The development of equipment to reduce risk in rock climbing

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Abstract

The historical development of protection systems for rock climbing is summarized. Rapid advances in the design and availability of equipment since 1945 has enabled climbers to fall with much reduced risk of death or serious injury. Mention is made of the wider application of climbing protection equipment to industrial situations and some ideas for the discussion of climbing equipment in teaching examples are introduced.

Keywords: Rock climbing, mountaineering, rope, protection equipment, impact loads, falls.

Climb if you will, but remember that courage and strength are nought without prudence, and that a momentary negligence may destroy the happiness of a lifetime. Do nothing in haste; look well to each step; and from the beginning think what may be the end (Whymper, 1871).

Review of the development of rock climbing protection systems

Beginnings

Rock climbing, a branch of the wider sport of mountaineering, involves an element of risk. This is one of its attractions. In the approximately 120 years since the inception of rock climbing as a sport, the equipment used to protect participants from death or injury has developed from extremely rudimentary to scientifically sophisticated, enabling participants to increase standards of performance whilst still maintaining some element of risk. This subconscious adjustment of an individual's risk 'thermostat,' known as risk compensation, has been noted in other activities such as driving, which becomes bolder when the driver is protected by, for example, air bags, antilock brakes and seat belts.

To the uninitiated, the joining of a team of climbers together on a rope represents a source of danger since, should one slip, the remainder are pulled off. Indeed some of the earliest mountaineering accidents in the European Alps seemed to substantiate this idea, and the term *rope* was used as a noun to describe the system of the climbers and their connecting rope. One well-documented classic accident occurred on 14 July 1865. Whilst on the descent from the first ascent of the Matterhorn, Croz, Hudson, Lord Douglas and Hadow fell from the mountain to their deaths and would have dragged Whymper and the Zermatt guides, the Taugwalders, after them had the rope not broken (Fig. 1). In Whymper's epic book, *Scrambles Amongst The Alps* (1871), he observes that there is no good reason for employing a rope on easy rocks because its use is likely to promote carelessness, but on steep rocks it should be used by adopting the plan of moving only one at a time. He reported that a committee of the (English) Alpine Club tested ropes for mountaineering purposes in 1864 (see Kennedy, 1864) and approved two types, one of manila and one of Italian hemp; both of which could sustain 168 lb falling 10 feet, or 196 lb

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Fig. 1 Rope broken in the Matterhorn accident (Whymper, 1871).

falling 8 feet, and break at a dead weight of 2 tons. The manila rope weighed 6.4 lb per 100 feet (in order to avoid constant conversion in the text of original units, note that 1 lb = 0.45 kg, 1 foot = 0.030 m and 1 ton ≈1000 kg). It is worth noting that the above figures are equivalent to an average sized climber plus the weight of his equipment falling 3 m or a heavier climber falling just under 2.5 m. Manila hemp ropes were made from a fibre obtained from the Philippine abaca plant. The second type of hemp fibre, generally from the cannabis plant, came from India and Italy. Flax ropes were made from the fibre of the herbaceous plant of the same name. Until the advent of artificial fibres, all ropes were made from these natural sources.

The first half of the 20th century

The later years of the nineteenth century and early years of this century, saw a rapid increase in the severity of rock climbs made by an increasing number of climbers. Typically the climbers moved out of the security offered by gullies and chimneys (open grooves), to the more open faces of steep crags. A typical accident scenario at the start of the First World War, is recorded in a classic instructional book of the era by Abraham (1916). "The parting of a rope to which a climbing party is tied…is a frequent accompaniment of an accident. Yet this generally means that the leader has fallen, and but for the breakage of the rope the rest of the party must have been dragged down." Abraham then describes the system in which the leader climbs to a resting place or anchorage, whilst the second man "carefully watches the leader's upward progress, and slowly pays out his rope, probably around some outstanding knob of rock, known as a belay or belaying pin," Fig. 2.

Abraham further describes how the leader, after running out a length of rope, may be able to find a stone wedged in a crack such that, "it is often possible to untie the rope end from the waist, thrust it up behind the stone, *from below*, be it noted, and retie on again." This is an early description of what later became known as a running belay. He says that "the new English Alpine Club rope – and no other should be used – is tested to hold a 12-stone man falling 10 feet through mid-air." Since 12 stone = 168 lbs, this is exactly the same figure quoted by Whymper from 1864, that is 52 years previously.

Abraham described an accident on Eagle's Nest Ridge on Great Gable in 1909 and noted similar ones, when the rope broke at the position of the direct belay, after a leader had fallen. In addition to the accident described by Abraham, we might note that Owen Glynne Jones, a frequent climbing companion of the Abraham brothers, was probably

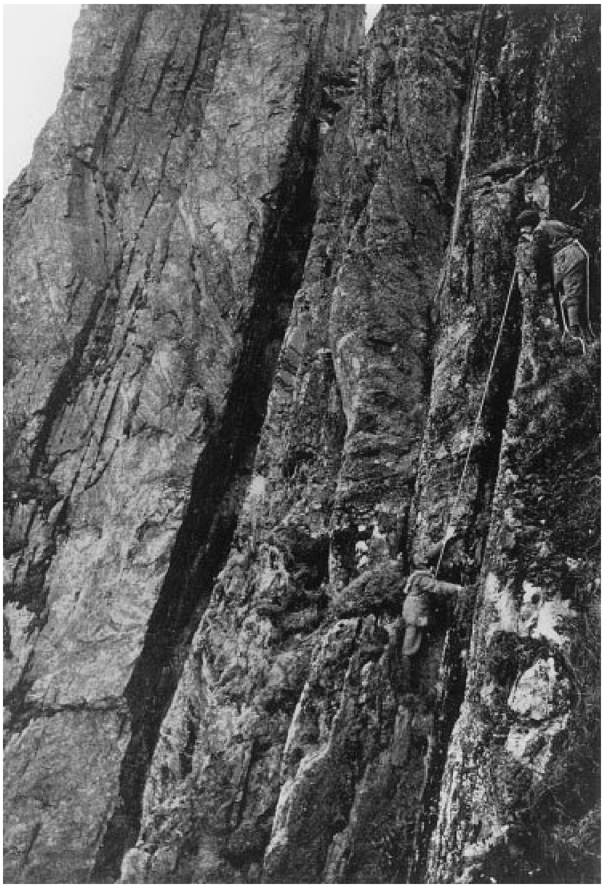

Fig. 2 The 'belaying pin' (Abraham, 1916).

the first to use the threaded belay in a climb with the Abrahams in 1886. Jones was killed in 1899 when the leading guide fell on a route up the Dent Blanche, pulling three other climbers, including Jones, to their deaths. The rope broke leaving one climber still on the mountain. The first fatal climbing accident in the Lake District occurred in 1903 when a party of four fell to their deaths roped together from Scafell Pinacle. It is surprising that in the face of these and similar accidents the lack of real rather than illusory protection to roped climbing parties continued for so many years. Abraham suggested that a double rope might offer a better safeguard, but states "the leader must never slip…If a leader has ever been known to fall, the writer would emphatically advise all climbers not to accompany such a one unless he takes on an inferior position on the rope." It is worth noting that if such advice were to be followed today, there would be a distinct shortage of leaders!

No review of the development of climbing techniques can ignore Geoffrey Winthrop Young's *Mountain Craft*, published in 1920. Young distinguished between an 'anchor,' that is a loop of inactive rope with which a stationary climber secures himself to a rock point, in order to protect himself and the rest of the party while somebody is climbing, and a 'belay' which is the rock-and-rope attachment by which the active rope of a moving man is protected while it is running out or being pulled in. Further, distinction was made between a 'direct belay' where the rope in action connects directly onto or around a rock spike and an 'indirect belay' where some from of human spring is interposed between the active rope and the solid rock. Young recognized that the direct belay was unsound to protect the leader because of the danger of the rope breaking. He then stated that "a long rope may take up much jerk in its elastic spring, but a short rope cannot. This should be more widely known." In a chapter of Young's book on equipment, written by Farrar, the properties of rope are discussed. Because of fatalities due to rope breakages, Farrar had some tests performed and reported that flax rope, in terms of strength and extension, surpassed weight-for-weight any other rope. For a 1.4-inch (3.5 cm) circumference rope, the breaking strengths of 1904 and 1992 lb were reported for flax and manila, respectively, along with corresponding extensions of 16.3 and 12.3% on a 5-foot length of rope. Further, the work required to break a test length of 5 feet was 451 and 332 foot-pounds (1 foot-pound ≈ 1.4 J). As far as the author is aware, these are the first references in the literature to the importance and quantification of the energy absorbing properties of rope.

These figures represent very low energy absorbing capabilities: as an approximation, noting that the work required to break the flax rope is 90 foot-pounds per foot, then an extremely short drop of a 12 stone man (168 lbs) on a dead belay will be sufficient to break the rope. We note that these figures seem small compared with the results for the Alpine Club drop tests mentioned earlier.

The publication of a paper in 1927, in the *Rucksack Club Journal* by Bower was remarkable for its penetration combined with humour (Bower, 1927); it will be referred-to later in the section on pedagogical applications. The tests reported by Young are recalled, together with later tests which gave a value of 152 foot-lb/foot for the resilience of manila rope. However, the conclusion remained the same, that "the rope will break no matter what its length may be, when it is fixed at one end to a belay just above a ledge from which the ecstatic experimentalist escapes to Erebus." In the light of subsequent developments, there follows an interesting suggestion "if a leader contemplates making a speciality of 'first descents' he had better invest in an oil-filled shock-absorber, in which the kinetic energy of the fall is absorbed by the oil being forced past the clearance between the piston and the cylinder. The latter is attached to a special waist belt, and the climbing rope to the piston rod. The more dashing juvenile spirits will then be readily identified from a distance by a sporty smell of Castrol pervading their neighbourhood." Despite the humour, the conclusion is serious and, by now, familiar: "The Moral of Morals then is: DO NOT FALL."

Bird, in the *Climbers Club Journal* of 1931, published an article called "the strength of ropes" (Bird, 1931) which summarized the current knowledge and added a little more, including the important consideration that the maximum load generated on the climber by the rope should not "from anatomical consideration" exceed 1000 lb. It should be remembered that the method of attaching the rope to the climber was very simple – a bowline knot round the waist. Thus shock loads were transmitted through a very small area and could themselves cause considerable damage to the falling climber – yet another reason for the conclusion of this paper, in which the results "confirm the oft-repeated dictum that the leader must not fall."

Complete lack of belaying by the leader, coupled with an inadequate follower's belay caused a fatality on Dow Crag in April 1932 and an injury to one of the climbers, H. W. (Bill) Tilman, which hampered him throughout his famous career, (Chorley 1932).

A further book by G. D. Abraham (1933), disappoints by adding nothing new to his earlier-cited work as regards ropes and belaying methods, but a paper by a climber then at the height of his powers, A. T. Hargreaves in the *Fell & Rock Club Journal* (1935), illustrates a classic indirect belay (see Fig. 3). He offers advice about a better attachment to the rope for the leader, by making a rudimentary harness under the armpits and over the shoulder and illustrates a free-running thread belay, in which a spare loop of rope is threaded round a clockstone and the rope is run through this loop rather than behind the clockstone. In end notes added by the Journal Editor (G. R. Speaker), a discussion is held on the ageing of ropes (with the advice to retire a rope after 100 climbing hours use) and the need to scrap a rope after a fall, together

Fig. 3 Attachment to an anchor (Hargreaves, 1935).

with some estimates of the reduction in rope strength caused by various kinds of knots (as much as 40%). There is a important reminder of a more general point: any form of stress concentration will serve to reduce the performance of a rope. The Munich method of using an independent waist rope is claimed to overcome several weaknesses – this is an early (the first?) example of acknowledgement of superior practice from overseas. Belaying by a loop and karabiner (an oval metal ring with a sprung side opening) was mentioned by Peacock in his textbook *Mountaineering* first published in 1941.

After the Second World War

The Second World War saw the introduction of a new 'wonder;' material, nylon, and commando soldiers were trained to climb using it and any other aid that made scaling cliffs possible: the ethics of sport had no place in the serious business of war. The popularity of rock climbing after the war merited the publication of a Pelican paperback book, *Climbing in Britain* by J. E. Q. Barford (1946). Details of hemp and manila ropes were given and it was added that "experiences in the services has shown the virtue of nylon and it is not improbable that soon this may become the standard rope." In austerity Britain, however, it was hard to come by as was money for any kind of climbing equipment; the author suggested that "As a measure of economy it is permissible to cut out an injured section of the rope and splice the join[!]"

Another handbook was published in 1955, The *Technique of Mountaineering* by J. E. B. Wright. Details of hemp rope were still being quoted and nylon was quoted as having a tensile strength of 4000 lb for full-weight (5.50 lb/100 foot) rope, but "although nylon remains more flexible than hemp when wet, one of its great disadvantages is that it melts quickly under friction heat." For this reason, a thin hemp waist line, wrapped four or five times round the body before being knotted was used in conjunction with a karabiner to attach the climber to a rope (the present author was introduced to climbing in 1963 when this method was still in common use). Wright recognized that "good mountain walking, climbing and the use of mechanical devices is, in the main, *applied dynamics*" and stated that "two dynamic theories are widely accepted; the dynamic theory of Kant which claims that energy is dependent upon mechanical activity and the doctrine of Leibnitz that all substance involves forces." One supposed he knew more about climbing than dynamics! He did, however, introduce to a wide audience the work of Tarbuck (1949–1952), who introduced a sliding friction knot to provide elasticity in the belay chain (see also the dash-pot of Bower) and Wexler (1950), who published theoretical calculations on the dynamic theory of belaying, which will be introduced in the next section of this paper.

Developments since the mid-1950s have been rapid and effective. The following summarizes what was already a brief summary, originally published to accompany a television programme *Fear of Falling* in 1993 (Stevenson, 1993).

The first type of nylon rope was hawser-laid, formed from three strands. In the 1950s a German company invented the *kernmantel* rope, which used narrow nylon strands running the length of the rope, the kern, protected from abrasion and dirt by a braided sheath, the mantel. This type of rope is less prone to kinking than the hawser laid nylon rope, has great strength; typically a 11 mm diameter rope has a breaking strength of 2300 kilograms and is now the only type of rope used for climbing.

In the 1960s the problem of tying onto the climber via a waist loop was addressed, Fig. 4. Using this method, the force of a fall was concentrated around the waist, where the soft internal organs, the ribs and the spine could be damaged. Further, after 10 min or so hanging in such a device, the climber would lose consciousness. Thus, despite the improvements in the rope properties, the traditional maxim, the leader must not fall, still held. The first solution was to use wide waist-belts. The first ones were made in leather from machine-belting from old woollen mills in the author's home district, Saddleworth. The leather was replaced when flat nylon webbing became available, but in 1970 Don Whillans invented the sit-harness, a belt with integral leg-loops which

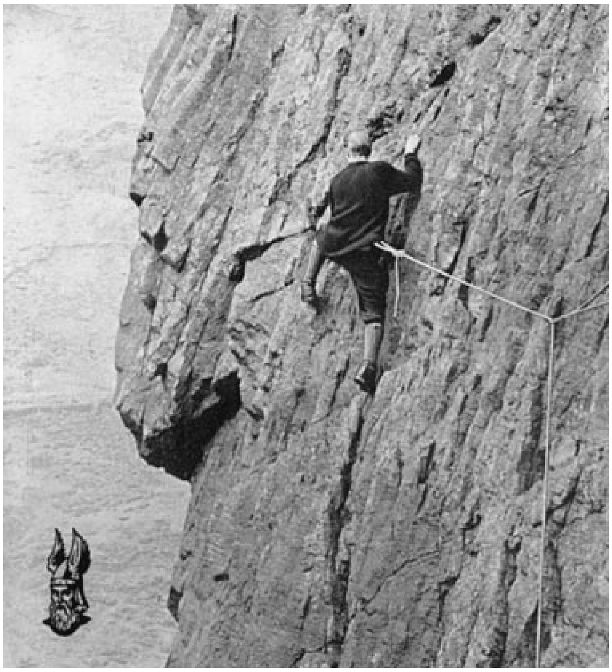

Fig. 4 An advertisement for rope *c.* 1965. Note the use of a running belay, the simple knotted waist attachment and the rubber soled boots.

transferred some of the load to the legs. Various improvements and modifications have subsequently been made and modern harnesses are now lightweight but comfortable and efficient in distributing load between thigh muscles and the pelvic girdle.

If no clockstone existed for the provision of running or main belays, climbers inserted their own small stones into cracks, this, in the main, avoiding the use of pitons (metal spikes hammered into cracks) which had been developed by the Munich school before the war but were generally thought unsporting by British climbers. Artificial clockstones made of steel, then aluminium became available in the late 1960s, in various sizes and geometries such as hexagonal and tapered wedge designed to suit most cracks (Fig. 5). During this period, the strength of karabiners improved dramatically with a combination of better, lighter materials (aluminium and titanium alloys) and better design to eliminate bending loads and strengthen the gate, through which the rope had to be inserted. Nylon webbing tape became available to attach the belay, natural or artificial, via a karabiner, to the main climbing rope or climber. These improvements in belaying opportunities, coupled with the improved rope and harness, meant that leaders might be able to fall and escape without serious injury. Although not the topic of this present review, it is worth noting that boots had remained unchanged for more than a century: heavy nailed boots being replaced by rubber soled 'Vibrams,' followed by thin but rigid 'Klettershuhe' and finally light but stiff smooth rubber 'PAs' or 'EBs' by around 1970 (see Brigham, 1976).

Recent Developments

One the most important developments in the last 15 years has been the introduction of friction belay devices. Such devices clip, via a karabiner, to the harness and a rope is passed through the device in such a way as to generate a large frictional force due to a large angle of wrap round the device. Holding a fall is thus made much more straightforward for the second man and, further, should the leader be injured, it is much easier for the second climber to transfer the load directly to the belay, release himself and go to the aid of the leader.

A further ingenious development has been the moving-cam belay device which can be inserted into parallel or flared cracks and can provide protection from high shock loadings. Introduced from America, these so-called 'friends' have made running belay placements both easier and more reliable.

Rising prosperity has enabled climbers to buy and use large quantities of protection equipment. Climbs which were previously difficult to protect can now be 'stitched' together with running belays. Systems of double rope operation are in wide use on more difficult climbs and the gear used is generally much more reliable. Ropes have adequate strength and resilience, belay devices are tenacious and strong and, in general, the weight of equipment to be carried by climbers has been greatly reduced. If the protection gear is correctly placed, the leader can be reasonably confident of surviving a fall. Indeed, many would say that if a leader does not fall, he is not trying a hard enough climb! In view of what was said earlier on risk compensation, it would be interesting to see if accident statistics have decreased with the availability of superior equipment. This study needs access to considerable historic and current data and, as far as the author is aware, has not yet been satisfactorily completed. A separate branch of the sport, performed on pre-bolted routes or even on indoor artificial climbing walls, has developed, which requires outstanding agility and gymnastic strength, but can be performed at almost no risk should a fall occur.

Fig. 5 Development of equipment. Clockwise from lower left: Alpine rope and boots *c.* 1900, top, dynamic loads measured in the mid 60s and, lower right, harness and chockstones introduced in the same period.

Simple theory of the dynamic loading of climbing ropes

As previously noted, an appropriate theory of the dynamic loads generated in ropes by falling climbers was produced by Wexler (1950). Although this theory contains several simplifications, it produces some sound general conclusions and is worth reproducing in part. Consider the situation shown in Fig. 6(a): a climber has moved above an anchor, A, past a running belay placed, at B, by a distance *H*/2, to C. At this time, the total length of rope run out is *L*. The climber then falls freely and vertically, as

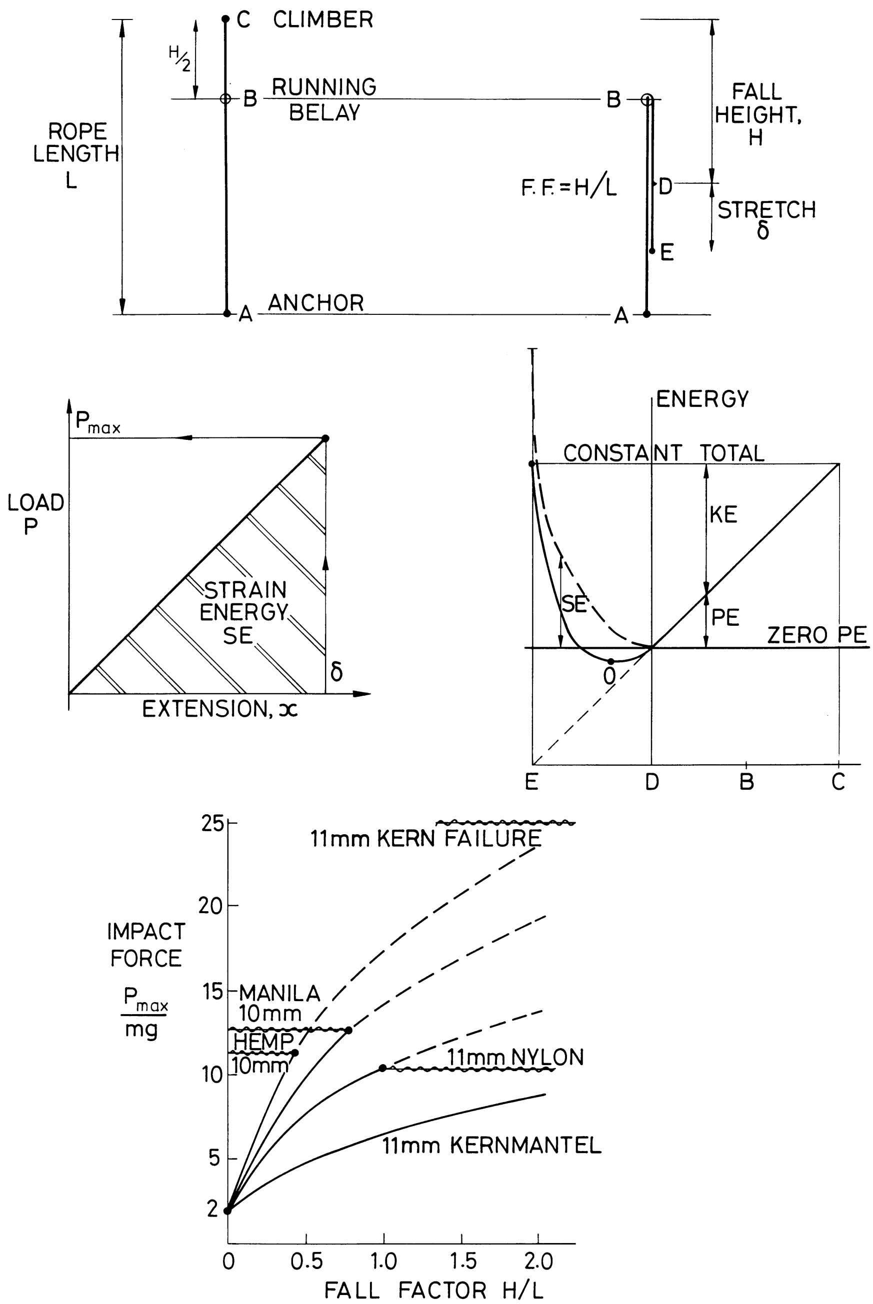

Fig. 6 Theoretical forces generated in a fall compared with rope strength. See text for details, rope diameter indicated in mm.

indicated in Fig. 6(b). At a distance $H/2$ below the runner, at D, the rope becomes taut and begins to extend. At position E, the rope has stretched by its maximum amount, δ, and the climber is momentarily at rest. The sequence of events can be described in terms of energy exchange, the total overall energy of the system remaining constant during the process. At point C, the energy of the system is the potential energy (PE) of the climber due to his elevated position. As he falls, PE is exchanged for kinetic energy of motion (KE) until the point D is reached. The rope's stretching then begins to store energy in the form of strain energy (SE). At E, the PE has been reduced to a minimum, the KE to zero and the strain energy is a maximum. If we assume that the rope is *elastic*, Fig. 6(c), then the load, P, induced in the rope is proportional to the extension, x. It is convenient to express the load as $P = kx/L$, where k is a measure of the rope's elasticity. The strain energy stored is the (shaded) area under the load/extension line and is given by $SE = kx^2/2L$. These energy changes are shown on the sketch of energy/position in Fig. 6(d), on which the PE datum corresponds to the height at D. Since $PE = mgh$, where h is the distance from the datum, m is the mass of the climber and g is gravitational acceleration, the PE decreases linearly from C to E, whilst strain energy begins to accumulate with the square of the stretch from D to E. Notice that the sum of the PE and SE follows the solid line drawn between ED and that the distance between the constant total overall energy, and this complete solid line is the KE. The maximum speed occurs at extension d when the force in the rope just balances the downwards force on the climber due to gravity in $mg = kd/L$, the minimum of the PE + SE sum, position O on Fig. 6(d).

By equating the total energy at C to the loss in PE and the gain in SE at E, we can write:

$$mgH = -mg\delta + k\delta^2/2L$$

The solution to this quadratic equation for the maximum rope stretch δ can be written

$$\delta = \frac{mgH}{k}\left[1 + \sqrt{1 + \frac{2k}{mg} \cdot \frac{H}{L}}\right] \qquad (1)$$

Alternatively, in terms of the maximum force p_{max} corresponding to the stretch δ,

$$P_{max} = mg\left[1 + \sqrt{1 + \frac{2k}{mg} \cdot \frac{H}{L}}\right] \qquad (2)$$

Notice that the static force required to support the climber's weight is mg, so that the square root term in eqn 2 represents the magnification factor due to dynamic loading, and for a given rope stiffness, k, and a given climber, m, depends on the ratio H/L; that is the height of the fall divided by the length of rope run out. This ratio has been termed the fall factor (FF). Note that the FF can vary from 0 to 2; a value of 1 corresponds to a fall past a running belay halfway between an anchor and the maximum height reached by the climber and a value of 2 corresponds to a fall past a fixed belay or anchor. *The absolute values of the height fallen are unimportant*: the forces generated are governed by the FF ratio.

Equation 2 has been evaluated for the case of an 80 kg climber falling on three different kinds of rope. The required stiffnesses, k, for manila and hemp were taken from data in a report in the *Alpine Journal* (Anonymous, 1931), and for nylon from Wexler (1950). As the fall factor increases, the dynamic loads increase. In each case, the force needed to break the rope has been added to the graph of Fig. 4. Notice that the relatively high stiffness for manila and hemp, means that high dynamic forces are generated and Fall Factors of approximately 0.5 and 0.75 are sufficient to break these ropes. The superiority of modern kernmantle is clearly shown: the low stiffness generates lower dynamic loads, such that even at FF = 2, the dynamic load is about 2.5 times less than the strength of the rope.

When these results were originally published, they caused considerable concern. Wexler (1950) showed how the dynamic loads could be reduced by resilient belays or by letting the rope slide on impact. Tarbuck (1949–1952) used the same arguments and suggested the use of an eponymous knot which could slide and absorb extra energy. Although resilient belays are still used, modern belay devices use sliding friction to attenuate dynamic loads. The simple analysis, resulting in eqns (1) and (2), can be used to estimate the time taken for the load to rise during dynamic loading. If the equation of motion for the mass is written as

$$m\frac{d^2x}{dt^2} = mg - \frac{kx}{L}$$

and reorganized to the standard form, it is easily recognized that it represents a single degree of freedom system subjected to a restoring force. If the rope could accept both tension and compression, the system would execute oscillations with frequency $\omega^2 = k/mL$. As an approximation, then, the rise time T_R to maximum load is given by the period of vibration/4. Thus

$$T_R \approx \frac{\pi}{2}\sqrt{\frac{mL}{k}}$$

Now the time taken for a climber to fall freely under gravity from 3 m above an anchor, to 3 m below is simply $\sqrt{(2H/g)}$ with $H = 6$ m and $g = 9.8 \text{ m s}^{-2}$, i.e. 1.1 s. Assuming an 80-kg climber falling on a kernmantle rope for which k is typically 1100 kg, then the load rises to a maximum in 0.23 s. This is an extremely short time; it is essential that the second man concentrates! The awful suddenness of the events subsequent to a fall has to be experienced to be believed.

It should now be clear that the high impact forces can injure a fallen climber – the stretch of the rope serves to limit these forces to an acceptable level. Military research on the opening impact of a parachute on the human body have suggested that 12 kN is the maximum force a body can withstand without injury. This figure has been used as the basis of a standard test laid down by the Union Internationale des Associations d'Alpinisme (UIAA). In this test, a drop weight is used to simulate a leader's fall. The weight is dropped free for 5 m with 2.8 m of rope in use, i.e. . an FF of 1.78. The weight used for a single rope is 80 kg and during the first fall the impact force must not exceed 12 kN. If this test is repeated after a short time interval, it is found that the stiffness of the rope increases, thus increasing the impact force. The effect tends to saturate after some 7 or 8 falls – a good rope will still then have an impact force of less than the maximum allowed value.

Recent research has discovered two references, Goodlet (1938) and Goodsell (sic) (1939), which predate Wexler's work. In the interest of priority, a discussion of these papers can be found in the Appendix.

Applications to other types of protection systems

Developments in rock climbing equipment have enabled many apparently dangerous industrial jobs to be performed in comparative safety (Hold, 1997). The maintenance of towers and cables of suspension bridges, the care of power lines and towers, the inspection of narrow flues in chemical plants, the cleaning of the exterior of high buildings and the investigation of bird nesting sites on steep cliffs are all examples of situations where 'personal protection equipment' against falls is vital.

When this paper was originally being written, two groups of climbers were pitched against each other at the site of the proposed Newbury by-pass in Southern England. One group have used their climbing skills to climb up trees which are to be uprooted and the other group have been hired at £250 per day to evict them!

In general, workers in these exposed situations wear a nylon webbing harness and are either protected by a climbing rope in the normal manner or are attached via a short webbing strap and karabiner to an anchor. The difficulty arises in that a fall onto this short attachment generates a Fall Factor of 1 and therefore high dynamic loadings which can injure the user. If the karabiner can slide downwards before it comes up against a stop then Fall Factors higher than 2 can be generated; a situation which can also occur on fixed cables such as those in the Dolomites known as Via Ferrata. To guard against these situations, special energy absorbing tape has been designed in which a loop of the tape is stitched together and folded in a zig-zag manner to occupy a short length. On impact loading, the tape 'unfolds' absorbing energy whilst its length increases, thus providing a kind of damper to absorb the shock. Such industrial safety lanyards have been designed to comply with detailed European Standards which require, *inter alia*, that the length of the lanyard including the energy absorber shall not exceed 2 m and that it should withstand a dynamically applied force of 100 kg with an FF of 2, such that the breaking force shall not exceed 6 kN and the arrest distance shall not exceed 5.75 m.

Many readers will recall seeing film of the spectacular land-diving, or *naghol* ceremony, held in the village of Vanuatu on the Pentecost Island in the South Pacific. This is part of an age old ceremony, the Festival of the Yams, held every April and May to celebrate and bless the crop. Village men and youths leap from a 24-m high wooden tower with only two springy liana vines tied to their ankles. If they judge the distance right, their foreheads will brush the soft soil, symbolically refertilizing it. Clearly, this is a very dangerous activity – during a very well-planned demonstration held to honour the visit of Her Majesty The Queen in 1974, a diver was killed. Strange then that people all over the world have copied this practice and re-named it *bungee jumping*. Naturally, devotees of this strange sport do not rely on the uncertain strength of liana vines, but use a specially developed bungee rope (Fig. 7).

Fig. 7 Bungee jumping on a thick, very elastic rope.

These ropes (or cords) are typically much thicker than climbing ropes, often in the order of 23 mm diameter. The internal structure consists of a large number (≈ 400) of elastomeric filaments which run the length of the rope. These filaments are held together by two outer layers of a woven synthetic material. The strength of such ropes is considerably lower than climbing ropes, e.g. about 600 kg, but the extension to failure is about an order of magnitude higher at about 170%. This very high elasticity gives the characteristic yo-yo motion at the end of a bungee jump and, of course, acts to reduce the dynamic loads in the rope. Typically, recalling that a bungee jump has a fall factor of 1, the jump of an average sized person will generate a peak dynamic load of about four times body weight and an extension of about 90%. Strong internal damping within the rope acts to reduce the amplitude of the oscillation at the end of the jump.

Pedagogical applications

Application of the principles of mechanics and materials to climbing offer the opportunity to inject relevance and excitement, as well as practical experience, into the teaching of young students of engineering. At my own University of Sheffield, we note that many students are attracted to our course because they (rightly) regard Sheffield as the leading centre of the UK climbing scene, and they avail themselves of the many opportunities to climb on gritstone outcrops in the surrounding Peak District and, latterly, on several indoor artificial climbing walls.

Any serious student should be directed to the paper by Bower (1927). This paper deals in a classical dry academic manner with the theory of climbing equilibrium using geometric and trigonometric analyses. The mechanics of slab and wall climbing, together with land traversing, are discussed together with the previously mentioned notes on belaying and rope strength. It is sobering to reflect that the quality of writing and the subtle humour, combined with sound practical conclusions, is not now generally seen in climbing club journals. Students may care to ponder on the complexity of the analysis and the brilliance of the use of English which was attained some 70 years ago and use this paper as a model for their own efforts!

More recently Hudson & Johnson (1976) produced an excellent article in a teaching journal in which they demonstrated the use of the principles of friction and equilibrium to climbing positions and discussed the mechanics of arresting a fall, including the effect of rope friction. This paper was the basis of an article designed for a much wider audience (Walker 1989) which subsequently appeared in Scientific American.

Some standard text books have included problems involving the dynamic loadings of climbing ropes: Sandor (1987) is a splendid example and also includes many cases of the application of mechanics principles to skiing, another area of considerable interest to many students. Jones (1993) devoted a chapter to this topic in a text book of case studies. The analysis of the dynamic loading of long thin structures is, of course, not new. It appeared in standard engineering text books long ago (e.g. Goodman, 1899). He examined the case of a weight falling onto a collar at the end of a vertical bar. The now well known $2\times$ magnification of load due to a suddenly applied load dropping through an infinitely small distance was derived. In a curious way, over the years Goodman's theory has become transmuted into the Goodman law of fatigue, which relates permissible levels of mean and cyclic stresses. Further discussion of this interesting point awaits a future publication. The dynamics theory of rope loading can, of course, be applied to problems such as the winding of heavy cages in mine shafts. When the author, early in his career, installed new gears in the winding mechanism of such systems and was 'invited' to be the first man down, he had more than an academic interest in the strength of wire ropes!

Further applications of climbing equipment technology to teaching programs could include discussions of materials developments (polymers, alloys, heat treatments) stress/strain relationships including nonlinear behaviour and strain rate dependence, the effects of stress concentration and, particularly in the design of karabiners, shape optimization and the minimization of bending effects.

Concluding remarks

For near 100 years since the inception of the sport of rock climbing, very little progress was made to improve the chances of surviving a fall. Since the Second World War rapid improvements in equipment and technique have been made and the level of risk involved has been substantially reduced. With correctly placed protection equipment, leaders now fall and live to tell the tale!

Appendix

During a literature search, the author found a paper in the *Climbers' Club Journal* (Goodsell, 1939), in which the theory of the dynamic loading of climbing ropes is developed, and which predates Wexler (1950). The stated affiliation of the author, Professor B. L. Goodsell, Cape Town University, caused enquiries to be made at that location. No Goodsell could be found in the records, but B. L. Goodlet held the Chair in Electrical Engineering just prior to and partly during the Second World War. Suspicions of a misprint in the *Rucksac Club Journal* were confirmed when an earlier paper, Goodlet (1938), came to light.

These two papers contain much identical material. The first begins thus: "Although it is generally known that the tension set up in a rope by the sudden arrest of a falling body is greater then the weight of the body, very few climbers realize how large this tension may be. The writer's attention was drawn to this matter by a recent fatal accident on Table Mountain, in which an apparently sound rope broke when the leader is said to have fallen an initial distance of only a few feet. A calculation made in an idle moment led to such an unexpected conclusion that the matter was pursued experimentally. Theory, experiments and conclusions are given below."

The accident referred to above happened in 1937, when Alan Sluman fell to his death on Slangolie Buttress, Table Mountain, whilst climbing in a party led by Brian Cameron. Goodlet's papers derive formulae for the dynamic loads generated by falls; show how the loads may be reduced by some form of secondary spring, thus anticipating Wexler's dynamic belay technique and stress the weakening effect of knots and the theory was supported by a number of experiments on both thin twine and climbing rope.

Goodlet had a distinguished career. Born in 1903 of British parents in St. Petersburg, he escaped from Russia during the Revolution and received an engineering education in Sheffield and Cambridge. After various academic appointments, he became Head of the Engineering Research and Development Division at Harwell and was later in charge of the mechanical design aspects of the Calder Hall reactor. Obituaries can be found in *The Times* of 28 October 1961 and *Nature*, 30 December 1961.

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