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The safety of rock climbing protection devices under falling loads

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Abstract

Safe participation in the sport of rock climbing is dependent on using a range of equipment and using appropriate techniques. However, the level of safety achieved will depend on the specific equipment used, in terms of design, type, adequate load rating and condition, and also upon the climbing technique as this can significantly help to minimise any impact loads in the advent of a fall. In addressing these issues, this paper describes some mechanical tests which have been carried using a specially designed drop load rig in which falling weights have been applied to samples of climbing rope to establish impact loads. The load-time histories have been recorded and peak loads have been compared with those determined theoretically. In addition, some new and also used anchor nuts have been test loaded to failure and the different failure modes which resulted are described. Finally, the general design of climbing equipment is discussed.

Keywords: Climbing equipment; Safety; Impact loads

1. Introduction

Traditionally the sport of climbing involves ascending a rock face using natural features and climbing ability. However, there are inherent dangers involved and so it is sought to minimise these using safety protection devices and suitable techniques [1]. The design and condition of such climbing safety equipment plays an important role in establishing whether an injury occurs in the advent of a climber falling. The effect of normal usage, wear and environmental aging can significantly affect safety. Climbing rope, for example, (which is made from material having visco-elastic behaviour) must remain strong enough so as not to break yet provide sufficient flexibility to help minimise any peak impact load occurring. In addition, the various protection devices, such as wedge chocks, nuts and expandable cam devices used for achieving anchor points must remain fit for purpose and not fail when needed.

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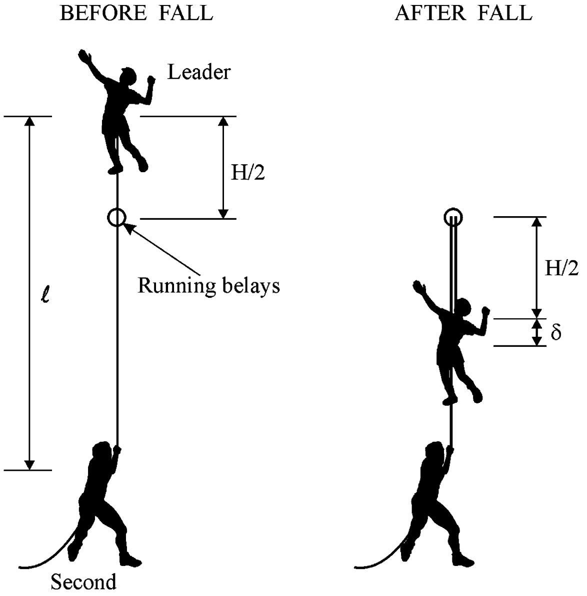

Fig. 1. Geometry of a simple fall.

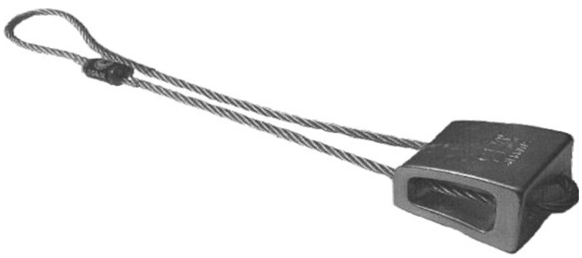

Fig. 2. A typical climbing anchor nut.

In order to analyse the behaviour of climbing equipment it is first necessary to consider modern climbing methods which is basically as summarised in Fig. 1. Typically, a lead climber ascends and descends with the assistance of at least one partner [2]. The lead climber will wear a harness with a rope attached which acts as an umbilical line (See Fig. 2).

Periodically the rope will be attached, via a karabiner, to a chock/nut sling device inserted into a natural crack – thus seeking to achieve a solid anchor point in a rock face; called a belay. There may be many of these, depending on the total height, climbed, and are spaced apart at such a distance that should the climber slip and fall, the distance is minimised such that major injury is avoided. The spacing distance at which the belays are located is very important and also role of the second and supporting climber in helping to absorb some of the impact is discussed in later sections. The length of rope, L and potential fall height, H is as illustrated in Fig. 1.

2. Equipment properties

During a climb, a number of components are used (rope, sling, karabiner, harness, anchor nut etc) which act like links in a chain whereby the success of the 'system' is dependent on the 'weakest link'. Clearly adequate strength is necessary but excessive strength can be undesirable if it comes at the expensive of greater weight and possibly higher stiffness also. Typically anchor nuts and slings are load rated at 12 kN. This is based on the maximum load which a person can withstand, as found from research on parachutists. Modern climbing ropes typically have strengths in excess of 25 kN as it is generally accepted that the rope is the component most vulnerable to wear and damage. Having a breaking strength about twice that of components such as anchor nuts, though, is questionable as load resulting from a falling climber must also be supported by a reactive load component thus doubling the effective force on the anchor.

It could be argued that anchor nuts and other components ought to have a strength twice that of the rope. Also, apart from strength, umbilical line flexibility is important, as with a bungee jumper, in reducing the maximum load upon impact.

3. Mechanics of an impact

The effect which the various parameters have on generated loads and equipment strength is best achieved by considering the mechanics of a falling object. Alternative approaches can be taken [3] but common approach is to determine the maximum (i.e., impact) force generated in a climbing rope during a fall by considering the conversion of potential energy of a falling climber into strain energy of the rope at maximum extension. The results of a simple analysis, which assumes linear elasticity of the rope, is summarised below – a more thorough derivation can be found in most basic engineering mechanics text books such as [4]. In reality the rope material is likely to be visco-elastic and with added effects such as rope knots and anchor components it means that the stiffness is not constant or the same along the full length. The consequences of these additional effects are discussed later in relation to the basic theory.

The geometrical model used for the theory is as shown in Fig. 1 whereby a second climber runs out a length of rope, L to a lead climber who is at a distance (specified as $H/2$) above a belay anchor point. Should the lead climber fall, the distance fallen will be H plus the maximum rope extension amount, δ which is usually a significant distance. The loss of potential energy (i.e. weight x total distance fallen) converts into strain energy (or work done) extending rope, which, at the critical peak extension/load state is the area under the force vs. extension curve) as given by Eq. (1).

Loss of potential energy = Gain in strain energy

$$\mathrm{mg}(H+\delta) = \frac{F\delta}{2} \tag{1}$$

$$= \frac{k\delta^2}{2} \quad \text{since stiffness, } k = \frac{F}{\delta} \tag{2}$$

$$= \frac{EA\delta^2}{2L} \quad \text{as alternatively } k = \frac{EA}{L} \tag{3}$$

Eqs. (2) and (3) present alternative forms of the gain in strain energy term. Eq. (2) incorporates the rope axial stiffness, k and Eq. (3) can be used if the rope has uniform flexural rigidity (the EA product where E is the elastic modulus and A, the rope cross sectional area).

Combining Eqs. (1) and (3), which is quadratic in terms of δ, then replacing force, F for δ, results in the following expression:

$$\text{Impact force}, F = \mathrm{mg}\left[1+\sqrt{1+\frac{2AE}{\mathrm{mg}}\left(\frac{H}{L}\right)}\right] \tag{4}$$

Or alternatively it may be expressed more generally, in stiffness terms, as follows:

$$= \mathrm{mg}\left[1+\sqrt{1+\frac{2kH}{\mathrm{mg}}}\right] \tag{5}$$

Eq. (4) is the form widely used by climbers (either knowingly or intuitively) as it shows that for a constant H/L ratio (commonly called the fall factor), the force at impact will be the same in theory for any given rope E, A and climbers weight mg. Consequently, climbers try to maintain a safe H/L ratio (i.e. potential fall distance/rope length ratio) so, for example, on a very high climb above the second support climber a greater climbing distance can be permitted from the nearest belay anchor than with a lower level climb.

The impact force equation expressed in terms of the umbilical line stiffness, k Eq. (5) shows how the force magnitude will be greater using stiffer rope and from falling a greater distance, H.

4. Experimental procedure

A simple rig was constructed for performing drop weight tests on samples of rope; with and without anchor nut supports used. An instrumented strain gauged load cell was fitted in series to measure the forces generated in the rope upon impact.

The rig comprised a pyramid shaped structural frame which supported the anchor nut in a simulated standard crevice device at the apex region, as illustrated in Fig. 3. A weight carrier was secured at the datum setting and the weight, when released was able to drop a distance of up to 85 cm.

The load carrier typically carried 5 kg weights up to a maximum of 55 kg (0.54 kN) and tests were performed using weights in increments between these ranges. The load cell signal was feed into a microprocessor for analysis. The rig was calibrated and an example of a typical load trace is displayed in Fig. 4. This trace

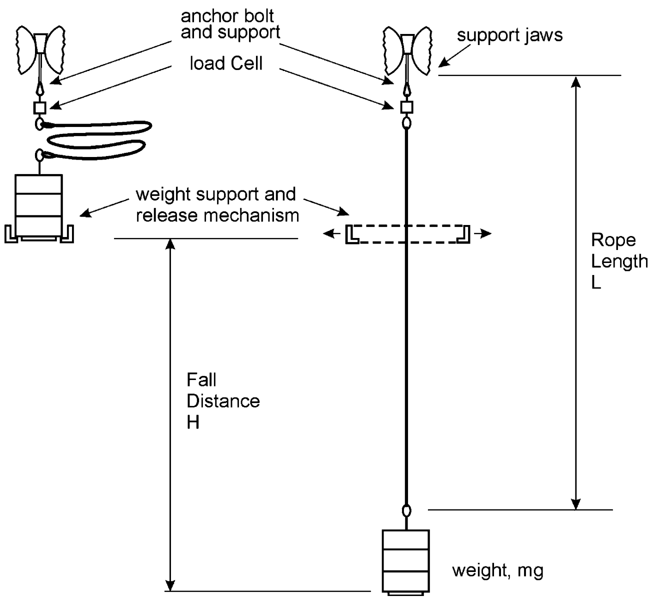

Fig. 3. Idealised drop weight test setup.

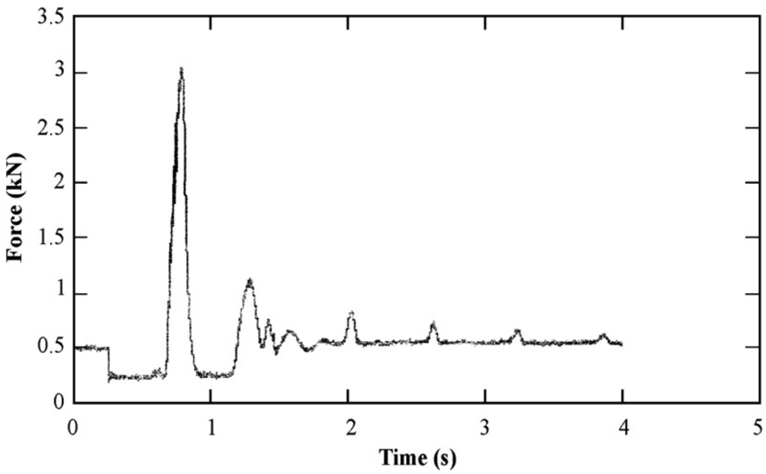

Fig. 4. Typical load cell force – time history under a drop test.

shows that the load cell force reduces during the weight falling period but not quite to zero. This is probably due to the fact that the load cell still supports some of the rope weight during the weight falling period.

The trace displayed in Fig. 4 shows how a static weight of about 0.5 kN increases instantaneously to a 3 kN peak force – thus representing a six fold magnification of the weight. This occurred using an 85 cm effective length of climbing rope falling a distance of 79 cm (equating to an H/l ratio of 0.9).

5. Test results

A range of tests have been performed to investigate the effects of rope length, fall factor (i.e., H/l ratio), repeat falls and rest periods. Salient details of some of the results are summarised below.

5.1. Test 1: Effect of changing rope length for a constant fall factor, H/L

This range of drop tests sought to establish whether the peak load in a rope remained constant using different rope lengths and fall heights whilst maintaining a constant H/L ratio as predicted by Eq. (4). A 55 kg weight was used and a constant fall factor, H/L of 0.9 was maintained on new rope samples in which the lengths and falling heights were altered accordingly. Fig. 5 shows how the theoretical peak load, as defined by Eq. (4), remain constant for different rope lengths and constant H/L ratio. The experimental results, scatter accepted, also follow a near constant peak force level but about 20% lower than the theoretically predicted force.

5.2. Test 2: Variation of peak load with changing fall factor, H/L

In this test the full 55 kg mass was used, in turn, with five new 85 cm long rope samples with each sample subjected to a different drop height; ranging from 79 cm to 19 cm in steps of 15 cm. This corresponded to a reduction in fall factor from 0.92 to 0.22 and each rope sample was only subjected to the one test. The effect on changing peak load is shown in Fig. 6.

5.3. Test 3: Effect of consecutive drops on maximum impact force

This series of tests involved attaching the mass carrier with 55 kg weight attached to the initially new 85 cm long rope sample and dropping the weight 79 cm. After a five minute period with the weight just hanging, it was then raised and after a five minute rest period the drop test was repeated. This sequence was repeated a further five times and the peak load recorded for each drop test. This procedure was also repeated using a new rope sample and using a climbing knot (which was retied after each drop test) and the results are plotted in

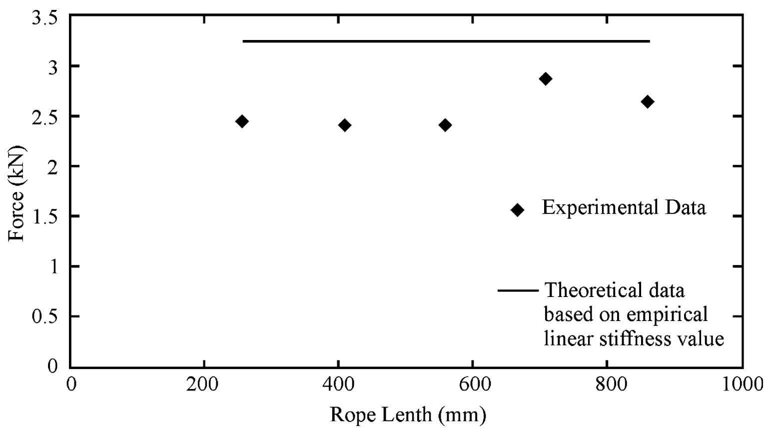

Fig. 5. Effect of a constant fall factor, H/L on rope force.

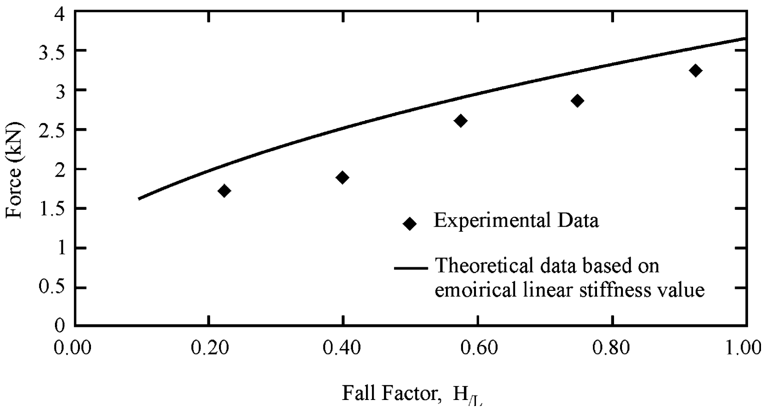

Fig. 6. Effect of increasing fall factor on peak force.

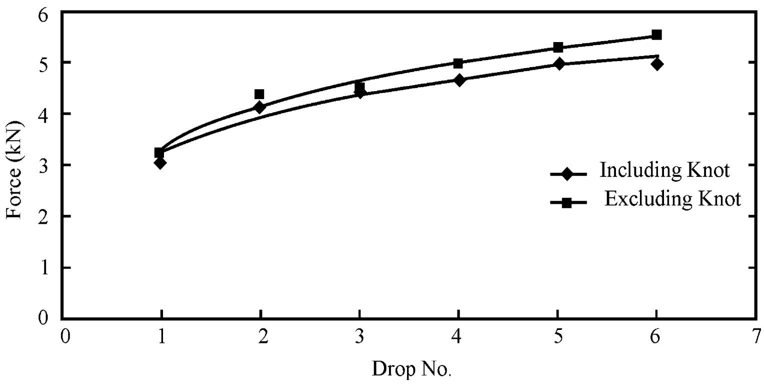

Fig. 7. Effect of repeated drop load on peak force.

Fig. 7. This test, it is felt, may be likened to a climber repeatedly falling, resting on the rope then re-climbing the rock face and falling again.

5.4. Test 4: Effect of rest periods between drop loads on peak load

Again the full 55 kg mass was applied to a new, 85 cm long rope sample and dropped from a height of 79 cm. As in test three the rope remained under a static tensile load for 5 min before being raised to the release

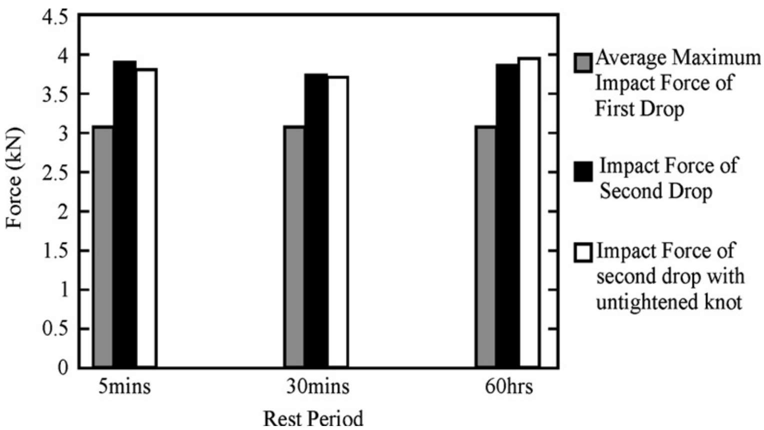

Fig. 8. Effect of repeat drop loading and rest periods.

Table 1
Summary of anchor nut static failure loads and failure modes

Anchor nut type	Failure load (kN)	Failure mode
New DMM (size 10)		
1st failure	12	Shear through upper wall
2nd failure	14	Plastic wall collapse
Used DMM (size 10)	13.5	Break in steel rope upper loop
Used zero (size 11)	11	Break in steel rope lower loop

position. After a 5 min rest period a second drop was carried out. Maintaining the same intermediate static load and rest period a total of six consecutive drops were carried out. The series of drop tests was also repeated using a new sample of rope but also incorporated a knot.

5.5. Test 5: Static loading to failure of anchor nuts

These tests were carried out using an Instron 100 kN tensile testing machine, using climbing nuts in new and used states. They were performed to determine the ultimate failure load and also the failure mode. The failed nuts are displayed in Figs. 8 and 9 and the ultimate loads are summarised in Table 1.

6. Discussion

The drop load test results on climbing rope samples (Figs. 5 and 6) indicate that the basic impact load Eq. (4), as derived using simple energy conservation, holds up well. The fact that experimentally measured peak loads have been found to be generally slightly lower than the theoretically predicted values was to be expected as effects such the rope knot, which is in series with the rope, tend to slightly lower the overall stiffness; a finding also found by other researchers [5]. In addition, the tendency for the not to slip slightly under load is a generally a beneficial feature. Also, as load – extension tests on the rope indicate that the axial stiffness was not constant but tended to increase with extension, as a constant and average value of stiffness was used in the analysis, this is a slightly pessimistic (but conservative assumption)

The anchor nuts tested to destruction (illustrated in Figs. 9–11) all failed at loads just above their specified load ratings despite all failure modes being different as summarised in Table 1. Analysis of these failures is helpful in assessing suitability of their designs as, although they all met their stated ratings, it is evident that there is scope for improvement in the interest weight reduction. The previously used nuts were vulnerable to failure in the upper and lower tight bend regions of the steel cables – which clearly loosen and fray with use. A sling design using a single rather than double rope length, albeit at greater strength, is thought preferable to avoid tight bends. In contrast, the brand new DMM manufactured nut initially failed with the tightly wound

Fig. 9a. A new DMM nut showing first stage failure.

Fig. 9b. A new DMM nut showing first stage failure.

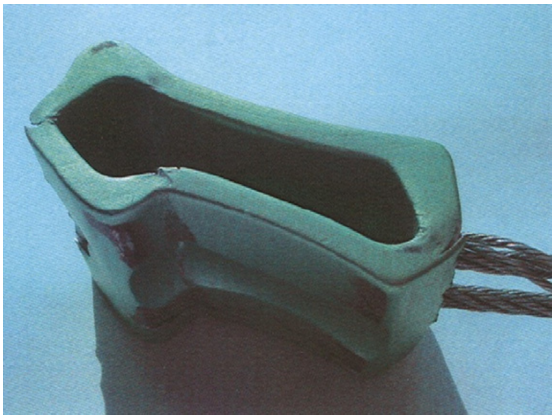

Fig. 9c. A new DMM nut showing second stage failure.

Fig. 10. Used DMM nut showing upper cable loop failure.

Fig. 11. A lower loop failure in a used zero anchor.

wire rope shearing through the anchor nut's relatively thin upper wall thickness. Interestingly, this nut demonstrated a second failure mode. Having cut through the upper wall the wire rope was then held by the lower wall thickness, eventually failing at a similar load through plastic distortion. Having an open section nut, therefore, appears to be very desirable from a weight efficient design consideration as it provides two modes of failure, the first mode can be used to 'cushion' the initial impact and the second mode to provide a final safety support.

The drop load tests on rope confirm the desirability to minimise overall rope stiffness and fall height so that generated impact loads can be minimised. This implies that lower load rated equipment can then be used; a finding also concluded by others [6].

7. Conclusions

Much has been learnt from testing rope samples under falling loads and testing anchor supports to destruction. The main findings are

1. The impact load equation, which is the basis for that widely used for determining desirable fall factors, appears reliable.
2. The stiffness of climbing rope slightly increased after having been subjected to successive falls and recovery times varied.
3. Impact forces increased (nearly doubling) when using aging rope.
4. Failure modes in new anchor nuts differed from that observed in well used ones and this has important implications upon design and usable life.
5. It is highly desirable to have greater flexibility in climbing rope – to minimise potential shock loads – rather than excessive strength.

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