Hang ‘Em High: How Far Can You Trust Your Belay Device?

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Abstract:
National or international standards do not presently exist for belay device testing[1]. The physics of fall arrest using rock climbing equipment, while well researched, has subtle aspects that still are not well understood within the rescue and climbing communities. Not all belay devices currently used by the rock climbing population can safely arrest the high force falls of multi-pitch climbing.

Methods:
A series of different dynamic drop tests and slow static tests were planned to measure the typical forces experienced during controlled rock climbing belays. This paper formulates a maximum credible impact force for belay devices based on estimates for the variations of fall factors, rope stiffness, and climber weight. A proposed standard minimum strength requirement is then established. Different test configurations are explored as candidates for strength tests of belay devices.

Results:
A static pull test and a drop test are recommended as a standard for belay device strength testing. A 12 kN minimum strength for multi-pitch rock climbing is recommended, and a 9 kN minimum strength for single pitch climbing is recommended.

Purpose

The purpose of this paper is to report on some preliminary third party testing of belay devices commonly used in vertical climbing where high forces can be generated. Our testing, while limited in scope, points to the need for belay device test standards. Presently, there are no standards of how a belay device should work, and there are no regulations for what materials should be used in the manufacturing or what load thresholds the device should survive. These design parameters are left to the discretion of the manufacturer. Unfortunately, some users may not be proficient in evaluating belay device effectiveness for safely arresting falls, and these users often have not had any formal training in using a specific device. Not all belay devices currently being used by the rock climbing community can both safely and repeatedly arrest a high fall factor fall. (Fall factor (ff) is defined as the distance of a fall divided by the length of the rope in service.)

While this report will not fully outline a set of standards for belay devices, it will outline some essential requirements that all belay devices should meet. In particular, we will outline some static and dynamic tests that we believe are useful in evaluating the strength of belay devices.

Background: What is a belay?

Belay defined-

1. To secure (a mountain climber, for example) at the end of a length of rope[2].
2. To cause to stop, arrest.

"Belaying is a fundamental technique for climbing safety, a system of using a rope to stop a fall if one should occur. Belaying can safely control the enormous amount of energy that a falling climber generates, but it takes practice to do well and requires an understanding of its underlying principles[3]."

A belay as defined by Rigging for Rescue is "to provide protection against a fall by handling a tensionless rope (belay rope) in such a manner that it may be taken in or let out as another person climbs, rappels, or ascends…yet be secure to hold this load…". Other studies have published that, "belay anchors (in climbing) can be subjected to loads of 3000 lbF (13.3 kN)[4]."

A common school of thought is that the friction created by the carabiner of the top piece prevents both the belay and anchor from being exposed to as much force as the climber side of the rope. During an initial test with a mechanical belay device, we measured the ratio of the rope loads for the climber side to the anchor side with multiple load cells. This ratio is important in estimating the peak forces that anchors see during a fall. Theoretical estimates of friction losses for a rope bending over a carabiner have been made for static loads[5, 6, 7], however, the behavior of ropes bending over a carabiner under dynamic loads is still debatable.

> ***Side note***: We found a ratio of 55% load on the test mass side of the rope and 45% on the anchor side. This ratio differs with what Duane Raleigh, Group Publisher for Rock and Ice Magazine found in their tests. They reported nearly a 66% to 33% ratio, respectively. However, Raleigh stated that "more testing with better methods should be performed[8]." Some of Raleigh's methods were similar to ours in trying to isolate the force by using an auto-blocking belay device. The discrepancy between Raleigh's results and our results is likely due to measurement methods; he used a single dynamometer on the anchor and derived forces from Petzl's force calculator web site[9]. As well, he used approximately 50-55 feet of rope in service with a knot tied into the harness of the test load. Others have documented that friction is as high as 52% over a carabiner (Soles, 1995), but only took into consideration static friction and the coefficient of friction in a static system, not a dynamic system that a lead climber would have to deal with. This is a subject area definitely in need of further investigation.

One of the simplest forms of a belay is a rope that runs from the belayer to the climber. As the climber progresses, the belayer has the job of arresting a fall. Simply holding a rope with bare hands has little chance of stopping a fall. Hand strength is limited[10,11,12] and, thus, early mountaineers exploited friction to amplify their belay holding ability.

Methods such as the hip wrap belay that use the friction between the hip and the rope amplify the load holding ability. The drawback of this simple method is that loads from some falls can generate enough force to overpower the belayer. Rope burns and dropped climbers have caused simple methods to be replaced by mechanical belay devices. However, even mechanical belay devices do not completely alleviate catastrophe as evidenced by the volumes of tragedies in Accidents in North American Mountaineering.

Four things must be in place to affect a successful belay:

1. An attentive belayer and/or device that is capable of arresting a fall;
2. A rope that meets or exceeds the Union Internationale Des Associations D'Alpinisme (UIAA) standard[23] (now the CE);
3. An non-dynamic anchor that is able to absorb the impact force;
4. A harness that is able to withstand the forces of a fall factor 2.

Clearly, most climbers are in agreement that a belay must be able to hold a severe fall[13]. Even if the entire pitch of protection pulls out, the belay system should persevere. The alternative is usually unacceptable injury or even death. The belay mitigates the risk of a fall. Not every climber accepts the same risk; the idea of the free soloist, when no gear is used at all, are embraced by some climbers, and scorned by others.

Belay devices exploit the mechanics of friction to control the rope loads and slippage during a fall, and they can also act as a load limiter by allowing rope slippage during the course of a fall. Belay devices are often designed to be user friendly. We contest that they should not only feed rope easily to a lead climber but also allow any belayer to arrest a fall, lower a fallen climber, or continue to feed rope to the lead climber as needed without damaging any component within the climbing system.

Currently, many belay devices are on the market, and the number of devices continues to increase each year. Each of the belay devices offers different advantages and disadvantages: some are very light in weight and can handle a single rope, while others may not only be able to belay two ropes but can also serve as rappel devices.

What are the variables in a fall?

The force generated in a fall depends on the weight of the climber, the length of the fall, and the stiffness of the rope. The stiffness of the rope is a function of the rope construction and length. Climbing ropes are manufactured to standards that control the stiffness of the rope[23], and this in turn limits the forces generated in a fall. Even with the controls placed on climbing ropes, fall forces can be significant, especially for older climbing ropes that have lost some of their energy-absorbing capability from prior use.

> Within the climbing community, the nomenclature of "Fall Factor" has been used to describe roped climbing falls. For a dynamic climbing rope, the peak force during a fall is a function of the ratio of length of rope in service to the height of the fall. Thus, a fall of 2 feet on 4 feet of rope has the same fall factor as a fall of 20 feet on 40 feet of rope. Both have the same fall factor.

Since most mechanical belay devices amplify the force from the belayer, they require action from the belayer to provide breaking strength in the form of tail tension. For these belay devices, a brake hand is mandatory to maintain arrest of the lead climber's load. For some devices, stopping a high fall factor load can be very difficult for even experienced climbers and can sometimes result in rope burns or worse. Lack of attention can also be fatal and can result in dropping the climber, a credible event when using an active device that demands tail tension. Absence of tail tension means there is not any amplification of tension.

Are belay devices strong enough?

Most climbers believe that belay devices are designed to be strong enough to stop a fall factor two[13]. Some manufacturers advise that fall factors greater than one, considered here to be a high fall factor, should not be exerted on their belay devices, limiting these devices to single pitch climbs. It is nearly impossible in a multi-pitch climbing configuration to avoid a high fall factor when beginning to climb above the anchor/belay just before and after placing the first piece(s) of protection.

What is the standard?

Some manufacturers understandably do not endorse their devices for use in solo lead climbing. Some do not approve their devices for use as an active/unconditional belay device, where a brake hand is mandatory to maintain arrest of the lead climber's load or for use as a rescue belay device. To have these capabilities, belay devices need to be designed and/or tested with those particular applications in mind.

The tests proposed here are not intended to show that a belay device meets all of the requirements advertised by its manufacturer. We performed a strength test to insure that, should a device work as intended, it would have sufficient strength to hold a fall without causing catastrophic damage to the rope or the belay device. We are not suggesting any device be used outside its intended scope. Through testing, we hope to determine if a belay device has sufficient strength to subsequently perform within its intended scope.

The consequence of not having a strength standard is:

- There is no way to have an independent verification of manufacturers' claims.
- There is no way to insure that the belay device is not the weakest link in the climbing system and, consequently, could cause a catastrophic outcome.
- The lack of belay device uniform strength ratings could generate a misunderstanding of the different belay device limitations.
- Death

Apparently, to obtain a CE rating, the device must first be somewhat passive, and presently each manufacturer is able to write its own standard for which its belay device qualifies since there is no set standard to aspire to. We are not concerned at this time with how the device limits the rope force though slippage, how well the device works in an un-attended mode, or how efficient the device is for amplifying friction. While these factors affect belay device performance, *we are only proposing tests for strength*.

Prior testing has evaluated belay devices in many configurations and for many different loads. For example, single climber load belay devices were shown to not perform well in rescue load configurations of 200kg. Testing by Scott, et al., showed most belay devices were not substantial enough to arrest the short falls[14,15]. According to Scott, belays in rescue situations may be of little or no benefit. Some rescuers use Single Rope Systems (SRS) with no belay[16]. The debate continues on whether SRS techniques were "safer" than with a belay in a main line failure. In this paper, we will only focus on belay systems for belaying a single rock climber.

To validate standard test usefulness, we conducted a series of prototype strength tests on a limited set of belay devices to better understand belay device and test nuances. In the sections below, we will report on our test methods and provide some detailed results from our testing to illustrate what we have learned.

Strength Performance Requirements:

How strong is strong enough? As has already been established, most climbers are in agreement that a belay device must be able to hold a fall. Does this mean a belay device should be capable of holding any conceivable fall? For example, should a rock climbing belay device, such as the ATC, be required to hold a fall factor two with a 600-lb weight on static rope that might arise in a rescue situation? If such a device could be designed and manufactured, then it would be quite popular.

Since there are limits to what can be achieved in belay device design, a set of strength requirements based on scope of use must be defined. Once the scope of use is defined, then a design event can be used to drive the strength requirements.

Four different events are typically discussed in engineering design:
1. Most probable event
2. The worst case event
3. The maximum credible event (MCE)
4. The design event

The worst case event is defined by what is possible. For a belay device, this means any event that a climber could conceivably deliver to the device. Some examples of worst case events might include: a fall factor two using static ropes and rescue loads; using your belay device to lower your vehicle or boat down a cliff; using a belay device with a wire rope; etc. Trying to design to the worst case event is certainly a hopeless task. Since achieving a design for the worst case event may not be possible, the next question is what event should be used to control the design?

Unlike the worst case event, the MCE is both conceivable and probable under the intended scope of use. As used here, “probable” means the chance that the event will happen is greater than the chance of winning the lottery. Defining a MCE is not simple. Not only must one imagine all of the legitimate uses of the device, the maximum probable loads for each use must be defined. The definition of the MCE includes a probability cut-off. Risk can be defined as probability multiplied by the consequence. Since different people accept different levels of risk, obtaining agreement on the MCE is quite difficult.

In some cases, the MCE for a belay device will be limited by the strength of the other components in the system.

Four different design events were selected for our prototype standard testing:

- Fall Factor 1
- Fall Factor 2
- UIAA-101 fall

Within each of the above tests, uncertainty is detected from test to test. An analysis of the source of uncertainty will help design testing that is representative with regards to the MCE.

Rope Uncertainty:

It is impossible to discuss belay devices without also considering the rope that will be used in the system. One of the unknowns in belay device testing is the condition of the rope. Current manufacturer’s testing tries to eliminate this uncertainty by using only new ropes with known properties. As ropes age their properties change. Some examples of factors that can have direct effects on belay device performance are:

1) Ropes can become harder to bend.
2) Rope treatments used to give a rope longer life can be applied, wear, or wash away.
    a) this can affect how well the belayer can grip the rope
    b) this can also affect the coefficient of friction
3) Fibers on the outer sheath can become broken or damaged, resulting in a change of rope friction as well as strength.
4) The inner core strands can straighten and result in a change of rope modulus.
5) The outer sheath can become tighter or looser with use.
6) Any external environmental factor(s), (i.e., water, ice, mud, sand, etc…)

While all of these variables cannot be accounted for in standardization processes, they can play a major role in a belay system’s efficacy. While using a new rope for each test can increase test repeatability, such testing may not reveal problems that can result from using used ropes with varying qualities. A wide range of testing could be performed with ropes of different sizes, construction, and ages. There is no documented standard to define when a used rope is too old or too stiff. The UIAA standards for dynamic ropes only apply to new ropes off the shelf. Using new ropes for each test could result in an under representation of the stiffness of actual ropes in use and result in a standard that does not adequately reflect the maximum credible event.

The peak force for the UIAA-101 single rope test is limited to 12 kN. Most manufacturers report peak forces much lower than 12 kN, and one would be hard-pressed to find a new 12kN rope for sale. While the UIAA-101 standard requires each rope to survive 5 drops, it does not require the force from subsequent drops after the first to be reported. Naturally then, the impact force increases with each drop as the rope looses elasticity.

Figure 1 shows a histogram of advertised impact force typical of ropes on the market as of autumn 2005. Impact force data was built by collecting the information of manufacturer's listings from climbing rope suppliers for single ropes only. It does not represent an exhaustive list of all ropes, nor are twin or double ropes included.

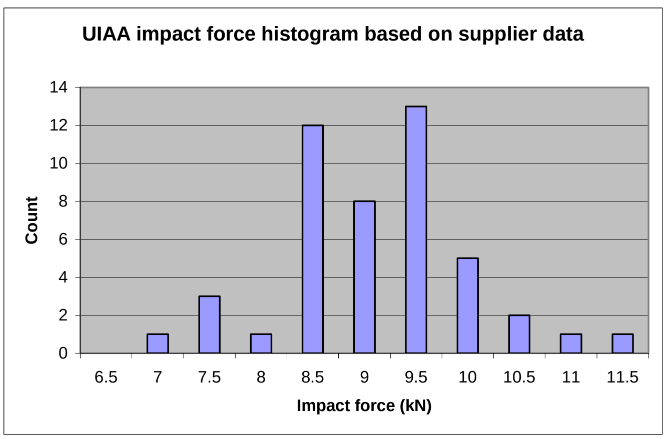


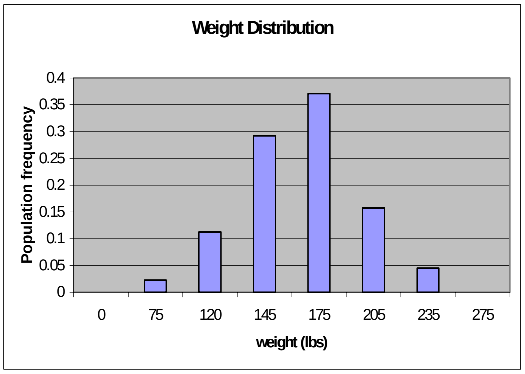
***Figure 1*: Histogram of rope UIAA impact force used to determine rope modulus.**

Mass uncertainty:

The UIAA test requires a solid and rigid mass of 80kg to represent a "typical" climber. There has been debate concerning the appropriateness of using a rigid mass to represent a climber. Many think that the rigid mass generates greater declaration loads than a human subject, due to the flexible nature of the human body. While most think that a rigid mass is both conservative and generates more of a load than expected from humans, there may be instances where a flexible mass could generate more force than a rigid mass. Currently, the use of a rigid mass as a conservative substitution for a human subject is an untested hypothesis.

In an attempt to represent our tests as realistically as possible, we wanted to account for the effects of arms and legs decelerating at different rates from the torso and head. With this goal in mind, we conducted all drop tests using a Rescue Randy rescue dummy with a seat sling, a tie-in, and a chest harness.

A simple survey conducted by the authors[13] showed that more than 20% of climbers weigh more than the test mass used in the UIAA rope acceptance test. Figure 2 shows the climber weight distribution reported from a sample of over 350 climbers. The distribution from our survey compares well with the data collected by Haines[17].



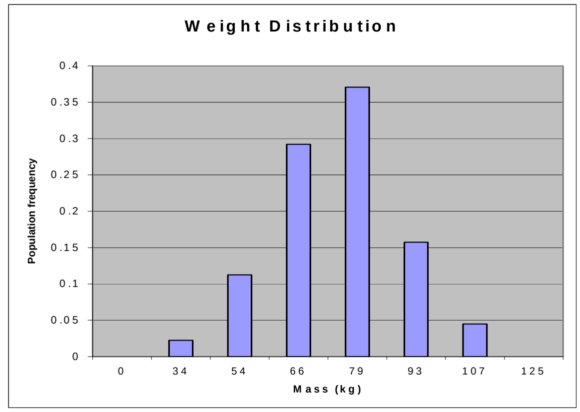


Figure 2: **Weight distribution for climbers.**

Gripping and Slipping Uncertainty:

During arrest of a fall, most belay devices are designed to allow rope slip to avert a 12kN (or feasibly greater) impact force on the top piece. While a few devices auto-lock (may be considered somewhat "passive" but still needing tail tension), most of the belay devices on the market require tail tension to activate the locking mechanism. This belay activation is usually achieved through the death grip of the belayer. Endurance grip is higher during the fraction of a second needed to arrest a fall than what can be exerted over a longer duration of time, and the gripping capability can vary greatly [18,19]. Variability in grip strength does not mean a standard strength test for belay devices must depend on an average griping capability. Indeed, any proposed test standard for a belay device that relies on manual tail tension has much to consider.

Several different design events could be used to account for the uncertainty in gripping ability. Ideally, any standard test should be repeatable, and most "mechanical hands" are not very repeatable. Designing a standard test to account for all of the variability that can be introduced in gripping is difficult. An upper bound on gripping strength is to assume it is infinite. Even if an infinite gripping strength is assumed, test design is still an issue. For example, several ways that can be used to simulate superhuman gripping strength include:

- Tie off tail to rigid anchor
- Weight attached to rope tail
- Stopper knot/locking device

Tying off the tail to a rigid anchor is realistic as sometimes belayers have to "tie off" their climbing partner by placing an overhand knot or a figure 8 on a bight on the belay side of the rope. Other examples could be, but are not limited to: snag on a tree stump, rat nest in rope coil, pinched rope in crack, or high friction around a rock. When a device is tied off, the load is shared between the belay and the rope tail. A weight attached to the rope has the advantage of limiting the maximum force in the rope tail. This method is hard to conceptualize in a drop test. The stopper knot is less likely to be used, but it still represents an event that is credible. Our testing shows that the stopper knot places the most demands on the belay device.

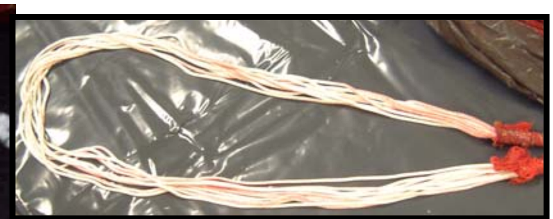


Figure 3 **"While hoisting a seriously injured climber from the Cathedral Spires Gully the aircraft experienced a decay in rotor RPM with a resulting loss of heading control and altitude. As the crew worked to control the aircraft the hoist cable struck a tree and separated. The rescue corpsman and climber were retained on the belay line[20]." The belay device in this scenario held a rescue load without failing the dynamic rope; note the stopper knot behind the device that spontaneously formed during the accident to prevent the corpsman and litter from hitting the ground and possibly bringing down the helicopter thereafter. The photo on the right shows the sheath stripped from core after being loaded with a stopper knot at the belay device.**

Fall Factor Uncertainty:

In order to estimate the uncertainty of the fall factor, we asked the question:
"What is the greatest fall factor you think you have ever taken in a fall?"

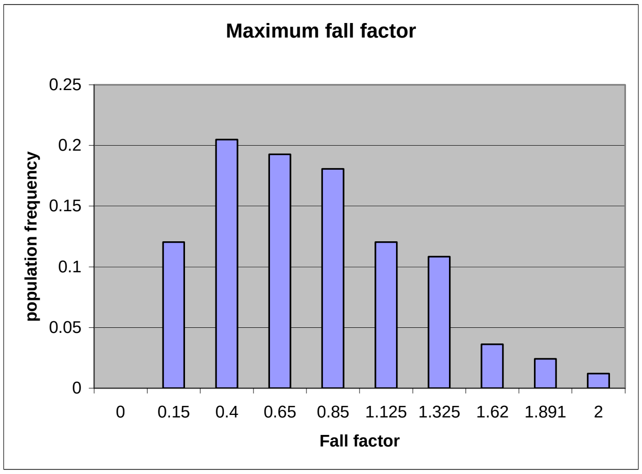


***Figure 4*: Maximum fall factor distribution with 9% answering "other"[13]. (Note: this chart plots the maximum fall taken by reporting climbers over the lifetime of their climbing; "other" means that the climber reporting did not know how to calculate what their fall factor was).**

The distribution shown in Figure 3 reports the results. As expected, a fall factor 2 is not common, but it does exist. Most falls are below a fall factor of 1.0. We acknowledge that such a survey could be prone to errors due to the natural tendency for most falls to become greater with each recounting. What may be interesting is the low number of factor 2 falls reported.

Rope Stiffness Uncertainly:

In order to estimate the maximum forces seen in a fall, we need to examine the rope impact loads as a function of rope modulus, fall factor, and climber weight. Webber and Hudson[21] measured the forces for falls that are beyond the UIAA standard.

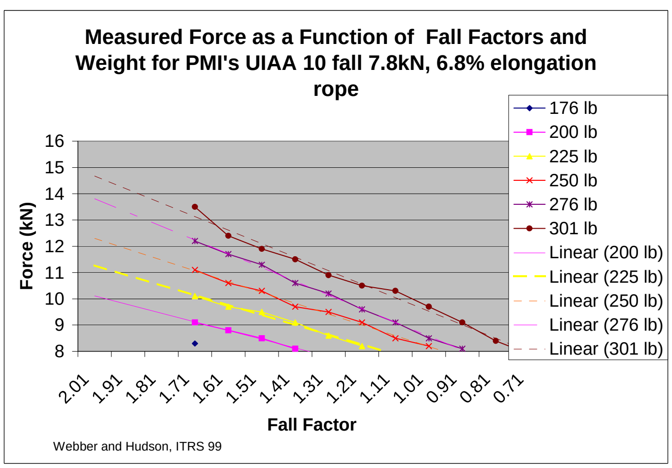


***Figure 5*: Force as a function of fall factor and weight. A linear (straight-line) approximation has been added to Webber and Hudson's data to project the data to a fall factor of 2.0**

Webber and Hudson's results shown in *Figure 5* were for new rope that reported a UIAA first drop peak force of 7.8 kN. There is a wide range of ropes on the market that have much higher first drop peak forces.

Figure 5 shows a plot of impact force based on a linear rope stiffness model, assuming the impact force in a fall is given by:

$$\frac{f}{W} = 1 + \sqrt{1 + \frac{2M}{W}\frac{h}{L}} \tag{1.1}$$

where the rope modulus, M, was assumed to be 6000. Attaway[22] presented more on the topic of impact force during a fall as a function of fall factor, rope modulus, and weight. While the match between the measured data from Webber and the calculated impact force is not a perfect match, the model is adequate for estimating how the impact force varies as the rope, fall factor, and weight all change.

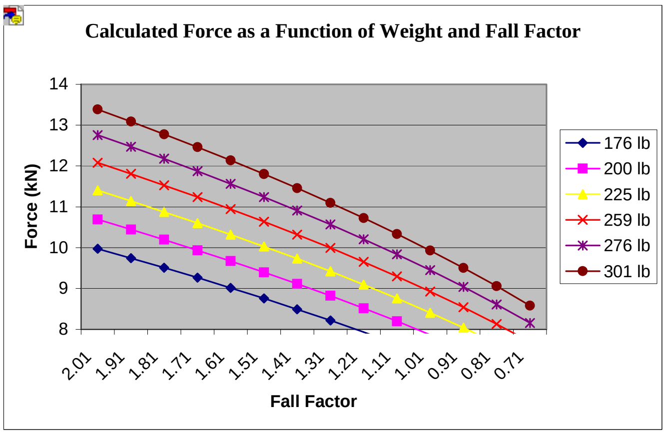


***Figure 6*: Calculated (impact) force as a function of weight and fall factor.**

By surveying a population of climbers, we have determined the variability of fall factors, climber weight, and rope stiffness. In the next section, this variability will be used to estimate the frequency that the climbing community will exceed a given force threshold as weight, rope stiffness, and fall factors are varied.

Credible Lifetime Impact Fall Force

In this section, we will try to determine the distribution of impact forces seen by the climbing community. This distribution estimate would be equivalent to watching thousands of climbers over their lifetime of climbing and recording the maximum peak force that each climber experienced. We will call this distribution the Credible Lifetime Impact Fall Force (CLIFF). Webster's definition of Credible: offering reasonable grounds for being believed. The Maximum Credible Event (MCE) would be the point on the CLIFF distribution where the probability drops to near zero.

We computed the CLIFF distribution as follows. Random draws from a climber population with a weight distribution shown in *Figure 2* and a maximum fall distribution shown in *Figure 4* were used to construct the distribution of fall impact force, shown in *Figure 7*. The rope modulus was also varied to match the impact force distribution shown in Figure 1.

The techniques used to generate *Figure 7* were simple. The Discrete Random Number Generate within Microsoft Excel was used to create 1000 random combinations of climber weight, fall factor, and rope stiffness based on the distributions for the variables determined from our survey. These random combinations were then used to compute the impact force using Equation 1.1.

The distribution for maximum impact force shown here is not the definitive word on impact force. Exceptions could be taken to our survey techniques, population size, and estimation of uncertainty. The intent here was to establish a method that would yield an estimate of the maximum credible event for belay devices.

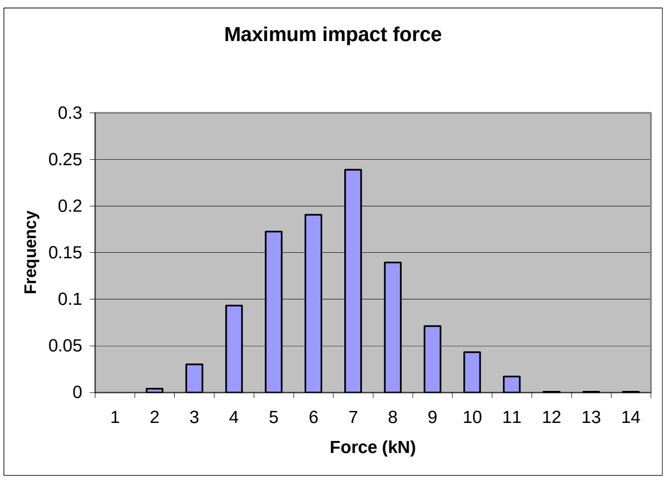


Figure 7: **Creditable Lifetime Impact Fall Force (CLIFF) - Expected maximum fall force distribution based on climber weight, rope stiffness, and maximum fall factor distribution.**

The estimates for the distribution of impact forces shows that the peak force in a fall could exceed the UIAA standard drop test about 2% of the time. Just because the peak impact force exceeds the 12 kN peak used in the UIAA test does not mean that the rope will break. The 12 kN peak force was based on the maximum force the human body can survive without mortality as defined by studies on military parachute jumpers, not the force required to break the rope.

If the strength for a belay device standard is set at 8 kN, based on the above analysis, then this force could be exceeded by 15 % of climbers, even with a new rope. If the peak force were set at 12 kN, then we could expect to see the maximum impact force exceeded by about 0.2% of the climbers. Does this mean that 2 out of 1000 falls will exceed the peak force? No. The question we asked was “What is the greatest fall factor that you think you have experienced?" The best way to view the above data is to think of it as the maximum force expected in any fall over a lifetime of climbing. Two climbers out of a population of 1000 could exceed a 12 kN maximum impact force.

This analysis may overestimate the peak force, in that it assumes that none of the belays are dynamic. Any slippage through the belay device could reduce the peak force. However, our analysis may underestimate the peak force since the rope modulus was based on data for new rope and an 80kg mass. As well, an underestimate may result due to weight of extra gear that was not added to the climbers' weight.

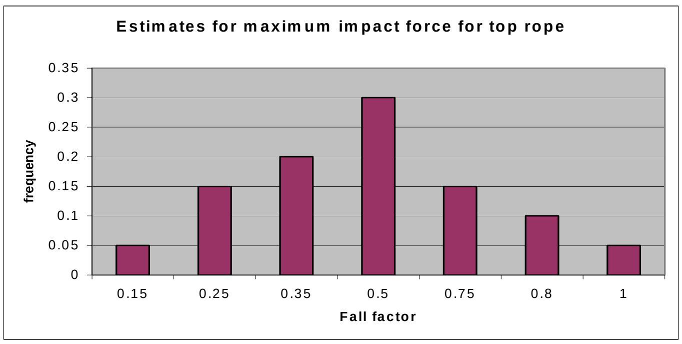


***Figure 8*: *Assumed* fall factor distribution when falls are limited to a fall factor less than 1.0.**

Figure 8 shows the fall factor distribution we assumed for the case where the falls are limited to below 1.0. The estimates shown here are intended to reflect the population of climbers that only top rope or climb in a gym.

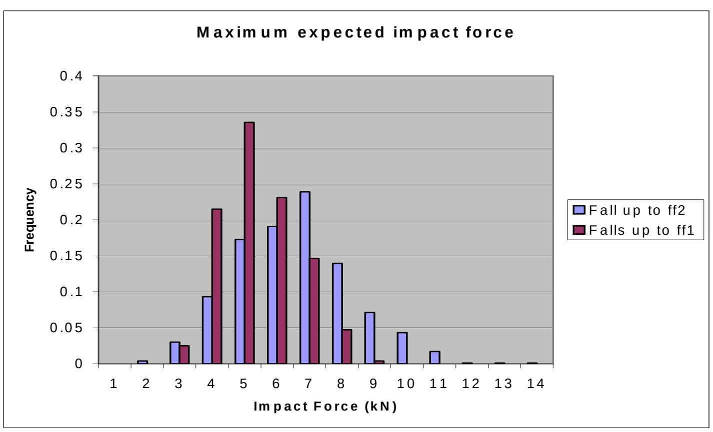


***Figure 9:* Maximum expected impact force for falls limited to fall factor 1.0 compared with impact force for all falls.**

Figure 9 demonstrates the maximum impact force when fall factors are limited to below 1.0 compared to the expected maximum impact force for fall factors up to 2.0. Limiting the fall factor to below 1.0 will result in about 2 percent of the falls being in the 8.5 to 9.0 kN range.

What's the Bottom Line?

Based on the above comparison, the maximum credible event (MCE) for belay loads with new ropes would be 12 kN for devices designed for all falls and 9 kN for devices limited to fall factors less than 1.0 (single pitch or top rope climbing).

Note that the MCE is not the worst case event. For example, the rope stiffness in the MCE was based on UIAA approved new rope data from an assortment of manufacturer's labels. The UIAA allows up to 12 kN impact force. A fall factor 2 taken by a 230-lb climber on a 12 kN rope would theoretically generate 15 kN impact force. While this is possible, it is not credible because new 12kN ropes are not sold by retailers.

Test Methods - Dynamic vs. Static Testing:

Should drop testing be used as a test standard for strength, or will a simple static test provide a reasonable measure of strength? The advantage of drop testing is that both rate effects and inertial effects are included. The disadvantage here is that the driving force is limited by the mass of the climber, the height of the fall, and the stiffness of the rope.

A static test has the advantage of allowing one to determine the margin available beyond the required strength limit. The peak force in a static event does not depend on the stiffness of the rope. The disadvantage of a static test is that it may not capture the true device behavior seen in a dynamic theater.

Dynamic Test:

The test methods explored here for belay device strength testing are based on a variation of the UIAA orientation for testing ropes[23] and the European Standard EN-892. The UIAA test and EN-892 for dynamic ropes is the standard by which nearly all other technical rock climbing gear is held.

The UIAA dynamic rope test clearly defines the methods of attachment for both ends of the test rope. For testing a belay device, minor variations from the UIAA test for rope attachments were needed: In our test, the bollard and rope clamp/mechanical hand, normally used to secure the rope to the fixed end, was replaced by auto-locking belay devices. Likewise, the knot used to attach the test mass was also replaced with an auto-locking belay device. Since both rope ends were attached using belay devices, stopper knots on the brake hand side were used to prevent slippage of the rope through the devices. All other parameters were kept the same as outlined EN-892 and UIAA-101.

Using belay devices on both ends of the rope was motivated by: 1) reducing the uncertainty of knots, 2) testing two devices during one test, and 3) simulating self belays used in rope solo climbing. By replacing the knots with a mechanical belay device, we were better able to account for energy absorption by knots. Attaway[22] showed that knots absorb different amounts of energy during a fall, depending on knot type and initial knot tension. By replacing the tie-in knots typically used in climbing with a belay device, we obtained a more repeatable test that allowed for greater consistency in the data. In addition, using a belay device at the climber tie-in allowed us to test a configuration that is commonly used in the climbing community.

In both the static and dynamic tests that were performed, the rope suffered damage, failed, or was let go at the belay device, with the exception of when testing a Grigri. In those tests, the rope failed unpredictably anywhere in the system but not necessarily at the belay Grigri. In essence, the rope would fail at an anchor knot (fig 8 or bowline) on the opposite side of the Grigri, or somewhere in the middle of the rope.

Strength testing under the UIAA-101 drop standard with a new rope results in an impact force very close to the rope impact force rating. For most devices, this force will not be sufficient to fail the device. Higher impact forces can be generated by increasing the fall factor, increasing the mass, or increasing the rope stiffness. Changing the rope stiffness is not practical. Increasing the fall factor of 1.7 to 2.0 will increase the impact force, but this increase is moderated by the square root in equation 1.1. The most effective way to increase the impact force is to increase the mass. Our testing goals were to develop a prototype dynamic test for belay devices. Our initial results are reported here are for cases where the fall factor was increased. We are still in the process of evaluating potential test standards using a variable mass to generate higher impact forces.

For our tests, dynamic force measurements recorded the force as a function of time at multiple locations in the belay system. Calibrated 5,000 lb NIST S-type load cells were placed on both the anchor and the top piece. The forces were measured and recorded on a Microstrain V-link wireless data logging system, using 12-bit accuracy at 2048 Hz for 10,000 sweeps.

Static Testing:

Slow pull testing was performed on a variety of belay devices. The goal of this testing was to see if slow pull testing, which does not capture all of the subtle details that occur in drop testing, can give a measure of the performance of a device.

How much of a load should a device hold in a static test? An upper limit could be the rope failure strength. Most of the devices we tested were capable of supporting the theoretical maximum load (i.e., the rope strength) when in the static pull forum. Reporting through a central agency, such as the UIAA, that a device meets or exceeds the strength test should be a mandatory requirement.

Belay devices respond differently depending on tail tension. With this in mind, we explored the following static belay device performance test:
Options:

1. no tail tension
2. 50 lbs tail tension at 10 degrees and 150 degrees off load axis
3. 100 lbs tail tension at 10 degrees and 150 degrees off load axis
4. 200 lbs tail tension at 10 degrees and 150 degrees off load axis
5. Stopper knot to prevent slippage through the device

The probability of option 5 being seen in the field may be low. However, not only does this possibility exist, it has been reported (see *Figure 3*) and is used frequently for allowing the belayer to be “hands-free” for a moment. The consequence could be quite high if the device cannot handle this mode of loading. The application of the other methods could be explored in detail, but more exhaustive research would have to be done.

In each of the above tests option 2-4 where slipping was allowed, we found about 0.5 m of rope (a nominal amount of rope that a typical belayer would have in hand) should be allowed to pass through the device. This slippage insures that the phenomena of sheath slippage and bunching can occur. For each test, the maximum load at any point in the test should be reported. Many of the belay devices depend on a combination of friction and rope grabbing to function. Reporting the results from a series of static tests with different tail tensions can give an indication of how strongly the slippage load depends on tail tension.

For reasons already described, we used option #5 for our testing.

Devices Tested:

The selection of belay devices used in our testing was based on the scientific principle known as “test what you have on hand”.

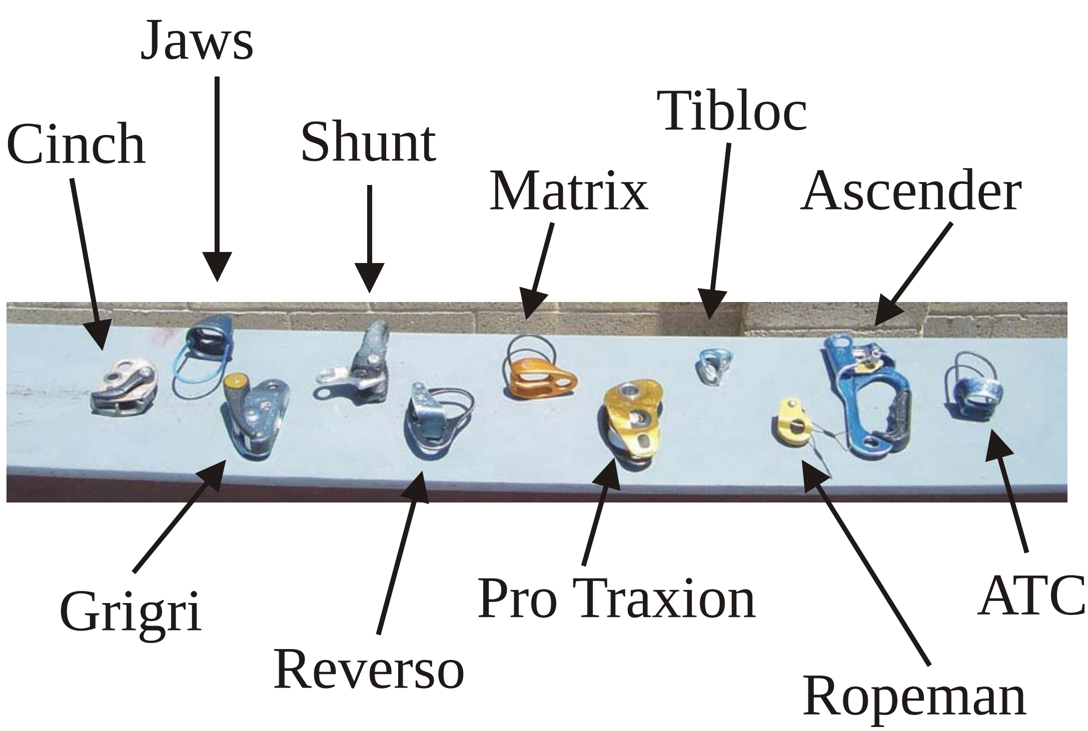


***Figure 10*: Different belay (both traditional and non-approved) devices tested**

Static Test:

Figure 11 shows the results for static pull test for different belay devices. Included in this set of tests are some devices that are not specifically designed to work as belay devices in lead climbing application. While mechanical ascenders are not recommended for belaying lead climbers, many climbers may find themselves attached by only one ascender in certain scenarios. While climbers often intend to use the ascender only for ascending rope, falls on ascenders, while not recommended, do happen. Ascenders are frequently used as self belays on low angle slopes, on snow or alpine terrain, and on fixed lines.

Each device was tested with a stopper knot behind the device to prevent rope slippage. The devices were pulled until either the device failed or the rope failed.

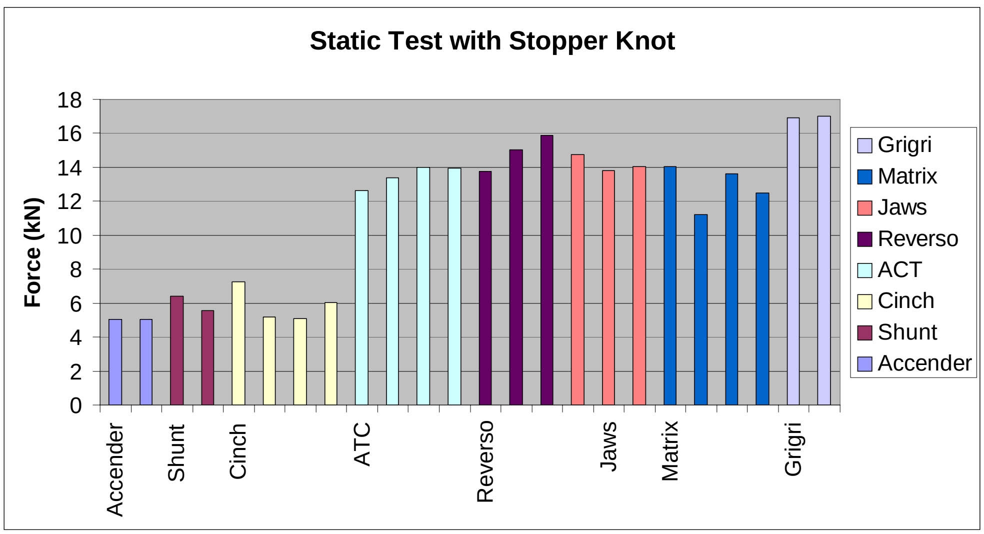


***Figure 11:* Static failure force for belay devices.**

Dynamic Testing

Figure 12 shows results from dynamic belay device testing using a fall factor 2 with a mass of 80 kg. The input energy in this series of drop testing was limited in this test by the mass and the stiffness of the rope. These test point out how it can sometimes be difficult to determine failure. While some would argue that a successful arrest is any arrest where the climber does not impact the ground, others would argue that a test that cuts the sheath so that the rope is not usable represents a failure. In Figure 12, a combination of tests that report failure and damage. We defined failure as climber hits ground and defined damage as any degree of sheath cut with core showing.

Time and resources prevented us from completed additional drop testing with an overdriven system using an increasing mass with each drop until failure is observed.

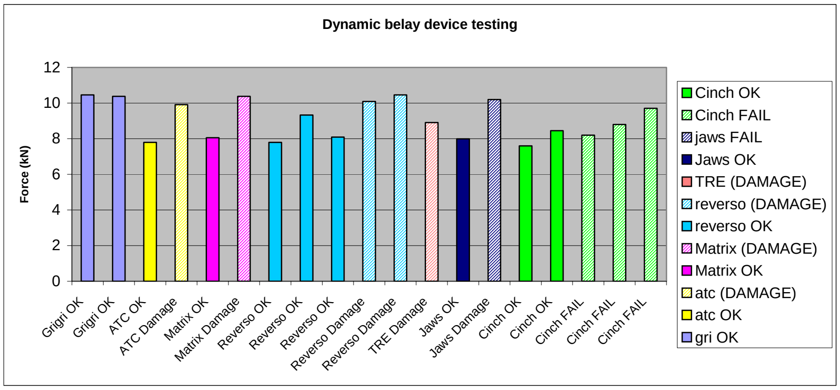


Figure 12: **Dynamic Results for different belay devices.**

Comparison of the static pull test shown in Figure 11 with the dynamic results in *Figure 12* indicates that static testing often produces a greater strength than dynamic testing.

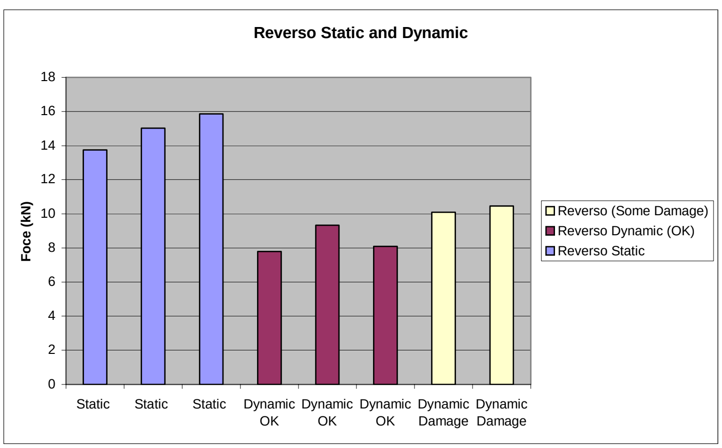


Figure 13: **Static and dynamic results for a Reverso with a stopper knot.**

Figure 13 shows both the static and dynamic results for the Reverso shown in the same plot. In both the static and dynamic tests, a stopper knot was used. Without the stopper knot, rope slippage could affect both the peak static and dynamic forces.

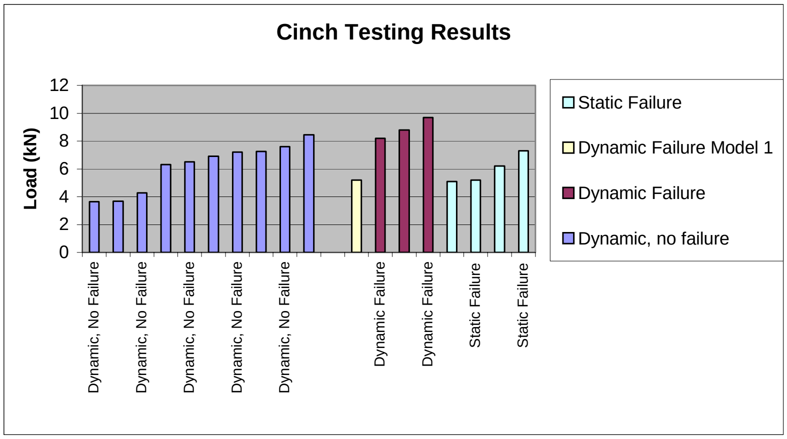


***Figure 14*: Static verse dynamic failure for Cinch.**

In addition to showing different peak failure load, static and dynamic testing also showed that some devices had more than one mode of failure. For example, when the Cinch becomes overloaded, the resulting rotation of the cam allowed the safety catch to no longer be engaged on the boss. At this point, one of two things happens:

a) The cam "clamshells" apart, allowing the rope to slip though the gap shown in the photo Figure 15. Slipping though this tight space can strip the rope sheath from the core. The rope is let go though a potential space only a couple of millimeters wide by letting go of the individual core bundles in rapid succession.
b) The cam fractures (see Figure 16):
   The cam of the device broke in an unpredictable way, but left a sharp edge that could cut and completely severe the rope.

Clam-shelling (method a) was observed in both static and dynamic tests. Failure by fracture (method b) was observed only in the dynamic test. Perhaps the reason is a result of a faster impulse delivery.

***Figure 15:* A static mode of failure for a device with tail tension; the rope is released from the belay device through the small gap shown.**

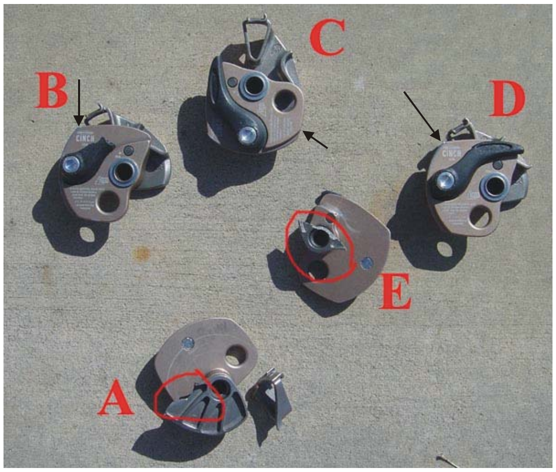


Figure 16: **Dynamic (A, C, D, and E) and static (B) failure modes for belay devices were not always similar and repeatable. Shown here is the Cinch.**

The observed slow pull failure loads were lower than the observed dynamic failure modes for the Cinch, but for the Reverso, the reverse is true. Static and dynamic failure modes need further investigating to understand how closely they are related. One could argue that both types of testing may indeed be prudent, as there are advantages and disadvantages to both.

Summary/Recommendations:

No strength standard exists for rock climbing belay devices. We believe that a standard based on a maximum credible event should be implemented. In this paper, we tried to establish a maximum credible event for belay devices based on estimates for the variations in fall factors, rope stiffness, and climber weight.

We designed and implemented several different test configurations to develop strength tests for belay devices. Limited dynamic and static testing indicates that static failure modes and static failure forces may not necessarily be similar to those found in a dynamic environment.

In addition to the static pull test, we recommend a dynamic test. In this test, belay devices would be tested in an overhand on a bight stopper knot configuration using a fall factor 2. A rope length of 2.5 m is suggested. A rope stiffness and mass combination that generates an impact force of 12 kN at the belayer should be required for general use devices, and a rope/mass combination that generates a 9 kN force should be required for devices limited to top rope/single pitch climbing. Different rope diameter (within specified limits) should also be tested in accordance with the above recommendations. The results should be published on the device or package insert or in some way made available to the public using these devices.

This paper has only addressed one aspect of belay device performance, strength. More drop testing should be performed on all devices both within their intended application and in other possible configurations. Results from this paper should be viewed as exploratory in nature. They do not represent a standard, and more testing may be required before finial conclusions can be drawn.

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