Synthetic Rope End Connections For Use In Timber Harvesting

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ABSTRACT

This paper describes a pilot study of end connections for ultra-high molecular weight polyethylene 12-strand braided rope (synthetic rope) for use in timber harvesting applications. Fourteen different end connections for 14mm and 16mm diameter synthetic rope were developed and break tested to determine suitability.

Three types of end connections were evaluated: *spliced*, *adhesives*, and *dry hardware*. Spliced end connections provided consistent performance in breaking strengths. End connections with adhesive had variable strength performance and are therefore not recommended. Within the dry hardware group, the pinned nubbin and knuckle link provided the highest breaking strengths. Suitable end connections for forest operations were: buried eye splice, Whoopie Sling, long splice, rope clamps, knuckle link, pinned nubbin, and in limited applications, rope clamps. Further research and development is needed on these six concepts with larger sample sizes and under testing and operating varied conditions.

Keywords: *synthetic rope, timber harvesting, logging, ultra-high molecular weight polyethylene, end connections, steel wire rope,*

Note: Mention of trade names does not constitute an endorsement by Oregon State University.

INTRODUCTION

Currently, steel wire rope is used universally in timber harvesting for skylines, guylines, winchlines, support lines, truck wrappers, chokers, and running lines. It has advanced ground-based and cable logging applications and is used in thousands of miles annually around the world. Its versatility, durability, and strength continue to meet the demands of logging.

Although steel wire rope is now the industry standard, it may not be the optimal solution. Steel wire rope is heavy and produces jaggers (broken wires that cause painful puncture wounds). Replacing wire rope could produce ergonomic gains as well as worker health and safety benefits.

Synthetic rope constructed of braided ultra-high molecular weight polyethylene (UHMW-PE) fibers has the potential to replace steel wire rope in timber harvesting. UHMW-PE has many advantages over steel wire rope. It is lightweight, has a strength-to-weight ratio that is approximately ten times that of wire rope of the same diameter, it floats, and is stronger than extra improved plowed steel (EIPS) wire rope of the same diameter up to 24mm diameter. UHMW-PE braided ropes do not kink, corrode, or absorb chemicals and water.

The most common synthetic rope materials in the past were nylon, polypropylene, and polyester [5]. Although widely available and popular in many applications, each material possesses undesirable characteristics for use with heavy loads. For example, wet rope of these materials can lose 20% of its strength [5]. In other applications requiring stretch, nylon is favorable because it has the lowest modulus.

Until the development of high-modulus fibers, polyester was the predominant rope choice for heavy load applications. It has a higher modulus than nylon and is stronger than nylon or natural fiber ropes [6]. These high-modulus fibers have higher elastic moduli compared to nylon, polyester, and polypropylene, and have significantly higher breaking strengths. DuPont Corporation in the 1970's introduced aramid fibers, known commercially as Kevlar™ [5]. Although these ropes were much stronger and more durable than their predecessors, they still had limitations. One of the major limitations was axial-compression fatigue, which can occur when tightly constrained aramid fibers are forced into compression causing the rope to fail [15].

Not long after the introduction of aramid fibers into the market, demand for ropes with higher tensile strength increased. The marine industries needed lightweight ropes that would sustain high loads at an extended number of cycles [5], [15]. In the mid 1980s, a joint project with Dutch State Mines (DSM) and Toyobo developed the first gel-spun UHMW-PE fiber. The first commercially available fiber was Spectra® developed by Allied Signal, Inc. (now Honeywell, Inc.) in the late 1980s [10].

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Since the mid 1980's, UHMW-PE fiber ropes have grown in popularity. Many companies use UHMW-PE ropes because of their low stretch, high strength, lightweight, and natural buoyancy. These characteristics translate into safer handling, better storage, shorter operational time, and less labor needed to complete tasks.

It has become possible to use ropes with strengths up to ten times the strength of steel for their weight [6]. UHMW-PE synthetic ropes are flexible, noncorrosive, and stretch little. Wire rope has limitations in water particularly because of its heavy weight and susceptibility to corrosion. The introduction and subsequent technological advances of high-modulus fibers, such as UHMW-PE, have made synthetic rope accepted in many industries. Fiber ropes overcome weight limitations, problems of corrosion, the need for lubrication, and other problems for the design and installation of deep ocean structures and moorings [5]. Synthetic rope (UHMW-PE braided rope) has proven itself in the offshore drilling, mooring, tugline, and powerline industries. The US Navy and US Coastguard have approved it for maritime operations and deep-sea salvage [4], [5].

An extensive literature search revealed limited testing of synthetic ropes in timber harvesting applications. The Forest Engineering Research Institute of Canada (FERIC) began trials in 1993 with synthetic rope in logging applications [3]. FERIC examined a braided aramid (Kevlar™) rope to use for skidding small logs with an all-terrain vehicle. The initial field trials revealed the fibers were durable, yet the rope was affected by ultraviolet solar rays and abrasive surfaces (i.e. rocks, logs, etc.). FERIC again investigated the use of synthetic rope in 1996 with field trials of synthetic rope mainlines on cable skidders for ground-based logging [8]. Both aramid (Kevlar™) and polyethylene (Spectra®) fiber ropes were tested and compared to the performance of steel wire rope. Foster et al. (1997) [6] reported Spectra® had more potential in logging applications than Kevlar™. Spectra® was lighter, had a higher breaking strength, less elongation, and was not sensitive to sunlight. However, there were notable disadvantages. Spectra® was more expensive and has a lower critical temperature than Kevlar™ [6]. In another trial, the Forestry and Forest Products Research Institute in Ibaraki, Japan used synthetic rope for tower guylines. It concluded that while high modulus ropes had potential in some logging applications, they were more prone to wear than their steel counterpart [18]. All three studies did show promise for synthetic rope for use in logging.
In 1999, Oregon State University formally recognized the potential of synthetic rope in logging and began research with field trials and laboratory testing [13]. The main difficulty with synthetic rope was adaptation with existing harvesting systems. For example, standard wire rope clamps, fist grips, etc. that would yield at least 90% breaking strength with steel wire rope will only yield ~60% breaking strength because of the rope's low coefficient of friction [7]. Synthetic rope has a much lower critical temperature compared to steel rope and is intolerant of heated connections. Despite its limitations, physical, chemical, and mechanical properties of the rope make it an excellent substitute for wire rope in some timber harvesting applications. Synthetic rope has merit within forest operations, but a major obstacle is linking it to existing harvesting systems. Current steel wire rope end connections designed for steel wire rope may not be suitable.

Knots are one of the oldest and simplest methods to connect ropes or to terminate them. However, knots are not a suitable end connection for the 12-strand braided synthetic rope. Knots significantly reduce the strength in synthetic ropes up to 50% because they bend the rope and distort the balanced construction and load distribution [6], [17].

In addition, because of UHMW-PE's low coefficient of friction and the high tensile loads typical in logging, knots could slip, break, or release under loading conditions. Due to initial testing during this study, synthetic rope properties, knots of any type are not recommended [9]. Therefore, new end connections are needed in forest operations.

RESEARCH OBJECTIVES

This study was designed with three main objectives to investigate synthetic rope end connections and their mechanical performance under loading conditions. The first objective was to determine suitable end connections and terminations for use with synthetic rope in logging. In addition, the objectives were intended to fill the knowledge gap about the mechanical performance of the rope with various end connections under varied load conditions. The second objective of the study was to quantify the breaking strengths of the synthetic rope and various end connections under cycled loading at ambient temperature. The third objective was to use break test performance and construction procedures to determine each end connection's suitability for logging.

The following questions were addressed in this research.

(1) Can end connections/terminations for the UHMW-PE rope be developed that retain adequate rope ultimate breaking strength?

(2) Can end connections/terminations be attached to the

rope and do these end connections have the potential to be feasible on the job site?

(3) In what applications of timber harvesting might these end connections be utilized?

END CONNECTOR DEVELOPMENT

Rope manufacturers identify splices as acceptable means to terminate or attach lengths of synthetic rope. The buried eye splice (BES) used in this study is a configuration where one rope end is buried within the rope itself for an eye and locks tight when tension is applied. Rope manufacturers use this buried eye splice because it retains the highest breaking strength compared to other end connections. Thus, the BES represents the ultimate breaking strength of the rope and was used as the benchmark to compare all end connector concepts in this study. End connections using splices are shown in Figure 1.

nections, the pinned nubbin and the knuckle link were new concepts. These end connections were designed and developed specifically with consideration of rope bend, fiber compression and torsion, and extremely high tensile loading for synthetic rope. End connections with dry hardware are shown in Figure 2.

End connections designed to utilize an adhesive were also considered. Two industrial adhesives were chosen because each was specifically designed to bond with polyethylene. Adhesives chemically bond the synthetic rope to the selected test end connection. The first adhesive, a two-component thermoset resin composition. Socketfast® Blue A-20 manufactured by Phillystran, Inc. of Montgomeryville, PA was developed specifically for bonding polyethylene [12]. The second adhesive used was a two-part acrylic, Scotch-Weld™ DP-8010 from 3M Corporation, St. Paul, MN, designed to bond to many grades of polyethylene [1].

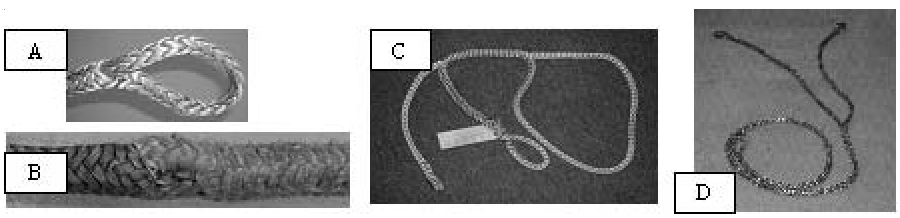

Figure 1. Spiced end connections: A) Buried eye splice; B) Long splice; C) Whoopie Sling; D) Y-splice.

End connections using only dry (without adhesives) hardware were developed on three levels. First, some end connection concepts were directly adapted from current steel wire rope technology. The rope clamps and pressed nubbin were unmodified. The second set of end connections were the splices, developed for UHMW-PE braided rope by the manufacturer. For the third set, two end con-

However, initial testing with end connections using the 3M adhesive with 16mm diameter synthetic rope resulted in breaking strengths that were approximately 3% of the catalogue minimum breaking strength value (CMV). Thus, the 3M proved to be unacceptable for timber harvesting applications and deemed unworthy of further testing under this research. End connections using the Socketfast® Blue A-20 adhesive are shown in Figure 3.

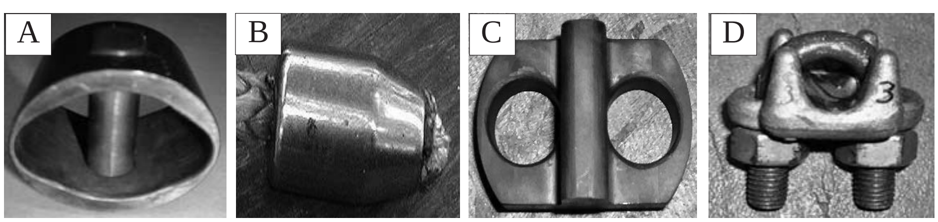

Figure 2. End connections with dry hardware: A) Pinned nubbin; B) Pressed nubbin; C) Knuckle link; D) Rope clamps.

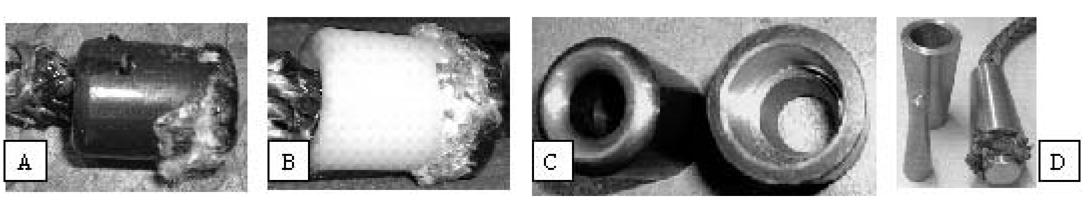

Figure 3. End connections using adhesive: A) Steel nubbin, B) UHMW-PE nubbin, C) Notched steel nubbin, D) SEFAC™(a proprietary design of fiber-maker DSM)

STUDY DESIGN

A statistical procedure for rope sampling and testing was established for two diameters of synthetic rope. The 14mm and 16mm diameters were chosen because they represented rope sizes readily available from the manufacturer, and their steel counterparts are commonly found on logging operations. The synthetic rope was delivered from the manufacturer on ten spools with certified break test reports, five spools for each diameter class. End connections (treatments) were allocated to the appropriate diameters and spools. Each spool represented a separate factory production run, each constructed at a different time. The study reduced any effects of original rope quality by randomly allocating rope test sections to end connectors, so as not to allocate all of the best or worst sections of rope to a specific end connector.

The study was a randomized complete block design and considered two separate experimental units: the 14mm and 16mm diameters. Each unit is grouped into five separate blocks, one block for each spool. Each of the five blocks had different treatment combinations or end connections. The 16mm diameter had 14 different end connections and the 14mm diameter experimental unit had 12 different end connections (end connections using 3M adhesive were omitted).

The study controlled other sources of variation with experimental procedures through:

- uniform test protocols
- uniform test equipment
- uniform sample preparation protocols
- uniform data collection protocols

METHODS

The rope used in this study was Samson Rope Technologies Amsteel®-Blue 12-strand braided UHMW-PE rope. All test specimens were prepared in accordance with Cordage Institute Standards CI 1500-99 §6 [2]. Samples were prepared 72 hours in advance of testing in the Knudson Wood Engineering Laboratory at Oregon State University under ambient conditions. Figure 4 shows the laboratory arrangement used for each break test.

All test sample end connections were tested against the buried eye splice strength. The buried eye splice with proper splicing techniques can retain 100% of new rope strength [16]. Using the Cordage Institute Standards (Test Methods for Fiber Rope CI1500-99) [1] and the synthetic rope manufacturer's Test Methods for Fiber Rope (SRT Test Method-001-02) [16] protocols, the test specimen was loaded ten times to 50% of the corresponding CMV breaking strength with the hydraulic ram traveling 0.1" per second. On the eleventh cycle, the test specimen was loaded to failure traveling at 0.03" per second. According to the rope manufacturer, the CMV for the 14mm is 178,791 N (50% threshold value = 83,395 N) and for the 16mm is 236,263 N (50% threshold value = 118,131 N). Once the sample failed, the test sample was examined for broken strands and examined at end connections and failure points. The cycle time, incremental tension applied to the rope specimen, and tension at failure were collected from each break test. The mean breaking strengths from each diameter subset for the buried eye splice were used as the benchmarks to compare end connectors in the study.

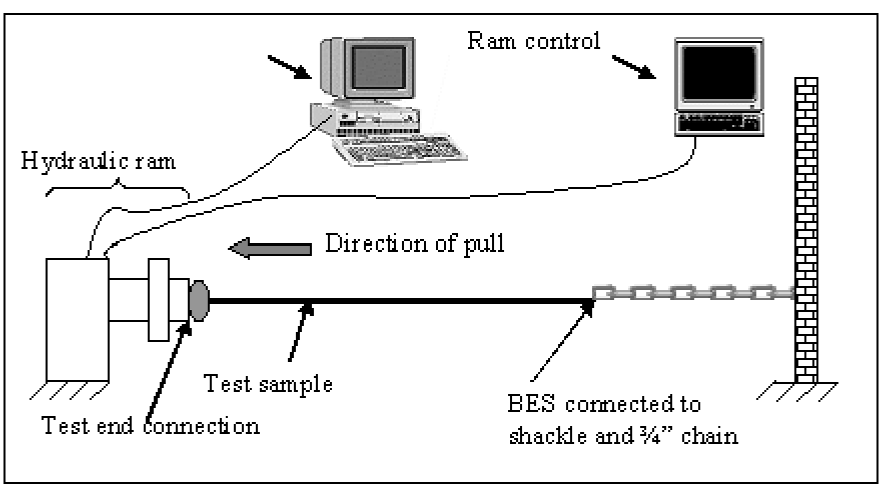

Figure 4. Break test set up in laboratory.

16mm DIAMETER RESULTS

There were 14 different end connections as treatments for the 16mm. The breaking strengths of the different end connections were highly variable. Overall, the splices, the pinned nubbin, and the knuckle link achieved the highest breaking strengths. The mean and distribution of the breaking strengths can be seen in Figure 5. From this plot, it is evident that the end connections #4 and #5, the Y-splice and the steel nubbin with Socketfast® Blue A-20 have the largest absolute amount of variation. Table 1 shows the mean breaking strength and the mean standard deviation for each of the 14 end connections tested.

From Figures 5 and 6, it is evident that the *spliced* connections had higher breaking strengths than all but two manufactured end connections. The rope end connections obtained between 69% and 94% of the CMV. As expected, the highest breaking strength of the spliced end connections was attained by the buried eye splice. The buried eye splice averaged of 223,243 N [50,187 pounds] and 94% of the CMV.

Because the data is normal and balanced, analysis of variance can be conducted. An additive model was constructed to determine if connection type and spool had an effect on the breaking strength. Each diameter has its own randomized complete block design using the model:

$$\mu\{BS|Con,Spool\} = CON + SPOOL$$

From the resulting analysis of variance, the spool (production run) is found not to be significant (p-value = 0.624). There is no significant block effect. Conversely, the connection type is found to be strongly related to breaking strength (p-value = 0.000).

In this study, the buried eye splice serves as the control end connection. It is the end connection, by which the manufacturer tests and documents the CMV. Dunnett's test was used to compare each of the *n-1* treatment (end connection) means with the control or BES. The Whoopie Sling (p-value = 0.426), long splice (p-value = 0.907), pinned nubbin (p-value = 0.999), and knuckle link (p-value = 1.000) breaking strengths are not significantly different from the mean breaking strength of the buried eye splice. A Tukey-Kramer multiple comparisons test classified these strongest end connections into the same group.

14mm DIAMETER RESULTS

The 14mm diameter test samples displayed similar results as the 16mm group. Of end connections with *dry hardware* the knuckle link and pinned nubbin had the highest breaking strengths with 104% and 99% respectively. The long splice had the second highest breaking strength relative to the buried eye splice with 100% of the buried eye splice.

A similar statistical analysis was performed with the 14mm diameter break test results for the 12 specimens as a percentage of the buried eye splice. Table 2 shows the mean breaking strengths and Figure 7 shows a box plot illustrating the spread of the data. Similar to the 16mm breaking strength performance, the *spliced* connections and the pinned nubbin and knuckle link had the highest breaking strengths. The spliced end connections obtained

Table 1. Average breaking strengths and standard deviations for 16mm diameter.

End Connection	(n - 5) for all	Mean Breaking Strength (N)	Standard Deviation (N)	Standard Deviation (% of mean)
1	Buried Eye Splice	223,242	5,743	2.6%
2	Whoopie Sling	202,710	11,884	5.9%
3	Long Splice	210,510	13,510	6.4%
4	Y-Splice	162,084	39,559	24.4%
5	Steel Nubbin w/ Socketfast Blue A-20	27,557	38,468	139.6%
6	UHMW-PE Nubbin w/ Socketfast Blue A-20	45,937	9,558	20.8%
7	Steel Nubbin w/ Scotchweld DP-8010	8,001	2,897	36.2%
8	UHMW-PE Nubbin w/ Scotchweld DP-8011	5,511	2,556	46.4%
9	Notched Steel Nubbin w/ Socketfast Blue A-20	75,023	12,739	17.0%
10	SEFAC w/ Socketfast Blue A-20	98,945	17,601	17.8%
11	Rope Clamps	134,753	11,895	8.8%
12	Pinned Nubbin	217,376	9,089	4.2%
13	Knuckle Link	227,625	6,196	2.7%
14	Pressed Nubbin	49,223	2,390	4.9%

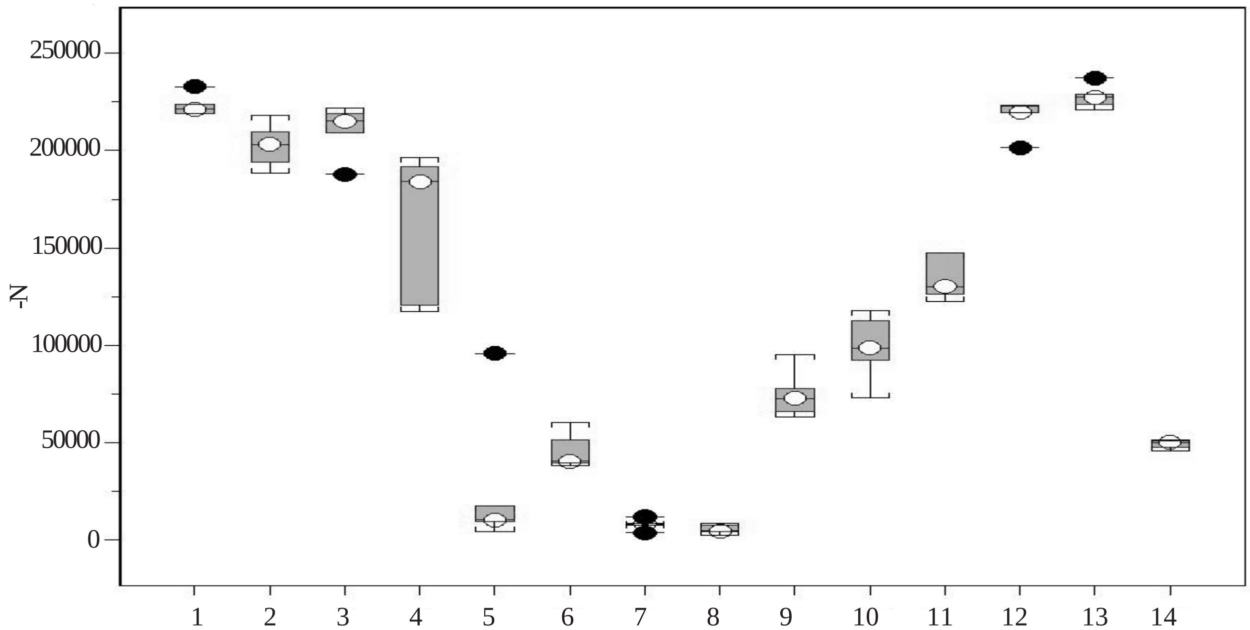

Figure 5. Boxplot of 16mm diameter performance. *Spliced* end connections numbered 1-4, *Adhesives* 5- 10, *Dry Hardware* 11-14. This box plot used the interquartile range (IQR) to distinguish distant values from those close to the body of the distribution. The IQR is the difference between the upper and lower quartiles (the range of the middle 50% of the data) [14]. The black dots represent extreme values relative to the mean and the white dots represent mean breaking strength. Whiskers represent the largest and smallest values that are 1.5 times the box length.

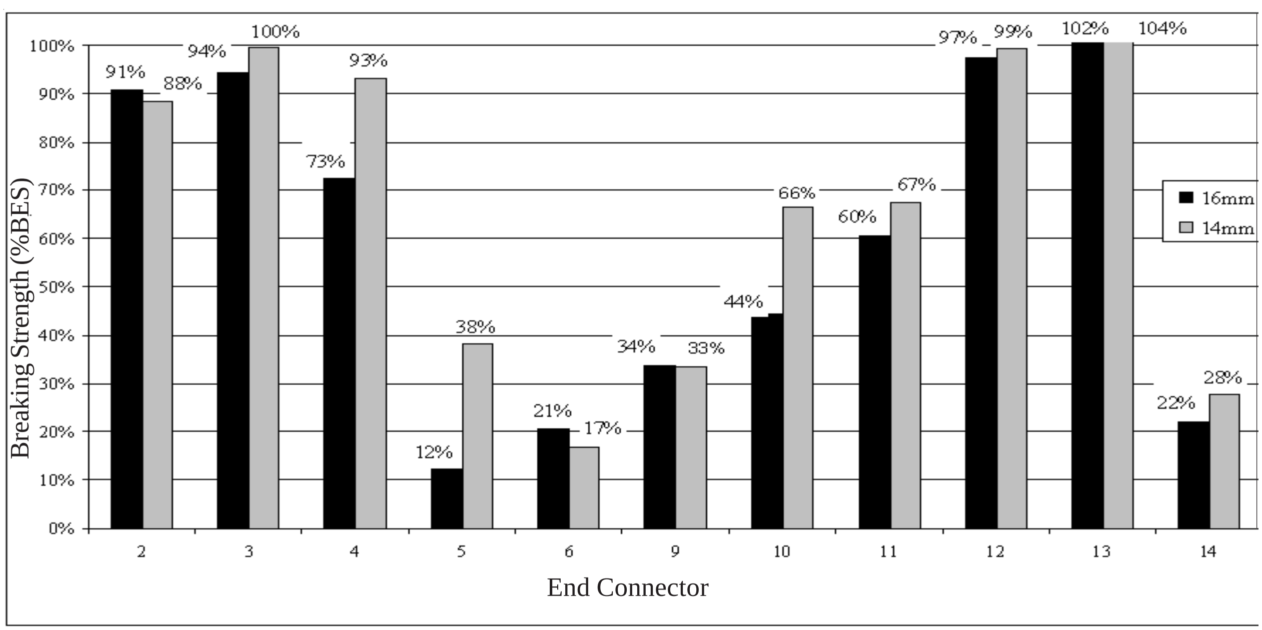

Figure 6. Mean breaking strength as a percentage of the breaking strength of the BES (3M samples omitted)

Table 2. Average breaking strengths and standard deviations for 14mm diameter.

End Connection	(n - 5) for all	Mean Breaking Strength (N)	Standard Deviation (N)	Standard Deviation (% of mean)
1	Buried Eye Splice	172,401	14,217	8.2%
2	Whoopie Sling	152,026	12,820	8.4%
3	Long Splice	170,430	9,422	5.5%
4	Y-Splice	159,942	5,131	3.2%
5	Steel Nubbin w/ Socketfast Blue A-20	65,078	20,467	31.5%
6	UHMW-PE Nubbin w/ Socketfast Blue A-20	28,502	17,306	60.7%
7	Steel Nubbin w/ Scotchweld DP-8011	N/A	N/A	N/A
8	UHMW-PE Nubbin w/ Scotchweld DP-8011	N/A	N/A	N/A
9	Notched Steel Nubbin w/ Socketfast Blue A-20	57,020	4,101	7.2%
10	SEFAC w/ Socketfast Blue A-20	113,513	28,526	25.1%
11	Rope Clamps	115,588	4,425	3.8%
12	Pinned Nubbin	169,331	12,523	7.4%
13	Knuckle Link	177,681	8,882	5.0%
14	Pressed Nubbin	47,704	1,394	2.9%

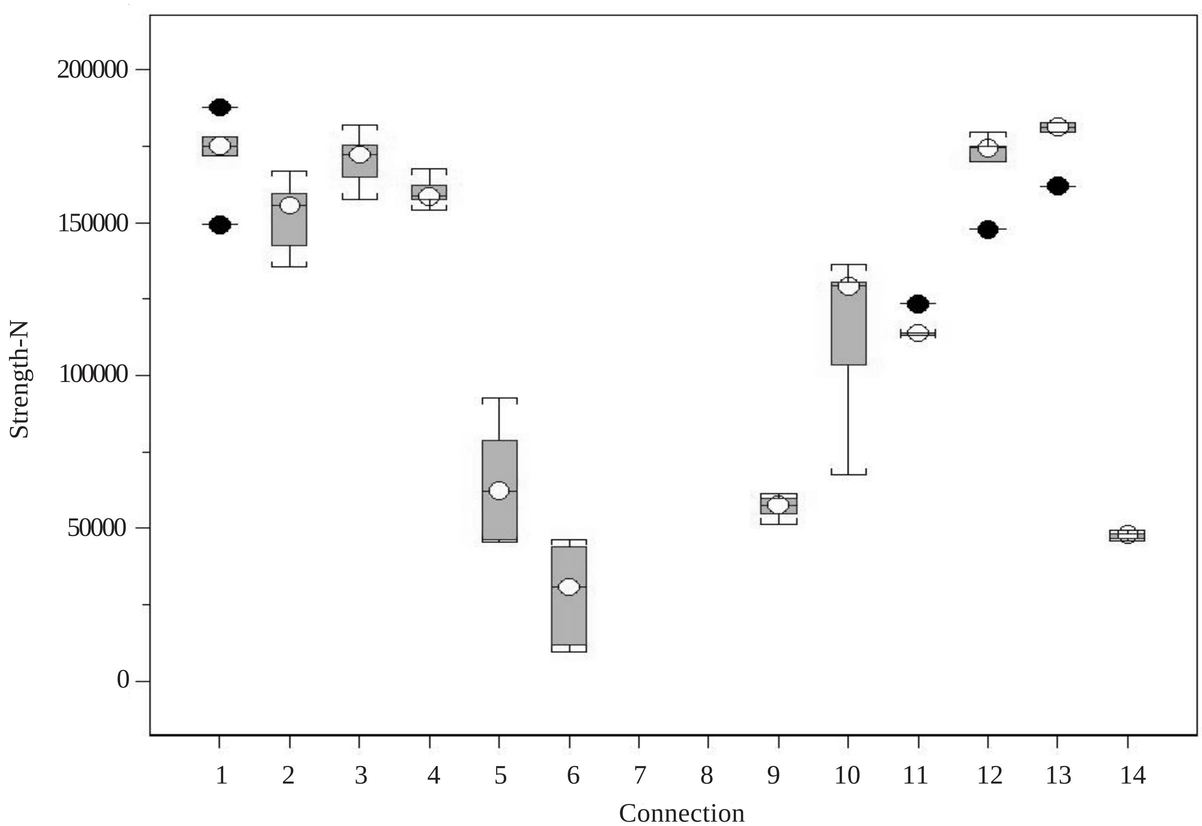

Figure 7. Boxplot of 14mm diameter performance. *Spliced* end connections numbered 1-4, *Adhesives* 5, 6, 9, 10, *Dry Hardware* 11-14. End connections 7 and 8 omitted in testing of this diameter class.

between 88% and 93% of the buried eye splice. The knuckle link had the highest breaking strength with 104% of the BES.

The same additive model used for the 16mm diameter class was employed to analyze the 14mm diameter class. From resulting analysis of variance, there was no significant block effect (p-value = 0.429) with spools, but the treatment effect was significant (p-value = 0.000). In addition to this quantitative analysis, the statistical significance of the breaking strengths was also examined. The Dunnett's test was used to compare each of the treatment means to the buried eye splice. The p-values show that the Whoopie Sling (0.162), long splice (1.000), Y-splice (0.684), pinned nubbin (1.000), and knuckle link (0.998) breaking strengths are not significantly different from the mean breaking strength of the buried eye splice. The Tukey-Kramer multiple comparisons procedure was used to make pairwise comparisons among the means of the end connection treatments. Similar to the 16mm results, six end connections with the highest breaking strength were grouped together: buried eye splice, Whoopie Sling, long splice, Y-splice, pinned nubbin, and the knuckle link. An important observation is that the Y-splice in the 14mm diameter class is included in this grouping because it had less variability in its break test performance. Hartter (2004) [9] provides more complete test results and an in-depth analysis.

DISCUSSION

The study was a randomized complete block design, with blocking on the five spools for each of the two diameters: 14mm, and 16mm. An analysis of variance revealed there was no significant block effect with both diameter samples. There was a significant treatment effect for each diameter class. Twelve and fourteen end connections were tested and the type of end connection primarily determined the breaking strength of the test specimens for 14mm and 16mm ropes.

According the rope manufacturer, the buried eye splice represents the ultimate strength of the rope. Table 3 shows the CMV reported by the rope manufacturer, the manufacturer certified break test results, and the actual breaking strength during testing (all values are from BES testing). The analysis of variance provides evidence that variability in the strength of the rope, measured as the spool effect, does not affect breaking strength for the 14mm and 16mm buried eye splice.

However, these data do show the inconsistent performance and large variability in some of the end connections, especially the end connections with adhesives. The potential sources of error are discussed in the coming paragraphs.

This pilot study only represents a small sample size: five samples in each diameter class and one sample from each spool. From the results of this study, it is evident that the breaking strengths of the BES, the end connection that represents the breaking strength of the rope, remains low compared to the manufacturer's catalogue values. According to the rope manufacturer, the CMV is one standard deviation from the mean breaking strength of the rope within that specific diameter class. It can be assumed that the rope sent from the manufacturer was made to their specifications and falls within a normal distribution of breaking strengths.

Table 3. Performance of the buried eye splice against certified values.

Diam.	Spool	Actual Breaking Strength (N)	SRT Certified Spool Break Strength (N)	% SRT Break Strength	% Catalogue Min. Break Strength	Mean Actual Breaking Strength (N)
14mm	B1	157,157	193,284	90.6%	98.0%	172,401
14mm	B2	171,872	186,292	92.3%	96.1%	
14mm	B3	187,741	184,819	101.6%	105.0%	
14mm	B4	149,283	186,078	80.2%	83.5%	
14mm	B5	177,953	198,475	89.7%	99.5%	
16mm	C1	218,882	236,281	92.6%	92.6%	223,242
16mm	C2	223,918	239,933	93.3%	94.8%	
16mm	C3	221,339	241,160	91.8%	93.7%	
16mm	C4	232,864	237,838	97.9%	98.6%	
16mm	C5	219,207	240,293	91.2%	92.8%	

ADHESIVES

Generally, end connections with adhesive performed poorly. Breaking strengths were low and variability in strength was high. Table 4 shows the mean breaking strength of each of the end connections tested. This table also shows the standard deviation for each end connection in relation to mean breaking strength and mean percentage of the CMV. Overall, the mean breaking strengths were well below the CMVs for both the 14mm and 16mm diameters.

This study has shown that potted terminations can produce breaking strengths in excess of 50% of the catalogue. The SEFAC™ was the only potted termination that had a mean breaking strength that met the 50% criteria. Nubbins with the Socketfast® Blue A-20 have potential because a maximum breaking strength of 95,547 N [21,555 pounds] was attained from one of the 16mm samples. This value represents 41% of the CMV. In addition, one of the 14mm samples of the same end connection achieved a breaking strength of 92,514 N [20,798 pounds], 52% of the CMV. The results are indicative of Socketfast® Blue A-20's potential.

Despite some promising results, end connections with adhesives exhibited the highest variability of all groups of end connections. Potted end connections (end connections with adhesives) are difficult to prepare and difficult to achieve control quality. Specifying an exact breaking strength for potted terminations is difficult because of inconsistent breaking strengths. Breaking strength varied by as much as 139% of the mean value (16mm steel nubbin with Phillystran adhesive).

All end connections were fabricated and those end connections with adhesives were potted under controlled conditions. Although each sample was carefully prepared, there a number of factors that could influence end connection performance during break tests.

First, internal rope strands and fibers unevenly covered with adhesive. It was difficult to apply a sufficient quantity of adhesive into the rope fibers and into the nubbin. Second, air pockets could have developed in the end connections and had an effect on performance. It was difficult with both the 3M and Phillystran adhesives to monitor adhesive distribution in the fibers and within the end connection during the potting procedure. In addition, it was also impossible to examine the nubbins internally to verify equal coverage of adhesive or presence of air pockets once the adhesives has set. Third, the low viscosity of the Phillystran adhesive made it difficult to prevent the adhesive from dripping down the interior of the rope. As a result, a segment of the rope near the end connection became rigid because of the hardened adhesive.

Potting techniques will likely vary from rigging shop to rigging shop and individual fabricator. In addition to the observed differences in end connection preparation, there are other factors that might also influence breaking strengths, such as machining tolerance, potting time, and interactions between materials. If controlled conditions and proper potting techniques in a laboratory cannot produce consistent breaking strength, then fabrication in the field or in a rigging shop is not likely to be any better.

Overall Suitability of End Connections: Strength, Variability, and Applications

Overall, end connections suitable for use with forest operations are the BES, Whoopie Sling, long splice, pinned nubbin, knuckle link. The rope clamps are also acceptable in limited specific applications. In their present state, end connections with adhesive do not appear to be suitable. See [11] for more extensive reports.

Table 4. Mean breaking strengths and standard deviations for nubbins with adhesives.

	End Connection (n = 5) for all	Diam.	Mean Breaking Strength (N)	% of Catalogue Min.	Std Dev (N)	Std Dev (% of Catalogue Min.)
5	Steel Nubbin w/ Phillystran	14mm	65,078	36.4%	20,467	8.7%
6	UHMW-PE Nubbin w/ Phillystran	14mm	28,502	15.9%	17,306	7.3%
9	Notched Steel Nubbin w/ Phillystran	14mm	57,020	31.9%	4,101	1.7%
5	Steel Nubbin w/ Phillystran	16mm	27,557	11.7%	38,468	21.5%
6	UHMW-PE Nubbin w/ Phillystran	16mm	45,937	19.4%	9,558	5.3%
7	Steel Nubbin w/ 3M	16mm	8,001	3.4%	2,897	1.6%
8	UHMW-PE Nubbin w/ 3M	16mm	5,511	2.3%	2,556	1.4%
9	Notched Steel Nubbin w/ Phillystran	16mm	75,023	31.7%	12,739	7.1%

Strength

Breaking strength was one key factor in determining overall suitability of end connections for use with current timber harvesting systems. A 50% CMV value was established as an initial cut-off value to decide quantitatively whether end connections were suitable.

The rope manufacturer recommends a minimum safety factor of 5:1. Thus, the maximum workloads should be 20% of the CMV [17]. In logging operations, the safety factor commonly is 3:1 and maximum workloads are approximately 33% of the breaking strength. For some of the weaker end connections tested in this pilot study, these permissible workloads of 20% or 33% of their mean breaking strengths would fall well below normal operating conditions in timber harvesting. A turn of logs may have a load of 15,000N or more and applying such a load to end connections with low breaking strengths would exceed permissible working loads.

Often operators will exceed the safety factor and incur substantially heavier loads. Though such an action may only happen infrequently, the synthetic rope end connection must have the strength capacity to withstand such loads. End connections that are significantly weaker and inconsistent in break tests should not be deemed suitable. Therefore, a 50% CMV cut-off value was chosen because of these safety concerns.

The end connections with mean breaking strengths of 50% of the CMV for each diameter class are shown in table 5. Table 5 also shows the breaking strength relative to the mean breaking strength of the buried eye splice. The results of the Tukey-Kramer pairwise comparisons and Dunnett's test of a control value can be used in the determination of suitable end connections for timber harvesting applications. Both procedures statistically show which mean breaking strengths are significantly different from each other. These tests are important because they group together the strongest end connections with the least amount of variance. For both diameter groupings, Whoopie Sling, long splice, pinned nubbin, and knuckle link did not have breaking strengths significantly different from the BES.

Variability

Variability was the second criterion in considering the suitability of each end connection. For example, the Y-splice breaking strength depends on splice construction, preloading the connection and lock stitching. Lock stitching prevents early pull-out of the Y-segment as the connection is loaded. Preloading the Y-splice also helps lock the splice and remove the construction stretch and looseness of the splice. However, the variability of the Y-splice is greater than other end connections, and thus further testing on this concept is warranted to determine suitability.

In the case of the pressed nubbin, low variability is an asset even though the ultimate strength is lower than our criteria. The pressed nubbin had relatively low breaking strength, but also low variability. The pressed nubbin has potential in some applications. This characteristic serves well where an end connection is designed to "break away".

Table 5. End connections that achieved a breaking strength of at least 50% of the CMV.

	End Connection (n=5) for all	Diam.	Mean Breaking Strength (N)	Mean % of BES	Mean % of Catalogue Min.
1	Buried Eye Splice	14mm	172,401	100.0%	96.4%
2	Whoopie Sling	14mm	152,026	88.2%	85.0%
3	Long Splice	14mm	170,430	98.9%	95.3%
4	Y-Splice	14mm	159,942	92.8%	89.5%
10	SEFAC w/ Phillystran	14mm	113,513	65.8%	63.5%
11	Rope Clamps	14mm	115,588	67.0%	64.6%
12	Pinned Nubbin	14mm	169,331	98.2%	94.7%
13	Knuckle Link	14mm	177,681	103.1%	99.4%
1	Buried Eye Splice	16mm	223,242	100.0%	94.5%
2	Whoopie Sling	16mm	202,710	90.8%	85.8%
3	Long Splice	16mm	210,639	94.4%	89.2%
4	Y-Splice	16mm	162,084	72.6%	68.6%
11	Rope Clamps	16mm	134,753	60.4%	57.0%
12	Pinned Nubbin	16mm	217,376	97.4%	92.0%
13	Knuckle Link	16mm	227,625	102.0%	96.3%

In the case of winch connections on skidding machines where the winchline is expected to break apart from the drum in emergencies so the load does not overturn the skidder or pull it down the hill.

Other considerations were end connection fabrication and construction time and procedure are important measures of suitability. Of the end connections that also meet the 50% criteria, only the SEFAC™ and rope clamps do not utilize a splice as a component of the end connection. The SEFAC™ potentially could be difficult to fabricate, making it less acceptable than other end connections.

Static Line Applications

All of the end connections and terminations deemed suitable for use with timber harvesting could be used in static line applications. Each end connection could have their place in forest operations. The BES is the all-purpose end connection. By making a simple spliced eye, the synthetic rope can be wrapped around trees, stumps, or equipment and then shackled to itself. In similar circumstances, steel wire rope clamps would work to secure lines.

The Whoopie Sling was designed for applications, in which adjustable lengths are needed. It alleviates the necessity of taking multiple rigging lines into the forest to set up support lines. Instead of using different lengths of support lines, the Whoopie Sling can adjust for length. Potentially only one sling would be needed because it can adjust to specific site conditions. With its two spliced eyes, it can connect easily to shackles or other support lines.

The long splice can also be used with static line applications. It can be used to repair damaged or severed winchlines. The long splice can also be used to extend a carriage to reach longer lateral yarding distances.

Rope clamps could serve well as a termination under static loads. To reduce the load on the end connection, several wraps around a tree or stump are recommended before connecting the rope clamps to the synthetic rope (similar to current steel wire rope practices in forest operations).

Running Line Applications

The pinned nubbin and knuckle link were designed for running line applications. Both of these connections could be used to secure synthetic rope to winch, yarder, or carriage drums. By utilizing a buried eye splice and minimal additional hardware, they can be produced quickly and without added hardware. More importantly, these designs allow quick connection into the drums and immediate use of the rope thereafter.

In addition, the long splice and BES can be used for running line applications just as they can be for static line operations.

CONCLUSIONS AND FUTURE RESEARCH

UHMW-PE braided rope (synthetic rope) has many advantages that make it attractive to the logging applications and specifically in static line and running line applications. Each application is governed by operating regulations, material, and strength requirements. It is therefore crucial that synthetic rope performance be held to similar standards for steel wire rope. As with steel wire rope, synthetic rope is only as strong as its end connection. Without out proper connections and end terminations, the rope cannot be utilized in a timber harvesting system. Proper connections and end terminations therefore need to be developed and tested.

This pilot study developed and tested fourteen end connections for 14mm and 16mm diameter synthetic rope to determine suitability for use in timber harvesting operations. End connections suitable for use with forest operations are the BES, Whoopie Sling, long splice, pinned nubbin, knuckle link and in limited specific applications, the rope clamps and pressed nubbin may have potential. Overall, the pinned nubbin and knuckle link had the highest mean breaking strengths in both the 16mm and 14mm diameter classes. The spliced end connections showed promise with the buried eye splice having the highest mean breaking strength.

End connections using adhesives to bond the synthetic rope to the end connection hardware were also tested. High variability and relative low breaking strengths characterize these end connections. Poor performance and complicated preparation procedures make these end connections unsuitable for immediate use in forest operations. More research is needed to determine if a suitable adhesive end connection can be designed that could be potted successfully in the field.

Further experience with Y-splices and Whoopie Slings is needed where loading is periodic, ranging from low to high loadings. It is necessary to ensure that the splice will not work loose under these conditions. Testing is also needed under shock loading conditions. SRT (2003) [17] defines shock loads as “a sudden change in tension – from a state of relaxation or low load to one of high load.” SRT (2003) [17] considers any sudden load that exceeds the workload (20% of CMV) by more than 10% is considered a shock load.

While not meeting the minimum 50% breaking strength criteria, the pressed nubbins also show promise in limited applications and further testing of this concept is recommended.

With suitable end connections identified, larger sample sizes could be tested. End connections could be tested on diameters up to 38mm ropes from various rope manufacturers. End connections and terminations in this particular project were tested at ambient conditions. Future research and field-testing could characterize the effects of various environmental conditions to determine suitability and safety.

Future research could also focus on the development of a synthetic rope choker design. Synthetic chokers will decrease weight and could reduce safety hazards for loggers in the field. Research could also investigate the operational performance of synthetic rope with other lightweight materials, such as UHMW-PE sheaves, tree shoes, and rigging.

The overall strength of synthetic rope and other properties make them useful in timber harvesting applications. It is hoped that this study will lead to continued research with synthetic rope of various types and manufacturers. Successful research, development, and rigorous field trials are necessary to provide further insight into its performance. Synthetic rope in selected timber harvesting applications has the potential to replace steel wire rope to the benefit of forest workers.

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