Chapter 6 Timber and cellulose

or Wooden ships and Iron men

‘Plastics are made by fools like me

But only God can make a tree.’

During the war, when we were doing research on strong plastics, Professor Charles Gurney used to recite this little ditty to me nearly every day and I found it depressing because wood was in fact a better material for making aeroplanes than the plastics which we could then produce. Even today there are classes of structures such as sailplanes and some kinds of boats for which wood is still the most efficient material available.

Not only are wood and other forms of cellulose technically efficient but they are also fantastically successful, judged by any quantitative criterion. Cellulose is the structural part of all vegetable matter and it is the strength and stiffness of cellulose which displays leaves and greenery to the sunshine so that photosynthesis can take place and become the principal chemical starting point for all forms of life. Cellulose forms on the average about a third of the weight of all vegetation and the world tonnage of plants is almost beyond computation, locking up in cellulose a large fraction of the world’s limited supply of carbon. Cellulose seldom occurs in animals but there is one rather dim little class of marine animals, the Tunicates, which are mostly made from cellulose. They look rather like elongated jellyfish and appear to have no structural virtues. However chitin, the structural polymer in insects, is very similar to cellulose.

When we come to the works of man, cellulose is still in the leading place. If we consider the timber which is sufficiently industrialized to get into the official statistics, the annual world consumption (not counting fuel) appears to lie between 800 and 1,000 million tons. The rough timber, fencing, bamboo, reeds, thatch and so on used by farmers and primitive people may possibly amount to nearly as much again, but naturally, no records are available. The world production of iron and steel is somewhere round 450 million tons, that of all other metals is negligible by comparison.[*] Since, weight for weight, the strengths of commercial steel and timber are comparable, the total of the burdens supported by wood may well be greater than those supported by steel, though no doubt many of the loads which steel carries are the more spectacular.

Since the density of wood averages about one-fourteenth of that of steel it may be that about thirty times the volume of wood is used, taking the world as a whole.

The ratio of the consumption of wood to steel varies considerably between different countries but it is not necessarily an index of the degree of industrialization or of technological advancement. England and Holland both use about 1,100 lb. of steel per head per annum as against about 700 lb. weight of wood. In U.S.A. the consumption of steel per head is about the same, 1,100 lb., but the consumption of timber per head is much more, about 2,400 lb. In Canada it is as high as 3,300 lb. per head per annum. The characteristic of less developed countries is that their consumption of both wood and steel, that is the total tonnage of their artifacts, is less.

Plant growth

Cellulose is an example of standardized production on the part of nature. Although plants vary so greatly in their shape, function and general appearance, the cellulose molecule is the same in all. It may vary slightly in length and in its physical arrangement but these are matters of detail; the chemistry is the same.

All the more advanced plants contain hollow, elongated, spindle-shaped cells (Plate 13) whose walls are made largely of cellulose. (Which is why it is called ‘cellulose’, ‘-ose’ being the chemical termination for sugars, ‘fructose’ is the sugar found in fruit, and so on.) These hollow spindles are the fibres which take the loads and provide the strength.

Initially the simple sugar, glucose (Figure 1), is synthesized in leaves from atmospheric CO_2 and water by the action of sunlight on the green catalyst chlorophyll. Like other simple sugars, glucose is soluble in water (which is why it is easily digestible) because it has five hydroxyl groups (see Appendix 1) which have a strong attraction for water molecules, and also because the glucose molecules are physically small enough to shuffle around fairly freely in a liquid, provided there are not too many of them. Concentrated solutions of glucose approximate to treacle.

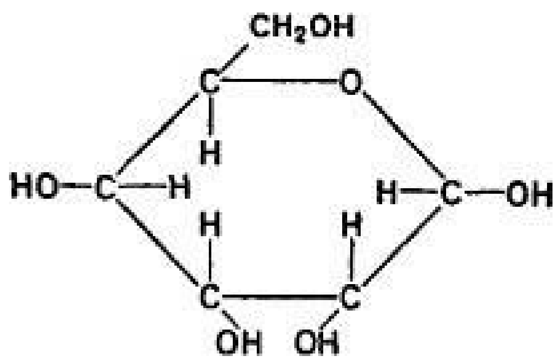

Figure 1. The glucose molecule.

Glucose in dilute solution in sap-water thus passes through internal passages in the plant until it reaches a growing cell. In the wall of the growing cell the glucose molecules are joined together

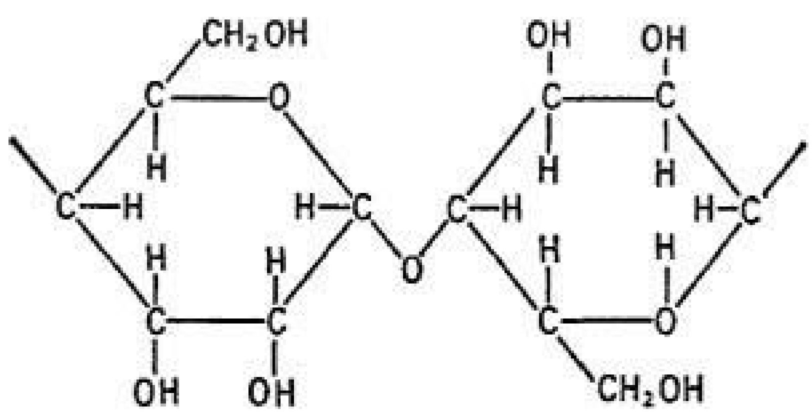

Figure 2. The cellulose chain. It is usually several hundred glucose units long.

endwise (Figure 2) by a chemical reaction known as a ‘condensation reaction’:

$$-\mathrm{OH} + \mathrm{HO}- \rightarrow -\mathrm{O}- + H_2O$$

The result is an oxygen linkage and a molecule of water which goes off in the sap.

This process is controlled in the plant by substances called ‘auxins’ though how it is done is not at all clear. The oxygen linkages between the sugar rings remain the vulnerable links in the cellulose molecule which may reach a length of several hundred glucose units. It is the oxygen link which is broken by the enzymes in the stomachs of animals, such as sheep and cows, which can digest cellulose and by the various fungi or rots which attack wood. It is also the linkage which is attacked by simple chemicals, such as bleaching powder, which are used by laundries, and accounts for the gradual weakening of shirts in the wash.

The cellulose chains which are laid down in the cell-wall are long and they have their length more or less parallel to the length of the cell or fibre, that is to say in the direction of the applied stress. The growth of cellulose is altogether a very remarkable business. If we consider an ordinary tree, by the time it is a few years old it has usually acquired a number of little branches, coming out more or less horizontally from the main stem or trunk. Each of these little branches is in effect a cantilever beam stressed in bending by its own weight (Chapter 2). This means, as we have seen, that the upper surface of the branch is stressed in tension and the lower surface in compression, like any other cantilever. As the bough grows thicker and longer, it gets heavier, and this increases the stress in the top and bottom surfaces near where the branch emerges from the trunk. The branch thickens and grows, like the rest of the tree, by laying down a layer of new material all over, under the bark and near the surface, each year. If this layer of new material were put down each summer free from mechanical stresses the beam or branch would droop until the new material took up the strain and we should have a tree like a weeping willow. In the majority of trees this does not happen. The boughs grow out from the trunk at nearly the same angle throughout the life of the tree and the sapling can be regarded as a geometrical model of the fully grown tree. It follows that, in the majority of trees, the new cellulose is laid down in the cell already containing the stresses and strains which it has to bear.

Working with hydroquinone and other fairly simple soluble substances, I have grown long needle crystals or whiskers (Chapter 4) which thicken by the growth of sleeve-like surface layers which are geometrically not unlike the growth layers in a tree. The initial whisker crystal or filament is often highly bent and the growth layers can be seen to exert a very strong straightening

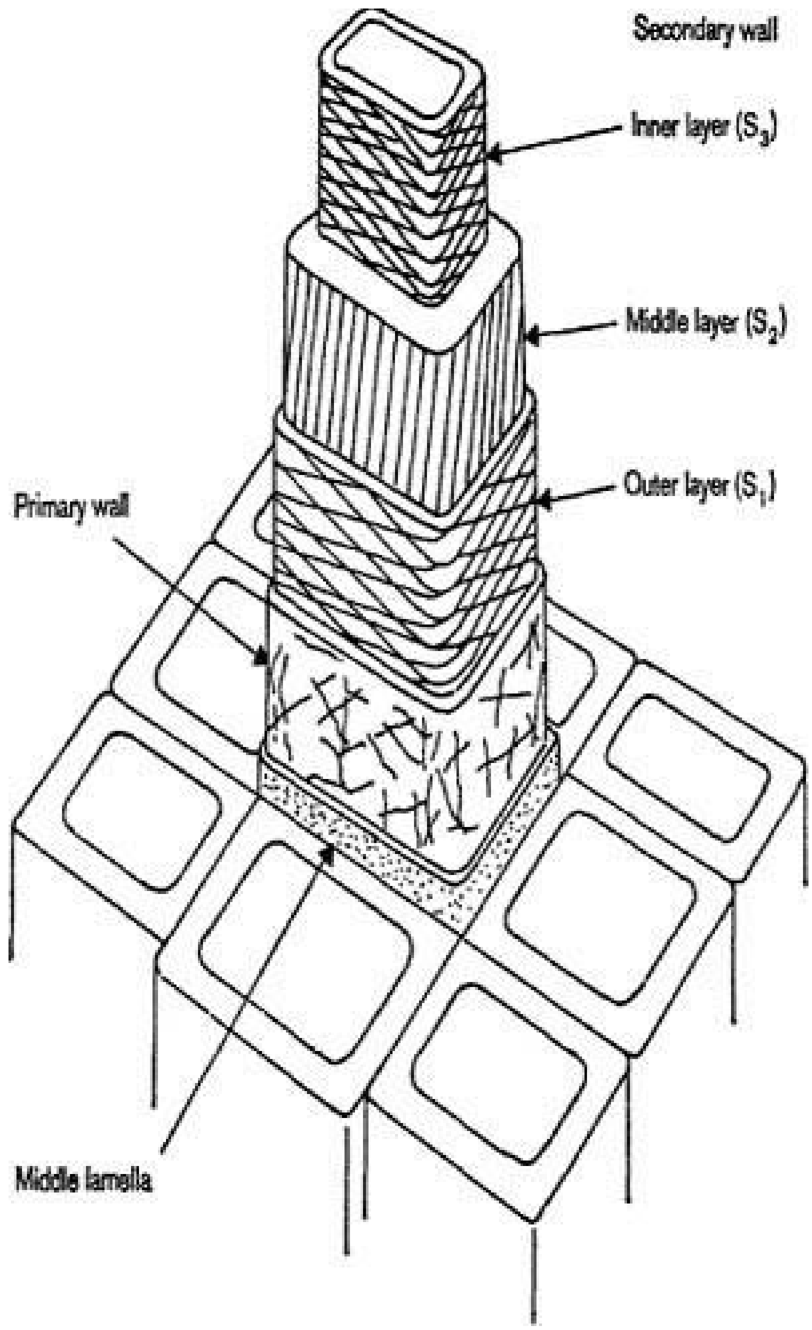

Figure 3. The cells in timber are very roughly rectangular in cross-section. The morphology of the cell walls is complicated but the disposition of the cellulose molecules and fibrillae is preponderantly helical, something like this diagram. (© Crown copyright.)

action on the bent filament, such that, by the time the sinuous initial thread has grown to a millimetre or so thick, it is invariably straight. From this it is clear that the growth layers of these crystals are formed under considerable mechanical stress if this is needed to straighten the crystal. This occurs quite frequently in simple, non-biological systems and there is no question of any additional controlling substance or biological mechanism being needed to cause it to happen. We might therefore suppose that it is normal for the growing bough to straighten under stress by some simple non-living mechanism. However, not all plants do this and a number of trees which normally produce straight, stress-carrying boughs can be grafted so as to behave like weeping willows. There is a suggestion that the growth-controlling auxin gravitates to the bottom of the bough and this produces more wood on the compression face, but to me, this is only a partial answer.

The cellulose chains are always simple thread-like molecules and do not branch by forming oxygen linkages at the sides of the sugar rings, as do other, weaker, polysaccharides such as starch. In the vegetable cell these cellulose molecules form very long, more or less crystalline, threads or fibrillae which are about 150–200 Å thick, say about 30 to 40 molecules wide. As we have seen, most of the internal volume of wood material is taken up with empty space, or at least by air and sap. The cell walls are comparatively thin and the cross-section of the cell is often roughly rectangular (Plate 8). These relatively thin walls are largely composed of cellulose, in the form of fibrillae, and Professor Preston, of Leeds, finds that these thin threads are disposed in the form of a very steep spiral or helix, wound around the longaxes of the cells (Figure 3). The helical angle varies between about 6° and about 30° but what is really remarkable is that the direction of the twist or helix – which may be either right-or left-handed – is always the same in any one tree. All this seems a very curious – indeed an eccentric – arrangement on the part of Nature who, if she had had a proper training in the theory of fibrous composite materials, would surely have known better.

A little while ago Dr Giorgio Jeronimidis came to work with me on just this subject. The first thing that George found was that the work of fracture of wood was quite exceptionally high, although of course it has nothing resembling a dislocation mechanism to help it. In fact the work of fracture, W, turned out to be around 10^4 J/m^2, which, weight for weight, is at least as good as a ductile steel and a good deal better than ‘tough’ composites like fibreglass. In fact the figure is much better than one would predict from composite theory (Chapter 8), supposing wood to behave like an artificial composite. As Punch would have said many years ago,’ collapse of Stout Party’.

Since this high work of fracture – which makes trees able to stand up to the buffetings of life and which makes wood such a useful material – cannot be accounted for by any of the recognized work of fracture mechanisms which operate in man-made composites, George set out to find out what was really happening.

Now the various cells in wood are glued to each other (by means of the various non-cellulosic constituents which exist in timber) in a way which is reasonably effective, but not very effective. This is why the paper-maker is able to make a fibrous pulp for your morning paper from wood. If a crack begins to penetrate into the wood across the grain, the Cook-Gordon mechanism – which we discussed in the last chapter – comes into operation in the region around the crack tip and the various cells become separated so that each of them operates as an independent helix, something like a drinking straw. When this happens the thin walls of the tubes are able to buckle, the helical fibrillae can then straighten themselves out and so the cell is enabled to elongate under the tensile load by something like 20 per cent. Both by calculation and by experiments with model cells, George was able to show that the process of buckling and elongation absorbed a great deal of energy. This process shows great cunning on the part of Nature, also a good deal of cleverness on the part of George. It adds, very usefully, to our repertoire of work of fracture mechanisms and, as we shall see, it seems likely to turn out extremely useful in the design and manufacture of artificial composite materials.

In fact the arrangement of the cellulose molecules in wood is partially crystalline and partially amorphous. The crystalline regions are held together sideways by hydroxyls which have got rid of all their attached water molecules and once the system has locked solid into a regular crystal, the interstices of the crystal become inaccessible to water. We know that this is so because the X-ray diffraction pattern, which shows the crystal lattice spacing, does not change when cellulose swells in water. On the other hand, cellulose absorbs both liquid and atmospheric moisture very actively and this, from the engineer's point of view, is one of its worst vices.

The proportion of crystalline material in natural cellulose varies a good deal but may be about thirty or forty per cent of the whole. The non-crystalline, that is the amorphous cellulose, has no mechanism for protecting its hydroxyls from moisture, since most of them are not firmly attached to their neighbours, and so they pick up a shell, round each hydroxyl, of any water molecules which are available. This naturally reduces their attraction for each other and so the forces holding the cell wall together laterally are diminished and the cell swells. It is stopped from passing completely into solution, partly by the large size of the cellulose molecules and, more, by the fact that, in natural cellulose, the whole system is tied together mechanically by the presence of the crystals, which are water-proof and form a good proportion of the whole mass. So-called 'regenerated celluloses', such as Cellophane, are made by dissolving natural cellulose by chemical methods which break up the crystals. The resulting solution is then precipitated to form a transparent film which is largely a tangied-up felt of individual molecules, and is much less crystalline. When such films are wetted they become very flabby indeed and lose all their strength. The Cellophane which is made for wrapping and packaging is therefore protected by a very thin coating, on each face, of a water-resistant lacquer. This gives sufficient protection for its ephemeral purpose but, after prolonged wetting, such materials are hopelessly weak, whereas natural celluloses retain a good part of their strength.

The natural celluloses which we use include a very large number of timbers, bamboo, cane, flax, hemp, cotton, ramie, sisal, esparto and so on. However, as we might expect, their mechanical behaviour and especially their swelling in water and the relation between their temperature and moisture content and their strength, differ only in detail and present much the same general picture.

The properties of wood

Trees grow in all shapes and sizes and their timbers look very different. These variations are however more or less superficial and the main differences between timbers lie in their density. Seasoned balsa has density of five to ten pounds per cubic foot (s.g. 0·1), spruce around thirty (0·45), oak about fifty (0·7) and lignum vitae between seventy and eighty (1·1). With quite minor additions and subtractions the actual wood substance has in all cases about the same chemical constitution and about the same density of ninety pounds per cubic foot (that is, much the same as sugar – say 1·5).

As we have said, the main structure of wood consists of large numbers of tubular cells or fibres of squarish cross-section fitting very neatly together (Figure 3 and Plate 8). There are minor distinctions in the geometrical arrangement of the fibres in different species. For instance, some timbers, notably oak, have a certain number of fibres, medullary rays, running radially in the trunk and thus crossing the longitudinal fibres at right angles. From the engineering point of view, however, all woods may be considered as bundles of parallel tubes, rather like bundles of drinking straws. Since the tubes are made of substantially the same material the large range of density is caused by the various thicknesses of the cell walls. One consequence of this is that, to a first approximation, most of the mechanical properties of different timbers are proportionate to their densities; a timber twice as dense will be about twice as strong and so on. This is not quite true but it is roughly so.

Wood substance consists of about sixty per cent of cellulose, various other sugar compounds and lignin, a substance having affinities to a resin, which impregnates adult wood substance in some fairly intimate way. Unlignified cellulose is birefringent, that is to say, it rotates polarized light because of its highly directional nature and it also stains brightly with certain dyes. Normal wood substance containing lignin does not do either of these things. However, immediately before mechanical failure, and before any weakness can be distinguished by mechanical methods, wood becomes both birefringent and easily stained by characteristic dyes. This is probably due to the early stages of George Jeronimidis' fracture mechanism of which we talked on page 135. These phenomena cannot be used as a warning of incipient fracture because, to observe the effects, it is necessary to cut thin sections of the stressed part and to look at it in an optical microscope. However, the method can be very useful when investigating accidents and it also serves to show how subtle is the nature of wood substance. Some tropical woods such as teak and greenheart contain small amounts of toxic chemicals and also of silica. These protect the timber from insects and rots but they also help to account for the high cost of working the best tropical woods because the silica blunts tools very quickly and the splinters of greenheart are poisonous.

As we have seen, wood depends for its defences against crack propagation partly upon Jeronimidis' work of fracture contrivance – which ensures that the critical Griffith crack length is a long one – and also, by way of a further safety device, upon the Cook–Gordon mechanism for stopping any crack which gets past George. The other mechanical properties of wood are very much what we should expect from a bundle of tubes or fibres. Laterally, that is across the grain, they separate or crush quite easily, so that the lateral tensile and compressive strengths are very low, only a few hundred pounds per square inch. The lighter woods, such as balsa, can be crushed with the finger. On the other hand, it is just because the fibre tubes can be crushed locally that wood can be nailed and screwed without splitting, provided we do not abuse the wood too much. Incidentally, nails and screws of reasonable size, put in with reasonable care, do not weaken the wood, as a whole, in any measurable way,[*] in other words wood is astonishingly resistant to stress concentrations.

The tensile strength of spruce, for instance, is around 17,000 p.s.i. or 120 MN/m^2 when carefully measured. This represents an elastic strain or interatomic separation of about 1·0 per cent, perhaps between a tenth and a twentieth of the theoretical strength. These figures are much better than those for most other engineering materials, especially cheap ones. A commercial mild steel strains elastically about 0·15 per cent. Weight for weight, the tensile strength of wood is equivalent to that of a 300,000 p.s.i. steel, which is four or five times the strength of the steels in common use. In practice, as we shall see, it is not very easy to make effective use of the high tensile strength of timber.

The weakness of wood is in compression along the grain. In this respect it is the opposite of cast iron, which is strong in compression and weak in tension. Again, a bundle of drinking straws glued together provides a realistic model. Under a compressive load the thin wall of one of the tubes decides to buckle or corrugate and all the rest have to follow it (Figure 4). The compressive strength of spruce generally lies between 4,000 and 5,000 p.s.i., say 30 MN/m^2. Weight for weight, this is still quite respectable, as compared with steel, but it is of course much less than the tensile strength.

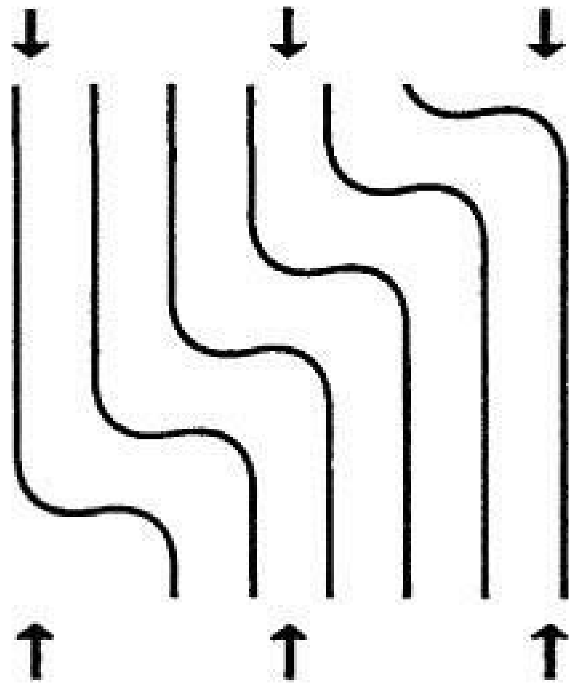

Figure 4. Compression failure in wood. On the clean, planed side-grain of the timber the failure can be seen with the naked eye as ‘creases’ running across the grain direction.

When wood begins to fail in compression little lines of buckled fibres can just be seen running diagonally or across the grain but these are easily missed unless the surface is clean and you know what to look for. For some time after the initial failure nothing very sensational or catastrophic happens, the wood just yields gradually. In most cases wood is used in bending and the result of gradual crushing on the compression side of a beam is to transfer load to the tension side. In this way, the nominal stress in a wooden beam before actual collapse occurs may be up to twice the true compressive stress. It is this which makes a structure made out of timber such a safe one, generally one can very nearly get away with murder. Again, timber is noisy stuff and it will frighten the wits out of you before it is in any real danger of breaking. Sailplanes are often launched by means of half a mile or so of wire, reeled in by a winch. Having no engine, gliders are delightfully silent, except for a slight noise from the wind so that one can hear the structure very well. On a fast, gusty launch a wooden glider will treat you to a series of creaks and groans, and occasionally bangs, which are alarming until you realize that it is all pretence and that the structure is not in the least danger of breaking up. In fact it puts on this performance several times a day. I am pretty sure that these noises do not proceed from incipient compression failures. I have often wondered where they do come from but confess that I have absolutely no idea. They are however counted to wood for righteousness: as long as one can hear a timber structure one is very unlikely to break it.

For its weight, therefore, the strength of timber is as good or better than most of its competitors. Strength however is not enough: one must also have adequate stiffness. Substances like Nylon have plenty of strength but they are not sufficiently stiff to make engineering structures. The Young’s modulus of spruce is about $1{\cdot}5$ to $2{\cdot}0 \times 10^6$ p.s.i. (12,000 MN/m^2) and the other timbers are, roughly, more or less stiff than this in proportion to their densities. Curiously, weight for weight, the Young's modulus of timbers is almost exactly the same as steel and aluminium and much better than synthetic resins. The good stiffness, combined with low density, means that wood is very efficient in beams and columns. Furniture, floors and bookshelves are usually best made in wood and so are things like flagstaffs and yachts' masts. The railways in America could be built very quickly and cheaply in the nineteenth century partly because of the efficiency of the timber trestle bridge.

As against these virtues, timber creeps. That is to say, if a stress is left on for a long time, wood will gradually run away from the load. This can be seen in the roof-tree of an old house or barn, which is generally concave. The creep of the wood is the reason why one must not leave a wooden bow or a violin tightly strung. The cause of the creep is most probably simply that, in the amorphous part of the cellulose, the rather badly stuck hydroxyls take advantage of changes in moisture and temperature to shuffle away from their responsibilities. It is unlikely that the crystalline part of cellulose creeps to any measurable extent.

Swellulose

No doubt it would not be beyond the wit of nature to join up the cellulose molecules sideways with primary chemical bonds so that it would be thoroughly tied together and would have much the same strength in every direction. However, as we said in the last chapter, it seems to be a condition for the strength and toughness of materials of this type that there should be planes of weakness parallel to the strongest direction. If not, wood would be something like a lump of sugar: homogeneous but weak and brittle. For its weight, there is really nothing wrong with the mechanical properties of wood and the weight of wooden structures is generally at least comparable to that of metal ones. We pay for this however in the vulnerability of wood to moisture.

Wood is affected by liquid water in the form of rain, rivers, seas and so on with which it may come into contact but, more importantly, it is affected by the moisture vapour which is always present in the air.

Air at any given temperature can hold so much moisture; any excess is precipitated as rain, fog, mist or dew. Such air is called saturated and thus the 'relative humidity' on a wet day is around 100 per cent. Indoors, or in drier weather, the relative humidity decreases, although it seldom falls much below 30 per cent even in hot dry climates.

All timbers tend to come to an equilibrium with the relative humidity of the surrounding air. Exposed for a long time to moist, saturated, air timber might settle down to a moisture content of 22 per cent or 23 per cent. In a very dry climate the moisture content might reach as low a figure as 5 per cent. Regarded as mere changes of weight these figures are of secondary importance. What is important is the effect of the moisture on the wood. The most important effect is that the wood shrinks or swells. The movement in the direction along the grain of the wood is negligible, as one would expect from the molecular structure. The cross-grain swelling and shrinkage is however very large. Every one per cent change of moisture content may cause about a half per cent shrinkage or swelling. Over the range of moisture contents likely to be reached in air the lateral dimensions of wood can thus change between five and ten per cent, that is up to an inch on a ten-inch-wide plank. Amateurs rather like to use wide planks if they get the chance, professionals are wiser and prefer narrow ones so that the movement at each individual joint is smaller. Of course one does not often get shrinkage and swelling as gross as ten per cent but as little as one or two per cent can be sufficiently troublesome. Paint and varnish slow down moisture changes in wood but they do not prevent them for no paint is impermeable to water vapour.

Even indoors, the relative humidity is changing all the time, especially between night and day. Floor boards and furniture tend to follow the humidity and this is the reason for the ghostly noises one hears in the house at night. If wood is physically restrained from shrinking when it wants to do so it will split, because it has almost no tensile strength across the grain. If it is physically restrained from swelling when it wants to swell, very considerable pressures are built up. The Egyptian method for quarrying large blocks of stone, such as Cleopatra's Needle, was to outline the shape by means of a stress concentration, in the form of a groove in the surface of the rock. Deep holes were made along this groove into which dry wooden pegs or posts were driven. These wedges were then supposed to have been soaked in water until the rock split along the required line.

The shrinkage of cordage and textiles is much the same in principle as that of wood. Individual fibres change their thickness but not their length with moisture changes, and it is the helical geometry of ropes and textile yarns which causes rope and cloth to get shorter when it gets wet. Flax sails, especially, were very porous and sailing ships 'in chase' would wet their sails to swell the fibres and reduce the porosity.

As we see, the most important effect of moisture on wood is to cause it to swell. A rather less important effect, from the practical point of view, is to change the mechanical properties. Thoroughly wet wood has something like a third of the strength and stiffness of completely dry wood. Biological materials always operate in the saturated state: this gets rid of the problem of shrinkage and swelling at the expense of a reduction in strength. In engineering, cellulose is never used in the completely dry condition so that the range of strength and stiffness is not quite as bad as it sounds.

Wet wood is rather easier to bend than dry but the principal agent for bending wood is heat. Traditionally, wood which has to be bent for tennis racquets and boat ribs is steamed. It is often supposed that the steam does something because it is steam. In fact the steam is a convenient way of heating the wood without drying it out and the mechanism is exactly the same as that used by hairdressers for curling hair. Sometimes amateurs wrap wood in hot wet rags when they want to bend it. The wetness of the rags does not accomplish much but the wood gets heated and the rags may insulate the hot wood and prevent it from cooling too quickly. Wood will not come to much harm in moist heat below about 140° C. but, of course, in dry heat it will soon crack due to shrinkage.

Seasoning

A great deal of rubbish has been talked about the seasoning of timber by craftsmen and by romantic but ignorant amateurs. Wood, as we have said, consists of closed tubes which, in the living tree are partly full of water, or rather sap. In freshly felled wood the moisture content varies but may be over 100 per cent of the weight of the dry wood substance. About 25 per cent of this water is absorbed in the hydroxyls of the fibre wall, the remainder is liquid water inside the cell. Seasoning consists in removing most of the water in a controlled way: essentially it is a drying operation and nothing more. It is necessary to bring the wood to a moisture content which is nearly at equilibrium with the environment in which the timber is going to be used for if this is not done one must expect warping and shrinkage. For external use a moisture content of perhaps 20 per cent may be suitable, for an unheated building about 15 per cent, and for a steam-heated environment about 8 or 10 per cent.

Since the cells are closed, spindle-shaped tubes, the liquid water inside them is not very easy to get out. It can only be dried out by diffusing it slowly through the tube walls. This would present no great difficulty if one were dealing with a single cell but real lumber contains many thousands and it is necessary to diffuse the water from the inner cells through the walls of most of the other cells which lie between them and the outer world. To do this it is necessary to maintain a moisture gradient between the inside and the outside of the wood. The sharper this gradient is, the faster moisture will be lost from the inside. On the other hand if the moisture gradient is too steep the outside will be notably drier, in the intermediate stages of seasoning, than the inside and so it will shrink more and will thus split. This is why one cannot season too fast without ruining the timber. Traditionally, wood was seasoned 'naturally' in the open air or in open, unheated sheds. This might take a year or so for planks an inch or two thick and seven years for large oak ship's timbers. With primitive methods and knowledge this is about the best that one can do. One of the reasons why the better shipyards and coachbuilders were expensive was that they kept large stocks of valuable timber seasoned and seasoning.

A great deal of technological work has been done recently on the seasoning of wood, and safe accelerated drying schedules have been worked out for all kinds and dimensions of timber. By carefully controlling the drying rates in large kilns the time for seasoning can be reduced to a matter of days or weeks. Another factor which reduces seasoning time is the modern tendency, because of the existence of efficient glues, to use timber in much smaller sizes, which of course dry more quickly. Timber which has been properly kiln-seasoned (which needs expensive kilns and close supervision) is in no way worse than 'naturally' seasoned timber and indeed is rather less likely to have picked up the infections of rot during the seasoning process. However, original or commercial sin keeps breaking in and there is undoubtedly a great deal of badly seasoned wood on the market.

The moisture content of wood may be determined simply by weighing a small sample before and after oven drying. In industry it is usually done with portable meters which measure the electrical resistance between two needles pressed into the wood and thus give the answer much more quickly.

Up to about 25 per cent moisture content the whole of the water in wood is held in association with the hydroxyls in the cell walls. At about 25 per cent moisture content however these hydroxyls become saturated and the cell walls can absorb no more water; this is known as the 'fibre saturation point'. Up to the fibre saturation point the lumen or hollow part of the cell is empty of water, above the fibre saturation point virtually the whole of the additional moisture exists as loose liquid water within the lumen. All the dimensional and mechanical changes in wood which are due to moisture occur below the fibre saturation point, that is between 0 per cent and 25 per cent moisture content. After that no further swelling takes place and the additional water simply adds, very considerably, to the weight of the wood.

Wood substance has a specific gravity around 1·4 but freshly felled timber floats (unless it is a very dense species) because, even in the unseasoned wood, there is a good deal of air. Wood will, however, eventually become waterlogged and sink though, like seasoning, this takes a considerable time. The crew of the Kon-tiki raft were worried lest their balsa logs should sink under them on their long voyage although, in the event, the soakage was not very great. The American clipper ships of the 1850s, the famous ‘soft-wood three skysail-yarders’, became water-soaked within about ten years by which time they had no doubt paid for themselves very handsomely. The hardwoods from which English ships were usually built are more resistant to soakage and there are several instances of wooden ships afloat and in service for over a hundred years.

Rot

Rot is caused by fungi which live parasitically on cellulose since fungi have no chlorophyl and cannot photosynthesize sugars for themselves. The spores of various fungi are nearly always present in woodwork, just as the germs of many diseases are present in our bodies, but they do not become active unless the conditions are favourable. Rots cannot flourish if the moisture content of the wood is below 18 per cent although the spores can remain alive in quite dry timber, waiting for a rainy day. Even when the moisture content rises above 18 per cent the fungi may not grow if the ventilation is good. As the moisture content of the wood in an unheated structure may be around 15 per cent, it only requires a small amount of damp in an unventilated corner to get the rot going. One cannot always control moisture content but one can generally arrange for ventilation and this is usually a sufficient preventative.

Many chemical treatments are effective in killing active fungi in wood but, in an old and complicated structure, the practical difficulty may be to reach the diseased parts without pulling the whole structure expensively to bits. If the rot is accessible one can generally arrange for ventilation anyway.

In the cyclic natural scheme of things some kind of decay is essential, otherwise not only would the earth be cluttered with the stems of most of the plants which have ever lived, but most of the world’s supply of carbon would be locked up in cellulose so that life could not be carried on. This is a general objection to the use of biological materials by man for nature’s planned obsolescence may be in conflict with ours.

Wooden ships

‘But not long after there arose against it a tempestuous wind called Euroclydon. And when the ship was caught, and could not bear up into the wind, we let her drive. And running under a certain island which is called Clauda, we had much work to come by the boat: which when they had taken up, they used helps, undergirding the ship; and, fearing lest they should fall into the quicksands, struck sail, and so were driven.’

Acts of the Apostles, Chapter 27.

The wooden sailing ship was par excellence the artifact which made the expansion of Western civilization possible and thus, more than any other device, was responsible for our present condition. Wooden sailing ships explored the world and later surveyed it. They carried passengers and troops, emigrants, convicts and slaves. They carried gold and coal, machinery and books, tea and wool, cotton goods and cheap tin trays, not only to the ends of the earth but also round the coasts and up the rivers. For hundreds of years the ship of the line was the ultimate argument of kings, frequently used. Ships like this are not things of a dim past, there were first-class passenger sailing ships on the Australian run within living memory* and there are Admirals alive who first went to sea in wooden sailing ships.

Although about the middle of the nineteenth century large improvements were made in both the hulls and the rigs of ships, for three or four hundred years before that the basic methods of construction remained nearly constant. The two controlling facts were that wood swelled and that metals were expensive.

Large ships were heavily framed from 'grown' timbers. That is to say the curved members, such as ribs, were built up of naturally curving wood, chosen to have the right shape. The watertight skin and deck were put on over this closely spaced framework of ribs and beams in the form of planks, nearly as thick as they were wide, which ran longitudinally at right-angles to the ribs. The planking and the underlying ribs thus formed a rectangular trellis with no diagonal bracing or shear members. The edges of adjacent planks were not fastened together mechanically but stood open so as to form a V-shaped groove.

Into this groove oakum, made by picking old rope to pieces in the prisons and workhouses, was driven by means of a mallet and a caulking iron which is a chisel-like tool with a groove along the edge. Outside the caulking there remained an open groove between the planks nearly half an inch wide. In the case of decks this had to be 'payed' which was done by running in hot pitch from a special ladle. When cold the surplus pitch was sufficiently brittle to be scraped off, leaving those pleasing black lines in the deck.* The bottom and topsides were payed or stopped with a putty-like composition. The point of all these arrangements was that the flexible caulking could accommodate shrinking and swelling of the planking, and to some extent movement of the hull, without leaking very much.

The whole structure was, and to some extent was intended to be, quite flexible, almost like a basket. Besides accommodating the shrinkage and swelling of the skin planks, it was supposed, perhaps correctly, that the flexibility of the hull contributed to its speed and sea-kindliness; certainly the Viking ships and the Polynesian canoes were even more flexible. When the much more rigid 'composite' constructions came in in Victorian times one or two of the racing clippers were built with hulls of deliberately controllable rigidity. Of one such ship her rivals would say, as she drew ahead, 'They've unscrewed the beams and we shan't see her again today.'

This was all very well and most wooden ships were watertight in harbour but, without exception, they all leaked when they got to sea. The rate of leakage varied from 'enough to keep the bilges sweet' to something very serious indeed. In spite of all the centuries which he had to learn about it the traditional shipwright seemed to be unable to understand about shear. Any shell structure subject to bending and torsion puts heavy shears into the skin and bending and torsion are just what a ship, especially a sailing ship, receives at sea. The orthodox ship construction was like a five-bar gate without the diagonal member.

Since there was no official way of taking the shear it was taken, unofficially, by the caulking which was squeezed and relaxed alternately, like a bath sponge. Occasionally, but surprisingly rarely, the labouring ship spat the caulking from some underwater seam, in which case she probably foundered. More often she just leaked and leaked and leaked. The danger was then, not that she would sink immediately, but that the crew would become exhausted from continual pumping and general misery, after which anything might happen.

When the situation became intolerable an attempt might be made to undergird or frap the ship by passing cables under the hull as St Paul describes in the Acts of the Apostles.* It has been done repeatedly since and very likely, in some corner of the ocean, an Arab dhow is being undergirded at this moment. The whole point of the undergirding cables was to provide some shear bracing and so unless the operation was done with a knowledge and accuracy which were rather unlikely in the circumstances, so as to get the cables roughly at forty-five degrees, the expedient probably had usually as little effect as it seems to have had upon Paul's ship.

As far as the Royal Navy were concerned the nuisance of excessive leakage was largely put a stop to when Sir Robert Seppings (1764–1840) introduced diagonal iron bracing into wooden hulls about 1830. Seppings, who used to say 'partial strength produces general weakness', seems to have been one of the first Naval Architects to have a clear mental picture of the stress systems in a ship's hull. In the merchant service wooden hulls were to a considerable extent replaced by composite and iron and steel construction after the middle of the century. A number of wooden ships continued to be built without adequate shear bracing, however, and such ships got more leaky as they got older, until, in an age when most of the pumping was done by hand, it became uneconomic to run them any longer. Up till 1914 Norwegian shipowners were still making money by buying up British sailing ships and running them with windmill pumps.

In spite of their faults, wooden sailing warships were in use for between three and four hundred years and were abandoned by Admiralties with reluctance because they were, in their context, most effective and economical weapons. They had a range and endurance, an independence of overseas bases and an ability to vanish indefinitely into vast spaces which we have only lately regained with the atomic submarine.

Fleet actions were rare, and strategic pressure was generally exerted by blockade and by the threat of a 'fleet in being'. However, until the middle of the eighteenth century it was considered impracticable to keep fleets continually at sea throughout the winter because of the severe and rapid deterioration in the condition of the ships. However, these difficulties were overcome by the efforts of devoted officers. To anyone familiar with the coasts, with sailing ships and with the cellulose molecule, the maintenance of the blockades of Brest and Toulon, winter and summer and in all weathers, must appear as an almost incredible feat. 'Those far-distant, storm-beaten ships, upon which the Grand Army never looked, stood between it and the dominion of the World.'[*]

Rope and spars came mostly from the Baltic states and the convoys got through with difficulty. Although the blockading squadrons very rarely saw the French they had daily and hourly to struggle with rope and canvas and timber which stretched and broke and rotted. Nelson wrote 'I have applications from the different line of battle ships for surveys on most of their sails and running rigging which cannot be complied with as there is neither cordage nor sails to replace the unserviceable stores and therefore the evil must be combated in the best manner possible.' In spite of this, Mahan wrote 'For twenty-two months Nelson's fleet never went into port, at the end of that time, when the need arose to pursue an enemy for four thousand miles, it was found massed and in all respects perfectly prepared for so sudden and so distant a call.'

When a sailing ship has a fair wind, even though it be a gale, the loads in her rigging are moderate. However when she is heeling and lurching her way to windward the aggregate of the tensions in the shrouds and stays which support the masts is comparable to the ship's displacement and may thus amount to several thousand tons. Until the middle of the nineteenth century the whole of this load, equivalent to the weight of many railway trains, had to be carried by hemp ropes which were always shrinking and swelling, rotting and stretching so that it called for great skill to avoid the loss of some or all of the masts and spars. There was therefore an understandable reluctance to undertake regularly long voyages to windward in rough weather. A voyage round Cape Horn, for instance, was quite different in character to the routine voyages to the East coast of the Americas or even to India. Bligh's crew, for example, in the Bounty mutinied after one appalling attempt to beat round the Horn in which the ship could barely be held together structurally. Eventually Bligh had to turn round and run in the other direction, right round the earth, into the Pacific. Bligh, though unpopular, was a superb seaman and, if he could not succeed, probably nobody else could.

Wire standing rigging was introduced into the Royal Navy in 1838. Its adoption by the merchant service seems to have been fairly gradual (and was not complete until the 1860s) because about this time hemp rope was improved by being laid up, or twisted, mechanically, and thus much more tightly, so that the creep was considerably reduced. By chance the introduction of better rigging more or less coincided with the gold discoveries in California. About half of the emigrants and all of the heavy cargo went by sea and by then numerous clippers were prepared to beat regularly from New York to San Francisco in a hundred days. In the years 1849 and 1850, 760 sailing ships beat round Cape Horn carrying between them 27,000 passengers. It is difficult to determine what proportion of these ships had wire rigging and which used the improved hemp but in any case it is clear that the West was largely won with better rope.*

Another important development was in the matter of chain cable. Hemp anchor cables have certain advantages but their drawback lies in the space needed to stow them; the enormous ventilated cable tiers in H.M.S. Victory are impressive. Chain, which was introduced in 1811, could be stowed in a small damp locker and so it can almost be said that chain cleared the space needed below for engines and coal bunkers.

When ships were slow and there were no dockyards on the other side of the world, the fouling of ships' bottoms by weed and the attack on timber by boring animals was a serious matter. Both problems were solved to a large extent by the introduction of copper sheathing about 1770. This did more than any other eighteenth-century innovation to increase the speed and range of ships and it was so successful that shipowners were most reluctant to use iron hulls which could not be coppered directly on account of electro-chemical action between the iron and the copper in salt water. Some iron hulls were sheathed with wood and then coppered. This was popular for warships but it made for a heavy hull. Many of the best racing clippers were therefore composite built. Cutty Sark (launched 1869) is planked with teak and greenheart bolted to wrought-iron frames, with adequate shear bracing. The bottom was sheathed with a brass alloy called Muntz metal. There are people who consider this arrangement as being the most perfect construction yet devised for ships of medium size. This may well be true but it is unfortunately also a very expensive one.

The fall in the cost of iron and steel plates in the 1870s made composite shipbuilding uneconomic and, towards the end of the nineteenth century most of the world's deep sea cargo was carried by big sailing ships of almost standardized construction with steel hulls, steel decks, steel spars and steel rigging. Such ships were completely watertight and could be manned by small crews. The loss of speed from their rougher bottoms was compensated by the fact that they could be sailed harder than wooden ships in blowing weather. Over the centuries officers had had to nurse their wooden ships for structural reasons and this had provided a certain measure of protection against excessive sail-carrying. Hard driving clipper captains regarded their new ships as unbreakable and, when expostulated with, would reply 'Hell, she's iron isn't she?' Quite a number of iron and steel ships were driven under and lost by this attitude of mind.

Steamships were in a minority until about 1890 and in any case tended to take the shorter voyages. Of course plenty of wooden steamships were built but the tendency was to turn to iron and steel earlier than in the case of sailing ships. This may have been partly because iron hulls resisted the vibration of the early engines better than wooden ones and also because fouling was less of a problem with continuous speeds and shorter voyages. It is the becalmed sailing ship which fouls quickly.

Orthodox wooden construction is still being used today for fishing vessels, minesweepers and yachts of up to four or five hundred tons. For racing yachts it generally provides the lightest of all hulls and it is also the cheapest way of getting a ‘one-off’ design built. In its cheaper forms it still suffers from the classical trouble of intolerable leakage in bad weather, especially because of the much higher loads put into the hull by modern rigs. It is true that it is possible to get over this by good workmanship and sophisticated construction but then the cost is higher than that of building in steel or plastics.