Physics for Cavers:

Ropes, Loads, and Energy

By William Storage & John Ganter

Everyone knows that force is what breaks a rope. But some might not realize that the force a rope experiences depends heavily on the properties of the rope itself. Few aspects of caving cause as much confusion as so-called *shock loads*. When cavers use this term they are usually talking about dynamic loads resulting from stopping a fall. When scientists talk about shock loads they are concerned with extremely rapid load application, such as that encountered in ballistics studies—nothing like what cavers mean. To a scientist, our loading conditions are simple physics, the stuff Newton worked on. But this "simple" Newtonian physics has important implications for rigging and vertical technique.

Dynamic loads arise from acceleration or deceleration of a mass. Weight is merely a static load, the consequence of gravity pulling on a mass. The relationship between the weight of an object and the force generated by its acceleration is more subtle. A falling body accelerates because of gravity, but this does not cause a dynamic or "shock" load. The dynamic load is caused when the body stops falling; when it is decelerated by an applied force. This force can come from a rope, or the ground. As the rope begins to store the energy of the falling climber, the load increases. It then decreases, during the rebound, down to a static load, the climber's weight.

Unlike popular usage, engineers and scientists have specific meanings for the commonly used terms. This is not merely jargon, because it prevents some of the misunderstandings that can lead to bad conclusions—a valid concern for cavers. A *force* is simply a load; a push or pull on an object. It can be thought of as a muscular effort. Formally, *work* is the product of force and distance; the distance through which the force acts. When a 180-lb climber ascends ten feet up a rope, he does 1800 lb-ft of work against gravity.

Energy is the capacity to do work. The amount of energy something possesses is exactly equal to the amount of work it can do. These concepts are needed to understand the way a rope behaves during a fall. When a force is applied to an object, it deflects. Most objects deflect elastically, like a spring, up to a point. When the applied force is removed, the deflection goes away. Energy is stored in the elastic deformation. Think of stretching a Slinky toy. Beyond an elastic limit, plastic *deformation,* or *yielding* occurs. Think of ruining a Slinky by stretching it too far. Energy is *consumed* in the yielding process; the object doesn't go back to its original shape.

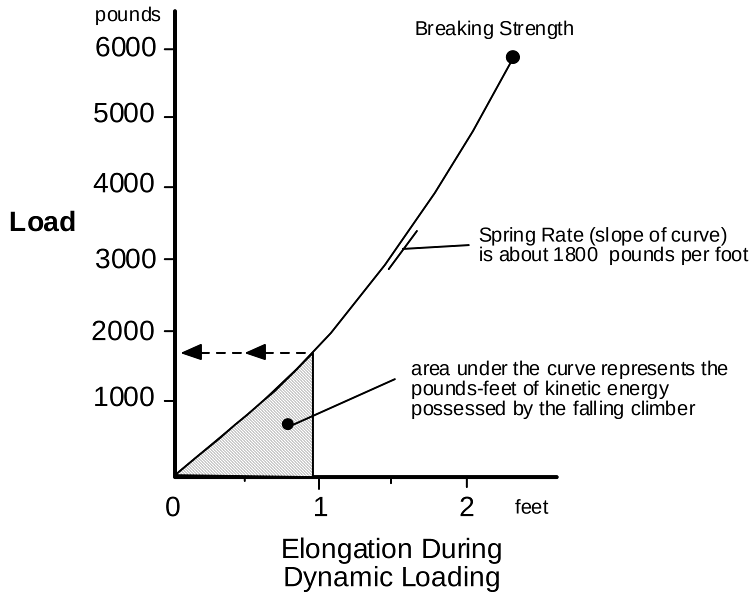


Figure 1: Rope characteristics represented graphically: The curve shows the elongation of a 10-foot length of 10-mm caving rope under loads increasing to the point of failure. The energy of a falling climber is merely a consequence of his static weight and the distance fallen. With these rope characteristics, the load resulting from deceleration can be determined graphically.

Every object can be viewed as a spring. It has a *spring rate,* a measure of the force required to deflect it an incremental amount. With some objects and materials, the spring rate is not constant, such as a rubber band that at same point suddenly gets very hard to stretch any farther. Steel does the opposite; once plastic deformation begins to occur, small increases in load have much larger effects on elongation. Most ropes have a fairly constant spring rate. Spring rate is easily seen graphically. It is the slope of a graph of force versus deflection (load vs. elongation).

Static rope is designed to have low stretch. Therefore, it has a high spring rate, compared to dynamic rope. A force versus deflection curve for a 10-ft length of typical 10-mm static caving rope is shown in Figure 1. It is important to note that this curve, and the spring rate derived from it, are for a specific length of rope. As with a coil spring, increasing the length decreases the stiffness, thus decreasing the spring rate. Cavers notice a lot of bounce at the bottom of a long, free pitch. Nearer the top, the effective "spring" length is short and the spring rate is higher; you don't bounce as much.

An interesting aspect of the curve in Figure 1 is that since work (or energy) is the product of force and distance, the area under the curve equals the energy required to break the rope.

In rock climbing, a belayed fall is a common occurrence. In a belayed fall much of the energy of the falling climber is converted to heat, because of rope drag through the carabiners at each point of protection. Because of rope stretch between the belayer and the climber, this is true even if no rope slippage occurs at the belay point (a "static" belay as viewed by the belayer). But usually, a lot of additional energy is absorbed or converted to heat by the belayer (a "dynamic" belay). These factors significantly reduce the resulting loads. In caving, falls are rare, but often result in a perfectly static belay, as is the case when a rebelay or secondary anchor fails. Even if climbing rope were used for underground rigging, the loads resulting from anchor failure would be much greater than the loads resulting from a fall of the same length in a normal rock climbing situation.

Consider a caver, who falls from his anchor point, with some amount of slack in the rope. From the definition of energy we see that he possesses energy (of falling: kinetic energy) equal to the product of his weight and the distance fallen. In this situation friction is negligible; his energy must be absorbed by the rope. If his energy is greater than the rope's energy storage capacity (the area under the curve), the rope will break.

If his energy is less than the energy storage capacity of the rope, he will experience an impact force, a dynamic load, when the slack goes out of the rope. His impact force (the force he and the rope and all the other rigging components experience) can be determined by starting to shade in (from left to right) the area under the rope's load-elongation curve. When the area shaded equals the area represented by the falling climber's energy, we can read the impact force (cavers' "shock load") right off the graph. To be accurate the climber's weight must be added to the resulting load, since it exists independent of the fall and dynamic load. For simplicity, we'll deal only with the dynamic portion of the load.

In the example of Figure 1, a 180-lb person takes a 5-ft fall, yielding 900 lb-ft of energy. From the graph we see that this energy results in a load of about 1900 lbs and a rope elongation of about 1 ft. This exercise shows, without the use of equations, that the dynamic loads on ropes and belay anchors are the *consequence* of rope characteristics.

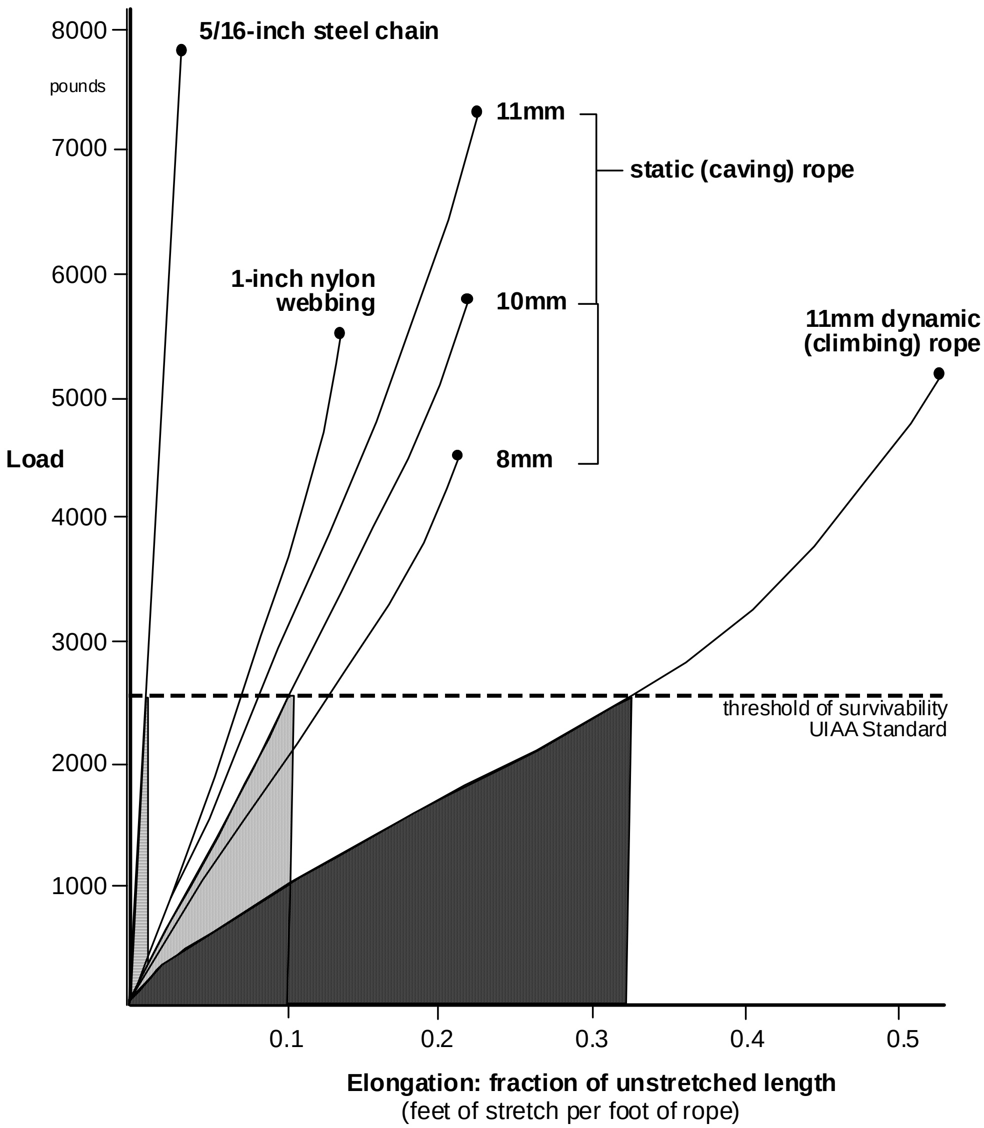
Figure 2 shows another version of the load-elongation curve. This time the elongation axis of the graph has been *normalized* to express elongation as a fraction (of the original, unstretched length) for a variety of ropes, etc. One foot of elongation in a 10-ft rope results from the same force that will cause 2 ft of elongation in a 20-ft rope; on this graph each elongation would be 0.1.

Now, remembering the definition of energy, we'll note that doubling the amount of slack in the rope before falling will double the distance fallen before the slack is used up, thus doubling the kinetic energy.

Combining these concepts lets us conclude that any increase in energy caused by increasing the amount of rope slack will correspondingly increase elongation, leaving the percent elongation unchanged. No change in percent elongation means no change in load; and the concept of *fall-factor* is born.

Fall-factor is the ratio of distance fallen to available rope slack (Figure 3). From this simple physics exercise we conclude that all falls of the same fall factor result in the same deceleration rate, regardless of the absolute distance fallen. In practical caving applications, conditions such as knot tightening, deflection of the human body, and harness movement on the body tend to significantly reduce loads in short-fall and low-fall-factor situations. But for our purposes we'll use this conservative and simplified model of reality. The climber in the examples above who fell from his belay point had a fall factor of one, regardless of the amount of slack.

In Figure 2 the energy storing capabilities of the ropes, webbing and chain can be used to determine the load (force) experienced by a climber falling with various fall factors.



	Energy Absorption per foot of rope	Fall factor possible for UIAA threshold of survivability	Calculations
(light hatched)	13 lb.-ft.	0.07	Area = Energy = 1/2 x 2650 x 0.01 = 13.2 lb.-ft./lb. ff = 13.2 lb.-ft./lb. ÷ 180 lb. = 0.07
(light grey)	133 lb.-ft.	0.7	A = 1/2 x 2650 x 0.1 = 133 lb.-ft./lb. ff = 133 lb.-ft./lb. ÷ 180 lb. = 0.7
(dark grey)	4300 lb.-ft.	2.3	A = 1/2 x 2650 x 0.32 = 424 lb.-ft./lb. ff = 424 lb.-ft./lb. ÷ 180 lb. = 2.3

Figure 2: Comparison of Load-Elongation Characteristics of several rope types: here elongation is expressed as a fraction of unstretched rope length: the curve is valid for any length of rope. The calculations show the determination of fall factor for a reasonable threshold of survivability, the UIAA standard. Rope curves are composites based on manufacturer data and our own testing. Webbing curve is based on Brew (1977).

For the chain the total area under the curve, to the point of failure, is about 120 lb-ft per foot of *rope/chain.* That represents the energy, per foot of unstretched chain, that will result in enough load to break the chain. Fall factor, the total number of feet you can fall, per foot of rope, equals the area under the curve divided by the climber's weight.

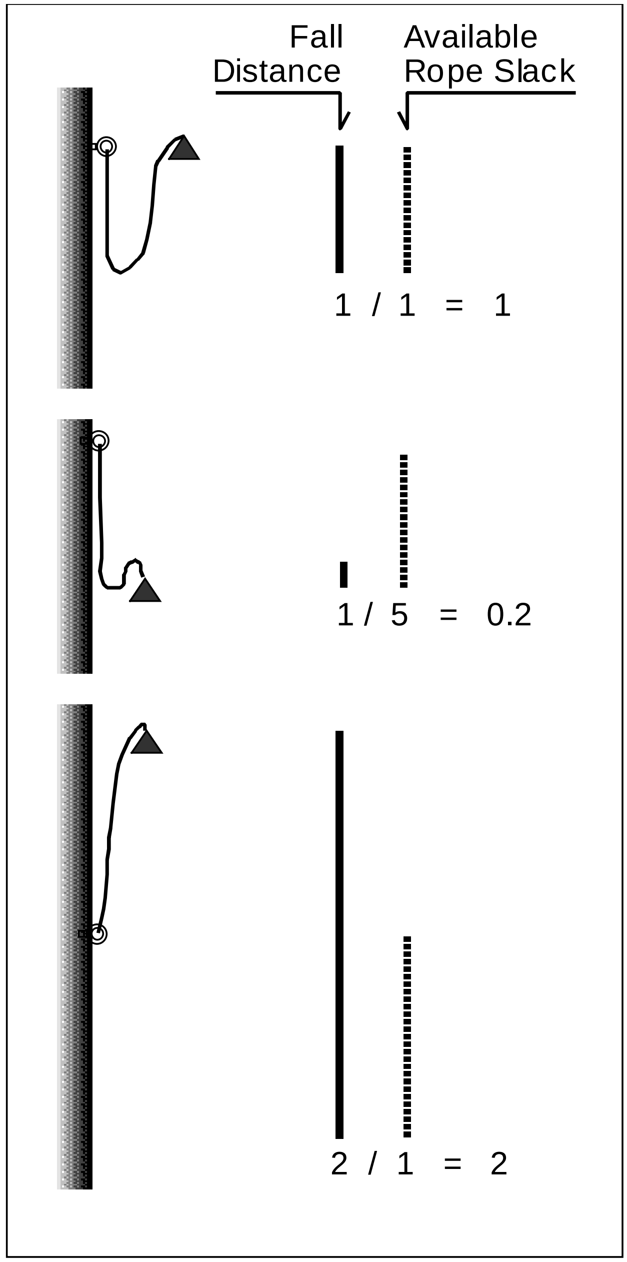


Figure 3: Fall Factors illustrated

In the case of the chain, a 180 lb-climber would break the chain with a fall of fall factor 0.67 (120 lb-ft per foot divided by 180 lbs. equals 0.67).

Unfortunately, humans cannot survive deceleration forces of 7800 lbs, the strength of the chain. At best, they can take about 15 G's (a force of 15 times their weight). The Union Internationale des Associations d'Alpinisme (UIAA) uses 2650 lbs as a maximum tolerable load for evaluating climbing ropes. For 2650 lbs on the chain, we calculate a fall factor of about 0.07. Helpful hint: do not belay with chains.
From the climbing rope curve, we calculate that a fall factor of 2.3 (by definition, fall factor 2 is the maximum possible) would be needed for a 180-lb climber to experience a deceleration load of 2650 lbs. In other words a fall of any length on a climbing rope might be survived if the faller didn't hit the ground or a ledge before being decelerated by the rope. Hence the survival rate of bungee jumpers.

From the curve for a 10-mm caving rope, we calculate that 2650 lbs equates to a fall factor of 0.7 for a 180-lb climber. This confirms what rope manufacturers tell us; lead climbing with caving rope can be risky and painful. A fall on a 10-mm caving rope will end in a load about three times greater than that resulting from the same fall on a climbing rope. A stronger 11.5-mm caving rope would result in a load about 10% *higher* yet, because its spring rate is 10% higher.

The issue of rope softening

Readers should be aware that the curves in Figures 1 and 2 are roughly accurate for new ropes. A lot of attention has been given to the reduction in rope strength that occurs with age. However, very little has been done to assess the change in spring rate, and the energy handling capability of an old rope. Unfortunately, spring rate is in most ways much more important for surviving falls than the strength value. Tests by Smikmator (1986) and Kipp (1979) clearly show that old rope is stiffer and produces higher loads than a new rope subject to the same fall. Testing by Stibranyi (1986) on Czechoslovakian climbing ropes produced the opposite results. Theory would tend to support the former conclusions, though. Testing by the German Alpine Club (Microys, 1977) showed a significant increase in stiffness of new climbing ropes that were cold and wet.

Tests conducted in a study by Smith (1988) indicate that treatment with concentrated fabric softener reduced the strength of a new rope. Frank (1989) showed that certain ropes treated with dilute softener (per manufacturer's recommendations) were stronger than the same rope without softening, after aging and washing. Frank reported that the likely mechanism at work explaining these results is that the fiber lubricants contained in new rope are lost with age, allowing the fibers to cut one another. Fabric softener replaces some of the lubricants. Excess softening leaves the rope effectively wet, with the corresponding loss in strength.

With this mechanism in mind, a further argument for treatment with fabric softener would be its effect on spring rate. Since a rope's spring rate is determined by both nylon material properties and fiber weave, it is likely that fabric softener will help prevent stiffening due to loss of internal lubrication. In dynamic situations, the underlying physics shows that preserving the spring rate is as important as preserving its strength toward the goal of avoiding rope breakage. Probably more importantly, preserving the spring rate will avoid the higher climber loads in falls that would come from a rope that had become stiffer with age.

Strength misconceptions

Now that everyone understands the science, let's go back and look at the popular misconceptions. Much of the caving literature uses such terms as "shock strength." This probably originated from intuitive physics, which while frequently accurate, has failed us miserably here.

The fallacy probably came from a situation like this. Two ropes, one nylon and one polyester, had the same strength, as measured by pull testing. But in a fall-factor = 1 situation, the polyester snapped like a twig and the nylon was unharmed. The obvious conclusions are that "shock strength" is a radically different property than tensile strength, that dynamic testing is needed to evaluate it, and that polyester has lower "shock strength" than nylon.

To an extent the latter conclusion serves us; we avoid belaying with polyester rope. But the first two conclusions are dead wrong, and have encouraged us to do a lot of unscientific dynamic testing, sometimes drawing even more inaccurate conclusions. Misinterpretation of test results has led cavers and rescue enthusiasts to believe that the speed of load application encountered in falls greatly affects the strength of the rope. Testing of nylon materials and seat belts by the aircraft industry simply does not support this (Figucia 1969). As we have seen, the speed of load application affects the value of the load (because of the deceleration rate), *not* the strength of the rope.

Probably the most harmful result of this situation is that "shock strength" has encouraged us (and equipment manufacturers, through competition) to make everything stronger. Some have advocated making caving rope stronger, to resist being cut by ascenders in the event of an anchor failure. Unfortunately, if low stretch is to be retained, stronger static rope will necessarily be stiffer, and the benefits of higher strength may not be realized because the greater stiffness causes higher deceleration loads. The probable end result is that there is a negligible reduction in chance of rope failure and a significant increase in chance of victim injury from high deceleration loads.

Another concern of dynamic loading is knot strength. Sharp bends in knots result in some fibers being loaded much more than others—a *stress concentration* occurs. Consequently they reach their ultimate load capability first and fail, leaving the remaining fibers more highly loaded and subject to failure. Knots used in caving reduce the rope's strength by 30-60%. For normal loading this is completely irrelevant. It only becomes important when the knotted rope strength falls below the threshold of human load tolerance in a dynamic situation such as a fall. Standard water knots, bowlines, lasso-bowlines, and figure-8s will reduce strength by about one half. A knotted 8mm rope, then, can fail with loads less than 2000 lbs. Thus knots with more gradual bends, causing less stress concentration, such as the figure-9 knot (Figure 4), must be used. It is reported to cause a strength loss of about 30% (Marbach 1980).

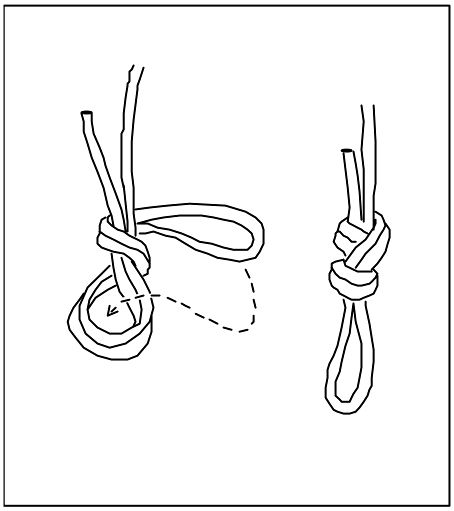


Figure 4: The Figure 9 Knot

In some circumstances, knot slippage can reduce dynamic loads by decreasing deceleration rates. Use of shock-absorber knots has been advocated by several caving texts. Alan Warild (1989) presents convincing evidence that the effect is too variable and unreliable to be used in caving. The shock-absorbing knots, usually overhand loops, *might* reduce loads, but they will definitely reduce strength of the whole system, provided the rest of the rigging is done correctly.

Recommendations

In summary, while an investigation into dynamic loading might initially appear to be merely an academic pursuit, several specific recommendations arise from it. In addition, the general concept of "stronger means better" is further revealed as dangerous and nonproductive. Some important implications of this study are:

1. Absolute fall height is not nearly as important as fall factor.
2. Don't belay lead-climbers with caving rope.
3. Avoid fall factors much greater than 0 with caving rope
    - Rig rebelays with the shortest rope loop possible.
    - Rebelays close to the top anchor must be bombproof, because there is so little rope to absorb energy.
    - Position primary and secondary anchors at pitch heads to minimize fall factor in event of anchor failure.

4. Small diameter rope requires special attention—use figure-9 knots.
5. Don't depend on shock-absorber knots.
6. Thicker ropes, while more abrasion resistant, will produce higher dynamic loads than thin ropes.
7. Treat ropes with fabric softener suitable for nylon fabric. Follow label directions and do not use high concentrations.

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ABOUT THIS DOCUMENT

Author's email: storage@nerve-net.com, jganter@sandia.gov

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