Yellow Spur Rope Failure Investigation

by

Rocky Mountain Rescue Group

March 6, 2011

On the morning of June 22, 2010, Joseph Miller fell while leading the second pitch of the Yellow Spur[1] route on the Redgarden Wall in Eldorado Canyon State Park[2]. During the fall the climber's rope failed, resulting in a fatal ground fall.

Due to the unusual occurrence of a climbing rope failure, the Rocky Mountain Rescue Group[3] (RMRG) conducted an accident investigation focused on the cause of the failure. This report contains the activities, findings and conclusions of that investigation. The intent of this report is to objectively determine what most likely happened during the accident. RMRG has no special relationship with any of the individuals or equipment manufacturers mentioned herein nor did RMRG receive any compensation for conducting this investigation. We encourage others to replicate our testing of this or similar scenarios.

Figure 1a shows a photo of the Yellow Spur route with the area of the accident outlined in yellow. The second pitch of the route starts from a tree and traverses to climber's left before heading up a dihedral (Figure 1b). The route was closed temporarily following the accident in order to gather on-site information in support of the initial investigation conducted by the Boulder County Sheriff's Office (BCSO). Prior to re-opening the route, a detailed inspection of the second pitch of the route was performed by RMRG, and photographs were taken of the climbing protection placed by Miller during the climb.

Interviews

Interviews with a number of nearby climbers who witnessed the events leading to the fall and/or the fall itself were conducted by RMRG. Miller's climbing partner, who was belaying at the time, was also interviewed. The primary purpose of these interviews was to understand the situation leading up to the fall and the sequence of events during the fall itself. The information provided by witnesses and the belayer were consistent with each other and allow us to present the following sequence of events:

Miller followed the first pitch, climbing it smoothly and without any difficulties. He reached the belay anchor set up by his partner at the tree in Figure 1b. During a brief discussion, he and the belayer decided that Miller would lead the second pitch. The belayer was anchored to the tree and was using an ATC-Guide (Black Diamond) in a standard belay configuration from his harness. Miller placed three pieces of climbing protection as he led the second pitch. The highest point on the route reached by Miller was in the lower portion of the dihedral in Figure 1b. The third piece of protection placed by Miller was near this high point. Miller appeared to be having difficulty with the climbing near the point where the third piece was placed and was being encouraged by the belayer. Miller fell shortly thereafter. During the fall, the third piece of

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[1] http://mountainproject.com/v/colorado/boulder/eldorado_canyon_sp/105748657

[2] http://parks.state.co.us/parks/eldoradocanyon/Pages/EldoradoCanyonHome.aspx

[3] www.rockymountainrescue.org

protection pulled out, but the first and second pieces held. Miller continued to fall straight down and past a small ledge. The speed of his fall appeared to slow very briefly as if the rope had begun to arrest the fall. However, the climbing rope then severed and Miller struck the ground near the base of the route.

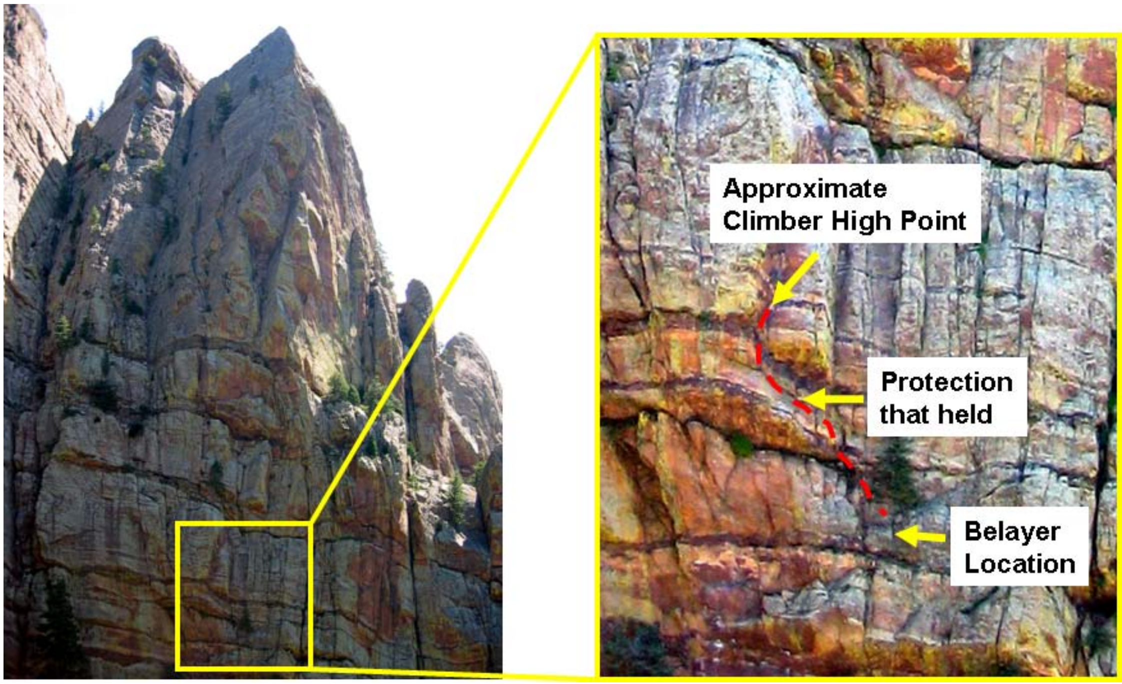

Figure 1. a) Accident location on the 2nd pitch of Yellow Spur. b) 2nd Pitch of Yellow Spur labeled with approximate climbing route (dashed line), and approximate locations of the belayer, protection and lead climber prior to the fall.

There are two additional important points from the belayer's account of the accident. First, he indicated that the initial protection placed by Miller had a long sling such that it did not cause the rope to change directions between the belayer and the second piece of protection. Second, the belayer indicated that he felt very little force on the belay from the fall. That is, he was not pulled significantly sideways or upwards by the rope as would typically be the case when catching a leader fall from this belay location. Immediately after the fall, the belayer pulled the remaining rope up to the belay and saw that the rope had been severed. He removed the first piece of protection placed by Miller before rappelling down to the base of the first pitch. The middle piece of protection (which held the fall prior to the rope failure) remained in place and was photographed during the initial investigation (Figure 2).

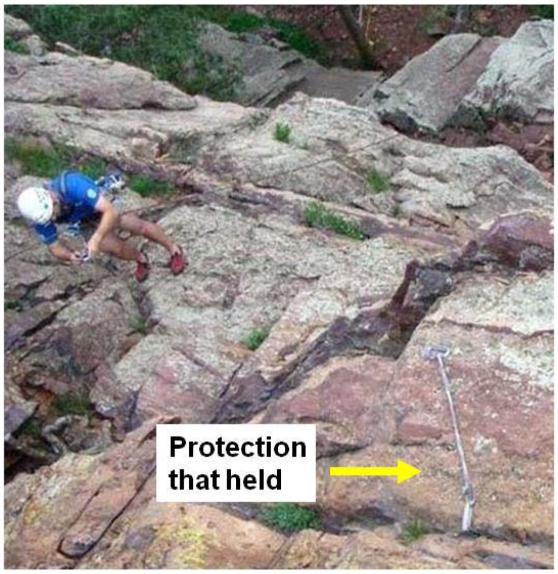

Figure 2. Protection that held during the fall (viewed from above).

Inspection of Equipment

The climber's rope was 200 feet (60 meters) in length, 9.7mm in diameter and manufactured by Beal. Three pieces of climbing protection had been placed by Miller while leading the second pitch. The highest piece was a #0.5 Black Diamond Camalot camming device that was attached with a 24-inch Dynex sling and two wire-gate carabiners. This piece pulled out during the fall. The second piece was a #0.4 Camalot, also with a 24-inch sling and wire-gate carabiners; this piece held during the fall. The lowest piece was a mid-sized stopper (unknown brand) placed a short distance from the belay.

A detailed inspection of all climbing equipment found on the route was performed. In general, the equipment appeared to be in good condition. Inspection of the #0.5 Camalot found damage to the lobes consistent with a shallow or open placement and a force considerable enough to pull the device from its placement (Figure 3). Damage to its associated carabiners and sling were also consistent with damage caused by high impact with rock. The #0.4 Camalot and its associated carabiners and sling were found to be in good condition. The climber's rope was inspected over its full length. The rope failure occurred approximately 20 feet (6 meters) from a figure-8 knot that connected the rope to the climber's harness. There were light abrasions along the rope for several feet on the climber's side of the failure. In addition, there were dark discolorations on the belayer's side of the failure consistent with a loaded rope moving across a carabiner. The remaining ~175 feet (53 meters) of rope was in good condition. During this investigation, we found no reason to suspect that there was any rope defect or that this rope was particularly susceptible to the damage that occurred.

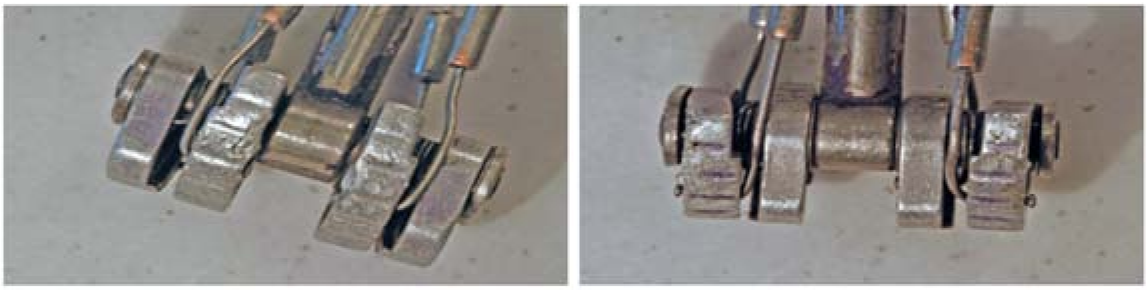

Figure 3. Close up of damage to cam that pulled out during fall.

Testing

RMRG Test Tower Facility

The majority of the testing presented in this paper was conducted on RMRG's 35-foot (10.7 m) tall steel test tower[4] (Figure 4). The tower is outfitted with a mechanical hoist and a stack of thirty 33-pound (15 kg) steel plates (for a total of 1000 pounds (455 kg)), which can be used to create a wide range of test loads. Drops are initiated using a pneumatic release mechanism (McMillan Design's "Sea Catch") and can be triggered either manually or via computer. Data is collected by a laptop computer with a National Instruments data acquisition card (Model 6251) and LabView 8.2 software. A variety of sensors collect load, temperature, and distance measurements. The load sensors have an operational range of up to 10,000 pounds (44.5 kN) and the data acquisition system allows sampling rates greater than 2500 samples per second. The

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[4] http://www.rockymountainrescue.org/randd.php

system is sufficient for capturing the critical information in the drop tests reported here. Additional details of the tower and testing equipment are available in Holden et al. 2009[5].

At any given time during the year, a number of studies are being performed at the RMRG test tower facility, including safety tests of rescue systems and new equipment. In addition, testing services are provided to other rescue organizations around the state, as time allows. Each scenario at the tower is planned in advance, and the set-up for each configuration can take several hours. The tests included in this investigation spanned seven days at the tower.

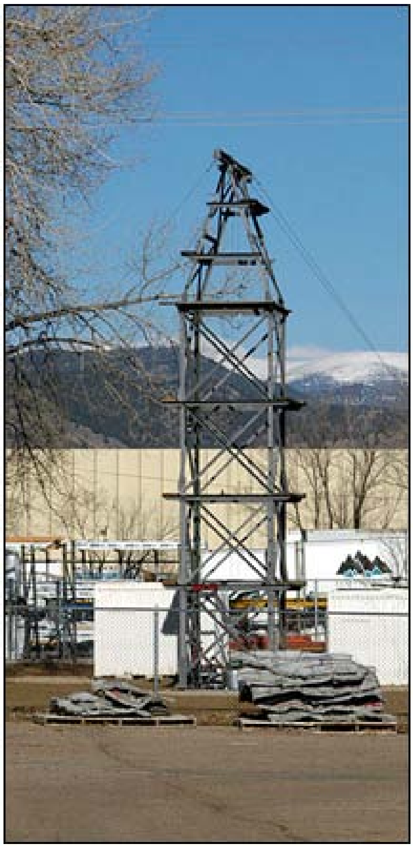
Figure 4. The RMRG test facility

Many of the following tests involved rope-over-rock configurations. A variety of rocks with similar density, crystalline structure, and sharpness to that found on the Yellow Spur route were collected and mounted on the tower. The majority were readily available flagstone (sandstone) slabs. The ropes utilized were all commercially available climbing ropes of diameters between 9.8 mm and 11 mm. During the drop tests, load sensors were mounted on both the climber and belayer sides of the rope to measure any differences in loading. All test sequences were recorded on digital video.

Fall Forces

The estimated distance of the climber's "leader fall" (not including the distance traveled after the rope severed) was 20-30 feet (6.1-9.1 meters). Such a fall can generate forces of around 800 pounds-force (3.6 kN). This force estimate is based on previous experiments and is highly realistic for such a fall. However, the belayer reported feeling significantly less force from the fall than he would have expected. Therefore, two testing sessions were dedicated to measuring the potential forces exerted on a belayer during such a fall under a variety of configurations.

First, a 165-pound (74.8 kg) rescue mannequin was used to simulate a leader fall of approximately 25 feet (7.6 meters). The configuration was designed to replicate the general geometry of the Yellow Spur accident: a clean fall was caught by a Bluewater Enduro 11 mm dynamic climbing rope running through a carabiner and down to an anchored belayer using a standard belay device (ATC). The photo in Figure 5 shows this configuration on the testing tower.

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[5] Holden, T., May, B., and Farnham, R. (2009). "On the Utility of Rescue Randy Mannequins in Rescue System Drop Testing." International Technical Rescue Symposium, Pueblo, CO. Retrieved February 13, 2011, from www.itrsonline.org/PapersFolder/2009/Holden-May-Farnham2009_ITRSPaper.pdf.

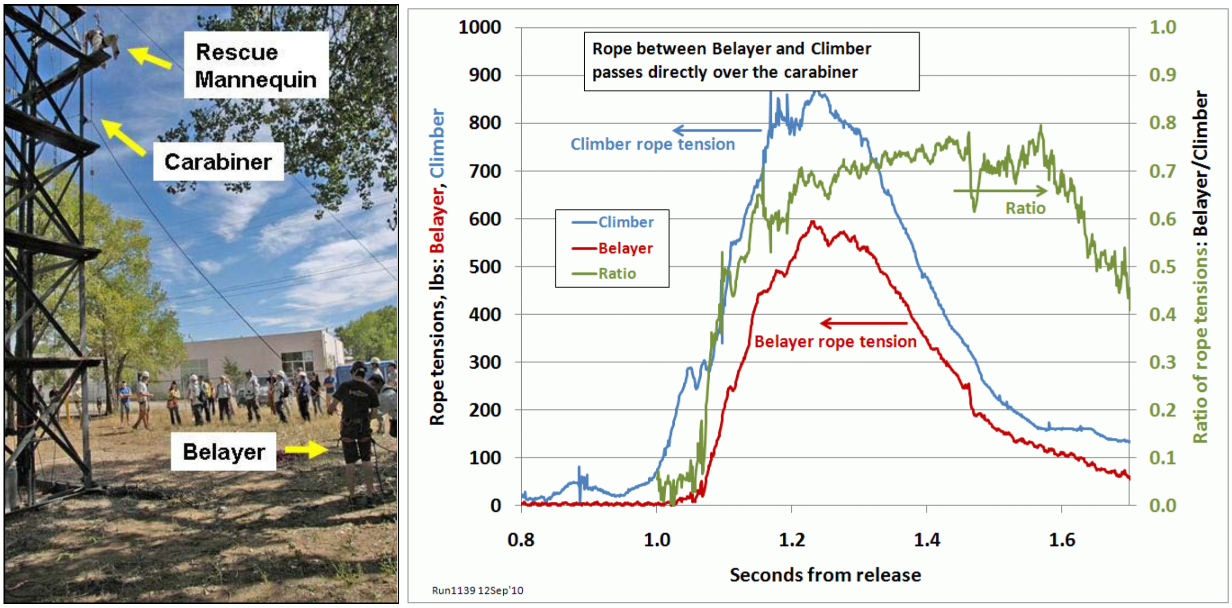

Figure 5. a) Climber and belayer forces drop test. b) Climber and belayer forces during leader fall.

Load sensors at the belayer and on the falling climber measured the resulting forces. Figure 5b shows the change in force (left vertical axis) and force ratio (right vertical axis) over time (horizontal axis). The force ratio is defined as the ratio between force experienced by the belayer to the force experienced by the climber. The force on the climber reached a peak of around 800 pounds-force (3.6 kN) at approximately 1.2 seconds. The force at the belayer was about 600 pounds-force (2.7 kN) at its peak. The ratio of the forces was approximately 0.7, consistent with the rope running cleanly through a carabiner.

The impact of 600 pounds-force (2.7 kN) lifted the belayer off the ground as the belay device caught the falling dummy during this test. Had a similar force been translated to the belayer during the Yellow Spur accident, he would have been yanked suddenly to the side (the second pitch starts with a traverse) as the rope came taught. Therefore, we can conclude that the belayer at Yellow Spur experienced a rope tension significantly less than 600 pounds-force (2.7 kN).

Fall Forces Over an Edge

The photo in Figure 2 shows the #0.4 Camalot and its associated sling and carabiners as they were found immediately after the accident. Prior to the fall, the climber's rope would have run up from the belayer, through the carabiner, and up to the climber's harness. As the climber fell past this point, the rope would have made a sharp bend through the carabiner and another sharp bend over the rock edge below the carabiner at the end of the sling. Another testing day was dedicated to measuring the resulting forces on a belayer under such circumstances. Figure 6a shows a close up of the geometry tested.

A quasi-static experiment was conducted to simulate the moment of peak loading. The belayer's end of the rope was anchored to the lower right. The rope was then run through a carabiner simulating the piece of protection that held, then back down over a rock edge. A 1000-pound (455 kg) weight was slowly lowered by a separate rope onto the climber's side of the configuration, simulating the peak tension in the rope. The rope tension on either side of the carabiner was measured separately.

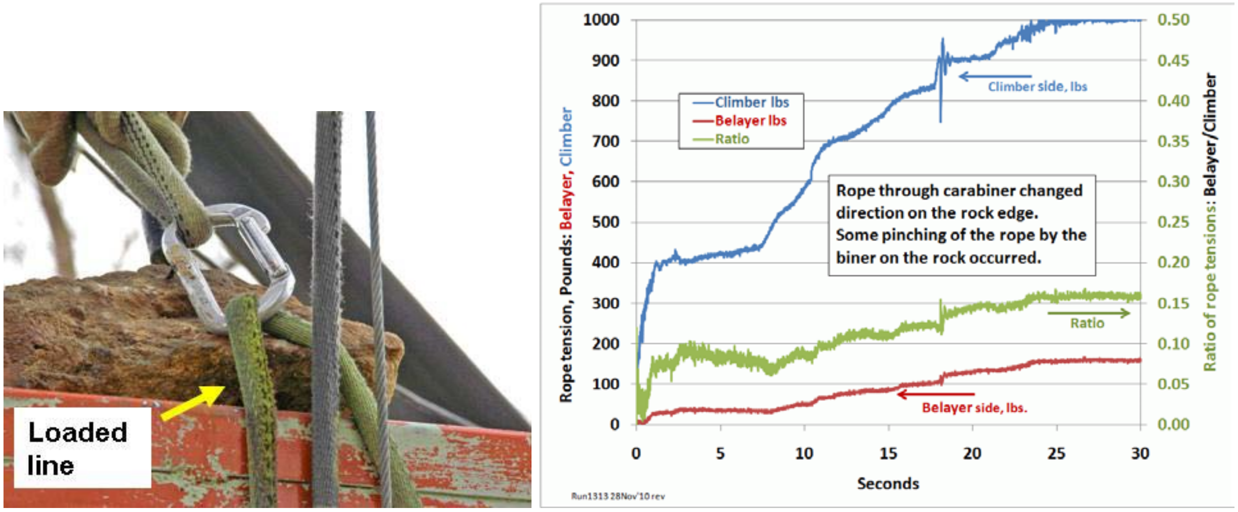

Figure 6. Rope changes direction over rock and through a carabiner: a) testing configuration & b) forces during a direction change.

Several variations of this general configuration were tested to determine whether and to what degree the carabiner could pinch the rope against the rock, and thereby contribute to a reduction of rope tension on the belayer's side of the carabiner. The results showed that the pinching effect may have contributed to the reduction caused by the rope bending over the rock edge. Figure 6b shows the forces measured in one such test as the weight is lowered onto the system. The graph includes the entire sequence from zero force on the climber's side to a peak of 1000 pounds-force (4.4 kN). During that time, the force on the belayer's side reaches a peak of approximately 150 pounds-force (0.7 kN) for a ratio of ~0.15. The reduction in force from climber to belayer in this configuration is quite large. When the climber's side of the rope is loaded to 800 pounds-force (3.6 kN), only 100 pounds-force (0.4 kN) occurred on the belayer's side.

These tests did not include manipulating the angle at which the rope bent over rock. However, the ratio of force reduction discussed above is exponentially sensitive to the angle of bend, such that an increase in the angle of bend would further reduce the belayer load. While it is difficult to determine the exact angle of bend that occurred during the Yellow Spur accident, the angle used in these tests was based on the photo in Figure 2 and is therefore similar to the angle that occurred during the actual accident. Therefore, these findings indicate that it is very possible for a belayer to feel little of the force of such a fall, given the geometry outlined above.

Comparison of Damage in Climber's Rope to Various Cutting Methods

Figure 7 shows images of the climber's rope at both sides of the failure. The damage occurred over approximately two inches of rope. A short length of the rope's core strands were pulled out of the sheath at the point of failure during the accident.

Figure 7. Climber's rope at either side of the failure.

The testing done as part of this investigation included cutting similar ropes under various conditions in order to determine the possible mechanism of failure. These tests show that ropes cut under different conditions display distinctive damage characteristics. Figure 8 shows two cuts performed under different test conditions. In each case, the rope was loaded to 800 pounds-force (3.6 kN), and the rope was cut with a sharp object. The image on the left shows the type of damage that results when a sharp knife is lightly pressed against a loaded rope. The damage occurred very quickly, and the strands showed very little elongation. The image on the right shows the type of damage that occurs when a sharp rock is used to saw across a loaded rope. The resulting damage was more uneven. Core strands near the sharp edge broke at approximately the same time as the sheath while core strands further away stretched and survived slightly longer.

Figure 8. a) Tensioned rope cut with a sharp knife. b) Tensioned rope cut with a sharp rock.

The damage characteristics of the accident rope (Figure 7) are consistent with the rock-cut test depicted in Figure 8b. These findings indicate that during the accident, the rope ran over a sharp object and failed at or near the highest point of tension.

Dynamic Drop Tests

Following the relatively static tests described above, the investigation team initiated a sequence of dynamic drop tests at the RMRG test tower. The primary purpose of these tests was to understand the combination of forces, angles, and rock structures required to cause the specific type of rope failure that occurred in this accident. The testing attempted to re-create the damage observed in the accident rope by creating fall dynamics that could have occurred during the Yellow Spur accident.

Rope Failure Test – Directly Over Sharp Edge

As mentioned previously, the photos taken on scene immediately after the accident led the investigation team to hypothesize that the climber's rope passed over the rock edge near the carabiner connected to the sling in Figure 2. It is possible that the rope failed as it passed over this edge. Two testing days were devoted to investigating rope failures directly over similar sharp edges of rock during a leader fall sequence.

In each test, a rock with a sharp edge was mounted to a beam on the test tower. Figure 9 shows a typical pre-drop configuration with the belayer's side of the rope attached to a load sensor. The rope then traveled through a carabiner, over a sharp edge, and down to a 200-pound (90.7 kg) weight stack on the climber's side. The rope used in these tests was a commercially-available 9.8 mm dynamic climbing rope.

Figure 9. a) Example pre-drop configuration. b) Typical partial rope failure result.

Numerous drop tests were executed with several variations of carabiner-to-edge locations, types of rock edges, and fall line angles, such that the rope slid 1 to 3 inches along the sharp edge during the simulated fall. Each test resulted in significant damage to the rope. However, in several cases, the rope did not sever completely. Figure 9b shows the rope damage after a drop where the sheath failed but the majority of core strands survived.

Figure 10a is representative of each of the tests in which complete failure occurred. The variability in the blue trace indicates the changes in force over time as the rope 'caught' temporarily on the rock edge due to friction and then released. The force drops suddenly to zero shortly after reaching its peak value, indicating the point of complete failure. The maximum load reached in this case was just over 1,200 pounds-force (5.3 kN) on the climber's side.

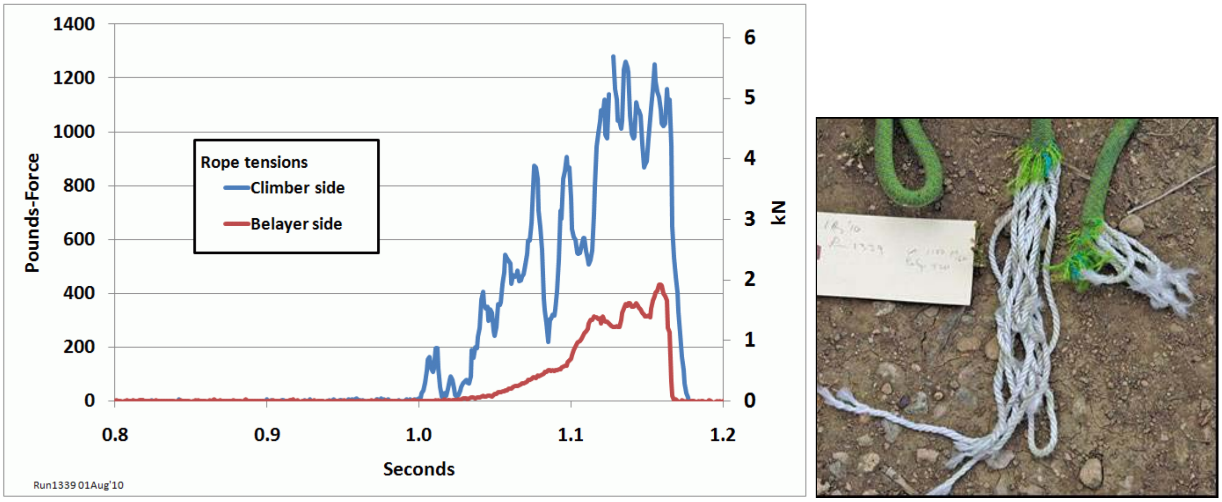

Figure 10. a) Typical loading during rope failure test. b) Typical damage caused during rope directly over sharp edge scenarios.

Figure 10b shows the type of damage done during each of the tests in which the rope failed completely. The sheath failed quickly and exposed the core strands to the edge. However, the core strands did not all fail at the same point. It is likely that as the rope is tensioned, it flattens across the edge, thereby protecting core strands that are further away, at least for a brief period of time. In addition, as the rope stretches, some of its length will become exposed to the edge and therefore the damage is spread across several inches.

While many of these tests were successful in creating complete rope failures, the characteristics of the damage were inconsistent with that of the accident rope (Figure 7). The damage to the accident rope occurs over a very short length, as if the contact point with the sharp edge did not change as the damage occurred. Therefore, it is unlikely that the accident rope failed due to the mechanisms or configurations demonstrated in this portion of the testing.

Pendulum Rope Failure Tests

Another possible mechanism for failure of the rope involves a fully loaded rope sliding sideways across a sharp rock edge. Conceptually, this is similar to the rope cut tests described above, where a sharp rock was used to saw across a loaded rope: the contact point of the rock on the rope does not change (Figure 8b). This mechanism may be present in a leader fall when the climber is not directly above the last piece of protection, introducing a sideways component to the fall. Based on previous testing at the RMRG test tower, the majority of such a pendulum movement occurs after the rope is highly tensioned. That is, a fall continues straight downwards until the rope stretches sufficiently to take a significant portion of the load, which then results in the falling object swinging from the fall line toward the last piece of protection. If there is a sharp edge between the climber and the last piece of protection, the rope will slide across it.

Two testing days were conducted to evaluate this pendulum failure theory. Figure 11a shows one of the many configurations used for the pendulum tests. The rope used during these tests was a commercially available 10.2 mm dynamic climbing rope.[6] A rock with a sharp edge was

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[6] This rope was thicker than the accident rope but it is reasonable to assume that a thinner rope could fail with the same characteristics.

mounted to the test tower. The test rope was attached to the tower approximately 3 feet (1 meter) higher than the rock and a weight stack was loaded onto the rope. In these tests, the weight was not dropped. Instead, it was allowed to swing sideways, dragging the rope along the sharp edge of the rock as indicated by the direction of the yellow arrows (Figure 11a).

The weight was pulled to the right side of the photo and attached to a release mechanism at the side of the tower. The blue piece of equipment clamped to the wooden beam is a smooth metal angle used to keep the loaded rope from rubbing on the rock edge prior to the release of the weight stack. This provided for less friction than would occur if the rope slid along the wood.

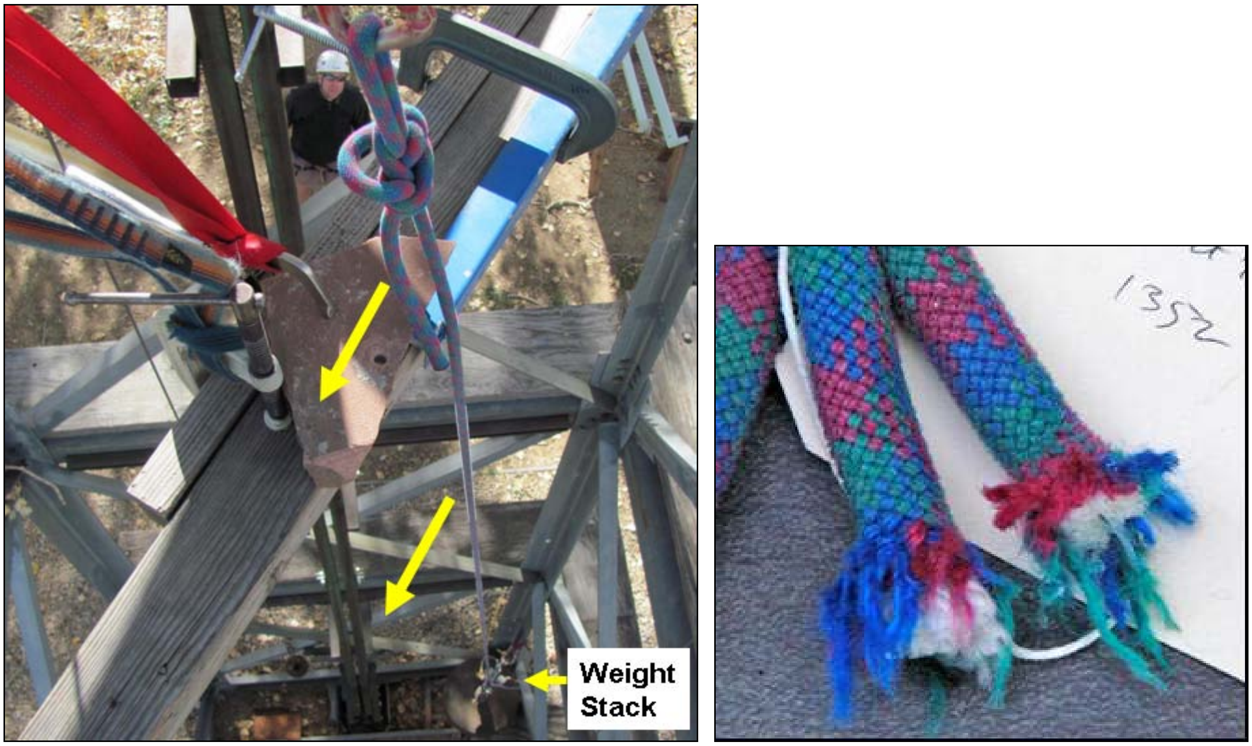

Figure 11. a) Test tower pendulum configuration. b) Pendulum test rope damage.

Different loads were used to simulate the downward force of a pendulum fall. Contact with the sharp edge of the rock during the pendulum resulted in considerable damage to the rope in each test. Using a load of 300 pounds-force (1.3 kN) caused the rope to fail, but only after sliding back and forth along the edge a number of times. However, there was no indication from witnesses to the accident that any such back and forth motion occurred prior to the rope failing. The remaining pendulum failure tests used a load of 760 pounds-force (3.4 kN). In each of these cases, the rope failed with only a single pass along the edge of the rock. Slow motion review of the video captured during the test showed that the rope passed over approximately 2 inches of the edge before failing.

Figure 11b shows the damage to the rope caused by the pendulum test with a load of 760 pounds-force (3.4 kN). The damage is isolated to a very short section of rope such that the sheath and core are cut at approximately the same location. The results of this test created a slightly cleaner cut to the rope than either the accident rope (Figure 7) or the test of the loaded rope cut by sawing a sharp rock across it (Figure 8b). In each of those cases, more of the core was exposed. Thus, it is possible that some amount of stretch occurred as the damage was occurring during the Yellow Spur accident. It is also possible that variations in the sharpness of the different rock edges could account for the different damage characteristics. However, it seems clear that this type of failure mechanism was likely responsible for the rope failure during the Yellow Spur accident.

Re-creation at Yellow Spur

As part of this accident investigation, RMRG attempted to re-create the conditions of the fall on Yellow Spur to evaluate interactions between the climber's rope and the rock during the fall. A fully-loaded fall sequence was not attempted on the route due to the time and resources required for such a recreation, the popularity of the Yellow Spur route, and the possibility of damage to the route itself. However, a simulated lead fall with a load of approximately 30 pounds-force (0.1 kN) was conducted from the climber's estimated high point in order to evaluate the pendulum characteristics of the accident, based on the best-known locations of the belayer, climber, and his protection.

The photos in Figure 12 show the start of the second pitch from the viewpoint of the belayer at the tree marked in Figure 1b. The investigator in the first photo (Figure 12a) is at the approximate location of the start of the fall. The rope (A) is an RMRG rope used by the investigators to access the route. (B) is the simulated climber's rope. The near end of the climber's rope runs through an investigator's belay device at the tree. The carabiner (C) is attached to a similar configuration of #0.4 Camalot and associated sling and carabiners that held the fall during the accident, and which have been placed according to the photo documentation in the initial investigation (Figure 2). The rope (D) connects the climber's rope and was used to provide weight during the drop.

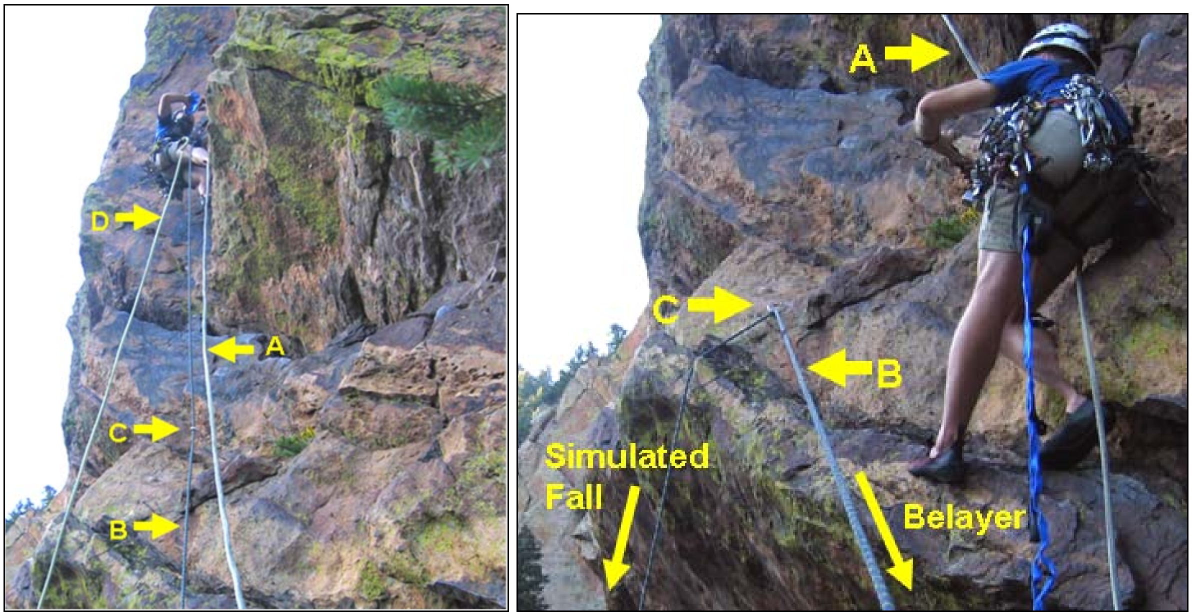

Figure 12. Re-creation configuration on Yellow Spur; a) just prior to dropping the rope & b) just after dropping the rope.

During the interview of the belayer, it was indicated that Miller fell straight down from approximately the investigators location (Figure 12a). In this re-creation, the investigator in the image dropped the simulated climber’s rope straight down without adding any outward or sideways component. While the amount of force resulting from this simulated fall is much lower than what would have occurred during the actual fall, the configuration was sufficient for estimating the general rope movement characteristics during the incident.

Figure 12b shows the resulting configuration of the simulated climber’s rope after being dropped from the position indicated in Figure 12a. In the image, (A) is the investigator’s access rope, (B) is the climber’s rope, and (C) is the carabiner. The fall line of the drop was about 2 or 3 feet (1 meter) climber’s left (into the image) from the resting location of the rope. The rope dropped straight down and then pendulumed climber’s right (toward the belayer) along the edge below the carabiner, finally ending up in the notch as shown in the image. The rope between the belayer and the carabiner did not contact any rock surface and there was no obvious place along that line where the rope could have snagged. The climber’s side of the rope hung in free space below the overhang at the bottom of Figure 12b. There are no other obvious edges near the carabiner other than the main edge over which the rope is draped. While there are certainly other possible rope movements that could have occurred during the actual fall, this sequence and resulting position are consistent with the available information.

Figure 13a shows the final configuration from just above the location of the #0.4 Camalot. The climber’s rope pendulumed left and down along the edge to its final resting point in the notch. The location of the carabiner is consistent with the photos taken immediately after the accident. Figure 13b shows a closer image of the edge that the rope slid over before coming to rest in the notch. The notch itself is sharp and the edge just to the right of the notch along the line the rope traveled is extremely sharp.

Figure 13. Re-creation on Yellow Spur. a) Looking down at the final configuration after simulated fall, b) Close up of the edge.

During the process of the re-creation, investigators saw no other combinations of fall characteristics and/or sharp edges that could match the known location of equipment that held during the fall and eyewitness information. If the rope movement during the actual fall followed a similar sequence as the re-creation, then nearly the full force of the fall would have been applied to the rope as it came taut over the rounded edge to the right in Figure 13a. It could then have pendulumed down along the edge toward the notch and across the very sharp edge shown in Figure 13b.

Analysis and Discussion

The purpose of this investigation was an attempt to understand the factors contributing to the death of Joseph Miller on June 22, 2010. The results indicate that a narrow set of circumstances likely led to the failure of Miller's climbing rope during a typical leader fall. Climbers may be comforted to know that it was difficult to re-create a complete failure of a standard dynamic climbing rope under realistic climbing conditions. The commercially-available climbing ropes utilized in these experiments often survived the severe tests undertaken, although with significant damage.

Non-pendulum drop tests wherein a climbing rope was loaded such that it ran for some distance over a sharp edge (without a significant lateral motion) resulted in sheath failure occurring significantly before core strands began to fail. In many cases, some of the core strands survived and ultimately held the load. This type of damage, however, was qualitatively different from the damage found in the accident rope. Therefore, it is unlikely that the failure of the accident rope was caused while elongating over a sharp edge.

Eyewitness reports indicate that the falling climber traveled straight downward and appeared to be decelerating immediately before the rope failure occurred. This is consistent with the rope failing under high tension during the maximum forces created in the fall. Furthermore, the damage found in the accident rope was consistent with results from the rock-cut and pendulum tests wherein a rope tensioned to approximately 800 pounds-force (3.6 kN) moved laterally over a sharp edge. These findings suggest that a pendulum effect contributed to the failure.

Potential Accident Sequence

While the exact alignment of the climber and the protection he placed cannot be determined with certainty, the best estimates suggest that the fall line from the climber's high point was a few feet climber's left of the #0.4 Camalot that initially held the fall. This geometry would have resulted in the climber falling straight down until the rope between the climber and the #0.4 Camalot began to stretch. The left hand pane of Figure 14 depicts the fall relative to this piece of protection (labeled 'R'). At this point in the sequence, shown in the middle pane of Figure 14, a pendulum effect would have begun, swinging the climber to his right. The rope would therefore have moved laterally across any rock edge between the climber and the #0.4 Camalot. The right hand pane depicts the potential configuration prior to rope failure from the side[7]. Re-creation of the accident events on the route itself demonstrated that such a sequence was possible and that the rope would have pendulumed across a sharp edge. It is therefore likely that Miller's rope failed under such circumstances.

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[7] This view is similar to the picture in Figure 12b taken during the re-creation.

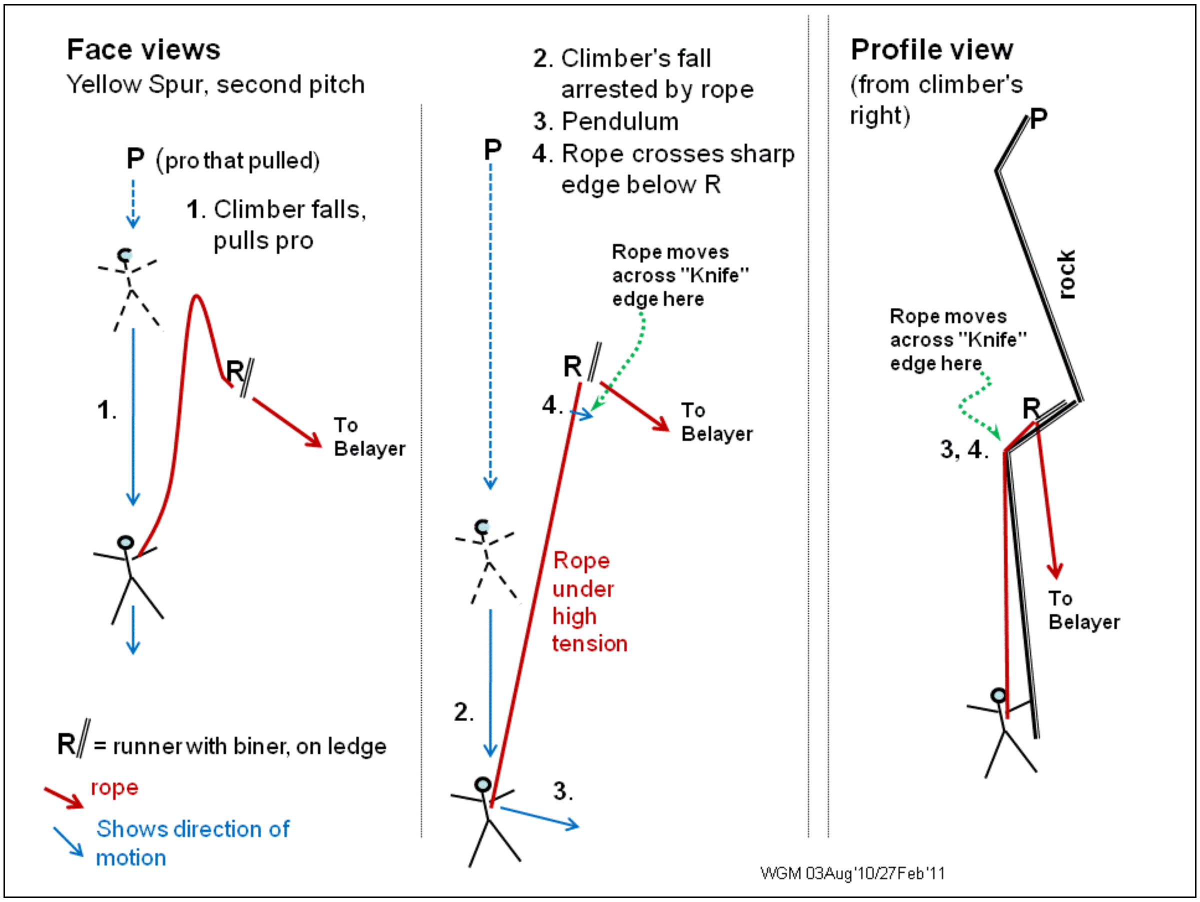

Figure 14. Potential accident sequence. Left and center pane depict sequence facing the route. Right pane depicts fall position prior to rope failure from the side.

Conclusion

There is no way to know exactly what caused the rope failure that resulted in Miller's death on Yellow Spur. However, it seems likely that a specific sequence of events occurred during this accident. First, the investigation found no indication of intrinsic (manufacturing) defect or deterioration of the rope or associated climbing equipment due to their prior use. Second, Miller appeared to be having some difficulty while climbing the route and took a typical leader fall, a fairly common occurrence among lead climbers. Third, it appears that Miller placed a piece of protection very close to his high point. Had this protection held, it is likely that the fall would have been arrested after only a very short distance. A combination of this highest piece of protection pulling out and the distance to the next piece resulted in a longer fall. Had the rope not failed, it is very likely that this longer fall would still have been stopped relatively safely. Fourth, the geometry observed during the re-creation of the accident indicated that the rope likely pendulumed across a sharp edge during the instant it was under high tension. If Miller's fall had not resulted in a pendulum, the rope may have survived running over the sharp edge (although likely with some damage). Had the fall generated a smaller force, it may also have survived the sharp edge. As with many accidents, it appears that a sequence of events rather than a single issue resulted in Miller's death.

Safety Lessons for Climbers

All lead climbers accept the possibility of a leader fall. Climbers evaluate and manage the level of risk they are willing to accept. Doing so effectively involves understanding the potential consequences of any fall. However, the general assumption among climbers is that “ropes do not fail” — or, at least, that rope failure is extremely rare. As such, climbing accidents that result in a rope failure attract considerable interest from the climbing community and may provide useful lessons for safety education. Two such lessons can be extrapolated from the current findings.

Lead climbers often place protection after passing a ledge in order to help prevent hitting the ledge during a fall. Protection may also be placed in order to prevent falling past the ledge, especially if such a fall would result in the rope running over a sharp edge. Clearly, any ledge with a sharp edge that a leader might fall past represents an extremely high risk factor. However, the rope failure tests done during this investigation suggest two additional factors to consider during such ledge transitions. First, lead climbers should attempt to visualize the geometry of a potential fall past a ledge, and consider whether a potential pendulum effect may result in a tensioned rope moving laterally across the edge. Second, climbers should consider how that geometry could differ given the failure of any piece(s) of protection along the route, possibly leading to the rope coming in contact with nearby sharp edges that may not be directly in line with the initial fall. In some cases, hazardous situations might best be managed by altering the route in order to avoid the area or even by backing off the route.

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