Rope Middle Marks and Failure in UIAA Drop Tests

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Contents

Introduction

This document suggests that an apparent "failure" of dynamic rope middle marks (produced by "permanent" pen markers), was due to local increases in coefficient of friction. The increase in friction was supplied by resins in the marking pens, and does not represent chemical degradation from solvents. In straight pull tests, dried Sharpie™ marks have no effect on the strength of nylon fibers. However, when the rope is pulled over a metal edge, as in the orifice plate of UIAA tests, the extra friction from the resins generates about 60% more heat in a small section of sheath and increases the chance of rope failure. This is not a scholarly paper; many of the references are in the spreadsheets used to make the calculations*. If you are truly interested in the details, contact me.

Background

About 2002, The UIAA announced a harsh conclusion that marking of the middle of ropes with permanent markers, such as Sharpie™ pens, could reduce the rope strength by 50%. Oddly, there was no indication that the middle markers provided on commercially available ropes, had been tested in the same way. There were some skeptical comments, such as:

https://www.blackdiamondequipment.com/en_EU/stories/experience-story-qc-lab-can-i-use-a-sharpie-to-mark-the-middle-of-my-rope/

"Personally I questioned the applicability of these tests in real-world scenarios. The UIAA test is consistent and an industry standard for sure, but it's also extreme. Their test imposes a violent high-impact (fall factor 1.78 with a static belay) on the same section (in the above-mentioned case, on the middle mark) of a rope, repeatedly, until it breaks. Not very realistic in everyday use. Think about that for a second: to have the middle of your 60-meter rope be the point where the rope is loaded during a fall, then you would have to be taking a HUGE 60-meter whipper—not very common.”

But the test results were reproduced by Mammut! Or maybe that was the before, and Mammut asked UIAA to investigate; I can’t tell from my web searches. Anyway, if you do the exact same thing, you will likely reproduce the results, whether or not they are relevant.

There were lots of “heated” exchanges on rock-climbing sites, and on summitpost, where polymer experts disdained the opinions of hoi poloi. The focus of internet commentary was typically the solvents in the markers. One of the solvents mentioned in older Sharpie™ MSDS was isopropanol, and the compatibility ratings for nylon and isopropanol are extremely varied (we will discuss the isopropanol scam later). But many solvents (such as water) weaken nylon only temporarily, as they are absorbed and desorbed. Some chemists claimed there might be unnamed actors in the Sharpies; but the overall “0” rating for health (given by people who have full access to the unnamed ingredients) argues against such hidden nasties. Of particular concern was that the pen makers might suddenly change the solvents without warning; indeed, the solvents in sharpies have changed markedly, as evidenced by changes in MSDS. However, the manufacturers clearly want to retain that “0” safety rating, and the laundry markers are designated as safe for synthetic fabrics. There simply aren’t many 0-rated solvents that will harm nylon. We have to bear in mind that the original tests did NOT involve Sharpie™ pen, and were done in a time of less concern for the safety of what are now household products. Before 1997, permanent markers often contained harsher solvents.

One of the best summaries I’ve seen is reproduced here:

http://www.treebuzz.com/forum/threads/marking-ropes.195/

Rarely, if ever mentioned in the exchanges, was the effect of the resins in Sharpies. The resins are referred to in older MSDS as “resins,” but become “additives” in later MSDS. They are proprietary ingredients, and are what make permanent markers like Sharpie™ “permanent.” The exact makeup of the resins is a trade secret, but the most common speculations are that they are urethanes, acrylics, or urethane-acrylic copolymers. And, they make the surface of the cloth/rope sticky. There are totally benign, initially water-soluble versions of resins, which need not be specified in an MSDS. Note even the Seamgrip (urethane glue) MSDS doesn’t list polyols used, just the hazardous components. MSDS85000 mentions Ethylene glycol monobutyl ether, a common solvent for acrylic resins. The most recent Sharpie™ MSDS mention no ingredients, since all have been certified non-toxic by independent labs.

The purpose of this document is to give another opinion: that the “strength reduction” was actually a reflection on the increase in the “friction” of the ropes, and the singular bizarreness of the UIAA tests. “Failure” may have little to do with “strength” or chemical alteration of the nylon. I can’t rule out the possibility that some sort of eutectic formed between the resins and nylon to lower the melting point, but have not found evidence that such exists.

Part of the reasoning is based on the analysis by Stephen Attaway [1], published on the web as xRopes.pdf, e.g. at http://lamountaineers.org/pdf/xRopes.pdf .

To be clear, the UIAA 101 for dynamic ropes is the overarching standard, but the multi-drop test specified in EN 892 is what was used, and UIAA 101 merely references EN 892.

The history: what we gather from web comments

The UIAA tests don't seem to be described in regard to how the marking pen was applied, or how they were sure of any degree of consistency in the mass of marker material transferred to the rope. The consensus seems to be that they marked up ropes, put the marked section over the carabiner (or over the metal orifice plate) in the UIAA drop test. To add to the confusion, there is reference to older test results, done by German climbing clubs as early as 1997. The UIAA definition of "losing half the strength" is rather singular, relating to the rope failing after half as many drop tests. But I had examined ropes marked by Sharpie™ pens, and the mark seemed very superficial, on only the outermost sheath fibers; the sheath itself is only part of the rope's strength.

Below is the diagram (Figure 1), starting from the UIAA specifications, and adding where they put the permanent pen "middle marks." The UIAA middle marker tests were probably done with a steel orifice plate (per EN 892, R=5mm). The image of the carabiner in Figure 1 is probably intended to give the reader some sense of the relevance of the test to climbing; the carabiner represents the "last piece of protection," and the drop represents a climber falling from 2.3 m above. The calculated fall factor (1.78) is large, partly because the rope on the belay side is so short.

Clearly the UIAA test is meant to be a standard, not realism, since the edge must be of hard steel. Few climbers will be carrying steel carabiners these days, and the differences among the thermal conductivities for steel types (even types of stainless), versus aluminum, are substantial. The standard simply says that the steel must have HRC hardness greater than 52. For comparison, the thermal diffusivity of a carbon steel with appropriate hardness, a514, is 1.42e-5 m^2/s; but a hard-worked stainless steel, t-301, is 4.06e-6 m^2/s, about 3.5 times lower. Thus a DODERO machine (as used by many compliant EN 892 drop tests) that uses stainless versus carbon steel for the orifice plate, is biased to keeping more heat in the rope. (Note that low-alloy steels may be used in the orifice plates, and will be corrosion-resistant enough to appear "stainless" in videos, but will have thermal properties similar to carbon steel.) The aluminum typically used in carabiners has a thermal diffusivity of ~4.8e-5 m^2/s, so a hard stainless may be as much as 12x more effective in keeping the heat in the rope, versus a typical aluminum carabiner, during a slow pull.

Figure 2 shows the manner in which ropes typically "fail" the UIAA drop test. The side of the sheath that rubs against the orifice plate/carabiner melts, exposing the core in subsequent falls.

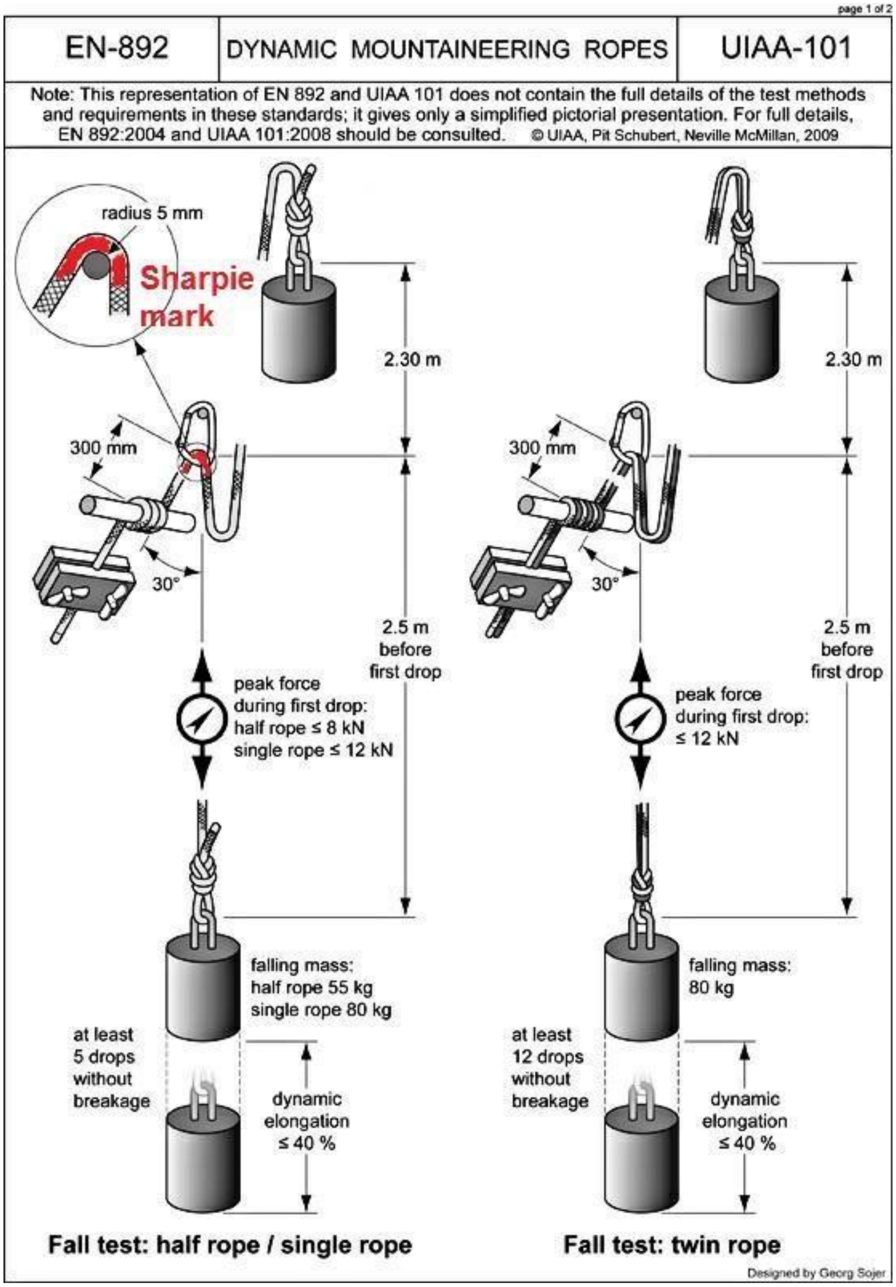

Figure 1. UIAA drop test schematic.

Figure 2. Rope desheathed by UIAA drop test.

Sharpie Does NOT Affect Strength in Straight Pull Tests

Many people have done straight pulls tests on sharpie-marked rope, and found no obvious effects (e.g. Black Diamond, as in previous reference). The problem with these tests is that most use figure-8-on-bights to attach each end of the test specimen to pull points, and the specimens break at the knots. Some say these knots maintain 75-80% of the original rope strength [11], but my own testing puts the strength retention as low as 66%. Thus with such tests, one can never know if the Sharpie did weaken the rope, just not as much as the knots weakened the rope. When a kernmantle rope is marked with Sharpie, and the pen mark is purposely included in a knot, the "rope" is weakened (http://www.supertopo.com/climbers-forum/1342794/Testing-marked-ropes-tofailure). This result is not too surprising; as we'll see, the Sharpie marks greatly increase the friction in the sheath (and likely increase the relative slippage of the core).

There is a simple way to remove the knot problem; it's called a capstan clamp, and it is used by professional testers of rope tensile strength. The idea is to provide a capstan with a much larger diameter than the rope, and then to wind the rope around the capstan several times, greatly reducing the tension that can be applied to the far end, which is then just held in a simple vise. A capstan clamp is on each end of the test specimen.

I decided to test the effect of Sharpie on the strength of nylon, by testing the effect on the individual yarns and braids used in typical kernmantle rope construction. By testing individual components, there is no need for the ultra-heavy-duty apparatus used in climbing rope pull tests. The disadvantage is that there tends to be more variation in individual yarn than ropes made of many yarns, so one must do at least 5 replicates to reduce the uncertainty of the mean (the ± reported here is the SD for all replicates, not the uncertainty of the mean). If one tests a very small diameter cord, the capstan can be just a carabiner, wrapped with medical tape to increase the friction, and a after about 6 wraps, a simple half-hitch is an adequate replacement for the "vise" (Figure 3). For thicker cord, I use a Hi-Lift jack to provide the tension, and two ¾" bow shackles to act as capstans (Figure 4).

The first set of tests involved twisted nylon yarns, as in the core of kernmantle ropes. My tests involved ten 1 m sections of 30 lb (13.6 kg) minimum breaking strength ***nylon*** kite line (from Premier Kites, Hyattsville MD); five were marked on 10 cm with black Sharpie (Magnum variant, purchased 2018), and five were left unmarked. Good kite line is very reliable, simply because people get angry when the line snaps and they lose their kites (but most is made of polyester these days). The Sharpie-marked portions of the line were stiff and the sharpie penetrated the line thoroughly; they were allowed to dry for two hours before the testing. The setup in Figure 3 was suspended from an industrial hanging scale, to which a video camera had been rigidly attached to record the digital display. The cords were gradually pulled to breaking with monotonically increasing foot pressure on the foot loop. The results: The unmarked line broke at 19.30±0.83 kg, and the Sharpie-marked broke at 19.35±0.15 kg. One Sharpie-marked cord broke near the end of the marked section; the other four broke outside the marks. In other words, the ***Sharpie mark had no effect on nylon tensile strength***. To be thorough, I tested four samples tied with figure eights on each end; those broke at 12.8±1.4 kg, or roughly 66% of the strength of the capstan-clamped samples.

Figure 3. "Capstan" clamps using carabiners

Figure 4. Hi-Lift jack set-up

The second set of tests involved twelve 7' (2.13m) sections of braided sheath, pulled off all-nylon "military grade" SecureLine 550 parachute cord. This test was intended to determine the effect of Sharpie on the strength of a high lay-angle braid (as the sheath of a kernmantle climbing rope), where the fibers necessarily rub against each other as the rope is tensioned. Six were marked in the middle 10cm with Sharpie (same Magnum variant); the penetration was thorough, and the marked sections were stiff after drying. This time both sets of sheaths were stored in plastic bags (after drying) for 6 weeks before the strength test. The jack and bow shackles were used, as it was anticipated at least 200 lbs of force would be needed to break the sheaths. (The sheaths collapsed to 1mm thick when weighted on the shackles, so the bow diameter was at least 19x as thick.) A ratcheting jack cannot provide a truly monotonically-increasing force; the force rises and falls slightly with each pump of the handle. A preliminary test showed that the highest force was experienced on the penultimate pump of the jack, and breaking occurred at a lower force on the next pump (probably after some nylon yarns had begun to tear), so these two forces were averaged; if just the penultimate force is used, the SD of the mean is about half as great. The unmarked sheaths broke at 111.4±10.9 kg, while the Sharpie-marked sheaths broke at 115.2±5.7 kg. Once again, there is no indication that Sharpie marks weakened the sheaths.

The Isopropanol Bogeyman

I was quite startled when Black Diamond put a warning in the package instructions, that nylon harnesses must never come in contact with isopropanol (isopropyl alcohol). I had read BD's documents, which report testing with ***other*** substances (http://www.blackdiamondequipment.com/en/qc-lab-acid-harness.html); so I had to wonder if BD had done their own testing on isopropanol, or simply trusted the wisdom reported in a Google search. The compatibility documents one can find on the web give wildly varying claims for the resistance of nylon 6 and 6,6 to isopropanol, from "extremely resistant" to "severe damage." Since isopropanol was in some Sharpies, this warning was relevant. So I have started some tests of my own.

I took five 1 m samples of the same kite line (same spool) used in the tests described above, and soaked them for two hours in isopropanol (99%, maximum 1% water; the cords were completely submerged at 73 °F), then air-dried them for two hours at 73 °F. I used the same breaking strength setup described above, with capstan clamps made from carabiners. The result: 19.88±1.43 kg for the isopropanol-soaked, versus 19.30±0.83 kg for the untreated samples (result above). Thus, there is ***NO evidence that isopropanol weakened the nylon***.

Many substances (e.g. water) temporarily weaken nylon as they sorb, but the strength normally comes back after they desorb.

The CoF Issue

Recently, I was trying to model the melting of nylon slings by polyester ropes, and had spent some time examining the effect of temperature on the Coefficient of Friction (CoF). On a lark, I painted both the nylon cover of the test capstan, and the polyester rope, with old Sharpie™. The measured CoF increased by 50%! This change could have a wider significance for testing. For example, if the marking pen covers the sheath where the rope is tied in a knot, the behavior of the knot in a pull test can be significantly altered.

Determining the Effective "Friction" Energy Loss in Attaway's Analysis

In the meantime, I had read S. W. Attaway's 1997 paper [1] "Rope System Analysis." Especially intriguing was his simple way of incorporating frictional losses into the analysis; you don't have to measure coefficients for rope travel over a rounded capstan with minimal force – you just have to measure the fraction force change as rope is pulled over a carabiner at realistic weights, and "internal friction" from deformation and bending [4] is incorporated inherently. I rederived the equations 20-31, corrected transcription errors in equations 30 and 31, and started to apply the analysis to the UIAA drop test. Figure 5 defines the basic terms in the analysis. The dimensions and mass in Figure 1, along with the supplemental information and experiments described below, allow modeling of the energy intensity on the orifice plate in the UIAA test.

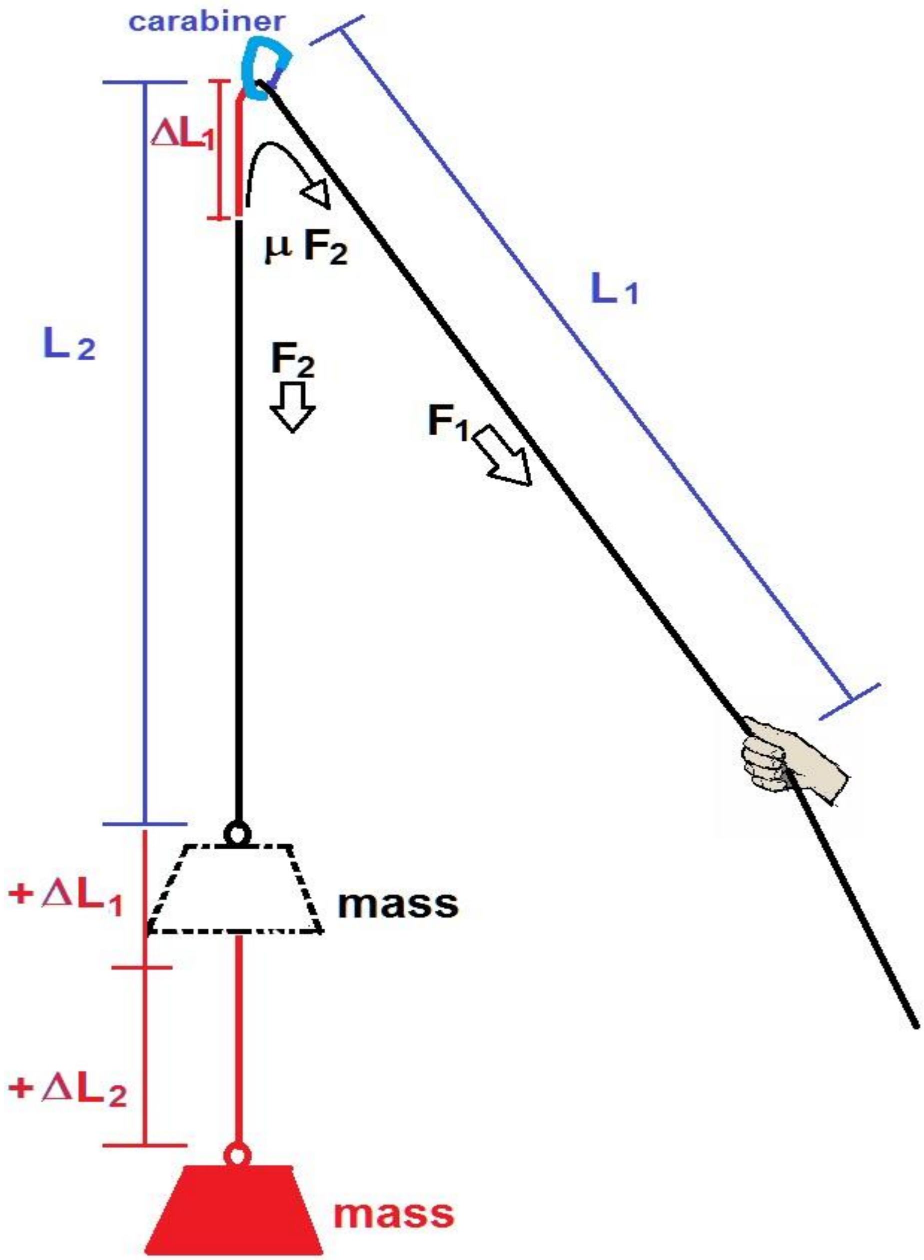

Figure 5. Terms in Attaway analysis.

Attaway's analysis merely denotes μ as a fraction of the impact force F_2 (see Figure 5). Thus the impact force on the "fall side" of the UIAA test is F_2, and is related to the "belay" force F_1, on the other (clamped) side of the rope by

$$F_2 = \mu F_2 + F_1.$$

I estimated μ in two different sets of tests; the end results for these two sets, in terms of relative energy density in L_1 are the same within 2%. Note that μ is related to the CoF, but is not the CoF.

The μ was measured with a static 8.4 mm polyester-sheathed rope, with polyester core. The rope radius is not expected to make much difference in slow pulls (that's the way CoF works). I don't expect nylon-sheathed rope would give different results, as I have done tests with nylon, nylon and polyester ropes have very similar measured ***dry*** CoF with metal, my pulls were slow, and my postulate is that the Sharpie coating is what controls the change in frictional behavior, not any chemical change in the fibers themselves. With dynamic ropes, it is extremely difficult to measure μ uncorrupted by the springiness of the rope. With a static rope and known mass on the L_2 side, about 20' of rope, at least half marked with sharpie for that measurement, is needed to reach a force plateau on the L_1 (pull) side. With dynamic rope, the pull is bouncy and a plateau is never reached, because of the "soft spring" in the system. So as in many physics problems, we measure the important parameters separately, and depend on the model to bring them all together.

In the first set of tests, I put an aluminum carabiner about 10' up, suspended from a sturdy tree limb, and did many pull tests over the carabiner. Steel carabiners would be more appropriate for comparison with the UIAA tests; but manufacturers of rope generally find that polished aluminum and steel give very similar CoF (as verified in the second set of tests). Half the tests used "clean" rope, and half used rope that had been coated with black Sharpie (about 12' of coating); the coated rope sat for a day before the tests. I used a calibrated industrial pull scale (500 kg capacity); a camera was rigidly fixed to the scale to record the digital display as video. The scale can either be placed on the pull side (in which case the scale mass must be taken into account), or above the carabiner, to measure F_1+F_2; I found the latter position provided less stable readings. Force/time readings from the scale were entered into an Excel spreadsheet. I used 30 lbs of weights on the "belay" (F_1) side of the carabiner, and walked off a stepladder gradually, trying hard to maintain a constant rate of pull on the F_1 side. The μ_u (unmarked rope) was experimentally determined was 0.413 ± 0.001, and μ_s (Sharpie-marked) was 0.537 ± 0.001. The angle at the carabiner was maintained at 150°.

A fault with these tests was that I didn't constantly refresh the Sharpie on the rope, through many set-ups before the measurements, so the Sharpie wore off as time went by, and so the pull force went down. In addition, they were performed when the temperature was well over 85°F, whereas UIAA 101 specifies 23°C ~73.4°F.

The second set of tests was very similar, but were done in my stairwell (the ceiling is very reinforced, to accommodate rope tests), and achieved a more controlled force on the pull side. This time I used two different sets of carabiners; one set of experiments used an actual Al-biner quickdraw (Metolius Inferno), and the second used a pair of tough steel carabiners (Metolius steel screwlock), so the rope went over a width of about 19 mm in the latter (the steel type is not specified; it appears to be a low-alloy, low-corrosion steel). The measured μ_s for these very different carabiner setups was 0.694±0.018 vs 0.699±0.022 -- essentially the same within experimental error. The measured μ_u for the unmarked ropes was 0.549±0.018. Bear in mind these were slow pulls, so there was little heating and little effect from the differences in thermal properties. For these tests, the space was limited, so the angle over the carabiner was 180°. I refreshed the Sharpie (and let it dry) on 10' sections of rope between tests, and the T was ~73°F.

Attaway's analysis allows one to start with fairly common rope characteristics, then plug in experimentally determined μ_u and μ_s for the normal and Sharpie-marked rope, respectively. I chose 26.7 kN for the modulus of the rope, the center of Attaway's range of 17.8 – 35.6; this is pretty consistent for the value of 9.5-10 mm dynamic ropes. I took the rope mass from the value of 66g/m, as given for "Alex Honnold signature 9.9mm."

From the corrected equations 17-32 in Attaway's analysis, the section of rope pulled over the edge ("carabiner") is

$$\Delta L_1 = F_2 \cdot L_2/M = (1-\mu) \cdot (L_1/L_2) \cdot \Delta L_2 \quad \text{and}$$

ΔL_2 can be obtained from

$$(M/(2 \cdot L_2)) \cdot ((1-\mu)^2 + 1) \cdot (\Delta L_2)^2 = 0,$$

where M is the modulus of the rope and ΔL_1 is essentially the length of rope pulled over the orifice plate/carabiner in the EN 892 drop test. The "friction" energy added to rope and carabiner by movement over ΔL_1 can be expressed as:

$$E_f = M \cdot \mu \cdot (1-\mu) \cdot (L_1/L_2) \cdot (\Delta L_2)^2/(2 \cdot L_2)$$

and the specific energy per unit length of ΔL_1 is:

$$SE = M \cdot \mu \cdot (\Delta L_2/(2 \cdot L_2)).$$

For the marked and unmarked ropes, calculated ΔL_1 (length of rope pulled over the carabiner/orifice) is 3.3 and 5.0 cm, respectively.

As Attaway noted, the energy lost to friction in the UIAA test is small compared to the total in the system; but the frictional energy is absorbed in a very small section of the rope, effectively the 3-5 cm that is pulled over the orifice plate in the UIAA tests. Notably, this is also the section of rope that fails in UIAA tests, typically by melting of part of the sheath on the metal edge. The total energy lost in this section of rope is not that different between the unmarked and Sharpie-marked cases. However, in the Sharpie-marked rope, the affected section (ΔL_1) is significantly shorter, so the energy density (SE) is significantly higher (about 30%), bringing that section closer to melting. The resultant SE is about the same for both the 1st and 2nd set of experiments, even though the absolute values of μ_u and μ_s differ between experiments.

But wait, there's more! SE actually has a component from true surface friction SE_{sf}, mainly applied to less than half the sheath that actually rubs on the metal surface of the carabiner/orifice plate, and a component SE_b

from bending and deformation of the rope. Jim Titt's tests [4] show that the belay rope requires 50% more force on the pull side, just going over an 180° bend on an almost-frictionless roller; a rope that is bent and ***also*** has surface friction uses about 100% more force on the "pull" side than is provided on the "belay" side. We can make the reasonable assumption that the component from bending, which contributes just to diffuse heating throughout the rope, is about the same in Sharpie-marked and unmarked ropes. Thus

$$^{u}SE = {}^{u}SE_{sf} + {}^{u}SE_{b} \sim 2\cdot{}^{u}SE_{b} \quad \text{and} \quad {}^{s}SE = {}^{s}SE_{sf} + {}^{s}SE_{b} \quad \text{and} \quad {}^{s}SE_{b} \sim {}^{u}SE_{b}$$

where the s and u superscripts denote Sharpie-marked and unmarked rope, respectively. Thus

$$^{s}SE_{sf}/{}^{u}SE_{sf} \sim ({}^{s}SE - 0.5\cdot{}^{u}SE)/(0.5\cdot{}^{u}SE) = 2\cdot({}^{s}SE/{}^{u}SE) - 1.$$

So if the ratio of specific energies in ΔL_1, for marked and unmarked rope. are about 1.3, the ratio of surface friction energies is about 1.6. That is the Sharpie-marked rope has 60% more energy produced on the carabiner side of the sheath, than the unmarked rope; but we don't know yet how this energy would get partitioned between the rope and the carabiner, or what fraction of the rope would see this energy in the very short time of the pull of ΔL_1 over the carabiner/orifice plate.

Let's speculate: rope manufacturers are under the gun to make the lightest ropes that will pass the UIAA tests, and they only need to pass the UIAA tests just barely. Putting an extra unintended 60% energy at the rope-metal interface may cause failure. Furthermore, whereas some of the energy loss calculated in Attaway's equation will be from bending of the rope, the Sharpie-marked rope will have most of the "new" energy concentrated in the sheath surface in contact with the metal. Thus ***we already have a reason that Sharpie marks would make ropes in UIAA tests fail more quickly, and it has nothing to do with the actual "strength" of the rope***. But let's see if we can make a stronger case that this small amount of extra energy is enough to cause rope failure.

Calculating Heat Division

Now, an important note: the calculated energy loss goes into heating of both rope and metal. The method of apportioning the heat to each is extremely complicated, and current knowledge does not allow an exact solution for the rope-metal edge system. The analyses of Jaeger[5] and Berry and Barber [6] (eq. 6) are crudely appropriate; they model a harder object "ploughing" into a softer object that moves over it with a specified Peclet number. In the extreme where the movement of rope on metal is slow, and the initial temperatures at infinity are the same for both rope and metal, the partition of heat into the metal is roughly proportional to the inverse of the thermal conductivity of the nylon, and the heat into the nylon is inversely proportional to the thermal conductivity of the metal. But then as the metal heats, energy should transfer back into the rope. But if the motion is fast, "new" rope is exposed to the metal in each tiny increment of time, doesn't have as much chance to heat up, and more of the heat actually goes into the rope; the lower the thermal conductivity of the metal, the more the heat goes into the rope. It is notable that equation 6 in [6] exactly reproduces the results for model 10i of Jaeger [5], which made no assumptions about the size of the asperities.

Consider the following very rough calculation from [6] equation 6. The analysis takes the characteristic dimension of the hard surface "asperity" as 0.6545 cm (half the circumference of orifice plate subtended by

150°, or half the metal-rope contact length of rope, under normal force, in the UIAA drop). It is difficult to estimate the speed of the rope; from plots of maximum force (Figure 6) the intense force plateau is perhaps 0.05 seconds, and we assume this is when the "belay" rope is being stretched over the edge – this corresponds to the region of rope destruction, which we take as 3.3-5.0 cm from the calculations above. This length is reasonably consistent with the DODERO tests shown on youtube [7] (Figure 2 shows approximately 4.5 cm of rope desheathed by melting, but it is unclear how much more rope is out-of-frame). The analysis by Henkel [9] (though using the sharp edge UIAA version of the drop test) shows intense melting over about 4 cm, with streaking on the rope sheath farther away. So 0.05 seconds to pull 3.3-5 cm gives about ~ 1 m/sec for the "belay" rope over the metal edge. If the edge were made of aluminum, the fraction of heat entering the rope would be 0.28; if a hard carbon steel, such as a514, it would be 0.49; and with stainless, it would be 0.76.

Clearly, this is a crude analysis, but is does give the warning that a stainless steel edge, while very appropriate for a shiny, tough experimental apparatus, may not appropriately model the typical carabiner used to protect a fall.

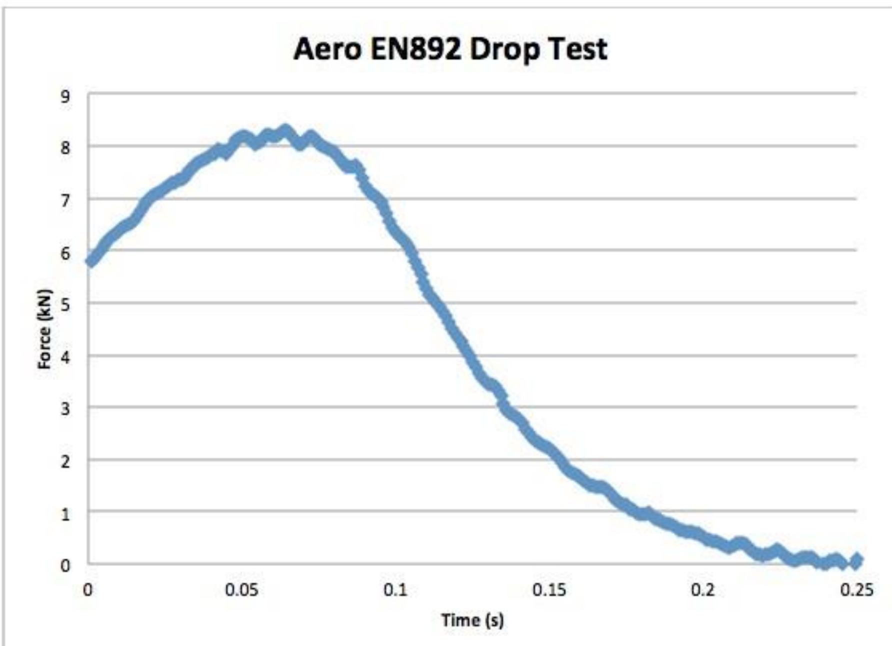

Figure 6. Force maximum in typical EN 892 drop test.

We can calculate the amount of "friction energy" that would be produced via eq. 26 (from Attaway [1]), then roughly correct for the bending energy, and determine what fraction of the rope could be brought to melting, using the temperature-dependent heat capacity, and heat of fusion of Nylon 6. We calculate that in the unmarked rope, the surface friction component is sufficient to melt about 1.4% of the UNMARKED rope in ΔL_1 if it is being pulled over a 514 carbon-steel edge; it is sufficient to melt 2.2% of the SHARPIE-MARKED rope when it is pulled over the same carbon-steel edge (division heat between metal and rope is considered). We can also estimate what depth into the rope, those percentages would correspond to, if the heating were just in the part of the rope that rubs on the carabiner; the calculated depth is ~0.14mm for the unmarked rope, and ~0.22 mm for the sharpie-marked rope. Now we ask is such a shallow depth is consistent with the diffusion of heat through the rope.

One point before we move on. I have searched long and hard to determine if the sheath of the rope is made of nylon 6,6 vs. the nylon 6 used for the core. Nylon 6,6 has a higher melting point, higher heat of fusion per mass, and very similar heat capacity. The same amount of energy from friction would melt a little less of the sheath, if it were made of nylon 6,6 instead of nylon 6.

How Much of the Rope Sees the Temperature Spike?

First, we should realize the limits of heat diffusion into a rope during the very short time when maximum force is experienced. Intense force is on the small section pulled through the orifice or over a carabiner, when the falling mass is first slowed. We begin by asking how well a very simple semi-infinite slab model reflects how heat diffuses through a rope that is heated on one side by frictional contact with metal.

I did a simple, crude experiment to measure the rate of heating. A short section (about 4 cm) of 9mm nylon kermantle rope was placed between a large pot of water that had just been boiling on the stove, and a large iron weight (Figure 7). A thermocouple was placed (perpendicular to the page in Figure 7) in the middle of the rope section. The test had many flaws, among which was the finite time to move the rope into position, so at "time zero" the left surface of the rope was already somewhat hot from the nearby pot. (I felt this warmth on my hand as I moved the left side of the rope up to the pot, and fumbled for a second to get a good thermal connection.) The rope had previously been "squished" so it was no longer cylindrical, but was closer to a square cross-section parallelepiped, as indicated in the figure.

The results of the centerline temperature measured by the thermocouple in the experiment, versus the slab model, are shown in Figure 8. As expected the slab model [9] overestimates the temperature at centerline. In the very short time of an actual transient in the UIAA experiment – less than 0.1 seconds – the rope and orifice plate will look infinite to the heat pulse. The thermal diffusivity is calculated using the conductivity perpendicular to the fibers as given in [10]; the conductivity parallel to the fibers is much higher.

Since the slab model has roughly the correct shape for the bulk of time, but overestimates the experiment temperatures (as delta above ambient) by about 1.5x, we will use the model as an overestimate of the depth of heating, and compare it with the experiment. (The assumption of a constant T on one side is conservative in comparison with the UIAA tests, as the heat source will be removed when the rope stretches past.) The semi-infinite slab overestimates the time for heating in most of the experiment; the seeming reversal at the beginning is partly due to the dearth of data points, and the finite time taken to set up the experiment, which caused the thermocouple and rope to heat up slightly before time 0. There are other aspects of the reality (such as lack of an infinitely smooth surface) that cause deviations. But the figure shows that the simple semiinfinite slab model is reasonable for ***gross*** multi-second behavior, and is likely to overestimate the heating. As we will saw in a previous section, the rapid speed of the rope over the orifice plate means that during the rapid pull where the rope generally fails, no 1 cm section of rope will be in contact with the orifice plate for more than ~0.1 seconds (likely less). How far could the heat propagate into the rope in that time, say if we assume the initial surface is at the melting temperature of nylon 6 (220 C)? According to the slab model: in 0.1 sec, the temperature will have reached just ½ the melting T at 0.11mm. (Note that if we were to calculate the characteristic distance $d \sim \sqrt{(D \cdot t)}$, where D is the diffusion coefficient estimated for the rope, and t=0.1 sec, we get ~0.11 mm as well.) These shallow depths are consistent with the previously calculated depth to melting, and are likely overestimates – ***assuming diffusion***.

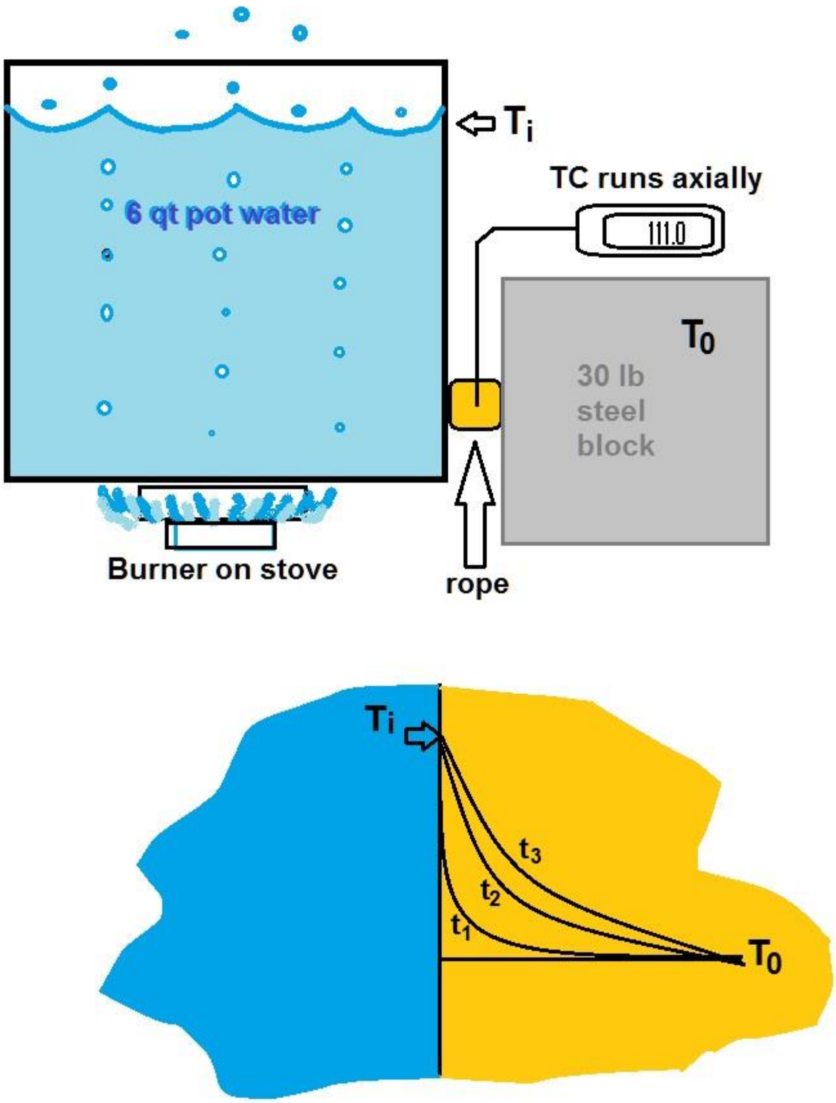

Figure 7. Conduction experiment and infinite slab model.

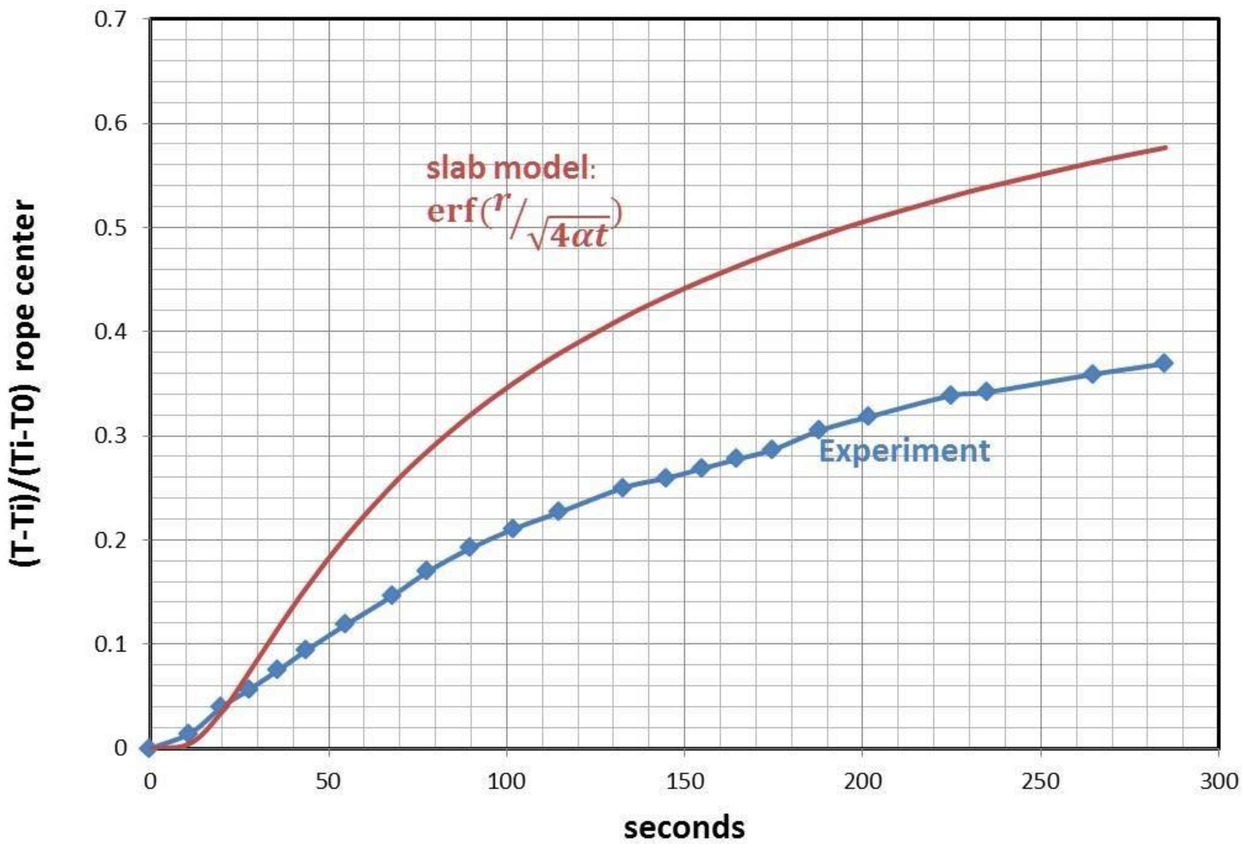

Figure 8. Results for slab model and experiment.

Now back to reality. Figure 9 shows a close-up of a 10 mm dynamic rope:

Figure 9. Nature of sheath on dynamic 10mm rope.

The individual strands of the sheath braid are ~1 mm, with the topography more than 0.1 mm, so the simple conduction layer is very dubious in this region of 0 to 0.11 mm. At the small scale, what likely happens is flash heating of the asperities ("convex out" parts of yarns). As the asperities melt, the strands are broken and the sheath fails, even if just a fraction melts. Simple conduction may work below this layer, or as melt is forced into the valleys between asperities, but by that time, it is irrelevant. The thermal conductivity of nylon increases as it melts, thus we cannot make a more complex analysis.

What We Have Not Considered: Increasing Stickiness with Temperature

Most urethane and acrylic resins degrade well below the melting temperature of nylon 6, forming a very sticky mess. In addition, as nylon starts to melt, it tends to become very sticky. I have done many tests on the melting of nylon slings by repeated rope friction, where I supply the friction by back-and-forth pedaling of my legs, under at least half body weight, with my feet in stirrups on a rope hung over the sling. When the sling develops sufficient surface melt, there is a sudden increase in the force needed to maintain a pedaling rate. Thus for both marked and unmarked ropes, there may be a catastrophic feedback as the surface components degrade and greatly increase the surface coefficient of friction against the carabiner. Such a feedback might happen first on the Sharpie-marked rope.

But Didn't the Length of Exposure Affect the Strength in the UIAA Tests?

The only such "evidence" I could find is this (from Sterling Ropes): "Recent tests conducted by two rope manufacturers have found significant strength reductions (45% reduction after seven days influence, and more than 50% reduction after three weeks influence) after application of markers on the rope." Given that there is no indication of standards for the Sharpie application (*i.e.* amount of fluid applied to the rope, dimensions of application), 45% reduction, and "more than 50%" are effectively the same number. There was a bias to believe the mysterious strength loss (which doesn't affect straight pull tests, hmm) was somehow chemical degradation. There are things that could happen over several weeks, that wouldn't involve the actual chemistry of the nylon fibers, but could affect surface properties, such as the CoF; for example, the resins in the markers could gradually harden. Materials I have coated with urethane do not completely cure for weeks.

Conclusions

Sharpie™ marks significantly increase the friction between the rope and metal edge/carabiner, and in the extreme conditions of the UIAA 101 drop test, can add 60% to the energy intensity in the section that typically fails. Only a small part of the sheath need melt to make the yarns discontinuous, causing sheath failure and exposing the core. There is probably a great increase in the coefficient of friction between sheath and metal edge, as the Sharpie marks, then the nylon, melt and degrade. None of these failure modes require any roomtemperature degradation of the nylon by Sharpie™ components. Indeed, there is evidence that without a frictional metal edge, or a knot including the pen mark, Sharpie™ has little effect on nylon rope strength. The desirability of maintain a "0" MSDS safety rating, and the company's promotion of Sharpies™ to mark synthetic cloth, strongly argues against future incorporation of nasty components.

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*In September 2018, my hard drive crashed and my last backup was corrupted, as the computer was backing up during the crash. I have older backups of most files, and I've since redone some calculations from notes, but it may take me a while to reproduce everything. I had brain surgery in August, so this has not been at the top of my priority list.