AN ABSTRACT OF THE THESIS OF

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Abstract approved:

John J. Garland

Steel wire rope is the accepted standard in logging. It is strong, durable, stiff, and dependable in the logger's arsenal. However, steel wire rope has several disadvantages: its strength to weight ratio is low; it is difficult and time-consuming to splice; and used wire ropes contain jaggers. Ultra-high molecular weight polyethylene (UHMW-PE) braided rope has potential to replace steel wire rope. The offshore mooring and shipping industries have appreciated it for years. Characteristics such as a specific gravity less than one (it floats!), high flexibility, low stretch, and ease of splicing make the synthetic rope useful. At equivalent diameters, synthetic rope has an equal or greater breaking strength to that of steel wire rope, but at 1/7 the weight.

This thesis is an investigation of the end connectors for the unique physical, mechanical, and thermal properties of UHMW-PE 12-strand braided rope that make this technology of interest in logging applications. This studied focused on three diameter classes of the synthetic rope that are common to logging operations: 3/8", 9/16", and 5/8". Within each diameter class there were five different spools representing separate production runs. A randomized complete block design was used with each diameter class and the corresponding five spools a separate population. Following the laboratory tests, the breaking strengths were compared to the buried eye splice.

Three types of end connectors were evaluated during this pilot study. They are identified as *spliced*, *adhesives*, and *dry hardware*. Spliced end connections provided consistent performance in breaking strengths. The end connections with adhesives had variable strength performance laboratory tests and are therefore not recommended. Within the dry hardware end connections, the pinned nubbin and knuckle link provided the highest breaking strength relative to the buried eye splice.

This project has accomplished its objectives. It was the first extensive study on end connections specifically designed for synthetic rope. New end connections were developed and steel wire rope connections were modified to meet the strength and usability criteria for timber harvesting operations. Suitable end connections for forest operations were: buried eye splice, Whoopie Sling, long splice, rope clamps, knuckle link, pinned nubbin, and Y-splice. These end connections suitable for use with forest operations were identified and recommended user guidelines were given. Further research and development needs to be conducted on these seven concepts with larger sample sizes and in varied conditions.

Investigation of Synthetic Rope End Connections and Terminations in Timber Harvesting Applications

by
Joel N. Hartter

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APPROVED:

Major Professor, representing Forest Engineering

Head of the Forest Engineering Department

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Joel N. Hartter, Author

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DEDICATION

Für meinen liebsten Sonnenschein. Diese Arbeit ist nur möglich wegen deiner Geduld, unendlichen Ermutigung und besonders deine ständige Liebe. Dafür bin ich dir zu großem Dank verpflichtet.

Preface

Logging is a difficult and demanding working environment. Workers must continually maneuver in thick brush and slash, work on steep slopes, and operate equipment. In many operations in the Oregon Coast Range, the steep slopes require cable systems. Steel wire rope is the accepted standard in the industry for these types of operations. It is strong, durable, and readily available. However, there are some drawbacks to using this material. Principally, steel wire rope is heavy and susceptible to bending fatigue.

An alternative to steel wire rope is ultra-high molecular weight polyethylene synthetic rope (synthetic rope). Synthetic rope is 1/7 the weight of steel and comparable in breaking strengths for diameters of 1" and under. It does not absorb water, it floats, it has an ultra-violet protection coating, and there are no jaggers. Synthetic rope is durable, resistant to most chemicals and lubricants, and does not corrode. Synthetic rope has potential in cable operations for guylines, snaplines, mainlines, and droplines for the carriage. Additionally, it can be used in running line applications on skidder winches to pull logs to the skid trail. This study investigates the use of end connections and terminations for implementation of synthetic rope into timber harvesting applications.

This research sought to answer the following questions.

1. Can end connections and terminations for the ultra-high molecular weight polyethylene (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?

The objectives of this project are to modify or develop suitable end connections for synthetic rope for use in the logging industry; break test these end connections; and assess the suitability of each in timber harvesting applications. Within this thesis, end connection concepts are discussed, as well as the experimental design and methodology to test these end connections. Following the break testing of the end connections under various conditions, the results are analyzed. To form the basis for usability, recommendations are made for each end connections in the logging industry.

This entire project was not only an investigation of implementing new materials and technologies in logging, but it is also an effort to reduce hazards in the workplace. Furthermore, this pilot study should stimulate further research of synthetic rope and end connections and be a catalyst for industry acceptance of synthetic rope.

Investigation of Synthetic Rope End Connections and Terminations in Timber Harvesting Applications

1 Introduction

1.1 Background

Currently, wire rope is used universally in timber harvesting for skylines, guylines, winchlines, support lines, truck wrappers, chokers, and running lines. It has contributed to the advancement of cable logging and is used around the world in thousands of miles annually. It is the all-purpose, durable, strong solution to meet the demands of logging. Although steel wire rope is now the industry standard, it is still not the optimal solution.

Synthetic rope constructed of braided ultra-high molecular weight polyethylene (UHMW-PE) fibers has potential to replace steel wire rope. It has been accepted in the offshore mooring and shipping industries for years. Characteristics such as a specific gravity less than one (it floats!), high flexibility, low stretch, and ease of splicing make the synthetic rope useful. When the same diameter of steel wire rope is compared to the same diameter UHMW-PE rope, the UHMW-PE rope has a higher breaking-strength-to-weight-ratio than steel wire rope by a factor of 10.

The main difficulties with synthetic rope are used with existing harvesting systems and its adaptation to current forest practices. Because of the rope's low coefficient of friction, 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 with the rope (Garland et al., 2002). Synthetic rope has a much lower critical temperature compared to steel rope and is intolerant of heated connections. Essentially, the rope's physical, chemical, and mechanical properties make it an excellent substitute for wire rope in timber harvesting applications, but these same characteristics make it difficult to couple with existing end connectors.

Because of steel wire rope's weight and tendency to produce jaggers (broken wires that cause painful puncture wounds), there are potential ergonomic gains as well as worker health and safety benefits by replacing the wire rope. The goal of the synthetic rope research is to replace wire rope with UHMW-PE (synthetic) 12-strand braided rope.

1.2 Research Problem

Steel wire rope is the accepted standard in logging; however, it has important disadvantages. Improvements in polymer technology have lead to the utilization of UHMW-PE in rope applications. Possessing the strength of steel, a higher strength to weight ratio, low stretch, and flexibility, UHMW-PE braided rope has much potential within the logging industry. If end connections and terminations for the synthetic rope could be used in logging with little strength degradation, the logging industry would likely accept this new rope technology.

1.3 Research Questions

The series of synthetic rope projects began in the summer of 1999 at Oregon State University producing early strength test results, ergonomic benefits, and economic potentials. The focus of the first project was to answer the question,

Can synthetic rope be an adequate replacement to steel wire rope in timber harvesting applications?

Under the umbrella of synthetic rope research at Oregon State University, comprehensive research of synthetic use in logging applications is underway. The first project was an investigation into the potentials of synthetic rope for use in logging and did not specifically address end connections and terminations for use with synthetic rope. The following research questions were investigated by this thesis:

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?

1.4 Hypothesis

The goal of this project was to modify or develop suitable end connections for synthetic rope for implementation with existing timber harvesting systems. Below is the hypothesis for the pilot study in null and alternative form.

H_o: Breaking strengths for end connections and terminations modified for use with synthetic rope are not significantly different from the buried eye splice.

For *End Connection*$_i$, there is no significant difference in breaking strength compared to control. Where i = 1-14 for the 5/8" diameter class end connectors; i = 1-12 for the 9/16" diameter class end connectors; and i = 1, 2 for the 3/8" diameter class end connectors.

H_a: Breaking strengths for end connections and terminations modified for use with synthetic rope are significantly different from the buried eye splice.

1.5 Research Objectives

The objectives of this project were 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 of the mechanical performance of the rope with various end connections under varied load conditions. This study assesses the strength of the synthetic rope under cycled loading at ambient temperature. Additionally, due to varied harvesting applications, different end connections and breaking strengths are required. This thesis determines each end connection's suitability for logging. Suitability is a subjective evaluation of laboratory performance, construction procedures, and cost.

The focus of this project was to develop and test end connectors of UHMW-synthetic rope for logging applications. Although chemical and physical properties as well as chemical interactions may ultimately determine an end connection's effectiveness, the goal of this project was not to experimentally verify these properties.

This project investigated the strength characteristics and feasibility of end connection concepts in logging. The research questions are addressed by the following objectives.

1.5.1 Objective 1

Develop and test end connections for use in the logging industry.

1.5.2 Objective 2

Quantify the breaking strengths for modified or newly developed synthetic rope end connections and terminations for further research and development.

1.5.3 Objective 3

Assess the potential usability of the synthetic rope end connections and terminations for timber harvesting applications.

2 Literature Review

2.1 Introduction

A review of literature is necessary to understand the current uses of UHMW-PE, its material properties, and design considerations for end connections. This chapter briefly examines the evolution of synthetic rope into high-modulus synthetic rope. It discusses the basics of UHMW-PE terminology, fiber and rope production, and synthetic rope properties. This literature review comments on high-modulus synthetic rope in other applications and the limited use in forestry. Finally, this section reviews Oregon State University's research into synthetic rope applications for timber harvesting.

2.2 History of Synthetic Rope

The most common synthetic rope materials are nylon, polypropylene, and polyester (Flory et al., 1992). Though widely available and quite popular in many applications, each material possesses some undesirable characteristics for use with heavy loads. Nylon has the lowest stiffness modulus and is favored for applications needing stretch. This fiber is strong when dry, but wet nylon rope can lose 20% of its strength (Flory et al., 1982).

Polypropylene ropes have a specific gravity less than 1, but they are weaker than nylon or polyester. In addition, polypropylene ropes may creep under large loads (Flory et al., 1992). Of these three fiber rope types, polyesters are the most desirable for heavy loads and in wet conditions.

Until the development of high-modulus fibers, polyester was the predominant rope choice for many heavy load applications. New high-modulus fibers have higher elastic moduli compared to nylon, polyester, and polypropylene, and they have significantly higher breaking strengths too. The Dupont Corporation in the 1970's (Flory et al., 1992) introduced Aramid fibers, known as Kevlar™. Although these ropes were much stronger and durable, there were some limitations. Axial-compression fatigue can occur when, "tightly constrained Aramid fibers are forced into compression" (Riewald, 1987). "Axial compression is caused by repeated bending of individual fibers when they are allowed to relax while tightly constrained within the structure of the rope (Banfield et al., 1999)." This type of failure was common in these ropes.

Not long after the inception of Aramid fibers into the market, demand for ropes with higher tensile strength increased. The marine industries wanted lightweight ropes that would sustain high loads at an extended number of cycles. In the mid 1980's, through a joint project with Dutch State Mines (DSM) and Toyobo, the first gel-spun UHMW-PE fiber was developed. The first commercially available fiber was Spectra® developed by Allied Signal, Inc. (now Honeywell, Inc.) in the late 1980s (Honeywell, 2002).

Since the mid 1908's, UHMW-PE fiber ropes have grown in popularity. Many companies have adopted UHMW-PE ropes because of their low stretch, high strength, light weight, and natural buoyancy. These characteristics translate into safer handling and storage, shorter operational time, and less labor needed to complete tasks. Table 1 shows typical rope properties for some of the most common materials.

Table 1. Typical rope properties of various materials

	Polypropylene	Polyester	Nylon	(i.e. Kevlar™)	UHMW-PE	Steel
Density (g/cc)	0.89	1.38	1.14	1.44	0.97	7.86
Tenacity (g/den)	7.5	8.6	8.4	26.4	40	3.1
Modulus (N/mm^2)	3,933	9,000	5,500	60,000	110,000	200,000
Elongation (%)	15	12.5	18	4	3.6	1.1
Coefficient of Friction	0.095	0.12	0.14	0.06	0.08	
Dry Abrasion Resistance	Good	Good	Fair	Poor	Good	Excellent
Wet Abrasion Resistance	Excellent	Good	Fair	Poor	Excellent	Excellent
UV Resistance	Fair	Good	Excellent	Poor	Fair	Excellent
Heat Resistance	Fair	Good	Good	Excellent	Poor	Excellent
Creep	Poor	Excellent	Excellent	Excellent	Fair	Excellent
Chemical Resistance	Excellent	Good	Good	Fair	Excellent	Excellent
Axial Compression Fatigue	Excellent	Fair	Poor	Good	Excellent	

(Honeywell, 2003)

2.3 UHMW-PE Fiber and Rope Production

UMHW-PE is produced by a unique low-temperature polymerization process and has an average molecular weight ten or more times that of conventional high-density polyethylene resins. As the molecular weight of polyethylene increases, significantly higher values are obtained for a number of important properties including impact strength, abrasion resistance, energy absorption, and resistance to cracking. The high tensile strength is specifically gained through a fiber morphology consisting of long chain molecules that align themselves along the fiber axis. However, this same process creates a highly refined fiber structure; thus, the fibers and the rope are highly susceptible to compression fatigue failure (Puget Sound Rope, 2004).

In addition, due to its increased molecular weight and the special polymerization process, UHMW-PE has a specific operating range of -400° F to 200° F with a safe working temperature of under 167° F (DSM, 2001). The long-chain molecules do not melt or flow like most thermoplastic resins. Therefore, heat treatment and molten compounds used in steel wire rope applications will not work.

Although UHMW-PE is heat sensitive and cannot work at the high temperatures that steel can withstand, UHMW-PE is still an advantageous substitute up to 167° F. AmSteel®-Blue, produced by Samson Rope Technologies of Ferndale, WA, is a 12-strand single braid rope made of Dyneema® SK75 UHMW-PE fibers. It is lightweight, flexible, and easily field-spliced. The rope's chemical, thermal, physical and mechanic properties make this rope attractive for use in logging applications.

The characteristic high strength of the UHMW-PE fibers is transferred to the rope. However, this transfer of strength is not 100%. Because the rope is twisted and braided, there is an efficiency loss of approximately 30%. In other words, the sum of the individual strengths of each UHMW-PE fiber does not equal the breaking strength of the rope. For example, each fiber initially has 100% breaking strength of a known value. When these fibers are combined together in 12 different strands and then braided, each fiber only retains approximately 70% of its original strength. Thus, there is an overall strength reduction from fiber to finished rope (Chou et al., 2002). However, the twists and braids are necessary to increase the worklife of the rope (the number of cycles a rope can withstand under a given tension). Using certain constructions, the fibers can share the load more evenly and reduce the peak load on any single fiber. This load sharing is essential to reduce long-term creep and tension fatigue.

All AmSteel®-Blue rope is constructed at the Ferndale, WA facility of Samson Rope Technologies (SRT). Samson Rope Technology receives a shipment of DSM-produced SK 75 fibers to begin the rope manufacturing process (Figure 1A). The fiber is then spun into a yarn (Figure 1B). The yarn is then twisted and spun into strands. AmSteel®-Blue is comprised of 12 of these individual strands. The strand spools are loaded onto bobbins and then braided through an automated process (Figure 1C).

Figure 1. A) Fiber delivered in spools B) Fiber spun into yarns C) Yarns spun into strands D) 12 strands braided into (uncoated) finished product

The rope construction is complete in Figure 1D. There are two final stages remaining in the rope manufacturing process. All finished rope is coated in a Samson Rope Technologies proprietary urethane ultra-violet protectant (Samthane®). Finally, breaking strength tests are conducted with random rope samples. The production process is complete and the finished rope ready for the customer.

2.4 Synthetic rope Use in Other Applications

The introduction and subsequent technological advances of high-modulus fibers, such as UHMW-PE, have made synthetic rope well accepted in many industries. It is now possible to have ropes with strengths up to 10 times the strength of steel for their weight (Foster et al., 1997). They are flexible, noncorrosive, and stretch little. Already, synthetic rope is used for outer space vehicles, deep-sea umbilicals, antenna guylines, lifelines on Navy vessels, and for mooring and towing of large vessels. Wire rope has limitations in water particularly because of its heavy weight and susceptibility to corrosion. Fiber ropes overcome these limits and other problems for the design and installation of deep ocean structures and moorings (Flory et al., 1992).

2.5 Synthetic Rope Research in Forestry

Other industries have utilized synthetic rope for a number of years. Recognizing its high strength and light weight advantages over steel wire rope, the forestry sector began to examine the potentials of synthetic rope within forest operations. However, there has not been extensive utilization of synthetic rope. A literature search revealed only limited testing in timber harvesting applications.

Recognizing the potential of synthetic rope, the Forest Engineering Research Institute of Canada (FERIC) began trials with synthetic rope in logging applications. FERIC examined a braided Aramid (Kevlar™) rope. The rope was used for skidding small logs with an all-terrain vehicle. The initial field trials of this rope were surprising. The 3/8" diameter rope had a breaking strength of 9,000 pounds and 3% elongation at yielding (Dunnigan, 1993). The fibers were durable, yet the rope was affected by ultraviolet solar rays and abrasive surfaces (i.e. rocks, logs, etc.). These initial trials found that the synthetic rope had potential for logging applications and paved the way for further investigation of the rope.

FERIC again investigated the use of synthetic rope in 1996 with field trials of synthetic rope mainlines on cable skidders for ground-based logging. In this study, both Aramid and polyethylene (Spectra®) fiber ropes were tested and compared to the performance of steel wire rope. This study found Spectra® to have more potential in logging applications than Kevlar™. Spectra® was lighter, had a higher breaking strength, less elongation, and no sensitivity to sunlight. However, there were some disadvantages. Spectra® was found to be more expensive and have a lower critical temperature than Kevlar™ (Golsse, 1996). Despite these drawbacks, Spectra®, and hence braided polyethylene rope, was seen to have potential in logging applications.

In another trial, the Forestry and Forest Products Research Institute in Ibaraki, Japan used synthetic rope used for tower guylines and concluded that wear was a problem with the ropes. Due to bending over a fixed point and fatigue of the rope, the number of passes over the sheaves had a dramatic effect on the life of the synthetic rope. However, measuring the amount of damage was difficult and often more a subjective investigation of abrasion and wear. It was also difficult to quantify fatigue life. However, the synthetic rope did show promising results for use in logging (Uemura, 1998).

2.6 Synthetic Rope Research at Oregon State University

The research at Oregon State University began as a result of a trial by a logging contractor in Washington reporting the use of synthetic rope used for guylines (Anderson et al., 1999). The project focused on field trials and laboratory testing. The field trials were limited to ergonomic, health, and safety issues in completing typical logging activities. Heart rates and time to complete tasks were measured for line pulling, tree rigging, and carrying guylines. Not only is the task time less when using synthetic rope, but the first results also indicate that maximum heart rate is less for tasks using synthetic rope than tasks using steel wire rope. Furthermore, the recovery time for heart rates was significantly less with tasks using synthetic rope (Pilkerton et al., 2001).

Laboratory tests were also conducted to further understand the characteristics of UHMW-PE and to determine failure values. Samples were loaded according to the Cordage Institute’s standards by cycling to 20 percent of breaking strength 10 times and then loaded to failure. These tests yielded breaking strengths at acceptable levels. A second set of tests was conducted after discussions with the manufacturer. Samples were cycle loaded to 50% of the breaking strength and then pulled to failure. Similar results were attained for the second battery of tests (Garland et al., 2002).

The purpose of the first project was to begin to identify the UHMW-PE rope strength characteristics and to determine if it could be suitable for logging applications. Although the original project did not concentrate on end connections, some preliminary concepts were examined. Initial trials indicated that UHMW-PE 12-strand braided rope is suitable and the foundation for future research in end connections and terminations was laid out.

As the need for lightweight materials continues to be recognized in the logging, further investigation of synthetic rope was merited. Recently, synthetic rope has been evaluated for use in static rigging and winching applications. Leonard et al. (2003) studied the use of synthetic rope as guylines, intermediate support lines, tree straps, and snap guylines. In all four applications, the synthetic rope was found comparable in performance to steel wire rope. However, because the rope is lightweight, workable, and easy to bend, set-up times in the field were much lower than with steel wire rope. Although, it took approximately the same amount of time for descending the steep terrain with synthetic rope and steel wire rope, carrying steel uphill took twice as long (Leonard, 2003). Fewer trips to carry gear to the rigging tree were needed because more gear per load could be taken into the brush.

Pilkerton et al. (2003) investigated the use of synthetic rope in winching applications. Five case studies (three skidder winch lines, a carriage dropline, and a carriage mainline) were conducted to determine the effectiveness of the rope in logging. Operators were pleased with the lightweight line and the ease of pulling line through brush. Operational times and thus turn times decreased (Pilkerton et al., 2003).

Researchers also recognized that synthetic rope will not take the same abuse as steel wire rope and different operating criteria for synthetic rope are needed. Some operators encountered synthetic rope failures due to running the rope over jagged or sharp edges. Though the synthetic rope cannot sustain the abuse that wire rope can, the failed rope can be quickly spliced and repaired. The observations and subjective assessments collects from these trials were useful to characterize the rope's performance in practice. In both field trials, operators and loggers agreed that using synthetic rope to complete tasks in the woods was not only acceptable, but its characteristics maintain some distinct advantages over steel wire rope.

2.7 Research in End Connections for Synthetic Rope For Timber Harvesting Applications

Only one study found in the literature revealed the use of constructed end connections in timber harvesting applications other than splices or knots. This report investigated possible end connections and treatments to the ends of Kevlar™ and Spectra® fiber rope to make it more durable. Two designs were tested: the "rope-to-cable" and the "rope-to-chain" designs. The rope-to-cable design was constructed by splicing a short piece of steel wire rope with a steel termination to the synthetic rope. The rope-to-chain design attached the chain and clevis to the rope using a splice. An additional design was tested to protect the rope from severe abrasion by covering the end of the synthetic rope with a hydraulic hose.

Because of the inherent properties of synthetic rope, it was difficult to construct strong end connections that could withstand the rigors of logging (Lapointe, 2000). All designs failed early due to heavy abrasion and severed strands at the test site.

2.7.1 Knots

Knots are one of the oldest and simplest methods to connect ropes together or to terminate them. Further development in knots progressed through use in maritime, recreation, and technical rescue activities. However, knots are not a suitable end connection for the 12-strand braided synthetic rope without a core. It is not advisable to join ropes of different diameters or construction together. Moreover, the knots bend the rope, and they distort the balanced construction and load distribution. Consequently, some strands are seeing a higher proportion of the load. Knots significantly reduce the strength in synthetic ropes up to 50% (Foster et al., 1997). A table of typical knot strengths can be found in Section 5.9.2 (page 146) of this thesis. Knots are also not advisable because of the low coefficient of friction of the synthetic rope and the high tensile loads typical in logging that could cause knots to slip, break, or release. Knots are also not recommended by the rope manufacturer. Initial testing by Oregon State University confirmed this recommendation with knots yielding 10-50% of the rated breaking strength (Garland et al., 2002).

2.7.2 Splices

Splices are another way to terminate the end of the synthetic rope. An eye splice is used to put a permanent loop at the end of a rope for attachment. The buried eye splice is a concept similar to the common device known as a children's finger puzzle. With fingers inserted into each end, the harder one pulls, the tighter the device grips the fingers. The free end of the tapered and synthetic rope is first attached to a fid using duct tape. The fid is then threaded into the middle of the synthetic rope. A fid is an aluminum tapered needle-like rod with a hollow end to hold the rope and a pointed end to ease passage down the center of the strands. As the rope is pushed through itself, an eye is formed. Typically, the eye is adjusted to have a one fid-length circumference.

For an eye-length of one fid, the free end of the synthetic rope must be tapered from 12 strands to six strands. This is done by cutting a pair of adjacent strands, moving one pick (pair of strands) down the rope and cutting another pair, and moving one more down and cutting the final pair of strands. A pick count is the number of strands rotating in one direction in a specific length divided by the length and is expressed as picks per unit length (Foster et al., 1997). The six cut strands are removed and the rope end will be properly tapered. It is necessary to taper the end of the rope so that when it is tucked into itself, there will be a gradual transition from 12 strands, six strands, and then the end of the rope. It will provide a more even load distribution and it will "grab" the inner rope better as it constricts under tension.

Through extensive testing, the manufacturer has determined that the buried eye splice achieves the highest breaking strength. As a result, it is currently used as the test criteria for new rope constructions and concepts. It is the end connection by which the catalogue breaking strengths were derived. Preliminary testing at Oregon State University shows that the buried eye splice yielded the highest breaking strength at approximately 90% of ultimate strength of the synthetic rope itself (Garland et al., 2002). Because this end connection is the strongest reported strength, the testing strength for the rope becomes the buried eye splice. Splicing techniques are designed and developed explicitly by the manufacturer. Splicing can also be used to repair damaged rope by connecting the old rope to a new section. However, in some instances a splice is not always desirable or feasible.

2.7.3 Drum Attachments

There is also a need for a mechanical type of attachment used to secure a load, guylines, or the line to a winch drum. Stopper knots have been developed for marine applications. However, these knots induce a non-uniform load on the strands because the load is not as uniform the strands are bent and pinched around other strands. Thus, ultimate breaking strength of the synthetic rope is compromised and reduced. Mechanical and potted terminations are useful because they maintain rope strength. However, the synthetic rope is not ideally suited for conventional mechanical terminations because of its low coefficient of friction and unless a large reduction in strength can be tolerated (Foster et al., 1997). In addition, for synthetic rope with a low coefficient of friction, the size of the compression fitting must be increased. Such a rope termination has been developed by Esmet, Inc. of Canton, OH for use with some types of UHMW-PE rope (Esmet Inc., 2002) and work is currently underway to design a similar connection for AmSteel®-Blue rope.

2.7.4 Compression Fittings

Compressive fittings (rope clamps, pressed ferrules, wedged ferrules) designed for steel wire rope are also not recommended (Pilkerton et al. 2001). Steel wire rope clamps were also tried on a pilot basis. The initial tests yielded a breaking strength of approximately 60% of the manufacturer’s catalogue minimum value.

2.7.5 Epoxies

In the first OSU project, limited trials were completed with two low-temperature epoxies potted in steel ferrules. Test specimens failed at approximately 20% of minimum breaking strength at the point where the rope enters the ferrule. These results for potted end connections showed promise for use in timber harvesting. In some applications, this strength may be suitable. OR-OSHA calls for winchlines on tractors or skidders to be attached to the drums with end connections that will "breakaway" (OR-OSHA 437-007-0715(2)). For example, if a load of logs goes over a cliff and begins to drag the skidder with it, a failure in the end connection is required to release the load. More testing is needed to characterize the types and strengths of epoxies with end connections.

2.7.6 Shackles and Eye Splices

Leonard and others examined a limited number of end connections for use with guylines (Leonard et al., 2003). Buried eye splices were typically used in combination with shackles. The guylines were wrapped around a tree and then the eye was shackled back to the guyline. In addition, Leonard et al. (2003) found that a tightening, ratcheting device, such as a "come-along" could be used to tension the guylines. However, both these methods involve taking large, unadjustable lengths of rope and more hardware into the brush. Furthermore, shortening the guylines to the proper lengths by wrapping them around trees increases operational time and thus the advantages over steel wire rope are lost.

2.8 Test Standards

When reviewing literature, the standards for rope construction and testing must be examined. Test methods, measurement techniques, and a more controlled and standardized laboratory environment were reviewed.

The Cordage Institute is the recognized authority on rope construction and testing standards in the United States. The general standard, Fiber Ropes: General Standard CI 1201-96, covers characteristics and requirements for all fiber cordage ropes (Cordage

Institute, 1996). A second standard defines the procedure for test sample preparation, measurement and strength and extension testing. Rope manufacturers and other third party testing companies use the CI 1500-99 Test Methods for Fiber Rope (Cordage Institute, 1999). However, it should be noted that there is an error in Section 9.4.2 of this standard. The rate of travel of the pulling cross head during the break test should be not less than 20 seconds, not the reported "2 seconds."

Another standard for rope construction and testing is the European Standard EN 919 (European Committee for Standardization, 1995). The European Committee for Standardization is a regulating body similar to the Cordage Institute. This guideline provides documentation for the determination of physical and mechanical properties: net mass per meter, lay length, plait pitch, elongation, and tensile strength.

An additional source of information for test method standards is from the American Society for Testing and Materials (ASTM) A931-96. This test method covers tension testing of wire ropes and strands at room temperature, specifically to determine the breaking strength (ASTM International, 1996). A sister document to test the wire rope strands is ASTM D 4268-93. It specifies the procedures to determine diameter, circumference, linear density, breaking force, and elongation of non-steel fiber ropes.

2.9 Conclusions

Early in the history of synthetic rope, ropes constructed from polyester, nylon, and Aramid fibers were studied for many industrial uses. The advantages of UHMW-PE fiber rope over steel wire rope and natural fiber ropes were realized. Research into synthetic rope over the last three decades has steadily progressed into new materials and applications. There have been significant advances in rope-making technologies and discovery of new fibers to meet specific operational requirements. UHMW-PE fibers and rope-making processes were developed as a lighter yet strong alternative to steel. Synthetic rope has gained acceptance in many industries, but has remained a relatively unknown in the logging industry.

The review of the literature produced some modeling techniques for UHMW-PE synthetic rope, but not specifically 12-strand UHMW-PE. It is difficult to obtain this information because both 12-strand ropes and UHMW-PE fibers are relatively new. Therefore, some of these relationships must be adapted to suit the current needs of the project.

Although some initial studies of synthetic rope have been conducted in the early 1990's in Canada and the Pacific Northwest USA, there has not been an extensive amount of research devoted specifically to UHMW-PE and its potentials in logging. The worksite redesign grant at OSU offers tremendous potential to advance the knowledge of synthetic rope as an alternative to steel wire rope in timber harvesting applications.

Research on end connections has been extremely limited. Even in the offshore mooring and deep-sea salvage disciplines, there have not been specific studies completed in this area. In the case of logging, only steel wire rope end connections and terminations are currently the industry standard. A search of literature has found only installation guidelines, but no data from designed experiments. This lack of end connection testing documentation is a major shortcoming of all literature studied. Only different splicing techniques have been tested by rope manufacturers and offered as suggestions for end connections. There was also no literature found on the interaction of adhesives with UHMW-PE fibers. Manufacturers only recommend their product but cannot confirm its performance with ropes and fibers.

3 Materials and Methods

The goal of this investigation into end connections and terminations for synthetic rope is to meet the stated objectives of Section 1.5. This pilot study determined the feasibility of synthetic rope end connections concepts for timber harvesting systems. Although there are no scheduled field trials under the scope of this project, each concept was tested within a controlled laboratory environment for strength.

This section of the thesis discusses the design considerations specific to synthetic rope. It provides details about the materials used in end connection fabrication. Using selected design and material constraints, this section describes how each of the 15 different end connections was constructed for three different nominal diameter classes for Amsteel®-Blue: 3/8”, 9/16”, and 5/8”. Finally, this chapter discusses the statistical design, sources of variation, and the test procedures.

3.1 Design Considerations for End Connections

With each end connection, there are inherent design challenges. Synthetic ropes of various types have been around for nearly five decades. New advances are being made in polymer and fiber technology and many industries utilize synthetic rope. However, UHMW-PE synthetic rope in many applications, including logging, is yet to be fully studied. This pilot study provides insight into design considerations for end connections. The following subsections identify aspects that must be considered when designing and developing end connections for use with synthetic rope.

3.1.1 Creep

Polyethylene fibers have poor creep resistance (Warner, 1995). Creep is defined as deformation that accumulates with time (Dowling, 1993). The extension caused by a given force or stress caused by a strain in the fiber depends on the magnitude and duration each has been applied (Morton et al., 1975). When a load is sustained and then removed, there is an instantaneous extension of the rope. This total extension is divided into three categories: elastic deformation, primary creep, and secondary creep (Morton et al., 1975). Elastic deformation is immediately recoverable while primary creep is recoverable over a number of minutes or hours. However, there is still some unrecovered extension called secondary creep. The effects of secondary creep are cumulative in nature. The next time the rope is loaded, primary creep takes place at its initial rate, but secondary creep adds to the mechanical history of the rope by continuing where it left off. Thus, over the life of the rope the permanent elongation will increase.

However, most timber harvesting applications do not experience prolonged tensions. Most logging activities are dynamic in nature, meaning tensions are applied and released many times during the work day. Logs are winched to the roadside and delivered to the landing. Yarders, with large towers, control a system of cables that bring logs to the landing. However, logging operations are generally centralized at the harvest site for some time. Yarder towers can be set up for a week to two months at a time. Tailtrees, intermediate supports are rigged prior to log extraction and are taken down after the last log is brought to the landing. Thus, the static lines – guylines, snaplines, and support lines – can remain under tension for an extended amount of time. Although the tension on the static lines is well within the manufacturer specified safe working loads, tensions can reach 10-50% of the breaking strength to support logging operations.

Due to prolonged tension in synthetic rope and the introduction of heat to the system by engines and running equipment, creep must be considered in the development and analysis of end connections. Generally speaking, creep must also be considered if the operating temperature can become greater than 40% of the absolute melting temperature (Warner, 1995). For example, the absolute melting temperature of AmSteel®-Blue is between 291 and 311°F and 40% ranges between 116 and 124 °F. The onset of creep needs to be more thoroughly examined. Static line logging applications are generally only set up for a few days or a month at the most. Early investigation into these applications reveals that there may exist creep-influenced strength degradation. In fact, it is accepted among fiber manufacturers that UHMW-PE fibers only have a “fair” resistance to creep as opposed to steel, which has excellent resistance. However, exact values of creep resistance are proprietary information and commercially sensitive.

Because of limited research and field trials conducted with synthetic rope in timber harvesting, rope performance is not thoroughly characterized in all operating conditions. What is known is that as the rope is used longer, creep decreases. Consequently, the relative strength of the rope will increase because its "stretch" has effectively been eliminated. Compensation in the design of end connections is needed to account for creep. Materials that are bonded – the adhesive and nubbin – to the UHMW-PE rope should have similar creep properties. Additionally, a safety factor must be included for the expected creep under tension along with a breaking strength safety factor. A safety factor of 2:1 for creep is generally an accepted value. In other words, loads on the rope should not exceed 50% of its breaking strength to prevent the effects of creep.

3.1.2 Coefficient of Friction

The coefficient of friction is an important property of UHMW-PE to consider with end connection development. Many end connections for steel wire rope depend not only on the compressive strength of the material, but also on the frictional force caused by tension the end connection will withstand (Wire Rope Technical Board, 1993). Friction is the force that holds fibers together in a spun yarn or strands together in a braided rope (Morton et al. 1975). Because synthetic rope must meet the same strength requirements as wire rope, friction will play an important role. UHMW-PE fiber has a coefficient of friction of approximately 0.08. As a result, the coefficient of friction of synthetic rope is also quite low (0.09), and thus, there must be compensation in end connection designs for this low value. Friction is necessary in compression-based end termination designs. Frictional force equals normal force multiplied by the material's coefficient of friction. Because synthetic rope has such a low coefficient of friction, the only way to increase the frictional holding force is by increasing the normal force. These compressive forces would need to increase to provide the same holding strength as a steel wire rope connection.

3.1.3 Bending

The synthetic rope used in this investigation has 12 individual braided strands. Each of the yarns making up the strands and the strands in the rope are twisted. Twisted strand rope construction creates a structure that is more difficult to bend. However, rigidity and ultimate breaking strength are inversely related. The more twist in a rope, the more rigid it becomes, but it also loses strength. Conversely, if all of the strands were parallel in a rope, the rope would have a higher breaking strength, but it would be flimsy and almost formless. Therefore, the current twisted synthetic rope configuration already has some inherent strength loss.

Moreover, a sharp bend in synthetic rope can drastically reduce its breaking strength. In fact, any rope loaded in a bent state will break more easily than when it is straight (Morton et al., 1975). It may also reduce the life of the rope by applying tension at a bend and not in a straight-line pull. This pull puts pressure on the object about which the rope bends. Thus, the normal force from the object on the rope increases. With the increase in normal force and contact area, the frictional force also increases.

In addition, a sharper bend in the rope distributes the load less among the rest of the rope and strands. A larger bending diameter will increase contact area causing better load sharing between the strands.

The synthetic rope manufacturer has provided general guidelines for use. However, these guidelines were written with the concept of moving synthetic rope pulled over a sheave. According to the rope manufacturer, maximum efficiency and safety is achieved with at least a D/d bend ratio of 8:1 (Figure 2). The sheave diameter (D) should be at least 8 times the nominal diameter of the synthetic rope (d). The fiber manufacturer however recommends a bend ratio of at

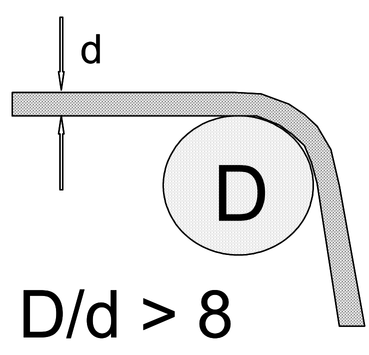

Figure 2. D/d ratio (Samson Rope Technologies C., 2003)

last 10:1, where the sheave diameter is ten times larger than the nominal diameter of the rope.

Additional testing by the manufacturer has yielded decreasing rope efficiency as the D/d bend ratio decreased. A 2:1 bend ratio resulted in approximately 65% min. rope breaking strength. For a 1:1 ratio, the synthetic retained approximately 50% minimum rope breaking strength (Chou et al., 2002).

A second D/d ratio is the ratio of the length of the eye splice to the diameter of the object over which the eye is placed (Figure 3). The D/d ratio is slightly different in this context. The D represents the length of the eye splice. The d is the diameter of the object around which the rope is placed. The synthetic rope manufacturer's catalogue recommends a minimum of a 3:1 ratio, but preferably 5:1 ratio (Samson Rope Technologies A., 2002).

The D/d bend ratio has been indirectly been tested in this project in conjunction with the pinned nubbin end connection concept. As noted, there is only data supporting specific applications. Because the end connection concept will experience only straight pull and there will are different forces and stresses associated, further examination is necessary into the lowest D/d ratio acceptable to attain safe working loads in timber harvest applications.

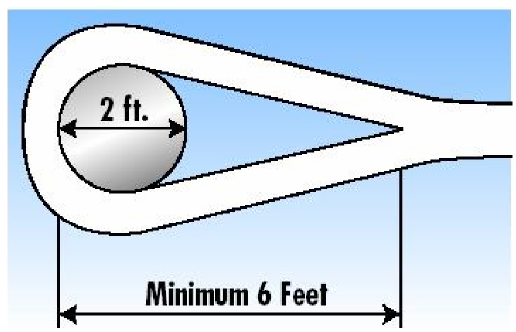

Figure 3. D/d ratio for eye splice (Samson Rope Technologies A., 2002)

3.2 Materials

The following subsections discuss the important material properties for stock and fiber UHMW-PE. Steel is another important material to consider. For an in-depth discussion of steel's material properties, refer to the Machinery's Handbook (Oberg et al., 1996).

3.2.1 UHMW-PE

Ultra-high molecular weight polyethylene is part of the polyolefin family. It is a white, semi-crystalline engineered thermoplastic. "Ultra-high", as it is commonly referred, has a molecular weight of approximately 3.1 million grams per mole (Schweitzer, 2000), giving better dimensional stability and physical properties than polyethylenes with lower molecular weight. However, with increased molecular weight and tensile strength, a special process is required to produce the material.

UHMW-PE is lightweight, easy to machine, and has excellent impact resistance. The chemical bonds in UHMW-PE fibers are constructed to withstand high tensile loading. In addition, solid UHMW-PE has different abrasion and wear characteristics. Its inherent strength and durability make solid UHMW-PE an attractive material for design concepts of end connections. Table 2 summarizes the main properties of UHMW-PE, and Table A4 in the Appendix contains a more complete list of physical and mechanical properties.

Polyethylenes are typically used in working environments containing, solvents, lubricants, acids – places where corrosion resistance is necessary. It is routinely used in storage tanks or piping. Because of its low coefficient of friction, UHMW-PE finds applications where slip plates or a clean, slick surface is required. It is also found in wear parts such as sheaves, joints, and bearings or in material handling systems.

Table 2. Key Properties of ultra-high molecular weight polyethylene

- Good abrasion resistance
- Excellent impact resistance
- Lightweight
- Easily heat fused
- High tensile strength
- Low moisture absorption
- Nontoxicity
- Non-staining
- Corrosion resistance

(Schweitzer, 2000)

The resistance to chemicals of UHMW-PE is quite good. It also has <0.01% water absorption in 24 hours. However, UHMW-PE's ultra-violet light resistance is only fair for continuous and prolonged exposure to sunlight at 73°F. UHMW-PE is also six times more abrasion resistant than steel. In addition, it has no cold embrittlement as it works from -155 °F to 180 °F (www.ultrapoly.com, 2002).

3.2.2 UHMW-PE Fiber and Rope

Although it is chemically the same material, the solid UHMW-PE and UHMW-PE fibers do maintain slightly different values for the material properties. However, the key properties shown in Table 2 sill apply.

The molecular structure of UHMW-PE fibers orients and aligns the molecules through a gel-spinning and drawing process that increases the molecular density. The fibers are up to 85% crystalline and have a 95% parallel orientation, which produce a plastic fiber with high tensile strength properties (www.goodfellow.com, 2003).

There are many high-performance, high density polyethylene fibers in use in industrial applications. Spectra® (Honeywell Corporation) and Plasma® (proprietary recrystallization process of Spectra®1000 fibers, Puget Sound Rope) fibers are well known commercially available products.

The fibers that make up the synthetic rope used in this investigation are Dyneema® SK75 1760 dTex. Dyneema® fibers are the proprietary product of DSM of the Netherlands, and are the strongest fibers in the world. They are 15 times stronger than steel fibers of the same weight and are 40% stronger than Aramid fibers (DSM, 2004).

Internal investigations by Samson Rope Technologies have determined that ropes constructed with Dyneema® fibers are superior to other commercial high-density polyethylene fibers (Samson Rope Technologies B., 2003). In tests of 12 strand braided rope conducted by Samson Rope Technologies, AmSteel®-Blue rope constructed of Dyneema® SK75 fiber had a better strength to weight ratio than ropes constructed with

Spectra 1000 fibers. Futhermore, AmSteel®-Blue had a longer fatigue life than Plasma® rope from Puget Sound Rope. Table 3 lists the chemical resistivity of these fibers and Table A1 in the Appendix lists key properties.

Table 3. Resistance of fibers to various chemicals

	Dyneema SK75	Aramid
Distilled water	0	0
Sea water	0	0
10% detergent	0	0
Hydrocholoric acid (pH=0)	0	2
Nitric acid (pH=1)	0	2
Ammonium hydroxide	0	0
Sodium hydroxide (pH>14)	1	1
Gasoline	0	0
Kerosene	0	0

0 = unaffected 1 = slightly affected 2 = seriously affected

(Adapted from DSM B., 2002)

For rope, Dyneema® fibers are twisted into yarns. The yarns are twisted together to compose each of the twelve strands. Finally, the strands are braided together to form the AmSteel®-Blue rope. Not only is the rope extremely light and abrasion resistant, but the construction discourages rotation in the rope. This means that during use, the rope strands will remain aligned and not rotate. Furthermore, the rope has high rigidity and low stretch. According to the rope manufacturer, steel wire rope stretches approximately 0.2% per 100 feet, while the synthetic rope stretches 0.70% in 100 feet at 20% of break strength. Although, synthetic rope has over three times the stretch of wire rope, the total stretch is still less than 1 foot in 100 feet. Figure 4 compares the breaking strengths of UHMW-PE synthetic rope, extra improved plowed steel wire rope, and swaged steel wire rope for five comparable sizes of ropes.

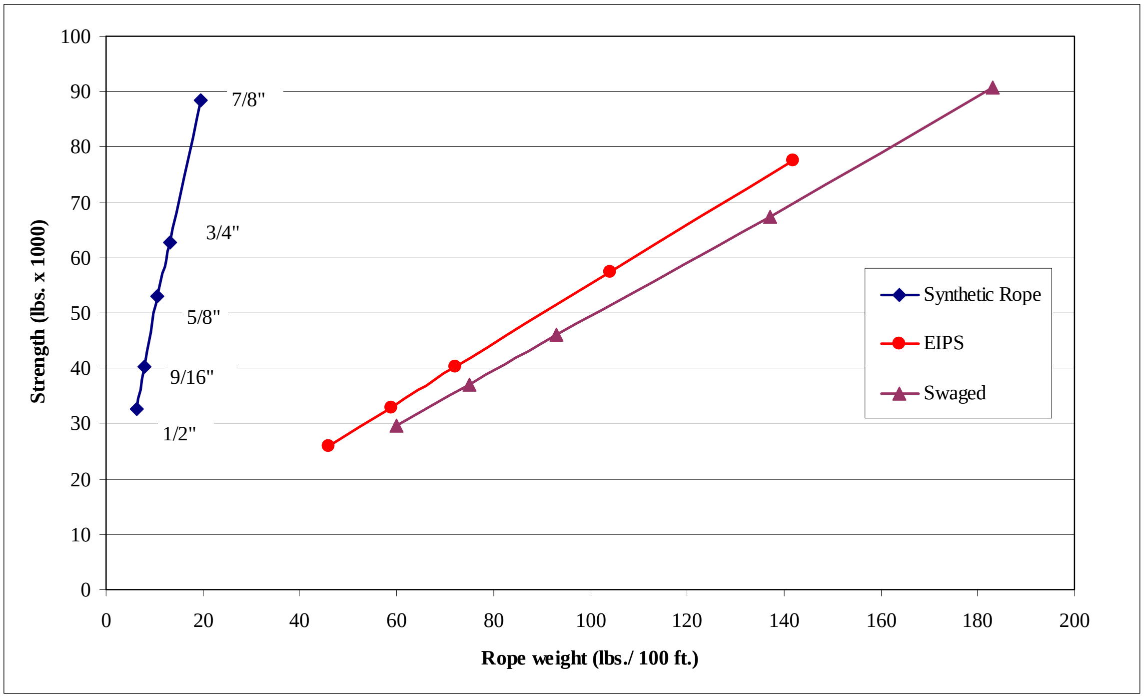

Figure 4. Breaking strength vs. rope weight

Due to the low weight and stretch, ropes constructed from UHMW-PE reduce the amount of “snap-back”. Snap-back is an effect when a length of rope fails. Kinetic energy is equal to one-half the mass of the object multiplied by square of the velocity. Because the mass of the UHMW-PE rope is much less compared to steel wire rope, the energy released when the rope fails is also considerably less.

3.2.3 Adhesives

Some end connection designs do not rely on mechanical fittings to attach the rope. End connections can be designed that utilize chemical bonds from an adhesive substance. Unfortunately, the low coefficient of friction and other chemical properties of polyethylene make synthetic rope resistant to most chemical bonding agents. Two industrial adhesives were chosen because each was specifically designed to bond with polyethylene. They were employed to chemically bond the synthetic rope to the test end connection.

In addition, the low melting temperature and unique thermoforming process of the strong bonds characteristic of UHMW-PE make bonding especially difficult. These chemical and physical characteristics of the synthetic rope make it especially challenging for traditional structural adhesives to attach synthetic rope to end connections.

The first adhesive chosen was Socketfast® Blue A-20 manufactured by Phillystran, Inc. of Montgomeryville, PA. The Socketfast® Blue is a two-component thermoset resin composition. It was designed specifically for potted terminations and polyethylene fiber synthetic rope. In addition, Socketfast® Blue is the only adhesive identified by both the fiber and rope manufacturer to provide a potentially strong bond to the UHMW-PE rope. Table 4 shows the key properties of the Socketfast® Blue adhesive.

Table 4. Phillystran Socketfast® Blue A-20 properties

Viscosity, mixed resin and hardener	200-400 cps
Working life, 73 deg. F	20-30 min.
Cure time (room temp., 73 deg. F)	24 hours
Compressive strength	>10,000 psi
Compressive modulus of elasticity	5.0 x 105 psi
Heat distortion point	150 deg. F
Shore D hardness	85 minimum

(Phillystran, 1997)

Compressive modulus of elasticity = ratio of normal stress to its corresponding strain for compressive stresses below the proportional elastic limit of the material (Conrad et al., 2004).

Shore D hardness = resistance of a material to indentation when a static load is applied. It measures the depth of penetration of an indenter on a scale from 0 to 0.1” (www.machinedesign.com, 2004).

Viscosity is a measure of the “fluidity” of the fluid or adhesive in this case (Young et al., 1997) and is measured in centipoises (1 pound/foot/second = 0.0006720 centipoises). This low-viscosity adhesive itself is a styrene. Therefore, it will heat up as it sets. Furthermore, the styrene monomer is glassy and brittle after it sets. The main properties of this adhesive are shown in Table 4.

The second adhesive used was the Scotch-Weld™ DP-8010 from 3M Corporation, St. Paul, MN (see Table 5). Although not specifically developed to adhere only to UHMW-PE, this product was recommended as one of few products that does bond to UHMW-PE. This structural adhesive has the ability to bond to dissimilar substrates and to polyolefins (3M, 2003).

The application is a one-step process because the accelerator and base are mixed at the proper 10:1 ratio in a self-contained mixing nozzle. The hand-held applicator provides an easy way to coat the rope and end connection. This adhesive was attractive for use in bonding the synthetic rope to the end connections because it is resistive to water, humidity, gasoline, and lubricants. The one-step applicator process would allow for easy potting in the field or workshop only one day before use on the worksite. Finally, the adhesive is an amine, which although it is not as hard as the Socketfast® Blue, it is more workable. When the Scotch-Weld™ is fully cured, it will not be as brittle as the Socketfast® Blue and would resist repeated working of the rope and end connection. Table 5 shows the key properties for the Scotch-Weld™ adhesive.

Table 5. 3M Scotch-Weld™ DP-8010 properties

Viscosity, Base/Accelerator	17,000/27,000 cps
Working life, 73 deg. F	10 min.
Cure time (room temp., 73 deg. F)	24 hours
Compressive strength	< 2,000psi
Compressive modulus of elasticity	7.0 x 104 psi
Heat distortion point	93 deg. F
Shore D hardness	70-80

(3M, 2003)

3.3 End Connection and Termination Designs Tested

The following subsections describe the end connections for synthetic rope that were tested under this project. All test specimens used new synthetic rope. Table 6 lists the end connections tested under this project. A detailed description of the *spliced*, *adhesives*, and *dry hardware* end connections can be found in the next subsections.

Table 6. End connection designs

	Spliced
1	Buried Eye Splice
2	Whoopie Sling
3	Long Splice
4	Y-Splice
	Adhesives
5	Steel Nubbin w/ Socketfast Blue A-20
6	UHMW-PE Nubbin w/ Socketfast Blue A-20
7	Steel Nubbin w/ Scotchweld DP-8010
8	UHMW-PE Nubbin w/ Scotchweld DP-8011
9	Notched Steel Nubbin w/ Socketfast Blue A-20
10	SEFAC
	Dry Hardware
11	Rope Clamps
12	Pinned Nubbin
13	Knuckle Link
14	Pressed Nubbin
X	Truck Wrappers (for 3/8" diameter only)

3.3.1 Buried Eye Splice

In this project, the buried eye splice is the control treatment, or benchmark. An end connection or termination is needed with the synthetic rope to use it in harvesting systems. The synthetic rope is essentially modified anytime it uses a splice or end connection. The rope manufacturer identifies the buried eye splice as retaining the most breaking strength when the rope is modified compared to any other end connection.

Thus, the buried eye splice becomes the benchmark to compare all end connector concepts. In this project, because the rope in a timber harvesting system is only as strong as its end connection, the breaking strength of the buried eye splice will be the effective 100% breaking strength of the rope. It is a simple splice to construct and is used in all diameter classes, but specifically for 3/8”, 9/16”, and 5/8” nominal diameters in this study. Figure 5 shows the eye of a completed buried eye splice.

Figure 5. Buried eye splice

3.3.2 Whoopie Sling

Loggers do not like to carry more equipment than required for a job. Cable operations are set up on steep slopes and over long spans. Traditionally, heavy cast steel blocks, shackles, and steel wire rope straps would be carried into the brush. Bringing this hardware out to the tailtree or intermediate support tree can be an arduous task. In fact, this equipment can be so heavy and bulky that more than one trip is often required.

Currently, steel wire rope guylines and support lines are the industry standard. Each is constructed to a specify length to meet job requirements. When the length does not meet the jobsite specific attributes, a second rope length is shackled to the guyline or the guyline is wrapped around the tree and terminated with forged steel rope clamps. The more hardware in the woods, the more weight and energy are expended to bring it in and out of the woods.

The Whoopie Sling concept has been developed to alleviate such a situation. Not only is the synthetic rope approximately seven times lighter than the steel wire rope guylines of the same diameter and length, but the Whoopie Sling is an adjustable sling.

The adjustable strap configuration allows the user to move from one guyline length to another without the addition of hardware or extra slings.

The Whoopie Sling is an adjustable strap concept made out of the same synthetic rope (see Figure 6). One end of the rope has a modified Brummel eye splice that will connect to the tower of the yarder, intermediate support jack line or a guyline. The main section of rope is used to create a length of the user's discretion. The free end is passed back through the middle of the rope, similar to the Buried Eye Splice procedure. The tail is then terminated with a butt-splice.

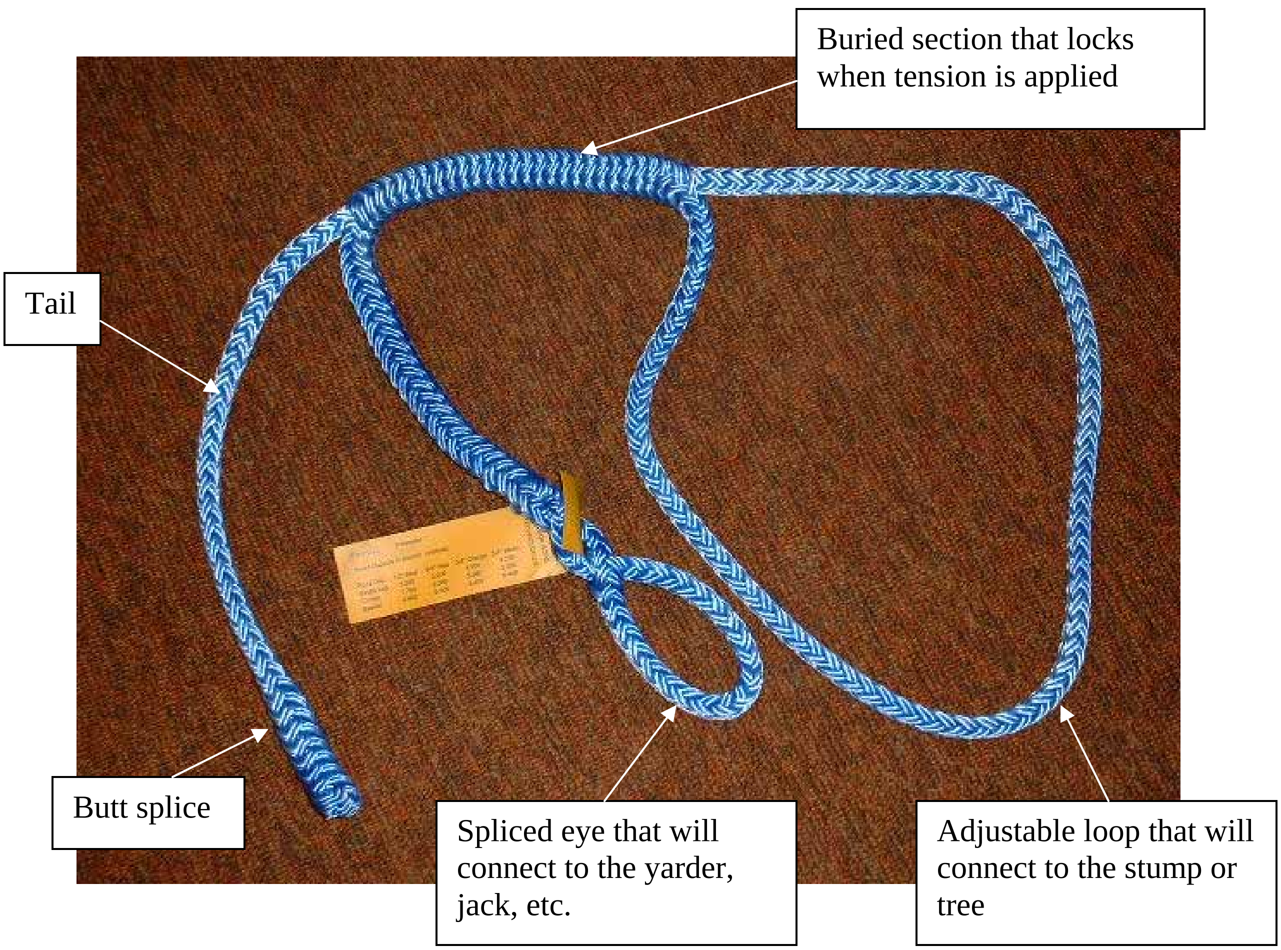

Figure 6. Whoopie Sling

The length of the Whoopie Sling can easily be adjusted. The user must pull on the loop to add length. Conversely, to decrease the length of the Whoopie Sling, the user simply pulls on the tail. The Whoopie Sling concept is based on the same constrictive principle used in the other splices. When tension is applied to the line, the rope constricts and grabs the buried section and the strap is locked into position. When tension is released, the sling is easily adjusted to a new length.

3.3.3 Long Splice

The long splice is used to join two pieces of synthetic rope together by a simple splicing technique. As discussed previously, knots significantly compromise the strength of the rope and thus are not an adequate way to connect two ropes together. In the case of the long splice, the ends of each of the ropes are tapered from 12 strands to six strands in a similar fashion as the buried eye splice (see Figure 7). Then, the end of rope 1 is threaded into a section of rope 2 (Figure 8). Additionally, at the same point, rope 2 is threaded into rope 1 (see Figure 9). Figure 9 shows the finished long splice using new and used rope.

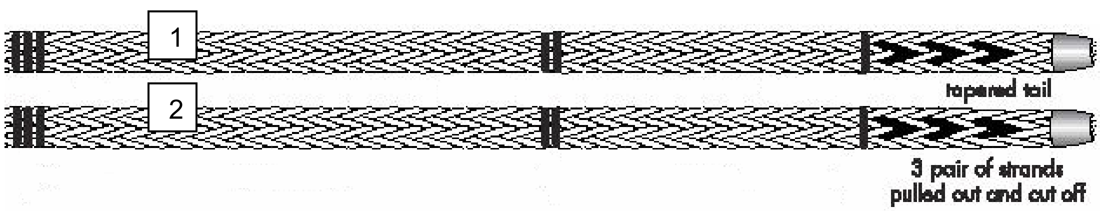

Figure 7. Taper procedure for long splice (Samson Rope Technologies A., 2002)

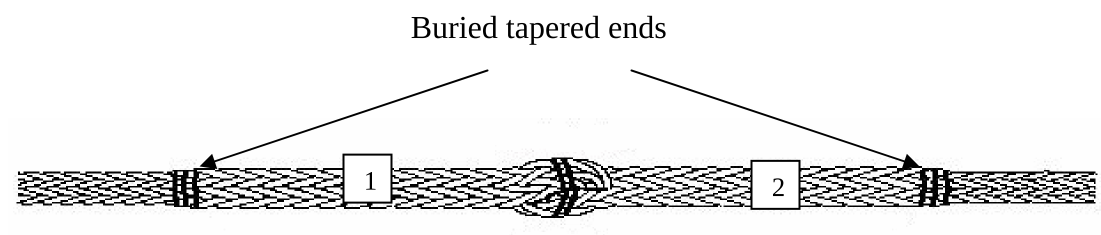

Figure 8. Finished long splice (Samson Rope Technologies A., 2002)

The long splice may be performed on used or new rope. As with the buried eye splice, when tension is applied to either end of the rope, the rope compresses on itself and holds.

Figure 9. Finished long splice

3.3.4 Y-splice

The Y-splice was derived as another solution to the problem of adjustable rope lengths (Figure 10). The Y-splice was created so that the user could bring one long rope with eye splices at each end into the field. Knowing that this length of rope works only for a distinct number of rigging scenarios, a second length of rope can be spliced into the main section of the rope. The separate length of the rope has a buried eye splice at one end. The tapered end can then be inserted at any point on the sling to add or subtract length to fit the particular guyline requirements.

The Y-splice is created similarly to the aforementioned splices. The main section of rope is a buried eye splice at each end. A separate length of rope is created with a buried eye splice at one end. There is a 50% taper from 12 strands to six strands at the free end of the rope. This free end is then inserted into the main section of the rope at a desired point. The main section of rope and the newly connected section of rope form a "Y". Tension on the Y-splice compresses the ropes together for the holding strength.

Figure 10. Y-splice

3.3.5 Steel Nubbins with Two Adhesives

The nubbin (also called a "ferrule") is a common and versatile end connection for use with steel wire rope in logging. It is a quick connection for use with yarders, carriages, and winch drums. An operator can easily insert the nubbin into a "ferrule pocket" on the drum, add tension, and secure the wire rope to the drum.

The nubbin is not only used in running line applications, but also in static line applications. It is used to connect guylines and support lines to additional lengths of rope. For example, a guyline is to be set up using a horizontal distance of 120 feet and there is only 85 feet of guyline. An additional length of rope with a steel nubbin attached can quickly be added to the system by using a double-ender hook (Figure 11).

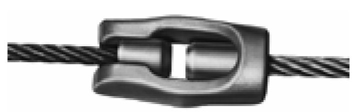

Figure 11. Double-ender hook showing nubbin connection

This low-tech connection is one of the most widely used connections in logging. Due to its availability and material properties, the ferrule was selected for use with synthetic rope. The steel B-5 nubbin has a tapered inner wall, which produces compressive stresses on the wire rope as a tensile load is applied axially. It is a quick connection that can easily slide into place. The nubbin is locked in place when tension applied to the line.

Due to the lack of heat resistance of the synthetic rope (T_g = 150°F), the conventional method for connecting steel wire rope to the steel nubbin with a zinc compound is not appropriate. The molten zinc would not only melt the UHMW-PE fibers, but it would not bond with them as well. However, a similar concept for the synthetic rope replaced the zinc compound with an adhesive.

Both the 9/16" and 5/8" diameter synthetic rope were used with the tapered wall B-5 nubbin. Using the manufacturer's specifications for steel wire rope, the equivalent nominal diameter synthetic rope was used. The free rope end is fed through the smaller hole of the ferrule. The exposed strands were unraveled and frayed. The fibers inside the nubbin were coated with an adhesive.

This study employed two different adhesives. The Socketfast® Blue A-20 was used to bond the synthetic rope to the steel and UHMW-PE nubbins. The Socketfast® Blue A-20 is a low-viscosity styrene adhesive and did not have a specific applicator or application process. Figure 12 shows the catalyst (right) that came with a pint of resin (left). The two compounds were mixed together and then applied to the test specimens in accordance with the manufacturer's application procedures

Figure 12. Socketfast® Blue A-20

The second adhesive is a two-part acrylic from 3M Corporation: Scotch-Weld™ DP-8010. This amine adhesive has a significantly higher viscosity than the Phillystran. In addition, the adhesive required a brush- or spray-on primer of 0.0001" thickness for steel surfaces. The specially designed adhesive application system (applicator gun, mixing nozzles, and plunger) provided a simple method for applying the adhesive to the synthetic rope and nubbins. The self-contained application system (Figure 13) omitted user error in mixing. A 10:1 mixing nozzle attached to the spout of the cartridge. A 2-ounce cartridge of the adhesive connected to the front of the gun. The nozzle was trimmed to provide a 1/16" diameter bead size of adhesive.

Figure 13. 3M Scotch-Weld™ DP-8010

Using this bead size of 1/16”, the nozzle could be inserted into the middle of the rope. Adhesive was also applied to the yarns as the strands were opened and frayed out. Moreover, the structural adhesive is granular and viscous (17,000 centipoises for base and 27,000 centipoises for accelerator) enough to collect inside the nubbin and within the rope strands and yarns. Additionally, the manufacturer recommended applying metal primer to the steel nubbins prior to potting.

The two obvious differences in the adhesives are the viscosity of the adhesive and the potting system. The Socketfast® Blue A-20 adhesive was extremely less viscous at only 200-400 centipoises. For this reason and because the catalyst was mixed differently, a different potting technique had to be employed (Phillystran, 1997).

All test specimens were prepared according to the standardized procedures. However, after the samples were pulled from the mold, it was evident that the adhesive coverage was not uniform. Figure 13 shows the differences in potted end connections using the same procedure. Most specimens appeared to have good adhesive coverage down to the fiber level (Figure 14B), but some had discontinuous coverage with differing thicknesses Figure 14A).

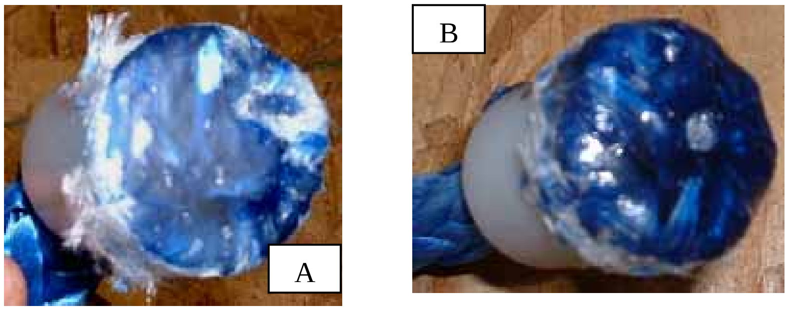

Figure 14. A) UHMW nubbin with less adhesive coverage
B) UHMW nubbin with more adhesive coverage

The work life of the Socketfast® Blue A-20 adhesive quoted by the manufacturer was 20-30 minutes, but experience in the laboratory was that for the first 30-35 minutes, the adhesive was still runny. Work life of the adhesive could be extended by applying the adhesive in a container with limited exposure to air. Air exposure directly reduces work life. However, as the adhesive reaches the terminus of its work life, it quickly coagulates. At this point, it turns into a jelly and should not be used for the end connections.

Due to the low viscosity the Socketfast® Blue A-20 adhesive, the end connections should be potted upside down, otherwise the adhesive will run down exterior and interior strands of the rope. Preliminary potted trials were conducted to determine the best way to pot the test samples. Although plastic zip-ties and molding clay were used to prohibit adhesive from passing through the rope interior, there was still leaking out the bottom of the nubbin. Due to the chemical composition of the Socketfast® Blue A-20 adhesive, care must be taken in determining materials to be used as potting molds because the styrene monomer may melt the mold as it pots.

From the outside, it appeared that there was adequate coverage. As the nubbins were inspected 72 hours following potting, the adhesive was not brittle and felt similar to a solid nylon.

3.3.6 UHMW-PE Nubbin With Adhesives

This test concept is essentially the same as the steel nubbin with adhesive; only the nubbin material has changed. The UHMW-PE nubbin is manufactured with the same dimensions as the steel B-5 version. Both the B-5 and UHMW-PE nubbins were tested with the same adhesives. Figure 15 shows the B-5 steel nubbin with the UHMW-PE nubbin.

Figure 15. B-5 Steel nubbin and UHMW-PE nubbin

3.3.7 Notched Steel Nubbin With Phillystran Adhesive

The nubbin used in this end connection is a modified B-5. A small “step” was made in the tapered wall. The notch was machined into the nubbin to allow for better compression of the rope and a higher breaking strength. In addition, the step also provides an extra lock when tension is applied to the rope. The synthetic rope was threaded through the nubbin, the strands were unraveled and frayed. The adhesive was then poured to fill the nubbin. As the adhesive cures, it bonds to the rope and to the nubbin walls. When straight tension is applied, the wall should provide an additional normal force upward.

Not only does the notch slightly increase the bond area, but also it provides a catch point, a bench, for the hardened epoxy to bond. As tension is applied, this notch makes it more difficult for the rope and adhesive to pull through the nubbin. Unlike with the smooth, continuous taper in the nubbin interior, the rope and adhesive must deform more to pass through the notched nubbin. Therefore, it can hold more load than the B-5 nubbin. Figure 16 shows the machined B-5 notched nubbin and Figure A8 in the Appendix shows the design and dimensions.

Figure 16. Notched nubbin

3.3.8 SEFAC™

The SEFAC™ design was provided by the fiber manufacturer. Various potting techniques had been considered by DSM for synthetic rope terminations. However, conventional designs had not been designed for high modulus fiber ropes with high strength and a low coefficient of friction. The SEFAC™ was designed to combine the strength of a compression fitting with the additional holding capacity of a structural adhesive. It adds two additional coupling collars that compress the rope against tapered walls.

This end termination was a two-piece system and its dimensions depend on the diameter of the rope. It had a steel socket and a tapered steel spike inserted into the center of the rope and into the socket. The initial drawback to this system was that it was a two-part system. In addition to the design, the fiber and rope manufacturer recommended the structural adhesive, Socketfast® A-20. The immediate drawback to this two-part system was that it was difficult to pot. The Socketfast® A-20 initially had the viscosity of a thin syrup.

The socket was potted upside down. The rope is threaded through the socket, the strands are unraveled and frayed. The Phillystran adhesive is then poured into the connection and the spike added. The spike is pushed into the rope to compress the rope to complete the compression fitting. Figure 17 shows the SEFAC™ concept. Although the rope at the end of the socket was tightened with a zip-tie and modeling clay was used to plug the gap between the rope and the socket, the Socketfast® Blue A-20 dripped through the inner strands of the rope. As a result of low viscosity, the adhesive covered as much as 8” below the end connection. The adhesive hardened this section of rope and seemed to make the rope sample brittle and perhaps more susceptible to failure under cyclic loading conditions.

Moreover, as the adhesive dripped out of the bottom of the socket and into the inner fibers and strands of the rope, the amount in the socket decreased. It was impossible to tell how much adhesive remained in the socket. As the adhesive dripped out, there was less bond strength between the adhesive and the socket walls and spike. After 72 hours, the terminations were checked. At this point, all adhesive set up, dried, and the gap at the bottom of the socket between the rope and the socket was plugged. Additional adhesive was poured into the socket until it was full.

Under this potting methodology, it was difficult to cover the internal fibers of the strands with the Socketfast® Blue A-20. The strands had to be frayed in order to increase adhesive coverage, bond area, and therefore bond strength. However, the rope could not be completely frayed inside the socket. It needed to have some form to retain strength of the rope construction. Completely undoing the unique 12-strand braid might weaken the rope under cyclic loading conditions.

Figure 17. SEFAC™

3.3.9 Rope Clamps

The wire rope clamps used in this pilot study were the standard Crosby® Clips used with steel wire rope. The quick connection was specifically designed for in-field installation. Made of forged galvanized steel, each clip is resistant to corrosion and rusting.

Wire rope clamps are u-bolt clips placed in series along the rope. The Synthetic rope is wrapped over itself, leaving enough rope for an eye. The rope that is overlaid on itself is clamped together using the u-bolt clips. The clips are properly spaced according to spacing dimensions found in the Wire Rope Users Manual (Wire Rope Technical Board, 1993) and tightened with a torque wrench to 45 foot-pounds (less than the 90 foot-pounds recommended because higher torque was not feasible). The Oregon OSHA Forest Activities safety code states that improved plow steel wire rope requires the use of three clips for diameters between 3/8" and 5/8", but also requires an extra clip added when "high strength wire rope" is used (OR-OSHA, 2003). In order to better test synthetic rope as a substitute for steel wire rope in forest operations, identical rigging practices were used. Therefore, four clips were used at a spacing of 4". Figure 18 shows a picture of this end connection.

Figure 18. Wire rope clamp

3.3.10 Pinned Nubbin

The pinned nubbin concept was developed using early research by the Synthetic Rope Research Team. The eye splice of the sample was fed into the nubbin and secured with a bolt that was fed through a bored hole in the nubbin. The rope was pulled tight so that the top of the eye was bent around the bolt. Initial trials of the 5/8" diameter rope prior to this study reached 39% of the catalogued minimum breaking strength (unpublished data). The results from further exploratory testing with 9/16" diameter rope in this study with nubbins are found Table 7 below.

Table 7. Exploratory testing results with bolts

Diameter	End Connection	Breaking Strength (lbs.)	% of Catalogue Minimum	% of Catalogue Average
9/16	B6 Nubbin with 1/2" Grade 8 Bolt	23077	57%	52%
9/16	B5 Nubbin with 1/2" Grade 8 Bolt	28699	71%	64%

The feasibility and breaking strength of this concept warranted further investigation under the scope of this project.

The pinned nubbin connection is a dry end connection, meaning it requires no adhesive only a mechanical means to attach the rope. The buried eye splice achieves the highest breaking strength, but does not work in every timber harvesting application.

To provide more compressive strength than the B-5 nubbin, a new socket was fabricated to use with the 5/8" and 9/16" synthetic rope. Figure 19 shows a diagram of how the eye splice of the rope is tightened, and Figure 20 shows the fabricated piece. Dimensions can be found in Figure A7 in the Appendix.

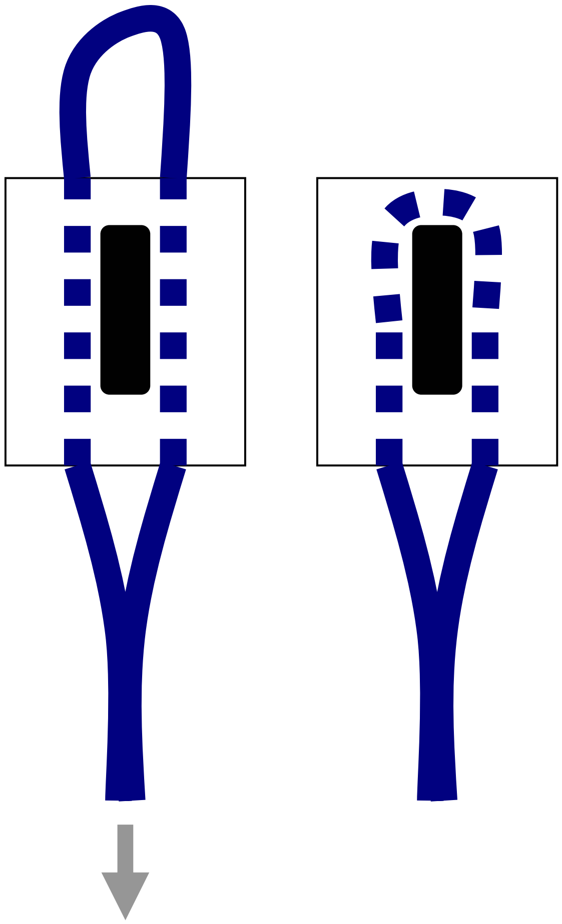

Figure 19. How the pinned nubbin works

Figure 20. Pinned nubbin

In order to keep the new nubbin as close to the B-5 dimensions as possible, this specific design relied heavily on material properties and heat treatment. When a load is applied to the rope, there is a substantial bending stress in the pin. To reduce deflection, a larger pin was needed than earlier bolts tested. As a rule of thumb, the larger the diameter of a pin, the more bending it can withstand. However, a larger pin would fill more of the inside volume of the socket and not allow the rope to fit inside the nubbin. Keeping all of the design constraints in mind, a new pin was designed. At the tested end of the specimen, there will be a buried eye splice. The synthetic rope will be threaded through the nubbin and the eye of the buried eye splice will be locked into the nubbin when the pin slides through the nubbin and through the eye of the rope.

3.3.11 Knuckle Link

The knuckle link was developed from a simple concept. Chain links can have relatively high tensile strength if the cast pieces are hardened through heat treatment. Not only do the chain links have high tensile strength, but also their material properties lend them to having high compressive strength. Using the strength advantages of a buried eye splice coupled with a quick connection, an initial concept was constructed with a small Grade 8 bolt welded across a chain link.

The idea was promising as it yielded approximately 85% breaking strength before the bolt failed. However, a better design was needed. The connection needed to be a single piece as the introduction of additional parts and materials increases tolerances and room for error. In addition, the chain link could not be used because the link was already heat treated. Weld points further weaken the material. Furthermore, the weld and material surrounding it become increasingly weak and prone to cracking when the part is heat treated.

Although the initial concept was not a sound design, it led to the development of the knuckle link (shown in Figure 21). This end connection for both 9/16" and 5/8" diameter synthetic rope was machined from a single piece of stock. The part was machined from A4 steel and then heat treated to a hardness of Rockwell_C 59. Dimensions can be found in Figure A6 in the Appendix.

Figure 21. Knuckle link

In addition, the choice of material to be heat treated is important. The initial design concept was modeled after a heat treated chain link with normalized round stock welded to it. However, welding a piece that is already heat treated is difficult and reduces its strength. If the piece is heat treated and then welded together, it cannot be heat treated again to increase strength. The weld is a weak point and it is extremely difficult to heat treat.

The design was modified in order to machine it from a single piece of stock. It was first attempted with solid 4140 Steel stock. 4140 Steel has good compressive and tensile properties. Extrapolating its use in similar applications, the normalized 4140 stock was heat treated. As a result of this heat treatment, the part developed a hairline crack, an obvious point of failure. This result shows that not only is the design important, but the knuckle link needed to be A4 grade steel.

The knuckle link is attached to the synthetic rope using an eye splice. As the rope is being spliced, it is first passed up through one hole, over the bar, and passed back down through the other hole. Then, the eye splice can be constructed with the knuckle link attached.

The knuckle link is a durable quick end connection that was designed to be used for static and running line applications. It is spliced directly into the rope and will not fall off when taken into the woods. It is also lightweight and can fit easily in a pocket. The major drawback with this design is that it leaves the rope exposed. Bending a rope over the bar puts a large stress on the rope and individual strands at that point.

3.3.12 Pressed Nubbin

The pressed nubbin concept was derived directly from steel wire rope applications (Figure 22). A hydraulic press is used to compress the steel nubbin onto the wire rope. Similarly, the same steel nubbins that correspond to 9/16” and 5/8” diameter wire rope were pressed onto the synthetic rope at 1800 psi using a 500-ton Esco hydraulic press (Black, 2004). No lubricants or tape were used on the rope so as to affect the performance of the test specimen during the break test.

Figure 22. Pressed nubbin

3.3.13 Truck Wrappers

The synthetic rope truck wrapper is a design similar to the steel wire rope truck wrappers (Figure 23). In the case of the synthetic rope truck wrapper, 3/8” synthetic rope is substituted for the 3/8” steel wire rope. For our tests, the 12 foot synthetic rope has a buried eye splice connected to a one-foot section of 5/16” chain at both ends.

Figure 23. Truck wrapper

3.3.14 End Connection Fabrication

All spliced end connections were constructed in the test laboratory using the rope manufacturer’s procedures. B-5 nubbins, 9/16” and 5/8” rope clamps, and the 5/16” chain for the truck wrappers were purchased from the local rigging shop.

Some end connections required fabrication: SEFAC™, UHMW-PE nubbin, notched nubbin, pinned nubbin, and knuckle link. These concepts were manufactured within specified tolerances at the machine shop at the Forestry Research Laboratory at Oregon State University. Completed products were then thoroughly inspected for quality. The dimensions for the final designs can be found in the Appendix.

3.4 Research Design

3.4.1 Choosing Test Rope Diameter Classes

In order to provide a thorough analysis, a proper statistical procedure for rope sampling and testing was also established. This investigation of end connections and terminations for synthetic rope is a pilot study. The purpose of this study was to determine which concepts are suitable for use in timber harvesting. Therefore, it was unnecessary to test all diameter classes of ropes. The study design required a representative sample of the diameter classes common to many logging applications.

Due to budget and rope quantity constraints, three rope diameters were tested. These nominal diameters, 3/8”, 9/16”, and 5/8” are common for many logging applications that require steel wire rope. The study was designed so that that 5/8” diameter synthetic rope guylines could be directly substituted for 5/8” steel wire rope.

These three diameters represented rope sizes that are readily available from the manufacturer and their steel counterparts are commonly found on logging operations. There were no modifications needed to the existing product, as the product was constructed the same as quantities commercially available. If the tested rope diameters were too large or too small, the synthetic rope could not be compared to the field research underway by project cooperators.

The proposed test laboratory was also considered. There were physical constraints on the size and length of rope that could be tested due to the data acquisition systems and the test apparatus. Break testing capacity was constrained by the maximum tensile load that the hydraulic ram could generate and the length of stroke for the hydraulic cylinder. The amount of rope needed for each splice and test specimen is directly proportional to the nominal diameter of the synthetic rope. With the laboratory workspace and safety constraints as primary concerns in rope size determination, smaller diameter classes were used in the study.

3.4.2 Spool Allocation and Variability Control

The synthetic rope for research from the manufacturer was delivered in specified quantities. The quantities of rope were separated and rolled onto spools. Because the rope was not one continuous length, but instead a number of separate spools for each diameter class, the end connections (treatments) were allocated to the appropriate diameters and spools. Each spool represented a separate production run, constructed at a different time.

The delivered product is an engineered product constructed under corporate and ISO 9001 quality standards. As with any engineered product however, there will be variability. All engineered parts and finished products are produced within a set of pre-approved standards and tolerances. If the product fails to meet the quality standards set forth by the company and/or customer, then the product is rejected. The same principle is true for the synthetic rope used in this research.

It is important to explain and control the variability of the incoming rope product. Due to manufacturing, fiber, and rope tolerances, the product delivered may not have equal breaking strengths to that of every spool. Some fibers or strands might be slightly smaller or have a slight divergence in twist. The fiber, yarn, and strand interchanges are located at different places within each rope. The Samthane® urethane ultra-violet protectant coating is applied manually. Coating quality and thickness can vary slightly. From a rope construction perspective, each of the rope spools was created within manufacturer specifications. The Samthane® coating process is done manually and therefore, each of the spools had a slightly different amount applied. As a result of the possible differences in rope quality, the manufacturer tested each finished batch of rope to determine if the minimum breaking strengths were met. A certified break test report was provided with each spool delivered.

According to manufacturer specifications, the catalogue minimum breaking strength is two standard deviations below the catalogue average breaking strength. Although the rope may meet the minimum breaking strength and fall within the distribution of breaking strength, the research rope will have some strength variability. The goal of this project was to study the effect of the end connection on the rope, not investigate the quality assurance procedures of the manufacturer. Accordingly, a research design was used that accounted for the variability of the rope spool to spool interaction.

3.4.3 Randomized Complete Block Design

A randomized complete block (RCB) experiment is a design where the experiment space is subdivided into blocks of experimental units. The units within each block are more homogeneous than the units in the different blocks (ASTM International B., 2002). This design is used to control some of the variability that may exist with the incoming synthetic rope from the manufacturer. The study considers three separate experimental units: the 3/8”, 9/16” and 5/8” diameters. Each of these units is grouped into five separate blocks, one block for each spool. Due to this blocking, the block-to-block variation does not affect treatment effect estimates (Ramsey et al., 2002).

Each of the five blocks have different treatment combinations or end connections. The 5/8” diameter experimental unit has 14 different end connections and the 9/16” diameter experimental unit has 12 different end connections. The design is “complete” because the block contains all of the treatments. The RCB design is set up so that the rope will be tested with each of the end connections and replicated five times.

A nuisance factor is defined as a factor that probably has an effect on the response variable, but the researcher is able to measure (Montgomery, 1997). In the case of a RCB, this factor may be unknown and/or uncontrollable. Randomization is used to protect the statistical analysis from such nuisance factors. To completely randomize this experiment, the order of rope lengths cut from the spool was pulled out of a hat.

Table 8 and Table 9 show the experimental blocks. Data from break testing from the corresponding spool and end connection were then organized into the cells of the table.

Table 8. Randomized complete block design for 5/8" diameter

	5/8" Diameter													
End Connection	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Spool														
1														
2														
3														
4														
5														
	Breaking Strength (lbs.)													

Table 9. Randomized complete block design 9/16" diameter

	9/16" Diameter													
End Connection	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Spool														
6							N/A	N/A						
7							N/A	N/A						
8							N/A	N/A						
9							N/A	N/A						
10							N/A	N/A						
	Breaking Strength (lbs.)													

For this study, what is important is the number of subplots, or number of spools. Each spool would consist of synthetic rope constructed from entirely separate production runs. Because of the quality assurance concerns of the incoming product, it was necessary to devise a study that would use more replicates of the same end connections, but on different spools of rope. This way, the variability of the breaking strengths of each spool of rope could be controlled. For statistical inferences, it was also better to use more spools and batches of rope rather than rope cut from a single batch.

This project focused on testing different end connections with the synthetic rope. The purpose was to measure if the mean breaking strengths of each end connection are significantly different from the control (buried eye splice). Therefore, the treatment in this pilot study is each end connection tested.

Due to the nature of timber harvesting applications and their operational requirements, not all rope diameters are appropriate for all end connections. A similar design was used for the 3/8" diameter rope that tests only two end connections (Table 10).

Table 10. Randomized complete block design for 3/8" diameter

	3/8" Diameter	
End Connection	1	2
Spool		
1		
2		
3		
4		
5		
	Breaking Strength (lbs.)	

3.5 *Sample Size Calculation*

This study and the amount of samples tested are constrained by time and money. It would be financially and logistically impossible to include a large sample size. A sample size of at least three is required to make any inferences to the sampled data and the population. However, large sample sizes require more time to run each test and measure the breaking strength of each test specimen. Large sample sizes are also costly. This is only a pilot study and results from it will be used to identify suitable concepts for further development. A sample size of 30 or more would be ideal because t-statistics become relatively constant near 2.0.

The sample size was determined to be five spools for each diameter class, using the practical significant difference method and Table 8 as shown in Equation 1.

Equation 1. Sample size calculation

$$n = \frac{\left[t_{df}(1-\alpha/2)\right]^2 S_e^{\,2}}{(\text{Practically significant difference})^2} \quad \left(C_1^{\,2} + C_2^{\,2} + \ldots + C_k^{\,2}\right)$$

(Ramsey et al., 2002)

In this study, we wish to determine if the new end connections results in a drop in breaking strength more than 30% of the catalogue minimum breaking strength. With a breaking strength of the test end connection less than 30% of the control, there may be substantial safety concerns and this end connection would not be suitable for all applications in timber harvesting. The ratio of the standard deviation to the difference between breaking strengths is estimated to be 10%. In addition, a 90% confidence interval was used in the calculation. Table 11 shows the calculations for the sample size.

Table 11. Sample size calculation

Trial	Estimated t-multiplier for 90% Confidence Interval	PSD	SE	C_1	C_2	n	Round n up to nearest integer
1	1.7	30	10	1	-1	2.57	3
Trial	**New t-multiplier**	**PSD**	**SE**	**C_1**	**C_2**	**n**	**Round n up to nearest integer**
2	2.353	30	10	1	-1	4.92	5
3	2.015	30	10	1	-1	3.61	4
4	2.132	30	10	1	-1	4.04	5
5	2.015	30	10	1	-1	3.61	4

PSD = 0.1*mu1 = practically significant difference
SE = .04*mu1 = standard error
n = sample size
C_1 = first coefficient
C_2 =second coefficient

From the calculations in the Table 11, a sample size of five was chosen. Either four or five could have been correct. However, a larger sample size tends to decrease the variance.

3.6 Sources of Variation

This study has controlled many sources of variation through experimental procedures. Below is a list of the steps taken to control sources of variation in this study.

- uniform test protocols
- uniform test equipment
- ambient temperature and environmental conditions in the laboratory
- uniform sample preparation protocol
- uniform data collection protocol

However, there are variables that could not be controlled and are inherent in the design, fabrication, and test performance of the end connections. Exact values of variables affecting the testing methods of the synthetic rope are difficult to pinpoint and describe. However, one of the principal variables is the unknown behavior of the rope with new end connections due to the properties of the interacting materials in tensile and compression. These variables do affect all hypotheses and in all testing procedures. The following subsections describe the main sources of variability identified.

3.6.1 Unknown UHMW-PE Properties and Behavior Under Testing Conditions

Both the UHMW-PE used to fabricate end connections and the 12-strand braided synthetic rope constructed from UHMW-PE fibers have unique characteristics. Although they share nearly all of the same mechanical, chemical, thermal, and physical properties due to their chemical make-up, the rope has individual characteristics that are not all currently known. Because the rope is braided with 12 individual strands made up of approximately 10^6 fibers, the fiber interaction is critical. The ability to study and characterize the rope properties at the fiber level are not within the scope of this project and the data received from the manufacturer must be used.

3.6.2 Description of Molecular Bond of Adhesives Within End Connections

It is not within the scope of this project to investigate the molecular bonds of the synthetic rope to the end connectors. This category includes the end connectors that are attached to the rope with a commercially available structural adhesive. Although, the end connection underwent strength testing, all that is known is whether the end connection met strength requirements under certain conditions. What is unknown is whether the bonds have weakened, deformed, or the molecules have completely disaligned themselves under axial loading of the synthetic rope.

3.6.3 Rope Quality Control From the Manufacturer – Low Breaking Strength

This variability cannot be completely controlled within the scope of the research. As with many engineered and manufactured goods, the synthetic rope has some variation due to fiber, tool, and other tolerances while it is constructed. Although the rope braids and structure are based on engineering principles, rope making is considered more of an art form than an exact science. There has been some quality control issues in the past where shipments received at Oregon State University have not met minimum breaking strengths noted in the manufacturer's catalogue. For this reason, certified break tests have been conducted and the reports have been delivered with each batch of rope. These reports indicate the maximum peak load of each load and it will also indicated if the batch is within 2 standard deviations of the catalogued average breaking strength. However, even though the rope may meet minimum strength requirements, there remains some difference in breaking strength from batch to batch.

3.7 Methods

This section describes the procedures for the break testing of the rope samples for the 3/8", 9/16", and 5/8" diameter classes. It discusses sample preparation and how the end connections were allocated to each of the five spools. In addition, this section describes the test set up and equipment. Specific break testing procedures from the rope manufacturer can be found in Section 8.9 of the Appendix.

3.7.1 Break Test Under Ambient Conditions

It is necessary to test the synthetic rope in the laboratory under normal working conditions that the rope would experience on a job site. The laboratory environment is a way to control variables and to isolate the effects of different end connectors on the breaking strength of the synthetic rope. All tests were conducted under ambient conditions.

3.7.1.1 Sample Preparation

All test specimens were prepared in accordance with Cordage Institute Standards CI 1500-99 §6 (Cordage Institute, 1999). All samples were prepared in the Knudsen Structural Laboratory in Richardson Hall at Oregon State University under ambient conditions. Depending on the end connection tested, the corresponding amount of rope was cut from the spool (see Section 8.5 in the Appendix). All end connections had four feet of "clear". Clear is defined as the amount of rope left between rope modifications or configuration alternations, such as the end of the taper of splices, terminations, or end connections. Figure 24 shows an example of a test specimen and labels the four feet of clear.

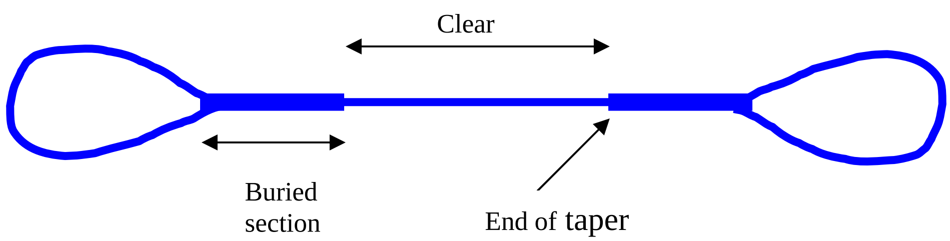

Figure 24. Drawing of a buried eye splice test specimen

Every test specimen was prepared at least 72 hours in advance of the test to control time variability in potting times. Preparing samples with this time window between potting the adhesives and break testing them assured that the adhesives have cured properly according to manufacturer specifications. Preparing the test specimens that use splices or hardware 72 hours before break testing controls some of the variability with sample preparation and ensures standardization of preparation of all test specimens.

3.7.1.2 Allocation of End Connections to Spools

There are five spools allocated for both the 9/16" and 5/8" diameter classes. Therefore, there are a total of 10 different spools for these two diameters. Using Table A6 in the Appendix, the length of synthetic rope needed for each test specimen was determined. The fid length depended on the nominal diameter of the rope.

A random number was assigned to each end connection for the first spool. Then, the random numbers and consequently the end connections were arranged in ascending order. The end connections were now randomly numbered and this was the cut order for the first spool. The appropriate amount for the first test specimen was pulled from the first spool and cut. The next amount was pulled and cut and so on until all specimens for the end connections have been cut. The same process is repeated for the remaining spools and new random numbers are assigned for each spool. To maintain the appropriate 3:1 D/d safety factor for splice length to pin size, a one fid eye was used for t he 9/16" and 5/8" diameter ropes. The truck wrappers also used a one fid eye because the rope was spliced around chain. The buried eye splice however used a two fid eye to maintain the safety ratio. To determine which spool of synthetic rope will be used for each specimen, the spool will be randomly assigned to the test sample.

3.7.1.3 Testing Methodology

Specifically, the experimentation of this project was conducted in the Wood Knudsen Structrual Laboratory. Figure 24 shows the laboratory set up for each break test. In keeping with manufacturer break test protocol, ropes were tested against pin sizes at least twice the nominal diameter of the rope (Samson Rope Technologies A., 2003). Each rope specimen with the buried eye splice was connected to 1-5/8" diameter shackle and pin. A ¾" chain secured to the wall was then connected to the shackle. The test end connection is then attached to the 1 5/8" diameter pin on the hydraulic ram. With all tests, the end connection concepts will be tested against the buried eye splice. The buried eye splice is a strong end connection for new and used rope and through proper splicing techniques can retain 100% of new rope strength and in used rope up to the same proportion of residual used rope strength (Samson Rope Technologies, 2001). As a result, the buried eye splice was used as the benchmark for end connector breaking strength.

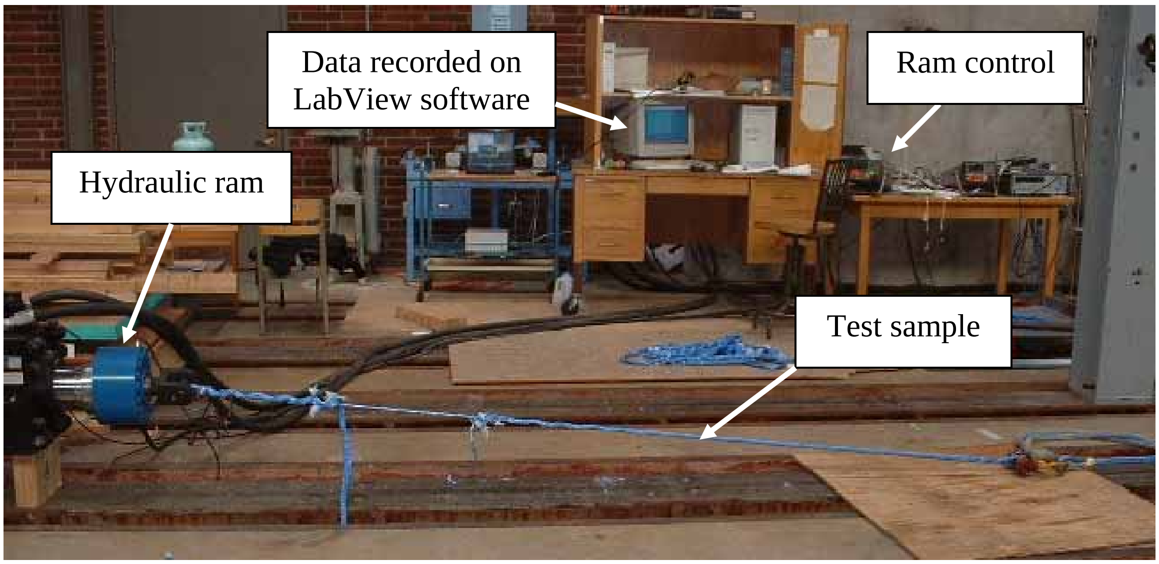

Figure 25. Laboratory test set up

Combining the Cordage Institute Standards (Test Methods for Fiber Rope CI1500-99) and the synthetic rope manufacturer's Test Methods for Fiber Rope (SRT Test Method-001-02) protocols, the test specimen was cycled 10 times at 50% of its breaking strength. The procedure was standardized for all end connector tests to reduce variability. The same loading was used time for all specimens and the incremental tension change in the hydraulic ram will remain constant throughout the break test.

Immediately following sample failure, the test was stopped. The hydraulic cylinder was held in position so that measurements and failure mode could be documented and photographs could be taken.

3.7.1.4 <u>Test Equipment and Data Collection</u>

The system consists of a set of integrated components supplied by MTS Systems Corporation of Eden Prairie, MN. The principal components of the test system are:

- Hydraulic pump, MTS-505.30 30 gpm at 3000 psi, assorted accumulators and control valves
- Servo-controller, MTS-407 with integrated position and force conditioners, function generator, and digital display
- Hydraulic cylinder, MTS-243-70, (216 kip tension, 328 kip compression), 20" stroke, integrated LVDT position sensor
- Interface Corporation load cell, model 1240BMT-200K

Secondary equipment includes custom fabricated fixtures to secure the hydraulic cylinder to the structural floor and fixtures as end point anchors to the structural reaction wall.

Each break test was performed in accordance with Sampson Rope Technologies Test Method-001-002 and laboratory safety guidelines (Appendix 8.9). Eye sizes were prepared to allow for the appropriate safety factors (Table 12).

Table 12. Break test eye size requirements

Nominal diameter	Fid size	Minimum eye size to meet 3:1 safety factor	Eye size
3/8”	7.75”	12”	15.5”
9/16”	12.25”	12”	12”
5/8”	14”	12”	14”

In addition, the four rope clamps were placed at 4” intervals on the rope and initially tightened to 45 foot-pounds. There was 4’ of clear left between the end of the buried taper of the rope and the end of each test end connection.

Each sample was secured to the hydraulic ram with a 1 ½” diameter pin. Samples were loaded 10 times to 50% of the corresponding catalogue minimum breaking strength with the crosshead on the hydraulic ram traveling 0.1” per second. Before the last cycle, all end connections and safety systems were checked. The rope clamps were retightened to 45 foot-pounds. All other end connections were not touched. On the eleventh cycle, the cycle was loaded to failure at 0.03” per second. Table 13 shows the 50% threshold values for each of the diameter classes tested.

The data collection for the experimentation was quite extensive. First, the ram was calibrated and electronically controlled. Data acquisition was done using a Windows NT based computer system running National Instruments LabView™ software and custom developed LabView VI application program to acquire measurement data from force and position sensors. The sample rate was 0.5 seconds. As the cylinder traveled inward, it applied more tension to the synthetic rope. The cycle time of the ram, each incremental tension, and maximum tension at failure was recorded by the computer.

Table 13. Threshold values for break testing

Nominal Diameter	Catalogue minimum breaking strength	50% of catalogue minimum
3/8”	18,401 lbs.	9,200 lbs.
9/16”	40,194 lbs.	20,097 lbs.
5/8”	53,114 lbs.	26,557 lbs.

A physical examination of the rope, end connection and place of failure were documented following the completion of each break test. Once the sample fails, the test sample was examined for broken strands, end connections, and other places of failure. These failure modes were recorded for each test sample.

This data was imported into Excel™ from its text format in order to manipulate it into usable information. From each break test, the cycle time, incremental tension applied to the rope specimen, and tension at failure was collected from the computer. Once inside Excel, the data was analyzed.

First, a thorough analysis was completed from the buried eye splice of the three diameter classes. The failure modes, ultimate loads, and elongation were closely examined. This information was recorded in a spreadsheet. The mean breaking strengths from each diameter subset were then used as the benchmark with which to compare other end connector concepts.

4 Results

This chapter summarizes the data analysis and presents the results. It first examines the normality of the data. Then, it discusses the results of the series of break tests for the 3/8", 9/16", and 5/8" diameter classes. The chapter will separately examine each end connection's break test performance within each rope diameter class. In addition, statistical analysis was performed on each diameter class. A more in-depth discussion of failure modes, breaking strengths, and statistical analyses is made in Chapter 5.

For this pilot study, there are 14 different end connections for 5/8", 12 for the 9/16", and 2 for the 3/8" diameters. Each end connector can be considered a treatment. It is assumed that each treatment has a normal distribution for a response variable and each has a different mean (Kuehl, 2000). For example, the 14 different end connections represent 14 treatment populations in the 5/8" diameter class. There are five replications for each treatment. The reference population is all possible end connections. Similarly, there are 12 treatments for the 9/16" diameter and 2 treatments for the 3/8" diameter.

4.1 Examination of the Data

The first examination of the breaking strength data for the 9/16" and 5/8" diameter classes was used to discover trends in the data. The breaking strengths of the 5/8" diameter class were divided by the catalogue minimum breaking strength of 53,114 pounds to obtain a relative strength. The 9/16" was divided by its corresponding catalogue minimum breaking strength of 40,194 pounds to obtain the relative strengths. In sum, there were 14 end connections in the 5/8" diameter class and 12 end connections in the 9/16" diameter class. Five spools different spools were used in each diameter class.

These relative breaking strengths were combined into categories: 0-9%, 10-19%, 20-29%, etc. The number of occurrences in each of these categories is presented in the following histogram. This graph shows the contribution of each diameter class to the overall frequency. Figure 26 shows a strong treatment effect on the breaking strengths.

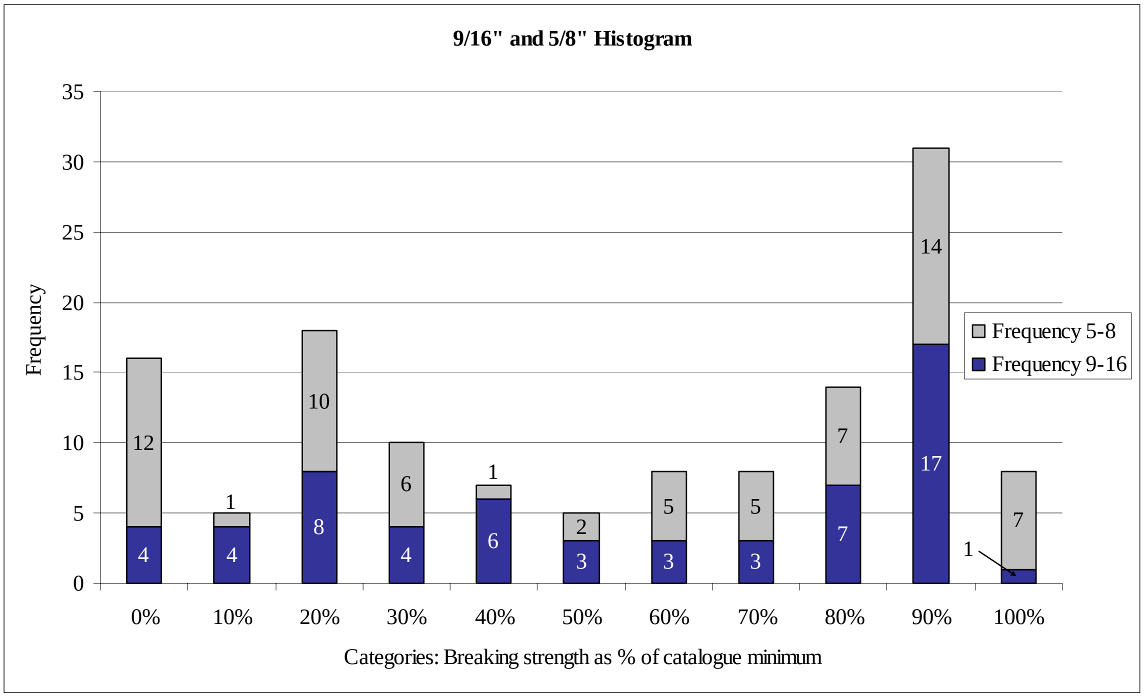

Figure 26. 9/16" and 5/8" histogram

Table 14 shows the mean 5/8" and 9/16" breaking strengths as a percentage of the catalogue minimum. The end connections shown represent the groups of end connections that obtain the highest breaking strength values. Although the mean percentage for the 9/16" Y-splice was 69%, it had three samples that broke at 78%, 81%, and 83%. However, each of these diameter classes must be examined separately.

Table 14. Mean relative breaking strength of the best performing end connections

End Connection	5/8" Mean Relative Breaking Strength	9/16" Mean Relative Breaking Strength
BES	96%	94%
Whoopie Sling	85%	86%
Long Splice	95%	89%
Y-Splice	89%	69%
Pinned Nubbin	95%	92%
Knuckle Link	99%	96%

4.2 5/8" Diameter Results

4.2.1 Break Test Results

The breaking strengths of the different end connections were highly variable. Overall, the rope end connections (splices), the Pinned Nubbin, and the Knuckle Link achieved the highest breaking strengths. The distribution of the breaking strengths can be seen in Figure 27.

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 amount of variation. Table 15 shows the standard deviation and variance for each of the 14 end connections tested.

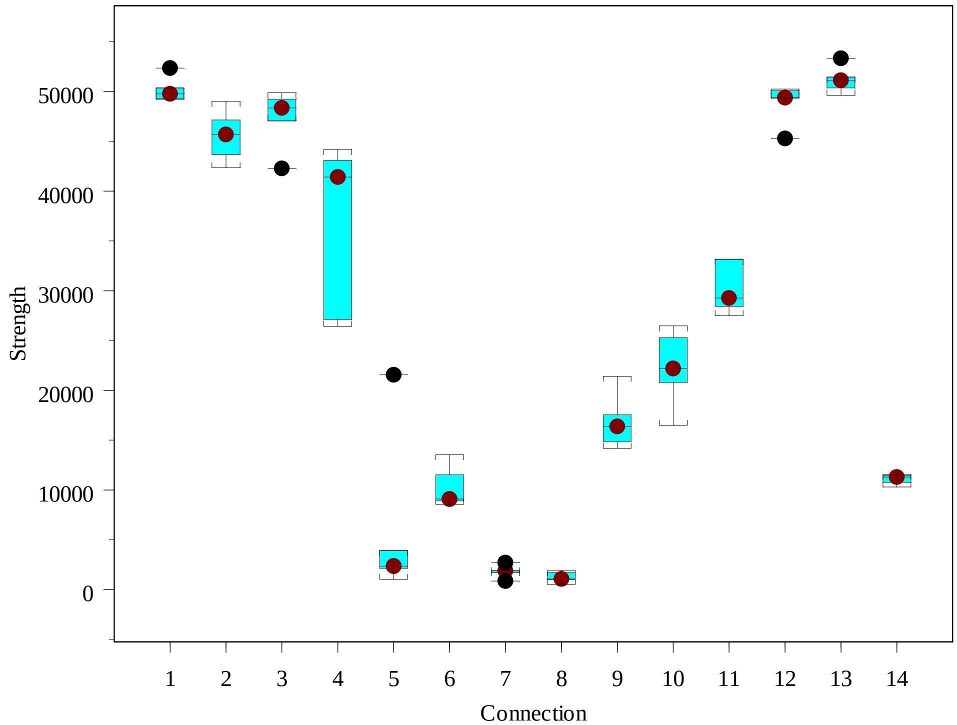

Figure 27. Box plot for 5/8" breaking strengths

Figure 29 (page 73) shows the average breaking strengths for the 14 end connections. From this chart, it is evident that the *spliced* connections had higher breaking strengths than all but two manufactured end connections. Figure 30 (page 74) shows the average breaking strength of each end connection as a percentage of the catalogue minimum. The rope end connections obtained between 69% and 94% of the catalogue minimum value of 53,114 pounds.

As expected, the highest breaking strength from the spliced end connections was attained by the buried eye splice. The buried eye splice averaged of 50,187 pounds and 94% of the catalogue minimum value.

Table 15. Breaking strength and standard deviation for 5/8” diameter

	End Connection (n = 5) for all	*Average Breaking Strength*	*Standard Deviation (lbs.)*	*Standard Deviation (% of mean)*	*Variance*
1	Buried Eye Splice	50187	1291	2.6%	1333708
2	Whoopie Sling	45571	2672	5.9%	5709876
3	Long Splice	47354	3037	6.4%	7379565
4	Y-Splice	36438	8893	24.4%	63270888
5	Steel Nubbin w/ Socketfast Blue A-20	6195	8648	139.6%	59830976
6	UHMW-PE Nubbin w/ Socketfast Blue A-20	10327	2149	20.8%	3693395
7	Steel Nubbin w/ Scotchweld DP-8010	1799	651	36.2%	339213
8	UHMW-PE Nubbin w/ Scotchweld DP-8011	1239	575	46.4%	264161
9	Notched Steel Nubbin w/ Socketfast Blue A-20	16866	2864	17.0%	6561020
10	SEFAC	22244	3957	17.8%	12525497
11	Rope Clamps	30294	2674	8.8%	5720263
12	Pinned Nubbin	48868	2043	4.2%	3339707
13	Knuckle Link	51172	1393	2.7%	1551940
14	Pressed Nubbin	11066	537	4.9%	230899

Figure 32 (page 75) shows the breaking strength of each end connection relative to the buried eye splice and Figure 33 (page 76) shows the breaking strength of each of the five samples for each end connection.

4.2.1.1 Spliced End Connection Results

The lowest average breaking strength of the spliced end connections was the Y-splice. However, if the raw data is closely examined, the results can be displayed another way. Spools C1 and C2 failed after the first cycle. These test specimens failed at an average of 26,759 pounds and 50% of the catalogue minimum. However, spools C3, C4, and C5 failed when the specimens were tensioned to failure on the eleventh cycle. These three test samples failed at an average of 42,890 pounds and 81% of catalogue minimum. If the values are differentiated in this way, this explains why the Y-splice overall average is only 36,438 pounds. Omitting the two spools that broke early, the average maximum load attained is significantly higher.

4.2.1.2 Dry Hardware End Connection Results

Two other *dry hardware* end connections achieved at least 90% of catalogue minimum breaking strengths. The pinned nubbin had a breaking strength of 48,868 pounds and 92% of the catalogue minimum. The knuckle link broke at an average of

51,172 pounds and 96% of the catalogue minimum. These values represent the highest breaking strength achieved of all end connections tested. Furthermore, this average breaking strength was higher than the average breaking strength for the buried eye splice.

Although, the rope clamps did not have nearly the breaking strength of the splices, pinned nubbin, or knuckle link, this end connection still provided over 50% breaking strength. The rope clamps had an average breaking strength of 30,294 pounds, 57% of the catalogue minimum. Additionally, the rope clamps were the strongest end connection that did not incorporate any kind of splice. The eye for each sample was formed using the standard wire rope clamps. Clips were spaced using the manufacturer's guidelines for steel wire rope of the same diameter.

4.2.1.3 SEFAC™ Results

Of the potted end connections, the SEFAC™ had the highest breaking strength. This end connection had an average strength of 22,244 pounds and 42% of the catalogue minimum. Because it was a compression fitting, the spike was pulled further into the socket and created more holding force. The holding forces originated from the Phillystran Socketfast® Blue A-20 in combination with compression. This configuration created better performance instead of relying on the glassy, brittle epoxy solely to withstand the axial load.

4.2.1.4 Steel and UHMW-PE Nubbins Results

The nubbins potted with the Phillystran Socketfast® Blue A-20 consistently performed better in the testing than the nubbins potted with the 3M Scotch-Weld™ DP-8010. The Socketfast® Blue A-20 was less viscous and therefore provided more complete coverage. It soaked through the strands and yarns to bond the fibers better than the thicker DP-8010 adhesive. The notched nubbin had the highest average performance with 32% breaking strength of catalogue minimum and 16,866 pounds.

Additionally, although the UHMW-PE nubbin had a significantly less compression and hoop strength, it had an average of 7% higher breaking strength than its steel counterpart. Moreover, the UHMW-PE nubbin's breaking strengths were more consistent with a standard deviation of 2,149 pounds.

Of the potted nubbin end connections in the 5/8" diameter class, the notched steel nubbin had a substantially higher average peak load with a standard deviation of only 17%. The steel nubbin's performance was highly variable. It had a standard deviation of 8,648 pounds and a range of 1,035 to 21,555 pounds. Furthermore, the steel nubbin's performance shows that strength not only depends on careful potting, but also on overall coverage and fiber infiltration of the adhesive.

Finally, Figure 29 and Figure 30 (pages 73and 74) show the performance of the nubbins potted with the DP-8010. Although the steel nubbin's breaking strength was slightly higher than the UHMW-PE nubbin, they were still significantly lower than the nubbins potted with the Socketfast® Blue A-20. The steel and UHMW-PE nubbins only achieved 3% and 2% respectively of the catalogue minimum.

4.2.2 Statistical Results

4.2.2.1 Analysis of Variance

Because the data is normal and balanced, analysis of variance can be conducted. There is no interest in comparing the 5/8" with the 9/16" diameter ropes and thus the 5/8" and 9/16" strength data can be analyzed separately. A simple 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:

$$Breaking\ Strength = Connection_i + Spool_j$$

From the resulting ANOVA table below (Table 16), the spool is found not to be significant (p-value = 0.624) and therefore, there is no significant block effect. Conversely, the connection type is found to be strongly related to breaking strength (p-value = 0.000).

Table 16. ANOVA table

	Connection	Spool	Residuals
Sum of Squares	24239033491	41324896	817430651
Deg. of Freedom	13	4	52

Residual standard error: 3964.823
Estimated effects are balanced

	DF	Sum of Sq	Mean Value	F Value	Pr(F)
Connection	13	24239033491	1864541038	118.6108	0.0000000
Spool	4	41324896	10331224	0.6572	0.624486985
Residuals	52	817430651	15719820		

Although there are a few outliers in the normal QQ plot (Figure 28), the data is approximately linear. In addition, the Residuals vs. Fit plot (Figure 28) shows that the data is approximately normally distributed. Data point 22 is the most dramatic outlier in both plots, but was not discarded from the data set. This data point is the 5/8” steel nubbin with Phillystran test sample that achieved 21,555 pounds and all other samples were significantly less strong.

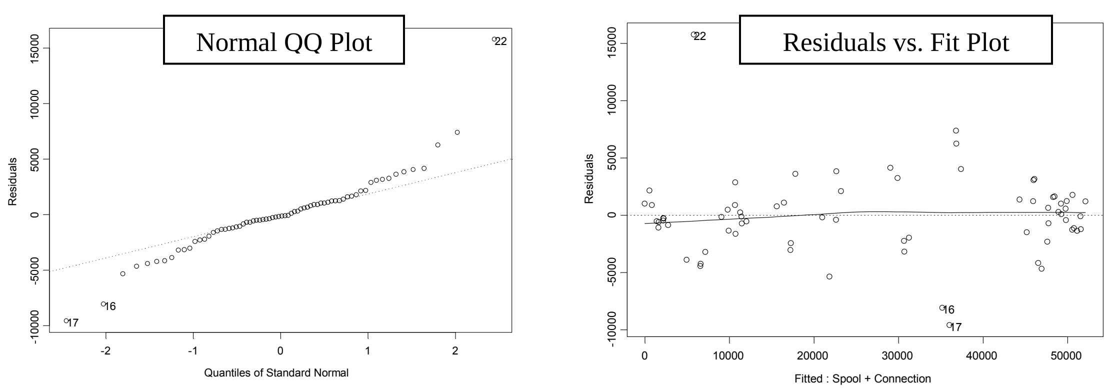

Figure 28. Normal QQ and Residuals vs. Fit plots for 5/8" data

4.2.3 Strength as a Percentage of the Buried Eye Splice

In addition to comparing the breaking strength of each test sample with the catalogue minimum value, each test sample was also compared to the buried eye splice. The relative breaking strengths can be seen in Figure 31 (page 75). The Whoopie Sling, long splice, pinned nubbin, and knuckle link represent the end connections with the highest percentages. Appendix 8.7 lists the actual values for each end connection and spool obtained from each break test and their respective breaking strengths as a percentage of the buried eye splice. Of the spliced end connections, the long splice obtained the largest percentage of the tested buried eye splice samples. The mean percent strength for the Long Splice was 94%, followed by the Whoopie Sling at nearly 91%. The Pinned Nubbin and Knuckle Link were the best performers with 97% and 102% respectively of the mean breaking strength of the buried eye splice.

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 catalogue minimum breaking strengths. Dunnett's test is used to compare each of the *n-1* treatment means with the control (Montgomery, 1997). The two-tailed t-test shows if any of the mean end connection breaking strengths are significantly different from the mean breaking strength of the buried eye splice. Table 17 shows the results of the Dunnett's multiple comparisons test. The higher p-values show that the Whoopie Sling, long splice, pinned nubbin, and knuckle link breaking strengths are not significantly different from the mean breaking strength of the buried eye splice.

Table 17. Dunnett's multiple comparisons

	Connection	Mean Strength	p-value
	5/8" Diameter		
1	BES	50186.77	
2	Whoopie Sling	45571.09	0.4256
3	Long Splice	47353.52	0.9070
4	Y-Splice	36437.99	< 0.0001
5	Steel Nubbin w/ Phillystran	6195.07	< 0.0001
6	UHMW Nubbin w/ Phillystran	10327.15	< 0.0001
7	Steel Nubbin w/ 3M	1798.70	< 0.0001
8	UHMW Nubbin w/ 3M	1239.01	< 0.0001
9	Notched Steel Nubbin w/ Phillystran	16865.88	< 0.0001
10	SEFAC	22243.65	< 0.0001
11	Rope Clamps	30293.66	< 0.0001
12	Pinned Nubbin	48867.98	0.9998
13	Knuckle Link	51172.20	1.0000
14	Pressed Nubbin	11065.67	< 0.0001

In addition to the comparison of the mean breaking strengths to a control, pairwise comparisons were made. The Tukey-Kramer procedure is used to make all comparisons between pairs of means (Table 18). This test bases the comparison on the studentized range distribution rather than the t-distributions, making it conservative (Ramsey et al., 2002).

Table 18. Tukey-Kramer pairwise comparisons for 5/8" diameter

	End Connection													
Tukey Grouping	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	X	X	X									X	X	
B				X							X			
C										X	X			
D									X	X				
E						X			X					X
F					X	X								X
G					X	X	X							
H					X		X	X						

Table 18 shows the eight groupings derived from the Tukey-Kramer procedure. The end connections are grouped together if they are not declared significantly different. Group A contains the buried eye splice (#1) and confirms that end connections Whoopie Sling (#2), long splice (#3), pinned nubbin (#12), and knuckle link (#13) are in the same Tukey-Kramer grouping. All other end connections are grouped differently.

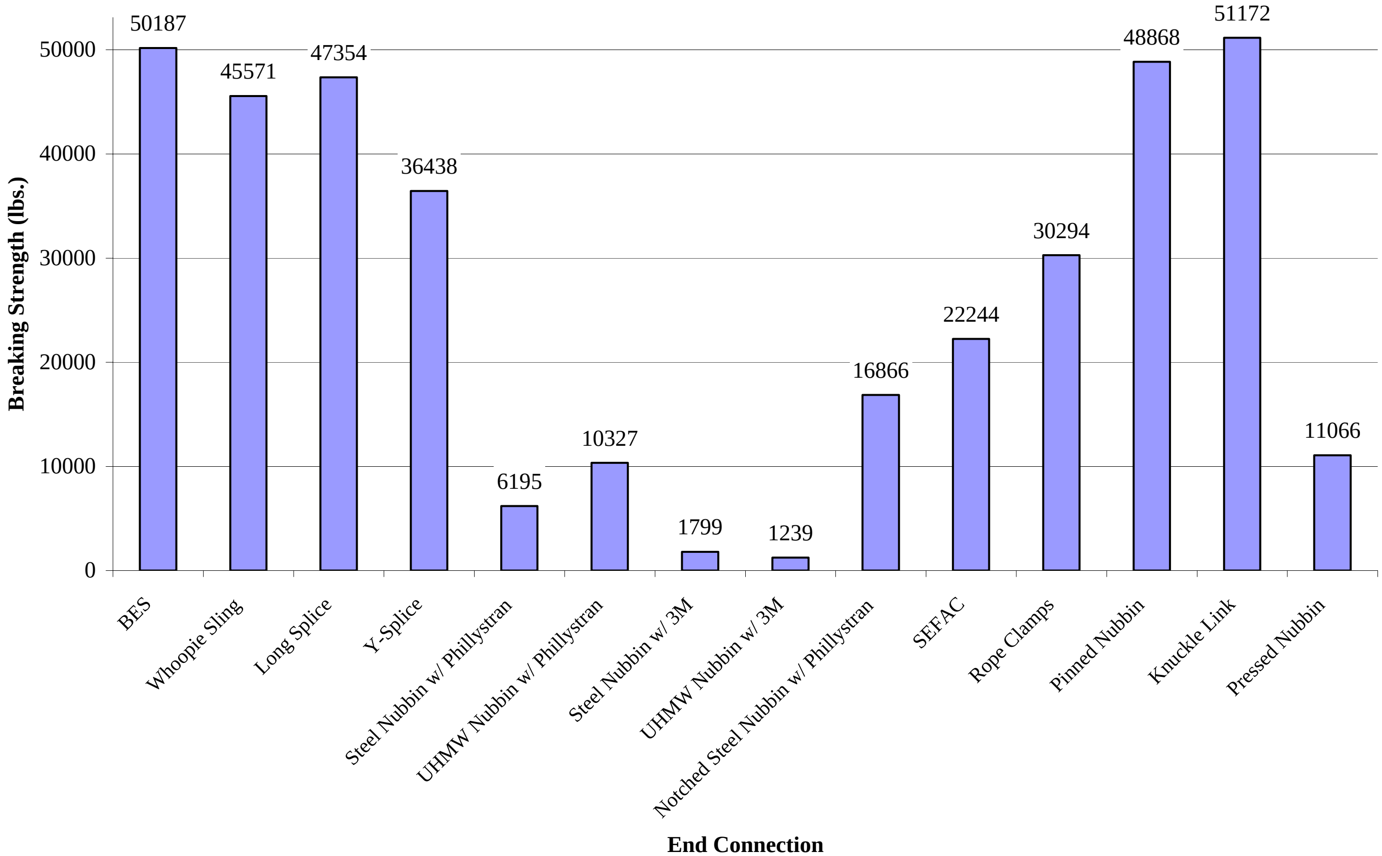

Figure 29. 5/8" synthetic rope end connection mean breaking strengths

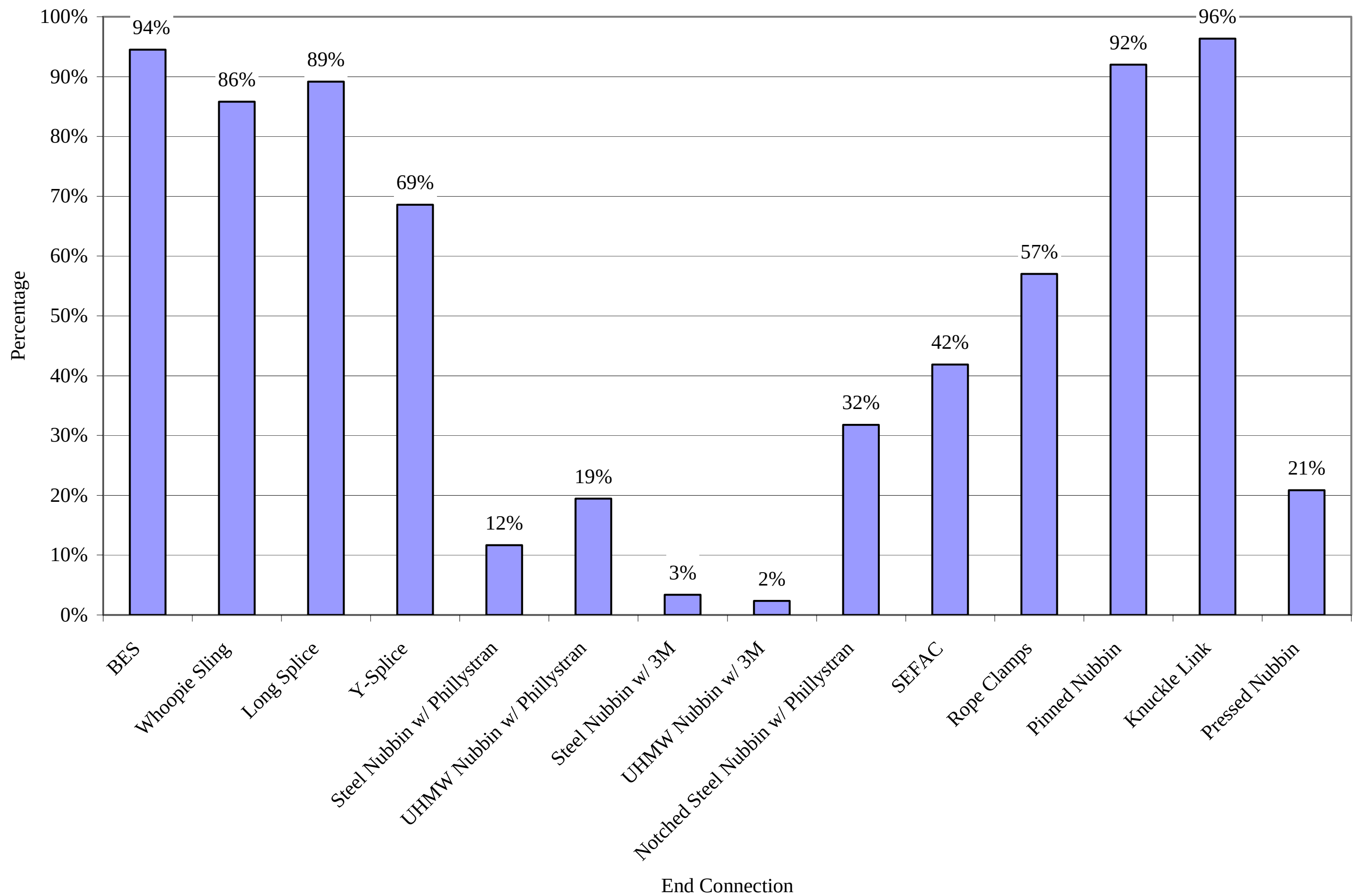

Figure 30. 5/8” diameter end connection breaking Strengths as a percentage of catalogue minimum

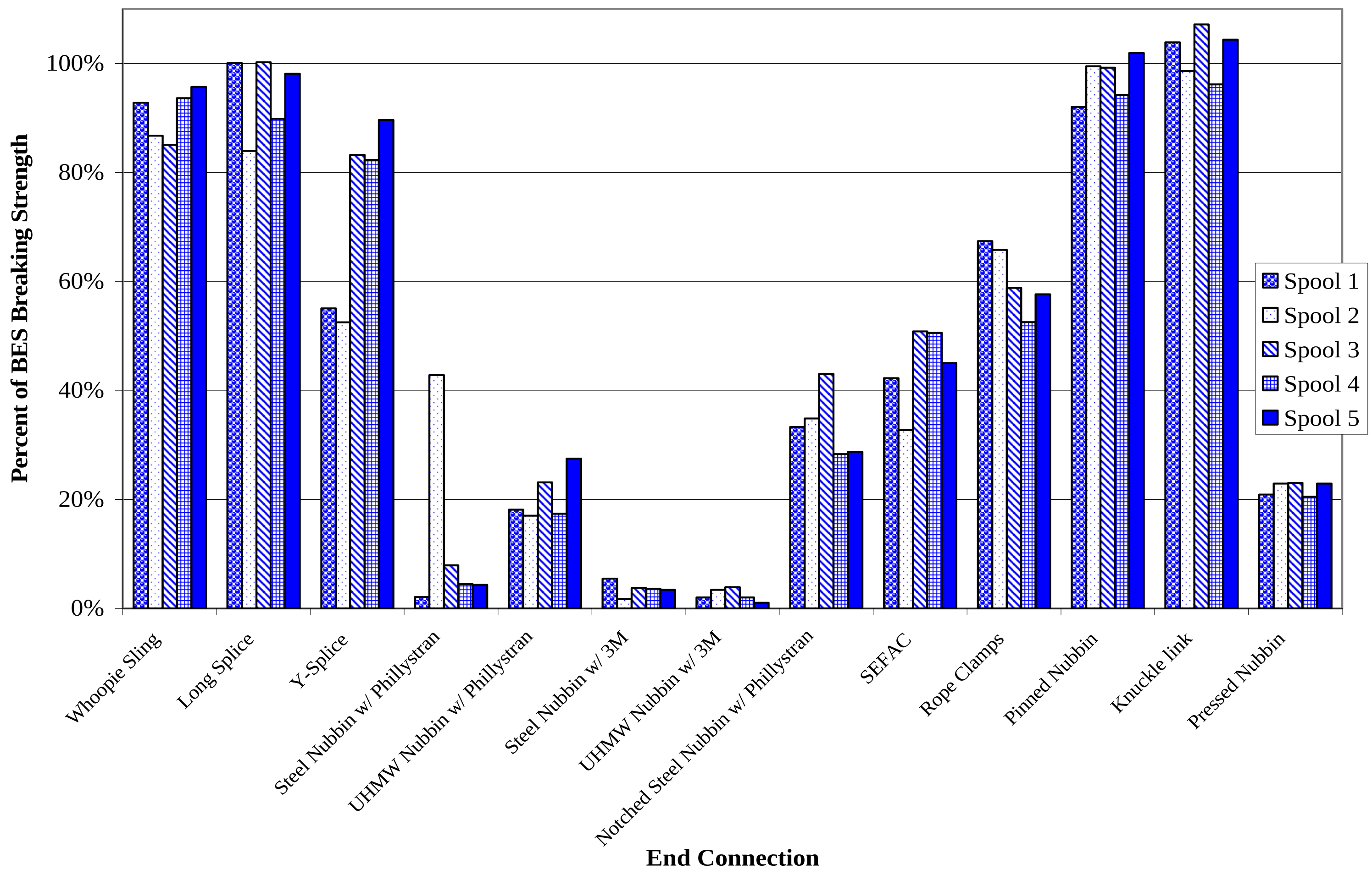

Figure 31. 5/8" diameter breaking strengths relative to the buried eye splice at 100%

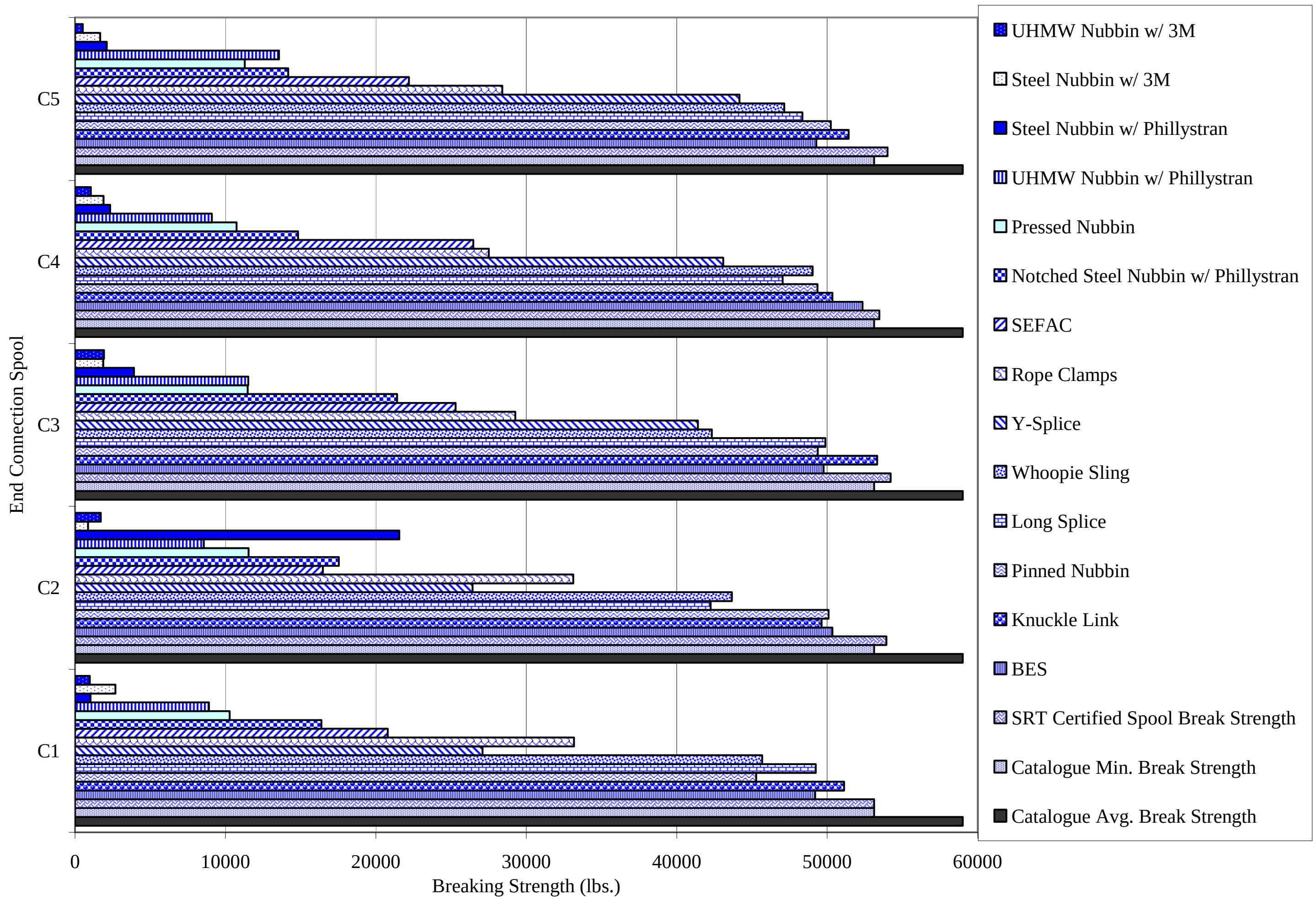

Figure 32. End connector breaking strengths for 5/8" diameter synthetic rope

4.3 9/16" Results

4.3.1 Break Test Results

The end connections on the 9/16" diameter rope performed similarly to the 5/8" diameter synthetic rope end connections. However, there were some differences: the nubbins using Scotch-Weld^{TM} DP-8010 were not tested. From the 5/8" results (see Table 15), the average peak loads of DP-8010 did not have a strong enough bond strength with the steel or UHMW-PE nubbin. Because the nubbins with DP-8010 only performed at 2 and 3% of the catalogue minimum breaking strength on 5/8" synthetic rope, they were too low to be suitable for any timber harvesting operations. Such low strengths present real safety concerns in any forestry application. Other than two end connections with the DP-8010 adhesive, all of the remaining 12 end connections were tested on the 9/16" diameter synthetic rope. Table 19 shows the average breaking strengths and standard deviations for the 9/16" synthetic rope.

Table 19. Breaking strength and standard deviation for 9/16" diameter

	End Connection (n = 5) for all	*Average Breaking Strength*	*Standard Deviation (lbs.)*	*Standard Deviation (% of mean)*	*Variance*
1	Buried Eye Splice	38757	3196	8.2%	8171647
2	Whoopie Sling	34177	2882	8.4%	6645409
3	Long Splice	38314	2118	5.5%	3589451
4	Y-Splice	35956	1153	3.2%	1064439
5	Steel Nubbin w/ Socketfast Blue A-20	14630	4601	31.5%	16936661
6	UHMW-PE Nubbin w/ Socketfast Blue A-20	6407	3891	60.7%	12109433
7	Steel Nubbin w/ Scotchweld DP-8010	N/A	N/A	N/A	N/A
8	UHMW-PE Nubbin w/ Scotchweld DP-8011	N/A	N/A	N/A	N/A
9	Notched Steel Nubbin w/ Socketfast Blue A-20	12819	922	7.2%	679977
10	SEFAC	25519	6413	25.1%	32901142
11	Rope Clamps	25985	995	3.8%	791518
12	Pinned Nubbin	38067	2815	7.4%	6340816
13	Knuckle Link	39944	1997	5.0%	3189926
14	Pressed Nubbin	10724	313	2.9%	78027

As with the 5/8" synthetic rope, the highest breaking strength was attained by the knuckle link at 39,944 pounds and 99% of the catalogue minimum breaking strength. All samples failed at the end of the splice taper, but not all on the hydraulic ram side of the sample that has the test end connection. The pinned nubbin had the next highest breaking strength at 95%. These two designs have relatively small standard deviations with a maximum of 7.2% from the average. Thus, end connection samples have performed consistently in the load tests.

Figures 38-41 on pages 86-89 summarize the break data for the 9/16" diameter class. Figure 38 shows the mean breaking strength of the end connections tested. The mean breaking strength relative to the catalogue minimum value and the buried eye splice are shown in Figures 39 and 40 respectively. Finally, Figure 41 provides the breaking strength of each of the five samples for each end connection.

4.3.1.1 Spliced End Connection Results

Similar to the results of the 5/8" diameter load tests, the 9/16" tests showed a consistent performance in the spliced end connections. As expected, the buried eye splice had the highest breaking strength of the rope splices at a mean of 38,757 pounds. However, strangely enough, this strength was still below the knuckle link's average. As expected, spliced end failures occurred predominantly at the end of the taper of the eye splice.

The long splice was the next strongest splice connection at 38,314 pounds and 95% of the catalogue minimum. All failures occurred at the end of the tapers of the tucked rope. Moreover, there was no sign of failed strands at the rope interchange.

The 9/16" Y-splice performed more consistently than the 5/8" rope samples. The average breaking strength for the five samples was 35,956 pounds, 89% of catalogue minimum. Comparing these five samples to the 5/8" samples, the standard deviation was 3%, whereas the 5/8" samples had a 24% standard deviation. Although, there is a significant spread in breaking strength, these results do not indicate faulty sample preparation methods. All samples were prepared in accordance with Section 3.7.1.1. The Y-splice samples also did not fail in a homogeneous manner; all samples failed differently. One specimen failed at the end of the taper of the inserted tail. Another broke the lock-stitch and simply pulled out of the main section. A third broke at the exit point of exit of the inserted y-section. Although the breaking strengths were consistent and within 3% of the average, this result does not imply that failure mechanisms will be the same. As is the case with many of the end connection samples, failure points can be different for each sample.

The Whoopie Sling specimens in the 9/16” diameter class performed similarly to the 5/8” diameter test samples. The 9/16” samples broke at an average of 85% of the catalogue minimum. The average peak load was 34,175 pounds and had a slightly higher standard deviation of 8.2%. The failures however also occurred at the same points, the exit point of the adjustable tail with the butt splice. The rope segment that fails is the rope that was buried and not the segment with the tail. Figure 33 and 34 show a test sample before and after a break test.

Figure 33. Before break test

Figure 34. After break test

4.3.1.2 Adhesive End Connection Results

Within the group of adhesive end connections, the tests results for the 9/16” test samples were somewhat different from the 5/8” diameter class. Of the potted end connections in the 9/16” diameter class, the notched steel nubbin had a substantially higher average peak load of 44,619 pounds (34% of the catalogue minimum value) with a standard deviation of only 7.2%. In addition, to the notched nubbin performing better in the 9/16” diameter class than the 5/8” diameter, the steel nubbin with Phillystran adhesive obtained a higher mean breaking strength as well. The unmodified steel nubbin with the Socketfast® BlueA-20 samples had an average breaking strength of 14,630 pounds, 36% of the catalogue minimum. Again, the performance of the specimens varied significantly. However, the notched nubbin specimens had more consistent breaking strengths with a standard deviation of 7.5% and an average peak load of 12,819 pounds.

The UHMW-PE nubbin with Socketfast® Blue A-20 had an average breaking strength of 6,407 pounds, 16% of the catalogue minimum. In comparison, the 5/8" UHMW-PE nubbin samples had an average strength of 19%. Although the relative breakings strengths were similar, the standard deviations were quite different: the 9/16" specimens had a standard deviation of 61% and the 5/8" had 21%. There was high variability in the breaking strengths due to potting, the inclusion of air pockets, or adhesive coverage on the rope fibers.

In addition, the 9/16" steel nubbins with Socketfast® BlueA-20 performed variably. The average breaking strength was 14,630 pounds, 36% of the catalogue, with a standard deviation of 31.5%. The last potted fitting, the SEFAC™ had similar variability in the breaking strength with a standard deviation of 25.1%. Due to the compression forces and the strong bonds of the styrene adhesive, the SEFAC™ performed over 50% better than the nubbins using only the adhesive. The Socketfast® Blue A-20 is a glassy and brittle adhesive once it has set, and therefore, is susceptible to failure under cycling loads. However, the SEFAC™ did obtain an average breaking strength of 63% of the catalogue minimum breaking strength (range between 15,225 pounds, 29,334 pounds).

4.3.1.3 <u>Dry Hardware End Connection Results</u>

The remaining dry end connections (those end connections that utilize hardware, but not the use of adhesives) performed substantially less than the pinned nubbin or the knuckle link. The rope clamps achieved an average breaking strength of 25,985 pounds, 65% of the catalogue minimum. Because the sample procedure was standardized and the end connection was designed to utilize the wire rope clamps, the breaking strengths for the five samples were relatively consistent. As a result, the standard deviation was 3.8%

Finally, the pressed nubbin had an average breaking strength of 10,724 pounds and only 27% of the catalogue minimum. Similar to the rope clamps, the pressed nubbin end connection only uses the steel nubbin. Because the sample preparation was also standardized, the variability in breaking strength was reduced, with a standard deviation of only 2.9%.

4.3.2 9/16" Statistical Results

The first step in the analysis is to look at exploratory plots. Figure 35 shows the distribution of the breaking strength for the 12 end connections tested. From this plot, it is evident that the connections with the adhesive had the most variation: SEFAC™, Steel nubbin with Socketfast® Blue A-20, and UHMW nubbin with Socketfast® Blue A-20. The distribution of the breaking strengths is approximately normal.

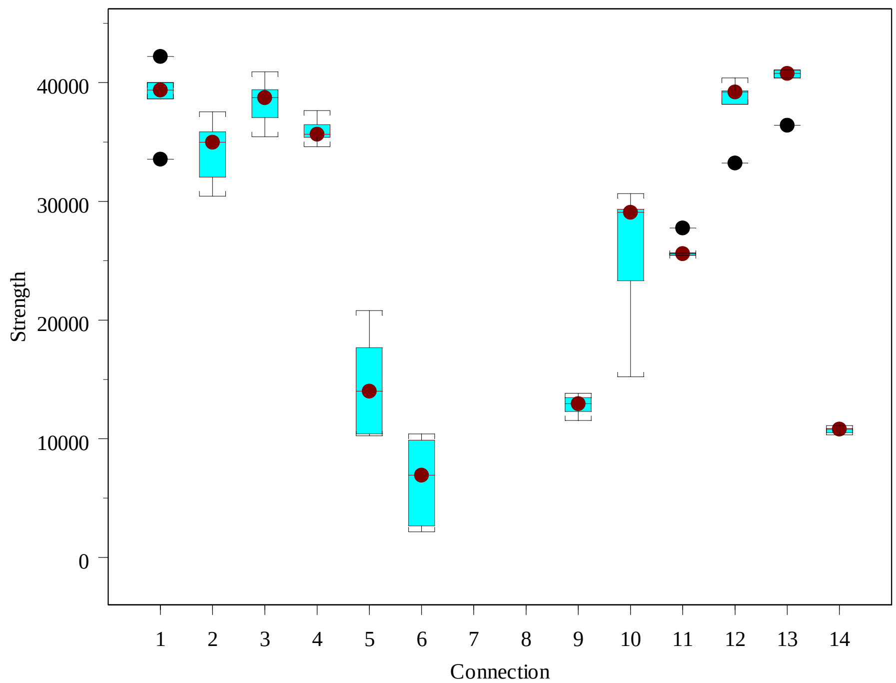

Figure 35. Box plot of 9/16" diameter breaking strengths

4.3.2.1 **Analysis of Variance**

The same additive model used for the 5/8" diameter class was used for the 9/16" diameter class. had an effect on the breaking strength. Each diameter has its own randomized complete block design using the model:

$$Breaking\ Strength = Connection_i + Spool_j$$

Table 20 shows the resulting analysis of variance table. There is no significant block effect (p-value = 0.4295) with spools, but there the treatment effect is significant (p-value = 0.0000). In addition, the sum of squared residuals for *Connection* is substantially greater than for *Spool*, meaning that there is more variation among treatments than among spools.

Table 20. 9/16" ANOVA table

	Connection	Spool	Residuals
Sum of Squares	8668788322	37751854	424740380
Deg. of Freedom	11	4	44

Residual standard error: 3106.958
Estimated effects are balanced

	DF	Sum of Sq	Mean Value	F Value	Pr(F)
Connection	11	8668788322	788071666	81.63847	0.0000000
Spool	4	37751854	9437963	0.97770	0.4294628
Residuals	44	424740380	9653190		

The Normal QQ plot in Figure 36 shows an approximately linear fit to the model. The Residuals vs. Fit plot in Figure 36 shows an approximate normal distribution. As with the box plot, points 28 (Steel Nubbin with Phillystran), 22 (UHMW-PE nubbin with Phillystran), and 38 (SEFAC™) had the largest residuals and can be attributed to the inconsistent performance of end connections with adhesive.

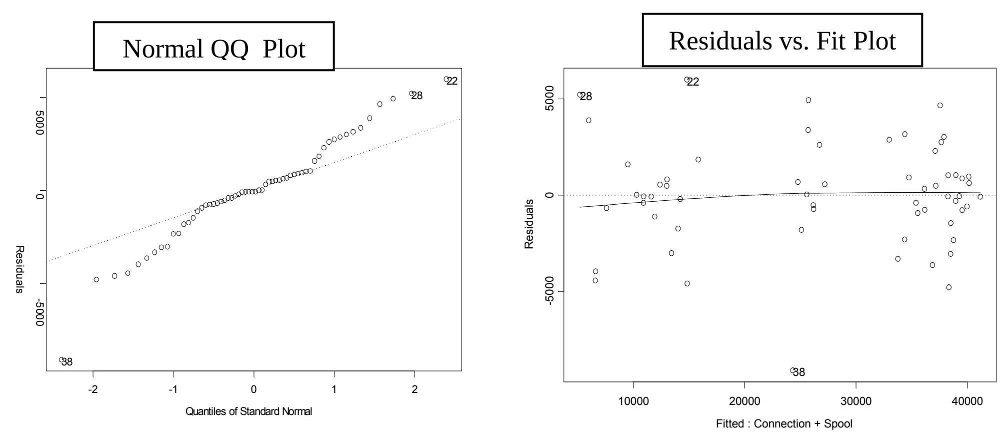

Figure 36. Normal QQ and Residuals vs. Fit plots for 9/16" data

4.3.2.2 Strength as a Percentage of the Buried Eye Splice

Similar to the 5/8" diameter test samples, the 9/16" test samples' breaking strengths were compared to the buried eye splice (Figure 37 and Figure 38 on pages 86-87). The relative breaking strengths can be seen in Figure 39 (page 88). the Whoopie Sling, long splice, Y-splice, pinned nubbin, and knuckle link represent the end connections with the highest breaking strengths relative to the buried eye splice. Section 8.7 in the Appendix lists the actual values for each end connection and spool obtained from each break test and their respective breaking strengths as a percentage of the buried eye splice. The mean percent strength for the long splice was nearly 100%, followed by the Y-splice at 93%, and then the Whoopie Sling at 88%. The pinned nubbin and knuckle link continued to be the best performers of end connections with hardware. The pinned nubbin achieved 99% and the knuckle link had a mean value of nearly 104%.

Similar to the performance of the 5/8" diameter test samples, the 9/16" test samples for the SEFAC™ and rope clamps were the next highest group of performers. The SEFAC™, performed at and average of 66% of the buried eye splice. However, there was large variability among the blocks as the breaking strengths ranged from 36% to 76%. The rope clamps on the other hand were more consistent in their performance. The mean breaking strength relative to the buried eye splice was 67%, with values ranging from 60% to 76%.

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. Table 21 shows the results of the Dunnett's multiple comparisons test. The p-values show that the Whoopie Sling, long splice, Y-splice, pinned nubbin, and knuckle link breaking strengths are not significantly different from the mean breaking strength of the buried eye splice. An important observation is that the Y-splice in the 9/16" diameter class is not significantly different because it had less variability in its break test performance. The standard deviation for the 9/16" was 3.2% and for the 5/8" diameter, it was 24%.

Table 21. Results from Dunnett's multiple comparisons for 9/16” diameter

9/16" Diameter

	Connection	Mean Strength	p-value
1	BES	38757.32	
2	Whoopie Sling	34176.74	0.1625
3	Long Splice	38314.21	1.0000
4	Y-Splice	35956.42	0.6843
5	Steel Nubbin w/ Phillystran	14630.13	< 0.0001
6	UHMW Nubbin w/ Phillystran	6407.47	< 0.0001
7	Steel Nubbin w/ 3M	N/A	N/A
8	UHMW Nubbin w/ 3M	N/A	N/A
9	Notched Steel Nubbin w/ Phillystran	12818.60	< 0.0001
10	SEFAC	25518.76	< 0.0001
11	Rope Clamps	25985.11	< 0.0001
12	Pinned Nubbin	38067.02	1.0000
13	Knuckle link	39944.35	0.9982
14	Pressed Nubbin	10722.43	< 0.0001

The Tukey-Kramer multiple comparisons procedure was used to make pairwise comparisons among the means of the end connection treatments. Table 22 shows the Tukey groupings for the 9/16” diameter rope. This table shows that the first grouping consists of the highest performers mentioned in the previous paragraphs: buried eye splice, Whoopie Sling, long splice, Y-splice, pinned nubbin, and the knuckle link. The second grouping follows with the rope clamps and the SEFAC^{TM}. Lastly, the mean breaking strengths of the adhesive nubbins (UHMW-PE and steel, and notched steel) along with the pressed nubbin were not significantly different and consisted of the last two groupings.

Table 22. Tukey groupings for 9/16" diameter

	End Connection													
Tukey Grouping	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	X	X	X	X								X	X	
B										X	X			
C					X	X			X					X
D						X			X					X

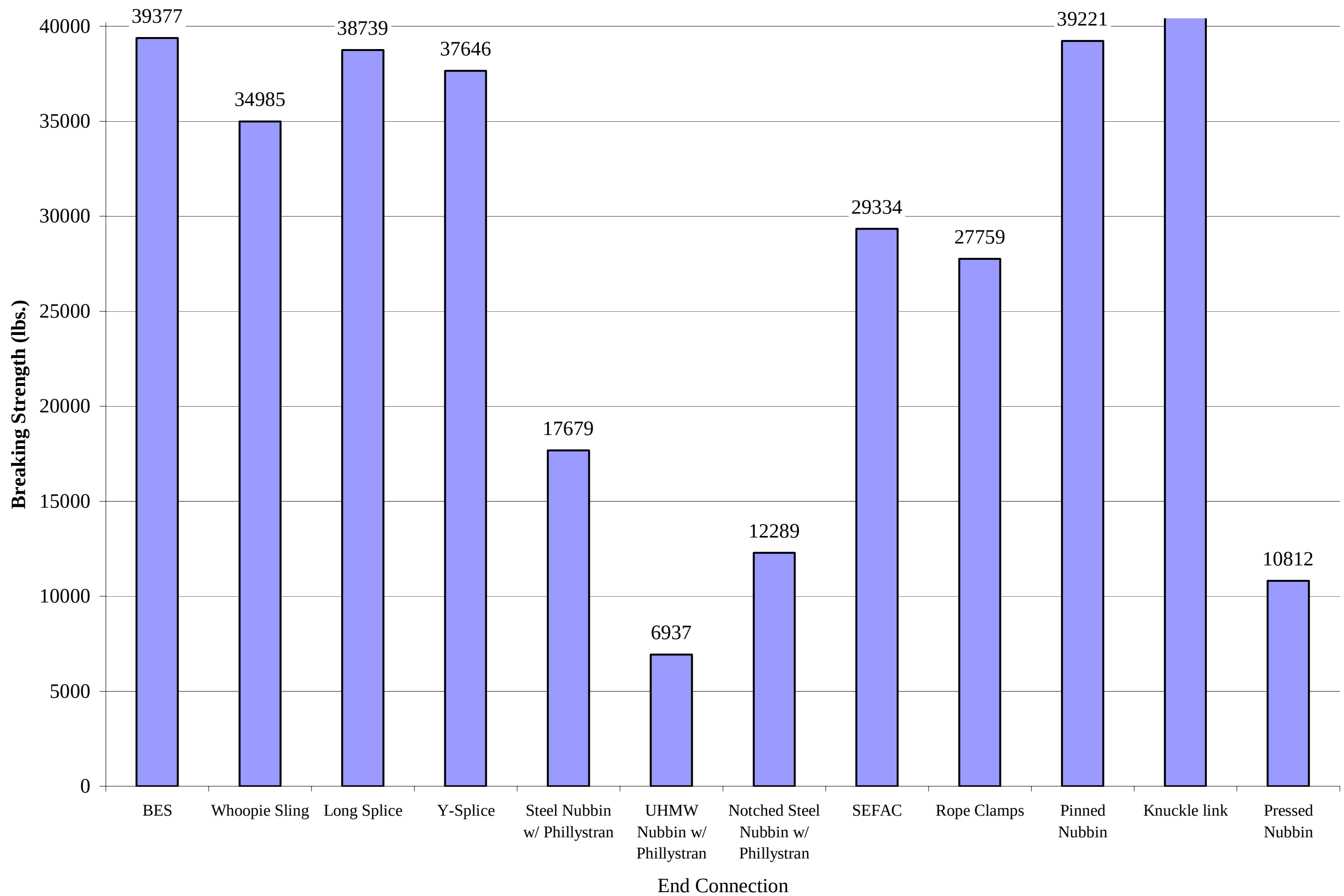

Figure 37. 9/16" diameter synthetic rope end connection mean breaking strengths

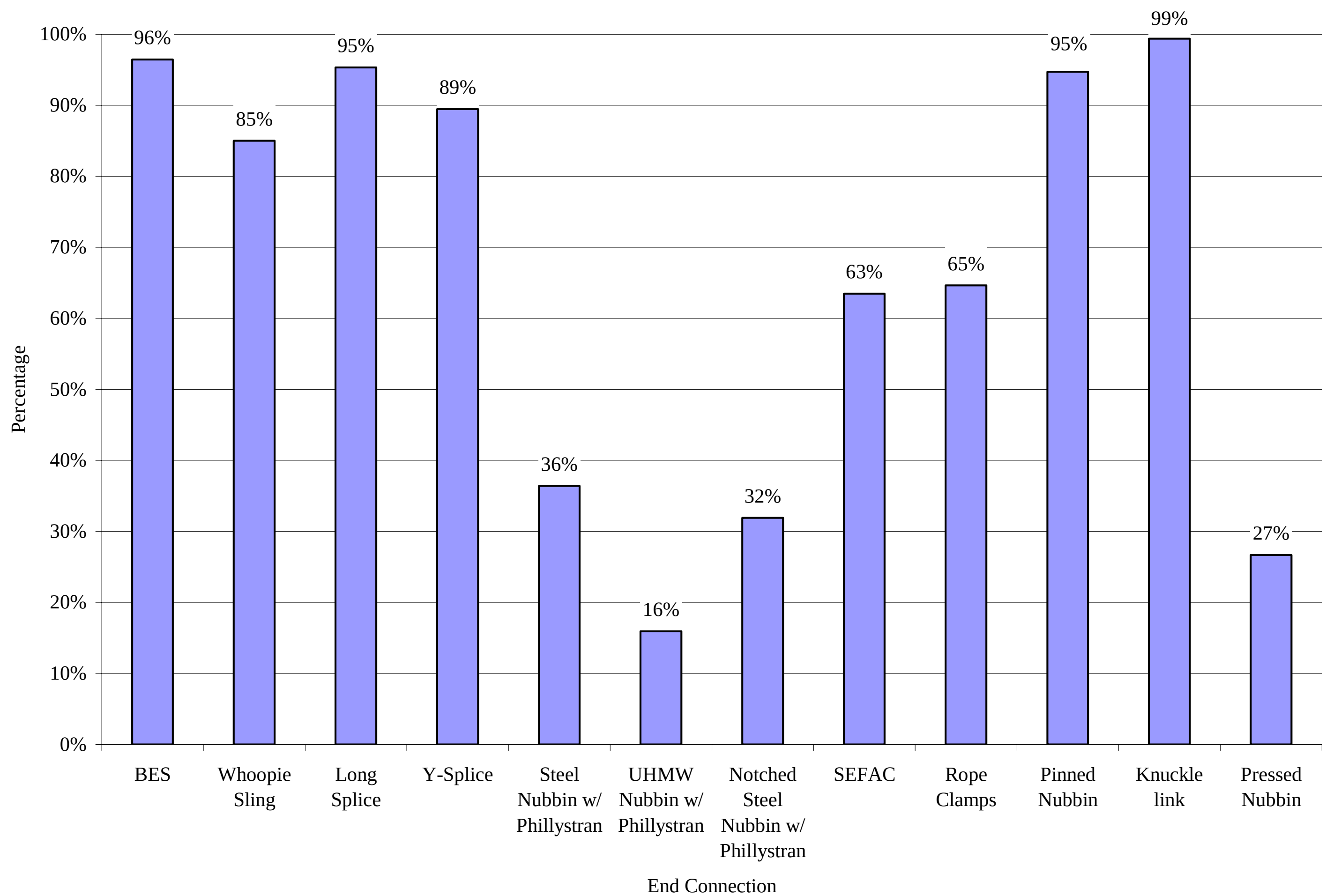

Figure 38. 9/16" Diameter average breaking strength as a percentage of catalogue minimum strength

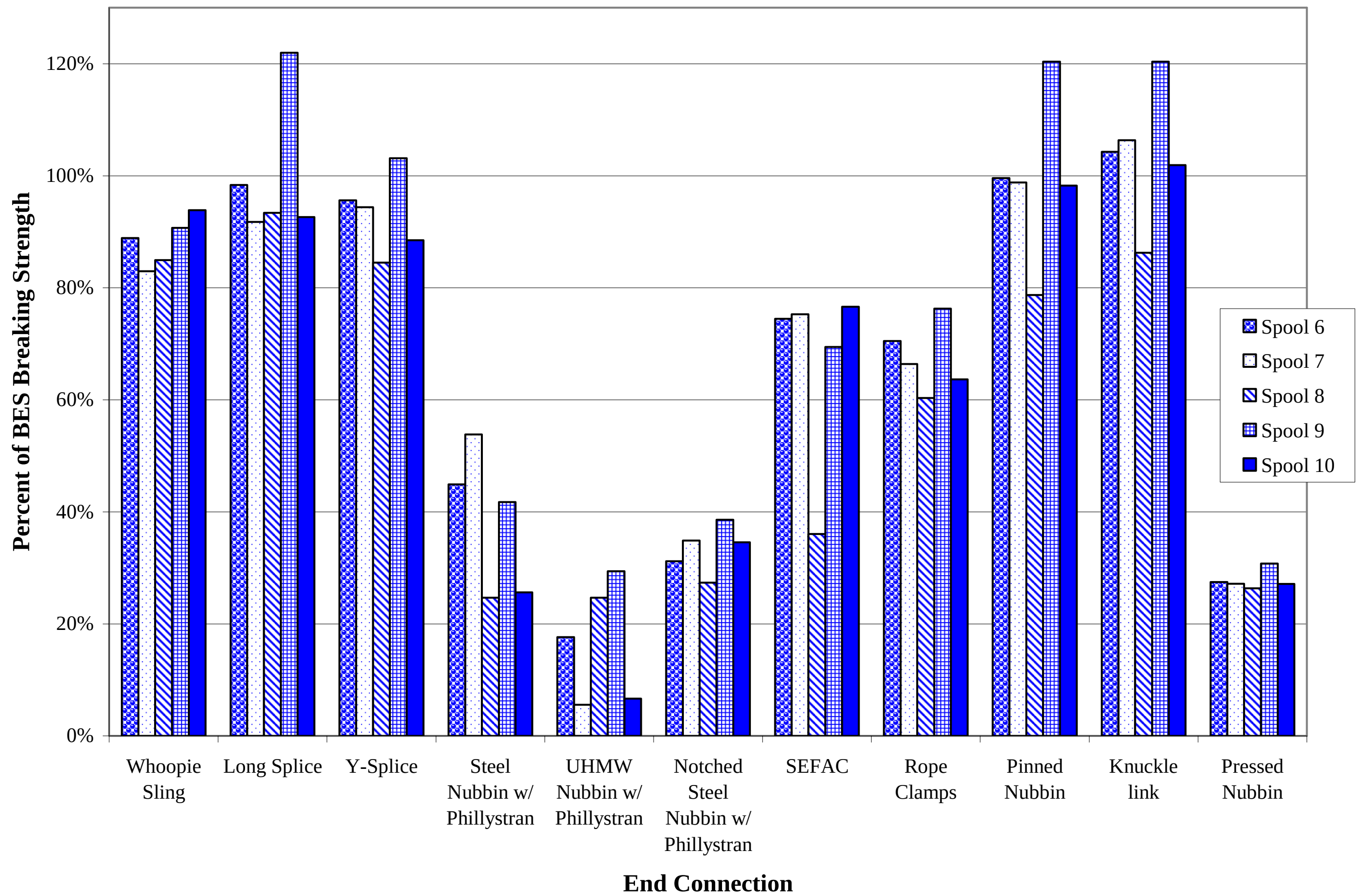

Figure 39. 9/16" Diameter Breaking Strengths Relative to the Buried Eye Splice

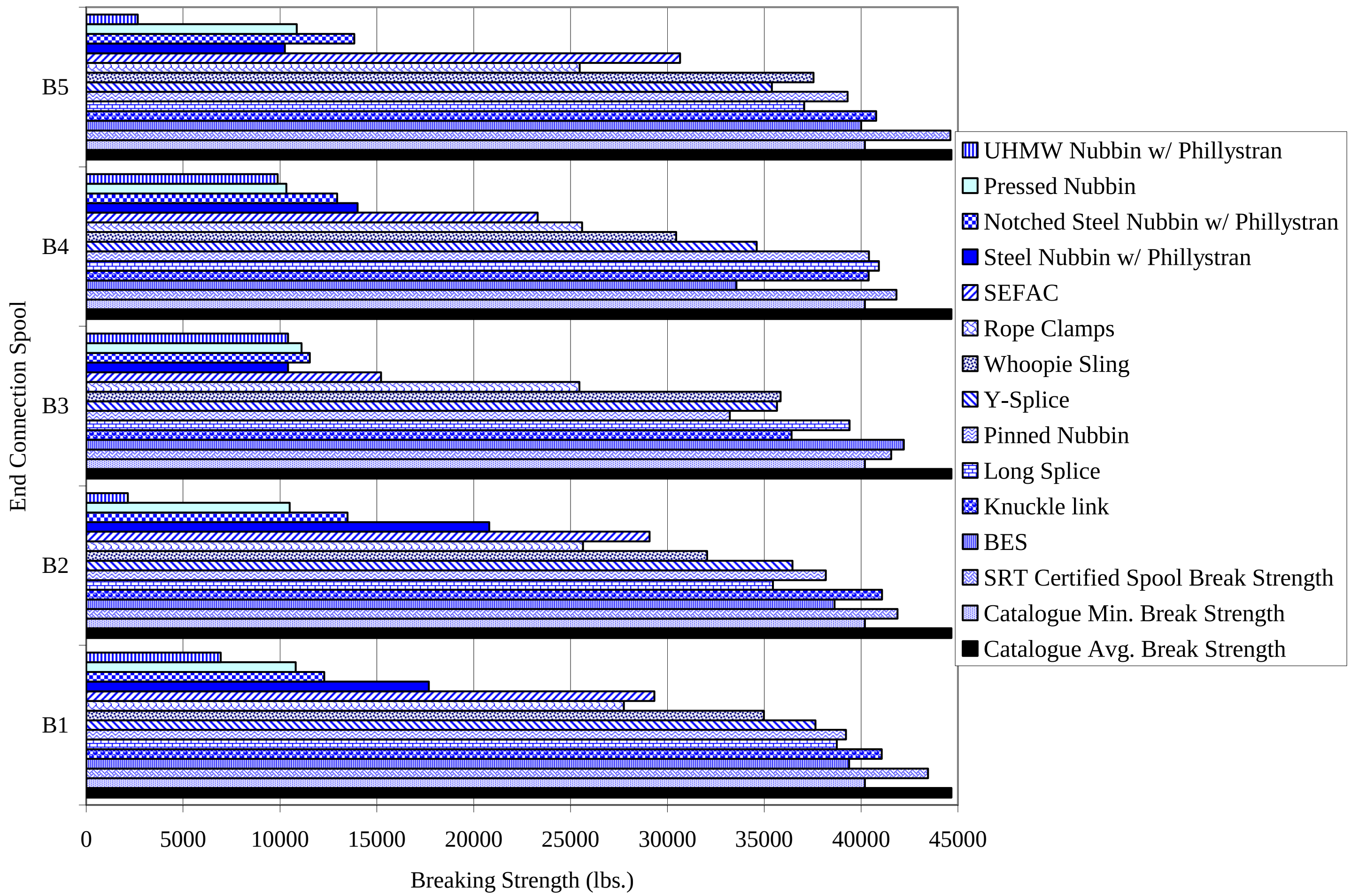

Figure 40. End Connector Breaking Strengths for 9/16" Synthetic Rope

4.4 3/8” Results

4.4.1 Break Test Results

Only two end connections were tested with the 3/8” diameter synthetic rope. As with the 9/16” and 5/8” diameter classes, the buried eye splice was also tested. In addition, truck wrappers were tested. Figure 41 shows the mean breaking strength for both end connections.

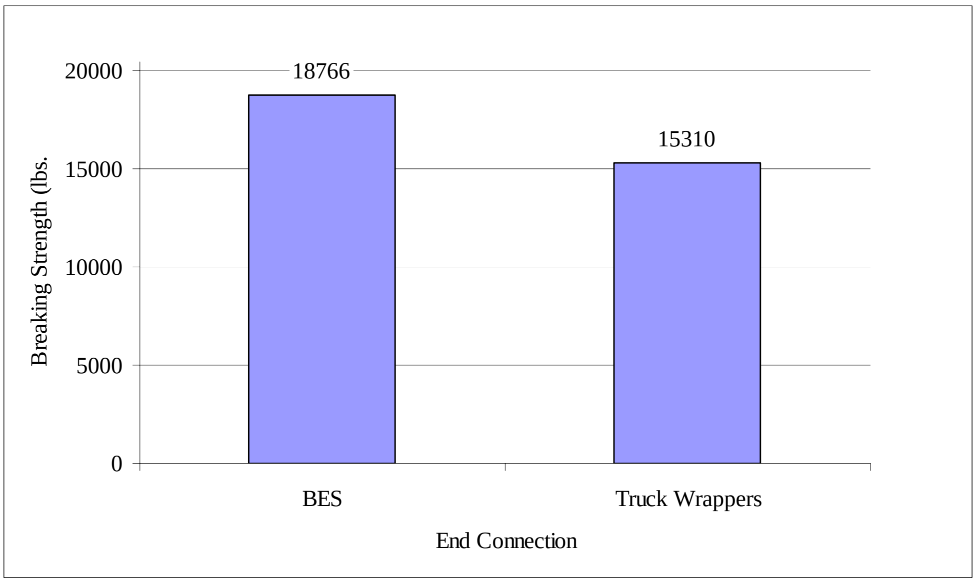

Figure 41. 3/8" diameter mean breaking strengths

The average ultimate loads are shown in Table 23. Figure 42 shows the breaking strength of the end connections as a percentage of the catalogue minimum value of 18,401 pounds. The buried eye splice had a relative mean breaking strength of 102%, while the wrappers had a relative mean breaking strength of 83% of the catalogue minimum.

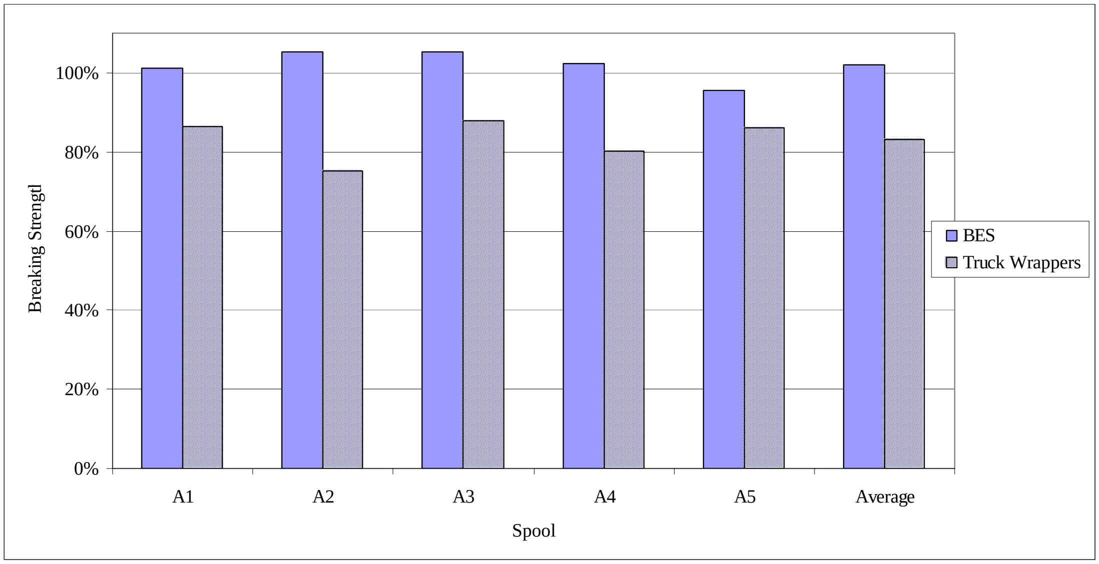

Figure 42. 3/8" Breaking strength as a percentage of catalogue minimum

The second end connection tested was the truck wrapper. The truck wrappers had breaking strengths that ranged from 13,847 pounds to 16,186 pounds with a standard deviation of 979 pounds. However, the average breaking strength of the truck wrappers was 15,310 pounds.

The range of values for the truck wrappers may be a small cause for concern. Although the 5 samples did exceed the minimum OR-OSHA requirement of 15,000 pounds with an average of 15,310 pounds breaking strength, the standard deviation was 979 pounds. The breaking strengths were as low as 13,847 pounds, which is significantly lower than the required 15,000 pounds.

Table 23. Breaking Sstrength and standard deviation for 3/8" diameter

End Connection	***(n = 5) for all***	***Average Breaking Strength***	***Standard Deviation (lbs.)***	***Standard Deviation (% of mean)***
1 Buried Eye Splice		18766	738	3.9%
2 Wrappers		15310	979	6.4%

Figure 43 shows the ultimate loads for both end connections from each spool. This figure plots these breaking strengths with the catalogue minimum, catalogue average, and peak loads reported from the certified Samson Rope Technologies break test report for each spool. The average breaking strength for the buried eye splice was 18,766 pounds.

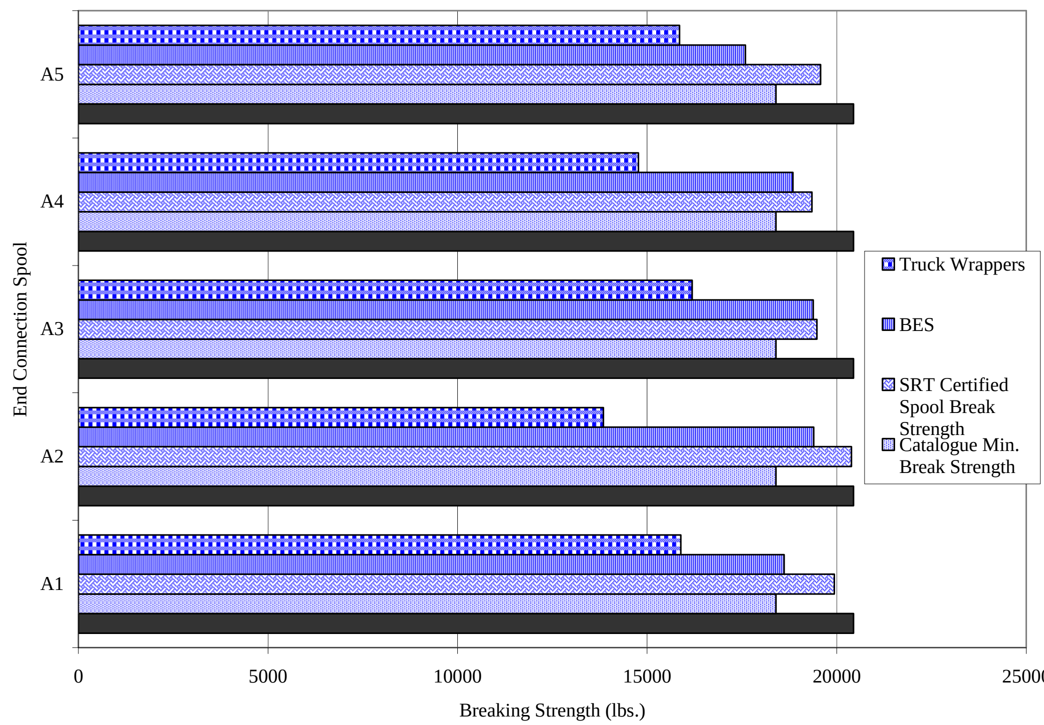

Figure 43. End connector breaking strengths for 3/8" synthetic rope

4.4.2 3/8" Statistical Results

Because the same experimental design was applied to all diameter classes and each class was treated as a separate randomized complete block design, the same analysis can be applied to the 3/8" diameter. First, an exploratory boxplot was created to examine the distribution of the breaking strengths for each connection (Figure 44).

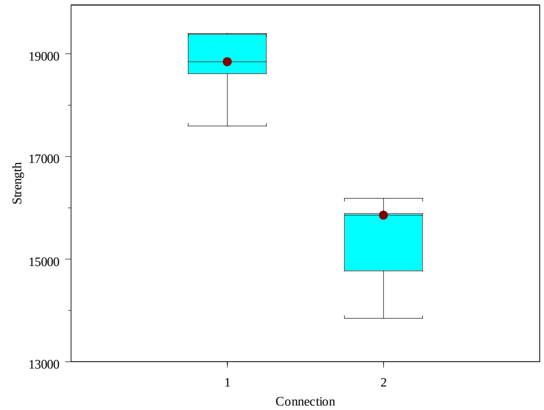

Figure 44. 3/8" diameter boxplot

Table 24 shows the ANOVA table from the same additive model as used for the 9/16" and 5/8" diameters: *Breaking Strength* = $Connection_i + Spool_j$

Similar to the 9/16" and 5/8" diameters, there was a significant treatment effect (p-value = 0.0058). However, there was not a significant block or spool effect (p-value = 0.7727).

Table 24. 3/8" ANOVA table

	Connection	Spool	Residuals
Sum of Squares	1856353	29863711	4152794
Deg. of Freedom	4	1	4

Residual standard error: 1018.9203
Estimated effects are balanced

	DF	Sum of Sq	Mean Value	F Value	Pr(F)
Connection	4	1856353	464088	0.447013	0.00583343
Spool	1	29863711	29863711	28.764930	0.77266528
Residuals	4	4152794	1038199		

The fit of the residuals are plotted in Figure 45. The distribution appears fairly normal and that they are not clustered. Because only a limited number of end connection types and thus only 10 samples were tested, the plot reflects these characteristics.

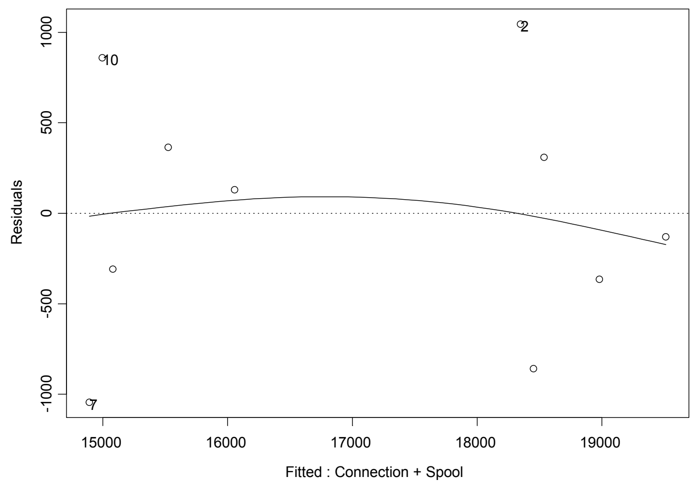

Figure 45. Residuals vs. Fit plot

On the left side of the graph, the residuals for the truck wrappers are plotted and on the right side, the buried eye splice residuals are plotted. The curvature of the graph makes sense because two distinct groups of end connections were tested. In addition, looking at the Normal QQ plot and the Response vs. Fit plots (Figure 46 and Figure 47), there is approximately a linear relationship. Therefore, the data was not transformed.

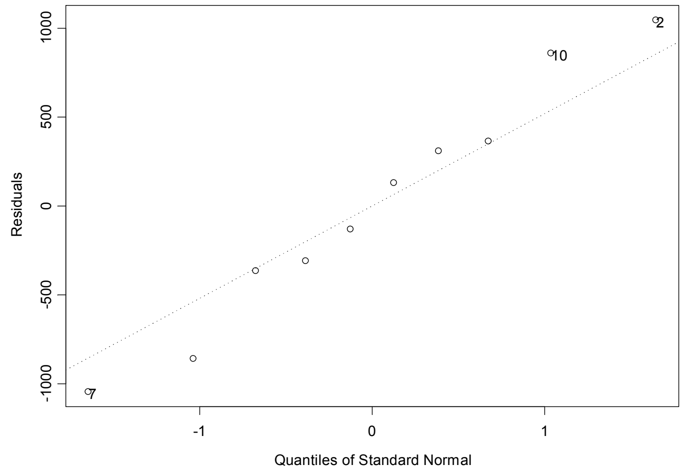

Figure 46. Normal QQ plot

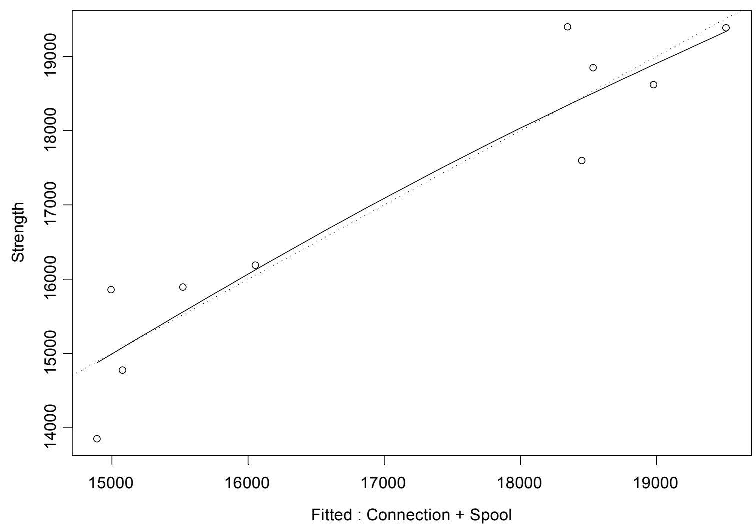

Figure 47. Response vs. Fit plot

4.4.2.1 <u>Strength as a Percentage of the Buried Eye Splice</u>

Relative to the breaking strength of the buried eye splice, the truck wrappers had a mean breaking strength of nearly 82% with a standard deviation of 5% to 7%. The relative strengths ranged from 71% to 90%. Table 25 shows the breaking strengths as a percentage of the buried eye splice and their respective standard deviations.

Table 25. 3/8" breaking strength as a percentage of the buried eye splice

	BES	Truck Wrappers	Standard Deviation
Spool 1	N/A	85.3%	7.2%
Spool 2	N/A	71.4%	6.9%
Spool 3	N/A	83.5%	5.0%
Spool 4	N/A	78.4%	6.1%
Spool 5	N/A	90.1%	6.0%
Mean	N/A	81.6%	

Although there were only two end connections tested at the 3/8” level, Dunnett’s multiple comparisons procedure was performed. This procedure is still useful because it compares the mean breaking strengths with a control and accounts for the variation among the five samples that make up the mean. A simple t-test would determine significance by only examining the two mean values. From the Dunnett’s procedure, the wrappers’ mean breaking strength was significantly different from the buried eye splice (p-value = 0.0058).

5 Discussion

The previous chapter presented results of the individual end connections over the three diameter classes. This chapter provides a description of the failure modes and the effects of failure on the rope and end connections. Furthermore, this chapter assesses the suitability of end connections for use in timber harvesting. This chapter uses the statistical analysis from the preceding chapter, the break test performance, and the effects on the rope as a basis to determine if the end connections can withstand the rigors of forest operations. Following the examination of end connection suitability, recommendations are made. The chapter finishes with implications and further research needs from this pilot study.

5.1 Failure Modes of End Connections for 9/16” and 5/8” Diameters

This study tested 15 total end connections. Fourteen different end connections in the 5/8” diameter were tested, twelve in the 9/16” diameter and two for the 3/8” diameter class. Table 26 shows the 15 different end connections tested for these diameter classes. Each concept tested a different design, and thus, the reactive forces and stresses were different in each. Different end connections produced different breaking strengths. The splice end connections tested different splice configurations and the rope’s ability to constrict on itself and resist the tensile load.

Table 26. End connections tested

	Spliced
1	Buried Eye Splice
2	Whoopie Sling
3	Long Splice
4	Y-Splice
	Adhesives
5	Steel Nubbin w/ Socketfast Blue A-20
6	UHMW-PE Nubbin w/ Socketfast Blue A-20
7	Steel Nubbin w/ Scotchweld DP-8010
8	UHMW-PE Nubbin w/ Scotchweld DP-8011
9	Notched Steel Nubbin w/ Socketfast Blue A-20
10	SEFAC
	Dry Hardware
11	Rope Clamps
12	Pinned Nubbin
13	Knuckle Link
14	Pressed Nubbin
X	Truck Wrappers (for 3/8" diameter only)

Additional hardware was also evaluated. Some hardware was adapted from current wire rope technology and some new designs were developed. The strength of wire rope hardware was also combined with the holding strength of adhesives. Different end connections produced unique breaking strengths, and failure modes are different from those commonly seen in wire rope.

The failures of the end connections were catastrophic (save the nubbins with 3M Scotch-Weld™ DP-8010 adhesive). As a result of the stored energy in the strands, the synthetic rope would often recoil. The failure modes of individual end connections were examined along with the failure effects on the rope and hardware. The following subsections discuss the performance of the end connections in break tests.

5.1.1 Buried Eye Splice

The buried eye splice continues to be the standard end connection for many synthetic rope applications. The splice is easily performed and represents the rope breaking strength listed in the manufacturer's catalogue (Samson Rope Technologies A., 2002).

There were two failure modes that occurred during the break tests. The most common was the rope breaking at the end of the rope taper where the buried tapered tail ends inside the rope (Figure 48). At this point, there is an apparent redistribution of loads. The load is shared between two rope segments in the buried section to the end of this taper, the load is taken by a single rope segment. The constrictive forces on the strands are thus distributed differently. Each strand sees a different load because the tensile force is divided between fewer strands. The manufacturer recommends minimizing this transition effect by using a 50% taper on the last fid-length of the buried tail (Stenvers, 2003). Any modification in the rope structure that causes an immediate change in rope form will be a weak point in the rope. Additionally, a common characteristic of this failure mode is having one strand remaining unbroken. As the strands fail, it is assumed that most of the energy is kinetic (i.e. the rope springs back upon failure). Some of the energy however, is converted to heat. This heat energy will be discussed later in this chapter.

The second failure is less common and occurred when the test specimen broke within the "clear" section (Figure 48). The clear section is defined as the section of rope that is unmodified and untreated between the two eye splices. Although a standardized procedure was used to construct the buried eye splice, samples did break differently.

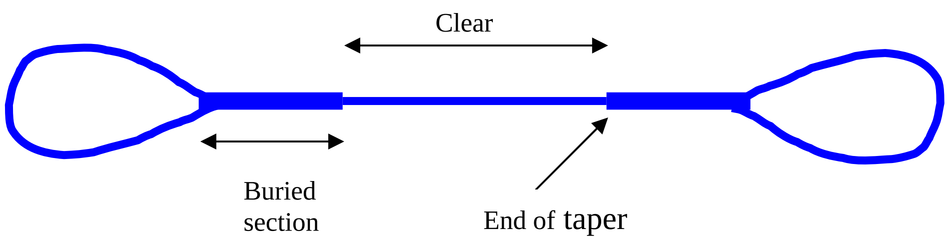

Figure 48. Diagram of buried eye splice test specimen

Table 27 shows the two types of failure modes for the buried eye splice from the three diameter classes and the associated breaking strengths. These results do not imply that there is any correlation between the point of failure and the breaking strength of the rope. Table 28 shows the mean breaking strengths for each of the three diameter classes over the five spools.

Table 27. Failure modes and associated breaking strengths

Diameter	BES Failure Mode	No. of occurences	% of Catalogue minimum	Mean Breaking Strength (lbs.)
5/8"	End of taper	4	94.9%	50414
5/8"	In the clear section	1	92.8%	49280
9/16"	End of taper	4	96.5%	38787
9/16"	In the clear section	1	96.1%	38638
3/8"	End of taper	5	102.0%	18766
3/8"	In the clear section	0	N/A	N/A

Table 28. Mean breaking strengths of the buried eye splice

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue minimum
3/8"	18766	102.0%
9/16"	38757	96.4%
5/8"	50187	94.5%

5.1.2 Whoopie Sling

During testing of the Whoopie Sling, the test specimens had the same point of failure in all but one case. The Whoopie Sling broke at the exit point of the adjustable tail with the butt splice. The rope failure occurred in the segment that was buried and not the tail section.

As with the buried eye splice, the load on the Whoopie Sling is distributed differently through the buried section than on the ends of the sample near the eyes. At the point where the tail exits from the adjustable section, a change in load distribution on the strands occurs. This transition is similar to the failure point on the buried eye splice. Although the point of failure was the at the tail exit, the end of the tail with the butt splice was not experiencing any of the load. It remained limp and unstressed. This is an important concept because the unstressed tail means that the buried section was holding the tensile load and that slippage of the tail was minimal. The Whoopie Sling was effective in holding approximately 85% of the catalogue minimum breaking strength (Table 29).

Table 29. Mean breaking strengths of the Whoopie Sling

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	34177	85.0%
5/8"	45571	85.8%

5.1.3 Long Splice

Aside from the buried eye splice, the long splice had the highest breaking strength of the tested spliced end connections. The 9/16” diameter samples had an average breaking strength of 38,314 pounds 95% of the catalogue minimum of 40,194 pounds (Samson Rope Technologies A., 2002). Similar to the other spliced rope end connections, the most common point of failure was at the end of the buried tail taper. All but one sample broke in this way. Only one sample broke at the rope interchange where the two ends are tucked into each other. Table 30 shows the failure modes, number of occurrences, and mean strengths for each diameter. Table 31 shows the overall mean breaking strengths for the two diameter classes.

Table 30. Failure modes and associated breaking strengths

Diameter	Failure Mode	No. of occurences	% of Catalogue minimum	Mean Breaking Strength (lbs.)
5/8"	End of taper in LS	4	91.6%	48626
5/8"	End of taper in BES	1	79.6%	42264
5/8"	Rope interchange	0	N/A	N/A
9/16"	End of taper in LS	4	94.3%	37901
9/16"	End of taper in BES	1	99.9%	40161
9/16"	Rope interchange	1	88.2%	35446

Table 31. Mean breaking strengths for the long splice

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	38314	95.3%
5/8"	47354	89.2%

From these results, it is evident that the long splice does not create a weak point when splicing two ropes together. The long splice was designed specifically to be used in two different situations. Long splices may connect two used pieces of rope together after a failure, or a new section of rope may be spliced into an existing used rope.

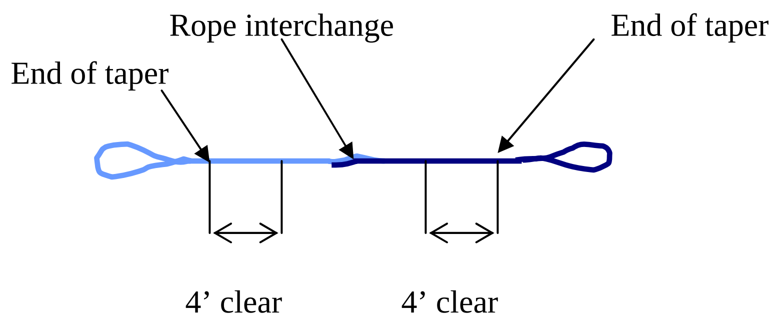

Figure 49. Long splice diagram

The tests performed show that the long splice does not produce a weak point at the rope interchange most of the time (Figure 49). However, the one sample that broke at the rope overlap cannot be ignored. Careful splicing techniques are essential to ensure proper loading of the strands. Even with careful preparation methods, absolute rope breaking strength can vary due to rope construction practices. Loading of the strands may not be uniform due to the way rope is used.

Careful and uniformed splicing procedures do not always produce the same results. Long splice tests were in a controlled setting and within that setting, breaking strengths varied. In the case of the 5/8" diameter rope, the average breaking strength was 46,354 pounds, or 89% of the catalogue minimum. Sample C2 broke at 78% of the catalogue minimum, whereas the other four samples averaged a breaking strength of close to 90% of catalogue minimum breaking strength. However, the long splice does meet many of the timber harvesting needs. It is the only spliced end connection that will connect two pieces of used or new rope. The long splice allows in-field replacement of damaged or severed sections of synthetic rope while retaining a high percentage of the breaking strength of the rope. In the absence of this end connection, loggers would discard used synthetic rope.

5.1.4 Y-splice

The Y-splice is not currently used within the logging industry. It has found limited applications within the shipping, high-tension power line, or deep sea salvage industries for example. Due to these industries' use of high strength rope in dynamic applications, the Y-splice has been absent in use. The Y-splice is best suited for static line applications.

The Y-splice concept is similar to the long splice in that it allows the user to attach a separate length of rope to the existing length or spool (Figure 50). The Y-splice was designed so that an additional length of line, or perhaps more than one, can be attached to the main section to provide a better load distribution. When a guyline is loaded, each eye of the rope segment will hold the load. The Y-splice however, behaves differently. Instead of the main section holding the entire load, a segment is spliced into the main section. Now, the load can be shared between two sections of rope. Though this concept appeared promising in logging, it had to be tested in a controlled laboratory setting.

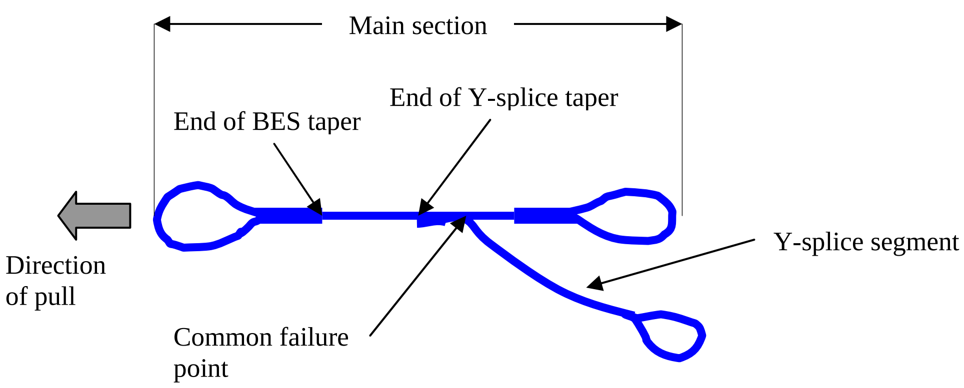

Figure 50. Y-splice diagram

For both the 9/16” and 5/8” diameter test specimens, the most common point of failure was at the exit point of the added section of rope within the main section. This particular failure is an area of concern. Table 32 shows the different failures of the test samples and their respective breaking strengths. One 9/16” and three 5/8” samples’ spliced tail simply pulled out of the main section during the test. In two cases, samples were unable to withstand ten cycles before failing. In the other two cases, the samples underwent the ten cycles, but failed early in the eleventh cycle. The mean breaking strengths for the Y-splice are shown in Table 33.

Table 32. Failure modes and associated breaking strengths

Diameter	Failure Mode	Spool	No. of occurences	% of Catalogue minimum	Mean Breaking Strength (lbs.)
9/16"	Exit of Y-segment	B1, B3	2	91.2%	36656
9/16"	End of taper in Y-segment	B4	1	86.1%	34610
9/16"	Tail pulled out	B5	1	88.1%	35397
9/16"	End of BES taper	B2	1	90.7%	36462
5/8"	End of taper in Y-segment	C1, C2, C3	3	59.6%	31643
5/8"	Tail pulled out	C4, C5	2	82.1%	43631

Table 33. Mean breaking strengths for the Y-splice

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	35956	89.5%
5/8"	36438	68.6%

All ten samples were lock-stitched with the appropriate polyester stitching rope. The purpose of the lock stitch is to prevent pulling the splice out while working the synthetic rope segments. The lock stitch is not intended to add strength or support any loads. Tests found that the lock stitch is essential in the pretensioning phase of the test. Initially, the main section of the rope is connected to the hydraulic ram. The other end lies limp and unconnected on the test bench. It is not loaded during the entire break test. The spliced tail of the Y-splice is attached to the chain. Because tension is not applied to both ends of the main section of rope, the unconnected main section of the rope does not provide any gripping or compressive strength to hold the untensioned Y-splice section. Without a lock-stitched sample, the Y-splice section tends to slip out of the main section of the rope. Although the lock stitch essentially “locks” the Y-splice into the main section of rope, it only provides holding strength until the rope constricts enough to grip the Y-splice. Therefore, it was essential that the tensioning of the rope be done slowly and carefully.

Because of the tendency of the Y-splice to slip from the main section under conditions where both ends of the main sections are not under tension, **the Y-splice should not be used in situations where shock loading is possible in untensioned rope segments.** Pretensioning must be done slowly and carefully and the inability of the main section of rope to quickly grip the Y-splice with no pre-tension applied to it limits the use of the Y-splice. **If both ends of the main section of rope were tensioned along with the Y-splice, then the rope would constrict on the Y-splice section from both axial directions.**

Despite this major drawback, the Y-splice did perform well in laboratory tests. The 9/16” diameter samples performed more consistently than the 5/8” samples. In two out of the five samples, the specimens failed in locations other than at the exit point of the Y-splice section. The Y-splice can attain high breaking strengths. The average breaking strength for the 9/16" diameter specimens was 89% of the catalogue minimum with individual strengths ranging from 86-93%. These results are relatively consistent.

The 5/8" test samples, with an average of 69% of catalogue minimum breaking strength, were less consistent. The Y-splice section of samples C1 and C2 failed (pulled out) during the first full cycle of the break test. All samples were prepared in a controlled environment and the pretensioning was done at the same rate for all samples. These results do show variation in the rope construction and compressive forces on the Y-splice section within the main section of rope. Omitting these two samples would yield an average of almost 81% of the catalogue minimum. These results are strikingly different from what is reported as the five-sample average, but it is still not permissible to ignore the other two lower data points. Samples C3, C4, and C5 show a more positive result with higher breaking strengths. Low breaking strengths and the inability to withstand cyclic loading of samples C1 and C2 may not be isolated incidents. Tests were performed under close scrutiny and controlled conditions. Loggers, rigging shop employees, and equipment operators must be keenly aware of the importance of slow, careful pretensioning procedures with the Y-splice. They should also know that breaking strengths of 80-90% might be attainable, but improper use of the Y-splice and lack of pretensioning can drastically reduce its strength.

5.1.5 Pinned Nubbin

The pinned nubbin was developed during this study to solve the challenge of achieving acceptable breaking strengths with a durable termination. Until this concept was tested, the spliced rope end connections consistently achieved the highest breaking strengths. However, some timber harvest applications require a solid termination on the rope. Traditionally, winch drums have a ferrule pocket where steel wire rope connected to a steel nubbin slides into position and locks into place. For the drum applications on equipment, an eye splice may not be appropriate.

The pinned nubbin combines the strength and holding force of the splice connection with the durability of hardware. It achieved an average of 95% of the catalogue minimum breaking strength for 9/16” diameter test samples and 92% for the 5/8” diameter samples.

The pinned nubbin was designed using basic engineering strength of materials and beam deflection principles. There were also some size design constraints of the typical ferrule pocket for drums. The rope manufacturer recommended a D/d ratio of no less than 3:1. Initial testing with a simple Grade 8 bolt found that the D/d ratio could go less than 1:1 (rope diameter = 5/8”; bolt diameter = 1/2”) and still achieve respectable breaking strengths. However, with increasing diameter of the pin, there was less room for the rope to bend around the pin and fit inside the nubbin. The pinned nubbin was designed to maximize volume inside, but also provide enough wall strength to withstand the axial compression the nubbin would endure on the test bench and on a winch drum. Furthermore, the width of the pin was reduced, while the length was elongated. This new pin shape provided more strength and was less susceptible to bending fatigue. The nubbin was designed so that the synthetic rope would fail before the pin. Table 34 shows the mean breaking strengths for the 9/16” and 5/8” diameters

Table 34. Pinned nubbin mean breaking strength

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	38067	94.7%
5/8"	48868	92.0%

Test samples failed in two distinct ways. The breaking strengths of these test samples are shown in Table 35. The first failure mode was experienced in eight of the ten specimens. These eight rope samples failed at the end of the tapered buried tail. This same failure was seen in many of the spliced rope connections. Such a failure is good evidence that the end connection is doing its job at withstanding the axial loading. Also, the nubbin is withstanding the compressive loading on the test block.

Any effects of the sharp bend in the rope around the pin and other unseen effects of the nubbin are secondary to the stresses at the end of the taper. Essentially, this failure mode shows that the rope is failing before the effects of the end connection can cause a failure.

Table 35. Failure modes for the pinned nubbin

Diameter	Failure Mode	Spool	No. of occurences	% of Catalogue minimum	Mean Breaking Strength (lbs.)
9/16"	End of taper in BES	B1, B2, B4, B5	4	97.7%	39276
9/16"	Top of eye (in nubbin)	B3	1	82.7%	33231
5/8"	End of taper in BES	C1, C2, C3, C4	4	91.4%	48525
5/8"	Top of eye (in nubbin)	C5	1	94.6%	50239

However, the second failure mode (seen in Figure 51) was at the top of the eye where the rope was sharply bent around the pin.

Figure 51. A) Pinned nubbin before break test

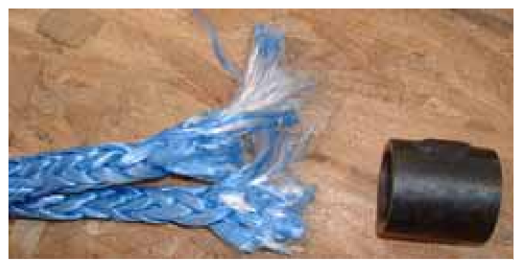

Figure 51. B) Pinned nubbin after break test

This failure mode occurred once in each diameter class, meaning that the 5/8" and 9/16" synthetic ropes are susceptible to bending failure. In the case of the 9/16" diameter, sample B3 failed at 74% breaking strength, significantly lower than the other four 9/16" test specimens. Sample B3 failed at the top of the eye and the other four samples failed at the end of the taper. In comparison, 5/8" sample C5 failed at the top of the eye and had a breaking strength of 93% breaking strength. Sample C5 had the highest of the five 9/16" test samples. Therefore, it is difficult to draw inferences between failure modes for the pinned nubbin.

5.1.6 Knuckle Link

The knuckle link was the second end termination developed as a combination of a buried eye splice and designed hardware. It achieved an average of 99% of the catalogue minimum breaking strength for the 9/16” diameter test specimens and 96% of the catalogue minimum for the 5/8” diameter specimens (Table 36). This concept is similar to the pinned nubbin. It combines the holding strength of a buried eye splice with the rigid material properties of steel hardware for a termination.

As with the pinned nubbin, the knuckle link had the same two failure modes: at the end of the taper and at the top of the eye where the rope is sharply bent around the “pin” (seen in Figure 52). All of the 9/16” specimens broke at the end of the taper, whereas two of the 5/8” specimens failed at the top of the eye (Table 37). In this case, the larger diameter could have an effect on the forces generated as the rope is pulled and bent sharply around the pin. It should be noted the knuckle link pin is wider and longer than the pin on the pinned nubbin. The knuckle link generated higher breaking strengths, possibly due to the higher D/d ratio. Table 38 shows the D/d ratios for both the pinned nubbin and the knuckle link.

Figure 52. Knuckle link in test block with test collar before break test

Figure 53. Failed knuckle link after break test

Table 36. Knuckle link mean breaking strength

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	39944	99.4%
5/8"	51172	96.3%

Table 37. Failure modes for the knuckle link

Diameter	Failure Mode	Spool	No. of occurences	% of Catalogue minimum	Mean Breaking Strength (lbs.)
9/16"	End of taper in BES	B1-B5	5	99.4%	39944
9/16"	Top of eye (at knuckle)	N/A	0	N/A	N/A
5/8"	End of taper in BES	C2, C4, C5	3	95.0%	50469
5/8"	Top of eye (at knuckle)	C1, C3	2	98.3%	52228

Table 38. D/d ratios for the pinned nubbin and knuckle link

End Connection	Pin Diameter (D)	Diameter (d)	D/d ratio
Pinned Nubbin	1/2"	5/8"	0.8
		9/16"	0.9
Knuckle Link	5/8"	5/8"	1.0
		9/16"	1.1

5.1.7 Rope clamps

The use of wire rope clamps was an attempt to combine existing steel wire rope technology with synthetic rope. Four standard Crosby® Clips were used to secure the tail of the rope to itself. No modifications were made to these clips prior to break testing the test specimens. Although the recommended pressure is 90 foot-pounds, it was only physically possible to tighten each bolt to 45 foot-pounds with a torque wrench. After the tenth cycle of the cyclic loading phase of the break test, some bolts had become loose as the diameter of the rope became smaller. All bolts were retightened to 45 foot-pounds before the eleventh cycle (specimen loaded to failure) began. Even though the pretest procedure was standardized, different breaking strengths were attained. The 9/16" samples obtained an average of 65% of the catalogue minimum breaking strength. The 5/8" samples were slightly lower at 57% of the catalogue minimum (Table 39).

Table 39. Mean breaking strength of rope clamps

Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.
9/16"	25985	64.6%
5/8"	30294	57.0%

Because the wire rope clamps were unmodified prior to testing and were originally designed for wire rope applications, the breaking strength of the rope could have been decreased simply by using the clamps. Wire rope is resistant to sharp objects and to pinching; synthetic rope is not. Standard wire rope clamps are forged. The bottom bracket is especially rough and when enough compressive force is applied, may cut into the synthetic rope. Any burs or sharp edges were smoothed prior to testing. Under intense compressive forces and axial loading, the movement of the rope on the forged bracket itself during cyclic loading could help initiate failure.

Additionally, the rope diameter decreases as the axial tension increases. The bolts are rechecked and tightened following the initial ten cycles, but not during the cyclic loading. As the diameter decreases, there is less surface area in contact with the u-bolt. Holding strength thus decreases and rope begins to slip. Figure 54 shows an example of this phenomenon.

Figure 54. Test specimen exhibiting rope clamp slippage after a break test

The addition of the fourth clip into the system was an attempt to mitigate the slipping. However, the three wire rope clamp configuration was not tested.

As expected, the failure of the clamps generates heat. All samples had at least one unfailed strand. This failure is similar to the spliced connections where the unfailed strands are quickly pulled through the rope. This causes some recoil near the eye, but it also causes frictional heat build-up. Enough heat is generated that the rope clamps are warm to the touch following failure. In fact, some bolts were heated enough that the u-bolt threads expanded and hindered immediate loosening and removal of the nuts.

Although this end connection concept achieved 57% and 65% breaking strengths for the for the 5/8” and 9/16” diameter synthetic rope respectively, there could be some improvements to reduce wear or early failure. The forged fitting could be smoothed. A stainless steel version of these clips is available. However, a smooth surface characteristic of stainless steel reduces the coefficient of friction and the ability of the SEFAC™ resist axial loading. The clip and u-bolt could be coated with a rubberizing agent to increase grip strength and reduce abrasion from the forged pieces. Another problem with this system was the slipping of the clips. Whether the last clip (furthest from the eye) slipped first and created a snowballing effect with the others is not known. If the slipping of the rope through the last clip furthest from the eye could be prevented, the breaking strength of this end connection could increase. Is equal spacing of the four clips at given intervals appropriate? Perhaps the third clip could be placed closer to the last clip to prevent slippage. Another option is to place the clips closer together to prevent the slippage of the clips and bunching of the rope seen in Figure 54.

Finally, a Fist Grip® rope clip could be used instead of the u-bolt wire rope clamps. This design may provide a more uniform load distribution and its geometry might be better suited to grip the synthetic rope. However, this concept has not yet been tested with synthetic rope.

5.1.8 SEFAC™

As noted in the previous chapter of this thesis, the SEFAC™ attained an average of 42% of the minimum breaking strength for the 5/8" diameter and 63% for the 9/16" diameter. Although the 9/16" test samples show some promise, this end connection performance must be questioned. A quick test of the 5/8" SEFAC™ without the adhesive yielded only 12%. Although a single sample was tested, it indicated that the adhesive is necessary to provide increased breaking strength.

The potting method with the Phillystran Socketfast® Blue A-20 adhesive is extremely messy and the fumes are strong. In addition, the adhesive has a low viscosity. Under controlled conditions, it is difficult to prevent it from running down the interior of the rope. In addition, it was extremely difficult to monitor the adhesive distribution in the fibers and within the socket under these controlled conditions. Varying amounts of adhesive coverage directly affected the performance of each test specimen. Better coverage meant more bond area and increased breaking strength. However, it was nearly impossible to monitor the adhesive coverage and ensure equality among the five test samples.

Some flags must be raised when considering the SEFAC™ termination in the field or even in a rigging shop. Weight is an important consideration. Table 40 shows the weights of the SEFAC™ and rope weight for 100 feet. The 5/8" SEFAC™ weighs 15% of the 100-foot rope weight and the 9/16" SEFAC™ weighs 13% of the 100-foot rope weight. These end connections may be too heavy and difficult fabricate to be considered for timber harvesting applications.

Table 40. SEFAC™ and synthetic rope weights

	Weight (lbs.)
9/16" SEFAC	1.2
5/8" SEFAC	1.4
100 feet of 9/16" Amsteel Blue	7.9
100 feet of 5/8" Amsteel Blue	10.2

Furthermore, the inability to ensure complete coverage of the rope fibers is a serious problem. Inconsistent breaking strengths are a safety concern. Under controlled conditions, the 5/8" SEFAC™ achieved a maximum breaking strength of 26,474 pounds, 50% of the catalogue minimum. Although the maximum value of the five test samples was 50% of the catalogue minimum, the standard deviation was 6,413 pounds. Such a large variation in strength makes it difficult to suggest which value to use for logging applications. Table 41 summarizes the SEFAC™ test results.

Table 41. SEFAC™ break test results

Diameter	Spool	Breaking Strength (lbs.)	% of Catalogue Min.	Avg. Breaking Strength (lbs.)	Avg. % of Catalogue Min.
9/16	B1	29334	73.0%		
9/16	B2	29077	72.3%		
9/16	B3	15225	37.9%	24234	63.5%
9/16	B4	23300	58.0%		
9/16	B5	30658	76.3%		
5/8	C1	20782	39.1%		
5/8	C2	16473	31.0%		
5/8	C3	25293	47.6%	22256	41.9%
5/8	C4	26474	49.8%		
5/8	C5	22195	41.8%		

The performance of the 9/16" SEFAC™ samples is similar. Of the five 9/16" SEFAC™ samples, the maximum breaking strength achieved was 30,658 pounds, 76% of the catalogue minimum. However, the average breaking strength of these 5 samples was 25,519 pounds, only 64% of the catalogue minimum. The lowest value achieved from the testing was 15,225, only 37% of the catalogue minimum. It is evident that the breaking performance is quite variable and again raises the question as to which value to use as the breaking strength for the end connection. However, when considering timber harvesting systems, safety should be the number one concern.

The SEFAC™ was tested because the fiber manufacturer recommended it. DSM tests have obtained 70% ultimate breaking strength with 10 mm (0.39") diameter ropes (DSM B., 2002). It is a unique end connection for synthetic rope because it combines the bonding of an adhesive with a compression fitting. Breaking strength performance consistency is a primary concern with the SEFAC™ end connection. The variability of the breaking strengths is too large under controlled conditions. **From the results of the 5/8" and 9/16" diameters in this study, the SEFAC™ should not be recommended for use with timber harvesting applications.**

5.1.9 Pressed Nubbin

The pressed nubbin was another attempt to use existing technology with synthetic rope applications. However, it only achieved an average breaking strength of 27% of the catalogue minimum for 9/16" and 21% of the catalogue minimum for 5/8". Overall, the pressed nubbin held approximately 10,000 pounds for both diameters (Table 42). Although the two diameter classes have different mean percentages of the catalogue minimum value, a t-test concludes that the two means are not significantly different (p-value = 0.2545). All five samples of each diameter class failed in similar fashion: the rope pulled out and there was no recoil.

Table 42. Pressed nubbin break test results

Diameter	Spool	Breaking Strength (lbs.)	% of Catalogue Min.	Standard Deviation	Avg. Breaking Strength (lbs.)	Avg. % of Catalogue Min.
9/16	B1	10812	26.9%			
9/16	B2	10498	26.1%			
9/16	B3	11118	27.7%	0.8%	10688	26.7%
9/16	B4	10326	25.7%			
9/16	B5	10867	27.0%			
5/8	C1	10284	19.4%			
5/8	C2	11539	21.7%			
5/8	C3	11472	21.6%	1.0%	11009	20.8%
5/8	C4	10742	20.2%			
5/8	C5	11292	21.3%			

When the samples failed however, there was evidence of heat build-up on the end of the rope. Immediately following failure, there was a strong odor and a cloud of blue dust from the urethane coating. In addition, the same type of fiber pilling seen on the rope splice end connections. This effect is due to the heat build up. There are two possible sources for this heat build up. During the break test, friction causes the increase of heat as the rope being pulled through the pressed nubbin. However, there may be a second source of heat that is induced into the end connection system even before the break test commences. The Esco 500 ton hydraulic press applies a compressive force between 1,800 and 2,000 psi to each nubbin (Black, 2004). Heat is generated and due to the confined space; there is nowhere for the heat to dissipate. The trapped heat near the end connection may adversely affect the synthetic rope's strands.

These results also show that a simple compression fitting that is simply crimped uniformly around the outside synthetic rope strands yields a minimal breaking strength. This end connection may have immediate use as a simple end connection with a breakaway effect for a drum. Its performance was consistent in break testing with only 0.8% and 1.0% standard deviation from the catalogue minimum breaking strength in the 9/16" and 5/8" diameters respectively. The addition of a bonding agent such as a structural adhesive prior to the crimping process, may provide an increase in holding strength and should be tested.

5.1.10 Nubbins With Adhesives

Generally, the adhesives performed poorly. Breaking strengths were low and variability in the strengths was high. Table 43 shows the mean breaking strengths of each of the end connections tested. In addition, this table shows the standard deviation for each end connection in relation to mean breaking strength and mean percentage of the catalogue minimum breaking strength. This table shows that the nubbins with that achieved the higher mean breaking strengths also had the higher standard deviations and variances. Conversely, the end connections with the lowest mean breaking strengths (i.e. nubbins with 3M adhesive) had much lower standard deviations and variances.

Table 43. Mean breaking strengths and standard deviations for nubbins with adhesive

End Connection	Diameter	Mean Breaking Strength (lbs.)	% of Catalogue Min.	Standard Deviation (lbs.)	Standard Deviation (% of Catalogue Min.)	Variance
Steel Nubbin w/ Phillystran	9/16	14630	37.7%	4601	11.4%	16936661
UHMW Nubbin w/ Phillystran	9/16	6407	16.5%	3891	9.7%	12109433
Notched Steel Nubbin w/ Phillystran	9/16	12819	33.1%	922	2.3%	679977
Steel Nubbin w/ Phillystran	5/8	6195	33.7%	8648	16.3%	59830976
UHMW Nubbin w/ Phillystran	5/8	10327	56.1%	2149	4.0%	3693395
Steel Nubbin w/ 3M	5/8	1799	9.8%	651	1.2%	339213
UHMW Nubbin w/ 3M	5/8	1239	6.7%	575	1.1%	264161
Notched Steel Nubbin w/ Phillystran	5/8	16866	91.7%	2864	5.4%	6561020

The adhesive had unpredictable failure modes. Table 44 shows the failure modes and the number of strands that failed for each sample tested. It was difficult to maintain a sufficient quantity of adhesive into the rope fibers and into the nubbin to hold. The adhesives simply did not hold during break testing (Figure 55). The end of the rope segment simply pulled out of the nubbins and often before the 10 loading cycles were completed. The second failure mode was when the bond was retained. As a result, some or all of the rope strands failed at the exit point of the nubbin (Figure 56).

Table 44. Failure modes and number of failed strands for nubbins with adhesive

End Connection	Diameter	Spool	Breaking Strength (lbs.)	Failure Mode	# Failed Strands
Steel Nubbin w/ Phillystran	9/16	B1	17679	Exit point of nubbin	10
Steel Nubbin w/ Phillystran	9/16	B2	20798	Exit point of nubbin	11
Steel Nubbin w/ Phillystran	9/16	B3	10413	Exit point of nubbin	7
Steel Nubbin w/ Phillystran	9/16	B4	14011	Exit point of nubbin	12
Steel Nubbin w/ Phillystran	9/16	B5	10251	Exit point of nubbin	1
UHMW Nubbin w/ Phillystran	9/16	B1	6937	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	9/16	B2	2151	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	9/16	B3	10419	Exit point of nubbin	0
UHMW Nubbin w/ Phillystran	9/16	B4	9872	Pulled out of nubbin	9
UHMW Nubbin w/ Phillystran	9/16	B5	2658	Pulled out of nubbin	0
Notched Steel Nubbin w/ Phillystran	9/16	B1	12289	Exit point of nubbin	8
Notched Steel Nubbin w/ Phillystran	9/16	B2	13480	Exit point of nubbin	7
Notched Steel Nubbin w/ Phillystran	9/16	B3	11542	Exit point of nubbin	11
Notched Steel Nubbin w/ Phillystran	9/16	B4	12946	Exit point of nubbin	9
Notched Steel Nubbin w/ Phillystran	9/16	B5	13837	Exit point of nubbin	10
Steel Nubbin w/ Phillystran	5/8	C1	1035	Pulled out of nubbin	0
Steel Nubbin w/ Phillystran	5/8	C2	21555	End of connection	10
Steel Nubbin w/ Phillystran	5/8	C3	3925	Pulled out of nubbin	0
Steel Nubbin w/ Phillystran	5/8	C4	2341	Pulled out of nubbin	0
Steel Nubbin w/ Phillystran	5/8	C5	2121	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	5/8	C1	8908	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	5/8	C2	8563	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	5/8	C3	11517	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	5/8	C4	9094	Pulled out of nubbin	0
UHMW Nubbin w/ Phillystran	5/8	C5	13553	Pulled out of nubbin	9
Steel Nubbin w/ 3M	5/8	C1	2682	Pulled out of nubbin	0
Steel Nubbin w/ 3M	5/8	C2	858	Pulled out of nubbin	0
Steel Nubbin w/ 3M	5/8	C3	1874	Pulled out of nubbin	0
Steel Nubbin w/ 3M	5/8	C4	1898	Pulled out of nubbin	0
Steel Nubbin w/ 3M	5/8	C5	1682	Pulled out of nubbin	0
UHMW Nubbin w/ 3M	5/8	C1	986	Pulled out of nubbin	0
UHMW Nubbin w/ 3M	5/8	C2	1706	Pulled out of nubbin	0
UHMW Nubbin w/ 3M	5/8	C3	1935	Pulled out of nubbin	0
UHMW Nubbin w/ 3M	5/8	C4	1050	Pulled out of nubbin	0
UHMW Nubbin w/ 3M	5/8	C5	519	Pulled out of nubbin	0
Notched Steel Nubbin w/ Phillystran	5/8	C1	16373	Pulled out of nubbin	4
Notched Steel Nubbin w/ Phillystran	5/8	C2	17545	Pulled out of nubbin	10
Notched Steel Nubbin w/ Phillystran	5/8	C3	21414	Pulled out of nubbin	11
Notched Steel Nubbin w/ Phillystran	5/8	C4	14822	Pulled out of nubbin	10
Notched Steel Nubbin w/ Phillystran	5/8	C5	14175	Pulled out of nubbin	11

Figure 55. Failed notched nubbin sample where bond did not hold

Figure 56. Failed notched nubbin sample where 10 of 12 strands failed

5.1.10.1 All Nubbins With Scotch-Weld™ DP-8010

Although the steel and UHMWW-PE nubbins with the Scotch-Weld™ DP-8010 were potted under controlled conditions, their breaking strength test performance was extremely low for the 5/8" diameter specimens. According to manufacturer specifications, the overlap shear stress is 754 psi and the tensile strength of the adhesive itself is approximately 2,000 psi. This means that under laboratory tests, the ½ $in.^2$ bond area held, but the substrate (UHMW-PE strips) yielded at 754 psi (3M, 2003). The bond area for the nubbin is approximately 3 $in.^2$, so theoretically it could hold approximately 6,000 pounds of axial tension. However, the breaking tests of the samples only achieved a maximum breaking strength of 1,934 pounds with the UHMW-PE nubbin and 2,682 pounds with the steel nubbin.

After 72 hours of pot time, all nubbins appeared to have good adhesive coverage. The recommended pot time of 8-24 hours was exceeded; so all test specimens were fully cured. Finally, the laboratory was a controlled environment and slight differences in humidity and temperature likely did not play a significant role in sample failure. With all of these factors considered, the samples still broke at lower than expected strengths. As tension increased in the rope during the break test, the rope compressed and the bond with the wall of the nubbin broke. The adhesive within the rope was also compressed. Thus, the diameter of the rope became smaller and constricted further as it was pulled along the interior taper of the nubbin. Essentially, as the test sample was pulled axially, the rope was compressed and the adhesive was plastic enough that it deformed to fit through the opening of the nubbin. As a result, the low breaking strengths achieved, it was determined that the 9/16" diameter rope would not be tested.

5.1.10.2 Nubbins With Phillystran Socketfast® Blue A-20

The nubbins with the Socketfast® Blue A-20 potted and performed differently than those with the Scotch-Weld™ DP-8010. Compared to the Scotch-Weld™ DP-8010, the Socketfast® Blue A-20 was more brittle and glassy. Therefore, it could not be worked, deformed, or compressed. When the sample was cycled, the adhesive did not hold. It seemed that the bond between the rope and the nubbin wall broke. Examination of the failed samples revealed that the adhesive bonded well to the polyethylene fibers. Under the tension and compression caused by the break tests, the "glued" rope in the nubbin was prohibited from compressing. Even though the bond to the wall of the nubbin may have broken earlier in the test cycle, the prohibition of compression prevented the rope from being pulled through the opening in the nubbin.

In fact, the breaking strength of the steel nubbin with the Socketfast® Blue A-20 is promising because a maximum breaking strength of 21,555 pounds was attained from one of the 5/8" samples. This value represents 41% of the catalogue minimum breaking strength. Moreover, one of the 9/16" samples achieved a breaking strength of 20,798 pounds, 52% of the catalogue minimum. These breaking strengths are over eight times that achieved with the Scotch-Weld™ DP-8010. These higher values may be viewed skeptically, but they show higher breaking strengths are possible with the Socketfast® Blue A-20.

Although high breaking strengths were attained in few tests, it is difficult to pinpoint exactly the conditions under which they occurred. All end connections were potted under the same conditions, on the same day, with the same rope construction, and with the same methodology. All end connections were tested using the same equipment. Under these circumstances, how can one potted end connection out-perform all of the others? Statistically, the spool effect is not significant for the 5/8" diameter (p-value = 0.6245) and for the 9/16" diameter data (p-value = 0.4295). There must be other sources of variation, such as an interaction with the adhesive and the synthetic rope's urethane coating or the bonding of the fibers to the adhesive. It was impossible for me to examine internally the nubbins to verify equal coverage of the adhesive. Therefore, there may not have been equal distribution of the adhesive within the nubbin. Air pockets may have also formed during potting.

In addition, to the steel nubbins, two other nubbins were tested with the Socketfast® Blue A-20. The notched nubbins had slightly higher breaking strengths than the steel nubbins. Finally, the third nubbin tested with the Socketfast® Blue A-20 was the UHMW-PE nubbin. The UHMW-PE nubbins had the most dramatic deformation and failures of any end connection tested. Assuming that the nubbin can be modeled as a cylinder under uniform loading, it is subjected to normal stresses in the circumferential direction. This normal stress is created through the axial loading of the rope during break testing. As the rope is pulled and the adhesive bond holds, the nubbin is forced to compress, thus creating a hoop stress (Hibbeler, 2003). Compression strength of UHMW-PE is between 2,700 and 3,600 psi (Schweitzer, 2000), while 4140 steel is greater than 80,000 psi (Oberg et al., 1996). Inherently, the UHMW-PE nubbin does not have the hoop strength that the 4140 steel nubbin has due to material properties. Under the compressive loading, the UHMW-PE nubbin deforms, causing the outer diameter to grow. Additionally, as the outer wall stretches, the adhesive bond between the nubbin wall and the Socketfast® Blue A-20 is shattered.

The brittle characteristics of the Socketfast® adhesive do not allow the adhesive to also deform. The adhesive however still remains bonded to the rope fibers. As tension increases, it is slowly pulled through the opening in the nubbin as the nubbin deforms outward (Figure 57).

Immediately following sample failure, the nubbin dimensions were measured. These values were compared to initial dimensions in order to quantify the amount of deformity. Figure 58 shows the test UHMW-PE nubbin before and after a break test.

Following sample failure, the outer diameter of the nubbin did not deform uniformly. Instead, the part of the nubbin that was being compressed against the load block (D1) deformed more because this part of the nubbin was experience the strongest opposing forces (Figure 58). The diameter, D1 increased by 0.1172” from diameter measurements averaged for the nubbin. Conversely, the upper portion of the nubbin that was not compressed directly against the load block (D2) increased in diameter by 0.0305”.

Figure 57. UHMW-PE nubbin before and after load test

Over time, some of this deformation is recovered after the load is released, similar to rope elastic deformation and hysteresis (Samson Rope Technologies A., 2002). However while much deformation is recoverable, the nubbin still does not return to its original form. The nubbin’s outer and inner diameters remain larger. **Therefore, UHMW-PE nubbins cannot be used in practice with this expansion property.**

5.2 Failure Modes of End Connections For 3/8” Diameter End Connections

The failure modes for the 3/8” diameter test samples were similar to the other two diameter classes. The buried eye splice broke at an average of 18,766 pounds and 102% of the catalogue minimum breaking strength. In addition, all five samples had the same failure mode: at the end of the buried eye splice taper. Data is shown in Table 45.

The second end connection tested with the 3/8” diameter synthetic rope was the truck wrapper. The truck wrappers had a mean breaking strength of 15,310 pounds and 83% of the catalogue minimum breaking strength. The lower breaking strength is most likely due to the fact that the rope is spliced around the 5/16” chain. The sharp bend in the rope and a nominal D/d ratio less than 1 reduces the breaking strength. The top of the chain over which the rope bends creates a weak point in the rope. Thus, the rope failure will be at the top of the eye. Rope strengths will be less than ultimate strengths for the buried eye splice because of the spliced chains.

The 3/8” diameter average breaking strength of 15,310 pounds exceeds the Oregon-OSHA 15,000 minimum requirement for load securement (OR-OSHA 437-007-1015(2), 2003). OR-OSHA requires this minimum strength for all truck wrappers for on-highway roads to secure logs to the truck.

Table 45. 3/8" diameter break test results

End Connection	Diameter	Spool	Breaking Strength (lbs.)	Failure Mode	Mean Breaking Strength (lbs.)	% of Catalogue Min.
BES	3/8"	A1	18616	End of taper in BES		
BES	3/8"	A2	19394	End of taper in BES		
BES	3/8"	A3	19382	End of taper in BES	18766	102.0%
BES	3/8"	A4	18845	End of taper in BES		
BES	3/8"	A5	17593	End of taper in BES		
Wrappers	3/8"	A1	15888	Top of eye		
Wrappers	3/8"	A2	13847	Top of eye		
Wrappers	3/8"	A3	16187	Top of eye	15310	83.2%
Wrappers	3/8"	A4	14771	Top of eye		
Wrappers	3/8"	A5	15856	Top of eye		

5.3 Rope Response to Failure

When the rope fails, there are some notable effects on the rope. The two main effects are: recoil and fiber melt. These two effects were common in many test samples, but the presence or severity of failure effects are not necessarily associated with any end connection. What happens to the rope upon failure is based upon individual rope construction and the loading of the strands. Ideally, each of the strands should equally share a fraction of the load. However, because of rope construction, that is not necessarily the case. Still, there is no way to predict failure effect. Four samples may have the same effect and the fifth may be completely different.

5.3.1 Recoil

There appears to be no relationship between recoil and breaking strength of the test sample (Table 46). Figure 58 shows 5/8" diameter buried eye splice test samples. Figure 58A shows severe recoiling and the rope deformed in a spiral pattern. It is stiff and the rope has spun so tightly that the eye has constricted around the pin. This sample broke at 49,206 pounds. Figure 58B shows another sample with only the slightest recoil and the eye is without deformation. This sample broke at 49,279 pounds.

After each test, the sample's failure was examined. Table 46 shows the number of recoil occurrences resulting from break tests for each diameter class.

Table 46. Number of recoil occurrences in break testing

Diameter	Total Samples with Recoil	Total Samples Without Recoil
3/8"	5	5
9/16"	26	34
5/8"	20	50
Total	51	89

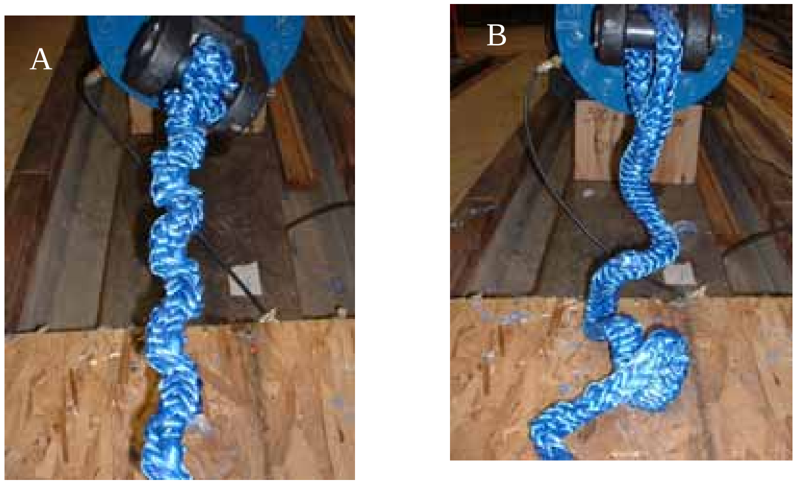

Figure 58. A) Buried eye splice with recoil   B) Buried eye splice without recoil

5.3.2 Fiber Melt

Performing break testing on fourteen different end connections has produced various failure modes and various rope effects from these failures. During break tests, the majority of the samples failed less than the entire 12 strands (only 10 or 11 strands failed). Out of 140 total tests performed over three diameter classes, 51% of the test samples had at least one, but less than twelve strands fail. Of these break tests, 83% of those break tests produced failed samples with ten or eleven failed strands only, leaving up to two strands intact. Table 47 shows the number of occurrences for each strand failure pattern.

Table 47. Number of failed strands during break tests

Diameter	Total Samples with 10 or 11 Strands Failed	Total Samples with 12 Failed Strands	Total Samples with 0-9 Strands Failed
3/8"	5	5	0
9/16"	28	13	19
5/8"	25	11	34
Total	58	29	53

Immediately when the sample failed 10 or 11 strands, the remaining strands are quickly pulled through the rope. It is possible that this quick pulling of the unfailed strand(s) builds up heat caused by friction. As each strand is being pulled through the rope, essentially unbraiding itself and unwinding its way through the rope construction, heat increases until motion in the strand ceases.

A pilling effect was following the break tests is a pilling effect on the rope fibers. This pilled material that looks like tiny blue balls on the fibers of the unfailed strand, which are caused by the heat generated. This effect is most often seen on the spliced rope end connections because they attain some of the highest breaking strengths, and therefore, have the most the kinetic energy upon failure and heat generation. The question of interest is whether this pilling is of fiber or urethane coating nature.

Differential scanning calorimetry (DSC) was completed of a sample of the pilled material to determine which material was melted (Figure 59). DSC provides a rapid test method for determining changes in specific heat capacity in a homogenous material (ASTM International B., 2002). In this case, the pilled material was tested against a reference piece of UHMW-PE fiber taken from a section of Amsteel®-Blue. By raising the temperature of the reference pan and the sample pan to a desired point, transitions in the material such as crystalline peaks and melting points can be observed. From the valley in the heat flow curve, the melting temperature is determined. Since there is only one valley in the curve, the melting point is not skewed. There are no other transitions and it can be assumed that the material tested was a mostly polyethylene. The 138°C matches the melting temperature for polyethylene. Therefore, the sample was comprised of mainly one material.

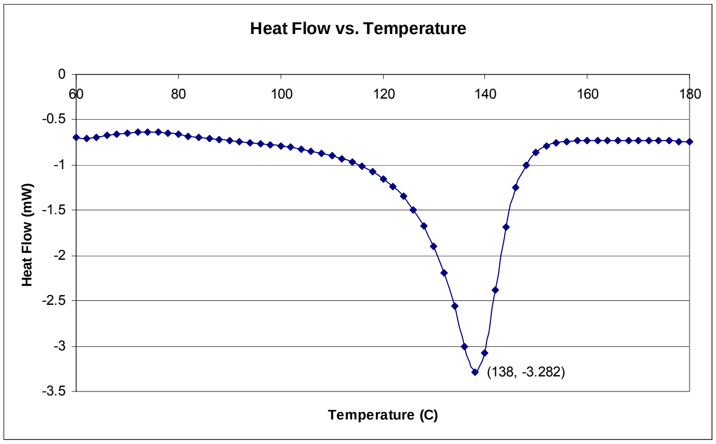

Figure 59. Differential scanning calorimetry output

From the DSC test, the pilled fiber is the effect of excess heat build up. It could be the after-effects of rope failure or it may be cause by tensile loading of the sample. In both cases, there is enough heat generated to melt a small number of fibers within the unfailed strand. This finding can be used in future testing and development of rope construction. Failures do generate heat, but until now it was not widely known what temperatures could be generated as a result of rope failure.

5.4 Statistical Analysis and Interpretation

This study was set up as a randomized complete block design, with blocking on the five spools for each of the three diameters: 3/8”, 9/16”, and 5/8”. From the analysis of variance for each diameter, there was no significant block effect. No surprise however, was that there was a significant treatment effect for each of the three diameter classes. Two, twelve, and fourteen end connections were tested with the 3/8”, 9/16”, and 5/8” diameters respectively and it follows that the type of end connection should primarily determine the breaking strength of the end connection.

Examining the 5/8” diameter data more closely, Tukey-Kramer pairwise comparisons were made to determine which groups of end connections were significantly different from other groups. Group A consists of the end connections that achieved the highest breaking strengths: buried eye splice, Whoopie Sling, long splice, pinned nubbin, and knuckle link. Similarly, the Dunnett's test shows that the mean breaking strength of the Whoopie Sling, long splice, pinned nubbin, and knuckle link are not significantly different from the buried eye splice. From this same test, all other end connections' mean breaking strengths were significantly different from that of the buried eye splice.

The five nubbins-plus-adhesive configurations were not all grouped together. Instead, several groups were created that overlapped such as Group G and Group H. Interesting though is that in addition to these two groups that contained only adhesive nubbins, Group E and Group F consisted of Phillystran adhesives and the pressed nubbin. Therefore, the pressed nubbin did not have a mean breaking strength significantly different from the steel nubbin with Phillystran and the notched nubbin with Phillystran. However, it should be noted that the mean of the steel nubbin with Phillystran was skewed because of the test sample from Spool 2 that achieved 21,554 pounds (variance = 59,630,976; standard deviation = 8,648). Omitting this value, the mean breaking strength drops to 2,355 pounds for the four samples, which could change the Tukey-Kramer grouping. The notched steel nubbin with Phillystran adhesive was more consistent. It had a smaller variance of 6,561,020 and a standard deviation of 2,864 pounds.

The 9/16" results are similar to those of the 5/8" diameter. The Dunnett's test resulted in the same significant end connections as compared to the buried eye splice. However, the Tukey-Kramer groupings were somewhat different from the 5/8" diameter. Most noticeable is that there are only four groups instead of 8 groups. This circumstance is due partially to that fact that 12 instead of 14 end connections were tested and partially because the adhesive nubbins performed better in this diameter class. Due to the results of the 5/8" break tests and limited financial resources, it was decided to omit the 9/16" test series for the 3M Scotch-Weld™. The omission of these test samples and thus the lower breaking strengths caused different Tukey-Kramer groupings to occur.

In addition, each of the end connections with the Phillystran adhesive had higher breaking strengths than their 5/8" counterpart. In addition, the Y-Splice's breaking strength was more consistent in this diameter class. Its standard deviation was only 3.21% of the mean whereas the 5/8" had a standard deviation of 24.41% of the mean. As a result of this low variance, the first Tukey-Kramer grouping was the buried eye splice, Whoopie Sling, long splice, Y-splice, pinned nubbin, and the knuckle link.

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 not only which mean breaking strengths are significantly different from each other, but also both tests have grouped together the strongest end connections with the least amount of variance.

Finally, the 3/8" diameter class analysis is different from the other two because only two end connections were tested. Similar to the 9/16" and 5/8" diameters, there was no significant spool effect. It follows that the mean breaking strength of the truck wrappers would be significantly different to the buried eye splice (p-value = 0.0058) because there were only two end connections tested in this diameter class.

From the results of this pilot study, it is clear that the spool used for testing does not have a significant effect on the breaking strength of each type of end connection. These results do show some measure of quality control at the manufacturer level. However, a true measure of quality control is the variability. If the sample size were to increase, then the variance should decrease.

According the rope manufacturer, the buried eye splice represents the ultimate strength of the rope. Table 48 shows the minimum and average values reported in the rope manufacturer's catalogue. The variability in the strength of the rope could help explain the inability of the test samples for the 9/16" and 5/8" buried eye splices to achieve the catalogue minimum value (only one sample of ten was greater than the minimum value). Table 49 shows the results of the buried eye splices for the three diameter classes against three certified measures of quality: the certified breaking strength for each spool provided, the catalogue minimum, and the catalogue average.

Table 48. Catalogue minimum and average breaking strengths reported by the rope manufacturer

Diameter	Catalogue Minimum Breaking Strength (lbs.)	Catalogue Average Breaking Strength (lbs.)
3/8"	18401	20445
9/16"	40194	44660
5/8"	53114	59015

(Samson Rope Technologies A., 2002)

The 9/16” samples obtained a mean breaking strength of 96% and a range between 83% and 105%. The 5/8” samples achieved a mean strength of 95% with a range between 92% and 98%. However, the 3/8” diameter had a mean breaking strength of 102% of the catalogue minimum and ranged from 95% to 105%. Table 49 summarizes the results of the three diameter classes.

Table 49. Performance of the buried eye splice against certified values.

Diameter	Spool	Breaking Strength (lbs.)	SRT Certified Spool Break Strength (lbs.)	% SRT Break Strength	% Min. Break Strength	% Avg. Break Strength	Mean Breaking Strength (lbs.)
3/8	A1	18616	19937	93.4%	101.2%	91.1%	
3/8	A2	19394	20390	95.1%	105.4%	94.9%	
3/8	A3	19382	19479	99.5%	105.3%	94.8%	18766
3/8	A4	18845	19344	97.4%	102.4%	92.2%	
3/8	A5	17593	19577	89.9%	95.6%	86.1%	
9/16	B1	39377	43452	90.6%	98.0%	88.2%	
9/16	B2	38638	41880	92.3%	96.1%	86.5%	
9/16	B3	42206	41549	101.6%	105.0%	94.5%	38757
9/16	B4	33560	41832	80.2%	83.5%	75.1%	
9/16	B5	40005	44619	89.7%	99.5%	89.6%	
5/8	C1	49207	53118	92.6%	92.6%	83.4%	
5/8	C2	50339	53939	93.3%	94.8%	85.3%	
5/8	C3	49759	54215	91.8%	93.7%	84.3%	50187
5/8	C4	52350	53468	97.9%	98.6%	88.7%	
5/8	C5	49280	54020	91.2%	92.8%	83.5%	

None of the test samples attained strengths that exceeded the catalogue average value (CAV) and only two samples out of the three diameter classes (A3 and B3) obtained a breaking strength close to the certified breaking strengths provided by the rope manufacturer. From this data and because these test samples were tested according to the manufacturer’s protocol, there appears to be a quality issue.

Admittedly though, this pilot study only represents a small sample size: five samples in each diameter class and one sample from each spool. If the breaking strengths were truly normally distributed, then a larger sample size would yield breaking strengths of the buried eye splice greater than the CAV and catalogue minimum.

5.5 Unexplained Variation With Adhesives

It is important to examine the data closely to determine if there are outliers. Scatterplots were constructed from the 9/16”, 5/8”, and 3/8” data (Figure 60-Figure 62). The 3/8” data shows no cause for concern. In most of the 9/16” data, there does not appear to be any outliers. However, the SEFAC™ specimen from spool 3 had a breaking strength of 15,225 pounds with a group mean of 25,518 pounds. Excluding this data point from the data set would yield a mean of 28,092 pounds.

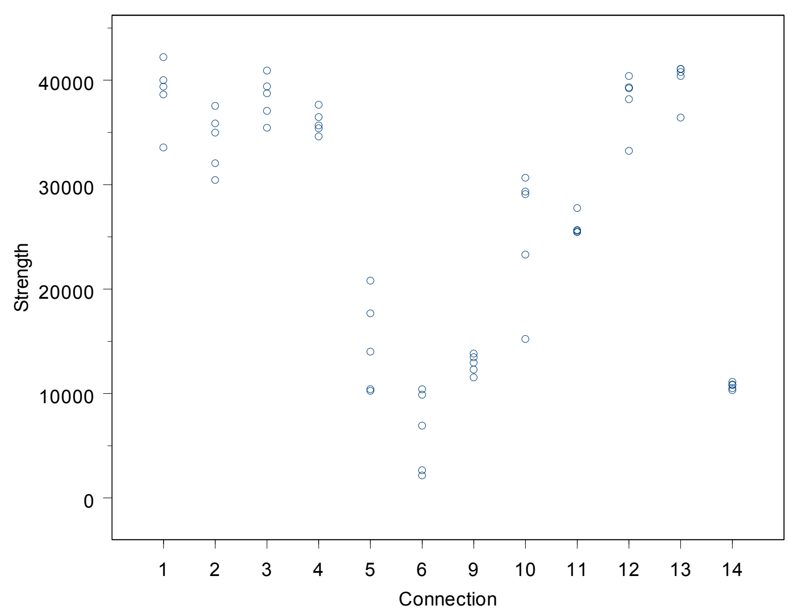

Figure 60. 9/16” scatterplot

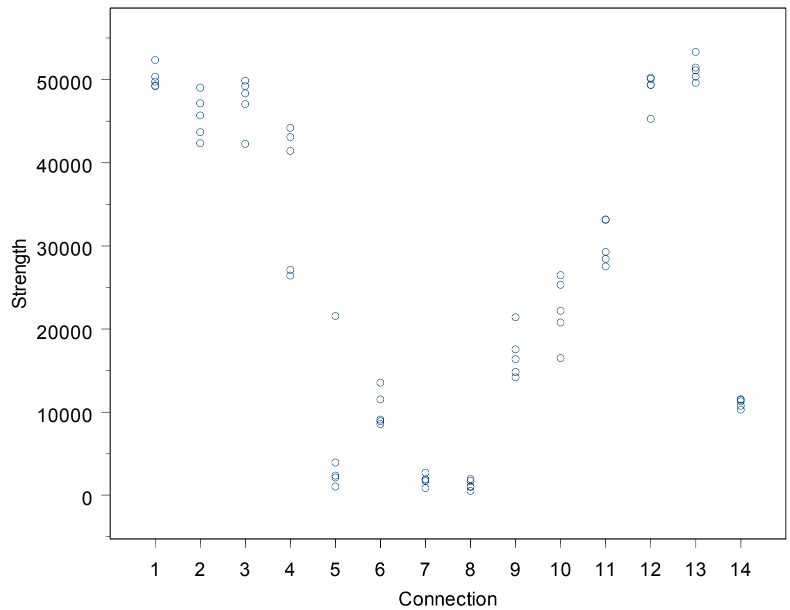

Figure 61. 5/8” scatterplot

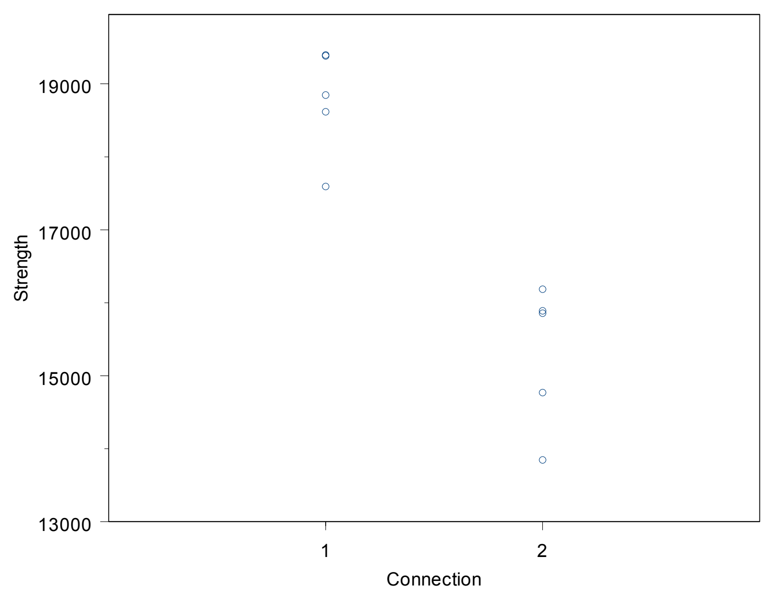

Figure 62. 3/8” Scatterplot

The 5/8" data had more variation among the different spools. The most significant outlier in the 5/8" data was with the steel nubbin with Phillystran adhesive. The mean breaking strength for this group was 6,195 pounds. However, excluding the single data point that achieved a breaking strength of 21,554 pounds, the mean dropped significantly to 2,355 pounds. The Y-splice data was also a cause for close examination. Two test samples broke lower than the other three. Overall, the mean breaking strength for the Y-splice was 36,438 pounds. Excluding the two data points, the mean was 42,890 pounds. The mean of the two points was 26,759 pounds. Could it be that the two samples with lower breaking strength are outliers, or could they be more representative of mean performance of the Y-splice?

This data shows the inconsistent performance and large variance of some of the end connections. The one data point with the steel nubbin and Phillystran adhesive is an extreme case, but it does show how under controlled conditions, nubbins can be potted differently. Perhaps a lower mean breaking strength of 2,355 pounds is more representative, but 21,554 pounds was attained. This could be an anomaly, but it is an experimental outcome and the breaking strength that was attained. In fact, it shows the potential of the adhesive and how strong the bond can be.

Perhaps there was some random error in the procedure, but these observations could also be the manifestation of variability inherent with the bonding process of the adhesives. If the latter is the case, then the value(s) should be retained and analyzed in the same manner as the other data (ASTM International C., 2002). In the case of the adhesives, the same procedure was used for applying or potting the end connections.

Furthermore, all test specimens were tested in the specified standardized procedure. End connections were fabricated and potted under controlled conditions. However, the internal covering of the adhesive on the strands and fibers could have varied; air pockets could have developed in the end connections; or there is some other bond interference mechanism. There was no way to discern these internal differences. Thus, the strengths obtained in this study represent actual data and the breaking strengths that were attainable. Similarly, no other data points were removed from the data set.

5.6 Scope of Inference

This study is a randomized investigation of end connections for 5/8”, 9/16”, and 3/8” synthetic rope. Inferences of breaking strength performance can thus be made to all spools of these diameter classes of AmSteel®-Blue and end connection (assuming the manufacturer did not provide all of the “good” or “bad” spools of rope).

5.7 Overall Suitability of End Connections

Breaking strength was the primary factor in determining overall suitability of end connections for use with current timber harvesting systems. A cut-off value was established to judge quantitatively whether the end connections were suitable. This cut-off value was set at 50% of the catalogue minimum breaking strength. The 50% values used were:

- 5/8” diameter = 26,557 pounds.
- 9/16” diameter = 20,097 pounds.
- 3/8” diameter = 9200 pounds.

Those end connections whose mean breaking strength was 50% of the catalogue minimum for each diameter class are shown in the table below. In addition to breaking strengths relative to the catalogue minimum, Table 50 also shows the breaking strength relative to the average and the buried eye splice.

Table 50. End connections that achieved a breaking strength of at least 50% of the catalogue minimum

Diameter		End Connection	Mean Breaking Strength (lbs.)	Percent of Buried Eye Splice	Percent of Catalogue Minimum	Percent of Catalogue Average
3/8"	1	Buried Eye Splice	18766	100.0%	102.0%	91.8%
3/8"	2	Truck Wrappers	15310	81.6%	83.2%	74.9%
9/16"	1	Buried Eye Splice	38757	100.0%	96.4%	86.8%
9/16"	2	Whoopie Sling	34177	88.2%	85.0%	76.5%
9/16"	3	Long Splice	38314	98.9%	95.3%	85.8%
9/16"	4	Y-Splice	35956	92.8%	89.5%	80.5%
9/16"	10	SEFAC	25519	65.8%	63.5%	57.1%
9/16"	11	Rope Clamps	25985	67.0%	64.6%	58.2%
9/16"	12	Pinned Nubbin	38067	98.2%	94.7%	85.2%
9/16"	13	Knuckle Link	39944	103.1%	99.4%	89.4%
5/8"	1	Buried Eye Splice	50187	100.0%	94.5%	85.0%
5/8"	2	Whoopie Sling	45571	90.8%	85.8%	77.2%
5/8"	3	Long Splice	47354	94.4%	89.2%	80.2%
5/8"	4	Y-Splice	36438	72.6%	68.6%	61.7%
5/8"	11	Rope Clamps	30294	60.4%	57.0%	51.3%
5/8"	12	Pinned Nubbin	48868	97.4%	92.0%	82.8%
5/8"	13	Knuckle Link	51172	102.0%	96.3%	86.7%

Due to the variance in the breaking strengths for each connection, an accepted and published value was identified as the cut-off. For example, the Y-splice's breaking strength is not only dependent on splice construction, but it is also dependent on preloading conditions and lock-stitching. Lock-stitching the connection is required to prevent slippage and ultimately early pull out of the Y-segment. The catalogue minimum represents an independent cut-off value that the end connections can be measured against.

Many times, 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. Therefore, end connections that are significantly weaker and inconsistent in break tests are not suitable.

Qualitative measures of suitability are also used to determine suitability of end connections. For instance, end connection fabrication and construction procedure is important. Of the end connections that meet the 50% criteria, only the SEFAC™ and rope clamps do not utilize a splice as a component of the end connection.

5.7.1 SEFAC™

The SEFAC™ could be potentially difficult to fabricate, as there are three designs given for each given set of dimensions. The design was recommended by the rope fiber manufacturer following initial exploratory trials, was used for this study. For design dimensions, refer to Figure A9 and Figure A10 in the Appendix.

5.7.2 End Connections With Adhesives

Potted end connections are difficult to prepare and it is extremely difficult to achieve control quality. It is also difficult to identify an exact breaking strength for potted terminations because of inconsistent breaking strengths. This study has shown that breaking strength varied by as much as 139% of the mean value. Potting techniques will vary from rigging shop to rigging shop and the person fabricating the end connection. Moreover, machining tolerance, materials, pot time, and environmental conditions can ultimately make significant differences in breaking strengths in potted end connections.

This study has shown that potted terminations can produce breaking strengths in excess of 50% of the catalogue. However, the SEFAC™ was the only potted termination that had a mean breaking strength that met the 50% criteria. A final consideration for potted termination is a compression fitting. Exploratory testing of the SEFAC™ with the 3M Scotch-Weld™ DP-8010 showed that 50% of the catalogue strength was achieved in one case. Although the Phillystran Socketfast® Blue had a stronger bond in end connections without a compression fitting, these new results show how critically dependent the compression fitting is to overall breaking strength of the potted termination.

In addition to potting concerns, use of the SEFAC™ with existing harvesting systems must also be considered. Current drums and winches are designed with ferrule pockets designed to fit standard ferrule shapes (e.g. B, D, or L series). The tapered shape and diameter to length ratio of the SEFAC™ socket is not compatible with current systems. For the diameter it fits, it is 1.6 times heavier for 9/16” diameter and 1.9 times heavier for 5/8" than a typical B-5 nubbin. Weights for the hardware used in the end connections are shown in Table 51.

Table 51. Weights of end connection hardware

Hardware	**Weight (g)**
Notched B5 Nubbin	306
B5 Nubbin	335
UHMW-PE Nubbin	41
Pressed Nubbin	535
Pinned Nubbin	336
Knuckle Link	395
9/16" Wire Rope Clip (4 pieces)	1968
5/8" Wire Rope Clip (4 pieces)	2013
5/8" SEFAC™	625
9/16" SEFAC™	546

5.7.3 Rope Clamps

The rope clamps are another type of end connection that should be closely scrutinized. There are two types of common compression clips used with wire rope: forged "u" type grips and Fist Grips® (also called chair type grips). Under this study, the forge type u-grips were used because of their use on current forest operations. This u-grip clip was designed for use with wire rope. However, the forging process can leave rough edges on the u-grip that have the potential to sever strands of the rope. During this study, only 45 foot-pounds of torque could be applied to each nut, and that was difficult to do without securing the rope. Moreover, once the rope was pre-tensioned, the rope diameter reduced. As a result, each of the nuts had to be retightened with a torque wrench. Often logging operations last more than a single day and rigging lines may be left under tension for days at a time. As a result, there may be creep in the rope and the bolts may begin to slip. At the start of each day, the clamps should be retightened properly.

The wire rope clips achieved a mean breaking strength of 25,985 pounds. for the 9/16" diameter and 30,293 pounds for the 5/8" diameter, over 60% of the catalogue minimum. Speaking strictly on the basis of breaking strength, the wire rope clips are suitable for timber harvesting applications. See Section 5.8.3 for use guidelines and recommendations.

5.7.4 Suitable End Connections

Despite some of the inconsistencies in the performance of the SEFAC™ and the wire rope clips, nubbins, and Y-splice, there were other end connections that showed promise. The Whoopie Sling, long splice, buried eye splice, knuckle link, and pinned nubbin had the highest breaking strengths in the 9/16” and 5/8” diameter. The construction of these five end connections is based on several splicing techniques. The buried eye splice, long splice, and Whoopie Sling were all designed by the manufacturer for different purposes. All three of these end connections displayed consistent performance in the break tests.

The pinned nubbin and knuckle link consistently displayed the highest breaking strengths relative to the buried eye splice. Although the buried eye splice is relatively quick, inexpensive, and does not require added hardware, it may not be usable in some situations. The pinned nubbin and knuckle link are concepts designed specifically for both running and static line operations. They can be used to secure lines to skidder winches, or carriage drums and also used to quickly connect with steel rope connectors.

In summary, this study has developed and tested different end connection and termination concepts suitable for applications in timber harvesting. Not all end connection concepts tested achieved the suitable breaking strength. Instead, the variance among end connections was substantial. Sometimes, the end connection that has the highest breaking strength is not the most suitable for an operation. For example, if a load suddenly began to roll down over a cliff, the end connection on the winch drum should break before a skidder follows. Therefore, breaking strength is not the only consideration.

Considering strengths for each end connection, failure mode, and construction procedures. The following end connections can be considered suitable:

- Buried eye splice
- Whoopie Sling
- Long splice
- Rope clamps – in selected applications
- Knuckle link
- Pinned nubbin
- Y-splice – with careful construction and pre-tensioning

In standardized break tests, the pinned nubbin and knuckle link concepts provide ultimate loads within 5% of the catalogue minimum. Finally, it should be noted that another option is available when to choosing suitable end connections for synthetic rope. If an end connection does not mean minimum breaking strength requirements for a system, perhaps a larger diameter synthetic rope with a higher breaking strength rating and associated end connection could be used. This pilot study assumed direct substitution for steel wire rope of equivalent diameter. Although a larger diameter synthetic rope would be used, it would still be lighter than its steel counterpart.

5.8 Using Synthetic Rope in Existing Timber Harvesting Systems

From the previous section, the end connections suitable for use with timber harvesting have been identified from those tested in this pilot study. The following subsections discuss the way the end connections and terminations could be utilized.

5.8.1 Static line Applications With Synthetic Rope and End Connections

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 buried eye splice 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 Y-splice could also be used in a similar capacity. Instead of having a single tie-off to support a support line, this splicing technique allows the load to be shared by multiple anchor points. By splicing into a support line, the additional line can be secured to a stump or tree.

Finally, the long splice can also be used with static line applications. The long splice's purpose is to repair broken synthetic rope segments or to extend a length of rope. Broken or damaged sections of rope can be cut out and a long splice can add a new section of rope so that only a portion of the rope need be replaced. When wire rope breaks, the length of rope is cut out and replaced – seldom long spliced. The synthetic rope long splice allows the broken section to be cut out and the remaining rope can be spliced back into the used section. Therefore, the long splice can bring substantial savings in operating costs.

5.8.2 Running Line Applications With Synthetic Rope and End Connection

The pinned nubbin and knuckle link were designed for running line applications. Although the knuckle link had a slightly higher mean breaking strength in both the 9/16" and 5/8" diameters, the pinned nubbin has a certain advantage. With the rope wrapped around the knuckle link, this design could leave the rope exposed to potential damages. The design of the pinned nubbin has the rope wrapped around the pin sunk lower into the pin and protecting the rope. 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 relatively inexpensively. More importantly, these designs allow quick connection into the drums and immediate use of the rope thereafter.

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

5.8.3 Use Guidelines and Recommendations

Along with selecting suitable end connections for timber harvesting applications, recommendations for use of synthetic rope with end connections follow from this pilot study.

1. End connections and termination concepts have been developed through controlled laboratory testing and engineering analysis. Materials selection and fabrication for the hardware is essential not only for the strength of the end connection, but also for the safety of the workers. Furthermore, when fabricating connectors, one should know the material properties and the effects of welding and heat treating. In summary, it is not advisable to inappropriately use any material available, weld a bolt on, and put it into use in the field. Such actions jeopardize the safety of the entire crew.
2. Potted end connectors are not recommended.

Potted terminations are not recommended for a number of reasons. When potting, it is difficult to ensure even coverage of the adhesive at the strand and or at the fiber level. Two different methods have been attempted in this pilot study, but both procedures yielded nubbins with inconsistent breaking strengths. In addition, there can be extreme variability with potting environment and techniques. A worker in a rigging shop or worker in the field might construct the end terminations in different environments, e.g. different temperature, humidity, etc. Moreover, each person may be unfamiliar with potting techniques or may hasten the potting time in order to put the rope back into service. Such practices only increase the chance of failure and unsafe working conditions. Potted terminations' breaking strength performance are inconsistence even in a controlled environment. Finally, bond strength with certain materials is quite weak. Currently there is no potted termination recommended by the manufacturer due to synthetic rope properties.

Wire rope clip construction must be considered in this evaluation. Due to the forging process to create the bracket in which the rope sits, the steel is has rough edges with grooves. In addition, use with wire rope can tool the forged steel and create jagged edges that can cut the rope. As the rope is compressed by the u-bolt and tensioned axially, fibers and strands can be damaged.

As a result, four recommendations should be made when using the wire rope clip concept with synthetic rope.

3. Do not use wire rope clips that have been used previously with steel wire rope. Additionally, the bracket should be checked for sharp edges and grooves that the rope can catch on.
4. The u-bolt and bracket should be free of any abrasive surface. However, smoothing the steel also reduces the coefficient of friction and can increase slip. The use of a rubberized plastic coating for these pieces is suggested. The coating is commercially available and can easily be applied and used approximately 24 hours later. The rough forged steel surface will be covered but not induce slippage.
5. Try a different compression fitting that would offset the strands instead of compressing the together. Both the u-bolt and fist-grip wire rope clip configurations compress the rope together to form the eye. If each piece of rope could be compressed individually, slippage might be reduced.

6. Static lines using wire rope clips should not be load bearing. In other words, wraps should be taken on a tree or stump to hold the load and then the rope secured using the clips. As tension increases, rope diameter decreases to the nominal diameter. Thus, the compression and holding forces of the clips decrease causing the end connectors to slip.

In addition, recommendations can be made regarding the spliced end connections.

7. The breaking strength of splices depend on construction. The manufacturer's splicing instructions should be carefully and completely followed. Fids should be properly sized and tails should be the appropriate length and taper. The size of the eye should be the only aspect of the construction that will vary from instructions.
8. Splices can be completed in a matter of minutes. The distinct advantage of the spliced end connections is that they can be used immediately. However, care must be taken when installing the splice into the new rigging system. When being carried into the woods and rigging configurations are set up, the tail of the splice can slip out. The tail remains in place only when tension is applied. Therefore, it is advisable to lock-stitch all splices prior to use with the appropriate material.

Finally, overall recommendations regarding general use of synthetic rope are made.

9. Synthetic rope cannot take the abuse that steel wire rope can. Operators and loggers should be careful not to step on the rope, run it over with equipment, sever its strands, or drag it over abrasive or sharp surfaces. Synthetic rope has many advantages to steel wire rope, but

these can only be realized with proper rope care. Consult the manufacturer's catalogue for general care and handling.

10. The new synthetic rope must be pre-tensioned slowly.
11. New rope must be spooled on a drum with some tension on it. As a rule of thumb, the new rope that has not had the construction stretch taken out of it should be spooled using 2-5% breaking strength of the rope. The rope must be pre-tensioned in order to receive the full breaking strength of the rope. Otherwise, there will be some pretension stretch.
12. Avoid operational situations with excessive heat and heat build-up. The synthetic rope has a critical temperature of 70°C (158°F) and temperatures at or above this level will seriously affect rope properties. It also presents a major safety hazard.
13. Inspect the rope often for severed strands and fibers, creep, and other damage. Consult the manufacturer's rope inspection and retirement guidelines.
14. Good judgment should be used when using the synthetic rope in forest operations. According to the rope manufacturer, normal working loads should not exceed 20% of the minimum breaking strength (Samson Rope Technologies, 2001). Working loads are loads that a rope is subjected to in everyday activity. If normal operations consistently require large working loads, a larger diameter synthetic rope with a higher breaking strength rating should be considered.

5.9 Exploratory trials

In addition to the formal designed experiment described in this thesis, additional exploratory trials were conducted to conceptually determine the effects of additional end connections and terminations. The following sections describe the concepts that were tested.

5.9.1 Sockets and Nubbins

Several socket and nubbin end connections were also tested in order to determine their suitability (Table 52). These tests were useful for two reasons. First, the SEFAC™ tests can be used to examine the effects of different socket and spike configurations. When a socket was used with a pin of equal length to the socket, the maximum load achieved for the 5/8" diameter was 34,332 pounds. This breaking strength was substantially higher than the maximum obtained from the configuration used in the designed study (26,474 pounds). The design used in this study is shown in Section 8.8 of the Appendix. Additionally, the SEFAC™ tested with the 3M Scotch-Weld™ adhesive achieved a maximum strength of 26,129 pounds, 49% of the catalogue minimum. Although the 3M Scotch-Weld™ had extremely weak bond strength with the nubbins, the breaking strength was substantially higher with a compression type end connection. In fact, the 26,129 of catalogue minimum obtained in this test was only slightly less than the maximum load using the Phillystran Socketfast® Blue A-20 adhesive. Finally, the exploratory test of the SEFAC™ without adhesive shows that adhesive is necessary for the end connection's strength. Using only a compression fit, the rope slips and pulls out under tension.

Second, initial testing of the pinned nubbin concept using off-the-shelf Grade 8 bolts proved marginally successful in terms of breaking strengths. A hole was bored through the nubbins. Bolts were slid through the new hole and eye splice and secured with nuts. The rope wrapped around the bolts had less than a 1:1 bending ratio. The ultimate strengths achieved from the break testing shows an engineered design was needed. The simple solution of over-the-counter bolts would not yield high breaking strengths. In addition, end connection strength was not dependable for a few reasons. Because of manufacturing imperfections, bolts might fail at lesser loads. In addition, exposed threads of the bolts could cut rope fibers. The bolts cannot withstand the stresses and deflection in the bolt. Therefore, this design was determined unsafe and unsuitable for use with forest operations. As a result of exploratory testing, the current pinned nubbin was engineered and developed.

Table 52. Additional end connection concepts tested

Diameter	End Connection	Breaking Strength (lbs.)	% of Catalogue Minimum
5/8	SEFAC with 3M Scotchweld DP 8010	26129	49%
5/8	SEFAC without adhesive	6650	13%
9/16	SEFAC - socket:spike = 1:1	28745	72%
5/8	SEFAC - socket:spike = 1:1	34332	65%
5/8	SEFAC - socket:spike = 1:1	23145	44%
9/16	B6 Nubbin with 1/2" Grade 8 Bolt	23077	57%
9/16	B5 Nubbin with 1/2" Grade 8 Bolt	28699	71%

5.9.2 Knots

Knots are not recommended by the manufacturer for use with synthetic rope. Due to asymmetric loading, bending, and pinching of the strands, knots can significantly reduce rope strength. Table 53 shows the percentage of breaking strength retained when conventional ropes are tied with a bend, hitch, or knot. Although the ultimate tensile load for UHMW-PE rope is much higher than ropes of polyester or nylon construction, knots still are not suitable end connections for UHMW-PE rope. Because the coefficient of friction for UHMW-PE rope is significantly lower than nylon or polyester, there is more slippage. In addition, the long chain molecules of the strands lose strength when they are bent and constricted. Therefore, UHMW-PE rope might have less retained breaking strength with knots, hitches, and bends than reported in Table 53.

Table 53. Percentage of breaking strength retained for common knot, bend, and hitch configurations with conventional ropes not constructed of high modulus fibers

Type of knot, bend or hitch	Percentage of Retained Strength
Clove Hitch with Half Hitch	60%
Cow Hitch	85%
Bowline	60-70%
Anchor Bend	
• Over 5/8" diameter ring	55-65%
• Over 4" diameter post	80-90%
Two Half Hitches	
• Over 5/8" diameter ring	60-70%
• Over 4" diameter post	65-75%
Square Knot	43-47%
Sheet Bend	48-58%
Fisherman's Knot	50-58%
Carrick Bend	55-60%
Timber Hitch	65-70%
Round Turn	65-70%

(Foster et al., 1997), (Samson Rope Technologies A., 2002)

Although not formally part of the designed experiment of this pilot study, some exploratory testing of knots was conducted in the laboratory to better understand the effects of knots specifically with UHMW-PE rope. Table 53 shows the configurations that were tested. Although Table 53 reported a strength retention of 60-70% for the bowline knot, Table 54 reports an average of 32% of the catalogue minimum breaking strength. In addition, the cow hitch tested achieved only an average of 58% of the catalogue minimum. Other configurations were tested, but the cow hitch had the highest breaking strength.

Table 54. Results of exploratory testing of knots with Amsteel®-Blue

Diameter	Knot	Breaking Strength (lbs.)	% of Catalogue Minimum
9/16"	Bowline	12754	32%
9/16"	Bowline	13141	33%
9/16"	Figure 8	13193	33%
9/16"	Taught Line Hitch	15780	39%
9/16"	Blake's Hitch	18685	46%
9/16"	Tarbuck Knot	12730	32%
9/16"	Blood Knot	13414	33%
9/16"	Double Stevedore	19799	49%
9/16"	Improved (tucked) Half Blood Knot	8000	20%
9/16"	Double Stevedore	22307	55%
9/16"	Cow Hitch	24261	60%
9/16"	Cow Hitch	22747	57%
9/16"	Dyneema Fish Knot	21231	40%
3/8"	Double Fisherman's with safety knot	6424	35%

5.10 Implications

From this study, significant advancements in end connections and termination for UHMW-PE braided synthetic rope are possible. Many different end connections have been tested and designed. Due to the hardware added, the durability of the end connection and the breaking strength, synthetic rope can be used in different aspects of forest operations. Further research and development needs to be conducted on several of these concepts. This research has defined some suitable end connections for synthetic rope. Not all forest operations require maximum breaking strength for rope applications. End connections have been tested that break at different strengths and can be used in selected systems. Additionally, nearly 100% breaking strength of synthetic rope is attainable with some end connections.

Moreover, this technology should not just be utilized in the forestry sector, but also in applications for other industries: offshore mooring, tuglines, water salvage, military operations, helicopter long line operations, land-based towing and winching, off-road vehicles, high-tension powerlines, and even in space. Although this research was conducted with smaller diameter ropes, it shows which end connections are possible and perhaps these results could be extrapolated to other diameters.

Overall, there are many advantages for the adoption of synthetic rope within the forestry sector and beyond. Some of the major advantages of synthetic rope are:

- It reduces cardiovascular recovery time
- It could reduce or prevent injury.
- It has less stored energy under high tension. When compared to steel wire rope, essentially the only mass that the rope is carrying is the end connection.
- The rope usually will fail linearly.
- It creates less residual stand damage. When the rope is wrapped around trees for support lines, guylines, etc. there is less scarring and biting into the bark.
- There is less fire hazard as the synthetic rope does not produce sparks when pulled over rocks.
- It can reduce set up time. Workers have to take less hardware into the field with them, make fewer trips, can climb trees faster and set up rigging safer with lighter materials.
- It could increase payload. Load calculations are based on the strength of steel and weight of steel. In addition, load sizes are reduced because helicopters and carriages must support not only the payload, but also the entire spool of rope. As synthetic rope provides equivalent strength to the same diameter in steel wire rope, a larger load could come to the landing by using synthetic rope.
- Used synthetic rope can be recycled.
- It is not corrosive and thus does not need to be lubricated. As lines are drug through the water and left in the rain, the polluting lubricants will not be washed into streams and the soil. This is especially important with offshore and shipping applications where the corrosive seawater environments demand continuous lubrication. Fewer pollutants mean better water quality.
- It is a naturally buoyant rope that will float. It will not be drug along the bottom of streams, reefs, or sea floors.

- The lighter material spooled on the skidder winches, yarders, and other machines means less weight on the forest floor.
- It has 1/7 the weight of comparable diameter steel wire rope and therefore, more line can be spooled on a winch drum. The longer line can be used to reach logs at further lateral yarding distances. Thus, fewer skid trails could be required.
- It does not conduct electricity.

However, one of the biggest drawbacks with synthetic rope remains: cost. It is estimated that AmSteel®-Blue costs between three to five times equivalent steel wire rope. Currently, Samson Rope Technologies and other UHMW-PE rope manufacturers produce rope on an order basis and by customer specifications. The rope is priced according to the quantity ordered. As the commercial demand for the rope increases, availability will also increase and as a result, cost should decrease.

Another major disadvantage of synthetic rope when compared to steel wire rope is its susceptibility to abrasion, wear, and cutting. It is widely known that synthetic rope will not take the abuse that wire rope can take. UHMW-PE is softer than steel and synthetic rope is constructed of tiny fibers braided together. Therefore, it is susceptible to snagging along jagged rocks. In addition, special preparation must be done on the machinery or rigging hardware before using synthetic rope in the harvesting system. Steel wire rope can create grooves or sharp edges that will instantly sever a synthetic rope during operation. Even trampling synthetic rope with boots or machinery can potentially damage the rope. Synthetic rope has many potential benefits, but those benefits will not be fully realized if crews handle the synthetic rope as badly as they currently handle steel wire rope.

5.11 Future Research and Testing

Although this particular study is concluded, it is just the beginning for formalized end connection and termination research for synthetic rope. This project was a pilot study. As the first extensive investigation of end connections for UHMW-

PE rope for use in timber harvesting applications, many concepts were identified and designed. Some concepts were adapted from hardware or techniques already in use with steel wire rope or from other synthetic rope applications. The idea of this project was to begin formal research and select which concepts would warrant further attention. Now that the breaking strength of selected end connections has been quantified, work can be done to modify or refine these designs.

As a pilot study, a number of end connections were developed and tested, but only five replications were conducted. Now that suitable end connections have been identified, larger sample sizes could be chosen. End connections could be adapted and tested on more rope diameters. Although 3/8”, 9/16”, and 5/8” diameters are commonly used rope sizes, larger diameters up to 1 ½” could be tested.

Another concept of interest is a synthetic rope choker design. Although the choker was not developed under this project, demand for it exists. The choker is extensively used in cable, skidder, and helicopter logging. It is an essential piece of rigging that connects the logs to the dropline, winchline, or dropline to bring the logs to the landing. Synthetic chokers will not only decrease weight, but more importantly, they will reduce the safety hazards and hardships of carrying them into the brush.

Furthermore, the choker is considered expendable; it is the first to fail if a load is too large. A choker must be strong enough to hold loads, must not detach or slip off during transport to the landing, must release quickly, and must break before the winchline or dropline fails. A synthetic rope design would be extremely useful in logging applications. Unlike a steel choker that is much stiffer, the new design must consider the difficulty of pushing the synthetic rope under a log.

There are additional rope manufacturers around the world that produce UHMW-PE braided rope from Dyneema® or Spectra® fibers. This project chose one particular product, but this does not mean that this research is not applicable to other 12-strand braided ropes. It was chosen to be a general representation of UHMW-PE rope and to test its applicability in forest operations. Other synthetic ropes offer slightly different characteristics such as increased strength, decreased weight, or an additional protective coating. Other products should be investigated and tested for specific use criteria.

Furthermore, additional rope constructions exist due to demand by industries and their operational requirements. Tech 12™ produced with Technora® fibers, for example, is a stiffer rope with more abrasion resistance than the AmSteel®-Blue, but with a lower breaking strength and reduced the number of cycles to failure. Plasma® produced by Puget Sound Rope is constructed from Spectra® 1000 fiber. Through a proprietary recrystallization process that heats the fibers and draws them further to eliminate stretch, a stronger 12-strand braided rope with better abrasion resistance is constructed (Puget Sound Rope, 2004). With the elimination of some of the stretch however, the number of cycles to failure are reduced.

In the end, different rope manufacturers, constructions, and materials may be more suitable for specific operational conditions in other forest operations. However, it is important to consider that ropes designed for lower creep, increased abrasion resistance, less stretch, or more rigidity may sacrifice breaking strength and the number of cycles to failure. Ropes designed for specific site requirements should be tested accordingly.

Research could also investigate the operational performance of synthetic rope with other lightweight materials, such as UHMW-PE or nylon sheaves. These materials offer the advantage of a decreased coefficient of friction. Similar to UHMW-PE rope, UHMW-PE and nylon have a stronger compressive strength to weight ratio than that of steel. Because of its inherent material properties, steel sheaves are good heat conductors. Synthetic sheaves could reduce heat build-up as the rope passes through and reduce operational hazards from heat or damaged UHMW-PE rope.

UHMW-PE is advantageous in many cases. It has a low coefficient of friction, good wear properties, is readily available, and has relatively low critical and melting temperatures. Other engineered plastics on the market have greater tensile strength due to glass fiber reinforcement. In addition, these materials have higher melting temperatures. Some of these plastics' properties are compared to UHMW-PE in Table

55. Such materials could be better than UHMW-PE as in the case of the nubbin. As discussed earlier, the UHMW-PE nubbins had little hoop strength and consequently deformed quite heavily. New plastics are lighter than conventional end connections and their temperature ranges should withstand operational conditions. However, their performance with adhesives or other end connection designs is not known and should be investigated.

Table 55. Material properties of selected engineered plastics

Material	Hardness	Tensile Modulus	Tensile Strength	Flexural Modulus	Melting Temperature
UHMW-PE	50-70 Rockwell R	29,000-174,000	3,000-6,000 psi	77,000 psi	270 F
Ultem® 1010	109 Rockwell M	520,000	16,000 psi	510,000 psi	660-750 F
Ultem® 2300 R	114 Rockwell M	1,350,000	24,500 psi	2,100,000 psi	660-750 F
Verton® FR-700-10 EM HS		287,000	41,000 psi	2,290,000 psi	535-565 F

(GE Plastics A., 2004), (GE Plastics B., 2004), (LNP Engineering Plastics, 2004), (www.ultrapoly.com, 2002)

Along with other engineered materials, better potting procedures and adhesives could be investigated. Although the amine structural adhesive (Scotch-Weld™ DP-8010) had a lower bond strength, it has some properties that warrant further examination. The Phillystran Socketfast® Blue A-20 was a styrene monomer compound. When it potted, it became glassy and brittle. During break tests, the Phillystran adhesive broke apart in small sharp pieces. It was too brittle to withstand the cycling of the rope. In the case of the UHMW-PE nubbin, the nubbin deformed, but the glassy Phillystran adhesive did not and it simply shattered. The 3M adhesive on the other hand was less brittle. It was softer and flexible. These properties are attractive to withstand normal operating conditions of variable tensions and cycling.

Further research of the SEFAC™ connection could yield greater consistency and breaking strengths. For example, more tuffing of the rope strands could allow better adhesive coverage and increase the bond strength. The geometry of the socket and spike in the SEFAC™ design could be changed. The current design was constructed purely from the recommendation by the fiber manufacturer. Initial tests used a socket length to spike length ratio of less than 1:1. Initial testing has shown that increasing the ratio to 1:1, increases breaking strength by approximately 5%. Furthermore, the socket was designed to account the unstretched diameter of the rope, not the stretched or nominal diameter.

Although the SEFAC™ does show some promise with an average of over 50% breaking strength, further research is necessary to reduce the variability in breaking strength. However, it is not within this project to further manipulate and modify SEFAC™ design constraints and test them.

End connections and terminations in this particular project were tested solely at controlled ambient conditions. Although the Samson Rope Technologies reports that AmSteel®-Blue is unaffected by the cold, heat, or water, these environmental conditions may have an adverse interaction between the synthetic rope and end connections. Freezing conditions could be simulated and laboratory tested. Logging is a year-round occupation and harvesting operations in many countries are conducted in cold conditions. Research could determine whether cold and dry or cold and wet conditions adversely affect UHMW-PE and end connector performance. Forest operations are also conducted in hot environments. Simulated warm, moist and warm, dry conditions could also be tested in the laboratory. Controlled ambient conditions can test the effects of different end connections on breaking strength of the synthetic rope. However, environmental conditions such as extremely hot and cold temperatures are possible on work sites and should be field tested for suitability and safety.

In addition to varying work site conditions, the breaking strength, creep, or other mechanical properties of synthetic rope could be affected by radiation heat. On a hot summer day, when a yarder or carriage is exposed to direct sunlight, heat can build up. In addition, combustion engines create heat and even with the heat dissipated through natural convection, water coolers, or air blowers, the engine housings still trap some of the hot air and radiate heat. The synthetic rope on the yarder or carriage spool can be subjected to higher temperatures. With a critical temperature of 150°F for AmSteel®-Blue, it is imperative to quantify the amount of heat generated in this case. A test could be set up to determine localized heat effects.

Finally, with all of the additional environmental conditions, a more thorough standardized testing procedure should be defined. As stated earlier in Section 2.8, test procedures for this pilot study followed Samson Rope Technology's own SRT Test Method-001-02 protocol that was derived from the Cordage Institute's CI 1500-99 Test Methods for Fiber Rope. The SRT test protocol implies testing only dry ropes. Section 10 in the document briefly describes the conditions under which "wet testing" should occur (i.e. soak the sample for 24 hours and perform the test described in SRT Test Method -001-02). There is no discussion about testing under freezing or localized heat conditions in current synthetic rope testing documents.

6 Conclusion

Since the inception of the Synthetic Rope Research project in summer 1999, there have been many advances in polymer technology. UHMW-PE braided rope has proven itself in the offshore drilling, mooring, tugline, and powerline industries. The US Navy (Flory et al., 1992) and Coastguard have approved it for use within their maritime operations and deep-sea salvage (Fisheries and Oceans Canada and the Canadian Coast Guard Search and Rescue, 2000).

UHMW-PE has many advantages over steel wire rope. It is lightweight, has a strength to weight ratio of approximately 10:1 that of wire rope, it floats, and it is stronger than EIPS wire rope up to 1" diameter. Synthetic rope does not kink, corrode, or absorb chemicals and water. Compared to steel wire rope of the same breaking strength or diameter however, synthetic rope costs 4 to 6 times that of steel (Pilkerton et al., 2001). Gains in productivity can offset the costs of current rope prices. Rope prices are based on current quantities produced. If the demand were higher, supply would increase and prices might drop. Moreover, it is projected that a 10% increase in productivity could benefit the contractor 1000 board feet per day (Garland et al., 2002).

Logging is also one of the most difficult jobs in terms of workloads and cardiovascular demands (Pilkerton et al., 2001). The use of steel wire rope presents hazards such as jaggers and heavy pulling combined with daily operations of rigging, climbing, and carrying. Preliminary results show that when using synthetic rope compared to tasks completed using wire rope, the recovery time is shorter with synthetic rope and thus fatigue is less (Garland et al., 2002).

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 used in a timber harvesting system. It is therefore essential for this implementation that suitable end connections be developed and tested.

This project has accomplished many objectives. It was the first extensive study on end connections specifically designed for synthetic rope. New end connections were developed and steel wire rope connections were modified to meet the strength and usability criteria for timber harvesting operations. End connections suitable for use with forest operations were identified and recommended user guidelines were given.

It is hoped that by answering the research questions, this study will lead to further research of synthetic rope. Successful research, development, and promotion will lead to industry-wide acceptance. The eventual goal of the synthetic rope research is for adoption of synthetic rope in timber harvesting applications as a substitute for steel wire rope.

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8 APPENDIX

8.1 Material Properties

Table A1. Main Textile Properties of Dyneema® SK75 1760 dTEX

Dyneema® Properties	Twisted yarn (Z25)
Tenacity (GPA)	3.2
Modulus (GPA)	105
Elongation (%)	3.6
Bobbin Weight (kg yarn/bobbin)	4

GPA = Gigapascal
Tenacity = tensile stress expressed as force/unit linear density of unstrained Specimen (Samson Rope Technologies A., 2002)
Bobbin = a cylindrical or slightly tapered barrel, with or without flanges, for holding slubbings (Smith, 2004)
Bobbin weight = net weight of the fiber or yarn contained on the bobbin (Smith, 2004)
Modulus = the change in stress to change in strain at some point on the load-elongation curve as determined by the tangent at that point or by the secant that connects an incremental range of stress or strain. (Foster et al., 1997)

Table A2. Physical Properties of Dyneema® SK75

Water and Chemicals	
Resistance to UV light	Very good
Boiling water shrinkage	< 1%
Moisture regain	None
Specific Gravity	0.975

(DSM, 2001)

Table A3. The Dyneema® fiber properties in combination with the 12-strand braided configuration, produce AmSteel®-Blue.

Nominal Rope Diameter (in)	Weight (pounds/100 ft)	Average Strength (pounds)	Minimum Strength (pounds)
3/8”	3.71	20,445	18,401
9/16”	7.90	44,660	40,194
5/8”	10.61	59,015	53,114

(Samson Rope Technologies A., 2002)

Table A4. UHMW-PE Properties

Thermal Properties	
Melting Temperature	132 °C
Maximum Working Temperature	82 °C
Minimum Working Temperature	-104 °C
Thermal Expansion	.0013 inches/foot/degree F
Coefficient of Linear Thermal Expansion	0.0002 $°C^{-1}$
Dielectric Strength	900 KV/mm
Specific Heat	1.9 kJ/kg/K

Frictional Properties –	
$\mu_{dynamic}$	~0.14
μ_{static}	~0.16
$\mu_{dynamic}$ on polished steel – Dry	0.10-0.22
$\mu_{dynamic}$ on polished steel – Water	0.05-0.10
$\mu_{dynamic}$ on polished steel – Oil	0.05-0.08

Physical and Mechanical Properties	
Specific Gravity	0.94
Water Absorption (24 hr. @ 73°F)	0.01 %
Tensile Strength at Break	6,600 psi
Elongation at Yield	2,900 psi
Elongation at Break	350%
Hardness, Rockwell	R50
Hardness, Shore D	65
Density	0.94 g/cm^3
Poisson’s Ratio	0.46

(www.ultrapoly.com, 2002) and (Schweitzer, 2000)

Table A5. UHMW-PE Fiber (Dyneema® SK75 1760 dTex) Properties

Thermal Properties	
Melting point	144-152 °C
Maximum Working Temperature	70 °C
Minimum Working Temperature	-150 °C
Thermal Conductivity at 23°C	20 W/m/K (axial)
Thermal Expansion Coefficient	-12.10^{-6} per K
Dielectric Strength	900 kV/cm
Frictional Properties –	
$\mu_{dynamic}$ on polished steel	0.17
$\mu_{dynamic}$ on steel	0.06
Mechanical Properties	
Creep (22°C, 20% load)	1.10^{-2}% per day
Axial Tensile Strength	3 GPA
Axial Tensile Modulus	100 GPA
Axial Compressive Strength	0.1 GPA
Axial Compressive Modulus	100 GPA
Transverse Tensile Strength	0.03 GPA
Transverse Modulus	3 GPA
Specific Modulus	9,000 cN/tex
Specific Strength	3.5 N/tex = 40 g/den = 3.4 GPA
Specific Tenacity	265 cN/tex
Density	0.97 g/cm^3
Extension to break	3.8%
Modulus	110 N/tex = 1250 g/den = 107 GPA
Shrinkage at 100 °C	< 1%
Tenacity	2.7 GPA

tex = width in grams of 1,000 meters of material (Foster et al., 1997)

gram/denier = weight of fiber per 9,000 meters of material (Foster et al., 1997)

denier = the system used internationally for the numbering of silk and man-made filament yarns (Foster et al., 1997)

(DSM, 2001)

8.2 Synthetic Rope Breaking Strength Compared to Steel Wire Rope

Figure A1 shows how the breaking strength of UHMW-PE 12-strand braided rope compares to extra-improved plowed steel (EIPS) and swaged wire rope.

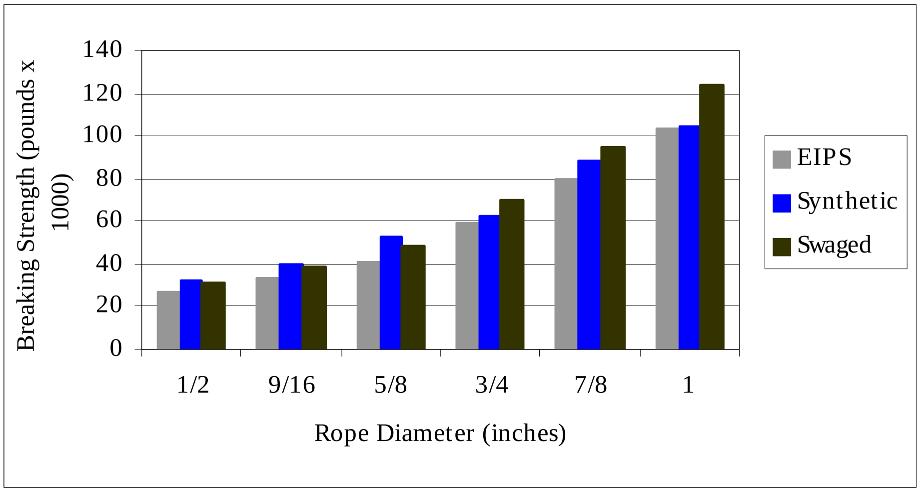


Figure A1. Breaking Strength vs. Rope Diameter (Garland et al., 2002)

8.3 Elongation Resulting From Break Testing

The following chart shows the elongation of the test specimen as load is applied. Most of the elongation in the specimen shown in this graph happens on the initial loading of the of the sample. This elongation is known as the construction stretch of the rope. The rope stretches less as load increases. The graph also shows the next nine cycles. On the eleventh cycle, the specimen is loaded to failure. The failure is represented by the highest peak in the graph (Figure A3).

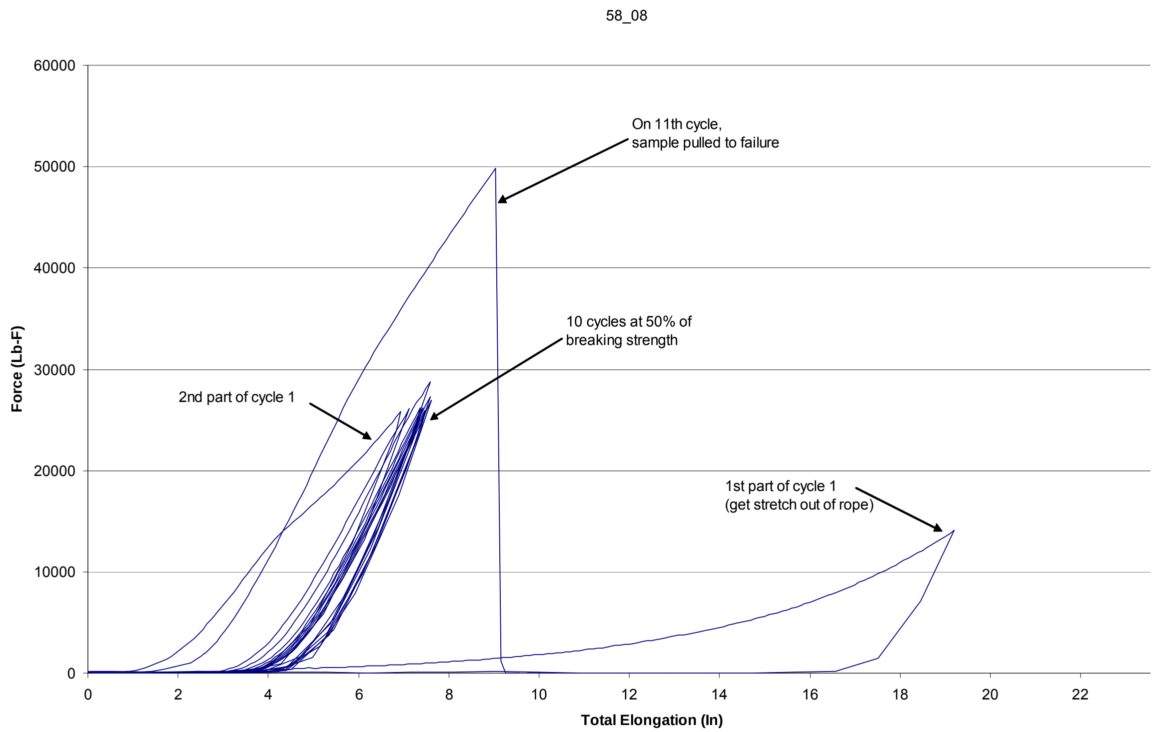


Figure A2.Typical Plot of Force vs. Elongation of 5/8” diameter AmSteel®-Blue rope (Pilkerton et al., 2001)

8.4 Test Equipment

The hydraulic ram test equipment and measurement system in the Knudsen Laboratory at Oregon State University consists of a set of integrated components largely supplied by MTS Systems Corporation of Eden Prairie, MN.

Principle components:

- Hydraulic pump, MTS-505.30 30 gpm at 3000 psi, assorted accumulators and control valves.
- Servo-controller, MTS-407 with integrated position and force conditioners, function generator, and digital display.
- Hydraulic cylinder, MTS-243-70, (216 kip tension, 328 kip compression), 20" stroke, integrated LVDT position sensor.
- Interface Corporation load cell, model 1240BMT-200K.

Secondary equipment include:

- Custom fabricated fixturing to secure the hydraulic cylinder to the structural floor.
- Fixtures as end point anchors to the structural reaction wall.

Data acquisition:

- Windows NT based computer system
- National Instruments LabView software
- Custom developed LabView VI application program to acquire measurement data from force and position sensors.

Calibration and certification:

Load Cell Calibration Certification

Model: 1240BMT-200K
Serial: 104896
Procedure: C-1257
Capacity: 200 Kilopounds
Date: April 1, 1999

Force Standard: STD-16	NIST# 822.07/259991
Standard Indicator: BRD1	NIST# 811/249920-92
Test Indicator: BRD4	NIST# 811/249920-92

Testing authority: Interface Inc.
7401 East Butherus Drive
Scottsdale, AR 85260 USA

MTS Transducer Calibration Data

System: USC.186238
Transducer Model/Type: 243.70T Serial: 1020787
Conditioner Model: 407.12 Serial: 1010931
Channel Designation: Temposonic
Date: June 10, 1999

Testing authority: MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344 USA

A dead weight verification was also performed in the Knudsen Laboratory at Oregon State University to 3890 pounds in May 2003.

8.5 Rope Allocation For End Connections

Table A6. Test Specimen Rope Length Requirements

Test End Connection		Total Length of Rope Needed for Each Test Specimen	Control
1	Buried Eye Splice (BES)	7.5 fids + 4’ clear + 7.5 fids	BES
2	Whoopie Sling	2 fids+1fid+2.25fids+3.5fids+4' clear+1fid+.5fids	BES
3	Long splice	7.5 fids + 6.5 fids min. + 7.5 fids	BES
4	Y-Splice	main section: 7.5 fids + 1 fid + 4.5 fids + 7.5 fids Y section: 7.5 fids + 4' clear + 5 fids	BES
5	Steel nubbin w/ Socketfast® Blue A-20	7.5 fids + 4’ clear + .5’	BES
6	UHMW-PE nubbin w/ Socketfast® Blue A-20	7.5 fids + 4’ clear + .5’	BES
7	Steel nubbin w/ Schotchweld DP-8010	7.5 fids + 4’ clear + .5’	BES
8	UHMW-PE nubbin w/ Scotch-Weld™ DP-8010	7.5 fids + 4’ clear + .5’	BES
9	Notched nubbin w/ Socketfast® Blue A-20	7.5 fids + 4’ clear + .5’	BES
10	SEFAC™	7.5 fids + 4’ clear + .5’	BES
11	Rope clamps	7.5 fids + 4’ clear + (12* diam + 1 fid + 12 * diam)	BES
12	Pinned Nubbin	7.5 fids + 4’ clear + 7.5 fids	BES
13	Knuckle Link	7.5 fids + 4’ clear + 7.5 fids	BES
14	Pressed Nubbin	7.5 fids + 4’ clear + .5’	BES
	3/8” BES	8.5 fids + 4’ clear + 7.5 fids	BES
	3/8” Truck wrapper	7.5 fids + 4’ clear + 7.5 fids	BES

8.6 Procedures on Potting and Some Experimental Notation

Before conducting the formal trials with the Phillystran Socketfast® Blue A-20 adhesive, exploratory trials were conducted with a different potting technique to determine its suitability. The first technique attempted is shown in Figure A3 by applying the adhesive into the large end of the nubbin and have the length of the sample hang below. This method could ensure application of the adhesive down to the individual fiber level. However, the Phillystran Socketfast® Blue A-20 was extremely viscous (200-400 cps) and as a result of the low viscosity, adhesive leaked through the hole in the nubbin and through the strands of the rope. Although the rope was secured with a zip-tie and the hole was plugged with modeling clay, the adhesive traveled through the center of the rope and internal strands. The adhesive continued to run down the sample until it set up approximately 3-12" from the nubbin. Once the adhesive began to set, the leaking stopped and only one half to two-thirds of the adhesive remained.

Figure A3. First potting attempt with Phillystran Socketfast® Blue A-20

After waiting 72 hours, the nubbins were revisited and refilled. After an additional 72 hours, the nubbins were tested. Their respective breaking strengths for the steel, UHMW-PE, and notched nubbins for 5/8 diameter are shown in Table A7.

Table A7. Results from end connections tested using a different potting technique

Diameter	End Connection	Breaking Strength (lbs.)	% of Catalogue Minimum	Potting Technique
5/8	UHMW Nubbin w/ Phillystran	8130	15%	Large diameter up
5/8	UHMW Nubbin w/ Phillystran	7089	13%	Large diameter up
5/8	UHMW Nubbin w/ Phillystran	2737	5%	Large diameter up
5/8	UHMW Nubbin w/ Phillystran	7672	14%	Large diameter up
5/8	UHMW Nubbin w/ Phillystran	6036	11%	Large diameter up
5/8	Steel Nubbin w/ Phillystran	18942	36%	Large diameter up - filled after 72 hours to replace adhesive that leaked through bottom
5/8	Steel Nubbin w/ Phillystran	9293	17%	Large diameter up
5/8	Steel Nubbin w/ Phillystran	17072	32%	Large diameter up - filled after 72 hours to replace adhesive that leaked through bottom
5/8	Steel Nubbin w/ Phillystran	2833	5%	Large diameter up
5/8	Steel Nubbin w/ Phillystran	8234	16%	Large diameter up
5/8	Notched Steel Nubbin w/ Phillystran	16373	31%	Large diameter up
5/8	Notched Steel Nubbin w/ Phillystran	17545	33%	Large diameter up
5/8	Notched Steel Nubbin w/ Phillystran	21414	40%	Large diameter up
5/8	Notched Steel Nubbin w/ Phillystran	14822	28%	Large diameter up
5/8	Notched Steel Nubbin w/ Phillystran	14175	27%	Large diameter up

Inconsistent breaking strength performance of these end connections caused a review of the potting technique. The primary concern however was the leakage of the adhesive into the strands. It was determined that the Phillystran was too viscous to have the nubbin potted “upside down.” Therefore, a new potting strategy was devised. Then end of the sample was fed through the nubbin and frayed. The end of the specimen was then wrapped with nitrile and secured with a zip-tie (see Figure A4 A). It was then inserted into a mold cut out of extruded polystyrene foam (see Figure A4 B) for 72 hours.

Figure A4. A) UHMW-PE nubbin with Phillystran adhesive potting in mold
B) Potted UHMW-PE nubbin with Phillystran adhesive

There was a major trade-off with this potting method. This new method did ensure that there was no leakage through the strands and interior of the rope specimen. All adhesive was collected in the nubbin. However, it was difficult to ensure complete coverage of the adhesive down to the fiber level. The potted nubbins are compared in figures Figure A5.

Figure A5. A) First potting attempt with Phillystran adhesive
B) Potting technique used in pilot study

The second method was better than the first for a couple of reasons. The most important feature of this method is how the form of the end termination after the adhesive has set up. As seen in Figure A5B, the frayed fibers are turned up and pressed along the outer wall of the nubbin. As the adhesive is applied through the top of the nubbin, all excess adhesive will run to the bottom and cover all of the frayed fibers. As a result, the fibers on both side of the nubbin wall are bonded to the UHMW-PE.

A secondary reason was that there was no leakage of the adhesive down the length of the specimen. Therefore, this method tested the strength of the end connection and was not affected by excessive adhesive outside of the nubbin.

8.7 Break Test Data

Table A8. 5/8” diameter end connections and breaking strength

	5/8" Diameter End Connections and Breaking Strengths (lbs.)													
	BES	Whoopie Sling	Long Splice	Y-Splice	Steel Nubbin w/ Phillystran	UHMW Nubbin w/ Phillystran	Steel Nubbin w/ 3M	UHMW Nubbin w/ 3M	Notched Steel Nubbin w/ Phillystran	SEFAC	Rope Clamps	Pinned Nubbin	Knuckle Link	Pressed Nubbin
Spool 1	49206.54	45674.66	49237.06	27090.45	1034.55	8908.08	2682.45	985.72	16372.88	20782.47	33163.45	45285.04	51130.37	10284.42
Spool 2	50338.75	43661.50	42263.79	26428.22	21554.57	8563.23	857.54	1705.93	17544.55	16473.39	33120.73	50088.50	49631.53	11538.70
Spool 3	49758.91	42340.09	49874.88	41409.30	3924.56	11517.33	1873.78	1934.81	21414.18	25292.97	29269.41	49377.44	53324.78	11471.56
Spool 4	52349.85	49029.54	47042.85	43087.77	2340.70	9094.24	1898.19	1049.81	14822.39	26474.00	27505.91	49349.98	50344.85	10742.19
Spool 5	49279.79	47149.66	48349.00	44174.20	2120.97	13552.86	1681.52	518.80	14175.42	22195.43	28408.81	50238.94	51429.45	11291.50
Mean	50186.77	45571.09	47353.52	36437.99	6195.07	10327.15	1798.70	1239.01	16865.88	22243.65	30293.66	48867.98	51172.20	11065.67

	5/8" Diameter Breaking Strength as Percent of BES													
	BES	Whoopie Sling	Long Splice	Y-Splice	Steel Nubbin w/ Phillystran	UHMW Nubbin w/ Phillystran	Steel Nubbin w/ 3M	UHMW Nubbin w/ 3M	Notched Steel Nubbin w/ Phillystran	SEFAC	Rope Clamps	Pinned Nubbin	Knuckle link	Pressed Nubbin
Spool 1	N/A	92.82%	100.06%	55.05%	2.10%	18.10%	5.45%	2.00%	33.27%	42.24%	67.40%	92.03%	103.91%	20.90%
Spool 2	N/A	86.74%	83.96%	52.50%	42.82%	17.01%	1.70%	3.39%	34.85%	32.73%	65.80%	99.50%	98.60%	22.92%
Spool 3	N/A	85.09%	100.23%	83.22%	7.89%	23.15%	3.77%	3.89%	43.04%	50.83%	58.82%	99.23%	107.17%	23.05%
Spool 4	N/A	93.66%	89.86%	82.31%	4.47%	17.37%	3.63%	2.01%	28.31%	50.57%	52.54%	94.27%	96.17%	20.52%
Spool 5	N/A	95.68%	98.11%	89.64%	4.30%	27.50%	3.41%	1.05%	28.77%	45.04%	57.65%	101.95%	104.36%	22.91%
Mean	N/A	90.80%	94.45%	72.54%	12.32%	20.63%	3.59%	2.47%	33.65%	44.28%	60.44%	97.40%	102.04%	22.06%

Table A9. 9/16" diameter end connections and breaking strengths

	9/16" Diameter End Connections and Breaking Strengths (lbs.)														
	BES	Whoopie Sling	Long Splice	Y-Splice	Steel Nubbin w/ Phillystran	UHMW Nubbin w/ Phillystran	Steel Nubbin w/ 3M	UHMW Nubbin w/ 3M	Notched Steel Nubbin w/ Phillystran	SEFAC	Rope Clamps	Pinned Nubbin	Knuckle Link	Pressed Nubbin
Spool 6	39376.83	34985.35	38739.02	37646.48	17678.83	6936.65	N/A	N/A	12289.43	29333.50	27758.79	39221.19	41061.40	10812.38
Spool 7	38638.30	32052.61	35446.17	36462.40	20797.73	2151.49	N/A	N/A	13479.61	29077.15	25640.87	38180.54	41085.29	10498.05
Spool 8	42205.81	35852.05	39401.25	35665.89	10412.60	10418.70	N/A	N/A	11541.75	15225.22	25460.82	33230.59	36407.47	11117.55
Spool 9	33560.18	30447.91	40921.02	34609.98	14010.62	9872.42	N/A	N/A	12945.56	23299.98	25598.14	40399.17	40393.07	10326.00
Spool 10	40005.49	37545.78	37063.60	35397.34	10250.85	2658.08	N/A	N/A	13836.67	30657.96	25466.92	39303.59	40774.54	10858.15
Mean	38757.32	34176.74	38314.21	35956.42	14630.13	6407.47	N/A	N/A	12818.60	25518.76	25985.11	38067.02	39944.35	10722.43
	9/16" Diameter Breaking Strength as Percent of BES													
	BES	Whoopie Sling	Long Splice	Y-Splice	Steel Nubbin w/ Phillystran	UHMW Nubbin w/ Phillystran	Steel Nubbin w/ 3M	UHMW Nubbin w/ 3M	Notched Steel Nubbin w/ Phillystran	SEFAC	Rope Clamps	Pinned Nubbin	Knuckle link	Pressed Nubbin
Spool 6	N/A	88.85%	98.38%	95.61%	44.90%	17.62%	N/A	N/A	31.21%	74.49%	70.50%	99.60%	104.28%	27.46%
Spool 7	N/A	82.96%	91.74%	94.37%	53.83%	5.57%	N/A	N/A	34.89%	75.25%	66.36%	98.82%	106.33%	27.17%
Spool 8	N/A	84.95%	93.36%	84.50%	24.67%	24.69%	N/A	N/A	27.35%	36.07%	60.33%	78.73%	86.26%	26.34%
Spool 9	N/A	90.73%	121.93%	103.13%	41.75%	29.42%	N/A	N/A	38.57%	69.43%	76.28%	120.38%	120.36%	30.77%
Spool 10	N/A	93.85%	92.65%	88.48%	25.62%	6.64%	N/A	N/A	34.59%	76.63%	63.66%	98.25%	101.92%	27.14%
Mean	N/A	88.27%	99.61%	93.22%	38.15%	16.79%	N/A	N/A	33.32%	66.38%	67.42%	99.16%	103.83%	27.78%

Table A10. 3/8" diameter end connections and breaking strengths

3/8" Diameter End Connections and Breaking Strengths (lbs.)

	BES	Truck Wrappers	Truck wrapper break strength as % of BES
Spool 1	18615.72	15888.38	85.35%
Spool 2	19393.92	13847	71.40%
Spool 3	19381.71	16186.52	83.51%
Spool 4	18844.61	14770.59	78.38%
Spool 5	17593.38	15855.73	90.12%
Mean	18765.87	15309.64	81.58%

Table A11. 5/8" compiled Results

5/8" Compiled Results

Catalogue Min. Break Strength	53114	lbs.
Catalogue Avg. Break Strength	59015	lbs.

End Connection	Diameter	Spool	Breaking Strength	SRT Reported Spool Break Strength	% SRT Break Strength	% Min. Break Strength	% Avg. Break Strength	Average Breaking Strength (lbs)	Avg. Break Strength (% of Catalogue Min.)	Standard Deviation	Failure Mode	# Failed Strands	Completed 10 Cycles? (Y/N)	Cycles Completed	Recoil
BES	5/8	C1	49206.54	53118	92.64%	92.64%	83.38%	50186.77	94.49%	1291.18	Tail exit - wall end	11	Y	10	5
BES	5/8	C2	50338.75	53939	93.33%	94.77%	85.30%				End of taper - ram end	11	Y	10	5
BES	5/8	C3	49758.91	54215	91.78%	93.68%	84.32%				End of taper - ram end	10	Y	10	4
BES	5/8	C4	52349.85	53468	97.91%	98.56%	88.71%				End of taper - wall end	12	Y	10	1
BES	5/8	C5	49279.79	54020	91.23%	92.78%	83.50%				In "clear" section	12	Y	10	2
Whoopie Sling	5/8	C1	45674.66	53118	85.99%	85.99%	77.40%	45571.09	85.80%	2671.58	Tail exit	11	Y	10	5
Whoopie Sling	5/8	C2	43661.5	53939	80.95%	82.20%	73.98%				Tail exit	11	Y	10	3
Whoopie Sling	5/8	C3	42340.09	54215	78.10%	79.72%	71.74%				Tail exit	11	Y	10	5
Whoopie Sling	5/8	C4	49029.54	53468	91.70%	92.31%	83.08%				End of taper - Brummel eye splice - wall end	9	Y	10	4
Whoopie Sling	5/8	C5	47149.66	54020	87.28%	88.77%	79.89%				Tail exit	10	Y	10	3
Long Splice	5/8	C1	49237.06	53118	92.69%	92.70%	83.43%	47353.52	89.15%	3037.18	End of taper of long splice	10	Y	10	2
Long Splice	5/8	C2	42263.79	53939	78.35%	79.57%	71.62%				End of taper in eye	11	Y	10	3
Long Splice	5/8	C3	49874.88	54215	91.99%	93.90%	84.51%				End of taper of long splice	10	Y	10	5
Long Splice	5/8	C4	47042.85	53468	87.98%	88.57%	79.71%				End of taper of long splice	10	Y	10	3
Long Splice	5/8	C5	48349	54020	89.50%	91.03%	81.93%				End of taper of long splice	12	Y	10	5
Y-Splice	5/8	C1	27090.45	53118	51.00%	51.00%	45.90%	36437.99	68.60%	8893.18	Tail pulled out	0	Y	1	0
Y-Splice	5/8	C2	26428.22	53939	49.00%	49.76%	44.78%				Tail pulled out	0	Y	1	0
Y-Splice	5/8	C3	41409.3	54215	76.38%	77.96%	70.17%	26759.34	50.38%		Tail pulled out	0	Y	10	0
Y-Splice	5/8	C4	43087.77	53468	80.59%	81.12%	73.01%				End of y-splice taper in main section - ram end	10	Y	10	1
Y-Splice	5/8	C5	44174.2	54020	81.77%	83.17%	74.85%				End of Y-splice taper in tail section	12	Y	10	0
Steel Nubbin w/ Phillystran	5/8	C1	1034.55	53118	1.95%	1.95%	1.75%	6195.07	11.66%	8648.05	Pulled out of nubbin	0	N	0	0
Steel Nubbin w/ Phillystran	5/8	C2	21554.57	53939	39.96%	40.58%	36.52%				End of connection	10	N	0	0
Steel Nubbin w/ Phillystran	5/8	C3	3924.56	54215	7.24%	7.39%	6.65%				Pulled out of nubbin	0	N	0	0
Steel Nubbin w/ Phillystran	5/8	C4	2340.7	53468	4.38%	4.41%	3.97%				Pulled out of nubbin	0	N	0	0
Steel Nubbin w/ Phillystran	5/8	C5	2120.97	54020	3.93%	3.99%	3.59%				Pulled out of nubbin	0	N	0	0
UHMW Nubbin w/ Phillystran	5/8	C1	8908.08	53118	16.77%	16.77%	15.09%	10327.15	19.44%	2148.66	Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	5/8	C2	8563.23	53939	15.88%	16.12%	14.51%				Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	5/8	C3	11517.33	54215	21.24%	21.68%	19.52%				Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	5/8	C4	9094.24	53468	17.01%	17.12%	15.41%				Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	5/8	C5	13552.86	54020	25.09%	25.52%	22.97%				Pulled out	9	N	0	0
Steel Nubbin w/ 3M	5/8	C1	2682.45	53118	5.05%	5.05%	4.55%	1798.70	3.39%	651.16	Pulled out of nubbin	0	Y	0	0
Steel Nubbin w/ 3M	5/8	C2	857.54	53939	1.59%	1.61%	1.45%				Pulled out of nubbin	0	Y	0	0
Steel Nubbin w/ 3M	5/8	C3	1873.78	54215	3.46%	3.53%	3.18%				Pulled out of nubbin	0	Y	0	0
Steel Nubbin w/ 3M	5/8	C4	1898.19	53468	3.55%	3.57%	3.22%				Pulled out of nubbin	0	Y	0	0
Steel Nubbin w/ 3M	5/8	C5	1681.52	54020	3.11%	3.17%	2.85%				Pulled out of nubbin	0	Y	0	0
UHMW Nubbin w/ 3M	5/8	C1	985.72	53118	1.86%	1.86%	1.67%	1239.01	2.33%	574.63	Pulled out of nubbin	0	Y	0	0
UHMW Nubbin w/ 3M	5/8	C2	1705.93	53939	3.16%	3.21%	2.89%				Pulled out of nubbin	0	Y	0	0
UHMW Nubbin w/ 3M	5/8	C3	1934.81	54215	3.57%	3.64%	3.28%				Pulled out of nubbin	0	Y	0	0
UHMW Nubbin w/ 3M	5/8	C4	1049.81	53468	1.96%	1.98%	1.78%				Pulled out of nubbin	0	Y	0	0
UHMW Nubbin w/ 3M	5/8	C5	518.8	54020	0.96%	0.98%	0.88%				Pulled out of nubbin	0	Y	0	0
Notched Steel Nubbin w/ Phillystran	5/8	C1	16372.88	53118	30.82%	30.83%	27.74%	16865.88	31.75%	2863.79	Pulled out of nubbin	4	N	0	0
Notched Steel Nubbin w/ Phillystran	5/8	C2	17544.55	53939	32.53%	33.03%	29.73%				Pulled out of nubbin	10	N	0	0
Notched Steel Nubbin w/ Phillystran	5/8	C3	21414.18	54215	39.50%	40.32%	36.29%				Pulled out of nubbin	11	N	0	0
Notched Steel Nubbin w/ Phillystran	5/8	C4	14822.39	53468	27.72%	27.91%	25.12%				Pulled out of nubbin	10	N	0	0
Notched Steel Nubbin w/ Phillystran	5/8	C5	14175.42	54020	26.24%	26.69%	24.02%				Pulled out of nubbin	11	N	0	0
SEFAC	5/8	C1	20782.47	53118	39.13%	39.13%	35.22%	22243.65	41.88%	3956.88	At end of socket	11	N	0	4
SEFAC	5/8	C2	16473.39	53939	30.54%	31.02%	27.91%				2 strands failed inside socket and rest slipped out	2	N	0	0
SEFAC	5/8	C3	25292.97	54215	46.65%	47.62%	42.86%				At end of socket	12	N	0	1
SEFAC	5/8	C4	26474	53468	49.51%	49.84%	44.86%				Slipped out	0	Y	10	0
SEFAC	5/8	C5	22195.43	54020	41.09%	41.79%	37.61%				At end of socket	11	N	0	5
Rope Clamps	5/8	C1	33163.45	53118	62.43%	62.44%	56.19%	30293.66	57.04%	2674.01	Last clamp - furthest from eye	10	Y	10	1
Rope Clamps	5/8	C2	33120.73	53939	61.40%	62.36%	56.12%				Last clamp - furthest from eye	10	Y	10	1
Rope Clamps	5/8	C3	29269.41	54215	53.99%	55.11%	49.60%				Last clamp - furthest from eye	1	Y	10	0
Rope Clamps	5/8	C4	27505.91	53468	51.44%	51.79%	46.61%				Last clamp - furthest from eye	9	Y	10	0
Rope Clamps	5/8	C5	28408.81	54020	52.59%	53.49%	48.14%				Last clamp - furthest from eye	1	Y	10	0
Pinned Nubbin	5/8	C1	45285.04	53118	85.25%	85.26%	76.73%	48867.98	92.01%	2043.19	End of taper - wall end	11	Y	10	4
Pinned Nubbin	5/8	C2	50088.5	53939	92.86%	94.30%	84.87%				En d of taper - wall end	11	Y	10	5
Pinned Nubbin	5/8	C3	49377.44	54215	91.08%	92.97%	83.67%				End of taper - ram end	11	Y	10	
Pinned Nubbin	5/8	C4	49349.98	53468	92.30%	92.91%	83.62%				End of taper - wall end	11	Y	10	5
Pinned Nubbin	5/8	C5	50238.94	54020	93.00%	94.59%	85.13%				Middle of eye	12	Y	10	0
Knuckle Link	5/8	C1	51130.37	53118	96.26%	96.27%	86.64%	51172.20	96.34%	1392.81	Top of eye	12	Y	10	0
Knuckle Link	5/8	C2	49631.53	53939	92.01%	93.44%	84.10%					12		10	
Knuckle Link	5/8	C3	53324.78	54215	98.36%	100.40%	90.36%				Tope of eye	12	Y	10	0
Knuckle Link	5/8	C4	50344.85	53468	94.16%	94.79%	85.31%				End of taper - ram end	12	Y	10	3
Knuckle Link	5/8	C5	51429.45	54020	95.20%	96.83%	87.15%					12		10	
Pressed Nubbin	5/8	C1	10284.42	53118	19.36%	19.36%	17.43%	11065.67	20.83%	537.24	Pulled out	0	N	0	0
Pressed Nubbin	5/8	C2	11538.7	53939	21.39%	0.217244041	19.55%				Pulled out	0	N	0	0
Pressed Nubbin	5/8	C3	11471.56	54215	21.16%	0.215979968	19.44%				Pulled out	0	N	0	0
Pressed Nubbin	5/8	C4	10742.19	53468	20.09%	0.202247807	18.20%				Pulled out	0	N	0	0
Pressed Nubbin	5/8	C5	11291.5	54020	20.90%	0.212589901	19.13%				Pulled out	0	N	0	0

Table A12. 9/16” compiled Results

9/16" Compiled Results

Catalogue Min. Break Strength	40194	lbs.
Catalogue Avg. Break Strength	44660	lbs.

End Connection	Diameter	Spool	Breaking Strength	SRT Reported Spool Break Strength	% SRT Break Strength	% Min. Break Strength	% Avg. Break Strength	Average Breaking Strength (lbs)	Avg. Break Strength (% of Catalogue Min.)	Standard Deviation	Failure mode	# Failed Strands	Completed 10 Cycles? (Y/N)	Cycles Completed	Recoil
BES	9/16	B1	39376.83	43452	90.62%	97.97%	88.17%	38757.322	96.43%	3196.02	End of taper	11	Y	10	3
BES	9/16	B2	38638.3	41880	92.26%	96.13%	86.52%				Broke in middle of rope	11	Y	10	5
BES	9/16	B3	42205.81	41549	101.58%	105.01%	94.50%				End of taper	12	Y	10	2
BES	9/16	B4	33560.18	41832	80.23%	83.50%	75.15%				End of taper	12	Y	10	1
BES	9/16	B5	40005.49	44619	89.66%	99.53%	89.58%				End of taper - ram end	11	Y	10	5
Whoopie Sling	9/16	B1	34985.35	43452	80.51%	87.04%	78.34%	34176.74	85.03%	2882.15	Exit of rope at tail	11	Y	10	3
Whoopie Sling	9/16	B2	32052.61	41880	76.53%	79.74%	71.77%				Exit of rope at tail	11	Y	10	4
Whoopie Sling	9/16	B3	35852.05	41549	86.29%	89.20%	80.28%				Exit of rope at tail	11	Y	10	5
Whoopie Sling	9/16	B4	30447.91	41832	72.79%	75.75%	68.18%				Exit of rope at tail	11	Y	10	2
Whoopie Sling	9/16	B5	37545.78	44619	84.15%	93.41%	84.07%				Exit of rope at tail	11	Y	10	
Long Splice	9/16	B1	38739.02	43452	89.15%	96.38%	86.74%	38314.212	95.32%	2118.21	End of Long splice taper	12	Y	10	5
Long Splice	9/16	B2	35446.17	41880	84.64%	88.19%	79.37%				Long splice rope interchange	12	Y	10	3
Long Splice	9/16	B3	39401.25	41549	94.83%	98.03%	88.22%				End of BES taper	11	Y	10	4
Long Splice	9/16	B4	40921.02	41832	97.82%	101.81%	91.63%				End of BES taper	12	Y	10	4
Long Splice	9/16	B5	37063.6	44619	83.07%	92.21%	82.99%				End of long splice taper - ram end	10	Y	10	3
Y-Splice	9/16	B1	37646.48	43452	86.64%	93.66%	84.30%	35956.418	89.46%	1153.49	Y-splice section at exit point of main section	12	Y	10	1
Y-Splice	9/16	B2	36462.4	41880	87.06%	90.72%	81.64%				Broke in rope main section	10	Y	10	3
Y-Splice	9/16	B3	35665.89	41549	85.84%	88.73%	79.86%				Exit point of Y-splice	12	Y	10	2
Y-Splice	9/16	B4	34609.98	41832	82.74%	86.11%	77.50%				End of taper of Y-splice section	11	Y	10	5
Y-Splice	9/16	B5	35397.34	44619	79.33%	88.07%	79.26%				Pulled out	0	Y	10	0
Steel Nubbin w/ Phillystran	9/16	B1	17678.83	43452	40.69%	43.98%	39.59%	14630.126	36.40%	4601.18	Exit point of nubbin	10	N	0	0
Steel Nubbin w/ Phillystran	9/16	B2	20797.73	41880	49.66%	51.74%	46.57%				Exit point of nubbin	11	N	1	5
Steel Nubbin w/ Phillystran	9/16	B3	10412.6	41549	25.06%	25.91%	23.32%				Exit point of nubbin	7	N	0	0
Steel Nubbin w/ Phillystran	9/16	B4	14010.62	41832	33.49%	34.86%	31.37%				Exit point of nubbin	12	N	1	0
Steel Nubbin w/ Phillystran	9/16	B5	10250.85	44619	22.97%	25.50%	22.95%				Exit point of nubbin	1	N	2	0
UHMW Nubbin w/ Phillystran	9/16	B1	6936.65	43452	15.96%	17.26%	15.53%	6407.468	15.94%	3890.60	Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	9/16	B2	2151.49	41880	5.14%	5.35%	4.82%				Pulled out	0	N	0	0
UHMW Nubbin w/ Phillystran	9/16	B3	10418.7	41549	25.08%	25.92%	23.33%				Exit point of nubbin	0	N	0	0
UHMW Nubbin w/ Phillystran	9/16	B4	9872.42	41832	23.60%	24.56%	22.11%				Pulled out	9	N	0	0
UHMW Nubbin w/ Phillystran	9/16	B5	2658.08	44619	5.96%	6.61%	5.95%				Pulled out	0	N	0	0
Notched Steel Nubbin w/ Phillystran	9/16	B1	12289.43	43452	28.28%	30.58%	27.52%	12818.604	31.89%	921.94	Exit point of nubbin	8	N	0	0
Notched Steel Nubbin w/ Phillystran	9/16	B2	13479.61	41880	32.19%	33.54%	30.18%				Exit point of nubbin	7	N	0	0
Notched Steel Nubbin w/ Phillystran	9/16	B3	11541.75	41549	27.78%	28.72%	25.84%				Exit point of nubbin	11	N	0	0
Notched Steel Nubbin w/ Phillystran	9/16	B4	12945.56	41832	30.95%	32.21%	28.99%				Exit point of nubbin	9	N	0	0
Notched Steel Nubbin w/ Phillystran	9/16	B5	13836.67	44619	31.01%	34.42%	30.98%				Exit point of nubbin	10	N	0	0
SEFAC	9/16	B1	29333.5	43452	67.51%	72.98%	65.68%	25518.762	63.49%	6412.99	Exit point of SEFAC	12	Y	10	0
SEFAC	9/16	B2	29077.15	41880	69.43%	72.34%	65.11%				Exit point of SEFAC	12	Y	11	0
SEFAC	9/16	B3	15225.22	41549	36.64%	37.88%	34.09%				Pulled out	0	N	0	0
SEFAC	9/16	B4	23299.98	41832	55.70%	57.97%	52.17%				Exit point of SEFAC	11	Y	10	5
SEFAC	9/16	B5	30657.96	44619	68.71%	76.27%	68.65%				Exit point of SEFAC	12	Y	12	
Rope Clamps	9/16	B1	27758.79	43452	63.88%	69.06%	62.16%	25985.108	64.65%	994.68	Last Clamp - furthest from eye	11	Y	10	0
Rope Clamps	9/16	B2	25640.87	41880	61.22%	63.79%	57.41%				Last Clamp - furthest from eye	11	Y	10	0
Rope Clamps	9/16	B3	25460.82	41549	61.28%	63.34%	57.01%				Last Clamp - furthest from eye	11	Y	10	2
Rope Clamps	9/16	B4	25598.14	41832	61.19%	63.69%	57.32%				Last Clamp - furthest from eye	11	Y	10	0
Rope Clamps	9/16	B5	25466.92	44619	57.08%	63.36%	57.02%				Last Clamp - furthest from eye	9	Y	10	1
Pinned Nubbin	9/16	B1	39221.19	43452	90.26%	97.58%	87.82%	38067.016	94.71%	2815.32	End of taper - wall end	11	Y	10	5
Pinned Nubbin	9/16	B2	38180.54	41880	91.17%	94.99%	85.49%				End of taper - wall end	11	Y	10	5
Pinned Nubbin	9/16	B3	33230.59	41549	79.98%	82.68%	74.41%				Top of eye	12	Y	10	0
Pinned Nubbin	9/16	B4	40399.17	41832	96.57%	100.51%	90.46%				End of taper - wall end	11	Y	10	5
Pinned Nubbin	9/16	B5	39303.59	44619	88.09%	97.78%	88.01%				End of taper - ram end	11	Y	10	
Knuckle link	9/16	B1	41061.4	43452	94.50%	102.16%	91.94%	39944.354	99.38%	1996.85	End of taper - ram end	11	Y	10	4
Knuckle link	9/16	B2	41085.29	41880	98.10%	102.22%	92.00%				End of taper - wall end	11	Y	10	5
Knuckle link	9/16	B3	36407.47	41549	87.63%	90.58%	81.52%				End of taper - ram end	11	Y	10	5
Knuckle link	9/16	B4	40393.07	41832	96.56%	100.50%	90.45%				End of taper - ram end	11	Y	10	5
Knuckle link	9/16	B5	40774.54	44619	91.38%	101.44%	91.30%				End of taper - ram end	12	Y	10	0
Pressed Nubbin	9/16	B1	10812.38	43452	24.88%	26.90%	24.21%	10724.258	26.68%	313.32	Pulled out	0	N	0	0
Pressed Nubbin	9/16	B2	10498.05	41880	25.07%	26.12%	23.51%				Pulled out	0	N	0	0
Pressed Nubbin	9/16	B3	11117.55	41549	26.76%	27.66%	24.89%				Pulled out	0	N	0	0
Pressed Nubbin	9/16	B4	10326	41832	24.68%	25.69%	23.12%				Pulled out	0	N	0	0
Pressed Nubbin	9/16	B5	10867.31	44619	24.36%	27.04%	24.33%				Pulled out	0	N	0	0

Table A13. 3/8" compiled results

3/8" Compiled Results

Catalogue Min. Break Strength	18401	lbs.
Catalogue Avg. Break Strength	20445	lbs.

End Connection	**Diameter**	**Spool**	**Breaking Strength**	**SRT Reported Spool Break Strength**	**% SRT Break Strength**	**% Min. Break Strength**	**% Avg. Break Strength**	**Average Breaking Strength (lbs)**	**Avg. Break Strength (% of Catalogue Min.)**	**Standard Deviation**	**Failure Mode**	**# Failed Strands**	**Completed 10 Cycles? (Y/N)**	**Cycles Completed**	**Re**
BES	3/8	A1	18615.72	19937	93.37%	101.17%	91.05%	18765.868	101.98%	737.76	End of taper - wall side	11	Y	10	
BES	3/8	A2	19393.92	20390	95.11%	105.40%	94.86%				End of taper - wall side	11	Y	10	
BES	3/8	A3	19381.71	19479	99.50%	105.33%	94.80%				End of taper - wall side	11	Y	10	
BES	3/8	A4	18844.61	19344	97.42%	102.41%	92.17%				End of taper - ram side	11	Y	10	
BES	3/8	A5	17593.38	19577	89.87%	95.61%	86.05%				End of taper - wall side	11	Y	10	
Wrappers	3/8	A1	15888.38	19937	79.69%	86.35%	77.71%	15309.644	83.20%	978.77	Top of eye - wall end	12	Y	10	
Wrappers	3/8	A2	13847	20390	67.91%	75.25%	67.73%				Top of eye - wall end	12	Y	10	
Wrappers	3/8	A3	16186.52	19479	83.10%	87.97%	79.17%				Top of eye - ram end	12	Y	10	
Wrappers	3/8	A4	14770.59	19344	76.36%	80.27%	72.25%				Top of eye - wall end	12	Y	10	
Wrappers	3/8	A5	15855.73	19577	80.99%	86.17%	77.55%				Top of eye - ram end	12	Y	10	

8.8 End Connection Designs

This section shows the drawings of the pinned nubbin, the knuckle link, and the notched nubbin. It also shows the two proprietary calculation sheets from DSM used for the design of the SEFAC™ for the 9/16" and 5/8" diameters.

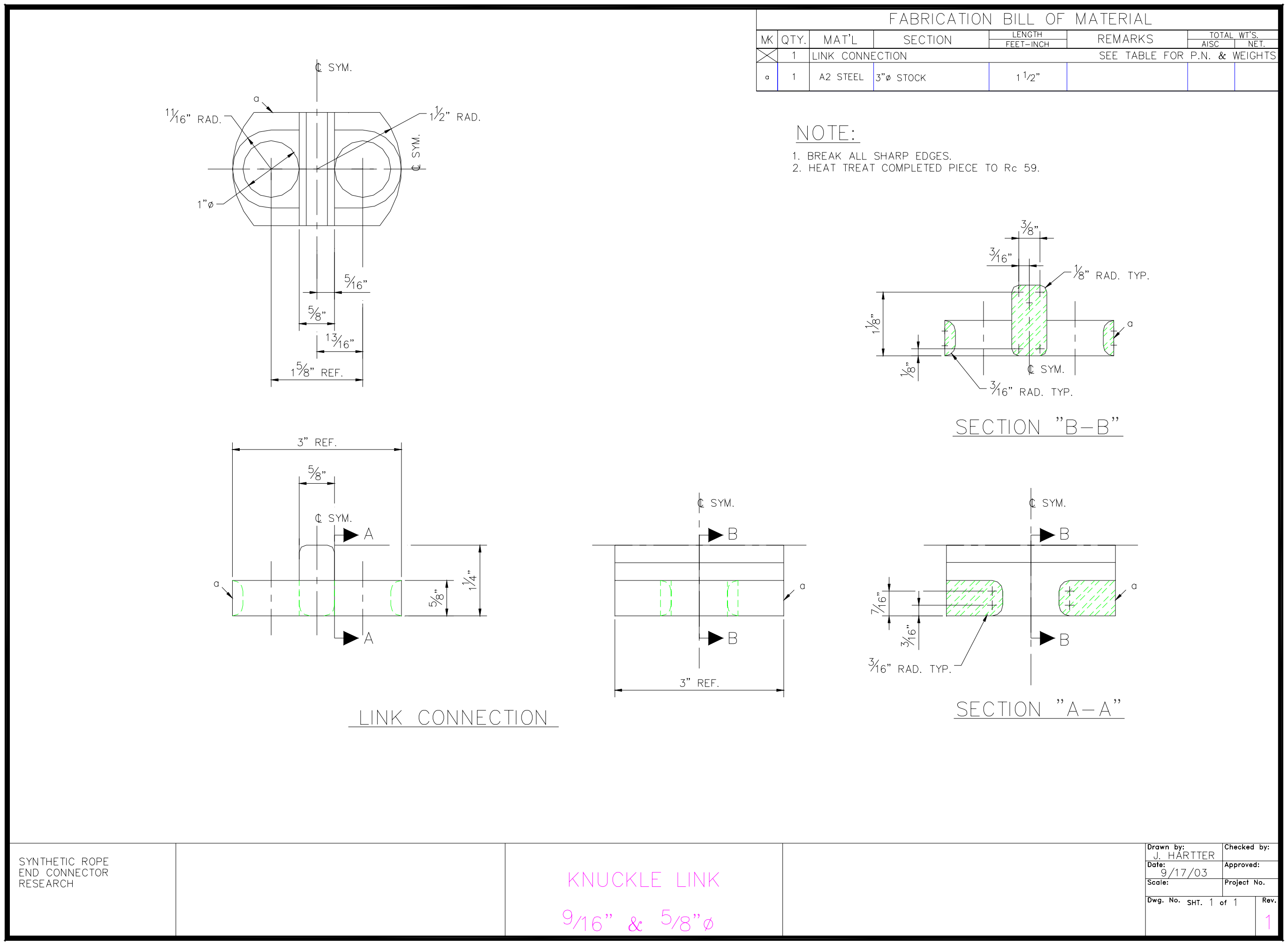


Figure A6. Knuckle Link

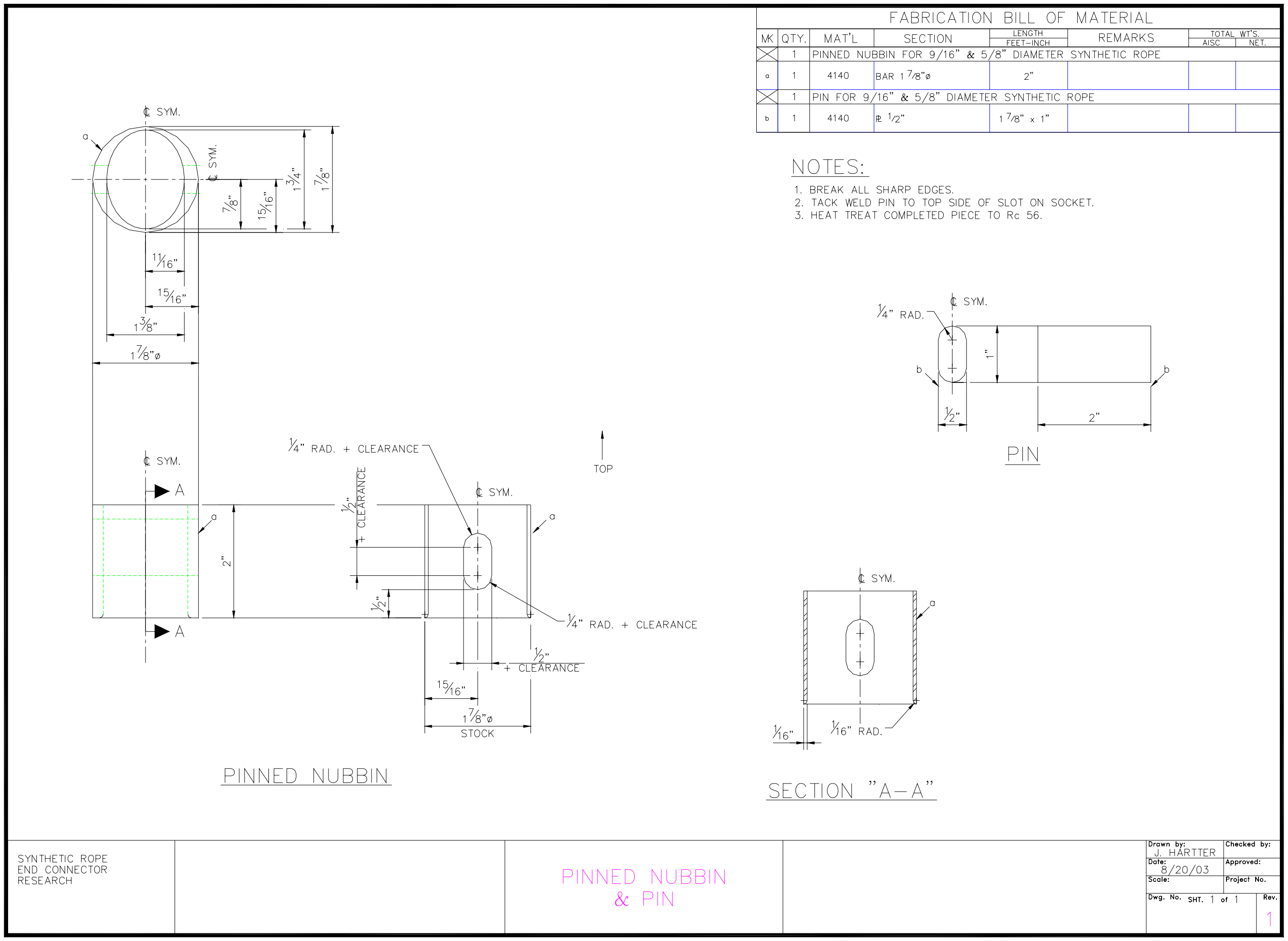


Figure A7. Pinned Nubbin

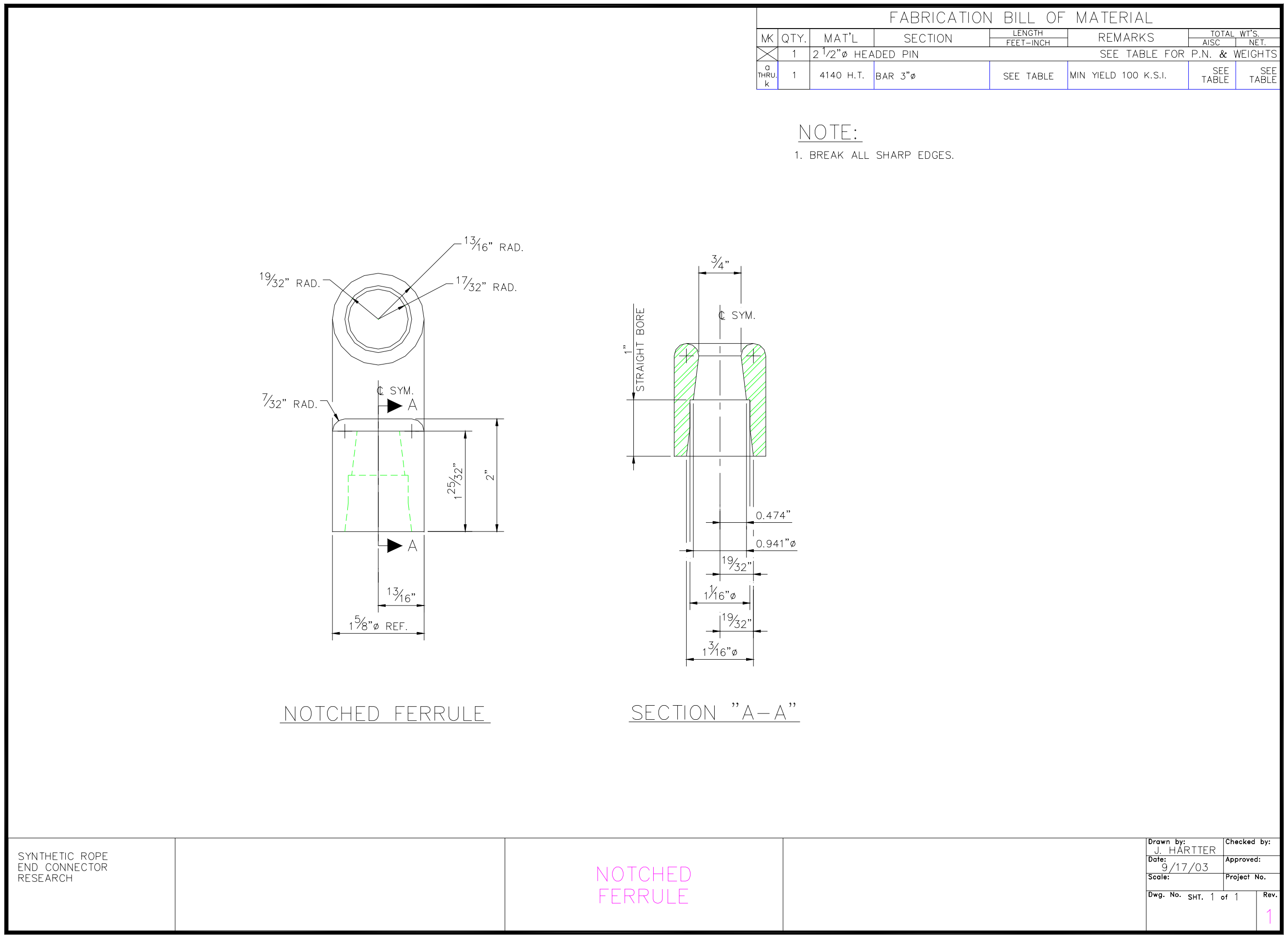
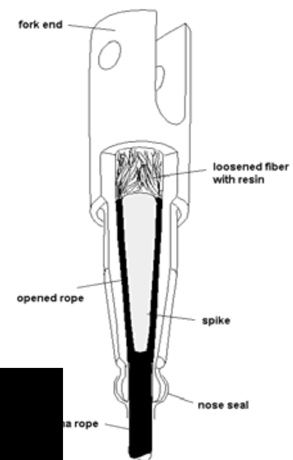


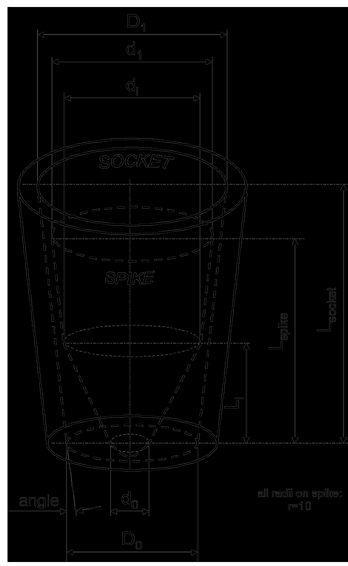
Figure A8. Notched nubbin

Socket-spike calculation for Dyneema HMPE ropes



Rope data

material	Dyneema	fiber #2	fiber #3	
density	0.97	1	1	kg/dm^3
share	100%	0%	0%	
D_{rope}	15.875	mm		
W_{rope}	118	g/m		



Socket geometry

D_1	28.10	mm
D_0	17	mm
angle	4	°
L_{socket} / D_{rope}	5	-
L_{socket}	79.375	mm

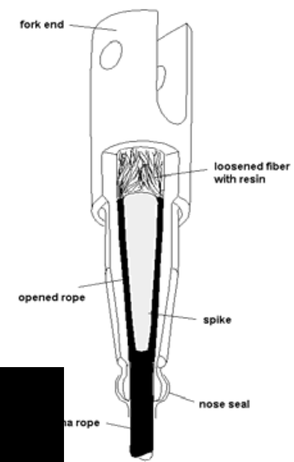
Spike geometry

L_{spike} / D_{rope}	5	-

spike with const volume		spike with const angle		spike with intermediate design		
				change over factor	0.67	
d_1	25.19	d_1	22.68	d_1	24.69	mm
				d_i	20.99	mm
d_0	11.58	d_0	11.58	d_0	11.58	mm
L_{spike}	79.38	L_{spike}	79.38	L_{spike}	79.38	mm
				L_i	52.92	mm

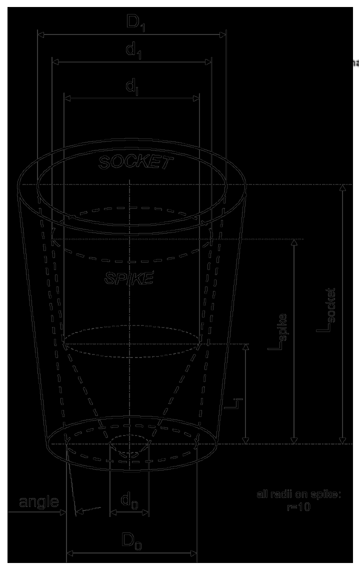
Figure A9. 9/16" SEFAC™ design by DSM

Socket-spike calculation for Dyneema HMPE ropes



Rope data

material	Dyneema	fiber #2	fiber #3	
density	0.97	1	1	kg/dm^3
share	100%	0%	0%	
D_{rope}	18.85	mm		
W_{rope}	153	g/m		



Socket geometry

D_1	33.18	mm
D_0	20	mm
angle	4	°
L_{socket} / D_{rope}	5	-
L_{socket}	94.25	mm

Spike geometry

L_{spike} / D_{rope}	5	-

spike with const volume		spike with const angle		spike with intermediate design		
				change over factor		0.67
d_1	30.00	d_1	27.29	d_1	29.45	mm
				d_i	25.06	mm
d_0	14.11	d_0	14.11	d_0	14.11	mm
L_{spike}	94.25	L_{spike}	94.25	L_{spike}	94.25	mm
				L_i	62.83	mm

Figure A10. 5/8" SEFAC™ design by DSM

8.9 Samson Rope Technologies Test Method

Test Methods for Fiber Rope	Reference No: SRT Test Method-001-02	Effective Date: March 14, 2003
		Supersedes: April 28, 2002

1. Scope

These test methods specify procedures to determine essential physical characteristics of fiber ropes. This test method will cover testing for diameter/circumference, linear density, pitch/lay, breaking force, un-cycled elongation, and cycled elongation.

Samson Rope Technologies (SRT) created this test method, to reduce the inconsistencies created when using other test methods, such as ASTM D4268 or CI-1500. These methods are widely accepted throughout the cordage industry; however, they contain methods, which allow very wide tolerances and/or generalize certain procedures. SRT believes that specifying specific instructions, when testing our products, will provide the most consistent data for both SRT and our customers.

This method complies with both the ASTM D4268 and the CI-1500 standards.

2. Terminology

2.1 Constructional Parameters – These are defined as measurements of diameter and circumference, lay lengths (pitch), and linear density.

2.2 Performance Parameters – These are defined as measurements of breaking force and elongation (all types).

2.3 Nominal Diameter – “Labeled” diameter

2.4 Reference Tension – A low force used as a reference point in most test procedures. Calculated in accordance with 4.4.

2.5 Lay/Pitch – The distance, parallel to the axis of the rope, of a strand to make one revolution around the rope.

2.6 Picks Per Inch (PPI) – The number of strands rotating in one direction for a distance of one inch.

2.7 Linear Density – The mass of a rope, normally expressed as pounds per 100 feet (lbs/100ft).

2.8 Relaxed Weight – The linear density of a rope in its relaxed state. This figure is useful when determining finished production weights. These are also used in our literature, to give the customer an accurate estimation of coil/reel weights.

2.9 $200d^2$ Weight – The linear density of a rope while under reference tension. This figure is generally more accurate and more repeatable than relaxed weights.
2.10 % Contraction – The difference, expressed as a percentage, in sample length between a $200d^2$ load and relaxed.
2.11 Breaking Force – The maximum force recording during a break test on a rope.
2.12 Tuck – A free strand of the rope placed between the rope strands during splicing.
2.13 Capstan Break – A break test, which no splices or knots are used. The rope is wrapped around a cylindrical fixture several times allowing the rope to grip the fixture as the sample is loaded.
2.14 High Modulus Fiber – These are fibers that have tenacities greater than 15 grams/denier (gpd). Modulus reflects stretch resistance or stiffness versus load.
2.15 Un-cycled Breaking Force – The breaking force of a rope, which has not been cycled.
2.16 Initial Elongation – The percentage of elongation at a given load on an un-cycled rope. This elongation is experienced during the initial loading of a rope.
2.17 Non-Elastic (while working) Elongation – The percentage of elongation experienced after a rope has been cycled. A portion of this elongation is recoverable after time.
2.18 Permanent (residual) Elongation – The percentage of elongation experience after a rope has been cycled and allowed time for relaxation. This elongation is non-recoverable.
2.19 Recoverable Elongation (Hysteresis) – The percentage of elongation that is reclaimed following a relaxation period after the rope was cycled.
2.20 Total Elongation – The maximum elongation experience during cycle loading to a given force.
2.21 Elastic (Working) Elongation – The percentage of elongation that is immediately recovered when tension is removed from a rope.

3. Sampling

3.1 Test Specimens – Special care should be taken when removing test specimens for laboratory testing. The rope should be removed from the reel or spool by pulling the rope directly from the reel, allowing the reel to turn freely. If the rope is in a coil, the coil shall be placed with the core vertical in such a way that the rope will uncoil down from the outside, and the bands then removed. The outer end shall then be grasped firmly and carried around the coil until a length of more than 10 ft has been unwound.

3.2 Conditioning – Unless specified, standard conditioning of the rope specimen is not required

4. Diameter and Circumference

4.1 Scope – This test procedure determines the diameter and circumference of a rope.

4.2 Tensioning Device – This device is used for applying the reference tension to the specimen. The device shall have a calibrated load indicator or allow the use of calibrated weights. The device shall be calibrated at least once per year. The method of verification and pertinent data should be in accordance with ASTM specification
E4 with force measuring instruments directly traceable to the National Institute of Standards and Technology.

4.3 Measuring Devices
4.3.1 Circumference Determination
4.3.1.1 A narrow flexible measuring tape, having zero to very low stretch, calibrated in 1/32" increments.
4.3.2 Diameter Determination
4.3.2.1 A narrow flexible "Pi" tape, having zero to very low stretch. This tape shall be calibrated to measure diameter when wrapped around the circumference of the rope. The tape shall indicate diameter in .01" increments (minimum).
4.3.2.2 Calipers may be used as long as the jaws cover the width of two strands on each side of the rope. The caliper shall indicate diameter in .01" increments (minimum).

4.4 Procedure – Using the nominal diameter, calculate the reference tension using the following formula:

$$P = 200d^2$$

P = reference tension in pounds
d = nominal diameter in inches

Place test specimen in rope tensioning device, making sure approximately 11 feet of rope is between the grips, knots, or splices. Note: A minimum of 3 feet should be used depending on sample size. Apply the reference tension. Measure the diameter and/or circumference directly on the specimen using one of the measuring devices described in 4.3. Take two additional measurements at different locations on the sample. Report the average result to the nearest .01".

When using the measuring tape, wrap the tape around the rope, making sure the tape lies flat, apply moderate tension, and take reading. If using the caliper, apply moderate compression, tighten the lock screw, remove, and read indicator. When using a caliper, take measurements on a plane perpendicular to the previous measurement.

5. Lay/Pitch, Picks Per Inch (Braids)

5.1 Scope – This procedure determines the lay/pitch or picks per inch (ppi) of a rope.

5.2 Tensioning Device – See 4.2

5.3 Measuring device – A graduated tape or rule capable of measuring the length of the sample to the nearest 1/16".

5.4 Twisted ropes

5.4.1 Lay/Pitch

5.4.1.1 Procedure – Place the sample in the tensioning device and apply the reference tension. In an area undisturbed by the terminations, place a mark on the center of one strand. Beginning with the next strand count ten strands for every strand in the rope construction. Example: If the rope is a 3 strand, count down 30 strands. Note: If sample size is limited, a minimum of 2 times the number of strands should be counted. On the final strand, place a mark on the center of the strand. Measure the distance between the two marks and record the distance in inches to the nearest 1/16." Perform two additional tests and report the average result. The actual lay should be calculated as follows:

$$L = D / X$$

L = Lay
D = distance between marks
X = multiplier (in the example above the multiplier would be 10; 3x10=30)

5.4.2 PPI – N/A

5.5 Braided ropes

5.5.1 Lay/Pitch.

5.5.1.1 Procedure – Place the sample in the tensioning device and apply the reference tension. In an area undisturbed by the terminations, place a mark on the center of one strand. Beginning with the next strand count one strand for every two strands in the rope construction. Example: If the rope is a 12 strand, count down 6 strands. On the final strand, place a mark on the center of the strand. Measure the distance between the two marks and record the distance in inches to the nearest 1/16." Perform two additional tests and report the average result.

5.5.2 PPI

5.5.2.1 Procedure – Place the sample in the tensioning device and apply the reference tension. In an area undisturbed by the terminations, place a mark on the center of one strand. Beginning with the marked strand count a minimum of 1x as many strands as in the rope construction. Example: If the rope is a 16 strand, count 16 strands. Make sure the counted strands are the same twist direction and moving down parallel to the axis of the rope. On the final strand, place a mark on the center of the strand. Measure the distance between the two marks and record the distance in inches to the nearest 1/16." Calculate the PPI as follows:

PPI = N/D

N = Number of counted strands
D = Distance between marks

6. Linear Density

6.1 Scope – This test procedure determines the linear density of a rope.

6.2 Tensioning Device – See 4.2

6.3 Weighing Device – Balance or scale calibrated to measure the mass of the specimen to an accuracy of .5% of its total mass. The device shall be calibrated at least once per year. The method of verification and pertinent data should be in accordance with ASTM specification E4 with force measuring instruments directly traceable to the National Institute of Standards and Technology

6.4 Measuring Device – See 5.3
6.5 Procedure

6.5.1 Relaxed Weight – Place test specimen in rope tensioning device, making sure at least 3 feet of rope is between the grips, knots, or splices. Note: If sample size permits, a longer sample should be used, preferably 10 feet. Apply the reference tension. Release the load, allowing the rope to remain straight (using a straight edge will aid this task). Measure and mark a distance of 3 feet (or a longer sample can be used). Cut the sample at the marks and weigh on the weighing device. Calculate the relaxed weight to the nearest .01 pounds and record in pounds per 100ft (lbs/100ft) using the following formula:

A = P / F x 100

A = Relaxed weight in lbs/100ft
P = sample mass in pounds
F = sample length in feet

6.5.2 $200d^2$ Weight - Place test specimen in rope tensioning device, making sure at least 3 feet of rope is between the grips, knots, or splices. Apply the reference tension. While the sample is tensioned, measure and mark a distance of 3 feet (or longer). Release the load. Cut the sample at the marks and weigh on the weighing device. Calculate the $200d^2$ weight to the nearest .01 pounds and record in pounds per 100ft (lbs/100ft) using the following formula:

$$A = P / F \times 100$$

$A = 200d^2$ weight in lbs/100ft
P = sample mass in pounds
F = sample length in feet

6.5.3 Alternative Method – This method should be used when both $200d^2$ and relaxed weights are needed.

6.5.3.1 $200d^2$ and Relaxed Linear Density - Apply the reference tension. While the sample is tensioned, measure and mark a distance of 3 feet (or longer). Remove load and allow rope to relax for approximately 2 minutes. Measure relaxed length. Calculate % contraction as follows:

$$C = ((L_1 - L_2) / L_1) \times 100$$

C = % Contraction
$L_1 = 200d^2$ length
L_2 = relaxed length

Cut at marks and weigh the sample. Calculate 200d2 weight as follows:

$$A = (P / L_1) \times 100$$

$A = 200d^2$ Linear density
P = sample mass in pounds
$L_1 = 200d^2$ length

Calculate relaxed weight as follows:

$$B = A+C$$

B = Relaxed Liner density
$A = 200d^2$ Linear density

C = % Contraction

7. Breaking Force

7.1 Scope – This test procedure determines the breaking force of a rope.

7.2 Specimen Preparation – Sample preparation is an important part of obtaining accurate results. All test samples shall be prepared as described below.

7.2.1 Length – For ropes, with a circumference less than 5,” the “body” (undisturbed section between the terminations) of the test sling shall be a minimum of 5 feet. For ropes having a circumference of 5” and larger, the body shall be 12X the circumference. This “body” measurement shall be made from a point approximately 1” from the last tuck of the splice. When buried splices are used, the “body” measurement shall be made from a point approximately 1” from the end of the buried tail. When capstan breaks are required, the “body” measurement shall be made from a point approximately 1” from where the rope last touches the capstan. When performing capstan breaks, the body on ropes 5/8” and smaller may be a minimum of 1 foot. *Note: When sample size is limited or machine limitations exist, a shorter sling maybe used for informative testing only. Test samples for Research and Development or determining specifications must meet the SRT minimum length criteria.*

7.2.2 Splicing – Only SRT recommended splices should be used. For detailed instructions, see the SRT Splicing Manual or visit the SRT website at www.samsonrope.com. Note: For instructions on splices not covered in the SRT Splicing Manual or website, contact the SRT Engineering Department.

7.2.3 Eye Size – The minimum eye size for all test samples shall be a minimum of 3X the diameter of the test machine fixture (i.e. pin, post, or capstan).

7.3 Apparatus (Testing Equipment) – The tensile testing machine must meet all of the requirements described below.

7.3.1 Cross Head Speed – Rate of travel shall be constant throughout the test. Cross head speed should be set so that the sample will reach 20% of its estimated breaking force with a time period of 20 – 200 seconds.

7.3.2 Stroke and Bed Length – The stroke and bed length shall be long enough to extend the specimen to rupture in one continuous pull.

7.3.3 Sample Holding Fixtures – The holding pins, posts, or capstans on both the fixed and pulling ends of the test machine shall have a minimum diameter of 2X the diameter of the rope.

7.3.4 Force Indicator – The test machine shall be equipped with a force indicating device, so that the maximum force, required to rupture the specimen, is stored or indicated after the test is complete.

7.3.5 Calibration – The test machine shall be calibrated at least once per year. The method of verification and pertinent data should be in accordance with ASTM specification E4 with force measuring instruments directly traceable to the National Institute of Standards and Technology.

7.4 Procedure – The specimen shall be cycled 10 times from reference tension to the prescribed loads listed below.

Class I (Olefin/Polyester/Nylon Fibers) = 20% of estimated breaking force.
Class II (High Modulus Fibers) = 50% of estimated breaking force

After the tenth cycle is complete, load the rope until destruction. Record the "peak load" as the breaking force. *Note: If the difference between the actual breaking force and the estimated breaking force is more than 15% of the actual, a retest shall be performed, cycle loading to n% of the actual breaking force.* Un-cycled tests may be performed when necessary; however, results must be reported as "un-cycled" breaking force. A statement shall be made that results were determined in accordance with SRT Test Method, Class I, II, or un-cycled.

8. Initial Elongation (Un-cycled Elongation)

8.1 Scope – This test procedure determines the elongation of a rope during initial loading.

8.2 Specimen Preparation – See 7.2 (exception: sample must have at least 30" of clear body)

8.3 Apparatus – See 7.3

8.4 Procedure – *Note: If breaking force is unknown, test in accordance with section 7, before beginning this procedure.* Place sample in test machine and apply the reference tension. While the sample is under reference tension, place two marks a minimum of 30" apart. The two marks should be clearly marked around the circumference of the sample and be beyond the effect of the splices. While the sample is under reference tension, the distance is measured between the two gauge marks. This is distance A. The sample is then loaded up to 20% load and the distance is measured between the two gauge marks. This is distance B20%. The sample is then loaded to 50% load and the distance between the gauge marks is measured once again. This is distance B50%. *Note: Additional measurements may be taken at any load up to 50%. For safety reasons no measurements should be* *taken beyond 50% load.* Calculate the elongation to the nearest 0.1% using the following formula:

100 (Bn% - A) / A (For each load)
Extrapolate elongation to break if necessary.

Report percent initial elongation at a particular load. If extrapolated, report percent initial elongation at break.

9. Cycled Elongation

9.1 Scope – This test procedure determines elongation of a rope after cycle loading.

9.2 Specimen Preparation – See 8.2

9.3 Apparatus – See 7.3

9.4 Procedure– *Note: If breaking force is unknown, test in accordance with section 7, before beginning this procedure.* Place sample in test machine and apply the reference tension. While the sample is under reference tension, place two marks a minimum of 30" apart. The two marks should be clearly marked around the circumference of the sample and be beyond the effect of the splices. While the sample is under reference tension, the distance is measured between the two gauge marks. This is distance A. The sample is then cycled 50 times from the reference tension to a specified load (normally 10%, 20%, or 30%). At the top of the 50th cycle, the distance is measured between the two gauge marks. This is distance C. At the bottom of the 50th cycle, another measurement is taken between the two gauge marks. This is distance D. The sample is then allowed to relax, under 0 tension, for 30 minutes (+/- 1 min). After this rest period, the rope is loaded to reference tension and a distance measurement is taken between the two gauge marks. This is distance E.
Calculate cycled elongation(s), to the nearest .01%, using the following formula(s):

Non-Elastic (while working) Elongation: NE = 100 (D-A) / A
Permanent (residual) Elongation: PE = 100 (E-A) / A
Recoverable Elongation (Hysteresis): RE 100(D/E – 1)
Total Elongation: TE = 100 (C-A) / A
Elastic (Working) Elongation: EE = 100(C/D – 1)

Report appropriate elongation at n% load. *Note: If elongations are required at different load levels, a separate sample must be used at each different load.*

10. Wet Testing

10.1 Procedure – When required, the sample shall be soaked in tap water for 24 hours. Appropriate test(s) are performed as described above.

11. Reporting

11.1 State that specimens were tested in accordance with SRT Test Method – 100-01. Report all results, as required. When more than one test is performed, record the average result, stating that the result is an "average."

Test Method for Used Fiber Rope

This test method determines the breaking force of a used fiber rope. This test method will cover testing for breaking force only; other physical measurements such as diameter/circumference, linear density, and lay/pitch, are to be determined per standard SRT Test Method for Fiber Ropes.

Used ropes are tested in a similar manner to new ropes. However, since ropes do suffer damage from abrasion, cuts, misuse, improper storage or over tensioning, it can be expected that some strength loss will occur, depending on the severity of the rope's condition. Since the ultimate breaking strength is unknown, the rope will only be pre-cycled to 20% of its new rope minimum strength, regardless of the fiber type.

This method complies with both the ASTM D4268 and the CI-1500 standards.

Breaking Force

Procedure - The specimen shall be cycled 10 times from reference tension to 20% of the new rope published minimum breaking strength (regardless of fiber type).
After the tenth cycle is complete, load the rope until destruction. Record the "peak load" as the breaking force. Un-cycled tests may be performed when necessary; however, results must be reported as "un-cycled" breaking force.

Specimen Preparation – Sample preparation is an important part of obtaining accurate results. All test samples shall be prepared as described below.

> ***Length –*** For ropes, with a circumference less than 5," the "body" (undisturbed section between the terminations) of the test sling shall be a minimum of 5 feet. For ropes having a circumference of 5" and larger, the body shall be 12X the circumference. This "body" measurement shall be made from a point approximately 1" from the last tuck of the splice. When buried splices are used, the "body" measurement shall be made from a point approximately 1" from the end of the buried tail. When capstan breaks are required, the "body" measurement shall be made from a point approximately 1" from where the rope last touches the capstan. When performing capstan breaks, the body on ropes 5/8" and smaller may be a minimum of 1 foot. Note: When sample size is limited or machine limitations exist, a shorter sling maybe used for informative testing only. *Test samples for Research and Development or determining specifications must meet the SRT minimum length criteria.*

Splicing – Only SRT recommended splices should be used. For detailed instructions, see the SRT Splicing Manual or visit the SRT website at www.samsonrope.com. *Note: For instructions on splices not covered in the SRT Splicing Manual or website, contact the SRT Engineering Department.*

Eye Size – The minimum eye size for all test samples shall be a minimum of 3X the diameter of the test machine fixture (i.e. pin, post, or capstan).

Apparatus (Testing Equipment) – The tensile testing machine must meet all of the requirements described below.

Cross Head Speed – Rate of travel shall be constant throughout the test. Cross head speed should be set so that the sample will reach 20% of its estimated breaking force with a time period of 20 – 200 seconds.

Stroke and Bed Length – The stroke and bed length shall be long enough to extend the specimen to rupture in one continuous pull.
Sample Holding Fixtures – The holding pins, posts, or capstans on both the fixed and pulling ends of the test machine shall have a minimum diameter of 2X the diameter of the rope.

Force Indicator – The test machine shall be equipped with a force indicating device, so that the maximum force, required to rupture the specimen, is stored or indicated after the test is complete.

Calibration – The test machine shall be calibrated at least once per year. The method of verification and pertinent data should be in accordance with ASTM specification E4 with force measuring instruments directly traceable to the National Institute of Standards and Technology.

Procedure – The specimen shall be cycled 10 times from reference tension to **20% of the new rope published minimum breaking strength (regardless of fiber type).**

After the tenth cycle is complete, load the rope until destruction. Record the “peak load” as the breaking force. Un-cycled tests may be performed when necessary; however, results must be reported as “un-cycled” breaking force.