Knotted Versus Sewn Terminations in Cow's Tails: A Comparison of Dynamic Performance and Static Strength Across Varying Lanyard Lengths

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I. INTRODUCTION

Cow's tail lanyards are an integral component of the industrial rope access technician's kit. Incorporated into both the work positioning and fall protection systems, cow's tails connect the technician's harness to ascenders, backup or fall arrest devices, anchor points, and even rescue casualties. In most of these uses, the cow's tail is an unweighted system component, standing by to arrest a fall in the event of a failure in the main suspension system. Typically made from dynamic kernmantle rope, cow's tails are either terminated with manufacturer-sewn eyes or user-tied knots, depending on the user's preference, industry or geographic location.

The impetus for the current research was to determine if, and how, traditional cow's tails could fit into the in-progress American National Standards Institute (ANSI) Z359.8 standard entitled *Safety Requirements for Rope Access Systems*. The ANSI Z359 suite of standards covers myriad topics related to traditional fall protection, such as personal fall arrest and positioning systems, rescue systems, ladder safety systems, and subsystem components such as harnesses, carabiners and energy absorbers. In general, ANSI Z359 requires that fall arrest equipment meet certain static strength requirements, while also keeping impact forces below pre-determined levels.

Industrial rope access technicians often speak anecdotally of the benefits of knots over sewn terminations in cow's tails, pointing to the knot as a makeshift energy absorber that absorbs energy as it tightens under load. Indeed, previous research has shown the potential benefit of knotted cow's tails over sewn cow's tails (Long et al., 2001; Borie, 2006). However, the current research delves deeper into the difference between sewn and knotted cow's tails, specifically using an ANSI-based perspective and singling out the scaffold knot for further analysis. The testing investigates the following questions:

- Do cow's tails meet current ANSI requirements for average and maximum arrest forces?
- What is the strength of knotted cow's tails compared to their sewn counterparts?
- How much rope is needed between the cow's tail and anchor to successfully mitigate arrest forces?
- Should there be a maximum allowable cow's tail length?
- Is it necessary to tension the knots prior to dynamic testing?
- Can the cow's tails withstand a two-person factor two fall?

A total of 54 drop tests were performed, with cow's tail eye-to-eye lengths varying from 17.5 inches to 39 inches. Terminations included sewn eyes as well as pretensioned and untensioned scaffold knots. Most tests were conducted with a factor one fall using a 282-pound weight, while some tests were conducted with a factor two fall and/or a 582-pound weight. Static breaking strength tests were also conducted on three knotted cow's tails for comparison to manufacturer-supplied minimum breaking strength data on sewn cow's tails. Numerical findings of this research are reported in imperial units due to the ANSI context. Data cited from references are reported in their original format, with the imperial equivalent, if necessary, in parentheses.

II. LITERATURE REVIEW

This research focuses on the comparison of cow's tails that are terminated with manufacturer-sewn eyes to those that are terminated with user-tied scaffold knots (Figure 1). The scaffold knot was found to be referenced by names such as the "barrel knot" (Long et al., 2001), "double overhand on itself" (O'Neill) and "half a double fisherman's" (Borie, 2006). All these reference a single knot, which is a two-wrap version of the "scaffold knot," as defined by *The Ashley Book of Knots* (knot #1120, Ashley, 1993).

Three research papers on cow's tails were found that included an analysis of the scaffold knot. A report prepared by Lyon Equipment Limited for the United Kingdom Health and Safety Executive (Long et al., 2001) compared 11 mm (7/16 in) dynamic rope cow's tails terminated with sewn-eyes, scaffold knots, overhand knots and figure-eight knots. Long et al. summarize that "the best material for cow's tails is knotted dynamic rope." When subjected to factor two falls with a 100 kg (225 lb) weight, 60 cm (23.6 in) cow's tails terminated with scaffold knots provided the lowest mean impact force (n = 3) at 6.32 kN (1,420 lb). All cow's tails terminated with sewn eyes (n = 3) exceeded the load cell's capacity of 10 kN (2,250 lb) when subjected to the same test.

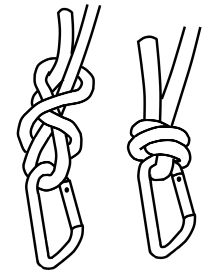

Figure 1. The two-wrap scaffold knot.

Borie (2006) conducted a staggering number of tests on cow's tails: over 200 dynamic and static tests examined variables such as construction, fall factor, loading history and age. Unfortunately, much of the quantitative data is not transferable to industrial rope access—especially in the United States—because a relatively light drop weight of only 80 kg (176 lb) was used to replicate a recreational caver. Additionally, no tests were conducted on cow's tail with both ends terminated by scaffold knots.

In addition to favorably reducing impact force, the scaffold knot has been shown to have a high breaking strength. Conducting a static strength test with an extension rate of 2 inches per minute, O'Neill found that scaffold knots in 8 mm (5/16 in) cord (n = 11) reduced the minimum breaking strength (as defined by the mean breaking strength minus three standard deviations) by only 5% of the manufacturer's rated minimum breaking strength of unknotted cord.

Despite the existing data on the dynamic and static performance of cow's tails, there is still additional need to examine sewn and knotted cow's tails from a United-States-based perspective. Included in the ANSI Z359 standards are two metrics that have not previously been incorporated into dynamic testing of cow's tail: the use of a 282-pound test weight, and an analysis of the average arrest force (in addition to the maximum arrest force).

ANSI Z359 standards apply to fall arrest equipment that is intended for users within the weight range of 130 to 310 pounds (ANSI Z359.15 §1.1). To test the dynamic performance of equipment at the upper end of this capacity range, ANSI specifies the use of a 282-pound rigid test weight (ANSI Z359.15 §4.1.3). Research has shown that during dynamic testing, this 282-pound rigid test weight is a good approximation of a 310-pound human body (Gravitec, 2007). As a historical side note, ANSI Z359 previously used a 220-pound weight to replicate a 310-pound worker.

The other metric recently adopted by ANSI Z359 is the average arrest force. Historically, the only metric used to determine whether fall arrest equipment provided sufficient energy absorption was the single highest-force data point recorded during a drop test. This maximum arrest force is typically limited to 1,800 pounds for dorsally-connected fall arrest equipment (ANSI Z359.15 §3.2.5). Until recently, ANSI Z359 required the maximum arrest force on front-mounted harness attachment points to be below 900 pounds (ANSI Z359.1 §3.2.2.5a). However, the in-

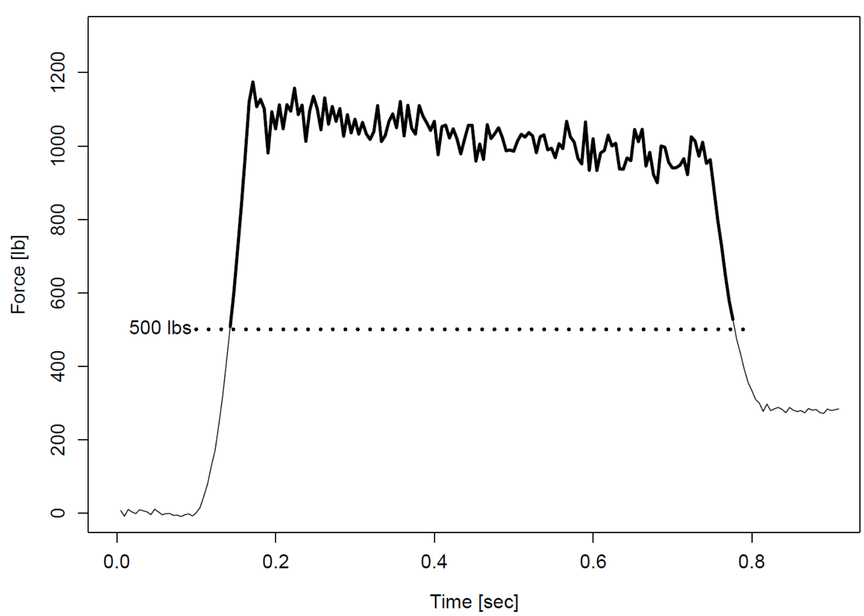

Figure 2. A theoretical plot of dynamic testing of a stitch-tearing energy absorber. The data points in bold, over 500 pounds, are averaged to calculate the average arrest force.

progress ANSI Z359.16 standard on ladder fall arrest systems purportedly limits the frontal maximum arrest force to 1,800 pounds.

Rather than looking at only the single highest data point, the average arrest force is the arithmetic mean of all data points recorded during a drop test that are greater than 500 pounds (ANSI Z359.15 §4.1.15) (Figure 2). ANSI limits this average arrest force to only 900 pounds for fall arrestors on vertical lifelines (ANSI Z359.15 §3.2.5), but allows up to 1,575 pounds for 12-foot-free-fall shock absorbing lanyards that have been environmentally conditioned (e.g. submerged, heated, or cooled) (ANSI Z359.13 §3.2.5.2).

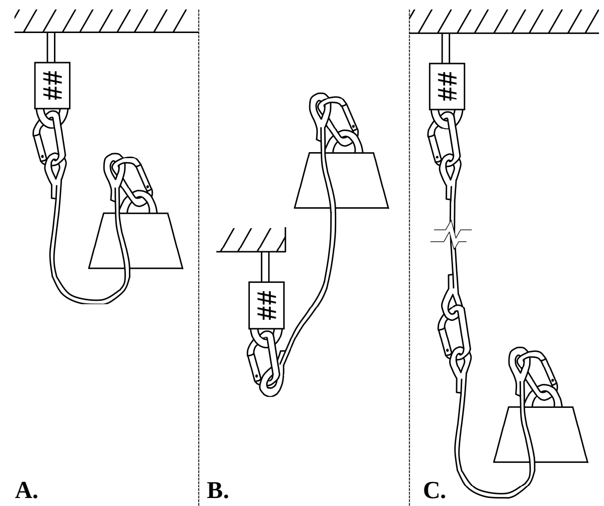

Figure 3. The research analyzed factor one falls (**A**), factor two falls (**B**), and cow's tails oriented in factor one orientation, but at the end of a 10-foot length of static rope (**C**).

III. TEST METHODS & SAMPLE BREAKDOWN

Test Equipment and Setup

A Rock Exotica Enforcer load cell was used to measure and record data during the dynamic tests. This load cell measures tensile forces up to 20 kN (4,500 lbs) with an accuracy of 2% and a sampling rate of 500 Hz.[1] Static testing was conducted on a TestResources testing machine, using a sampling rate of 50 Hz and an extension rate of 3 inches per minute.[2]

The test weight used to replicate a 310-pound worker was a 282-pound rigid weight, per ANSI standards (ANSI Z359.15 §4.1.3). Some tests were conducted to replicate a two-person load and consisted of the 282-pound weight and an additional 300-pound rigid weight, for a total weight of 582 pounds. Though it would have been preferable to use two 282-pound weights, a second identical test weight was not available for use.

Both factor one and factor two falls were conducted during dynamic testing. Although the definition of fall factor seems simple enough—the length of the fall divided by the length of the connecting system—it is more complicated during testing of cow's tails, where carabiners and other testing hardware are a significant percentage of the system's length. Because user-chosen connectors could be as long as ladder hooks or as short as screw links, we chose to exclude all connecting hardware when calculating fall factors. For example, the length of a factor one fall on a 24-inch cow's tail was 24 inches (not 30 inches, as would be the case if you were to include the 6 inches of carabiner as part of the lanyard length) (Figure 3A). Likewise, the length of a factor two fall on a 24-inch lanyard would have been 48 inches (Figure 3B).

Test Samples

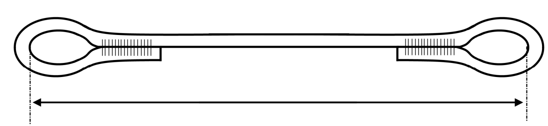

Figure 4. Cow's tails were measured between the bearing points of each eye.

All of the knotted cow's tail samples were tied by hand using PMI's 11 mm (7/16 in) Latitude dynamic rope. This is the same rope used in the construction of PMI's Dynamic Sewn Lanyard, which represented all but three of the sewn cow's tail samples. The three outstanding sewn samples were 24 inch (61 cm) Petzl Jane cow's tails, which are also constructed from 11 mm dynamic rope (Long et al., 2001).

[1] These specifications differ from ANSI's requirement for an accuracy of 0.5% and a minimum sampling rate of 1,000 Hz (ANSI Z359.7 §4.1.5). However, the elasticity of the samples indicates a 1,000 Hz may not have provided more accurate data. Also, 2% of full scale of the Enforcer represents 90 pounds, compared to 23 pounds if the accuracy were 0.5%.

[2] ANSI requires an extension rate of no more than 2 inches per minute (ANSI Z359.7 §4.1.5), but the elasticity of the samples indicates that a rate of 3 inches per minutes isn't qualitatively different.

Four lengths of cow's tail samples were tested: 17.5 inches, 24 inches, 32.5 inches and 39 inches (Figure 4). The knotted lanyards were tied to within ±1 inch of the desired nominal length after the scaffold knots were tightened by hand. Approximately half of the knotted lanyards were pretensioned with a 310-pound weight for one minute on the day prior to dynamic testing. The remaining "untensioned" lanyards were left tightened by hand.

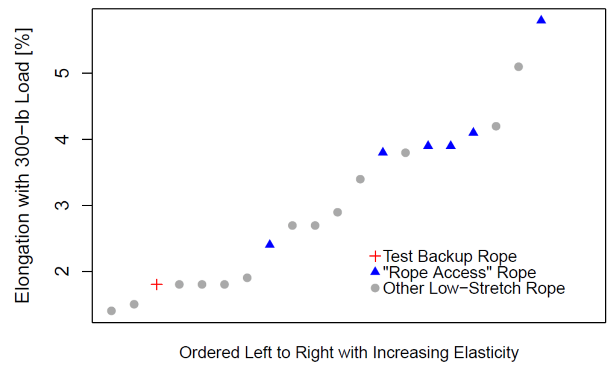

Figure 5. A survey[3] of 20 models of low-stretch and static 7/16-in (11mm) ropes shows that the model of rope used to represent the 10-foot length of backup rope is among the stiffest ropes available (red +). Blue triangles represent models of rope that are marketed with the phrase "rope access." Gray circles represent other models of static and low-stretch rope.

Six dynamic tests of sewn cow's tails were conducted with the lanyard in a factor one fall orientation, but connected to the bottom of a 10 foot section of 11 mm (7/16 in) PMI Classic Professional EZ-Bend static rope rather than directly to the load cell (Figure 3C). With the top end of this rope connected directly to the load cell, the test orientation was designed to replicate a factor one fall on a cow's tail with the technician 10 feet from the anchor. Though much less than a factor one fall when including the 10 feet of additional rope in the system, these tests were labeled as factor one falls for ease of comparison to the factor one falls attached directly to the load cell. The Classic Professional EZ-Bend is among the lowest-stretch ropes available, with an elongation of only 1.8% at 300 pounds tension (Figure 5)[3]. Additionally, the 10-foot section of rope had sewn eyes at either end, for connection via carabiner to the load cell and cow's tail, to remove all variability and energy absorption that knots would have introduced. This test setup was designed to provide a system with the least possible amount of energy absorption 10 feet from the anchor.

All cow's tail samples and static rope samples were new, then used for a single test and discarded.

Sample Breakdown

Figure 6 presents a breakdown of the 54 dynamic tests and 3 static tests conducted on cow's tails terminated with sewn eyes and scaffold knots. The majority of dynamic tests (45 samples) focused on factor one falls, with an attempt to equally represent the four sample types. Fewer samples were dedicated to factor two falls, because even though such a fall is possible, it would represent misuse of the cow's tail. Only 24-inch cow's tails were subjected to the factor two falls to initially focus on a subset of only one length of cow's tail.

IV. Test Results & Discussion

Overview of Dynamic Test Results

All of the cow's tail drop tests proved to be highly dynamic events. Graphs of the cow's tail tension over time show the tension to be sinusoidal, with dramatic secondary peaks (Figure 7). In nearly all of the tests, the weight rebounded enough to relieve the cow's tail of all tension prior to the secondary impact, which generated forces between 400 and 900 pounds.

Note that the different lanyard lengths have varying oscillation periods, with longer cow's tails providing a slower response than shorter cow's tails. Also of interest is the distinctly different shape of the plot compared to that of stitch-tearing energy absorbers (Figure 2).

[3] For comparative analysis, technical data on various models of 7/16-inch (11 mm) static and low-stretch ropes were retrieved from the websites of BlueWater Ropes, Pigeon Mountain Industries and Sterling Rope.

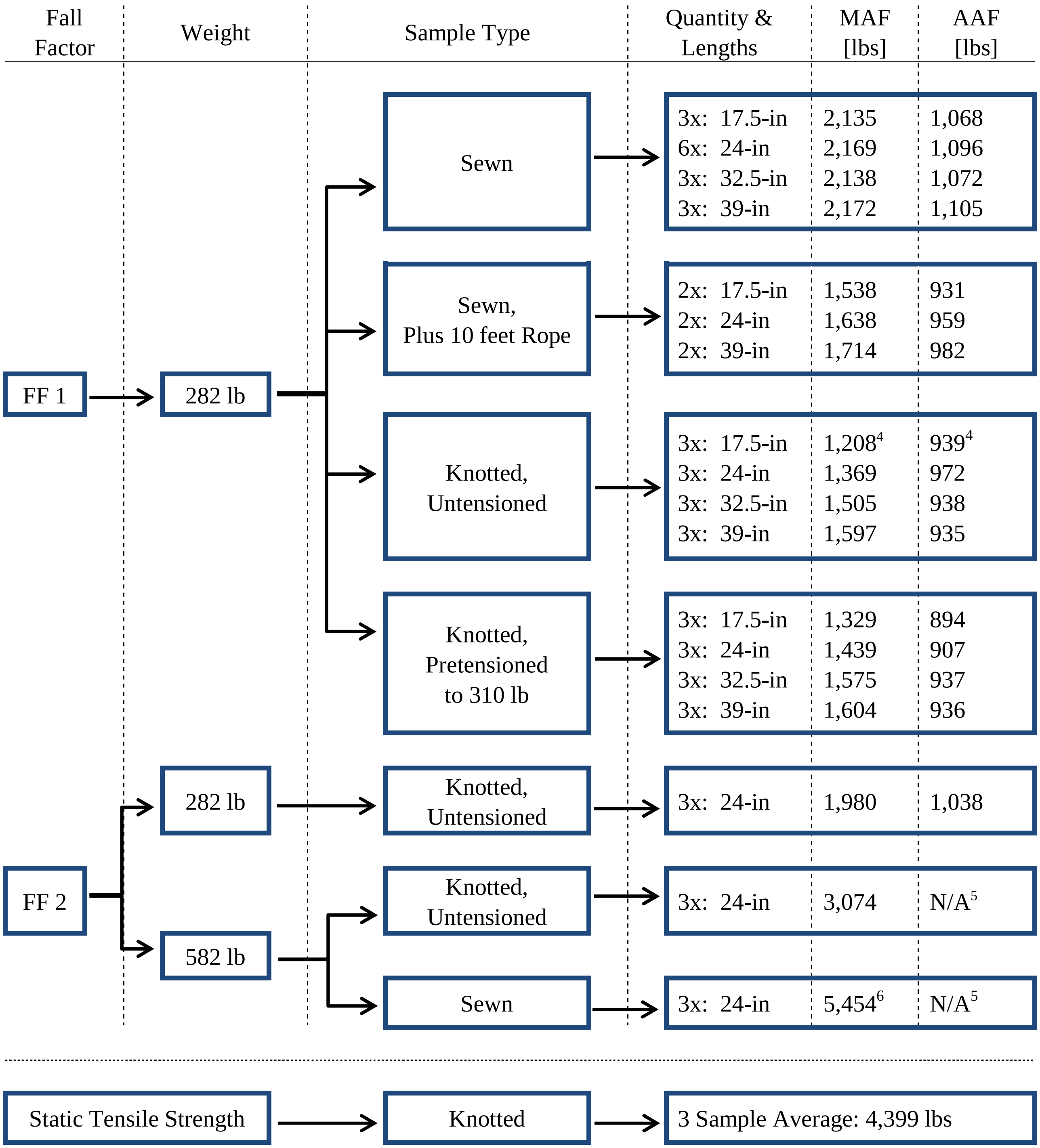

Figure 6. A flowchart of the dynamic and static tests that were conducted. Category averages for dynamic testing include maximum arrest force ("MAF") and average arrest force ("AAF").

[4] One data file from this sample set was lost. Average MAF and AAF represent the two remaining files.

[5] Average arrest force is irrelevant for test weights over 500 pounds, because even the weight at rest would be calculated into the average "arrest" force.

[6] The data from only one specimen in this set was recorded, to prevent damage to the load cell. The accuracy of this data is unknown, as the test exceeded the load cell's maximum stated measurement of 20 kN (4,500 lbs).

Fall Factor One, 282-Pound Weight: Maximum Arrest Force

Consistent with previous research (Long et al., 2001; Borie, 2006), knotted cow's tails demonstrated a superior ability to keep maximum arrest forces at acceptable levels during factor one falls with the 282-pound weight (Figure 8A). Conversely, in identical testing, sewn cow's tails generated maximum arrest forces well above the ANSI limit of 1,800 pounds. Whereas the maximum arrest force for sewn cow's tails ranged from 2,032 to 2,221 pounds, the maximum arrest force for knotted cow's tails ranged from 1,194 to 1,610 pounds, with pretensioned knots exhibiting slightly higher arrest forces than their untensioned counterparts.

However, once the 10 feet of rope is added between the cow's tail and the load cell, the maximum arrest forces for sewn cow's tails drop considerably. With the same 282-pound weight and factor one fall orientation, but with the cow's tail connected indirectly to the load cell via 10 feet of static rope, the maximum arrest forces for sewn cow's tails ranged from 1,526 to 1,717 pounds (Figure 8A). Though still greater than the forces generated by knotted cow's tails, these are below the ANSI limit of 1,800 pounds—indicating that even relatively short lengths of rope between a rope access technician and the anchor aid in mitigating arrest forces.

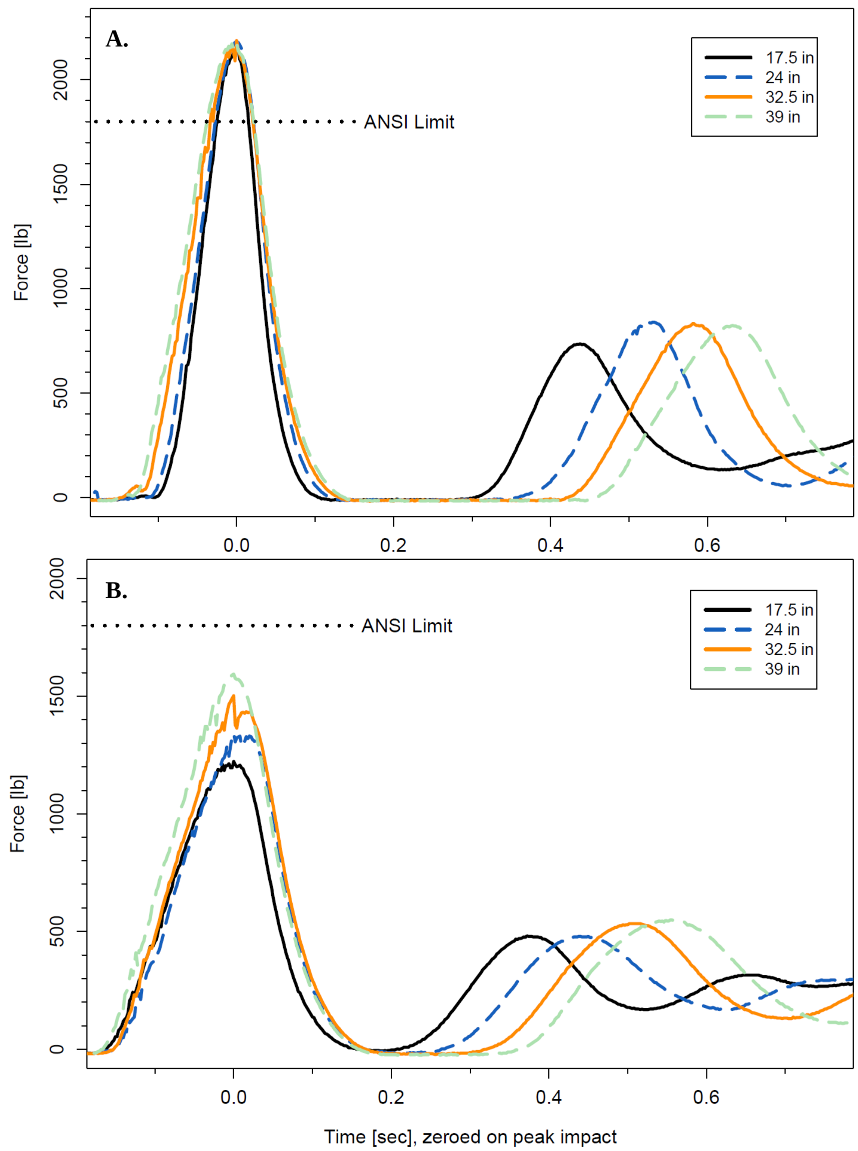

Figure 7. Examples of the tension in sewn (**A**) and knotted (untensioned) (**B**) cow's tails during dynamic testing using a 282-pound weight and factor one fall. Only one of each sample length is shown for clarity.

Interestingly, maximum arrest forces for sewn cow's tails are fairly constant across all lengths for factor one falls. This confirms mathematical modeling of a dynamic rope as a spring (Attaway, 1996), wherein the maximum arrest force is dependent on the fall factor, not the actual fall length. However, in the knotted cow's tails as well as the sewn cow's tails attached to 10 feet of static rope, longer lanyard lengths are associated with higher maximum arrest forces. Knotted cow's tails generally exhibited a permanent elongation of 10 to 11 inches across all lengths (compared to only 1 to 2 inches for sewn lanyards) (Figure 9), indicating that the knots provide a fixed deceleration distance of approximately 9 inches more than sewn lanyards. As lanyards become longer, this 9 inches become proportionally smaller, creating higher arrest forces. With the sewn lanyards attached to 10 feet of static rope—a system which includes no knots—the increasing maximum arrest forces are certainly due to the increasing fall factor of the system as a whole. That is, a 39-inch fall on a 10-foot system is proportionally longer than a 17.5-inch fall on a 10-foot system.

Fall Factor One, 282-Pound Weight: Average Arrest Force

As with the maximum arrest force, sewn cow's tails exhibited distinctly higher average arrest forces than knotted cow's tails during factor one fall testing with the 282-pound weight. However, only two knotted specimens—both 17.5-inch cow's tails—succeeded in keeping the average arrest force below 900 pounds. Overall, the average arrest forces for knotted cow's tails ranged from 882 to 1,005 pounds. The pretensioned knots yielded more tightly grouped data points than their untensioned counterparts, as well as a clear link between longer lanyard lengths and higher average arrest forces. The average arrest forces for the standard sewn cow's tails ranged from 1,050 to 1,114 pounds, and 924 to 984 pounds for the sewn cow's tails attached to 10 feet of static rope.

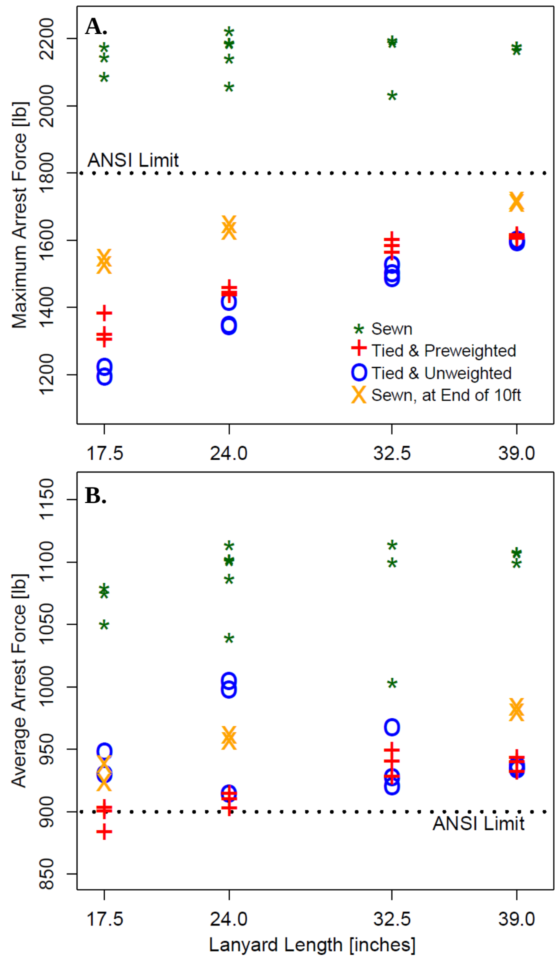

Figure 8. A comparison of maximum arrest force (**A**) and average arrest force (**B**) during factor one fall dynamic testing, across four cow's tail lengths. Cow's tail terminations include sewn, pretensioned knots and untensioned knots. Also included are factor one fall tests on sewn cow's tails at the end of 10 feet of static rope.

Fall Factor Two

After demonstrating the ability to successfully mitigate maximum arrest forces (though not average arrest forces) during factor one falls, knotted lanyards were dynamically tested with a factor two fall and the 282-pound weight. The three samples tested, all 24 inches long, on average generated a maximum arrest force of 1,980 pounds and an average arrest force of 1,038 pounds (Figure 6), neither of which met the desired thresholds.

Additionally, three sewn and three knotted samples were tested with the 582-pound weight in a factor two fall test. This test was intended to determine whether the lanyards were able to withstand a worst-case-scenario fall during a rescue. All of the cow's tails successfully arrested the fall, though with varying degrees of material failure. The sewn samples remained largely intact, with visible tearing of only a few stitches at each eye termination. All of the knotted samples exhibited complete sheath failure; one sample also had a few core strands fail. The knotted cow's tails again generated lower maximum arrest forces (3,074 pounds average, n=3) than sewn cow's tails (5,454 pounds, n=1[6]). Though the ANSI 1,800-pound limit isn't transferrable to this two-person scenario, it's important to note that the sewn cow's tail generated maximum arrest forces greater than the 5,000-pound requirement for single-person anchors (ANSI Z359.1 §3.2.5.1). Also note that the average arrest force is irrelevant when using test weights over 500 pounds, as the weight itself is greater than the 500 pound cutoff for the calculation of average arrest force.

Static Tensile Strength

Three knotted cow's tails samples were statically tested to failure at an extension rate of 3 inches per minute, for comparison to PMI's stated breaking strength of 5,000 pounds for the Dynamic Sewn Lanyard. To minimize extension, the cow's tails were tied as short as physically possible: about 5 inches long. Even with such a short initial length, the

Avg. Eye-to-Eye Length Increase [in]

Sewn	1.6 (n=15)
Pretensioned Knots	10.2 (n=12)
Untensioned Knots	10.9 (n=12)

Figure 9. During factor one fall testing, knotted cow's tails tended to permanently elongate 10 to 11 inches, while sewn cow's tails only exhibited one or two inches of permanent deformation.

samples extended approximately 30 inches before failure.

With a standard deviation of 491 pounds, the calculated minimum breaking strength of the knotted samples was 2,926 pounds. At a loss of 41% of the sewn strength (Figure 10), this represents a strength loss that is clearly greater than the previously reported 5% loss in strength (O'Neill).

		Breaking Strength [lb]
Knotted Samples	Sample #1	4,267
	Sample #2	4,813
	Sample #3	4,118
	Average	4,399
	St. Dev.	491
	MBS	2,926
	Sewn MBS	5,000
	Knotted Loss in MBS	41%

Figure 10. A comparison of the minimum breaking strengths ("MBS") of knotted cow's tails to sewn cow's tails.

V. CONCLUSIONS

In factor one fall tests with a 282-pound weight, cow's tails constructed from 7/16-inch dynamic rope and terminated with scaffold knots were able to keep maximum arrest forces below the ANSI requirement of 1,800 pounds. However, the average arrest forces were still frequently above 900 pounds, indicating that knotted cow's tails are not the ideal connection for arresting falls on a rigid anchor. Similarly, the sewn cow's tails generated excessive maximum and average arrest forces. Both sewn and knotted cow's tails created a rebound in the test weight followed by a significant secondary impact. When used as a direct connection to an anchor, both knotted and sewn cow's tails should be limited to usages where the fall factor is less than one. In higher fall factor scenarios, equipment with more energy absorption is required.

As the rope access technician descends farther from the anchor, the backup rope begins to contribute to the energy absorption characteristics of the fall arrest system. At 10 feet from the anchor, even with a static rope and knotless system, the static rope provides sufficient additional energy absorption to keep the maximum arrest force less than 1,800 pounds for sewn cow's tails. Although average arrest forces remained above 900 pounds, they were greatly reduced. Likely any small addition of elasticity into the system (e.g. longer distance to anchor, knotted backup rope, less stiff rope) would allow for favorable average arrest forces with the sewn cow's tail.

Despite the increased energy absorption of knotted cow's tails, they were found to have significantly reduced minimum breaking strengths: less than 3,000 pounds, compared to 5,000 pounds for sewn cow's tails. Whether a breaking strength of 5,000 pounds is necessary for the knotted cow's tails is debatable, as both sewn and knotted versions successfully arrested factor two falls conducted with the equivalent weight of two people. Because the cow's tail is a piece of personal equipment, not general rigging, it is unlikely to ever experience a force greater than a two-person factor two fall. By any standard, however, less than 3,000 pounds is an inadequate strength for industrial life safety equipment.

As to whether cow's tails should be limited to a maximum permissible length, there was no definite demarcation separating cow's tails into "safe" or "dangerous" categories by length. Overall, of the 17.5-inch to 39-inch lanyards tested, longer lanyards did tend to indicate higher maximum and average arrest forces (the exception to this trend being maximum arrest forces in sewn lanyards, which were relatively constant across all lanyard lengths). Demarcations aside, where possible, it's preferable to keep fall distances and arrest forces as small as possible with the use of shorter lanyards.

During dynamic testing, knotted cow's tails that had been pretensioned generated higher maximum arrest forces than their untensioned counterparts. The pretensioned knots also created cleaner, more linear data in the calculation of average arrest forces. This trait, combined with the real-world likelihood of knotted lanyards being weighted by the user, indicate that pretensioning of cow's tail knots is an important step in the dynamic testing process.

VI. Acknowledgements

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