Theoretical Analysis of Rescue Belay Behaviour

by Alan Sheehan B.E.
Senior Vertical Rescue Instructor New South Wales State Emergency Service

Rescue Belays have been a topic of considerable debate and more recently some research. For some time various people have done tests to measure the dynamic loads developed in a belay event – usually as worst case analysis based on a minimal practical length of rope of 3m. More recently some testing has begun on belay devices, to find what works, what doesn't, and the device's ability to mitigate the dynamic forces involved. One aspect of research, however, that the author has yet to see any research being done on is the amount of movement of the rescue load during a belay event. The laws of physics suggest this can be very significant in long rope systems – a fact seemingly overlooked by researchers so far, with their primary concern being the forces involved in belays and the consequently short belay test rigs.

This paper theoretically analyses the amount of movement during a belay event, and discusses the implications of that movement. It is hoped this will encourage practical testing to start on this topic, increase rescuer's understanding of how belay systems work, and draw attention to the risks that so far appear to have been overlooked by many belay users and proponents.

For the analysis, I chose a number of rope lengths: 3m, 10m, 25m, 50m, 100m, 150m, and 200m.

As this is a theoretical analysis, I have chosen nominal rope characteristics based on requirements of AS4142.3 Static Life Rescue Lines as being typical. Actual ropes may vary from this. I have also assumed that Hooke's Law applies. I.e. that stress is proportional to strain (and force is proportional to elongation). It may be expected that nylon, particularly in the form of kernmantel rope is not linear, however, this deviation from linearity cannot be considered significant unless practical testing proves it to be, and does not affect the concepts that rescuers need to understand to be aware of the risks, limitations and behaviour of a belay system.

Based on AS4142.3 requirements for Static Line Rescue Lines, it is assumed that when an 80 kg load is applied to the rope, it will stretch 3%. Applying Hookes Law, a 200kg rescue load will therefore stretch the rope 7.5%.

We can calculate the amount of elongation in the rope simply by multiplying the length of the rope by the elongation (stretch) as a percentage. So from Table 1, we can see that a 200kg rescue load on a 100m rope will actually stretch the rope another 7.5 metres. In other words, the load line would be stretched about 7.5m before the load is lifted off the ground.

Fundamental to the operation and behaviour of a belay is that the belay rope does not carry any load. The load line carries the load, while the belay line is unloaded until a belay event occurs. A belay event is some failure in the load line system which causes the load to be dropped onto the belay line. Ideally the belay should have no load and also no slack, however, in practice there is often some slack in the belay line.

When a Belay Event occurs, the load is suddenly transferred to the belay line. This is actually a fall factor zero situation. Fall Factor is a conceptual dimensionless number calculated as the distance of free fall divided by the length of rope catching the falling object. It is a term commonly used in climbing circles, and often poorly understood and misleading. A fall factor zero situation is actually a "special case" taught in engineering courses. It is essentially the same situation as a vehicle travelling across a bridge – the weight of the vehicle is applied to the bridge relatively suddenly. As the bridge responds by deflecting to support the weight, the mass of the vehicle develops a component of velocity downwards. When the bridge has deflected enough to hold the weight of the vehicle if it were parked on the bridge, the downward momentum carries the vehicle and bridge below the equilibrium position. This dynamic effect results in the dynamic loads and deflections on the bridge equalling twice the static load.

The same thing happens in a belay. Hence the theoretical dynamic loads and deflections (movement) in the belay are twice the static load and stretch. This can be practically demonstrated with a simple weight on an elastic band or piece of shock cord. Hang a weight on a piece of shock cord. Note the position of the weight under static conditions. Now lift the weight until the shock cord just goes slack and release the weight. The weight will oscillate about the static equilibrium position with an initial amplitude equal to how far the weight was lifted. So from no load on the shock cord at the top, it gets stretched to twice the static weight and elongation at the lowest point. It is worth noting here, that belay devices limit the forces generated in the belay event by slipping or allowing *more* movement of the belayed load than theoretically calculated in this paper. So belay devices allow more movement of the belayed load in order to reduce the forces generated.

So this means, for our rescuer and casualty on the end of a 100m rope, if they are dropped in a belay event, that they will move 15 metres before coming to rest and being accelerated back up to oscillate around the static equilibrium point! 15m is a long way to drop! It may be of little concern in the ideal free hanging pitch, but how many pitches are truly free hanging? Most are against a face, across ledges, through vegetation or structures, etc. There is a lot of potential for injury to both the litter attendant and the casualty in such a belay event. The worst case would be when the rescue load was lifted exactly the static elongation above the ground or a ledge. In this case, the rescuer and casualty would hit the ground or ledge with maximum velocity. So consider a rescuer and casualty on a 100m rope, lifted just 7.5m off the ground when a belay event occurs. They will hit the ground at 8.577 m/s, or the same speed as free falling 3.75m! More than enough to seriously maim a rescuer underneath a stretcher!

This means that a belay system is not as safe as most people consider them to be unless the pitch is entirely free hanging and the rescue load is more than twice the static stretch in the rope above the ground. So the bottom 15% of any pitch is the danger zone where the belay may not provide adequate protection. A corresponding danger zone exists above every ledge or obstacle that could cause injury in the event of the rescue load being dropped.

It is interesting to note that few, if any, organizations that do long vertical rescues use belays. Typically the big, long pitch rescues are done by wilderness rescue groups and

mountain rescue organizations. The primary reason they don’t use belays is likely to be due to weight. Carrying 2 long ropes into a remote location places additional physical requirements on those crews, and in some situations would adversely affect their safety, survivability, risk of injury, and likelihood of a successful rescue. So they have learned to work safely without a belay – with single rope systems. Interestingly, if a belay was employed in many of these situations, the benefit might well be negligible!

So why are these risks in rescue load belaying not more obvious? Partly, it is because the organizations that use belays are working on relatively short pitches, probably less than 50m in height. It is also partly because the frequency of rescues is relatively low, and the incidence of load line failures resulting in belay events even lower! It is interesting, if not ironic, that the reliability of the single rope system is largely what prevents the hazards of the belay system from being recognised!