fabricated from fibre rope tension members, which are stretched between the columns and maintained under tension. Figure 12.1(a) shows the design for the Auger net and Fig. 12.1(b) shows the Åsgard platform with the net installed

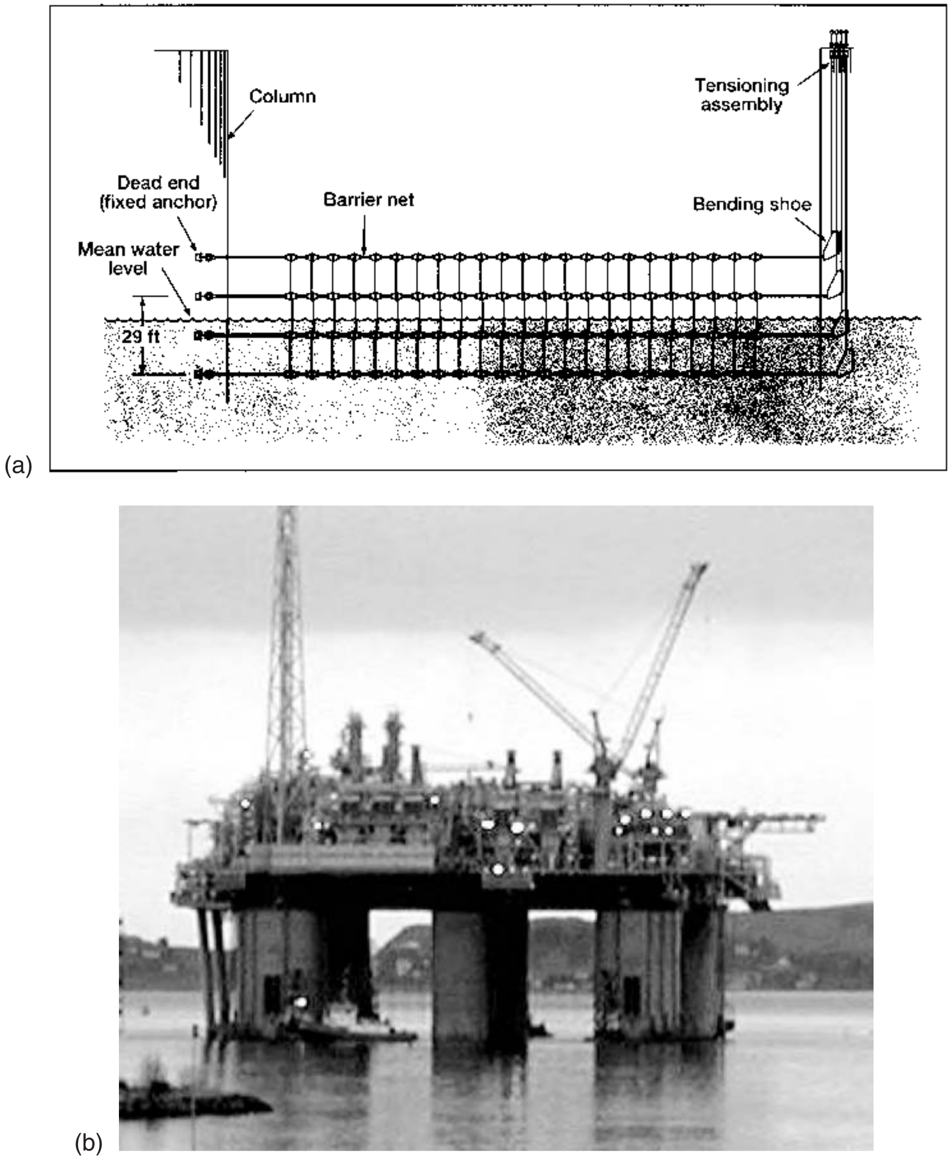


Fig. 12.1 (a) Typical net design. (b) Floating production system with RPN installed. Tow out from shipyard.

Fig. 12.2 Platforms with net, on location offshore: Åsgard above, Heidrun below.

as it was being towed out of the shipyard where it was built. Figure 12.2 shows the two platforms on site. Some design parameters for the Heidrun net are described below.

12.2.2 Basic requirements

The basic design requirement is to arrest a North Sea offshore supply vessel of 5000 metric tons displacement that approaches the net at a velocity of 2 m/s (7.2 km/hr, 4.5 mph), and stop the vessel before it reaches a dangerous proximity to the riser.

The energy that must be absorbed by the net can be established:

$$E = \tfrac{1}{2} m V^2$$

where E is energy of impact, m is vessel mass, V is maximum vessel velocity relative to the platform.

The design process involves calculating net deformation subject to this energy of impact. The maximum allowable penetration is set by the distance from the position selected for the net on the platform to the riser minus some safety margin.

12.2.3 Basis of design

Other requirements, besides stopping an encroaching vessel within a set distance, are typically imposed on the design. Some important ones, together with some detailed design considerations, are:

- the RPN must last for the life of the platform with minimum maintenance;
- the system must be completely passive;
- the energy absorbed in stopping a vessel must be stored in the ropes of the net portion of the RPN;
- a safety margin on energy absorption is required;
- load sharing for the several ropes that will make up the net needs to be established;
- the RPN must be very rugged (during handling and installation, under wave action, due to exposure to the environment, and when impacted by a vessel);
- the RPN must be maintained under high tension throughout its life;
- it must fit onto the platform structure without interfering with other facilities;
- under impact, the rope must break before anchoring structures on the platform are overloaded;
- the RPN must not interfere with supply vessel operations;
- lifting points on the RPN and appropriate rigging hardware on the net and platform must be included in the design to allow for an efficient installation, and possible removal and replacement later if necessary.

The rationale for some of the above requirements is:

- repairs or replacement offshore would be extremely difficult and very weather dependent; therefore, long maintenance-free life is essential;
- since an impact from an errant vessel could be completely unexpected, the RPN must be functional at all times without any intervention from power sources, controls or persons; thus, the passive requirement;
- mechanical, hydraulic, pneumatic, or a combination of springs used as energy absorbers are not considered practical because of the complexity, maintenance requirements and potential for deterioration from corrosion;
- wave drag can cause very large and potentially damaging displacements of the RPN unless a high tension is maintained; penetration under the platform upon vessel impact is reduced if there is a high initial tension; therefore, tension must be maintained;
- due to its non-uniform shape, and pitch and heave from waves, a vessel may not hit the ropes of the net evenly; therefore, the energy absorption must be based on some ropes being more heavily loaded than others; therefore, an assumption is made that the rope with the greatest load reaches its breaking strength, less a safety margin, at the design energy requirement;
- a typical RPN is a heavy (possibly 20 tonnes), ungainly structure that is extremely difficult to ship, lift, position, and anchor on the platform, so handling considerations are critical in the design.

12.2.4 Main rope selection

The net portion of the RPN is constructed of horizontal main ropes that are the primary energy absorbers. Vertical ropes are spaced along the span of the net to tie the main ropes together and to distribute the impact load.

Synthetic fibre rope with relatively high extensibility is the best choice for the main rope elements of the net because of high strength, near total resistance to marine induced corrosion, very high fatigue life and light weight. Synthetic fibre rope can be made to be cut and abrasion resistant by providing a rugged, non-load-bearing jacket that has been impregnated with a tough plastic. The smooth outer surface of the coating also provides some resistance to encrustation by marine growth.

Steel wire rope is not practical because of the corrosive environment, lack of energy absorbing capacity due to low extensibility, relatively high weight and small diameter (which may damage the impacting vessel). High-strength, industrial grade polyester fibre that is treated for marine service is well suited for the rope material. This fibre has relatively high extensibility and is very resistant to creep and stress relaxation. The latter property is essential since the rope will be maintained under relatively high tension throughout its life. Also, the properties of strength and modulus (elastic properties) are very stable over time.

Aramid and high-modulus polyethylene fibre lack the necessary extensibility for large energy absorption capacity, though they can be used when the available stopping distances are shorter. Nylon, polyethylene and polypropylene are subject to creep which makes them unacceptable. The strength and extensibility of nylon are affected by water and essential property stability is lacking.

Due to the considerable motion of the RPN caused by wave action, the long term bending fatigue properties of the rope are critical at the anchor points. The best rope construction for this service is known as 'wire rope construction' and is made in the same way as steel wire rope. This construction was selected for these properties. A braided jacket is provided over the core rope and is impregnated with cross-linked polyurethane (see Fig. 6.30). The rope is spliced at each end to create an eye which will fit into a metal termination.

12.2.5 Rope stabilisation and testing

Once assembled to length, the ropes are cycled several times to a relatively high percentage of their breaking strength to stabilise the splices and the rope structure. This treatment provides predictable load versus elongation performance, which is important for impact energy calculations. This may also remove some non-recoverable elongation in the rope, which reduces the take-up requirements of the tensioning equipment and eliminates the need to stabilise the assembly during installation on the platform.

Controlling the length of a rope that is in the order of 130 metres long is a challenge. The splicing marks on the rope that determine finished length must be made before splicing and stabilisation of the rope. Some testing is required to establish a template for cutting and marking the rope.

Break tests of conditioned ropes must be carried out to accurately determine the load versus elongation properties of the rope; a minimum break strength value has to be established for use in the energy absorption calculations; and a maximum break strength value has also to be determined, as it sets a design limit for terminations and the supporting structures on the platform.

12.2.6 Net configuration

The height of the net is determined by the shape of the vessel chosen as the model for the analysis, and the maximum pitch and heave for design sea conditions at the time of impact with the RPN. The number of main ropes in the net is determined by a trade-off analysis. More ropes reduce forces and add redundancy, but make the net more complex and probably more costly. In addition, the number of anchorages on the platform increases quickly as every rope has two ends that must be secured. The chosen design had four main horizontal ropes, spaced 3.5 metres apart. The length of the main ropes was set by the available space on the platform and was 130 metres. They cross the span between columns, pass around bend shoes so that they lead vertically alongside the column wall to near the platform main deck where they are anchored. The length of about 130 metres was necessary to achieve the energy absorption capacity with a reasonable size of rope. This also put the anchoring and tensioning facilities well above sea level. The frictional and wear characteristics at the bend shoes had to be verified by extensive testing because of the life requirement.

The vertical ropes are another important component of the net. During vessel impact they tie the horizontal ropes together and perform an important load transfer function that maximises the energy absorption capacity.

12.2.7 Force and strength determinations

A computer model was created to evaluate the effects of an impact. Forces in the main and vertical ropes, including the point of maximum force, were determined. A typical output of the model is shown in Fig. 12.3. It was helpful to include wave drag effects in the same model, in order to determine forces, deflections and angles at the constraints for fatigue calculations.

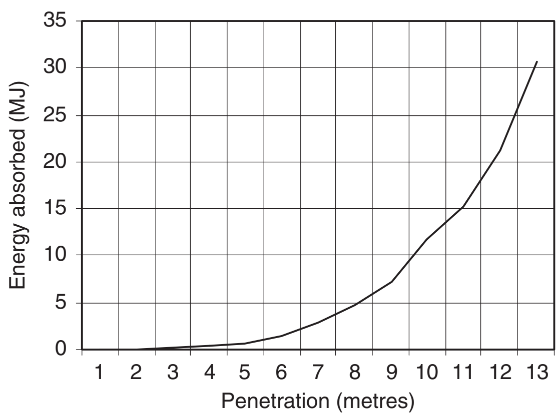


Fig. 12.3 Plot of penetration into the net versus energy absorbed. Computer data from Tension Technology International.

The rope strength is determined from the energy absorption requirement. A minimum strength of 650 tonnes was set.

The computer model was also designed to calculate the forces in the vertical ropes. The joints between main and vertical ropes must be designed for motion, contact pressure and rubbing action caused by wave action.

12.2.8 Anchoring and tensioning

Whereas the minimum breaking tension of 650 tonnes is determined by the energy absorption requirement, the anchors on the platform need to resist the maximum strength. The structural engineers wanted this set as low as possible and a value of 705 tonnes was selected. The difference of 8.5% was a challenge accepted by the ropemakers and was verified by prototype testing.

The tensioning capacity needed to be slightly higher than the net pretension which was 100 tonnes. The take-up (stroke) requirement for the tensioning equipment is a major design consideration. The length of take-up affects cost significantly and space on the platform was at a premium. The following is a list of variables that affect the take-up length for the tensioner. Note the influence of rope properties.

- Rope length tolerances as determined by the accuracy of locating eye splices.
- Stretch from installation tension to pretension.
- Creep over the life of the RPN.
- Positioning tolerances for hardware on the platform.
- Length change due to change in sag in the net from installation tension to pretension.
- Margin for contingencies.

Tension checking on the platform should occur two or three times per year, at least until a pattern is established. Retensioning may occur two or three times in the first two years but less afterwards.

12.2.9 Installation

The net was installed inshore at a shipyard. It was heavy, 20 tonnes, and difficult to lift because of its shape. Figures 12.4 to 12.6 show some of the installation highlights.

12.2.10 Summary

Riser protection nets to arrest large vessels in harsh environments are highly engineered systems. Ocean science, mechanical engineering, material science, instrumentation technology, project management and systems engineering are involved. Accurate knowledge of fibre rope properties and technology is essential to a good design.

12.3 Deepwater moorings

12.3.1 The need for fibre ropes

An engineering report by Samson Ocean Systems (McKenna, 1972) states that chain mooring systems lost effectiveness somewhere between 300 and 600 feet (100 and

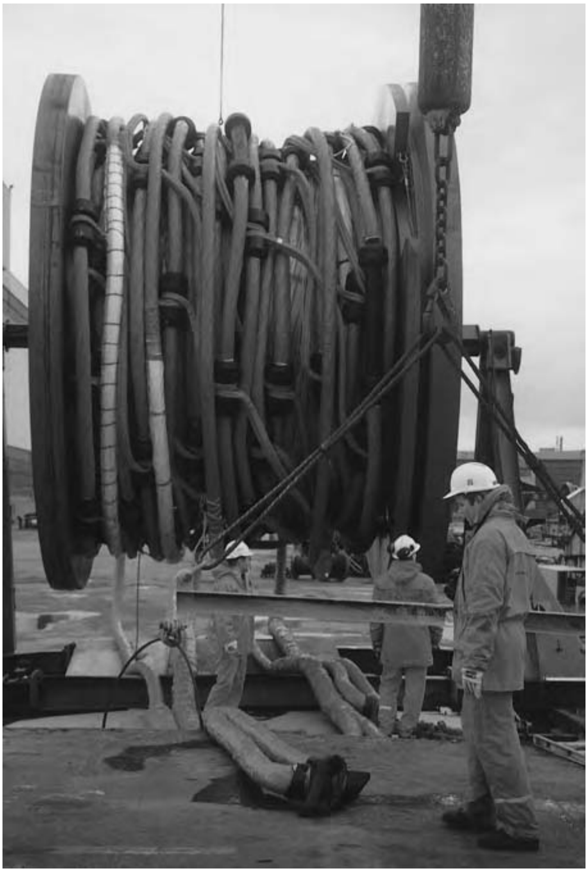


Fig. 12.4 Completed net arriving at the shipyard.

200 m). The report goes on to describe and analyse a composite system of a double-braid polyester line connected to relatively short chains (Fig. 12.7). It is claimed that this gives nearly equal performance at all depths and is superior to wire rope or chain over 200 m depth. However, the conservative preference of engineers for steel prevented commercial utilisation of such a system. Only the inadequacy of steel at still greater depths led to the recognition of the advantages of fibre ropes.

In the 1980s, the US Navy had ideas for mooring large floating platforms where they were needed for emergency operations. In addition to testing, they contracted Tension Technology International (TTI) to produce software to model rope performance (Leech *et al*., 1993; Hearle *et al*., 1993). The US Navy ideas remain on the drawing board, but a report in *The Sunday Times INNOVATION* section for September 27 1998 illustrates the vision. A picture from a proposal for *SeaBase* by *Kvaerner Maritime* shows a *Mobile Offshore Base* (MOB) that is 1600 metres long and 140 metres wide. On the top deck, there are large C-17 cargo planes, jet fighters and helicopters. The five lower decks could accommodate 10 000 troops, 3000 vehicles and 300 000 tonnes of supplies. The initial cost of the MOB is estimated at $6–10 billion – and one would guess that the mooring ropes might cost $10 million. In addition to their military potential, such large platforms could have future commercial or leisure use.

Fig. 12.5 Moving net to the installation barge.

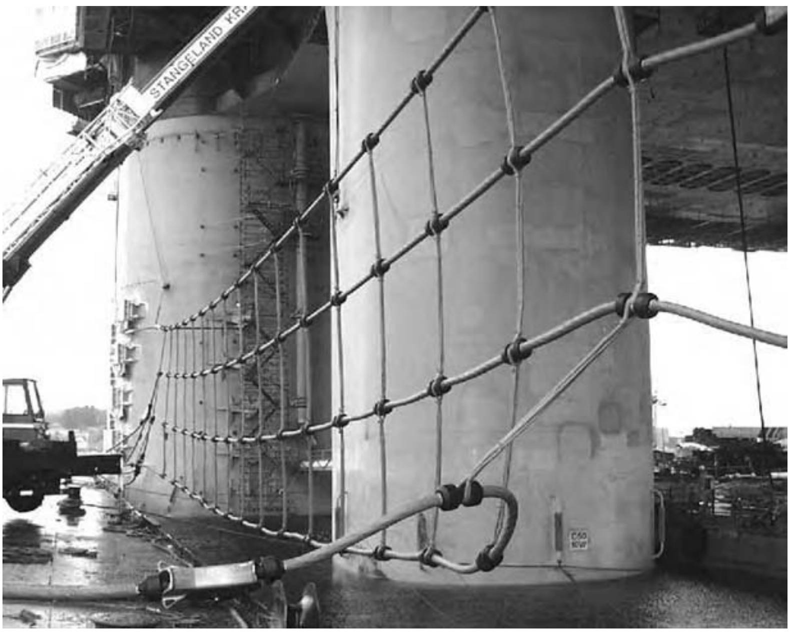


Fig. 12.6 Net partially installed.

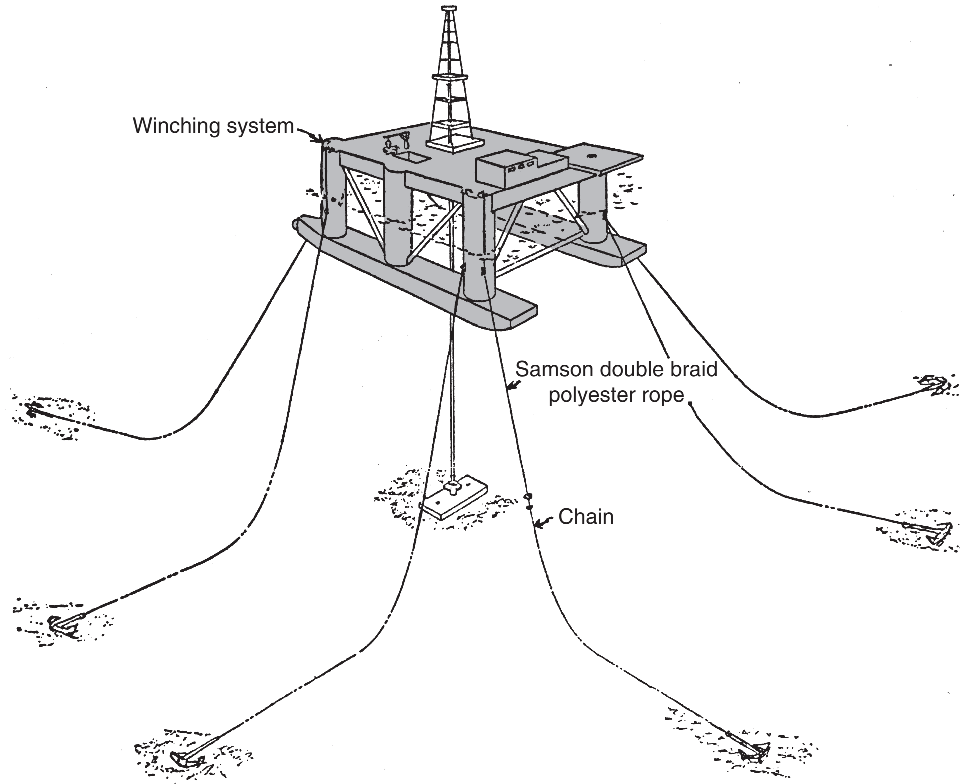


Fig. 12.7 A fibre rope mooring system as envisaged by one of the authors of this book (HAM) in 1972.

A more pressing demand came from oil companies, who wanted to expand production to greater depths. Steel wire cables are successfully used up to 500-metre depths, but are unduly heavy for 1000 to 3000 metres. Fibre ropes offered an alternative, but were untried. This has led to a number of Joint Industry Projects related to the use of ropes for oil-rig moorings and to the production of *Deepwater Fibre Moorings – an Engineers' Design Guide* (TTI and Noble Denton, 1999). In preparing this guide, experts with a fibre and textile background had to work with marine engineers, who were more used to steel, on the ways in which the complicated properties of polymer fibre ropes could be used as inputs to mooring analysis software.

An example of the advances is the installation since 1995 by Petrobras of polyester ropes on about 20 rigs off the coast of Brazil. The P36 rig, Fig. 12.8, has 16 lines, each 1800 metres long, with a diameter of 175 mm, weight of 23 kg/m (23 Mtex), and 1000 tonne break load. This uses over 600 tonnes of polyester yarn. Figure 12.9 is a schematic of a deepwater mooring.

12.3.2 System mechanics

The four criteria addressed by mooring analyses for deepwater moorings are:

- offset
- peak load

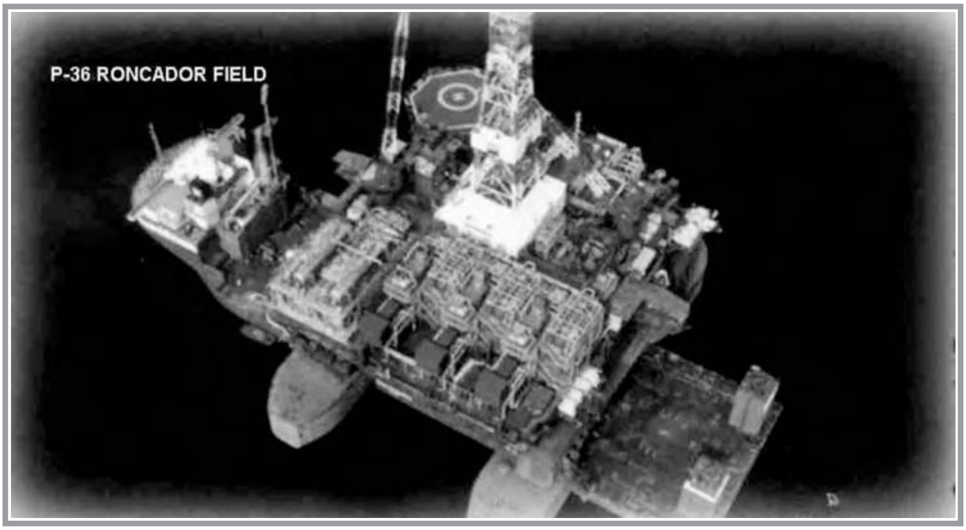


Fig. 12.8 P36 rig taut-leg moored at 1400 m depth in Roncador field, off Brazil, with 16 polyester rope lines to suction anchors. Reproduced by courtesy of Petrobras.

Fig. 12.9 Schematic of a deepwater mooring, from the cover of *Engineer's Design Guide*. From TTI and Noble Denton (1999).

- fatigue
- creep

Other factors which operators will take into account are:

- weight, which affects ease of handling
- bending and torsional properties
- external abrasion and cut resistance
- environmental effects: ingress of sand or other particles; marine growth; fish-bites; etc.
- presence of air, water or filler between rope components
- cost

Fibre ropes change the system mechanics. As can be inferred from Fig. 12.10, catenary steel moorings generate forces on the rig by the weight of the steel, whereas in taut fibre rope moorings the forces are due to rope extension. Quoting Brown and Hearle (1997):

> . . . the major uncertainties in predicting the dynamic behaviour of steel wire or chain catenary moorings involve the complex motions and associated forces, since the principal line property, its weight, is well defined, and material deformation is a secondary factor. For taut fibre moorings, where the motions are simpler, being principally due to axial extension, the major uncertainties are concerned with the complex line tensile properties, though some secondary factors need to be checked.

The two principal criteria, offset and peak load, are determined by the environmental forces, the mooring geometry, the line lengths and the rope tensile properties. As discussed below, this places limits on rope tensile modulus and fixes the choice of rope weight and material. At around 1000 to 2000 m, as in the current Petrobras installations, polyester ropes have suitable stiffness at the required break forces. However, at smaller depths, lower stiffness ropes would be needed, so that

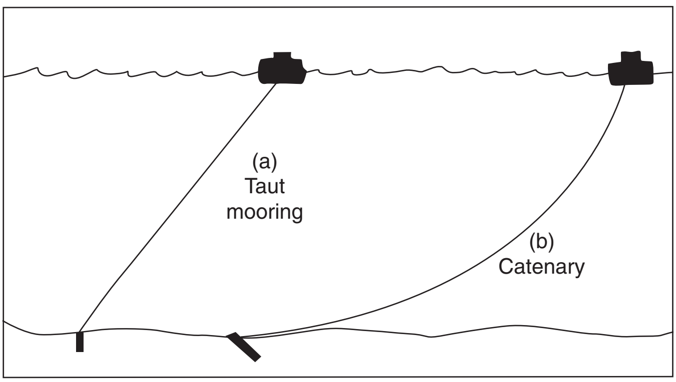


Fig. 12.10 (a) Taut fibre mooring. (b) Catenary steel mooring. Note that a whole mooring would consist of a circular array of a number of lines as in Fig. 12.7, of which only one is shown for each mooring. Taut moorings are steeper than catenary moorings, which sag more, so that taut moorings have a smaller footprint (the circular area enclosed by the mooring anchors on the sea bed).

nylon might be better, and, in greater depths or calmer environments, higher-stiffness ropes from high-performance fibres might be preferred. There are also potential benefits in the use of mixed systems, in which a lighter-weight high-strength fibre rope is used in part of the mooring with the necessary compliance coming from other elements, either more extensible ropes or heavy catenary sections.

12.3.3 Rope stiffness

Fibre ropes introduce a new feature, which is not commonly met in structural engineering. Provided the plastic limit is not exceeded, stress in steel is a single-valued, linear function of strain. For organic fibres, as described in Sections 2.5.3–2.5.5, stress is a multi-valued nonlinear function of strain, which depends on the total time-dependent prior history and the current deformation conditions. In addition, ropes as made undergo an irreversible elongation, known as bedding-in, during initial loading cycles due to tighter packing and local adjustments of length differences of the fibres, yarns and strands. More research is needed to better characterise rope tensile properties, and provide ways in which rope test schedules can give mooring analysts the necessary stiffness data in a useful form. The current position can be summarised (Section 12.3.3–12.3.6) by edited extracts from the Engineers' Design Guide (TTI and Noble Denton, 1999):

> If the mooring analysis is to use non-linear rope load–extension curves, which are different in recovery and change with history, then either extensive testing will be needed or an enhanced, computable, rope extension model will be required together with validation data. Such procedures are not yet available. [As a practical alternative] the load-elongation properties of fibre ropes . . . can be reduced to a number of linear elastic secant stiffness values for mooring calculations.
>
> The **minimum and maximum stiffness values** that are recommended for the mooring analysis are defined as:
>
> **Post-Installation Stiffness** – the secant stiffness over the load or strain range of interest in quasi-static loading immediately after installation. It is the stiffness which corresponds to the extensibility of the mooring lines under quasi-static load once the Minimum Installation Tensioning [30% of break strength for at least 1 hour] has been performed during installation.
>
> **Storm Stiffness** – represents the maximum secant stiffness in cycling from the mean load during the maximum design storm to the cyclic strain limits predicted in the maximum design storm. This stiffness will result in the largest loads being generated in the mooring lines as the platform moves compliantly in the storm.
>
> Both Post Installation Stiffness and Storm Stiffness are to be calculated from a reference length prior to the cycle in question, and not from the original rope length.
>
> The stiffness will increase if a more severe tensioning regime is applied after the Minimum Installation Tensioning specified above or following periods of operational cyclic loading. These Intermediate Stiffness values may be substituted for the Post-Installation Stiffness provided the appropriate installation and operation procedures are adopted. Note that insufficient data currently exists to establish formal relationships between the above measures of fibre mooring line

stiffness. However an example based on data from a polyester rope is illustrated in [Fig. 12.11].

Typical values of maximum ('Storm') and minimum ('Post-Installation') stiffness data for deepwater fibre moorings suitable for the initial design calculations, based on polyester, aramid and HMPE fibres, are given in [Table 12.1]. To a first approximation these stiffness values will scale with the break strength of the rope.

Where stiffnesses as specified in [Table 12.1] are inadequate to assure compliance with fatigue, offset, maximum load and minimum load limits, precise loading conditions should be defined to allow exact values of relevant load/extension data to be determined on a prototype rope. Suggested testing methods are [proposed in Table 12.2]. Typical intermediate stiffness values are included in [Table 12.1].

Total elongation of the fibre rope assembly throughout the design lifetime should neither exceed the take-up capacity of the winch system nor lead to

Table 12.1 Typical secant stiffness values in kN* for three rope materials in parallel yarn, parallel strand, and wire-rope construction ropes (based on a 10 000 kN [≈ 1000 tonne] breaking strength rope). From *Engineers' Design Guide* (TTI and Noble Denton, 1999). *i.e. (tension in kN)/(strain) = (tension in kN)/(metre elongation per metre length)

Rope material	Post-installed stiffness	Intermediate stiffness	Storm stiffness
Polyester	100 000	100 000–300 000	300 000–450 000
Aramid	330 000	330 000–600 000	600 000
HMPE	350 000	350 000–700 000	700 000

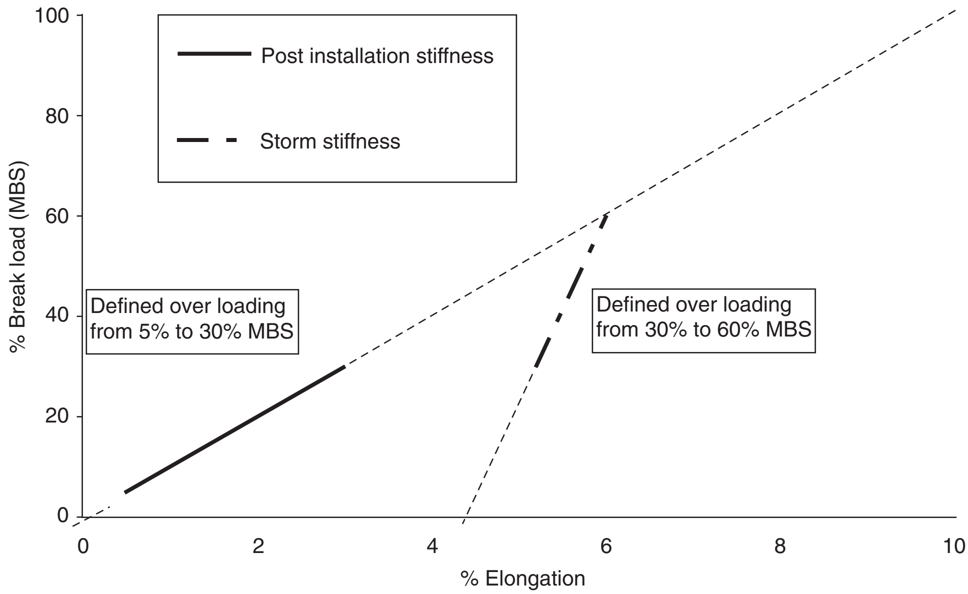


Fig. 12.11 Schematic load–extension graph for polyester rope showing two stiffnesses that are useful in mooring analyses. Post-installation stiffness corresponds to BQ in Fig. 5.2 and storm stiffness to FT. From TTI and Noble Denton (1999).

Table 12.2 Proposed test procedure for polyester rope. Adaptions may be required for ropes with higher stiffness or creep. From TTI and Noble Denton (1999)

At least 24 hrs after manufacture of test assemblies they should be put through the following experimental routine, with continuous recording of extension and elongation both between bearing points and on a pre-marked 1 m length of rope clear of the termination region. All cycles are to be sinusoidal. Cycles a) to g) and i), j) are to be conducted at a cyclic period between 1 and 10 minutes. Cycle h) is to be conducted at a period of between 5 and 15 seconds.

a) First loading to 30% MBS (mean break strength), recording lengths at reference tension and at 30% load (Note: the reference length is the length over the markers when first loaded to the reference tension)
b) Relax to 10% MBS and maintain 10% MBS load for one hour
c) Reload to 30% MBS (Define minimum post-installation stiffness as secant stiffness between 10% and 30% MBS on this cycle)
d) Relax to 10% MBS
e) Without pause, cycle up to 30% MBS and down to 10% MBS for 99 further cycles
f) Hold at 10% MBS for one hour
g) Reload to 50% MBS
h) Cycle over a strain range of ±0.25% around a mean load of 50% MBS for 10 000 cycles (Define maximum storm stiffness as the secant stiffness on the 10 000th cycle)
i) Increase load to 60% MBS. Hold for 1 hour. Drop to 30% MBS. Immediately record lengths between bearing points and over pre-marked length (Define total elongation at 30% MBS as length i) – length a)
j) Hold at 30% MBS for 3 hrs and re-measure (Define permanent elongation at 30% MBS as length – length a)

creep rupture. Elongation in fibre rope assemblies results from bedding-in of the rope structure and terminations and from both instantaneous extension and creep in the yarns. It will occur to a greater or lesser degree in all fibre rope assemblies under both steady and cyclic loads. The designer and installer should be informed by the rope manufacturer of the amount of elongation due to bedding-in and creep to be expected on loading during installation. The designer may calculate the effect of increase of line length between retensioning.

12.3.4 Effects of cyclic loading

High internal temperatures can occur in tension–tension fatigue cycling of ropes at high strain amplitudes. The maximum temperature rise depends on diameter, internal pressure, constructional type, sheath type and thickness, lubricant, presence of water or fillers and many other factors . . . joint industry studies indicate that heating effects will be small in large polyester ropes for strain amplitudes less than 0.25%. Temperature limits for PET, HMPE, nylon and aramid fibres are set out in [Table 12.3]. The designer should consider alternative constructions and materials if prototype tests indicate that equilibrium temperatures exceed the values there indicated.

Taut fibre rope moorings will contribute damping to the system from internal energy dissipation (hysteresis) in the rope and external energy dissipation due to movement in the water. The transverse drag force will vary linearly with rope

Table 12.3 Temperature limits: Information from yarn manufacturers and other sources. From TTI and Noble Denton (1999)

	Polyester	**Aramid**	**HMPE**	**Nylon**
Safe working temperature:				
Long term (1 month plus)	50°C	n/a	60°C	60°C
Short term (up to 10 minutes)	200°C	n/a	80°C	70°C
Melting-point	258°C	430°C*	150°C	260°C
Approximate values (over 0 to 50°C range) for:				
Drop in strength per 10°C	2.5%	n/a	6%	2.5%
Drop in modulus per 10°C	3%	n/a	4%	3%

* does not melt: onset of degradation

external diameter. Thus the drag force per unit length of a taut mooring rope will generally be equal to or greater than the drag force on a steel rope of equal strength. However, since a wire rope catenary mooring system experiences greater transverse movement than a taut fibre rope mooring system the wire catenary will generally produce greater drag. Line hysteresis damping factors [are 0.03] for polyester parallel strand and [0.06 for] steel wire rope [at 20% mean ± 10% or 14% break load]. The longitudinal axial damping factors for fibre rope are less than those for steel wire rope for similar motions but rise steeply with applied strain. Data is not currently available on the energy absorbed by the other modes of internal damping (bending, shearing and torsional) of fibre ropes, but these modes are considered to be the least significant.

Deepwater fibre mooring assemblies are subject to fatigue loading and the effect of fatigue on the mooring system should be considered. Since the fibre mooring assemblies covered by this guideline will be terminated to chafe chain at both ends, bend-over-sheave fatigue loading will be limited to any which occurs in deployment or retrieval operations. Tests are currently in hand to establish suitable D/d ratios for such deployment or retrieval purposes. It is assumed that each mooring leg component will be torque free, so avoiding rotational loading fatigue. Tension free-bending fatigue loading on taut mooring lines should be addressed by design of articulated terminations that minimise bending moments.

[Fig. 4.21], using data from OTC paper 4307 (Parsey (1982)) and based on extensive evidence, . . . shows that the tension-fatigue life of polyester ropes is greater than that of steel chain or wire ropes. Indications are that a similar situation exists for aramid and HMPE ropes. It should be noted that little of the above data has been derived on ropes of comparable construction or size to those required for FPS moorings. Appropriate tests should be conducted on prototype ropes where analysis indicates inadequate life. In the case of HMPE and other fibres, data on ropes of appropriate construction is scanty, and design should be based on appropriate tests on prototype ropes backed by modelling.

[Internal abrasion is not a problem in low-twist polyester ropes, unless there is ingress of foreign particles. One rope in a Petrobras installation is reported to have failed due to penetration by minute crustaceans (Costa, 1999). This form of damage can be avoided by protecting the rope or by inserting chain at necessary depth levels.]

Axial compression fatigue [see Sections 4.5.7 and 5.7.6], which may occur when a rope experiences an excessive number of cycles at low tension, can cause failures, but with proper precautions is avoidable. Although axial compression fatigue also occurs in steel, it is not generally a concern in catenary moorings because the weight of the rope ensures that substantial tension is maintained at all times. In taut moorings, the rope tension may fall to low values at certain times, or even go slack on leeward lines during storms. Under these conditions, axial compression fatigue, which is a consequence of repeated sharp kinking of fibres, may be a problem after a large number of cycles.

In order to prevent some rope components going into axial compression, it is not sufficient to maintain a positive tension on the rope as a whole [due to variable component lengths or to rope twisting] . . . A minimum tension is needed to maintain tension on all components. The problem of axial compression fatigue raises three practical questions for the mooring system designer, installer and user:

- What minimum tension on the rope is necessary in order to avoid components going into compression?
- How many cycles of axial compression can occur without serious damage to the fibres?
- What is the minimum cyclic load range below which cycling into compression can be ignored?

No general answer can be given to the first question, because the first compression mechanism is dependent on the quality of the rope manufacture in minimising variability and the second compression mechanism depends on the torsional mechanics of the total system . . . Provided the ropes are well made and not subject to significant twisting, the risk of axial compression should be small if the tension in polyester ropes does not fall below [a minimum tension level] . . . Based on yarn buckling tests [see Tables 2.10 and 2.11] provisional guidance can be given on how many axial compression cycles [below the minimum tension level] yarns can stand before serious strength loss occurs. [Guidance design limits for the minimum tension level and the number of allowable cycles are: polyester 5%, 100 000; HMPE 10%, 40 000; aramid 10%, 2000.]

Limited data currently exists to quantify the rate of strength fall-off experienced by full scale man-made-fibre rope assemblies for FPS moorings . . . Such moorings would be typically required to possess up to a 20 year design life. However, there is no evidence to suggest performance inferior to that of steel wire rope. For steel ropes it is assumed that break strength and fatigue life are independent of each other, and similar behaviour is evident for polyester . . . For fibre ropes the exceptions (which can be avoided by sensible design) are where axial compression fatigue or internal abrasion are significant mechanisms. These can cause a reduction in residual strength during cycling. In such cases, safety factors should be increased appropriately.

Instantaneous elastic extension is recovered when loads are reduced. However part of the creep under high loads is primary creep, which is recovered over time, when loads are reduced. This is known as delayed elastic recovery and can occur after storm conditions and affect mooring line tensions.

12.3.5 Twisting and bending

Twisting of a fibre rope changes its strength and, more seriously, can cause axial compression and structural fatigue. All components of a deepwater fibre rope mooring system should be torque-balanced, in order to minimise these problems. However, twisting cannot necessarily be completely eliminated during installation and operation. It can result from effects including:

- torque balance . . . not [being] perfect at all tensions
- rope variability [leading] to twisting
- buckling in three dimensions [accompanied] by twist
- twist [occurring during] handling

The relationship between axial strain and twist varies significantly depending on the type of rope construction being used. If the deviation from torque balance in the system is appreciable, a full analysis must be carried out. There should be no problem with twisting if the strain difference between the outside and the centre of the rope due to twist is less than 0.1% which for polyester is about 1% of break strain. This allows for a maximum of 1 turn in 50 rope diameters. As with the recommendations for maintaining minimum tension, a limited number of cycles at higher twist levels may be allowed during installation or at other times. However, it is suggested that these should not exceed 1 turn in 20 diameters.

The bending effects, particularly at terminations, of any lateral vibration of the line as a result of vortex shedding should be considered in the design, though from the limited data available the effects seem likely to be small in deep water. The very limited test data available suggests that the design should ensure that no more than 100 000 flex cycles are experienced on ropes terminated in Barrel and Spike Terminations at Bend Angles of ±1.5 degrees of arc. (Hobbs and Burgoyne, 1991). No equivalent data is available for Resin Socket or Splice Terminations. No data is available for any termination types at the much lower angles of bend anticipated for deepwater moorings.

12.3.6 Other factors

Most fibre ropes are highly resistant to UV and chemical attack even when unsheathed . . . Other external causes of degradation such as fishbite and external wear are a function of jacketing material . . . Synthetic fibres suitable for moorings are unlikely to show any chemical degradation as a result of exposure to marine growth. Loss of strength due to hydrolysis in polyester ropes will not occur to an appreciable extent unless the temperature is greater than 30°C for long periods of time. HMPE is not subject to hydrolysis. Aramid yarns are more affected by hydrolysis and, although this will not be a problem in most circumstances, the possible loss of strength should be evaluated in consultation with the yarn supplier.

Considerable energy will be stored elastically in the tensioned lines of a taut leg mooring and the safety implications for the crews and equipment of the floating platform if one of the lines was to break should be considered. The problem should be considered both during the installation of the mooring and when periodic adjustments of mooring line tensions are made during the lifetime of the installation.

Basic fibre materials do not give rise to any pollution concerns.

12.3.7 Optimisation and rope selection

Unless usage in the field over a period of years leads to unexpected problems, it is clear that fibre ropes provide a suitable way of mooring in deep water. Attention and the need for more research will then turn to optimisation in order to reduce cost and promote ease of operation. The minimum tension requirement to avoid axial compression fatigue is one aspect that needs more investigation. The guidelines given above probably err on the side of caution, and should be refined to relate to particular fibre types, rope constructions and quality specifications, and operational factors. The critical condition should be expressed in terms of minimum strain not minimum stress. This would favour the more extensible fibres, polyester and nylon, and be more severe for the newer high-modulus fibres. If the requirement can be relaxed, this would open a larger window of design options.

The main opportunity for optimisation is in the balance between rope stiffness and strength. Even within given rope materials and types, these factors are, to some extent, under the control of the fibre producer and ropemaker. A proper treatment of the subject would involve the complexities of the mooring mechanics, geometry and environment and of the rope properties. However, the following simplistic argument, even though lacking important detail, will show what considerations apply and indicate the general nature of the dependence on controlling factors. Strength and modulus are expressed as 'specific' quantities, namely force divided by rope linear density (i.e. mass/length) W.

Generally, rope specific strength S and modulus M increase together, but are not necessarily linearly related. We define a strength/modulus ratio $R = S/M$.

The peak load P, which must not exceed a fraction f of the rope break load SW and will be proportional to rope stiffness MW, is determined by the ratio of peak displacement D in storm conditions, to line length L. The mooring geometry needs to be taken into account, but it seems reasonable to introduce an increasing function F_1, in a relation of the form:

$$P = MW\mathrm{F}_1(D/L) < fSW \qquad [12.1]$$

The offset O, which should not exceed some value X, will be determined by the environmental forces F acting on the rig; will be opposed by the rope stiffness MW; and will be proportional to the length of the line L. A reasonable relation would include an increasing function F_2:

$$O = L\mathrm{F}_2(F/MW) < X \qquad [12.2]$$

Substitution and rearrangement then gives the two conditions to be satisfied:

$$\mathrm{F}_1(D/L) < fR \qquad [12.3]$$

$$W > (F/M)\mathrm{F}_3(L/X) \qquad [12.4]$$

where $\mathrm{F}_3(L/X)$ is another increasing function, equal to $[\mathrm{arcF}_2(X/L)]^{-1}$.

The first inequality is an absolute requirement. At a given depth, wave height and mooring geometry, there is no safe solution if the strength/modulus ratio is less than a critical value. The only alternative is to reduce the mooring angle in order to increase L. The criterion becomes less restrictive in greater depths as L will be larger. Having satisfied this inequality, the rope weight is then governed by the second inequality. Since it is desirable, on both cost and operational grounds, to minimise rope weight, the optimum solution would have a rope modulus as high as possible.

Values of strength and modulus are under the control of the ropemaker in two ways. The first is rope construction. Moduli can be reduced by increasing the angle of lay of yarns in the rope, though this will also reduce strength. The right balance has to be achieved and depends on the conversion efficiency for the fibre and construction. The second is by choice of fibre. Although the relevant moduli have different values in different cyclic loading conditions, an indication of relative fibre merit can be made with the quoted values of modulus and strength in Table 12.4. The values of the strength/modulus ratio R show the advantage of nylon for high values of D/L, namely severe conditions in shallow water, provided fatigue can be avoided. For calmer conditions and deeper water, the high-modulus fibres will be advantageous.

The values in Table 12.4 do not indicate any advantage in using lower modulus polyester, because of the large loss in strength. However these low-orientation polyester yarns have been optimised for general textile purposes. It is possible that, by altering thermomechanical processing, fibre producers could make lower modulus polyester yarns that meet the needs of the rope market. The more recently available 3GT and PEN polyester yarns may be suitable for some conditions. For aramids, the range of values for Kevlar show how fibres with different moduli can be produced to meet different market requirements.

Table 12.5 shows the results of mooring response calculations by Cloos and Bosman (1997) using a program from Marin. Although, the accuracy of the model may be limited, the trends are clear. The figures relate to a semi-submersible platform moored with 12 lines in the Gulf of Mexico and show both acceptable and unacceptable choices. The title of the paper is *With Synthetic Fibers you Beat Every Water Depth*. They conclude that a 1.25 MN nylon rope can be used at 450 m water depth, but that, in greater depths, the displacement will be too great. Polyester ropes can be used in excess of 875 m and aramid ropes, which will be lighter, from 1000 m.

Table 12.4 Density, strength and modulus, and calculation of ratio R. From Banfield and Hearle (1998)

	Density (g/cm^3)	Strength (N/tex)	Modulus (N/tex)	100 R*
Polyester				
High orientation	1.39	0.82	15	5.5
Low orientation	1.39	0.47	8.8	5.3
Nylon				
High orientation	1.14	0.75	4.8	15.6
Low orientation	1.14	0.37	1.0	37.0
Aramid				
Kevlar 29	1.44	2.1	58	3.6
Kevlar 49	1.44	2.1	80	2.6
Kevlar 119	1.44	2.1	43	4.9
Kevlar 149	1.44	1.6	98	1.6
HMPE				
Dyneema SK60	0.97	2.8	91	3.1
Dyneema SK75	0.97	3.5	110	3.2

* 100 × strength/modulus

Table 12.5 Mooring response. From Cloos and Bosman (1997)

	Aramid		Polyester		Nylon	
Break load (MN)	7.5	12.5	7.5	12.5	7.5	12.5
Weight (kg/m)	10.5	17.5	21.1	35.3	16.5	27.5
Displacement (m)						
at 500 m depth	25	20	35	25	50	35*
at 3000 m depth	110	70*	175	110	300	180
Peak load (% break load)						
at 500 m depth	102	93	73	85	68	59*
at 3000 m depth	52	42*	50	40	43	43

* Combinations with displacement ⪷70 m and peak load <60%. Polyester should satisfy the criteria in a range of 1000 to 2000 m depth.

Theoretical design studies, laboratory testing, field trials and now installations in the Campos Basin have demonstrated the potential for polyester rope moorings in depths greater than 500 m. The low-twist parallel strand and wire-rope constructions have been proven. Parallel yarn ropes are likely to be suitable, but have not been subject to the same evaluation. Depending on wave heights, there will be a shallow depth limit for the use of polyester ropes. Nylon ropes have potential to shallower depths, provided the problems of internal abrasion can be avoided. High-modulus fibre ropes, which would have lower weight, should be considered in greater depths, such as the suggested mooring of air defence platforms beyond the continental shelf.

12.4 Supply vessel moorings

Supply vessels usually moor to an offshore oil facility stern toward the platform, with the sea running on the stern as closely as possible. This can be seen in Fig. 12.12, which is a newer design of mooring that was developed to solve the problem described below.

Wave action causes vessels to surge fore and aft and, depending on the orientation to the waves, sway may also be involved. Due to the dynamics of the situation, the vessel cannot be held fast and the wave-induced motion must be accommodated. The amount of surge is mostly a function of wave height. Beyond about 3 metres wave height, it is dangerous for the crew to work on deck to load or offload cargo, so this places a limit on the operations and the design of a system to accommodate this motion.

For many years the standard procedure was to use two lines anchored to adjacent legs or columns at an elevation near the deck level of a supply vessel. In Fig. 12.12 assume that, in the old system, the lines from the vessel go directly to a column. A tag line would be used to pass these lines to the supply vessel, where the crew would fix them to the bitts on the corners of the stern. Breakage was common and it was inconvenient as well as expensive to replace them at the low level on the platform.

These mooring lines were simply too short. The surge had to be accommodated by the extensibility of the ropes. Typical lengths were about 25 metres and, if the

Fig. 12.12 A new design for supply-boat mooring.

breaking elongation is 15%, a safe elongation is no more than 3% to 4%, which means surge is limited to 1 metre or less. It is a close approximation to say that wave-induced surge of a supply vessel is equal to the wave height. As explained, this is about 3 metres maximum, well above what the short lines could accommodate without overloading.

This is an example of a strain-driven system. One particular operator kept increasing the mooring line size, but continued to break the ropes. Eventually he tried size 15 nylon with a strength of over 300 tonnes. One of the bitts was torn off the stern of the vessel.

The solution was to increase the length of the mooring system. Figure 12.12 shows the arrangement. A long line is anchored to a leg or column on the far side of the platform; it connects to a four-point connector which is suspended between two columns by other ropes. The mooring line goes from the connector to the supply vessel. The total length now might be 100 metres, enough to accommodate the surge of the supply vessel. A short segment of rope is inserted into the mooring line on the end; this can be easily changed since the wear and tear on the end is the most severe.

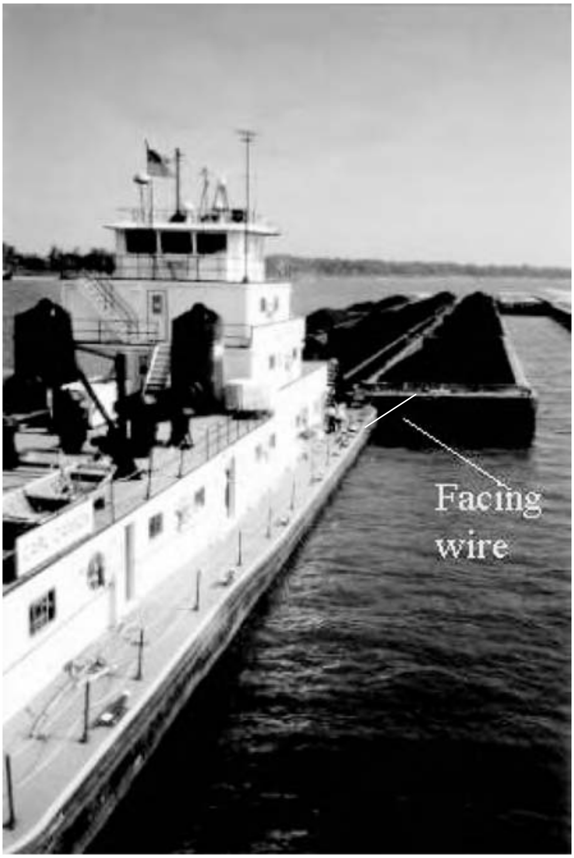


Fig. 12.13 Facing wire on pusher tug to move a raft of cargo barges. Reproduced by courtesy of Wellington.

Many of these systems have been installed and are highly successful. They have been used in locations known for bad weather, such as the North Sea.

12.5 Facing wires for pusher tugs

On the inland waterways of the United States, millions upon millions of tonnes of cargo are transported every year. Dozens of locks lift rafts of 15 or more barges, whose fully loaded weight would be about 1500 tonnes each, or a total of about 25 000 tonnes.

After the barges are lashed together, the bow of a pusher tug is secured to the barges by what are called facing wires (see Fig. 12.13). These run from a winch on the tug, around a pulley fairlead, to bitts or similar anchor points on the barges at the stern of the raft. They are kept under high tension during the tow and are the only connection holding the tug onto the barge. They see a considerable increase in tension when executing turns.

Steel wire rope was always used for this service. However, at a size of 25 to

30 mm diameter, the weight made handling difficult for the crew. It is necessary to pull line off the winch, run it aft through the fairlead, back to the bow and then take it across to the barge, which is at a different level from the deck of the tug. During transits through the locks, the tug must disconnect often, so a considerable amount of handling may be required, day and night. Back injuries are common. Also, dragging the wire across to the barges can cause a crewman to lose his balance, especially if there is a gap.

As use progresses, individual wires in the wire ropes began to break. Short stubs stick out and are infamous for the damage they do to hands, even with the best gloves.

About ten years ago, a few operators began to experiment with fibre ropes. Abrasion was a big deterrent and some boats quickly abandoned the effort. But a few skippers saw the benefits and decided to 'make it work'. The use of chafe protection, dressing of the fairleads and other rub points, and crew training and co-operation have led to widespread use of fibre rope.

The most popular product is HMPE 12-strand braid or 8-strand plait. The rope diameter is about the same as for the wire rope, but the weight is one-fifth that of the wire rope. And there are no wire hooks.

12.6 Parallel yarn ropes: antenna stays and other uses

A pioneering use of parallel-yarn *Parafil* ropes, which were developed by Michael Parsey while at ICI Fibres and are now made by Linear Composites Ltd, was in antenna stays. Figure 12.14 shows the 1967 installation at the naval signals station, HMS Forrest Moor, near Harrogate in England. In Type A *Parafil*, which was the available form, high-tenacity polyester yarns are encased in a plastic jacket; later installations used Type F with *Kevlar* 29 or Type G with *Kevlar* 49. Special terminations have been developed (see Fig. 7.14(c)). *Parafil* stays are used throughout the world by broadcasting companies, civil aviation authorities, and for military and civil communications. The Forrest Row antenna ceased to be used around 1980, but *Parafil* stays were left on one pole, and were in good condition when the pole was demolished, about 25 years after the ropes had been installed.

Antenna stays are an application where rope bending is minimal. The high strength and low extensibility of the parallel yarn construction is exploited, without incurring problems due to the high bending stiffness. *Parafil* ropes are resistant to UV degradation and show the usual advantages over steel wire ropes: high strength-to-weight ratio, resistance to environmental attack (virtually maintenance free), high fatigue life, and ease of handling. However, there is a special benefit for antenna stays. Steel cables require insulating links at frequent intervals. *Parafil* ropes have a high electrical resistance, so that insulators are unnecessary.

In an account of structural applications of *Parafil* Type G, Burgoyne (1988) includes a potential and an actual installation:

> Prestressed concrete is an obvious use for a high strength, high stiffness material like Parafil. The prestressing tendon is very highly stressed, but the tension is virtually constant. This allows maximum use to be made of the strength of the tendon, since only a small allowance has to be made for variations in the force, and the maximum force is applied in a controlled and measurable way by a jack.

Fig. 12.14 Antenna at HMS Forrest Moor, stayed with *Parafil* ropes.

'Conventional' prestressing places the tendon inside the concrete, in order to provide maximum corrosion protection to the tendon. In prestressing terms, the use of external cables is quite acceptable, and leads to significant savings in weight, since the thicknesses of the webs, and to a certain extent the flanges, do not have to be artificially increased to provide cover to the tendon. Various attempts have been made to prestress concrete externally [with steel tendons] . . . Although such structures show significant economic advantages, widespread adoption of the ideas has not taken place because of worries about corrosion of the tendon . . . expensive exercises [to protect steel] virtually negate the cost benefit of steel over Parafil, for which there would be no need to provide such protection.

The use of external prestressing in new construction requires a change in thinking by designers, to take advantage of a new material. One field where engineers

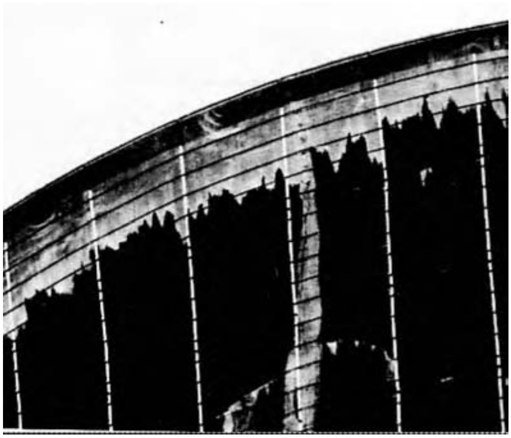


Fig. 12.15 Cooling tower repaired by wrapping with *Parafil* ropes.

> are being forced to look at new materials is in the field of repair of existing structures.
>
> Many existing structures are in need of repair for a variety of reasons. They may have been inadequately prestressed or reinforced to begin with, or there may have been corrosion of the steel subsequently. Some structures have to be reinforced to cope with larger loads, or because of settlement of foundations . . . Many of these structures can best be repaired by prestressing, since this usually enhances the integrity of the existing structure, without adding to the weight. In most structures, unless deliberately built with a view to the provision of additional prestress, spare ducts are not available and the structure must be externally prestressed. As with new construction, these cables have to be protected from corrosion if made from steel. Such protection would be unnecessary if the tendons were made from Parafil.
>
> One such set of structures that have been repaired in this way are three large cooling towers at Thorpe Marsh Power Station near Doncaster [*Fig. 12.15*]. These towers had been coated with gunite after the collapse of similar towers at Ferrybridge, but were recently found to have large vertical cracks at the top. They were repaired by wrapping the towers with Parafil ropes, which were supported off stainless steel brackets, and subsequently tensioned. In this case, not only did the Parafil offer benefits of freedom from corrosion, but also in the light weight, which allowed the ropes to be manhandled from light gantries during erection.

Burgoyne (1988) also mentions the potential of *Parafil* ropes in bridges and for supporting roof structures, particularly when these are of coated fabrics. However, conservatism has not led to any major use of this technology. Figures 1.27 and 1.33 shows two small structures: a bus station in Cambridge, England, and a footbridge in Aberfeldy, Scotland utilising *Parafil* ropes.

12.7 Kinetic energy recovery rope

Kinetic energy recovery ropes (KERR) have diametrically opposed requirements to the *Parafil* ropes. Their use depends on the high extensibility and energy storage

Fig. 12.16 Tank being pulled from a ditch by a KERR rope.

of nylon ropes. If a tank, or some other military or civilian vehicle, gets stuck, for example in a deep ditch, a tow rope is needed for a recovery vehicle to pull it out (Fig. 12.16). If a steel or other inextensible rope is used, then, as soon as the tank starts to move, the tension drops and the tank gets stuck again. With a KERR rope, the stored energy continues to drag out the stuck vehicle and there is little drop in tension. Also, in contrast to many other uses of ropes, the maintenance of loads over long periods is not needed. The rope can be extended to near its break load (with care that no one is in the line of snap-back if this is exceeded) and discarded after one use – the cost of the rope in relation to the loss of a tank being negligible. KERR ropes are typically eight-strand nylon ropes. After being used in a rescue operation, they often show considerable fusion of fibres within the rope and severe abrasion damage.

12.8 Failure and success with *Kevlar* aramid ropes

12.8.1 Learning from a fatigue failure

Following their commercialisation by DuPont in the 1970s, *Kevlar* p-aramid fibres have become important contributors to the advance of rope technology. However there was one notable early failure, which has been documented in a description of the failure by Riewald (1986) and on subsequent laboratory and field testing by Riewald *et al*. (1986). Good practice in rope design and application eliminates the causes of failure in *Kevlar* ropes.

In 1983, the derrick ship *Ocean Builder*, which was used in the erection of the *Lena* guyed tower in the Gulf of Mexico, needed to be moored in 320 metres of water. In order to avoid the high line sag of steel cables, as shown in Fig. 12.17, a taut mooring of *Kevlar* rope was planned to be used. The rope construction is shown in Fig. 12.18: eighteen load-bearing strands round a nylon core, all in a tight extruded nylon plastic jacket. This jacket had been cut away in order to make the

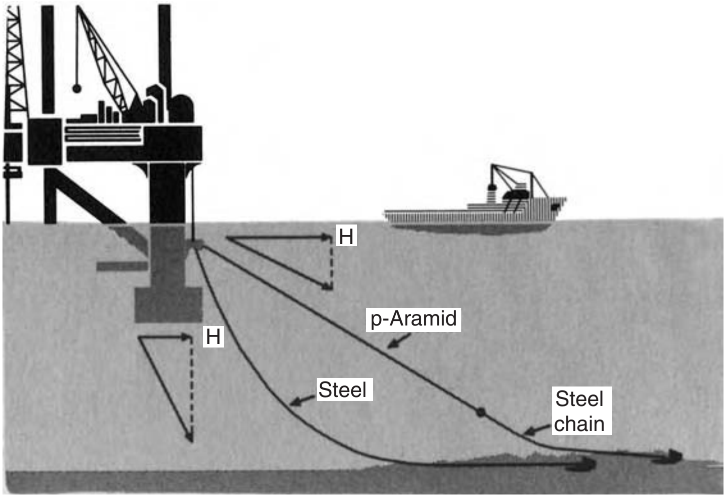


Fig. 12.17 Expected advantage of aramid lines over steel cables. From Riewald (1986).

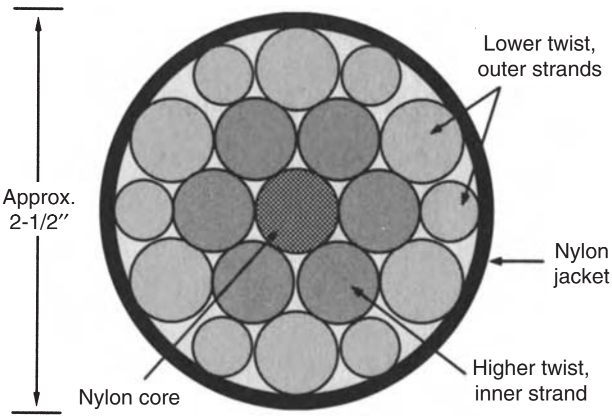


Fig. 12.18 Aramid lines tried for *Ocean Builder* mooring. From Riewald (1986).

spliced termination, which thus formed a rigid/flexible transition. The ropes were 64 mm in diameter, weighed 3.12 kg/m, and had a break load of 200 tonnes. Twelve lines, which were attached to anchors on the sea-bed and to a buoy on the surface, were pre-deployed ready for the arrival of the *Ocean Builder*. On first tensioning, after being picked up about five weeks later, four of the ropes broke, reportedly at 20% rated break load.

An extensive investigation was carried out by DuPont to find the cause of the failure. The ropes were not torque-balanced. As the buoy moved up and down due to wave action, the changes in rope tension caused the ropes to twist. Without a jacket, axial compression would cause the rope to birdcage, as shown in Fig. 12.19. With a jacket, the excess length forces the fibres within the strands into axial compression. Figure 12.20 shows the loss of strength due to axial compression fatigue (see Sections 4.5.7 and 5.7.6) in p-aramid fibres. The kinkbands associated with the

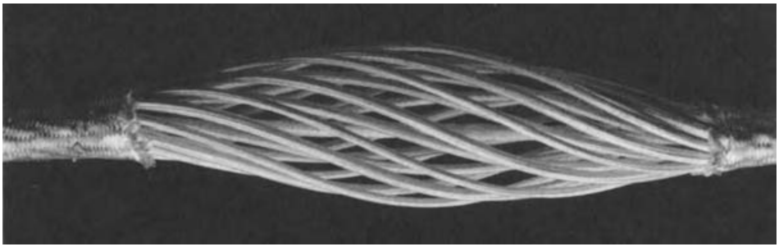


Fig. 12.19 Bird-caging when an unjacketed rope is axially compressed. From Riewald (1986).

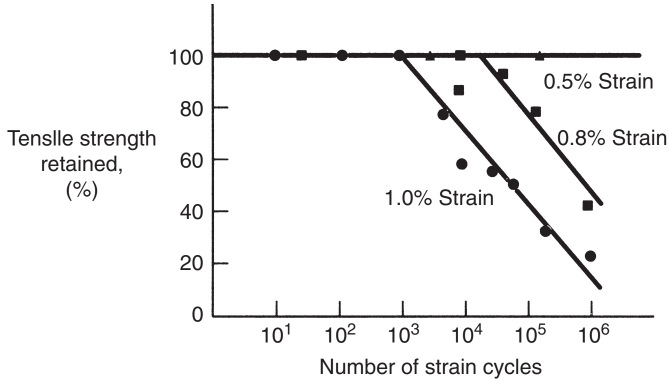


Fig. 12.20 Loss of strength in p-aramid fibres due to axial compression. From Riewald (1986).

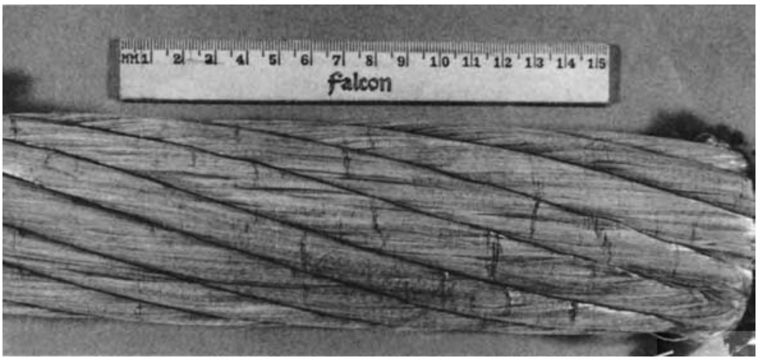


Fig. 12.21 Defects shown up by dyeing yarn. From Riewald (1986).

damage to the fibres were shown up by preferential dye absorption, Fig. 12.21. The tight jacket may also have contributed to axial compression, as indicated in Section 5.7.6. Sharp bending during handling was noted as another contributing factor. Riewald (1986) states '*This* [axial compression fatigue] *was a previously unknown degradation mechanism*'. Innovative advances commonly give rise to unexpected problems!

The five recommendations to avoid the problem can be summarised as:

- Use torque-free ropes.
- Increase the freedom of movement of fibres, for example by having higher twists [thus allowing smooth buckling instead of sharp kinks].
- Use lowest possible level of tightness of jacket.
- Keep the rope under tension to prevent flex or hinge points from developing.
- Use careful handling techniques.

There may be a simpler explanation of the failure. Although axial compression may have weakened the body of the rope, failures which occurred at the splice/jacket junction would be due to the bending and twisting occurring at this rigid/flexible transition. It is not good practice to have *Kevlar* in a pipe (the *Zylon* ST 811 plastic jacket) that joins a loose splice going to a buoy. The ropes were mostly not under tension, so the rigid flexible transition was a site for twisting and kinking. It is not surprising that concentrated bending at this point would cause filaments to start to fail.

12.8.2 An early success

At about the same time, there was a successful use of *Kevlar* ropes in the Netherlands. Revetments (heavy textile mats filled with aggregate) needed to be pulled into place while reclaiming land in the Eastern Scheldt region. The mat laying vessel, the *Cardium*, pulled itself along by winching on its mooring lines, which were ropes with a strength of 400 tonnes. The project required that the mats be laid to an accuracy of a few centimetres. The sag on steel wire ropes would have made this a difficult, if not an impossible, task to achieve. Furthermore, there was a risk that, due to sag, steel wire ropes would have contacted and damaged the mats. This was a serious concern since there was no procedure for recovering the mats and the delay to the project could have run into weeks.

Initially an 8-strand wire rope construction of *Kevlar* was tried as an insertion line. This worked well and trials were undertaken to replace the entire set of mooring lines with these Kevlar ropes. This was important because winching the eyes and shackles at the insertion points would have damaged the ropes. However, success in these trials was not a forgone conclusion, since the safety factor and D/d ratio were low (2:1 and 20:1 respectively). This trial was also successful and the steel wire ropes were replaced with *Kevlar*.

One problem arose. The ropes were picked up under load in the middle and this caused damage and a failure quite similar to that of the *Ocean Builder*. The uncontrolled and sharp flexing caused extensive filament failure. The ropes were then fitted with a proper pick-up arrangement, which stopped this acute flexing. From then on to the end of the project, the rope performance was trouble free.

12.8.3 Missile test facility

Another interesting application of *Kevlar* is described in extracts from a DuPont case history:

> **Missile test facility has unique application for DuPont Kevlar aramid cable.**
>
> **Strung across a three-mile gap between mountaintops, cable made of superstrong DuPont Kevlar aramid fiber provides a novel way to deploy aerial targets for ground-to-air missiles.**

As part of an ongoing effort to cut operating costs and reduce the environmental impact of its weapons testing programs, the U.S. Department of Defense (DoD) is constructing a unique, cable-based aerial target . . . at the south end of the Oscura Mountains in the north-central area of the White Sands Missile Range.

The main component of the system is a 2 1/8 inch rope . . . Because the Kevlar cable is one-fifth the weight of the equivalent strength steel cable, the cable sag can be established at the desired level with lower line tension. The lower tension leads to a higher operational safety factor. An additional benefit derived from the Kevlar cable is increased target speeds of up to 1000 mph, vs. a 600 mph speed limitation imposed by the steel cable . . . The exceptional strength of Kevlar was demonstrated in an earlier application at Sandia National Laboratories . . . aerial cables of Kevlar were used to hoist shipping containers of sensitive weapons to elevated positions for high-velocity impact tests.

With ends supported by winches anchored atop adjacent 8500-foot and 6000-foot mountains at White Sands, the cable spans more than 15 000 feet, making it the longest unsupported cable in the world. The cable will serve as a 'rail' for moving trolleys from which targets, ordnance and experimental apparatus will be suspended [Fig. 12.22]. Speeds and altitudes of targets can be controlled to simulate the realism of attacking aircraft. Trolleys will be able to attain a speed of 250

Fig. 12.22 Target on the *Kevlar* cable at the White Sands missile range. From Du Pont literature.

knots (288 mph) just from gravity; for higher speeds, rocket assists can be added. Altitude can be changed by raising or lowering the cable.

[The] cable of DuPont Kevlar aramid at White Sands is 2 1/8 inches in diameter, with 36-strand, right-lay construction. Kevlar is used as primary strength member overlaid with DuPont Dacron polyester Multiplex.

A very cost-effective alternative.

By way of comparison, the DoD estimates that to duplicate the testing which will be done at the new ACTC facility using conventional range methods would require an annual expenditure of $28.6 million to support the following activities:

- Launch of up to 65 drone targets, 33 of which would be destroyed.
- Flying of 15 manned aircraft missions to test a short-range air-to-ground missile.
- Mounting of more than 330 manned aircraft sorties, including those needed to test the short-range missile.

In sharp contrast, the new ACTC facility can be operated at an estimated annual cost of less than $2 million. Including construction costs, the facility should save the DoD $665 million over 25 years.

In addition to saving money, the cable system will have much less impact on the environment than a conventional target range – both during construction and in operation. Construction is being carefully managed to avoid or minimize disturbance to vegetation, wildlife and prehistoric sites. It is being conducted in accordance with federal and state guidelines and in consultation with appropriate authorities and organizations.

A wide variety of testing will be conducted.

The White Sands complex will be used to test a variety of DoD weapons systems, including short-range missiles which will be launched from the ground at moving targets suspended from the cable. In a reverse procedure, ordnance will be launched from platforms attached to the cable at targets on the ground. An estimated 400 tests per year will be conducted using the new cable facility.

According to Chris Eastin, vice president of Marketing for Nielson's, Inc., ACTC construction contractor, 'We believe the (ACTC) job will demonstrate how we can mesh the efforts of an experienced group of project supervisors and engineers with sophisticated construction management techniques to build a research facility that makes a singular contribution to our nation's security.'

12.8.4 Aramid slings

Another DuPont case history describes the use of aramid slings in lifting operations:

When St. John Shipbuilding, Limited, of Canada needed to lift the 550-metric-ton bow section of a Canadian naval frigate, they chose the new super strong and lightweight I & I Sling, Inc. SLINGMAX TUFF-PATH Extra Lifting slings [Fig. 12.23] . . . When [a Kevlar rope is] enclosed in a sleeve of CORDURA – Du Pont's air-textured high-tenacity nylon – the combination creates an extremely strong, lightweight and dependable sling that is easy to handle and can simply be rolled up and stored. The . . . slings . . . used for this lift weighed a total of 2600 pounds. Incumbent steel wire cables required for the same lift weigh 14 000

Fig. 12.23 Lifting a large yacht with super strong lifting slings made of a blend of high modulus fibres for light weight and covered with a special abrasion resistant nylon jacket. Reproduced by courtesy of Slingmax, Inc.

pounds. The lighter weight SLINGMAX slings are smaller in diameter and easier to handle than the incumbent steel wire cables. No special equipment is required and fewer men are needed for rigging.

According to Ray Moon, Rigging Engineer, 'the KEVLAR and CORDURA lightweight SLINGMAX slings made the whole job a lot easier, especially in rigging time.' The easy handling of the TUFF-PATH Extra Lifting slings 'required only a few minutes to rig the bow versus hours using steel wire cables,' said Dennis St. Germain of I& I Sling, Inc.

Once rigged, the double connection between loop and load of the TUFF-PATH sling essentially created two slings in one, increasing the protection against breakage – a key benefit in safe operation of heavy loads. Safety is always a main concern since back injuries are not uncommon when working with the heavy steel wire cables. At one-fifth the weight of incumbent steel wire cables . . . 'I'm very impressed with the safety aspects of the SLINGMAX slings,' said Gerald Daigle, Superintendent of St. John Building, Ltd. 'One man can handle the SLINGMAX sling. A steel wire cable used for a lift this size requires a crane just to lift it into place because one man cannot lift or even handle the four-inch-diameter steel wire cable.' 'It's fantastic; there's nothing like the TUFF-PATH Extra Lifting sling,' said Daigle, 'It makes the whole job easier; when you're finished you just roll it up, put it in a box and store it where it's dry. You can't coil steel wire cable and it gets in the way when left out in the elements.'

Tests prove that the SLINGMAX slings made of Du Pont KEVLAR and CORDURA resist the elements in addition to chemicals and flames. All SLINGMAX slings are also strength-tested and capacity-rated. Each of the 95-foot-long

TUFF-PATH slings used in the bow lift had a minimum breaking strength of 1.5 million pounds and was certified by Lloyd's of London.

12.9 Investigating failure

12.9.1 Vessel breakout from quay

A hurricane struck a major Caribbean port resulting in the breakout of a large cargo ship from the quay. It had been impossible to evacuate the vessel prior to the storm, but a crew had been put aboard to strengthen the mooring. After the hurricane, the fibre rope mooring lines from the ship and onshore facilities were obtained, and were seen to represent a considerable variety of types and sizes. The ship had six wire rope winches which were used to tension some fibre rope lines; the others were tensioned by using the gypsy heads of the deck machinery with stoppers to hold the tension while the lines were moved to the bitts. Altogether twenty-three lines were put ashore.

Tension Technology International (TTI) was requested to analyse the mooring arrangement to determine its efficiency.

At least one piece of all the lines had been salvaged and their location in the mooring pattern was identified with respect to the anchorage on the ship and the securing point on the quay. An estimate was made of the tension in each line when it was first installed. Drawings of the quay give the location of the cleats and bollards. The location of the ship relative to the quay was established. From these data, a drawing was made of the mooring arrangement, Fig. 12.24.

A computer model, *Optimoor*, had been produced previously by TTI to analyse quayside moorings for cargo vessels and tankers. This was available to study this mooring. *Optimoor* inputs the necessary information and computes the state of the mooring. A typical screen-grab from *Optimoor* is shown in Fig. 12.25.

The normal rated strength and extensibility of fibre and wire ropes are built into the program. The size and type of each mooring line, including those using steel wire

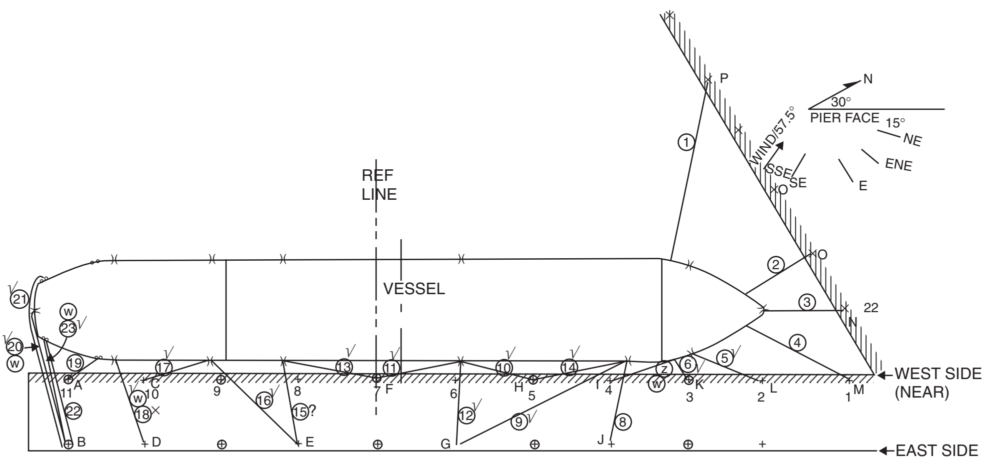


Fig. 12.24 Partial view of 23-line storm mooring.

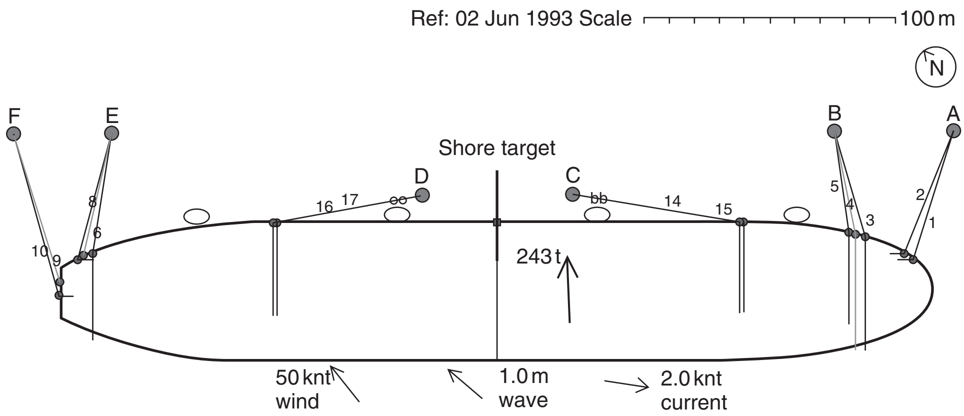


Fig. 12.25 Redrawn screen grab from *Optimoor*.

and fibre ropes in series and parallel, were entered. Fibre ropes are designated within the programme as new or used. The horizontal coordinates and elevation of each set of bitts or winches on the ship, the chocks at the edge of the deck, and the cleat or bollard on the quay were entered for each line. The estimated pretension for each line was entered.

By entering the draft and by selecting a vessel type from a list provided in the program, the wind (sail) area of the vessel is determined. There was no current in this case, but that could also have been covered. Wind speed and direction are also entered.

From all this, the computer uses an interactive process to balance all the forces in the entire mooring pattern and completes the calculation. This will give the tension in each mooring line for a particular pretension, wind speed and wind direction. The movement of the ship and its new position are also determined. After looking at the output, the investigator can change these parameters to analyse the sensitivity of one or more lines to pretension, wind speed or wind direction. The lines loaded closest to their breaking strength can be seen. It was assumed that a particular line has broken and the program was run again with that line omitted to see how the load distribution has shifted.

All of the broken lines were carefully examined (see Fig. 12.26). Some were new. The used ones were evaluated and residual strength estimated. These data were compared to the tensions calculated by the programme. From this work, a picture evolved as to the efficiency of the mooring arrangement. Worst case assumptions on pretension and rope strength revealed the lowest wind speed combined with the worst direction that may have caused the breakout. More likely values for pretension and rope strength gave an indication of the expected performance of the mooring.

The theory of applied mechanics and associated mathematics that are used in this computer program are well known. What makes it unique is the predictable data on rope performance that has been obtained through extensive test data on new and used rope. For mooring applications, the elongation properties are as important as strength. To analyse twenty-three ropes of mixed sizes and lengths would have been an impossible task without computer assistance. But once the

Fig. 12.26 One of 23 broken mooring lines.

model was set up, different scenarios were run and a good picture of the potential performance of the mooring system was obtained.

12.9.2 A loss under tow

Rope failures do occur and can have expensive consequences that end up in courts of law. One accident, which has been reported in the technical literature (Denton, 1989), involved the total loss of a jack-up unit with the following specification:

Type: Marathon Le Tourneau Class 52
Length: 61.9 m
Breadth: 51.2 m
Depth of hull: 6.7 m
Number of legs: 3
Length of legs: 108.8 m
Displacement: 6847 tonnes
Draft: 4.0 m

The unit was being towed round the coast of Australia by two tugs, each acting on a single towline. The forecast was for maximum 25 knot winds and decreasing swell, but 24 hours into the tow the wind was gale force and the swell increased from 3 to 6 m. Two of the tow ropes broke, but the weather conditions were sufficiently moderate to allow re-hook-up. Five hours later, the nylon rope stretcher on one of the towlines broke, and in the words of one of the crew 'all hell broke loose'. After securing all doors and hatches, most of the crew were evacuated by helicopter. Attempts to reconnect the towline failed and the skeleton crew abandoned the unit as darkness fell. Two hours after they returned at first light, the second towline broke and the unit capsized and sank in 55 m of water.

Denton (1989) discusses what happened before and after the line broke and reports on an analysis of motions and stresses. This showed how rope tensions could be reduced by appropriate ship handling. The rope issues were addressed by M R Parsey of Tension Technology International. The towlines consisted of steel cables with 12-inch circumference eight-strand nylon 6.6 rope stretchers to minimise the tensions developed in shock loading. The ropes were made up into grommets with soft eyes. Properly attached, this type of grommet would give a new dry strength of about 215 tonnes and a wet strength of about 190 tonnes, which should have been adequate. Nevertheless, the first stretcher had failed in calm weather, but was hooked up again, only to fail again after the storm broke. Tests showed that the ropes would lose about 4.4% of strength per day in this kind of towing service, due to internal cyclic abrasion of wet nylon. Placing soft eyes round a small shackle pin with a *D/d* ratio of about 0.8 to 1 (i.e. pin diameter less than rope diameter) would reduce the strength by a further 33%. These two factors meant that the rope system strengths were inadequate to support the tensions generated in towing.

12.9.3 Nylon abrasion: a pathological study of a mistaken choice

The third investigation did not require any analytical study, but it demonstrates the importance of choosing the right rope for the purpose – and also provided an interesting specimen for research on fibre failure by the fibre fracture group at UMIST. Getting what seems to be a better deal can lead to trouble. A three-strand polyester rope supplied by a good ropemaker had given excellent service to tie the skirt of a hovercraft to the vessel. Then a rope was returned to the ropemaker with a complaint. It was badly abraded and had almost broken where it was tied to an eyelet. Examination showed that it was not their rope and it was not polyester. A purchasing agent had found a cheaper rope, which *looked* much the same and had much the same strength – but it was a nylon rope, unsuited to stand up to repeated tensioning and flexing particularly over the eyelet in a wet environment. Once the substitute rope had been identified, that solved the problem as far as the ropemaker was concerned – but the rope was passed on for the research study.

The first stage in such an investigation of rope failure is to view the whole piece and record the superficial signs of wear. Figure 12.27(a)–(c) shows parts of the rope that are little worn (a), that have some broken fibres appearing on the surface (b), and that show severe damage in the eyelet region (c). The most obvious next step is to examine the most damaged region in a scanning electron microscope, as shown in Fig. 12.27(d). In practice, this is not very helpful. One can see a lot of split and broken fibres, but it is impossible to disentangle the mess to discover how the wear has occurred. It is always more informative to examine less damaged regions, in order to see how wear is caused. There is some slight surface wear in the least damaged region, as seen in Fig. 12.27(e), which shows the characteristic flattening of the fibres as material is worn away. The rope is then opened up to look at internal wear. Abrasion in the inter-strand region has led to excessive wear, with peeling away of strips of fibre, as seen in Fig. 12.27(f) and in more detail in Fig. 12.27(g). Rubbing of the material causes extensive fibrillation, which is also shown in the partial breakage of Fig. 12.27(h). The dominant cause of failure is thus abrasion of wet nylon fibres, due to the generation of shear stresses by slip and friction between

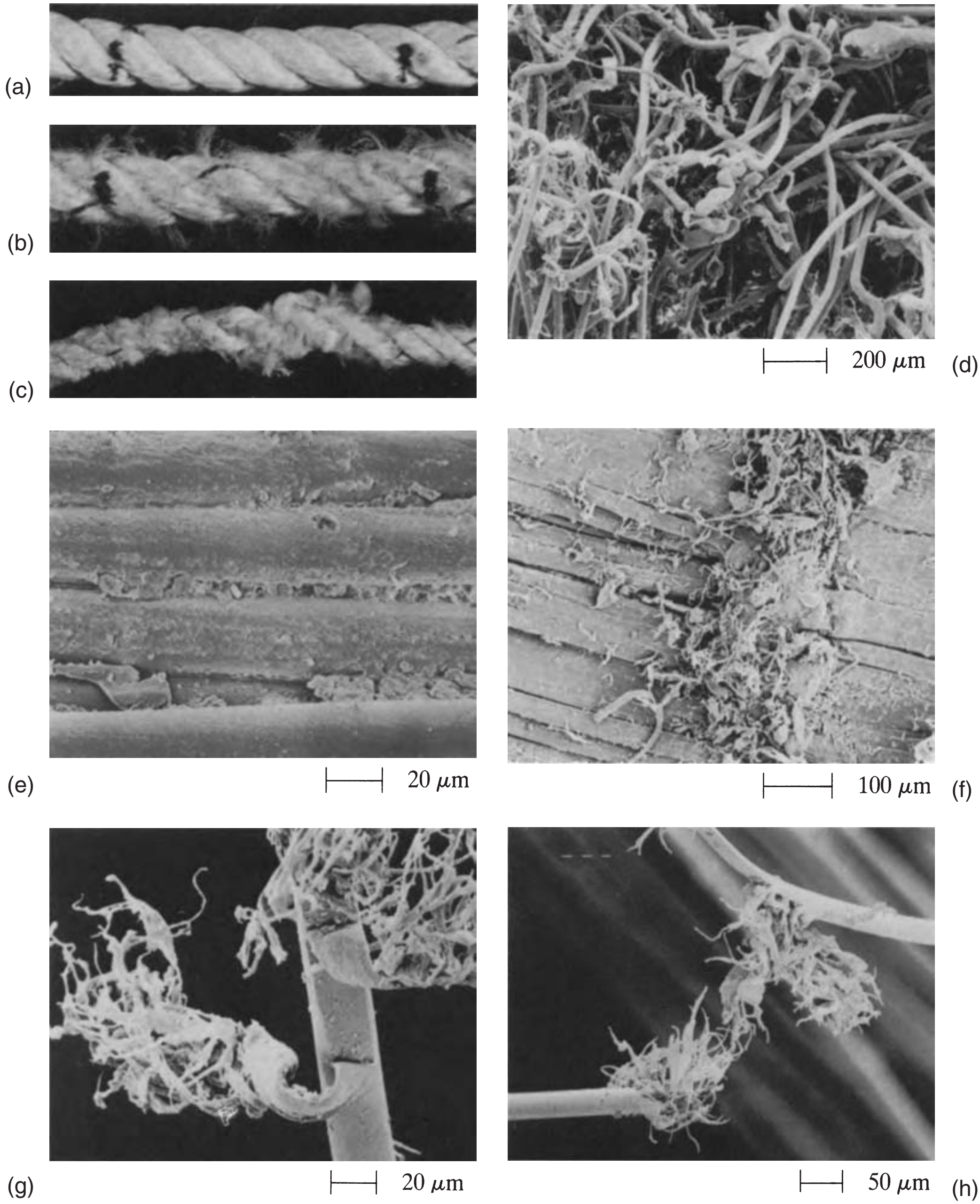


Fig. 12.27 Damaged rope from hovercraft. (a) Least damaged region. (b) Intermediate damage. (c) Most damaged region, where rope was tied to eyelet. (d) Surface of rope in region of severe damage. (e) Surface wear from least damaged region. (f)–(h) Inter-strand wear in least damaged region, showing fibre peeling and ultimate breakage. (a)–(c) are macro-photographs. (d)–(h) are scanning electron micrographs. From Hearle *et al.* (1998), which includes additional SEM pictures.

fibres (see Sections 4.5.2 and 5.7.4). Contact pressures, which determine the magnitude of the friction forces, will result from tension in a twisted structure where the rope is straight, but will be intensified in the eyelet region by the external pressure. Acute bending in the eyelet may also be a factor in causing damage to fibres.

12.10 Climbing ropes

12.10.1 Mountaineering

Ropes have always been associated with climbing. A 10000 year-old rock drawing, Fig. 1.1, shows a man climbing up ropes to collect honey. The utilitarian need to climb, whether on ships at sea or on buildings on land, required ropes. When mountaineering started as a sport in the nineteenth century, the early climbers used the available manila, cotton or other natural fibre ropes, and this continued through the advances in rock-climbing in the first half of the twentieth century and the early expeditions to Everest and other Himalayan peaks (see Figures 1.38 and 1.39). Today, the situation is very different: there is a range of specialised ropes with materials and designs suited to the different aspects of rock climbing. The extracts from the *Edelrid* catalogue in Fig. 12.28 illustrate the diversity of ropes designed for different mountaineering uses.

Nylon kernmantel ropes, which were invented by Edelrid, dominate the market for 'dynamic ropes', because the moderately high strength combined with high break extension gives a high absorption of energy to arrest the fall of a climber. The specific work of rupture w of nylon at 80 mN/tex (80 kJ/kg) is the highest in Table 2.3. Grades optimised for energy absorption, in contrast to the high-tenacity nylons more often used in ropes, could have still higher values, though their strength will be lower. A correction has to be applied for the conversion efficiency from fibre to rope. The critical relation for safety is:

$$CLw > Mgh.S \qquad [12.5]$$

where C is linear density of rope in kg/m, L is length of rope in m, w is specific work of rupture of rope in Joules per kg (µN/tex), M is mass of climber in kg, g is acceleration due to gravity in ms^{-2}, h is distance fallen in m, and S is the safety factor.

In the worst case, when the climber has ascended for the full length of the rope, h equals $2L$, so that the condition becomes:

$$Cw > 2Mg.S \qquad [12.6]$$

Two other features of nylon are favourable for climbing ropes. The comparatively low modulus prevents the applied forces being too large, and good elastic recovery means that the rope will withstand a number of falls. However, each shock imposed on the rope does use up some non-recoverable energy absorption, so that the residual work of rupture progressively decreases. For a simple linear model with constant parameters, Morton and Hearle (1993, p. 334) show that the number of shocks N that a fibre assembly can stand before breaking is equal to $[W/(1 - r)\ U]$, where W is the total work of rupture, r is the fractional work recovery and U is the magnitude of the repeated energy shocks. Discard criteria should be related to the number of times the rope is used to arrest a fall.

A disadvantage of nylon is the loss of strength and work of rupture when wet, but the effect can be reduced by special coatings. The newly available polyester fibre,

LIVE WIRE

SPECIAL PEOPLE - SPECIAL ROPES

FOR THOSE WHO WANT TO WALK THE UNTRODDEN PATH.
MAXIMUM SAFETY RESERVE-MINIMUM WEIGHT. WITH DRY-LONGLIFE TREATMENT.

LIVE WIRE RUST

7.6 MM
LIVE WIRE DRY

Sharp edge tested!

With a weight of 38 g per metre one of the most lightweight twin ropes on the market. The fall test results of 20–23 (Test Lab Stuttgart) set standards in this category. One of the first twin ropes to pass the sharp edge test!

1030 I saffron (142), patina (156), rust (167), steel (184)

8.3 MM
LIVE WIRE DRY

1031 I saffron (142), patina (156), rust (167), steel (184)

9.8 MM
LIVE WIRE DRY

Very lightweight single rope. No compromise in terms of safety and handling!

1032 I saffron (142), patina (156), rust (167), steel (184)

10.5 MM
LIVE WIRE DRY

1033 I saffron (142), patina (156), rust (167), steel (184)

Rope lengths
50 / 55 / 60 m.

9.8 MM

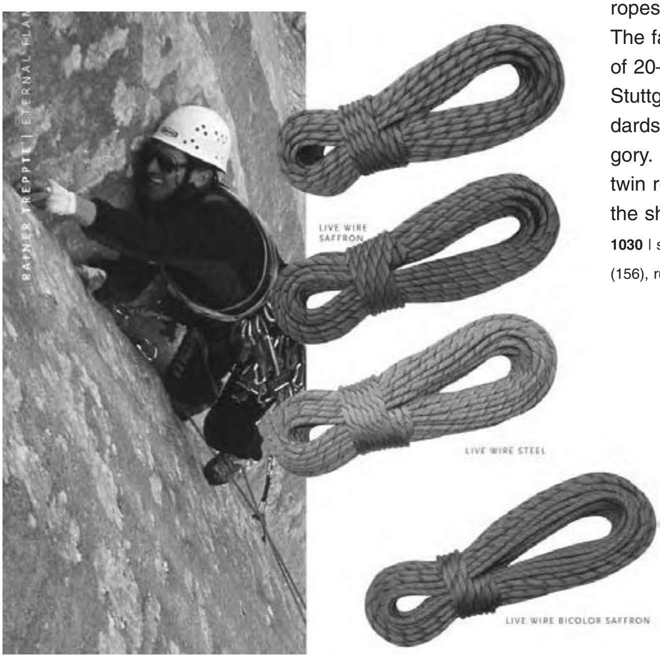
LIVE WIRE
BICOLOR DRY

1034–70 I 70 m, steel (184)

10.5 MM

LIVE WIRE
BICOLOR DRY

1035 I 60 m, saffron (142)



(a)

Fig. 12.28 The *Edelrid* range of climbing ropes demonstrates the modern specialism. (a) *Live Wire*. (b) The *Classics*. (c) Semi-static ropes. Except for *Pes-static Dry* (polyester) and *Canyon Rope* (polypropylene), these are all nylon ropes. Colour coding is important to ensure that the right ropes for the purpose are selected.

THE CLASSICS

SUPERB HANDLING AND AN ATTRACTIVE PRICE CHARACTERISE THE SKYLINE RANGE. EQUALLY SUITED FOR ALPINE USE AND CRAGGING.

9 MM SKYLINE

1196 | Longlife

1176 | Dry

tizian (002), navy (118)

maize (122), steel (184)

10.5 MM SKYLINE

1197 | Longlife

1177 | Dry

tizian (002), navy (118)

maize (122), steel (184)

11 MM SKYLINE

Sharp edge tested!

1198 | Longlife

1178 | Dry

tizian (002), navy (118)

maize (122), steel (184)

10.5 MM SKYLINE BICOLOR

1195 | 60 m, tizian (002)

Rope lengths
50 / 55 / 60 m.

ROCK ROPES

11 MM BIG AIR DRY

Sharp edge tested

Our favourite for the toughest challenge. From Yosemite to Greenland this multi-drop rope does it all. The Big Air holds a fall over a 0.75 mm edge easily.

1060 | 50 / 60 / 70 m, black-silver (017)

10.5 MM FAT ROCK

Ideal for frequent and intense toproping and working routes at the crag. The homogenous sheath structure reduces furring, friction and jamming.

1061 | 50 / 55 / 60 m, black-silver (017)

10.5 MM BIG JIM

A reliable and long lasting partner for the climbing wall. The higer sheath to core ratio makes frequent toproping no problem.

1062 | 20 / 30 / 40 m violet (004), yellow (020)

9 MM GLACIER ROPE DRY

For glaciers and snow plods. Its water-repellent surface keeps it dry.
Not suitable for ice climbing!

1176 | 30 / 40 m, tizian (002) navy (118), steel (184)

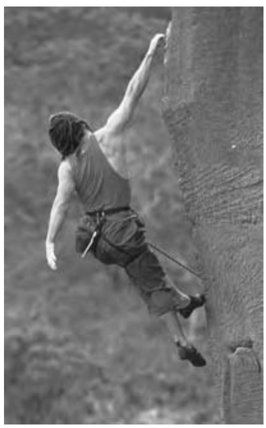
8 MM CONFIDENCE ROPE

Ideal for the occasional belay while scrambling.
Not to be used as a glacier rope!

1692 | 18 / 30 / 36 m red (002), blue (005)

ATTENTION

Snow and particularly ice crystals can penetrate the rope and cause damage to fibres. Crampons can also damage ropes. Check your ropes before and after use!



(b)

Fig. 12.28 *cont'd*

(c)

SUPERSTATIC
Strong, abrasion-resistant semi-static rope construction with extremely low elongation values. Ascender- and dirt-resistant sheath with an extra good grip. Tried and tested in many situations including rescues, winching operations and tropical research. For special applications also available in a Dry version.

9 MM LONGLIFE
2306 | white (001), blue (005)
2326 | Dry white (001)

10 MM LONGLIFE
2304 | white (001), black (017)
2324 | Dry white (001)

10.5 MM LONGLIFE
2303 | Longlife
2323 | Dry white (001)

11 MM LONGLIFE
2302 | white (001), red (002), black (017)
2322 | Dry white (001)

11 MM PROSTATIC
Very low elongation values and a particularly dense, abrasion-resistant sheath. Ideal for frequent abseiling.
2309 | white (001)

SOFTSTATIC
Maximum suppleness, flexibility and a reinforced dynamic component are the main characteristics of these speleo ropes. The ideal rope construction for rope bridges and traverse ropes.
2299 | 9 mm, white, tracer thread black (001)
2298 | 10 mm, white, tracer thread black/blue (001)
2297 | 10.5 mm, white, tracer thread black/red (001)

10.5 MM PES-STATIC DRY
Universal use. The most important advantages of this polyester rope are
- alkali- and acid resistance
- maintenance of length wet/dry
- UV-stable
- high temperature resistance
- low cold water shrinkage
- low elongation values
- water-repellent

2333 | white (001)

CANYON ROPE
Buoyant kernmantel rope with polypropylene fibres in the core. The improved sheath structure (2 braids) provides a better abrasion resistance for use in canyoning. EDELRID Canyon ropes meet the high safety requirements for semi-static ropes (EN 1891).
2295 | 9 mm, fluo-orange (010), lemon (040)
2294 | 11 mm, fluo-orange (010)

Attention:
A double strand of rope must be used when abseiling with the 9 mm Canyon Rope!

Fig. 12.28 *cont'd*

poly(butyleneterephthalate) [PBT or 3GT], which does not absorb moisture but is close to nylon in other properties may prove useful for climbing ropes.

There are other applications, for example in fixed ropes used in caving, where high strength and low extensibility are required. High-modulus grades of nylon are used in these so-called 'static ropes'. This category also includes the two exceptions to the use of nylon 6 or 6.6 in the *Edelrid* catalogue. Pes-static Dry takes advantage of the low elongation of polyester, together with its minimal change between wet and dry. Canyon Rope uses a polypropylene core.

12.10.2 Other applications

Mountaineering is only one of the uses for climbing ropes. Abseiling is carried out not only by rock climbers, but also for rapid descents from helicopters or buildings. Information given by Marlow Ropes describes ropes designed for this purpose. The standard abseil rope has a parallel polyester core with a 16 plait torque-free polyester jacket. The low stretch is claimed to reduce kinking and to aid fast, controlled

Table 12.6 Rapid descent ropes. Properties quoted by Marlow Ropes

	Standard abseil. 9 mm polyester	**Standard abseil. 11 mm polyester**	**Heat-resistant abseil. 11 mm polyester/ aramid**	**Fast rope. 40 mm nylon**
Weight (kg/m)	6.7	9.7	9.4	94
Break strength (kg)	1900	2800	3988	11 000
Break strength after 1 minute fire (kg)			1047	
Temperature tolerance (°C)	–70 to 100	–70 to 100	–70 to 500	
Extension (under 840 kg)	5%	5%		
Extension (under 200 kg)				30%
Ultra-violet resistance	excellent	excellent	poor	excellent
Colour	black or white		pale yellow	olive
	← good flexibility and abrasion resistance →			
	← good rot and chemical resistance →			

descent. A fire/heat resistant variant used for emergency escape systems has an aramid jacket. These ropes have standard NATO code numbers.

For swarming and fast roping, without the use of special equipment such as karabiners, a heavier, 8-strand nylon rope is used. Use of staple-fibre nylon allows for a good grip on the rope. (The Marlow brochure implies that this is cut from high-tenacity multifilament nylon.) The non-rotating performance enables problem-free deployment and the high extension absorbs dynamic loads, giving a smooth descent.

Some features of these ropes are given in Table 12.6.

Other ropes are listed by Marlow Ropes in an arborist range for use by tree surgeons.

12.11 Sailing and yachting

A similar story applies to ropes for sailing and yachting. The old natural fibre ropes picked off the shelves of an old-fashioned marine store have made way for a range of specialist ropes, many of them made from the new high-performance fibres. The choice depends on a balance of cost and performance and will differ from Sunday afternoon dinghy racing and leisure cruising to Olympic races and the America's Cup, as well as the function of the rope on the boat. Some very well-to-do racers even have ropes built to their own designs. If successful, they may find their way into the rope manufacturer's product line.

There are many ropemakers around the world competing for this important market. Although they may have their own particular slants on what is best, the general features will be similar. However, in order to be specific rather than diffuse about the wide variety of choice and the complexities of structure, we have chosen to describe the range of a particular manufacturer, Gleistein, who have been manufacturing ropes in Bremen, Germany, since 1824, without implying that this company is the market leader. Gleistein has many competitors, especially in Western Europe, UK and North America that make very similar products. Most have web pages and the reader is invited to perform a search; directories provided by trade associations such as the Cordage Institute or Eurocord may be helpful.

Direct quotes from the Gleistein catalogue are given in this section and trade names are also used as these are the references to various materials used by Gleistein, but the generic equivalent is provided or can be found in the glossary. Figure 12.29, from their catalogue, shows the locations at which ropes are used on yachts, and Gleistein comment in a way that would be echoed by other manufacturers of ropes for this market:

> The enthusiasm for sailing is an important spur for the development of superior products which have proven themselves in the toughest of conditions. As a result of this, you can find everything from a high performance regatta sheet to a simple whipping twine in our comprehensive yacht rope range.

In a selection from a range of rope diameters, Table 12.7 gives the break loads and linear densities of Gleistein ropes designed for use as sheets, which control the boom, and halyards, which hold up the sails. The demands on the ropes are low stretch, high strength and a long service life (except perhaps at the top of the competitive range, where replacement would be made between races, if it gave an advantage). Polyester is well proven. The newer high performance fibre ropes are technically superior but more expensive. Fibre ropes have always been used for sheets, because of the continuous handling, but they are now increasingly replacing steel wire ropes for halyards.

Surface frictional and wear characteristics are important for lines used on winches (capstans). Important features are a good grip when held under tension with a minimum number of wraps and smooth sliding when tension is released. A small change in grip can be immediately noticed by an experienced crewman and can result in an angry comment about the ropemaker if not to his liking.

For the mid-range 10 mm rope, comparative values of break stress in MPa, which relates to the thickness of the rope, and specific strength in mN/tex, which relates to rope weight, are given in Table 12.7. The load–elongation properties of the ropes, which range from 2% to 10% extension at 50% of break load, are shown in Fig. 12.30. All the ropes are spliceable using the correct techniques as described in Gleistein's 'Splicebook' (Gleistein, 2000). The different characteristics of the ropes, which are available in a variety of colours and may have other coloured marker yarns, are as follows.

Vectran, described as the ultimate sheet/halyard for racing and large yachts and ideal for hydraulically tensioned halyards and for backstays, has a 12-strand *Vectran* (liquid crystal aromatic copolyester) HS fibre core, with an intermediate cover of polyester staple fibres to give a good frictional grip between the core and the outer cover of 24 or 32 strand melt-dyed gold continuous filament polyester. *Vectran* rope, designed for the toughest conditions, has 'exceptional abrasion resistance whilst maintaining flexibility, elongation equal to steel wire rope, non-critical behaviour with modern sheaves, no measurable creep.'

In contrast to *Vectran*, another 12-strand rope, *Dyna One*, uses a protective coating of a polyurethane, *Geothane*, instead of a heavy jacket, in order to take maximum advantage of the high strength of *Dyneema SK75* HMPE fibre. As shown in Table 12.7, both on an area and a weight basis, *Dyna One* exceeds the strength of the other high-performance fibre ropes by upwards of 1.7 times and it has a strength/weight ratio eight times that of steel wire rope. Provided it is matched by the strength of fittings, this makes it 'the ultimate light weight sheet/halyard for racing yachts' and 'the choice of the winning boat'. However, there is a price to pay.

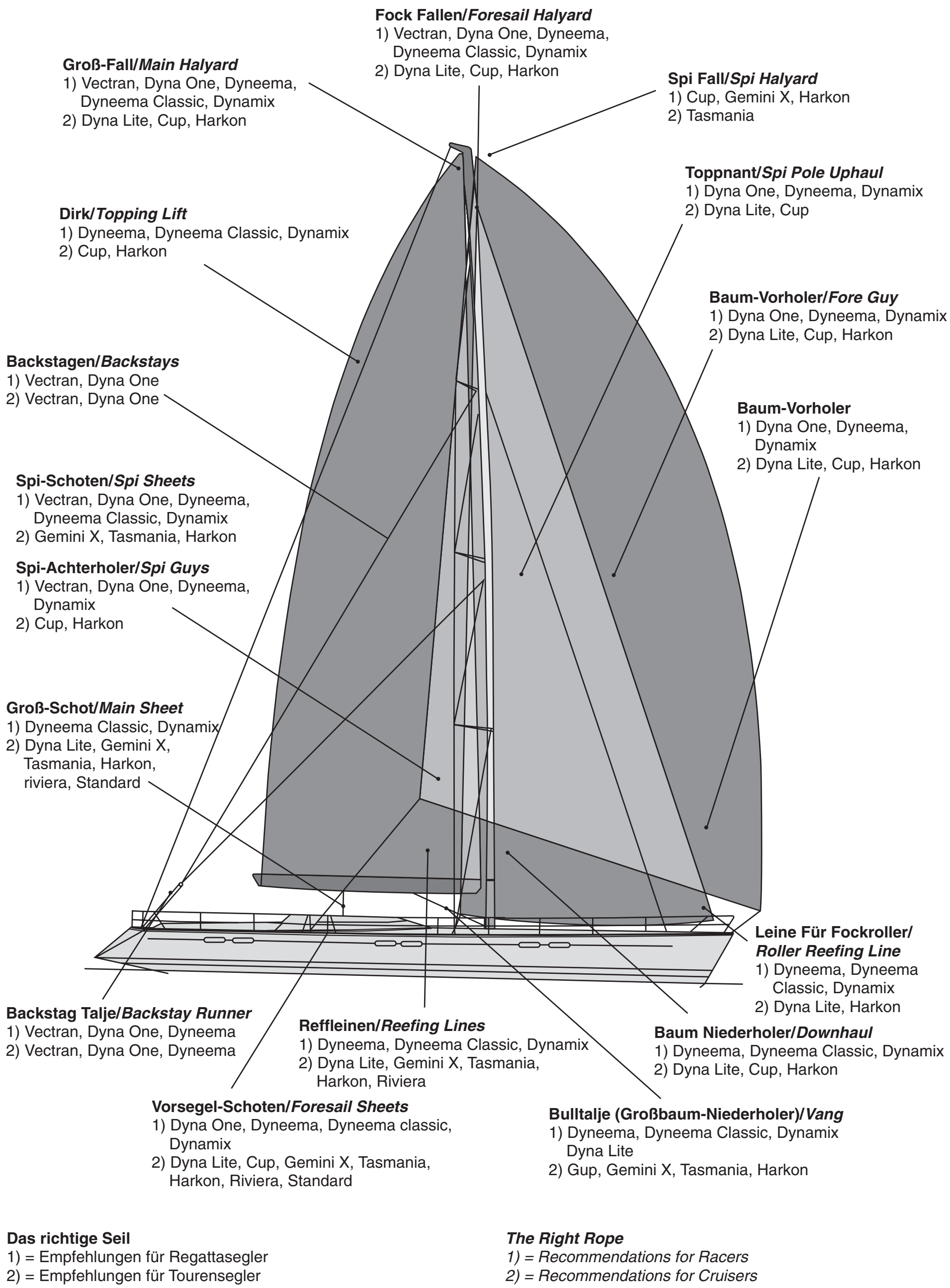


Fig. 12.29 Selecting the right rope. From a brochure by Gleistein of Bremen.

The loss of strength of HMPE with temperature and its low melting point mean that heating due to friction must be avoided. Fusion abrasion can be reduced by copious application of water or other liquids. In areas of contact, additional outer sheaths of plaited polyester may be sewn on, in order to improve handling and life expectancy.

Table 12.7 Break loads and weights for the Gleistein range of ropes for sheets and halyards. The top number is break load (BL) in kN; the second number is linear density (*LD*) *in kg/100 m*. The range goes up in steps of 1 mm diameter from 3 to 6 mm, then in steps of 2 mm to 24 mm. All types are available from 6 to 16 mm. For the 10 mm rope, comparative values are given for break stress (BS) in MPa = MN/M^2, specific strength *(SS) in kN/(kg/m) = mN/tex*, and the sail area (SA) in m^2 for which the 10 mm rope is suitable

Diameter (mm)		Vectran	Dyna One	Dyneema/ Dyneema Classic	Dyna-mix	Dyna Lite	Cup	Gemini X	Tasmania	Harkon	Riviera	Standard
3	BL						1.7					
	LD						*0.7*					
5	BL	10	23	12			6.0		5.0			
	LD	*2.3*	*1.44*	*2.10*			*1.80*		*1.60*			
10	BL	39	85	51	40	30	22	23.5	20	23	20	12.5
	LD	*7.20*	*5.80*	*6.80*	*6.65*	*5.92*	*7.30*	*6.50*	*6.80*	*7.20*	*5.40*	*6.30*
	BS	496	1082	649	509	382	280	299	255	292	255	159
	SS	*542*	*1466*	*750*	*602*	*507*	*301*	*362*	*294*	*319*	*370*	*198*
	SA	40	50	40	40	30	20	30	20	20	20	20
20	BL	145	312	190			85	100	80			
	LD	*32.5*	*24.9*	*28.0*			*26.0*	*29.0*	*29.8*			
24	BL	245	440	255			122.5	145				
	LD	*46.9*	*36.0*	*38.9*			*39.4*	*42.0*				

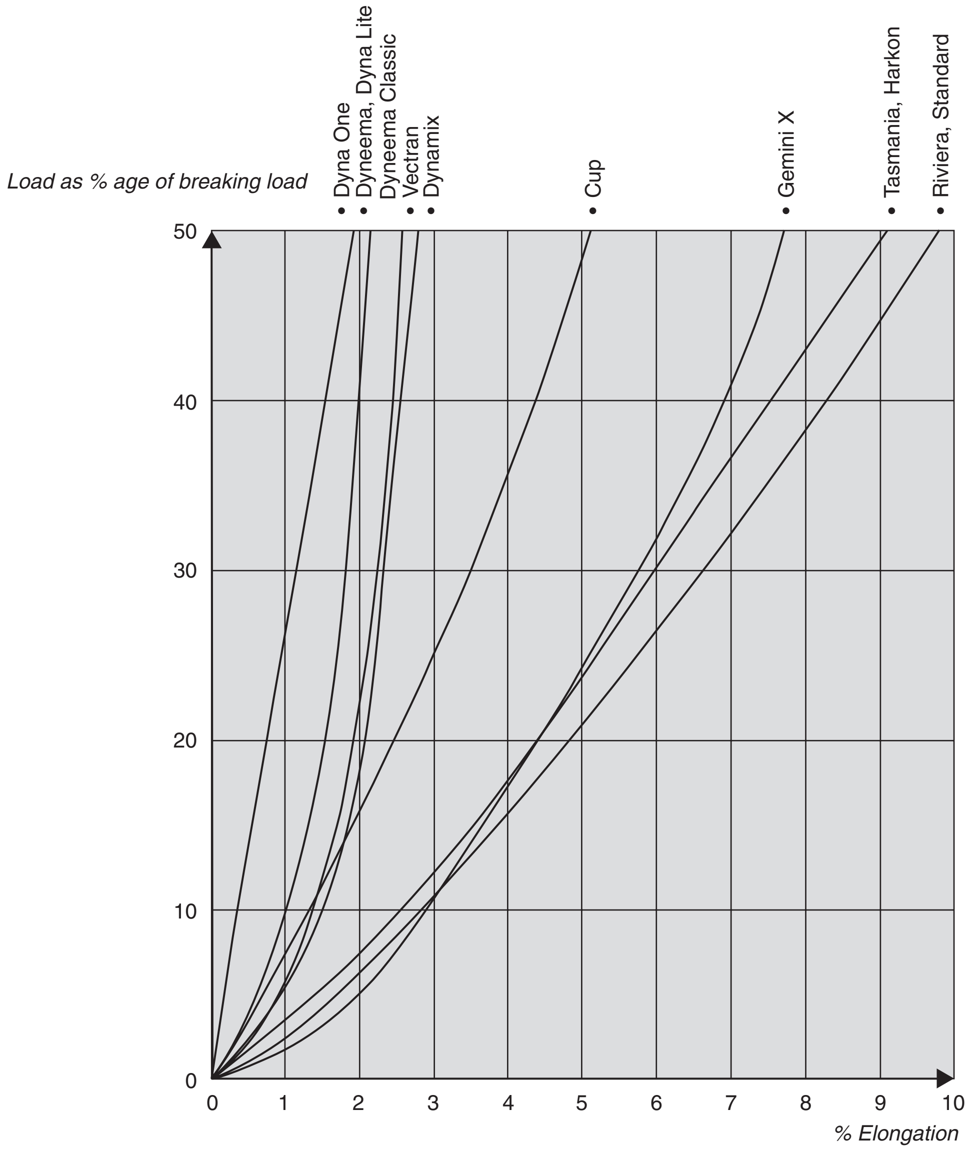


Fig. 12.30 Load–elongation curves of used sheets and halyards from the range produced by Gleistein. 'Used', in this instance, means after average usage under normal weather conditions and is simulated in the laboratory with 10 loadings at 20% of the break load. Taken from a Gleistein catalogue.

The HMPE rope, *Dyneema*, which has a construction similar to Vectran, namely a 12-strand braid of *Dyneema SK 75* within an intermediate cover of staple polyester and an outer cover of filament polyester, is more robust than *Dyna One* but has a lower-strength. *Dyneema Classic* is similar, but has a looser cover to give greater flexibility, easier spliceability, and improved handling at the expense of slightly reduced durability. The creep (non-recoverable stretch) of HMPE fibres means that long-term halyard adjustment may be necessary. The high modulus means that high shock loads will be transmitted to fittings which should be suitably designed or reinforced. In non-critical regions, where abrasion is not a problem, weight can be reduced by removal of sections of outer cover.

Dynamix combines *Dyneema* and aramid fibre in the 12-strand braided core, and is reported to combine the creep resistance of aramid with the flex fatigue resistance of HMPE. The outer cover needs to remain in place to protect the aramid from UV. *Dyna Lite* is a lower-cost rope with a heavier polyester jacket on a smaller *Dyneema* core: the slightly lower strength matches standard fittings.

The other six types are polyester ropes with long life expectancy for cruising yachts. *Cup* has a core of parallel, continuous-filament, high-tenacity polyester, which minimises stretch, an inner braided sheath of coarse synthetic fibre (not present in the more economical *Riviera*), and a polyester outer cover. The parallel core minimises the stretch of a polyester rope and fits these ropes for halyards, but they do not perform well running over blocks. For sheets, the greater flexibility and ease of handling of braided ropes are preferred. The double braid construction (12-strand core and 16, 20 or 24 strand cover) of *Gemini X*, which has a specially coated polyester for higher strength and durability, *Tasmania*, a lower cost rope, and *Harkon*, with a tight cover ideally suited for use on winches, gives equal load sharing between core and cover. *Standard* has a staple polyester cover, which gives a woolly grip to avoid slip when handled.

Another way of comparing ropes is by the rope diameter needed for a given sail area. *Gleistein* give the following formula:

$$\begin{aligned}&(\text{sail surface in m}^2)\times(\text{wind velocity in knots})^2\times 0.021\\&\quad=\text{power in daN}\times 5=\text{breaking force}\end{aligned}\qquad[12.7]$$

Comparative values of sail areas appropriate to the 10 mm ropes are included in Table 12.7. Steel halyards are about half of the diameter of the HMPE ropes and a third of that of the polyester ropes, but are much heavier.

In addition to their use in sheets and halyards, *Dyneema*, *Dyneema Classic*, *Cup*, *Gemini X*, *Tasmania*, and *Harkon* are all described by *Gleistein* as universal ropes ideal for guys, up/downhauls, reefing lines, Vangs and Cunninghams. (The Vang, also the Boom Vang, is a device that holds the boom down. It usually consists of a pulley at the foot of the mast and a pulley at the mid-line of the boom with a rope between them that pulls the boom down when the sail is luffing and tending to pull the boom up. Sometimes, on larger boats, this is a hydraulic device. The Cunningham puts tension on the luff, the length of mainsail that runs along the mast, to pull it tight or loosen as sailing direction dictates. The rope passes through a grommeted hole in the sail and is taken back to a fixing point.)

For mooring lines, the requirements are different. Properties of the range of *Gleistein* ropes are shown in Table 12.8 and Fig. 12.31. Note that the elongations at 50% of break load are at a higher range than the ropes in Fig. 12.30, reaching over 20% extension. *Polyester mooring line* is either a three-strand twisted rope or a four-strand square braid, which cannot kink. *Bavaria* has a 12-strand polyester core in a braided polyester cover. *Polyamide mooring line* has similar constructions to *polyester*, but has lower modulus and outstanding elasticity. *Geolon* has similar constructions in polypropylene. *Hempex* is a three-strand twisted rope made from hemp-coloured polypropylene staple spun, so that it simulates a traditional hemp

Table 12.8 Break loads and weights for the Gleistein range of ropes for mooring lines. The top number is break load (BL) in kN; the second number is linear density (*LD*) *in kg/100 m*. The range goes up in steps of 2 mm diameter from 6 to 32 mm, then in steps of 4 mm to 40 mm. *Bavaria* is available only from 6 to 20 mm. For the 10 mm rope, comparative values are given for break stress (BS) in MPa = MN/M^2, specific strength *(SS) in kN/(kg/m) = mN/tex*, and the length of the vessel (LV) in metres for which the 10 mm rope is suitable

Diameter (mm)		Polyester	Bavaria	Polyamide	Geolon	Hempex
6	BL	5.8	8.3	*7.35*	5.9	3.55
	LD	*3.0*	*2.6*	2.25	*1.7*	*1.6*
10	BL	16.8	20	20.4	15.3	9.0
	LD	*8.1*	*6.8*	*6.2*	*4.5*	*4.3*
	BS	496	254	259	195	114
	SS	*297*	*294*	*329*	*340*	*209*
	LV	6	8	8	*	*
20	BL	68.2	80.0	81.4	57.0	34.2
	LD	*32.0*	*29.8*	*24.5*	*18.0*	*16.0*
30	BL	147		174	125	73
	LD	*72.0*		*55.5*	*40.5*	*35*
40	BL	257		294	220	129
	LD	*128*		*99*	*72*	*62.3*

* 12 mm rope for 6 m vessel

rope, but has higher strength. In the USA, polyamide for mooring lines seems to be the most popular amongst the more serious sailors. Failures most commonly occur at fittings or especially at the chock on the vessel. Chafing gear is important. Wetting and drying from salt water is particularly damaging.

In order to complete their service to modern yachting, Gleistein make a range of general and sail-makers' cords, trim lines, leechlines and bolt ropes, which range in diameter from 1 to 10 mm. These are 8- or 16-plait braided cords in HMPE, polyester, nylon, and polypropylene. (Leechlines are used to fix the sail to the yard, and a bolt rope is sewn into the hem of a sheet to provide a ridge that can be retained in a slot.)

Another range is the Gleistein *Classics*, intended for use on older style, traditional vessels. *Hempex* is available in three-strand twisted or eight-strand braided polypropylene ropes. *Thempest* is a three-strand twisted rope made from a blend of dyed polyester and fibrillated polypropylene. The same blend is used in *Thempest Combi* to encase wire strands in a six-strand laid rope, which couples the properties of a wire rope with the convenient handling of a fibre rope. *Cup T* has a bronze polyester braid over the *Cup* construction described previously. *Fendex* is made of 12 *Hempex* strands braided over a wire rope core. These ropes are aimed at users looking for traditional rope, but 'the use of modern fibres [which give superior performance] does not mean a compromise in terms of appearance or handling'.

This case study demonstrates the diversity of rope products that have been developed for a single market. The range of products addresses the various demands of

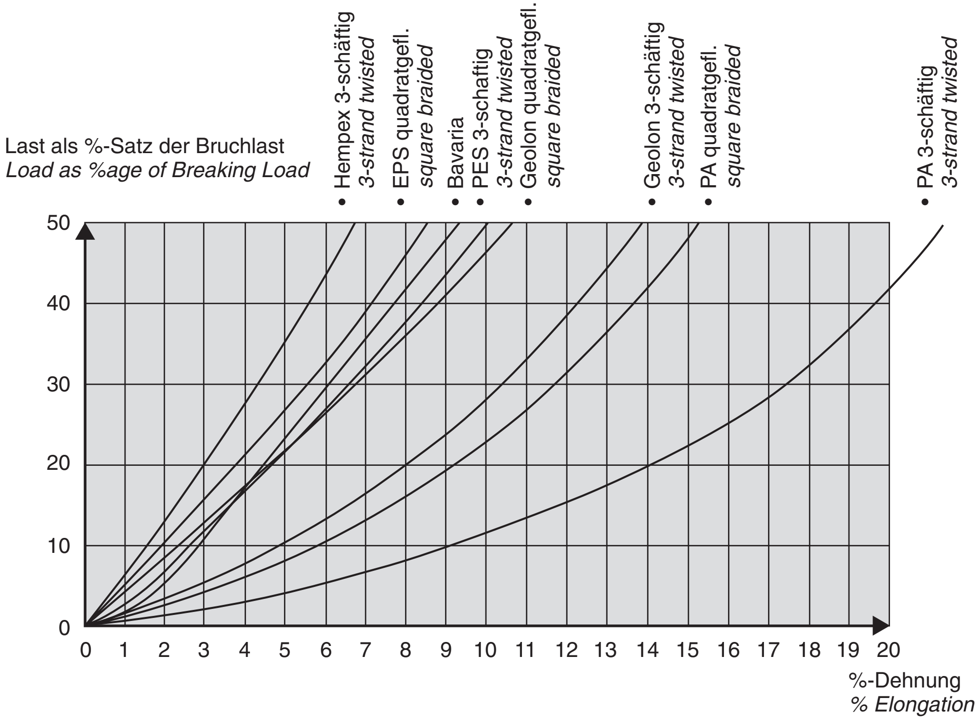


Fig. 12.31 Load–elongation curves of used mooring lines from the range produced by Gleistein. 'Used', in this instance, means after average usage under normal weather conditions and is simulated in the laboratory with 10 loadings at 20% of the break load. Taken from a Gleistein catalogue.

the different factions on a sail boat, cost and the fickleness of boat owners. In addition, it is interesting to note that all this is possible because of the variety of fibre materials and rope constructions that are available today.

12.12 Mussel ropes

The fishing industry is a major user of ropes in ship handling operations and in deploying nets. The nets themselves are made of cordage – and 'ropes and nets' are commonly placed in the same category of trade statistics. As is the rule for rope uses, strength, weight, extensibility, flexibility, durability and cost are the principal defining requirements for these fishing ropes, cords and twines.

However, there are exceptions to every rule. We conclude our case studies – and this book – with a use that has minimal mechanical demands, but has to provide the right environment for the growth of a living organism. New Zealand green-lipped mussels are the finest in the world and both a domestic industry and an export industry have grown up. Farming of the mussels had to be organised and this was done by suspending ropes on which the mussels could grow, in pairs from a frame. The essential requirement is thus that the ropes should be of the right size and surface

Fig. 12.32 Mussel ropes. From Donaghys, New Zealand.

character to suit the mussels. The ropes will easily fall within any strength or extensibility requirements. One mechanical property that is relevant is that the ropes should be torque-balanced so that, when handled properly, the pairs of ropes do not twist up when the they are pulled up to remove the mussels. Figure 12.32 illustrates the use of mussel ropes.

Appendix I

Quantities and units

Rope dimensions

The quantities and units used to describe dimensions and properties of fibres, yarns, cords and ropes have a diversity based on technical, historical and cultural factors. This Appendix describes the factors involved and provides guidance for inter-conversion.

The basic problem is that yarns and ropes contain open spaces within their structure. The area of cross-section is thus an ill-defined measure. Is it the sum of the areas of fibre cross-sections or the 'total area' of the yarn or rope? Furthermore, the boundaries are often poorly defined, so that the total area, the diameter and the circumference are uncertain quantities. Even for solid fibres, the lateral dimensions are so small that they are difficult to measure. This means that the conventional engineering quantities based on area or diameter are indefinite dimensions, though they need to be used in some applications and, for ropes, the circumference is an easy quantity to measure by wrapping a string round the rope.

The traditional *rope size number* was a satisfactory measure of rope circumference as long as there was little variation in rope types. The ASCE Glossary (1993) has the following definition:

> *A traditional nominal designation of the rope size. By marine industry practice, Rope Size Number is expressed as a dimensionless number, which corresponds to the measurement in inches taken by wrapping a tape around a three-strand rope having the same weight per unit length as the subject rope. Note*: *Because of differences in rope cross section geometries and rope densities, this measurement is not the actual circumference of the rope. General practice is to multiply Rope Size number by 8 to convert to the nominal diameter in* miilimetres *and to divide size number by 3 to convert to the nominal diameter in inches. Caution*: *Other systems of numbers are sometimes used to designate rope size in other industries.*

Table I.1 gives conversions for nominal rope diameters and circumferences.

Unless drastic changes occur, the mass of any given piece of rope is invariant, whereas its volume can change as packing factors alter. For fibres, yarns and ropes, the linear density, namely, the mass per unit length, is therefore the best way of characterising the size. This is often referred to as the *rope weight*. Historically, there are many units for yarn linear densities, i.e. direct (mass per unit length) units. There are also indirect (length per unit mass) counts, which derive from the number of hanks of a given length of yarn making a certain weight. The manufactured textile fibre industry adopted the silk unit of *denier*, but later a rational metric unit, *tex* (gram/kilometre), which is accepted by SI, was introduced and is now the preferred form. Because of the similarity in magnitude to denier, the sub-unit *decitex*

Table I.1 Metric/US size conversion

Nominal diameter (mm)	**Nominal circumference* (inches) (Size number)**	**Nominal diameter** (inches)**
6	–	$^1/_4$
8	1	$^5/_{16}$
10	$1^1/_8$	$^3/_8$
12	$1^1/_2$	$^1/_2$
14	$1^3/_4$	$^9/_{16}$
16	2	$^5/_8$
18	$2^1/_4$	$^3/_4$
22	$2^3/_4$	$^7/_8$
24	3	1
28	$3^1/_2$	$1^1/_8$
32	4	$1^5/_{16}$
36	$4^1/_2$	$1^1/_2$
40	5	$1^5/_8$
44	$5^1/_2$	$1^3/_4$
48	6	2
52	$6^1/_2$	$2^1/_8$
56	7	$2^1/_4$
60	$7^1/_2$	$2^1/_2$
64	8	$2^5/_8$
72	9	3
80	10	$3^1/_4$
88	11	$3^1/_2$
96	12	4
104	13	$4^1/_4$
112	14	$4^1/_2$
120	15	5
128	16	
136	17	
144	18	6
152	19	
160	20	
168	21	7
176	22	
192	24	8
216	27	9
240	30	10

* Nominal circumference in inches is also known as 'size number' and used mainly in the marine industry for size 6 and above.
** The conversion is not exact, but the list reflects industry accepted values.

(*dtex*) is widely used. For large ropes, the convenient unit is kg/m. For smaller ropes, kg/100m or lb/100ft are commonly used. The relations between these units are:

$$\text{tex} = \text{g/km}$$

$$\text{Megatex} = \text{kg/m}$$

$$\text{decitex} = 0.1\ \text{g/km (gram per 10000 metre)}$$

$$\text{denier} = \text{gram per 9000 metres} \qquad 1\ \text{denier} = 0.11\ \text{tex} = 1.1\ \text{dtex}$$

$$1\ \text{lb/100 ft} = 1.488\ \text{kg/100 m}$$

Table I.2 Unit conversions

Specific stress			Stress (density in g/cm³ times)		
1	–	N/tex, kJ/g, GPa/g cm^{-3}, (km/s)^2	1	–	GPa, J/mm^3
	–	10 cN/dtex, 10.2 gf/dtex, 11.3 gf/den		–	
	–	102 gf/tex, kmf, kgf mm^{-2}/g cm^{-3}			
		239 cal/g, 430 Btu/lb		–	102 kg/mm^2 145 ksi
10^3	–	mN/tex, J/g, MPa/g cm^{-3}	10^3	–	MPa, N/mm^2
	–			–	10^4 bar, 9869 atm
	–	145 000 psi/g cm^{-3}		–	145 000 psi (= lbf/in^2)
*10^6	–	N/kg m^{-1}, J/kg, Pa/kg m^{-3}	10^6	–	
	–	3.94×10^6 inchf, psi/(lb/cu in)		–	7.5×10^6 mm Hg
	–			–	
10^9	–		*10^9	–	Pa (= N/m^2), J/m^3, kg m^{-1} s^{-1}
	–	10^{10} dyn/g cm^{-1}, erg/g		–	10^{10} dyn/cm^2

* strict SI units
Other multiples are also used.
Gravitational units, written above as gf etc, are also found in forms such as: g, e.g. g/den, gm, or g-wt; lb or lb-wt; km, km-wt or Rkm.

The following is a typical set of values for a three-strand polypropylene rope as given in an American Group catalogue: diameter 1 inch, 24 mm; circumference 3 inch, 72 mm; weight 17.7 lb per 100 ft, 26.3 kg per 100 m. There is clearly a degree of approximation, because a diameter of 1 inch would give a circumference of π (3.142) inches. Circumference scales linearly with diameter but weight will scale as the square of diameter. Due to differences in fibre density and packing factor, other ropes will have slightly different weights for the same diameter.

Stress and specific stress

The diversity becomes enormous when covering stress, modulus and tenacity. Firstly, either volume or mass measures may be used. In physics and engineering, stress is defined as force/area. Because of the uncertainty of the area of cross-section of yarns, cords and ropes, and for solid fibres the ease of measurement of linear density, the use of specific stress, namely force/(linear density) is preferred. It is then easy to compare the conversion of properties from molecules to fibres to yarns to ropes: at all levels if the mass is known.

Secondly, gravitational force units, often abbreviating g-wt or gf to g or gm, may be used instead of the physically correct inertial units. Thirdly, quantities that are dimensionally identical can be defined and used in different ways. Fourthly, there is a choice of unit systems: CGS or SI metric units or the old British Imperial units, which are still widely used in USA. It is not uncommon to find mixtures, such as psi/(g/cm^3).

The preferred unit for specific stress, specific modulus and tenacity (specific strength)* is N/tex. Expressed in other ways, this equals stress/density in GPa/(g/cm^3) and energy per unit mass in kJ/g. The modulus in N/tex equals the wave velocity in (km/s)^2. Strength can also be expressed in terms of break length, namely the length of material that will break under its own weight. Kilometer-force is most used, but brochures of one fibre manufacturer give strength in inches. Finally, for the first 50 years of manufactured fibres the common unit was g/den. Because of the similarity in size, the use of cN/dtex, equal to 1.13 g/den, is common.

Table I.2 gives the conversion factors between the above units and many others, which may be found in the literature or used in particular contexts.

* Note that some American sources use *tenacity* to mean *specific stress*, but this is an undesirable usage.

One preferred usage is to define elongation as actual increase in length, extension as percent increase and strain as fractional increase. However, these three terms are often used interchangeably. The ASCE glossary (1993) defines *elongation* as 'quasi-permanent change in length' and *extension* as 'change . . . which is recovered', but this is not a distinction that would be commonly recognised.

Rope size and mechanical properties

For ropes as a whole, the following relations apply:

- rope area = rope linear density/rope density
- rope density = fibre density × packing factor
  where packing factor = fraction of rope cross-section occupied by fibre
- rope linear density = (number of yarns in rope) × (yarn linear density) × (contraction on rope formation)
- total rope mass (weight) = rope linear density × rope length

For a length of rope in use, the important mechanical quantities, both having units of force, are:

- break load, usually expressed in tonnes, equal to 1000 kilogram-force or 9807 (roughly 10 000) Newtons
- axial stiffness = tension/strain = tension/(elongation/initial length). This is also called spring constant, and, in engineering, referred to as AE, where A = area and E = modulus, or KL, where K = elastic spring coefficient (force per unit length extension) and L = length of spring.

The normalised properties are best expressed in terms of rope linear density. Although other units may be used, as discussed above, the relevant quantities are:

- stress = tension/area, preferably in MPa
- specific stress = tension/(linear density), with MN/(kg/m) equal to N/tex
- strain = increase in length/length
- strength = break load/area, typically in MPa
- specific strength = force/(linear density), with MN/(kg/m) equal to N/tex
- modulus = stress/strain = axial stiffness/area, in MPa or GPa
- specific modulus = specific stress/strain = axial stiffness/(linear density), in N/tex

These definitions lead to the following relations:

$$\begin{aligned}&\text{rope break load in MN } (\approx 100 \text{ tonne})\\&\quad = \text{rope weight in kg/m} \times \text{specific strength in MN/(kg/m) or N/tex}\\&\quad = \text{rope weight in kg/m} \times \text{fibre tenacity in N/tex}\\&\qquad \times \text{strength conversion efficiency (fractional)}\end{aligned}$$

There are analogous relations for stiffness.

Appendix II

Braid and plait terminology

There are many, often contradictory definitions of braid and plait (and associated terms such as braided, braiding . . . plaited, plaiting . . .). The following is our preference:

Braid: A material in which yarns or strands, which run along the length of the structure, are interlaced in a quasi-woven form. In all rope braids except 'solid braids', *q.v.*, two sets of yarns run in opposing angles (in 3D braids, used in composite reinforcement, there are more sets of yarns).

Plait: A sub-set of braids with a limited number of yarns and strands, which pass through the centre of the structure. The simplest example is the three-strand plait, made by hand, to plait hair or to make decorative cords.

The following particular definitions are relevant to ropes:

Flat braid: A braid in which carriers move backwards and forwards across the width of the structure. Used as webbings. Contrast with *circular braid*.

Circular braid: A braid in which carriers move in opposite directions around circumferential paths. Contrast with *flat braid*.

Hollow braid: Used as a specific term for a circular braid with a central hole, through which the strands do not pass. In actuality, with a limited number of strands, the braid collapses under tension to give a notional hole in a solid structure. With a large number of strands, the circular braid will have a true central hole, but it can be flattened to close the hole.

Single braid: Alternative name for a hollow braid.

Solid braid: Used as a specific term for a braid in which all the strands rotate in the same sense as they interlace from the inside to the outside of the braid. *Note*: Under tension, plaits and hollow braids with a limited number of carriers may be geometrically solid.

Eight-strand plait: A plaited rope with eight strands running as two pairs in one direction and two pairs in the opposing direction.

Eight-strand braid: A braided rope with eight strands running singly, four in each direction, to give a single, hollow braid.

Twelve-strand braid: A braided rope with twelve strands running singly, six in each direction, to give a single, hollow braid.

Double braid: A rope in which a core braid is surrounded by a cover braid, with both taking a substantial fraction of the load. Also called *braid-on-braid.*

Braid-on-braid: Alternative name for *double braid.*

The *ASCE Glossary* (1993) contains a number of conflicting definitions:

Braiding:

(i) The process of forming a braided rope structure, as distinct from an 8-strand or plaited rope structure.
(ii) Plaiting is sometimes distinguished from braiding by the preservation of original yarn lay length. By this distinction, in the process of braiding, the lay length of the yarns within the strands are altered.
(iii) Alternatively, plaiting is sometimes distinguished from braiding by the creation of a structure in which strands pass through the centre. By this distinction, braiding forms a structure with a hollow centre.
(iv) The process of interbraiding three or more strands such that they cross one another in diagonal formation. In this sense, braiding and plaiting are the same.
(v) The process of intertwining sets of yarns or strands according to a definite pattern by a maypole process.

Plaiting:

(i) The process of forming an 8-strand rope.
(ii) The process of braiding strands together such that their original strand-yarn lay length is preserved.
(iii) The process of interbraiding three or more strands such that they cross one another in diagonal formation.
(iv) The process of forming a rope structure in which the strands pass through the centre.
(v) Generally synonymous with braiding, but some manufacturers make distinctions between these processes.

Appendix III

UK trade data

Table III.1 is taken from the UK National Statistics: *PRODUCT SALES AND TRADE PRQ 17529 Cordage, Rope, Twine & Netting, Quarter, 1 2003*. This is available on the web (conveniently accessed through www.statistics.gov.uk – search 'twine'). The data for the four quarters of 2002 have been amalgamated in the Table. The total UK manufacturing sales of products in this industry (including netting) was over £86 000 000 ($130 000 000).

The figures under 'sales' are for UK Manufacturer Sales. The other columns are listed in PRQ 17529 as *Intra EC Exports and Imports* and *Extra EC Exports and Imports*. CN numbers are used in US data.

The following aspects of the data are noteworthy:

- More than half the manufacturing value of the whole industry is in the larger synthetic fibre ropes.
- The range of prices is from less than £1/kgm to over £15/kgm ($1.5 to $22/kgm). For individual products within the categories the range may be greater.
- With one exception, which is based on small quantities, export prices are all higher than import prices – in some categories over ten times greater. This reflects the sourcing of cheaper commodity products from lower cost countries in the EC or elsewhere and the manufacture and export of higher value products.
- Although these are UK data, they reflect the trends of the trade in developed countries.

Table III.1 UK trade data (The PCC and CN numbers are from two alternative classification systems)

Sales	VALUE (£1000s)				VOLUME (tonnes)				PRICE (£ per kg)			
	Export		Import		Export		Import		Export		Import	
	EC	other	EC	other	EC	other	EC	other	EC	other	EC	other
PCC 17521133 (CN 560710+56072910+56079010) Twine, cordage, rope and cables of sisal or other textile fibres of the genus Agave measuring more than 100 000 decitex (10 g/m), of jute or other textile bast fibres and of abaca or other hard (leaf) fibres EXCLUDING: – binder or baler twine												
2699	998	1164	356	388	806	224	345	473	1.37	4.78	1.05	0.82
PCC 17521135 (CN 56072990) Sisal twine measuring 100 000 decitex (10 g/m) or less EXCLUDING: – binder or baler twine												
0	39	188	116	94	230	99	119	114	0.18	1.91	0.99	0.95
PCC 17521153 (CN560721) Sisal binder or baler (agricultural) twines												
0	4	336	234	48	0.7	75	359	153	9.13	5.44	0.91	1.11
PCC 17521155 (CN 560741) Polyethylene or polypropylene binder or baler (agricultural) twines												
n/a	562	185	2370	544	737	90	3427	294	0.77	3.46	0.69	1.96
PCC 17521160 (CN 56074911+56075011+56075019+56075090) Cordage, ropes and cables, of polyethylene, polypropylene, of nylon or other polyamides or of polyesters, measuring more than 50 000 decitex (5 g/m), and of other synthetic fibres EXCLUDING: – binder or baler twine												
44220	4359	7498	6736	2864	1061	1184	3020	2002	4.02	6.37	2.27	1.53
PCC 17521170 (CN 56074990+56075030) Twines of polyethylene or polypropylene, of nylon or other polyamides or of polyesters measuring 50 000 decitex (5 g/m) [or less] EXCLUDING: – binder or baler twine												
2331	470	213	1314	482	34	35	917	180	15.33	14.71	1.48	1.83
PCC 17521190 (CN 56079090) Twines, cordage, rope and cables of textile materials EXCLUDING: – jute and other textile bast fibres – sisal – abaca or other hard leaf fibres – synthetic fibres												
1204	640	1196	445	3875	43	111	314	2005	15.48	11.50	1.43	1.32

Appendix IV

The theory of backtwist

If a yarn of diameter d is stranded round a core of diameter D without backtwist, one side of the yarn will always touch the core and the other side will always face away from the core. (The theory is described in terms of yarns being twisted into strands, but applies equally to strands being twisted into ropes.) As shown in Fig. IV.1, the paths taken by these two faces of the yarn are S_i and S_o (inner & outer). S_i is the face that always touches the core.

For the yarn to be torsion free, both these faces should have the same length S'. This means that there must be some twist during stranding and no one face will always touch or face away from the core. This is represented by S'. The twist angle is the twist in the yarn expressed in radians per lay length.

$$S' = \frac{1}{2}(S_i + S_{\mathrm{o}}) \qquad \text{[IV.1]}$$

and

$$S' = \sqrt{\left(S^2 + \frac{\Psi^2 \cdot d^2}{4}\right)} \qquad \text{[IV.2]}$$

where d is the yarn diameter

$$S_i = \sqrt{\left(\pi^2 \cdot D^2 + L^2\right)} \qquad \text{[IV.3]}$$

where D is the core diameter and L is the lay length

$$S = \sqrt{\pi^2 (D+d)^2 + L^2} \qquad \text{[IV.4]}$$

where S is the yarn length per lay length measured from the centre of the yarn i.e. the the yarn length at the pitch circle diameter

$$S_0 = \sqrt{\pi^2 (D+2d)^2 + L^2} \qquad \text{[IV.5]}$$

Substituting Equations [IV.3] and [IV.5] in Equation [IV.1] we have:

$$S' = \frac{1}{2}\left(\sqrt{\left(\pi^2 \cdot D^2 + L^2\right)} + \sqrt{\pi^2 \cdot (D+2d)^2 + L^2}\right) \qquad \text{[IV.6]}$$

Substituting Equation [IV.4] in Equation [IV.2] we have:

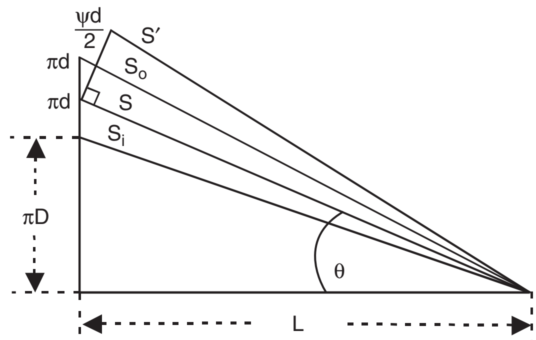


Fig. IV.1 Diagram of yarn paths.

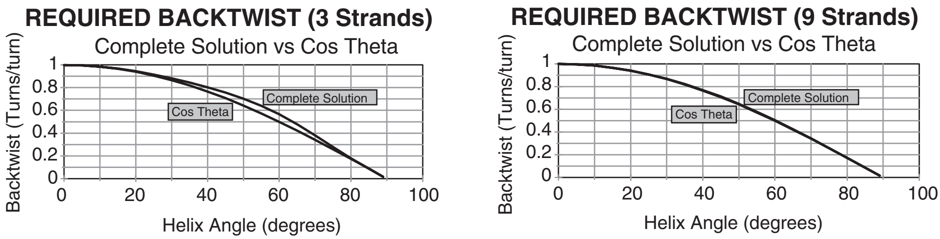


Fig. IV.2 Backtwist solutions.

$$S' = \sqrt{\left(\pi^2(D+d)^2 + L^2 + \frac{\Psi^2 d^2}{4}\right)} \qquad \text{[IV.7]}$$

where ψ = backtwist/lay length in radians/lay length
Dividing Equation [IV.6] and Equation [IV.7] through by L (where L = lay length)

$$\sqrt{\frac{\pi^2(D+d)^2}{L^2} + 1 + \frac{\Psi^2 d^2}{4L^2}} = \frac{1}{2}\left(\sqrt{\frac{\pi^2 D^2}{L^2} + 1} + \sqrt{\frac{\pi^2(D+2d)^2}{L^2} + 1}\right) \qquad \text{[IV.8]}$$

But

$$\tan\theta = \frac{\pi(D+d)}{L} \qquad \text{[IV.9]}$$

Therefore

$$\sqrt{\tan^2\theta + 1 + \frac{\Psi^2 d^2}{4L^2}} = \frac{1}{2}\left(\sqrt{\left(\tan\theta - \frac{\pi d}{L}\right)^2 + 1} + \left(\tan\theta + \frac{\pi d}{L}\right)^2 + 1\right) \qquad \text{[IV.10]}$$

Let

$$\sqrt{\left(\tan\theta - \frac{\pi d}{L}\right)^2 + 1} = F_1 \qquad \text{[IV.11]}$$

and let

$$\sqrt{\left(\tan\theta + \frac{\pi d}{L}\right)^2 + 1} = F_2 \qquad \text{[IV.12]}$$

Thus, substituting in Equation [IV.10], we have

$$\tan^2\theta + 1 + \frac{\Psi^2 d^2}{4L^2} = \left(\frac{F_1 + F_2}{2}\right)^2 \qquad \text{[IV.13]}$$

Then

$$\Psi^2 = \frac{4L^2}{d^2}\left[\left(\frac{F_1 + F_2}{2}\right)^2 - 1 - \tan^2\theta\right] \qquad \text{[IV.14]}$$

$$\Psi = \frac{2L}{d}\sqrt{\left(\frac{F_1 + F_2}{2}\right)^2 - 1 - \tan^2\theta} \qquad \text{[IV.15]}$$

$$\text{Required backtwist} = \frac{\Psi}{2\pi}\,\text{Turns/turn} \qquad \text{[IV.16]}$$

This closely approximates to

$$\text{Required backtwist} = \cos\theta$$

The two solutions are always very close and coincide almost exactly with 9 or more strands as shown in Fig. IV.2.

It would be possible to make a strander with variable backtwist but to date these machines are either rigid cage with no backtwist or planetary where the backtwist is one turn per machine turn.

The authors would like to express their thanks to Phil Roscoe of JDR Cable Systems for his considerable help in developing this theory.

Glossary

There are differing interpretations for the meaning of many terms found in this glossary. The intent is to harmonise, within this handbook, the definitions based on common usage in the rope industry as opposed to what may be found in the textile field or other technical disciplines. Additionally, in defining force, stress, elongation, strain, and the normalisation of some of these properties, it is essential that the definitions correspond to the theory as it is presented.

The definitions given here are our guide to the meanings of the various terms. Some are taken from lists published by ASCE (1993), ASTM (1993a), Cordage Institute (1996) [CI], The Engineers' Design Guide (TTI and Noble Denton, 1999) [EDG], The Textile Institute [TI] (Denton and Daniels, 2002), and Hoechst Celanese (1989) [HC].

Angle of lay: The angle at which the strands lie in relation to the axis of the rope. Also called *helix angle*, particularly for fibres in yarns and yarns in strands.
Area, fibre: The cross-sectional area based on the area of the filaments. Eq. [4.6].
Area, rope: The cross-sectional area based on the area determined from the measured or nominal diameter or circumference of a rope.
Axial stiffness: Normalisation of the property of extensibility. Tension/strain, (N). Also, slope of the tension vs. strain curve. See Sections 4.3.2 and Appendix I.
Backtwist: A process that removes twist in rope components that is added when plying these components into a larger structure. See Section 6.1.3.
Bedding in: A tightening of the rope structure, which causes an increase in length, under application of tension for a number of cycles after manufacture. [EDG]
Birdcage: The appearance of a rope in which the outer strands have been flared outward due to torque or avail compression, usually caused by sudden release of load. [ASCE]
Braid: A rope structure formed by interlacing of the strands. See Appendix II.
Braid, double: A rope with a hollow braided core and a hollow braid cover (sheath) where both share the load. Also known as braid-on-braid. See Appendix II.
Braid, hollow: A cylindrical braid in which each strand rotating in one direction alternately passes under and over one or more strands rotating in the opposite direction in a maypole fashion. See Appendix II.
Braid, single: See 'braid, hollow'.
Braid, solid: A cylindrical braid in which each strand alternately passes under and over one or more of the other strands of the rope while all strands are rotating around the axis with the same direction of rotation. On the surface, all strands appear to be parallel to the axis. See Appendix II. [CI]

Braid-on-braid: See 'braid, double'.
Break load: The actual force required to rupture a specific rope specimen. This may apply to the mean or average obtained from a number of specimens. Also called 'break force' or 'break tension'.
Breaking length: The length that will cause a rope to reach its breaking strength when suspended under its own weight. Eq. [4.10].
Breaking stress: Break load divided by fibre area. Eq. [4.5]. See Appendix I.
Cable laid rope: A rope formed by three or more ropes twisted to form a helix around the same central axis. The ropes that become the secondary strands are '*S*' lay and the finished cable is '*Z*' lay, or *vice versa*. [TI]
Construction: For rope, the geometrical arrangement of strands that defines the type of rope.
Contraction factor: A factor to account for the difference in yarn length compared to the rope length due to the helical path of the yarn. See eq. [4.1a] and [4.16].
Cord: A rope construction that is less than 4 mm in diameter.
Cycle length (braid): The length along the axis of a braided rope in which a strand makes one complete spiral around the axis.
Design factor: A number that is to be divided into the rated, preferably minimum, strength of a rope to allow a meaningful margin of safety (Section 8.2.2). See 'Working load limit'.
Dynamic loading: A rapid application of load that causes the force applied to the rope to significantly exceed the static or slowly applied load. The normal response characteristics of the rope are unchanged. Compare 'Shock loading'.
Elasticity: The property of a material by virtue of which it tends to recover its original size and shape immediately after removal of the force causing deformation. Compare 'extensibility'. [ASTM D 123]. [HC]
Elongation: The axial deformation caused by a tensile force measured in units of length but sometimes as a percentage of the original length. [HC]
Elongation, elastic: Axial deformation that is immediately recovered upon removal of the load.
Elongation, percent: The axial deformation caused by a tensile force reported as a percentage of the original length.
Elongation, permanent: Axial deformation that is not recovered upon removal of the load.
Elongation, recoverable: Axial deformation that is slowly recovered upon removal of the load.
Extensibility: The property by virtue of which a material can undergo extension or elongation following the application of sufficient force. Compare 'elasticity' ASTM D 123.
Extension: Commonly as a percentage and used interchangeably with elongation. See Appendix I.
Fatigue: Progressive damage by any mechanism caused by cyclic loading or long-term static loading.
Finish, marine: A finish applied to fibre intended for rope to improve its durability when used wet. It may be either a spin or over finish.
Finish, over: A lubricant or coating applied to a fibre over the spin finish after initial production to improve its properties.
Finish, spin: A lubricant or coating applied to a fibre during production. It may be selected to suit a particular application, such as rope.
Force: A physical influence exerted by one body on another which produces acceleration of bodies that are free to move and deformation of bodies that are not free to move. [ASTM-D-123]. Used for units of physical properties and discussions of mechanics of rope. Compare: 'load'; 'tension'.
Gauge length: A well-marked section of undisturbed rope, normally set at reference tension, that is used as the basis for elongation measurements.
Grommet: A continuous loop of rope produced by an end-to-end splice.
Hard laid rope: A rope in which the length of lay of the strands and/or the rope is shorter than usual, resulting in a stiffer and less flexible rope.
Hardness: Three strand laid rope can be made soft or hard depending of the degree of twist. The measure of this is known as hardness.
Hawser laid rope: A rope of three strands which are twisted to form helixes around the same central axis. [TI]

Helix angle: See 'Angle of lay'.
High-modulus: Applies to rope constructed from fibres with tenacity of not less than 1.3 N/tex (15 gms/denier) that yield rope breaking elongation in the order of 3% to 8%. Fibres are aramid, HMPE etc.
Hockle: Occurs in laid ropes when torque causes a loop to form in a rope. When pulled tight under tension, it causes permanent damage.
Hysteresis: Energy lost between loading and unloading cycles.
Kernmantle: A rope with a core of parallel yarns or lightly twisted rope yarns as strength member and with a tightly braided hollow braided jacket.
Kinkbands: Small Z-appearing kinks at the molecular level within fibres or in whole fibres in yarns caused by axial compression.
Laid rope: A rope produced by laying.
Lay: The direction of twist around the axis, right or left hand. In textile usage, right-hand is described as Z and left-hand as S.
Lay length: The length along the axis of a rope or strand in which a strand makes one complete spiral around the axis. Also 'Cycle length'.
Laying: A specialised twisting process whereby rope strands are wrapped around one another such that the original strand lay length is preserved.
Linear density: Mass per unit of length, e.g. kg/m, tex (g/km) or lb/foot (eq. [4.1a,b]. See Appendix I.
Load: An applied force. [ASTM-D-123]. Used extensively in this handbook as it conforms to common nomenclature in the rope industry and is used in discussions involving use of rope. Compare: 'force'; 'tension'.
Load, breaking: The force required to rupture a single specimen expressed in units of force. Compare 'strength, breaking'.
Low-modulus: Applies to rope constructed from fibres with tenacity of no more than 1.0 N/tex (11 gms/denier) that yields rope breaking elongation in the range of 10% to 30%; fibres are nylon, polyesters, polyolefins, etc. and natural fibres.
Modulus: Stress divided by (fractional) strain. Strictly for stress on an area basis. Where the context is clear, may be an abbreviation for *Specific modulus* (q.v.). See Appendix I.
Modulus, dynamic: Stress divided by strain under rapid loading, commonly between force limits in cyclic loading.
Modulus, elastic: See Modulus, dynamic.
Modulus, high: See High-modulus.
Modulus, initial: Stress divided by strain taken over the initial, usually linear, part of a stress–strain curve.
Modulus, low: See Low-modulus.
Modulus, secant: Stress divided by strain, taken between two points on a stress–strain curve. The lower value is often assumed to be at zero or reference tension stress.
Modulus, specific: Specific stress divided by (fractional) strain. See Appendix I.
Modulus, tangent: Stress divided by strain, taken from the tangent at a point on the stress–strain curve.
Overloading: Exceeding the working load limit (WLL) or a situation where the load and the way it is applied causes permanent damage.
Packing factor: The area occupied by fibre relative to the area calculated by measured or nominal diameter or circumference (eq. [4.3]).
Plaited: A rope produced by plaiting. See Appendix II.
Plaiting: Braiding with a limited number of carriers, in which strands travel through the centre of the rope. A plait does not have a hollow centre. See Appendix II.
Qualified person: A person who, by possession of a recognised degree or certificate of professional standing, or who, by extensive knowledge, training, and experience, has successfully demonstrated the ability to solve or resolve problems relating to the subject matter and work.
Recoil: The tendency of a fibre rope to snap back violently when it breaks.
Reference tension: A small tension to straighten a rope and tighten the structure to create a base line for elongation measurements. Specifications can be found in various test methods.
Residual strength: See: Strength, residual.

Risers: A flexible bundle of flow lines, tubing and control cables that extends from a floating offshore oil production platform to the seafloor.
Rope: A long, flexible assembly of fibres laid, braided or bundled together to serve as a tensile strength member [ASCE]. By British Standard, cordage greater than 4 mm diameter.
Rope density: Mass per unit volume, usually based on area determined from nominal diameter or circumference. Eq. [4.2].
Rope yarn: A first stage plying by twisting that creates a building block for successive plying to make strands.
Safety factor: See Design factor.
Shock loading: A sudden application of force at such a rate of speed that the rope can be seen to react violently and the normal response characteristics of the rope are changed. Compare 'dynamic loading'.
Size number: A non-dimensional number for designating the size of a rope. It corresponds to the nominal circumference, in inches, of a rope with a range of linear density centred on that circumference.
Snap back: See Recoil.
Soft laid rope: A rope in which the length of lay of the strands and/or the rope is longer than usual, resulting in a more flexible rope that is easily deformed.
Spliceability: See 'spliceable'.
Spliceable: The ability to form eyes in the end of a rope and to join two ends together by conventional splicing techniques.
Splicing: Interlacing or burying strands into a rope structure whereby friction is used to hold these elements so as to form eyes in the end of the rope (eye splice) or join two rope ends together (end-to-end splice). The junction must be secure and retain a high percentage of the rope's strength.
Stabilisation: Cycling of a rope specimen under relatively high tension to remove constructional and other forms of elongation that will not be recovered.
Staple: Fibre elements in short lengths but capable of coherence in a twisted structure.
Stiffness, axial: See Axial stiffness.
Stiffness, bending: The property by virtue of which a rope resists bending. When the context is clear, may be referred to as *stiffness*.
Strain, tensile: Extension under load divided by change in length. Strictly fractional, but may be quoted as a percentage. See Appendix I.
Strand: The largest individual element in the final rope making process.
Strand, multiple: For braids, two or more strands that have been wound onto the same carrier bobbin in parallel and then braided into the rope together; they are treated as a single strand.
Strength: A general term for a property that is a indicator of a particular rope's (or class of rope's) ability to resist rupture from external forces [adopted from ASTM D 123]. Compare 'Strength, specific'; 'Strength, breaking'; 'Load, breaking'.
Strength, breaking: A property that is a measure of a rope's ability to resist rupture expressed in units of force or stress. This should apply to the mean or average obtained from a number of specimens. Compare 'Load, breaking'.
Strength, minimum: A value set below the average or mean breaking strength of a set of rope tests of a specific type and size of rope calculated in accordance with a defined statistical procedure. Example: two standard deviations below the mean.
Strength, residual: The strength remaining after use. It may be estimated or determined by a destructive test.
Strength, specific: Break load divided by linear density. Eq. [4.7]. Also called *tenacity* (q.v.).
Stress: Force divided by area. Two definitions may be commonly encountered:

1. The tension divided by the fibre area, N/mm^2.
2. The tension divided by rope area based on a measured or nominal diameter, N/mm^2.

Stress, breaking: Break load divided by fibre area. See Appendix I.
Stress, specific: The normalised measure of resistance to elongation within a rope. The tension divided by the linear density N/(kg/m). The preferred unit for engineering calculations. See Appendix I.
Stretch: The ability to elongate. A general term applied to extensibility or elongation.

Tactile inspection: Manipulation of the rope by hand or other means to determine hardness and flexibility.
Tenacity: Alternative name for *specific strength*. In some American usage, it is used for specific stress, but this does not accord with the common meaning of the word. See Appendix I.
Tensile strength: See: Strength, breaking.
Tension: A uniaxial force tending to cause extension of a body or the balancing force within that body resisting that extension. [ASTM-D-123]. Used mostly with discussions on testing. Compare: 'Load'; 'Force'.
Textile yarn: The yarn as supplied to rope makers by yarn manufacturers. A number of textile yarns are twisted together to make rope yarns.
Thimble: A device of metal or other material that provides a large radius support in an eye in the end of a rope or in a grommet.
Twist: The number of turns of twist per unit length. Turns/m. [HC]
Visual inspection: Inspection by visual means, including magnification.
Working load limit (WLL): The working load that must not be exceeded for a particular application.
Yarn (rope): See Rope yarn.
Yarn (textile): See Textile yarn.

References

AMANIAMPONG G (1992) *Variability and visco-elasticity of parallel-lay ropes*, PhD thesis, University of Cambridge.

ANSI/NFPA 1983 (2001 edition) *Fire service life safetyrope, harnesses and hardware*, National Fire Protection Assoc, Hingham, Massachusetts.

ASCE (1993) *Glossary of Marine Fiber Rope Terms*, American Society of Civil Engineers, New York.

ASME (1996) *B30.9 Slings, Chapter 4, Synthetic Fibre Rope Slings*, American Society of Mechanical Engineers, New York.

ASTM (1993a) *D–123 Standard Terminology Relating to Textiles,* American Society for Testing Materials, West Conshohocken, Pennsylvania.

ASTM (1993b) *D–4268 Standard Test Methods of Testing Fiber Ropes*, American Society for Testing Materials, West Conshohocken, Pennsylvania.

BANFIELD S J and HEARLE J W S (1998) Comparative performance of fibre ropes for deep water moorings, OMAE 1998, *Proc. 17th Int. Conf. on Offshore Mechanics and Arctic Engineering*, Lisbon, July 1998, Paper 0358.

BEERS D (2001) in Hearle JWS (2001), pages 93–101.

BOSMAN R L (1996) On the origin of heat build-up in polyester ropes, *OCEANS 96 Conf.*, Fort Lauderdale, Florida.

BOSMAN R (2001) Test method for determining the assured residual life-span (ARELIS) of polyester mooring ropes, *2001 MTS/IEEE Int. Symp.,* Honolulu.

BROWN D T and HEARLE J W S (1997) Dynamic Behaviour of Chain, Wire and Fibre Rope moorings, *IIR Conference (Progress in . . . Moorings and Anchors . . . Deep Water Fields)*, Aberdeen, October 20–21.

BURGOYNE C J (1988) Structural applications of Type G *Parafil*, *Symposium on "Engineering applications of Parafil ropes"*, Imperial College of Science and Technology, London, 39–47.

CASEY, NEIL, (date unknown) data from testing at National Engineering Laboratory, East Kilbride, UK.

CHAMBERS J J (1988) Long term properties of Parafil, *Symposium on "Engineering applications of Parafil ropes"*, Imperial College of Science and Technology, London, 21–27.

CLOOS P J and BOSMAN R L (1997) *Conference on High Strength Fibre Cables*, Institution of Civil Engineers, London, November 26, 1997.

Columbian Rope Company (1986) *Efficiencies of common rope splices, knots, bends and hitches*, Product Information Bulletin, Columbian Rope Company, Guntown, Mississippi.

COOK M J, HAPPOLD E, LIDDELL W I, HEARLE J W S, HOBBS R E and PARSEY M R (1994) Technical/economic evaluation of cables for long-span structures, *IABSE Symposium*, Birmingham.

Cordage Institute (1993) CI B–1.4: *Fiber Rope Technical Information Manual*, Cordage Institute, Wayne, Pennsylvania.

Cordage Institute (1996) CI 1403: *Terminology for Fiber Rope*, Cordage Institute, Wayne, Pennsylvania.

Cordage Institute (2002) CI 1500: *Test Methods for Fiber Ropes*, Cordage Institute, Wayne, Pennsylvania.

Cordage Institute (2003) CI 2003: *Fibre Properties (Physical, Mechanical and Environmental) for Cable, Cordage, Rope and Twine*, Cordage Institute, Wayne, Pennsylvania.

COSTA L (1999) Presentation at Workshop, *OMAE Conference*, Newfoundland.
CROCI G, D'ASDIA P, D'AVALA D and MEOGROSSI P (1994) The valeria of Roman amphitheatres: the Colosseum, *IABSE Symposium*, Birmingham.
DENTON A A (1989) The loss of a jack-up under tow, *Marine Structures*, **2**, 213–231.
DENTON M J and DANIELS P N, editors (2002) *Textile Terms and Definitions*, 11th edition, The Textile Institute, Manchester.
DUNN B J (1977) *Ropes made from man-made fibres*, Bridon Fibres and Plastics, London.
FARNFIELD C A (1974) *A guide to sources of information in the textile industry*, The Textile Institute, Manchester.
FLORY J F (1997) U.S. Patent 5 611 636.
FLORY J F and BANFIELD S J (1992) How to identify the synthetic fibers used in rope making, *Marine Technology Society, MTS'92*, Washington, DC.
FLORY J F, GOKSOY M and HEARLE J W S (1988) Yarn-on-yarn abrasion testing of rope yarns. Part I: The test method, *J Textile Inst*, **79**, 417–431.
FRANCK R R (In press) *Bast and other plant fibres*, Woodhead Publishing Limited, Cambridge.
GILBERT K R (1954) in A History of Technology, Singer C, Holmyard E J and Hall A R (editors) Volume 1, 452–455, Clarendon Press, Oxford.
GILLISPIE C C, editor (1950) *A Diderot Pictorial Encyclopedia of Trades and Industry; 485 Plates selected from 'L'Encyclopedie' of Denis Diderot*, Dover Publications, New York.
GLEISTEIN TAUWERK (2000) *Splicebook*, Geo. Gleistein und Sohn, Bremen, Germany.
GOKSOY M (1986) *A study of yarn-on-yarn abrasion*, PhD thesis, University of Manchester.
GOKSOY M and HEARLE J W S (1988a) Yarn-on-yarn abrasion testing of rope yarns. Part II: The influence of machine variables, *J Textile Inst*, **79**, 432–442.
GOKSOY M and HEARLE J W S (1988b) Yarn-on-yarn abrasion testing of rope yarns. Part III: The influence of aqueous environments, *J Textile Inst*, **79**, 443–450.
GRAYSON J and CATLING D (1982) *Identification of Vegetable fibres*, Chapman & Hall.
GROSBERG P and IYPE C (1999) *Yarn production: theoretical aspects*, The Textile Institute, Manchester.
HEARLE J W S (1966) Structural mechanics of torque stretch yarns: the mechanism of snarl formation, *J Textile Inst*, **57**, T441–T460.
HEARLE J W S (1989) Chapter 2 of *Textile Structural Composites*, editors Chou T-W and Ko F K, Elsevier, Amsterdam.
HEARLE J W S, editor (2001) *High-performance fibres*, Woodhead Publishing, Cambridge.
HEARLE J W S, BURGOYNE C J and HOBBS R E (1992) Fatigue and length effects in fibre ropes, *IABSE workshop, Length effect on fatigue of wires and strands*, Madrid.
HEARLE J W S and GREER R (1970a) On the form of lamellar crystals in nylon fibres, *J Textile Inst*, **61**, 240–244.
HEARLE J W S and GREER R (1970b) Fibre structure, *Textile Progress*, **2**, No. 4.
HEARLE J W S, GROSBERG P and BACKER S (1969) *Structural mechanics of fibres, yarns and fabrics*, Wiley-Interscience, New York.
HEARLE J W S, HOBBS R E, OVERINGTON M S and BANFIELD S J (1995) *Modelling axial compression fatigue in fibre ropes*, 5th ISOPE Conference, The Hague, **II**, 273–277.
HEARLE J W S, HOLLICK L and WILSON D K (2001) *Yarn texturing technology*, Woodhead Publishing, Cambridge, UK.
HEARLE J W S and KONOPASEK M (1975) On unified approaches to twisted yarn mechanics, *Appl Polymer Symp*, No. 27, 253–273.
HEARLE J W S, LOMAS B and COOKE W D (1998) *Atlas of Fibre Fracture and Damage to Textiles*, Woodhead Publishing, Cambridge.
HEARLE J W S, PARSEY M R, OVERINGTON M S and BANFIELD S J (1993) Modelling the long-term fatigue performance of fibre ropes, *3rd ISOPE Conf, Singapore*, **II**, 377–383.
HEARLE J W S and PARSEY (1997) Performance prediction for deepwater mooring lines, *Conf. on contimuous advances in mooring and anchoring*, Aberdeen, IBC Technical Services, London.
HEARLE J W S, THWAITES J J and AMIRBAYAT J (1980) editors, *Mechanics of flexible fibre assemblies*, Sijthoff & Noordhoff, Alphen van den Rijn.
HEARLE J W S and YEGIN A E (1972a) The snarling of highly twisted monofilaments. Part I: The load–elongation behaviour with normal snarling. *J Textile Inst*, **63**, 477–489.
HEARLE J W S, and YEGIN A E (1972b) The snarling of highly twisted monofilaments. Part II: Cylindrical snarling, *J Textile Inst*, **63**, 490–501.
HEARLE J W S, and YEGIN A E (1973) The mechanics of torque-stretch yarns: a correction, *J Textile Inst*, **64**, 601–606.
HIMMELFARB D (1957) *The Technology of Cordage Fibres and Ropes*, Leonard Hill, London.
HOBBS R E (1984) In-service buckling of heated pipelines, *ASCE, J Transportation Enginering*, **110**, 175–189.
HOBBS R E and BURGOYNE C J (1991) Bending fatigue in high strength fibre ropes, *Int J Fatigue*, **13**, 174–180.
HOBBS R E and LIANG F (1989) Thermal buckling of pipelines close to restraints, *8th Internat. Conf. on Offshore Mechanics and Arctic Engineering*, The Hague, **5**, 121–127.

HOBBS R E, OVERINGTON M S, HEARLE J W S and BANFIELD S J (2000) Buckling of fibres and yarns within ropes and other fibre assemblies, *J Textile Inst*, **91**, 335–358.

HOECHST CELANESE (1989) *Dictionary of Fiber and Textile Technology*, Hoechst Celanese, Charlotte, North Carolina.

ISO (2001) *DIS 1968 Fibre ropes and cordage – terms and definitions*, Draft international standard, ISO, Geneva.

ISO (1973) *1968: Ropes and cordage – vocabulary*, ISO, Geneva.

JARMAN C (1986) *The Essential Knot Book*, International Marine, Camden, Maine.

JONES O G (1973) *Rock-climbing in the English Lake District (2nd edition)* E J Morten, Manchester, UK.

LAYARD A H (1853) *A second series of the monuments of Nineveh including bas-reliefs from the palace of Sennacherib and bronzes from the ruins of Nimroud*, John Murray, London.

LEECH C M (2003) The modelling and analysis of splices used in synthetic ropes, *Proc Roy Soc Lond* A, **459**, 1641–1659.

LEECH C M, HEARLE J W S, OVERINGTON M S and BANFIELD S J (1993) Modelling tension and torque properties of fibre ropes and splices, *3rd ISOPE Conf, Singapore*, **II**, 370–376.

LIU F C (1975) Kink formation and rotational response of single and multi-strand electromechanical cables, *Tech. Note N-1403*, Civil Engineering Laboratory, Naval Construction Batallion Center, Port Hueneme, California.

MANDELL J F (1987) Modeling of marine rope fatigue behaviour, *Textile Res J*, **57**, 318–330.

MCKENNA H A (1983) Developments in Fiber Rope Technology, *Oceans '83*, San Francisco, Marine Technology Society, Washington DC.

MCKENNA H A (1996) Mooring line termination technology, *Sea Technology*, July.

MEREDITH R (1952) Properties of textile materials. I – Tensile strength, breaking extension and stress–strain relations, *J Textile Inst*, **37**, P755–P764.

MEREDITH R (1953) in *Fibre Science*, editor Preston J M, The Textile Institute, Manchester, 236–262.

MERRY B (2000) *The Splicing Handbook*, International Marine/McGraw Hill, Camden, Maine.

MORTON W E and HEARLE J W S (1993) *Physical Properties of Textile Fibres*, 3rd edition, The Textile Institute, Manchester.

MURTHY N S, REIMSCHUSSEL A C and KRAMER V J (1990) Changes in void content and free volume in fibers during heat setting and their influence on dye diffusion and mechanical properties, *J Appl Polymer Sci*, **40**, 249–262.

Noble Denton and National Engineering Laboratory (1995), *Fibre Tethers 2000, Final Report*, Noble Denton, London.

OAKLEY K P (1950) *Man the tool-maker*, 2nd edition, British Museum (Natural History), London.

OCIMF (1987) OCIMF prototype rope testing, Oil Companies International Forum, London.

O'HEAR N (2000) *TTI course on Advanced Rope Technology*, Tension Technology International, Eastbourne.

OZAWA S and MATSUDA K (1989) in *High Technology Fibers, Part B*, edited by M Lewin and J Preston, Marcel Dekker, New York.

PARSEY M R (1982) Fatigue of SPM mooring hawsers, *9th Annual OTC*, Houston, Texas, paper OTC 4307.

PARSEY M R, private collection of data from various sources.

PAUL W (1967) *Untersuchungen über das Kraft-Dehnungs-Verhalten dreilitziger Seile aus synthetischen Fasern*, PhD thesis, Technical University Hannover, Germany.

PAUL W (1970) *Review of Synthetic Fiber Ropes*, Research and Development Project of the United States Coast Guard and the National Data Buoy Development Project, Cambridge, Massachusetts (NTIS AD-A084-622).

PEIRCE F T (1926) The weakest link theorem – the strength of long and composite specimens, *J Textile Inst*, **17**, T355–T368.

PHOENIX S L (1980) Statistical models for the strength of yarns and cables, in Hearle *et al*. (1980).

REBOUILLAT S (2001) in Hearle (2001), pages 23–61.

RIEWALD P G (1986) Performance analysis of an aramid mooring line, *13th Annual OTC*, Houston, Texas, Paper OTC 5187, 305–316.

RIEWALD P G, WALDEN R G, WHITEHILL A S and KORALEK A S (1986) Design and deployment parameters affecting the survivability of stranded aramid ropes in the marine environment, *IEEE Oceans '86 Conf Proc*, 284–293.

ROSS A L (1977) Cable kinking analysis and prevention, *ASME J, Engineering for Industry*, **99**, 112–115.

Samson Ocean Systems (1979), unpublished laboratory test, Samson Ocean Systems, Boston, Massachusetts.

Seattle Times (1994) April 17.

SMITH B and PADGETT A (1996) *On Rope*, National Speleological Society, Huntsville, Alabama.

STAUDINGER H (1932) Die *Hochmolekularen Organischen Verbindungen*, Springer–Verlag, Berlin.

TAN Z and WITZ J A (1992) Loop formation of marine cables and umbilicals during installation, *Proc 6th Int Conf on Behaviour of Offshore Structures* (BOSS 92), Bentham Press, London.

TAN Z and WITZ J A (1993) On the flexural–torsional behaviour of a straight beam subject to terminal moments, *J Appl Mechanics, Am. Soc. of Mech. Eng.*, **60**, 498–505.

TAN Z and WITZ J A (1995) On the deflected configuration of a slender elastic rod subject to parallel terminal forces and moments, *Proc Royal Soc*, **449**, 337–349.

Tension Technology International (1994) *Formulation and coding of a compression fatigue model, Final Report to US Navy*, Contract No. N.47408-93-R-7017, Tension Technology International, Eastbourne.

The Textile Institute (1985) *Identification of Textile Materials*, 7th edition, reprinted with corrections, The Textile Institute, Manchester.

TRELOAR L R G and RIDING G (1963) A theory of stress–strain properties of continuous filament yarns, *J Textile Inst*, **54**, T156–T170.

TTI and Noble Denton (1999) *Deepwater Fibre Moorings: an Engineers' Design Guide*, Oilfield Publications, Ledbury.

TYSON W (1966) *Rope: a history of the hard fibre cordage industry in the United Kingdom*, Wheatland Journals, London.

UIAA 101 (1998) *Dynamic Ropes* Union Internationale des Associations d'Alpinisme, Berne, Switzerland.

US Department of Commerce (1999) NAICS 314991: *Cordage, Rope, Twine, Netting*, Economic Census, Harmonized tariff schedule, Washington DC.

US Trade Commission (1989 through 1993), *Industry and Trade Summary 2841*, United States Department of Commerce.

VAN DER MEER S J (1970) *Dynamic mechanical properties of yarns, cords and plain-weave fabrics*, Doctoral thesis, Delft.

VAN DINGENEN J L J (2001) in Hearle (2001), pages 62–92.

VAN MILTENBURG (1991) Stress relaxation and tensile modulus of polymeric fibres, *Textile Res J*, **61**, 363–391.

WEEDON G (2001) in Hearle (2001), pages 132–144.

WHYMPER E (1871) *Scrambles Amongst the Alps*, Thomas Nelson, London.

WITTFOHT H (1984) *Building Bridges: History, Technology and Construction*, Beton, Dusseldorf.

WONG R (1981) *Strength, Elongation, and Energy Absorption of Synthetic Fiber Ropes*, Samson Ocean Systems, internal report 8–81, Boston, Massachusetts.

YABUTA T, YOSHIZAWA N and KOJIMA N (1982) Cable kink analysis: cable loop stability under tension, *Trans. ASME*, **49**, 584–588.

ZOROWSKI C and MURAYAMA T (1967) Wave propagation and dynamic modulus for continuous-filament twisted yarns, *Textile Res J*, **37**, 852–860.

Index