Belay Device Theory, Testing and Practice

by Jim Titt 30 Jan 2009

Belay plates are sad, neglected things, there are more studies on rope characteristics and impact forces than one can possibly imagine while the object that controls these forces is hardly ever examined or even considered.

Some tests have been performed and the results vary from useful through helpful to criminally irresponsible with some woeful knowledge of basic physics and material science often being displayed. The only really useful theoretical work on how belay devices work was done by Attaway but even he suffered from some simplification and the failure to fully appreciate the importance of the rope itself. The best practical tests on various belay devices are those by S. Ratzenburger and the DAV (German Alpine Association).

While many will wish to leave out the theory section with its implication of heavy duty mathematics this would be a mistake, without at least skimming it to get the concepts the rest of this work will probably be meaningless.

For independent comparison tests of a variety of belay devices see the bibliography attatched.

Theory

The Braking Force(s)

To the casual user it appears there are as many as three forces acting in a belay device to provide the necessary resistance. Bending, friction and squeezing or pinching. In reality the squeezing is only another way of increasing the force pressing the rope against the device to increase the frictional force so can be included in friction.

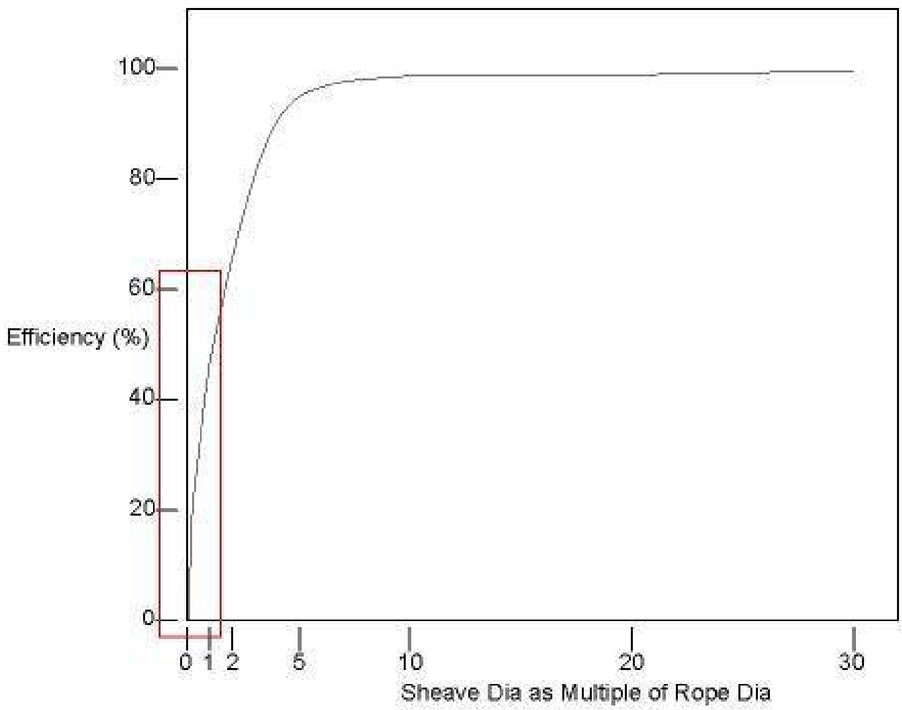
Knowledge of the relative role of these forces in a belay device is important in understanding how the device works and why the performance changes with varying load and rope diameter.

Bending
Bending force is the force involved in bending the rope, around a karabiner for example, and the amount of force required varies with the bend radius, angle, load, rope stiffness, construction and treatment.

Since the phenomena of reducing sheave diameter increasing the required bending force has been well known and understood in the cordage industry for centuries if not millennia it is surprising that no mention of this occurs in studies of belay devices. In his study of friction in rescue situations Attaway even managed to produce a mathematical model of abseil devices without even mentioning this. As we will see bending is the dominant effect in the great majority of belay devices and it is important to quantify it in order to understand how a device works. One clue to its importance lies in the heat generated in the device, if the only braking effect was friction then the majority of the energy in a falling/abseiling climber would go into the device which then heats up. To work out the total input, the proportion in the device and the rate of heat loss to the air is not particularly difficult and was performed many years ago by a caver studying long abseils. The end result was so far from reality that it was obvious some other effect was at work.

To calculate the bending force for a rope is shockingly difficult as the modulus of elasticity and friction between thousands of threads in a rope need to be worked out as well as the degree of rearrangement (flattening). It appears from other studies that to a certain extent some of the fibres in the rope are taken past the elastic limit anyway at the small radii climbing equipment uses so one would need to work out the extent that these fail as well. We can surmise this occurs from tests performed repeatedly pulling rope through a karabiner or repeatedly abseiling both of which demonstrate that the elongation characteristics of the rope change and its strength is reduced, in other words bending the rope at these radii is permanently affecting the rope.

Instead of calculating the bending force we can look at graphs of efficiency against pulley sheave relative diameters from various sources and we see curves like the one below. Of course we are working in the area outlined in red or possibly a bit higher and it is reasonable to assume this part of the curve is fairly speculative since the studies were interested in the other end of the efficiency scale. The marine cordage industry and the lifting industry already know that small radii are inefficient so they don't bother to study them much or if they do they don't publish this information.

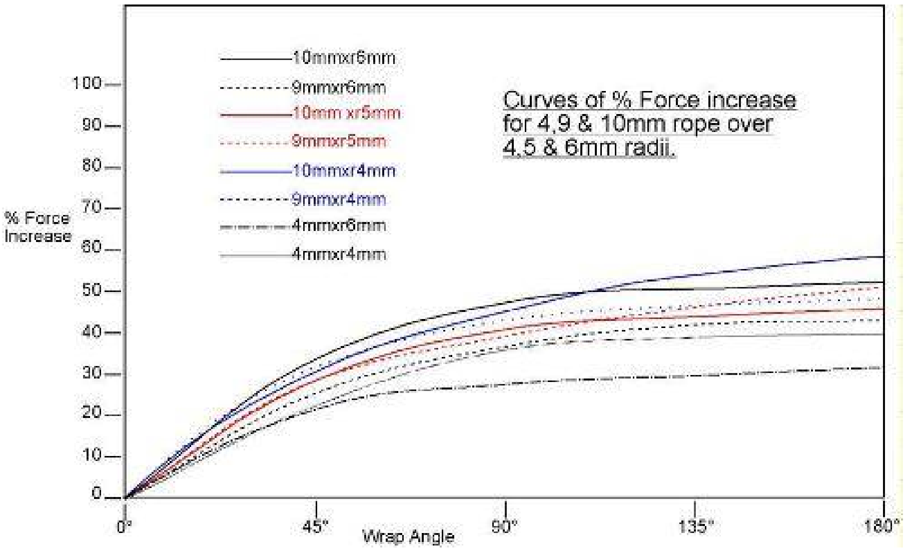


As no information of real use appears to exist it was desirable to measure the bending force in the range we wish to study. The way I did this was to arrange needle roller bearings of 8, 10 & 12mm horizontally on shafts and with a rope over them pull a known weight upwards at a constant speed, varying the wrap angle as required, the difference between the known weight and the measured pull force being the bending force. This was repeated for different loads and rope diameters. This I then expressed as a percentage increase over the original load for convenience. The first pull gives a slightly higher value than subsequent ones by approximately 5% as the rope becomes flattened to a certain extent and retains this so some of the work required to rearrange the threads has already been done. Which value one should take is a matter of conjecture and I used the average of the first three pulls.

Above a certain minimum load the curves become fairly consistent and for clarity I have left the lower load curves off the graph below. They are anyway in a load area we are not interested in, this graph is for forces between 300N and 600N.

It is easy to see that the major rise in force increase is in the first 90° with subsequent angular increases having little effect. The thicker the rope and the smaller the bend radius the higher the % force increase we see which is as one would expect.

(The curves are not as perfect as I would wish but the bending test is fairly difficult to do very accurately as the weight of the load cell has always to be taken into account, at my leisure I may try to improve the test and with some other rope diameters but for our purposes the results are perfectly adequate).



To see what contribution bending makes to a belay device we can now do some calculations:

Using a 12mm karabiner and a 10mm rope through a Sticht plate with known radii of 4mm the measured internal bend angles(the bends touching metal) from the hand are 80°, 185° and 42°. The initial force is 300N. From the graphs the first bend has 141,5% more friction so multiplied by 300N we get 424,5N. The second bend has an factor of 151.5% multiplied by the 424,5N gives 643N. The third bend factor is 129% multiplied by 643N gives a total bending resistance of 830N.

I then constructed a `frictionless´ belay device from needle rollers dimensionally identical to the Sticht plate above and test pulled this at the same angles, getting a result of 802N which is as close as I could have ever hoped for considering the difficulties in getting the rope bend radius figures. I then pulled the real Stitch plate and got 1320N so as we see the bending is a major (61%) part of the braking force. By singly testing over a roller and over a 12mm karabiner I could confirm this, the bending force in this case was is 61.3% of the total.

The average of 9 combinations of plates with different rope sizes and also using 10/12mm karabiners gives the contribution bending makes as 57%.

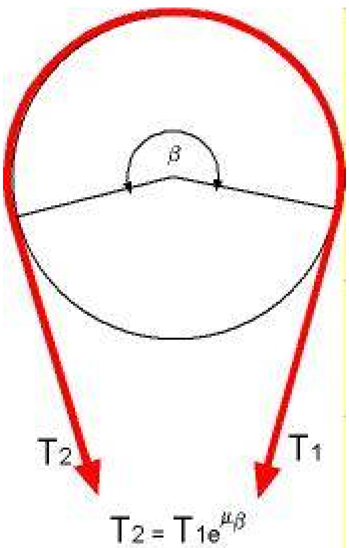
(Note: As I habitually use a 10mm karabiner on my belay devices I was interested to see no real difference in braking force compared to using a 12mm one.)

Some manufacturers use a smaller radius than 4mm on the incoming edge, a good example being the Petzl Reverso but if you pull a normal rope hard at 90° to this sort of radius you will see the rope doesn't completely conform as hand force alone is not sufficient to achieve such a small radius in a rope, in a dynamic situation even less so. Probably something like 3-4mm would be a more accurate figure to use. Too small an incoming radius makes belay plates liable to be grabby or sticky as the weave of the rope mantle tends to hang up on the edge (and climbers have a distrust of sharp edges near ropes) so some restraint is called for here.

Friction

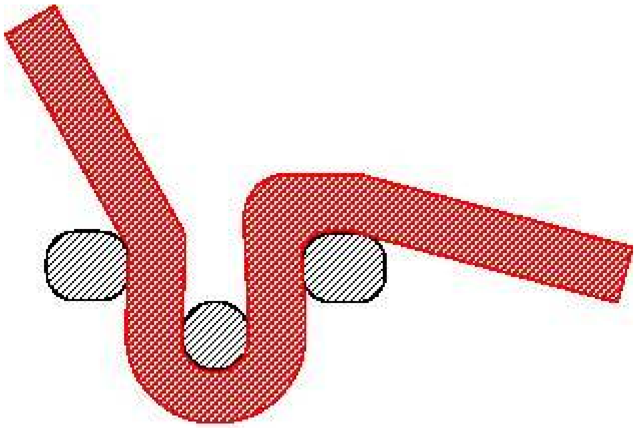
The Laws of Friction have been around a good few hundred years and state:
The force of friction is directly proportional to the applied load. (Amontons 1st Law)
The force of friction is independent of the apparent area of contact. (Amontons 2nd Law)

To work out what is happening in a belay plate should be easy, calculate the normal loads (the ones pushing the rope onto the aluminium) and multiply by the dynamic coefficient of friction for nylon and there you get the frictional force (resistance). In fact Amonton made this easier for us by deriving a formula (below) for loaded ropes going around things (capstan effect) so all you need to do is add up the total of the bends in radians, take the coefficient of friction (mu) and one of the forces, (say your hand grip,) and you can work out the braking force you will achieve. (Those of you that are still following this may know that this law is not exactly true for slipping ropes and the slip regime needs to be taken into account to achieve a Eulerian formula [Belofsky and others] but this is probably going a bit far for something as crude as a belay device with so many other variables!)



Where **e** is the exponential function (2.7183), **beta** the angle in radians and **mu** the coefficient of friction. **T1** is the initial (hand) force and **T2** will be the faller force.

Of course in a belay device the rope may well go like the sketch below but then it is merely a question of working through each bend at a time but note the section `Combining the Forces´ further down.



Important is to note that both the angle alpha and the coefficient of friction mu are exponential functions and any changes in these has a huge effect on the end results.

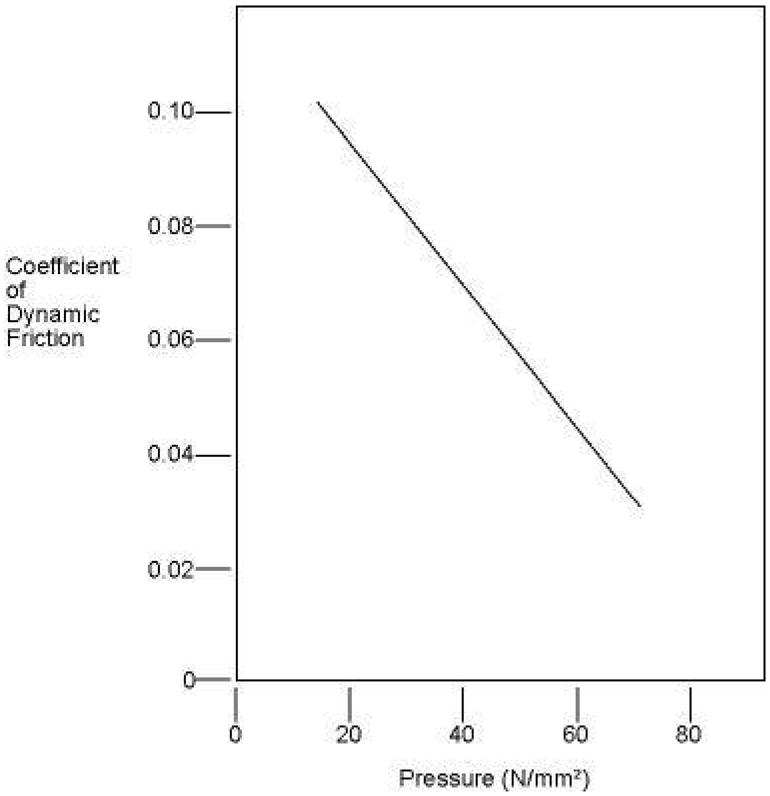
First we need to know at least one of the forces and it is logical to use the hand force since this is to a certain extent fixed, or at least lies in a well defined band. Tests by K & K Mauthner show there is a wide variation in the force that can be applied to a climbing rope by hand but the ‘normal’ range is between 150N and 400N. The value of 400N can certainly be considered at the top end for a big strong manual worker on a well used 10mm rope (both I and my brother have verified this) and is the value used in the Petzl fall calculator but when you get down to a new 9.2mm with a belay bunny on the end this is wildly optimistic. P. Randelzhofer used a value of 209kN as the average value identified by the Mauthners and the DAV tests used a value of 250N with a 9.5mm rope, their tests also included two different climbers belaying the drop tests and the force they could apply lay between these two values. Holding the falls was described as "unpleasantly hard but still controllable" by the test belayers. I settled on 300N as a reasonable compromise as I mostly tested with a 10mm rope. (Naturally you will not achieve this with a 4mm cord, or 7mm for that matter!)

We also require the coefficient of friction. The braking in a belay device has been shown to be dynamic (CMT Italy), that is, the rope is moving and has to be stopped. Therefore we need the dynamic coefficient of friction not the static one which are vastly different (not appreciating this fact rendered the results of at least three published tests useless). At this stage it is important to know that the dynamic coefficient of friction for Nylon 6 is not a constant and varies with pressure but is relatively constant with velocity, something which the authors of a few research papers really should have found out before starting their work. This naturally also throws a spanner in the works when applying Amontons Second Law.

The available quoted figures for the dynamic coefficient vary considerably, mainly because of the varied test pressures used. For example at 0.05N/mm² which is very low we are given a coefficient of 0.4 whereas industry sources give 0.28-0.3. Manning in a study of friction for rescue system mechanics tested at what I think is an unrealistically low pressure and measured a coefficient of 0.7, he used a different ASTM test (friction on floor coverings) than those used industrially (rotating steel plates under pressure) which give more normal results for the pressures we are working with. An often quoted value for the dynamic coefficient is in the range we are interested in of 0.16 dropping to 0,10 for water lubrication.

Another set of tests (below) by D.Fenz at higher loads shows that the decrease in coefficient with rising pressure is a linear effect and he measured values down to 0.03 for a nylon bearing material. In a moderately loaded device such as a Sticht plate the forces over the back of the karabiner are in the lower levels of pressure used by Fenz and a coefficient of 0.3 for the low loads and 0.16 for higher ones seem reasonable figures to use. (The material used by Fenz was a filled nylon bearing material with a somewhat lower coefficient then pure Nylon 6).

(The industrial standards for nylon are given against polished (2 micrometer) steel whereas those from Fenz are against stainless steel and from Manning against aluminium. The friction values for these materials is often stated to be different but definitive figures are impossible to come by and the effect itself appears to be very small.)



Lastly we need the contact angles, this is a simple matter of measurement though it is helpful to go along with others tests in regard to the operating angles of the rope, if only to be able to compare results. A study by the DAV for their tests gave an angle between the rope to the faller to the belay hand of 137° and this certainly seems a reasonable value to use, a greater angle being fairly impractical in a confined belaying situation. It is not stated whether the angle is before loading or loaded but I assumed it was under load as practically it doesn't make much sense otherwise. Of course this is only a suitable angle for some devices, others like a GriGri or HMS have other requirements.

Combining the Forces

Neither the bending or friction occurs in isolation, they work to influence each other in all braking phases through a belay device. As the bending force increases there is more force on the rope which increases the friction force but of course this changes the coefficient of friction. This changed force from both bending and friction effects the next portion of the device and so on.

While each effect can be expressed mathematically to combine these together in one formula is going to be complicated but would be a good topic for someone's post-graduate studies!

Some Additional Factors

Vee Grooves

To get more braking power various types of V-grooves are incorporated in the belayer hand side of some devices. The idea behind these is that the downward force of the belayer hand increases locally the normal force per unit area on the rope and hence provides a greater frictional force (Amontons First Law) though some increase will be lost as the coefficient of friction drops. Too aggressive V-slots make the device a bit grabby in use and can eventually damage or prematurely wear the rope, very aggressive V slots would take over from the belayer and make lowering almost impossible. To calculate the extra braking effect is quite difficult so it is better to measure this directly.

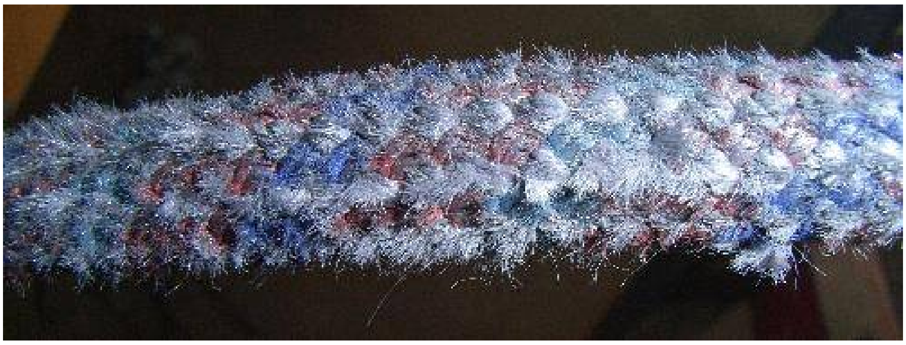
Squeezing

In some ways a bit of an urban myth, in most of the plates I have tested the rope isn't squeezed anywhere in use. Some manufacturers however try to make use of the karabiner being pulled forward under load to squeeze the outgoing rope and provide more friction. Too much bottom angle on the plate however and the krab tends to wedge and the device becomes grabby in use. Probably a reasonable idea but hard to get the right balance. This effect is also to an extent self-limiting as the force pushing the karabiner forward has to be greater than the force trying to straighten the rope, since the first is provided by the initial phase of the device and ones hand and the second by the faller it is easy to see which wins in the end.

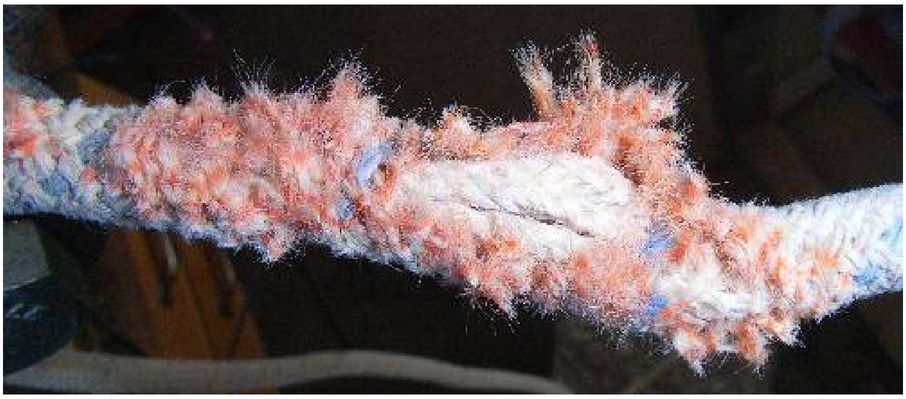
If you start getting too aggressive with this such as using two karabiners to force the rope onto the plate the rope quickly looks unhappy as the outer threads of the rope, already under considerable tension due to the bending moment get forced against the body of the plate, After one pull like this on our test rig the rope was already starting to get furred up with numerous broken threads in evidence. Check the underside rope entry of your plate is nicely rounded!

The two karabiner effect is not as great as one has been led to believe and as above is to an extent self limiting, with an increase of ca. 20% in our tests on 9mm and 10mm rope.

This was in good condition until it got the 2 krab treatment!



Or with an old, weathered rope and too much squeezing you get this:



Of course there is the option to squeeze the rope on the incoming side of the device and naturally this can bring enormous benefit as any increase here is magnified through the rest of the device, this is the principle behind the Wild Country SRC, Raptor and the now discontinued Salewa Antz and other similar devices. This also is the basic principle the Petzl GriGri and Edelrid Eddy use though both of these are semi-automatic and the lock-up cannot be controlled by the belayer.

Another way is to arrange the plate so that the loaded rope forces the dead rope onto the device body, this is the principle of the `guide plate´. Not many devices have been made with this principle for lead belaying though the Kong Robot could be used this way. I saw a device using this principle on my first Alpine trip in 1970 which was made from one short chain link welded at an angle to a long one, it appeared home-made but most things were then anyway. Out of curiosity I have made a couple up and played with the angles, around 135° seemed best and and also with two long links instead of one short and one long, while it gave good braking power the rope handling was not really acceptable requiring more delicacy than is usual for climbers. Paying out is relatively good but if you need to take in slack the device rides up into the locking position easily. Here's a picture for you home experimenters. One way to improve the handling might be to add a spring on the karabiner side as on some older Sticht plates, but I think marketing this weird monster with a spring on the back would be difficult to say the least! (Don't worry about the cuts through the links!)

Heat

While not directly affecting the performance of the device to a significant extent (until it melts the rope) the energy of a faller or for that matter an abseiler has to go somewhere and this is going to be in the form of heat.

The work of bending is manifested as heat inside the rope, both from the energy required to stretch and compress the threads and the friction between them and would be expected to be retained in the rope, any transfer to the belay device being miniscule. The work of friction produces heat at the interface between the rope and the device and the proportion which goes into which is a function of the relative thermal conductivity of the materials (this is a very complicated subject and the above is a simplification). Since the thermal conductivity of aluminium (250 W/m.K) is 1000 times higher than that of nylon (0.25 W/m.K)it is obvious that the bulk of the energy goes into the device and the karabiner and needs to be transferred into the air to keep the device getting too hot. A large surface area to increase the transfer to the air and high thermal conductivity to allow the heat to transfer away from the contact point through the device are the obvious requirements. Over the years aluminium has become the material of choice as it is relatively light allowing a larger surface area device to be built without climbers complaining about the weight. It also has a conveniently high thermal conductivity moving the heat rapidly from the contact point.

Of course in most devices a lot of the friction is generated at the karabiner and so using an HMS karabiner with more material and a larger surface area is not a bad thing either.

One manufacturer produces a belay plate from stainless steel with some interesting if undefined claims regarding reduced heat build up ("it stays a lot cooler") in long abseils. Since another manufacturer whose device is predominantly stainless steel specifically warns against long (over 50m) abseils due to the danger of overheating there is obviously some difference of opinion over this.

The thermal conductivity of stainless steel is vastly lower than that of aluminium (ca. 16 W/m.K) and therefore a higher proportion of the heat energy must go into the rope but conversely the heat going into the device is transferred away from the contact point and into the air less effectively. Naturally enough the rest of the plate is then cooler but the temperature at the contact point with the rope (which melts at relatively low temperatures) will be higher. Personally I think this is the wrong way round, I don´t care if the device is too hot to touch as long as the contact point is ice cold!

For climbers generally the above is all of purely academic interest since they abseil relatively short distances and rarely take 50m factor 2 falls, experience has shown that routine abseiling on the normal lengths of rope cause no problems. The extreme abseilers and cavers however routinely go 200+m and there other devices have to be used and the cavers rack shows the features which keep temperatures down, lots of bends to reduce the dependence on friction and a huge surface area to dissipate the heat.

Testing

All the above helps to build a mathematical model of a chosen design and more importantly shows the relative importance of the various factors in trying to make the perfect plate or analyse the performance of an existing one. In the end one still has to test the device and various methods are used to more or less effect and with more or less expense.

Currently there are no international standards for belay devices for use by climbers and with some thought it is easy to see some of the problems with establishing one. A major difficulty is deciding what parameters to use for braking force, a device perfect for bottom-roping kids on a climbing wall has different performance requirements to one expected to hold a fully equipped climber taking a long factor two fall on ice lines. If some parameters can be decided on, perhaps by having different categories of device, a further major problem is the test rope itself. To be an acceptable standard to international certification bodies some sort of standardised test rope will need to be defined and produced, presumably in various diameters. This is necessary because ropes vary considerably in their characteristics and allowing the device manufacturers to specify or supply the rope themselves could be open to abuse (a number of the device manufacturers have commercial interests in rope suppliers or make them themselves), or of course that old UIAA approved hawser-laid No. 4 will come out of the cupboard!

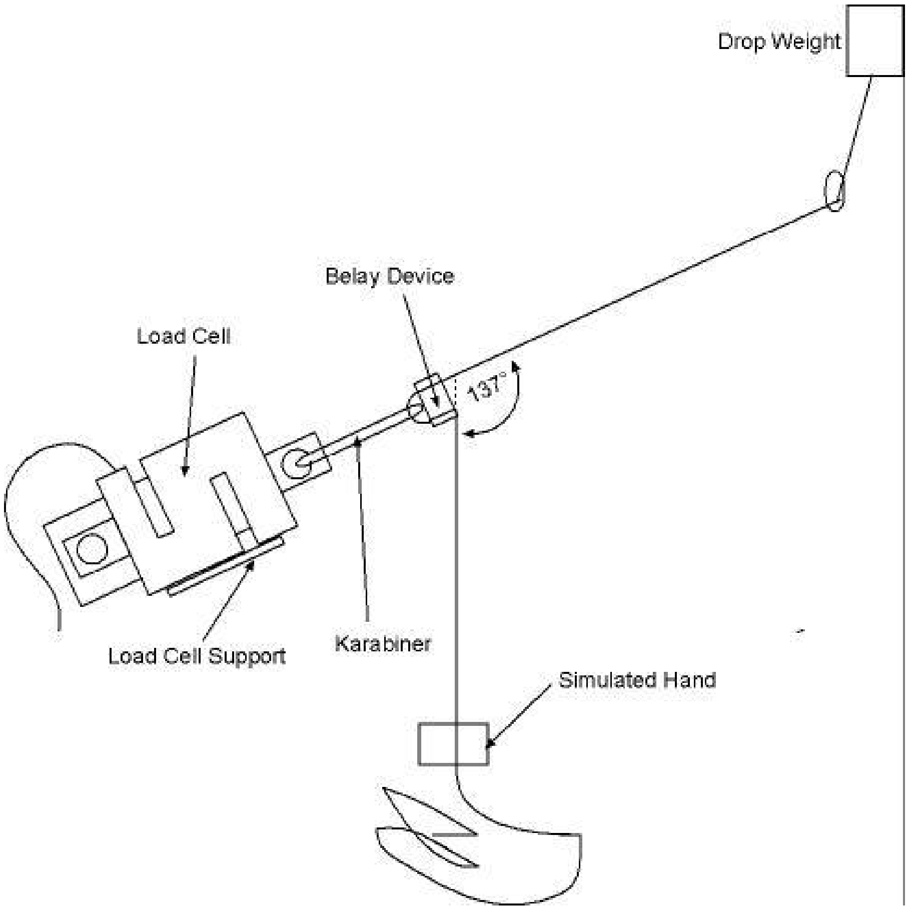
However, as I, like most other testers are to an extent interested in relative performance we can still get usable information from testing and it is virtually unavoidable.

Since the devices operate dynamically any form of static test is completely meaningless, as is shown above in a static test the work of bending is not measured and also the static coefficient of friction can be orders of magnitude higher than the dynamic coefficient. The two dynamic methods outlined below are currently the best solutions. To get accurate results it is necessary to test at the loads encountered in real life since, as we have seen above, the factors which affect a devices´ power are all load-dependent and in various ways follow a logarithmic pattern so simple extrapolation is not possible, above a very low limit these factors are not speed-dependent and the actual test speed makes little, if any difference.

One point should be noted, the test rope suffers considerably, particularly on the drop tower testing and the dynamic properties of the rope will alter from test to test. Even in non-drop testing the rope starts to glaze after a few pulls through the more powerful devices and the friction drops noticeably (ca 20%). For this reason it is essential to keep changing the rope and the drop tower method requires considerably more rope than a pull-test set-up.

Drop Testing

The excellent test system devised by Ratzenburger and subsequently used by the DAV and TÜV Süd give the nearest `real world´ results with the benefit of also allowing the slippage to be directly measured. Drawbacks are expense of a drop tower, enormous rope consumption and a slow test cycle. For research purposes it is not very practical as the braking cycle itself is extremely rapid making observation difficult. A simulated hand has also to be constructed which allows controlled slip of the braking rope at the chosen load (250N for the DAV), if a weight was used it would be subject to inertia due to the rapid acceleration changing the results considerably. (The inertial aspects of belaying have been investigated at length by the CMT in Italy and can be seen reviewed in the work by Moyer [bib.]

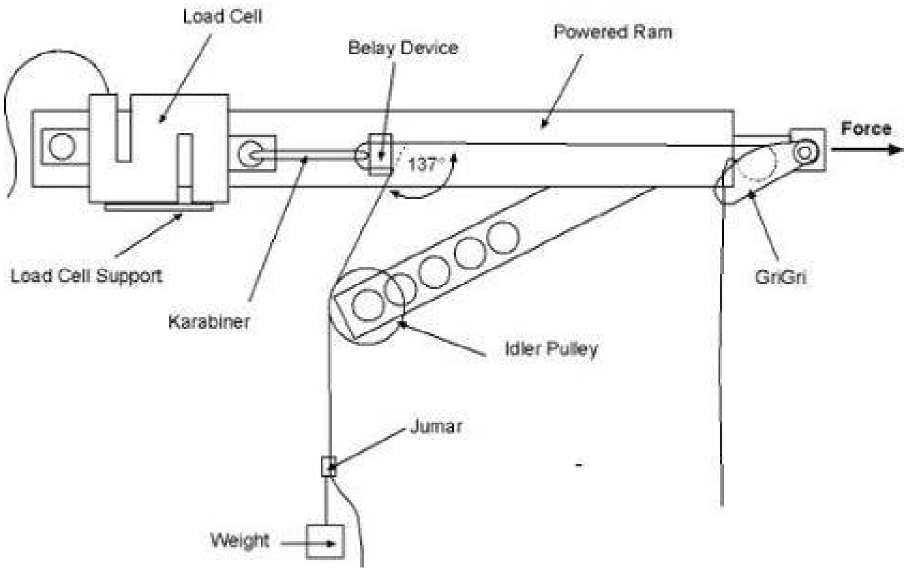


Pull Testing

The system used by Black Diamond and in a modified form by myself is far more suitable for development work as test cycles are enormously faster and rope consumption much lower, the capital costs and space requirements are also a fraction of those of a drop tower. The results are as accurate as a drop tower but the slippage resulting from a defined fall has to be calculated rather than read directly, though of course with the drop tower this also has to be calculated for any other fall then the standard one. This is not much work however and once a table has been drawn up a matter of seconds. Any standard weights can be used for the braking hand as the movement is at constant velocity so inertia is eliminated.

The first big advantage over the drop tower is that the action of the device can be observed in real time and even interfered with during a test pull, with a drop test one needs a high-speed camera to observe what is happening. The second advantage is the rope can simply be pulled through the GriGri the required amount to start a new test on a fresh length (and the lower weight adjusted as required), to re-hoist the weight and change the rope on a drop tower is a time-consuming job. When working with higher loads it is better to change from the GriGri as it will start slipping, adding a stopper knot and increasing the load further (7.4kN) allowed it to over-cam and jam up.

(The idler pulley is adjustable to be able to set the rope angle to compensate for various belay device lengths and to easily test varying angles. Whether the braking angle should be measured from the karabiner or the exit from the device is debatable).



Using The Results
The first thing to remember is to measure the rope angle to the load cell and rope angle to the weight under load because one needs to combine the vectors of the two forces (load cell measurement and `hand´ force) to get the true braking effect. It is surprising who has overlooked this!

Complex statistical analysis of multiple pulls is fairly unnecessary since the results are surprisingly consistent and in real life will vary considerably more depending on factors such as rope type, rope age and condition, belayer hand strength etc, I used the average values of 3 pulls for most work as I primarily was interested in comparative values.

You will notice I have tested with rope (cord) down to 4mm diameter. This helps to get a better idea of the characteristics of the various devices by giving a wider range of values. Additionally I wanted to see if it is possible to make a belay device which could satisfactorily function on this thin a cord!

Some studies such as Ratzenburger give the results as the braking force in kN for a given `hand' force in N but others, including myself prefer to divide the former by the latter to give the power ratio as this seems easier to visualise. It is important to note that this ratio will vary depending on the load so one should always specify the `hand' force in the results.

The results are of course specific to the ropes one has chosen to use, soft or hard, dry treated or not but this is inevitable until a "standard test rope" is developed. For published results the make, diameter and treatment of the rope used should be given to allow some comparison to be made.

Strength Testing

Climbers are so used to asking `how strong is it´ that this is inevitably asked about belay devices. For the great majority of devices the loads are extremely low and it would be difficult or impractical to make them as thin as they could be, anyway climbers wouldn't trust such a filigrane object and so it would never sell.

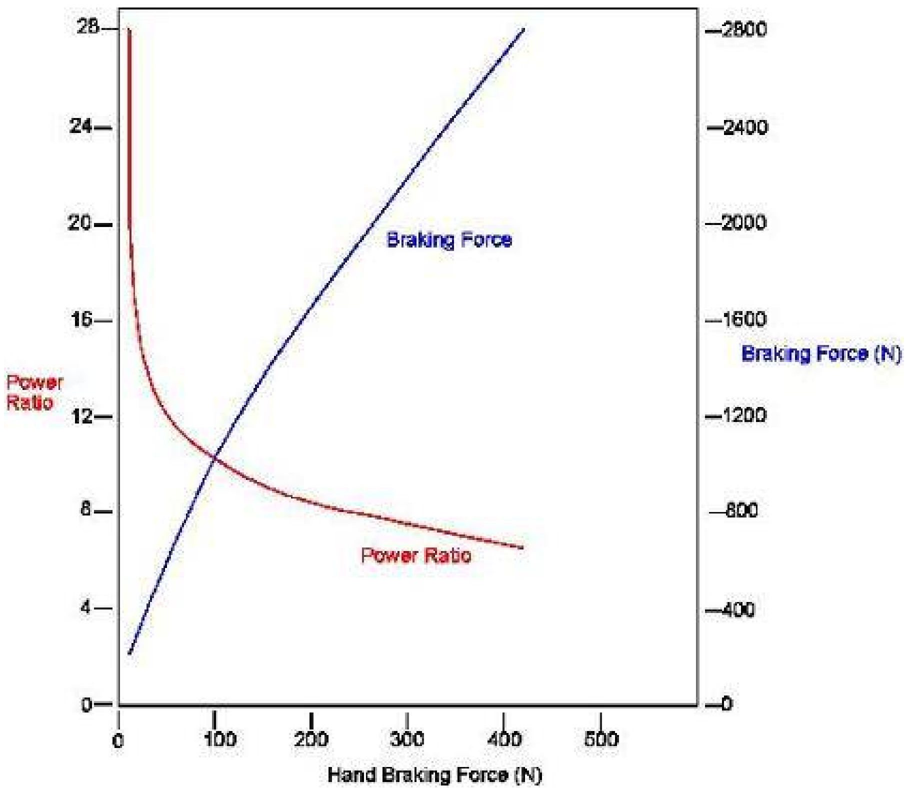
Things are different when the loads are not put through a karabiner as in a Sticht plate but rather are all contained in the device such as a plate in `guide´mode. The best tests for device strength where done by J. Marc Beverly and Stephen Attaway in a excellent and well worth reading paper; `Hang `Em High: How Far Can You Trust Your Belay

Device?´ (see the link in bibliography) where they tied a stopper knot behind the devices (the only way to impose high enough loads without slip) and performed both static and dynamic tests. Reassuringly all but one of the belay devices were able to withstand far higher loads than can in practice be applied before rope slip would occur.

Strength tests of other manufacturers devices were not part of my work.

Varying Braking Hand Strength

Obviously varying the hand strength of the belayer is going to have some effect on the braking force, in fact it makes a large difference and to check this I used my ATC XP as this is a fairly typical device. You can see why it is important to use real-life hand forces not just a convenient small weight!



Practice

WARNING

Belay devices in general are limited in their capabilities, something few climbers seem fully aware of. With only one exception no device available on the market is proven to be capable of stopping a climber in a reasonably long factor 2 fall and with most devices the belayer risks severe rope burns and loss of control even in considerably lower (less than 1) factor falls.

The energy involved in a long fall is considerable and the excess energy above that which the device can absorb is transferred into the belayers hand where it is converted into heat by friction. This rapidly causes the skin to heat up and friction burn whereupon an involuntary reflex releases the grip. An acceptable amount of slip through a bare hand is variously given as 0.5m and 1.5m depending on the strength of the grip. Alternatively the Petzl Fall Simulator uses a threshold of 1800J as the acceptable amount of energy before a rope burn warning is given, they allow much more rope (6+m) to slip through than I (and others) would consider reasonable to stop if not wearing gloves and in fact recommend (and illustrate in the instructions for their devices) the wearing of gloves for leader falls, something rarely seen today.

Auto-locking
Of these I have only seen independent tests on the Petzl GriGri and the Trango Cinch. While not everyone's ideal belay device or even suitable for some types of climbing the GriGri is the only device on the market proven in tests to hold factor 2 falls without damage to itself or the rope as the rope must not be held by the belayer, even though slippage occurs releasing the rope does not cause the faller to be dropped and the belaying action continues until the faller stops. From its design one can presume this could also the case with the Edelrid Eddy and possibly a few other similar devices but no information on slip is forthcoming from the manufacturers and no independent tests have been performed. The slip loads and slippage for the GriGri are given by the manufacturer for various rope diameters, an exemplary example of how things should be done.

(I tested the GriGri with 4 and 7mm ropes in the interests of continuity but these are outside its operating range and the results are not published. Petzl make a version of the GriGri for thin [7mm] rope which would be interesting to try).

The HMS (Munter or Italian Hitch)
This was developed for climbers (more specifically the karabiner required) by Mario Bisaccia and originally called the Mezzo Barcaiolo (the Italian for HMS) and incidentally has nothing to do with Munter who developed something else. With the exception of the auto-locking category this is still the non-plus-ultra of belay devices though it has some handling issues with rope twisting and using double ropes being adventurous. The braking power is head and shoulders above any current conventional device and the performance with thinner rope is still excellent. About the only other device than the above which could stop a decent factor one fall.

The Double HMS is little known outside of guide circles but if you need to lower a large weight this is the knot to use. To belay with it would be a nightmare. On test this was the strongest `belay´ device I have ever tested with a power ratio of 24:1 and defeated the GriGri on the other end of the rope! Surprisingly the rope showed absolutely no signs of distress after this and was probably the gentlest on the rope of all. Powerful enough to break both 4 and 7mm cord using our standard 300N hand force. Impressed!

Figure of 8
Designed as a lowering device but soon used for abseiling and belaying the humble (if rather large) 8 probably displays the most desirable belaying characteristic of any device with the least percentage loss of performance when used with thinner ropes but sadly only adequate holding power. As with the Munter Hitch rope twisting is a problem as well as using with double ropes. Big and almost extinct as a belay device.

The Sticht Plate/Tuber
Some people differentiate between these but I can't see any difference in principle and consider them all to be Sticht plates.

Developed from a chain link used by old sailors as a snubber to a simple plate with slots by Fritz Sticht and on to the latest aggressively styled and coloured product there are a multitude of these on the market. Dr Gary Storrick has a collection of over 130 different models and some improvement could have been expected over the last 40 years but in terms of holding power not a lot has changed while handling has improved a bit and the price has changed considerably!

In terms of braking power the traditional plate performs equally as well as it's modern relatives in the standard mode and even begins to outperform them with thicker ropes at the cost of becoming a bit "sticky". In fact testing with a chain link gave even better results than a proper Sticht plate and a number of modern devices, so much for progress! (Aluminium chain link brakes were made by MSR at one time, surely the smallest and lightest device ever produced).

The trend to thinner ropes has lead to all manner of high power options based on V slots with some creative names but even these fail to show any significant gain over a basic plate in it´s high power mode i.e. with two karabiners. For real high power putting one complete turn around the karabiner pushes the braking power up by over 100% and for abseiling on a single thin rope is a great idea but beware of rope damage as shown in the pictures earlier, for belaying it is surprisingly manageable but the extra turn tends to flip over a bit like with an HMS and care should be taken to make sure it comes on the spine side of the karabiner. (Hard to explain but easy to see if you play with this at home). Rope twist is also an issue if you are lowering. Of course at this stage you could just as well chuck the plate away anyway and use an HMS!

The actual slot length and width in the plate has an effect on the suitability of its use with varying diameter ropes, thinner ropes braking more effectively in smaller slots but this effect isn´t as great as one might think and making the slots smaller has a detrimental effect on the handling not to mention the fingers of steel required to get an older rope in the plate to start with!

Note: In some of the tests by the DAV for Sticht plates relatively higher values than expected were obtained for thin (ca. 8mm) ropes due to them being tested singly. Depending on karabiner and plate design the karabiner was twisting into the plate slot and jamming the rope, particularly in the tuber styles. Naturally one should not rely on this happening in real life and if using double ropes the effect will be much more unlikely.

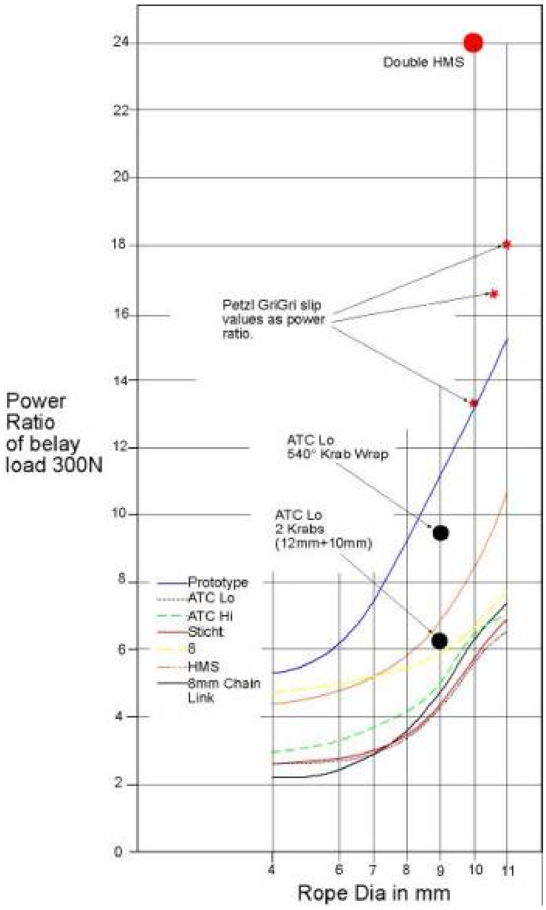
Test Results

The commercially produced devices (Petzl GriGri, Camp Sticht plate and Black Diamond ATC XP) are included as representative of their type and as yardsticks for comparison with other tests. I have no commercial interest in any of these products, consider them all to be of excellent design and these are in fact my personal belay devices. The Petzl GriGri slip values are from the manufacturers information and are consistent with my own results.

The test ropes were:- 10mm Mammut Alto, no treatment. 10mm Tendon Smart, standard treatment. 9mm Roca half rope, no treatment. 7mm & 4mm Tendon (Lanex) accessory cord.

The blue line `prototype´ is from tests of a development device made by myself to see what could reasonably be achieved without going to an auto-locking type of device.

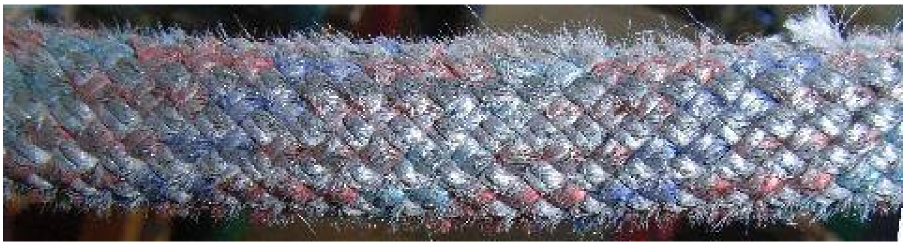
These tests were performed with a ‘hand’ weight of 300N and correction should be made when comparing these results with other tests. You can use the graph in the section "Varying Hand Strength" to obtain an approximate correction factor.



Rope Notes

I have not tested different types of rope as this was not my original objective but noticed a few points on the way:

- A soft, new rope gave about 20% less power than an stiff, old and well tested example.
- A dirty rope (grit) gave about 20% more power the first time pulled.
- A water-soaked rope gave 20% less power than the same dried, the main rope used in this test was not a dry-treated rope as I don't use these for my climbing.
- Most of the pull tests gave a certain amount of glazing on the rope, generally the higher the power of the plate the worse this was and subsequent pulls on the glazed parts gave a loss of power of ca. 20%. The rope companies assure us that this glazing has no effect on the rope and will disappear with use which it certainly appears to do.

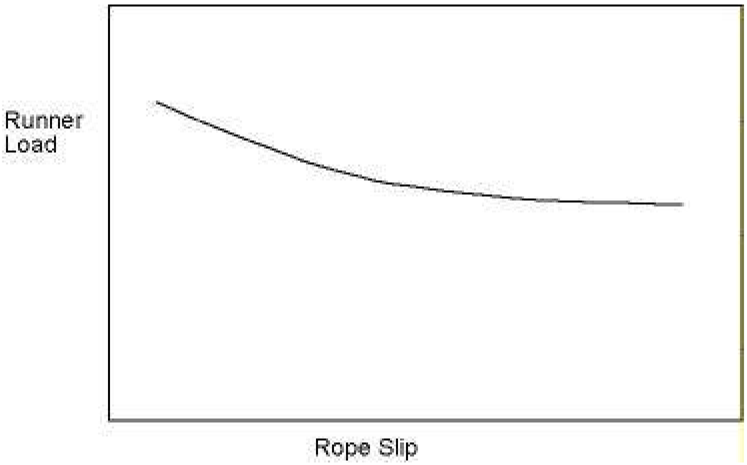


Dry treatment will inevitably lead to lower braking power, both due to the internal lubrication reducing the bending force and the coefficient of friction against the device itself being reduced. Reduced rope friction against the rock and karabiners are desirable characteristics and the increased suppleness of the rope is certainly pleasant but on the other hand knots, belay devices and the gripping ability of the belayers hand are considerably compromised by rope treatment, compounded by the ever thinner ropes. The difference between a battered 11mm wall rope and a super skinny treated one is enormous and something to bear in mind with a novice belayer straight from an indoor course. What the treatments are and their effects on friction and belaying ability are something rope manufacturers really should be informing us but are not.

Some Conclusions

As with many things, belay device performance is a compromise, a harder braking device stops the climber sooner but loads the system more, a softer one increases the risk of belayer failure. The limits to this compromise are clearly the ability of any part of the system to withstand the forces applied (i.e. a runner) and the amount of slip through the belayers hand which at a certain point will cause injury and loss of control.

To limit the forces on the equipment a more dynamic style of belaying is desirable but the effect is very much a diminishing one as the climber falls further, effectively increasing the fall factor as one can see from this curve of runner load against rope slip derived from various drop tests. The graph is dimensionless in this case but for a normal runner load of 5kN the rope slip is ca ¼ of the fall length after which the cushioning effect has become negligible. Naturally letting the climber fall further may also be a very bad idea!



The amount of slippage is limited by the amount of pain and injury the belayer is willing or able to tolerate and at some point in long falls there is going to be a break-even point where the belayer is better off letting go and saving himself from injury since he will anyway be going to be forced to drop the faller, sad but true! The DAV are quite clear in various articles that a large number of the belay devices used are unsuitable for high factor falls, particularly without wearing gloves, some manufacturers also give warnings but these tend to be much less prominent than the claims of massive holding power in the advertising!

If the system will tolerate it then going to a belay device with a higher braking power is the obvious solution and in most situations this is satisfactory but when climbing on protection of dubious worth then reducing the loading by using a new rope and equipment such as "screamers" may be the only possibility though the effectiveness is reduced the longer the fall..

The most desirable belay device would probably be one which allowed hands-free braking with a pre-determined braking force, allowing the belayer to decide what was an acceptable gear loading taking into account the possible dangers of increased fall distance (i.e. grounding). In the meantime a device which allows the belayer to dynamically control the braking force (wearing gloves as necessary) while being powerful enough to stop high force falls would be most desirable, the nearest we get at the moment is the H.M.S, but this has handling issues with double ropes.

Bibliography

A selection of websites with some useful information on belay devices and testing. Some are in German but contain information useful to non-German speakers.

http://storrick.cnchost.com/index.html- The non-plus ultra of belay plate collections! Ascenders, abseil devices, belay plates- this website has more than you can believe, over 1200!

http://www.jrre.org/biblio.html- The Association of Rope Rescue Engineering and Testing bibliography- links and references to all things concerned with rope.

http://www.xmission.com/~tmoyer/testing/Simulation_of_Climbing_and_Rescue_Belays.pdf- Tom Moyer on belay devices with a lot of useful information and some device tests. This was a powerpoint presentation so the dialogue is missing which would help fill up some gaps but still useful.

http://www.mra.org/services/grants/documents/Hang_Em_High_Final.pdf- Beverly/Attaway on possible standards and testing of belay devices with static and dynamic destruction (failure) tests of a lot of common devices.

http://www.jrre.org/ropes_101.pdf- Stephen Attaway with just about everything you need on calculating fall forces in ropes.

http://www.trango.com/pdfs/BelayDeviceTests.pdf- One from Trango, the U.S. manufacturer with some comparison tests done in a novel way!

http://oberon.ses.nsw.gov.au/resources/BelayBehaviour.pdf- Work on rope stretch in long ropes in rescue back-up belay situations.

http://www.jrre.org/att_frict.pdf- Stephen Attaway on friction and deriving Amonton´s capstan formula. Interesting mathematics but flawed.

http://www.mra.org/services/grants/ManningPaper.pdf- Timothy Manning on rope friction with an amazing coefficient!

http://www.alpenverein.de/template_loader.php?tplpage_id=85&mode=details&id=1226 - DAV/TÜV tests on some devices and how to do drop tests. In German but simple diagrams and tabular results. The original tests for this series and the test design were done by Peter Ratzenberger but are not available online.

http://www.bergundsteigen.at/file.php/archiv/2007/2/60-67%20%28die%20bremskraftverst%E4rker%29.pdf- More drop tests investigating the relationship between rope diameter and holding power including hand holding power. In German.