MECHANICS OF BUNGEE JUMPING

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Abstract. The sport of bungee jumping has become very popular worldwide over the past decade. The author was recently commissioned to investigate a fatal accident, which occurred during a bungee jump. As a result of this investigation, it has emerged that the equipment used for bungee jumping has evolved in an empirical way, using a mixture of braided rubber rope originally intended for aeronautical applications, and ancillary equipment designed for climbing protection. Many sporting organisations and government agencies have established codes of practice for bungee jumping. However, these codes are essentially empirical, and are not based on a quantitative materials engineering analysis of the forces generated in the load train in relation to the strength of the components. The fatal accident is presented as a detailed case study, in which the load/extension characteristics of the bungee rope and the end attachment webbing are measured, and used as the critical inputs to an energy-based analysis of the complete jumping process. It is shown that the bungee rope was unable to absorb all the potential energy of the falling jumper, with the result that the jumper broke away from the bottom end of the rope. The paper also discusses the urgent need for a quantitative code for the design and use of bungee jumping equipment, based on rigorous materials engineering analysis.

1. INTRODUCTION

The sport of bungee jumping has become very popular worldwide over the past decade. The author was recently commissioned to investigate a fatal accident, which occurred during a bungee jump. As a result of this investigation, it emerged that the equipment used for bungee jumping has evolved in an empirical way, using a mixture of braided rubber rope originally intended for aeronautical applications [1], and ancillary equipment designed for climbing protection. Many sporting organisations and government agencies have established codes of practice for bungee jumping [2-4]. However, these codes are essentially empirical, and are not based on a quantitative materials engineering analysis of the forces generated in the load train in relation to the strength of the components. The fatal accident will presented as a detailed case study, in which the load/extension characteristics of the bungee rope and the end attachment webbing are measured, and used as the critical inputs to an energy-based analysis of the complete jumping process. It will be shown that the bungee rope was unable to absorb all the potential energy of the falling jumper, with the result that the jumper broke away from the bottom end of the rope. The paper also discusses the urgent need for a quantitative code for the design and use of bungee jumping equipment, based on rigorous materials engineering analysis.

2. CASE STUDY

2.1 Background

A bungee-jumping accident occurred in the UK in 2002, which resulted in the death of the jumper. The following items were made available for the investigation: the bungee-jumping equipment used in the accident jump, together with similar items of equipment as used in other jumps; videotapes, including a videotape of the accident itself; photographs taken at the scene of the accident; and supporting documentation.

The essential details of the accident were as follows. According to the pathology report, the jumper weighed 132 kg and was 1.83 m high. He jumped from a crane-mounted cage, which had its floor approximately 53 m above ground level. The bungee rope consisted of three nominally identical cables used in parallel, and taped together with insulating tape at regular intervals. The inboard end of the rope was secured to a pair of snap hooks mounted on the vertical centreline of the cage, and positioned approximately 1.35 m above the cage floor. The rope passed vertically down through a large circular hole in the floor of the cage. Before the jump commenced, the rope would have turned back up again so that the outboard end would have entered the cage through the access gate and lain on the cage floor.

The jumper was attached to the outboard end of the rope by means of a pair of cuffs pulled tight around the lower legs. Each cuff was attached to the end of the rope by a webbing strap. Measurements of the cuffs indicated that, when a jumper was hanging upside-down from the outboard end of the rope, the soles of his feet would have been approximately 0.36 m below the end of the rope.

As a safety measure, the jumper was independently attached to the end of the rope by webbing secured to a body harness. The webbing was labelled "MAMMUT 2500 daN UIAA" and "Made in SWITZERLAND". Mammut are a well-known Swiss manufacturer of climbing equipment. 2500 daN means 2500 "deca-newtons", i.e. 2500 x 10 N = 25000 N (25 kN)(2.55 tonne). UIAA is the acronym for the "Union Internationale des Associations d'Alpinisme", which accredits mountaineering equipment as part of its activities. The strength rating applies to an endless sling (with a factory-sewn lapped joint), which is a standard item of climbing equipment. The nominal strength of a single length of webbing tape is half this figure, i.e. 12500 N. The piece of webbing attached to the body harness was a single length of tape, which appeared to have been cut and opened-out from an endless sling. The piece of webbing attached to the bungee rope was an endless sling. The endless sling and the single length of webbing were knotted together near the jumper's feet. The breaking strength of this assembly would have been less than 12500 N because of the weakening effect of the knot. The total length of the webbing assembly was 2.13 m, of which 1.28 m was single. Measurements indicated that, when a jumper was hanging upside-down supported by the cuffs, there would have been approximately 0.60 m of slack in the webbing.

In the accident, the jumper jumped off the edge of the cage through the opened gate, taking the outboard end of the bungee rope with him in the normal way. During the descent, he moved from an upright to an inverted position, and began to apply force to the rope. However, with the rope vertical and under tension, his legs pulled out of the cuffs. Tension was then applied to the safety webbing, the single length of which snapped at the knot near his feet. The jumper then descended by free fall to the ground below. He was wearing long trousers (made from thin smooth fabric) and short socks, but no shoes.

2.2 Examination and testing of bungee rope

The bungee rope was laid out flat on the floor and pulled straight but free of tension. The unstretched length of the assembly from the webbing loop at the inboard end to the karabiner at the outboard end measured 15.60 m. The bungee rope consisted of three apparently identical cables set side-by-side and taped together with insulating tape at regular intervals. The outboard end was protected with a padded sleeve covered with a fabric jacket. Each cable had a braided sheath (19 mm OD) containing a large number of fine, parallel rubber filaments as the load-bearing elements.

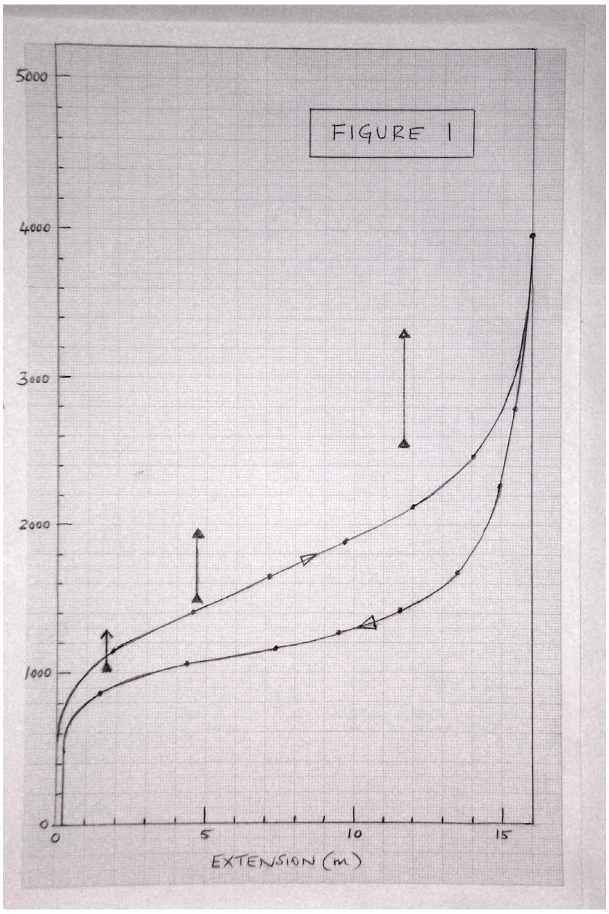

Fig. 1. Force/extension curve for the bungee rope, showing both loading and unloading curves (solid lines). The force/extension characteristics for a new rope consisting of three 19 mm cables, as specified by BS 3F 70, are shown as triangular data points.

The tapes and the padded sleeve were then removed, and the three cables separated. One of the cables was tested to an extension of 16.0 m (100% strain). At this extension, the measured force was 135 kg (1324 N). The force/extension curve for the complete assembly of three cables was obtained by multiplying the forces measured in the single cable by a factor of three. As shown in Fig. 1, the curve is highly non-linear, and is typical of that for rubber. Note that, at the extension of 16.0 m, the force rises almost vertically with extension. The breaking strength of the rope was not determined on safety grounds, but is likely to be much higher than the maximum force of 3972 N obtained from the test. Nevertheless, the rope had become a very stiff structural element at an extension of 16.0 m, and a small additional extension would probably have caused failure. The extension of 16.0 m can therefore be considered as being the "limit of extension" in practical terms.

The area under the force/extension curve represents the stored strain energy in the complete rope assembly. The fact that the unloading curve falls well below the loading curve means that only a proportion of the stored strain energy is released on unloading. This hysteresis energy loss explains why in a normal bungee jump, the jumper rebounds to a height significantly less than the height of the cage.

2.3 Testing of safety webbing

A tensile test to fracture was carried out on a webbing assembly identical to that which failed in the accident. Fig. 2 is a photograph of the sling after fracture, and Fig. 3 is a graph of the force/extension curve. The sling broke at only 5000 N near a knot.

Fig. 2. Webbing assembly identical to that which failed in the accident (after tensile test to fracture).

2.4 Analysis of data

The mechanics of the fatal jump was analysed using an energy-based approach. In the first stage of the descent, the jumper is in free fall. He progressively loses potential energy, which goes into progressively increasing his kinetic energy (and hence his speed). However, once the rope becomes taut and then stretches, it absorbs strain energy. In this second stage of the descent, the loss in the potential energy of the jumper is converted into strain energy as well as kinetic energy. This has the effect of slowing the jumper down. However, the jumper will only be arrested safely if all his potential energy can be absorbed as strain energy in the rubber.

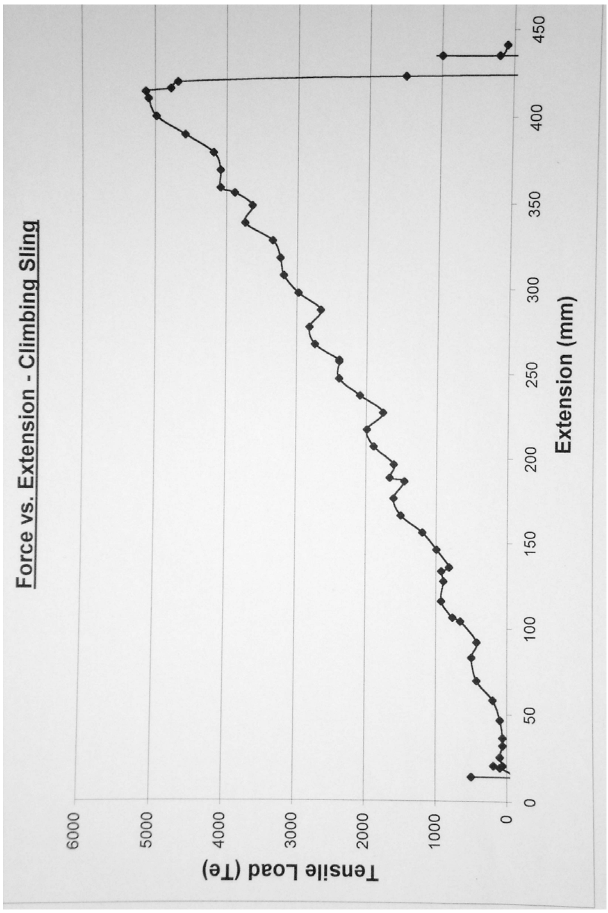

Fig. 3. Force/extension curve obtained from tensile test of webbing assembly shown in Fig. 2.

The calculations show that the maximum strain energy which the bungee rope can absorb before it reaches the limit of extension (the area under the loading curve in Fig. 1) is 28660 J. However, the potential energy released by the jumper as he falls to the limit of extension is 42344 J. This leaves a surplus of 13684 J as kinetic energy, so he continues to travel downwards (at a speed of 14.4 m/s) rather than being arrested by the rope.

Fig. 4 shows a graph of the speed of the jumper as a function of distance fallen, produced from the energy calculations. At the end of the first stage of the descent (free fall) the jumper has fallen 16.7 m and has reached 18.1 m/s. In the second stage of the descent (tensile extension of the rope) the jumper is slowed down progressively as the rope stretches, reaching a minimum speed of 14.4 m/s after falling a total distance of 32.7 m. Although this minimum speed of 14.4 m/s is much less than the speed which would have been reached in free fall (25.2 m/s) it is well in excess of the zero speed required for a safe arrest.

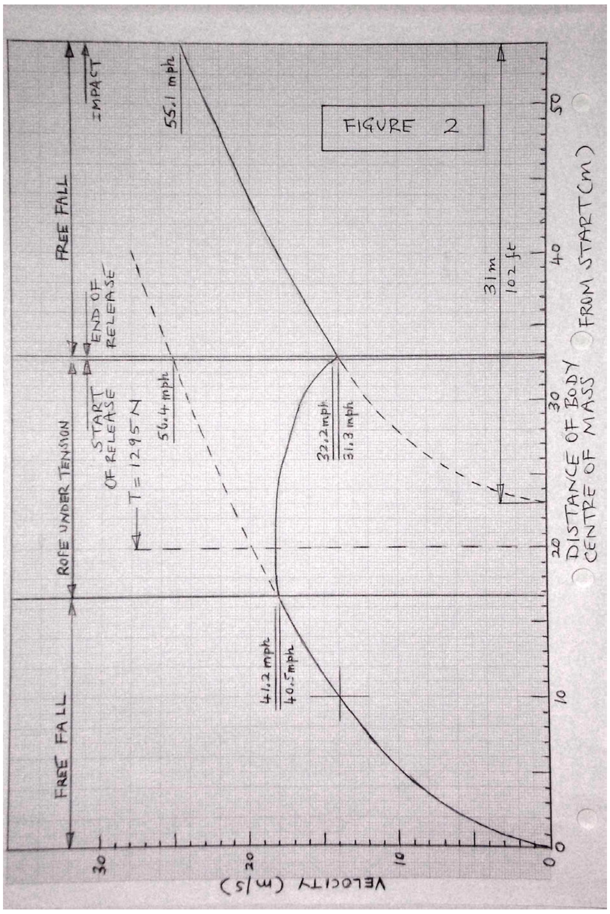

Fig. 4. Graph of speed of jumper versus distance fallen, obtained from the energy calculations.

Fig. 5 shows a graph of elapsed time as a function of distance fallen, produced from the energy calculations. The initial free fall lasts 1.85 s, and the rope extension lasts a further 0.95 s. The total time of 2.8 s compares very well with the average time of 3.0 s which was timed from the videotape of the accident. The small (7%) undershoot is probably due to neglecting wind resistance in the calculations.

2.5 Release from leg cuffs

The shape of the force/extension curve in Fig. 1 indicates that the force in the rope at the moment of release could have been anywhere between 3972 N (405 kg) and the breaking strength of the rope assembly. In this context, it is hardly surprising that the cuffs were pulled off the jumper's legs.

One should question the effectiveness of cuffs when used without footwear, since they are retained only by friction. Friction is unreliable, because it depends on the compressive force between cuff and leg (which cannot easily be controlled) and the coefficient of friction (which depends on many factors, such as condition of skin, type of clothing if worn, etc.). A more geometrical resistance to cuff release can be provided by wearing high-laced climbing boots. But even with properly anchored cuffs, it is difficult to see how it is possible to arrest a jumper moving at 14.4 m/s over a very small distance without causing high g-force damage to the body.

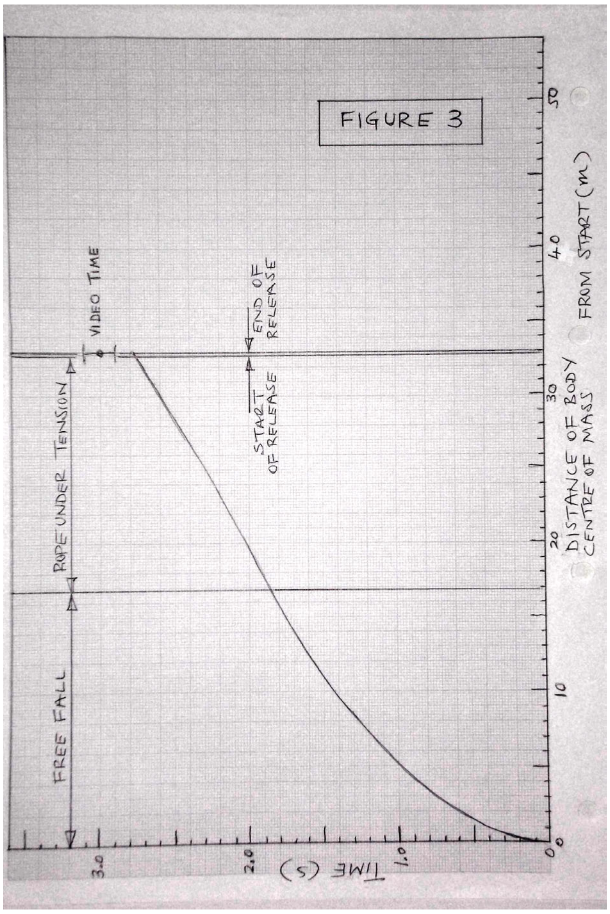

Fig. 5. Graph of elapsed time versus distance fallen, obtained from the energy calculations.

Assuming that the cuffs release at a force of 4000 N, and require a movement of 0.3 m to come off the legs, then release will require 4000 N x 0.3 m = 1200 J of work. Descent of the jumper by this additional 0.3 m provides a potential energy of 388 J. The decrease in kinetic energy is therefore 812 J. Thus, at the end of the release event, the jumper has kinetic energy of 12872 J and a speed of 14.0 m/s. This means that pulling the cuffs off the legs only slows the jumper by 0.4 m/s.

2.6 Snapping of safety webbing

Once the legs have pulled out of the cuffs, the remaining kinetic energy of the falling jumper (12872 J) must be absorbed by the safety webbing if arrest is to occur. The energy absorbed by the safety webbing was calculated from the area under the force/extension curve, and was found to be 940 J - only 7% of the 12872 J required for arrest. In other words, the webbing was totally inadequate in terms of static strength and, most crucially, energy absorbing capacity. A dedicated energy-absorbing device should have been used instead, capable of absorbing the kinetic energy of the falling jumper without applying excessive force to his body.

2.7 Force/extension curve of bungee rope

In spite of the manifest defects of the cuffs and the safety webbing, the root cause of the accident was the use of a bungee rope with an unsuitable force/extension curve. To have a safe arrest, the rope must absorb all the potential energy of the falling jumper well before the limit of extension of the rope is reached. This also limits the maximum force in the load-bearing system to reasonable levels, reducing the risk of cuff release. If the cuffs do release, a well designed safety webbing should not break in these circumstances. Finally, the risk of damage to the body is greatly reduced.

The bungee rope used in the accident was not safe to be used with a jumper weighing more than approximately 70 kg. A jumper of this weight would have extended the rope by 13 m - 3 m short of the limit of extension - producing a force of 2250 N (229 kg).

2.8 Conclusions from case study

The root cause of the accident was the use of a bungee rope with an unsuitable force/extension curve, only able to absorb 68% of the potential energy of the falling jumper at the limit of extension.

As a result, the rope did not arrest the falling jumper, who was consequently subjected to a large force, sufficient to pull the cuffs off his legs. Detachment of the cuffs was facilitated by the absence of high-laced climbing boots and the consequent reliance on friction alone for security. The wearing of smooth-textured trousers may also have contributed to cuff detachment.

Subsequent to cuff release, the safety webbing took the full force of the rope. Because of its low strength and totally inadequate energy absorbing capacity, the webbing broke and the jumper fell to the ground with a speed of impact equivalent to a free fall from a height of 31 m.

Finally, although the rope was only safe for a person weighing 70 kg, the jumper in the incident weighed 132 kg.

3. DISCUSSION

It should be noted that HELA [3] refer to the need to undertake deadweight drop tests to demonstrate that the cage height is properly set for the rope used and the jumper's weight, and to ensure the integrity of the complete rope system. However, the above analysis shows that such an approach is not only conceptually flawed, but is likely to overload the rope and cause permanent damage. It is essential to use the force/extension curve for the rope and perform an energy-based mechanics analysis to determine the limit of safe operating parameters. In this connection, it is noteworthy that an incident report from Central Bungee [5] refers to tests involving a four-cable bungee rope loaded to 115 kg. The load was in the form of sandbags supported in a canvas bag reinforced with webbing straps. On two consecutive occasions the bag burst at full extension, confirming the predictions of very high forces produced at the limit of extension.

Ropes should be tested on a periodic basis to ensure that there is no drift in the force/extension curve with time and usage. In this connection, it is instructive to compare the force/extension characteristics specified in BS 3F 70 [1] for new 19 mm cable. For 10% extension (1.56 m in the case study) the force must be at least 340 N (1020 N for three cables in parallel). For 30% extension (4.68 m) the force must be between 500 and 650 N (1500 and 1950 N for three cables). For 70% extension (11.70 m) the force must be between 850 and 1100 N (2550 and 3300 N for three cables). The minimum total extension must be 105% (16.38 m). These data points are plotted on Fig. 1. Comparison of the specified and actual data shows that the bungee rope has suffered considerable degradation of energy-absorbing capacity as the result of repeated use.

On the basis of the above analysis, it would appear to be only a matter of time before another similar fatality occurs. In the author's opinion, all bungee jumping which is open to the public should be banned until the operators do the following:

1. Prove by energy calculations, using the minimum properties for the ropes, and making an allowance for degradation in service, that the energy of the heaviest jumper can be absorbed by the rope significantly before it reaches the limit of extension, so that the jumper is brought fully to rest.

2. Prove by energy calculations that the maximum deceleration force on the jumper does not exceed a specified value so as to avoid physical damage to the person.

3. Fit a dedicated energy-absorbing device between the end of the bungee rope and the jumper's body harness, capable of absorbing any residual energy with an ample

safety margin should the bungee rope pull the ankle cuffs off the jumper.

If 1 and 2 are carried out properly, there should be little risk of the ankle cuffs being pulled off, so the backup attachment should hardly ever be used. Thus cost cannot be used as an objection to fitting a dedicated energy-absorbing device. Such devices are standard in the climbing world, and are also required when workers are suspended from ropes. They consist of webbing doubled back and forth many times and cross stitched together. Under excessive load, the stitching progressively pulls out, absorbing large amounts of energy in the process.

Calculations 1 and 2 only have to be done once for each configuration of ropes. The question of degradation requires ropes to be tested periodically for load-extension characteristics. When enough information has been gathered, it would be a simple matter to lay down a discard time (measured in number of jumps completed) after which the rope should be destroyed.

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