# Inspection Criteria for HMPE Rope

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***Abstract* – Accurately estimating the residual strength and discard/retirement criteria of used rope is becoming increasingly necessary in applications dependent on high modulus synthetic ropes. Precise measurement of residual strength on a used synthetic rope requires destructive testing of the line. This paper investigates the correlation between visual assessment and residual rope strength through statistical analysis of damaged HMPE ropes in order to establish accurate inspection criteria.**

***Keywords—HMPE; Synthetic Rope; Inspection; Retirement***

## I. Introduction

### *A. Preface to HMPE Rope*

Synthetic ropes made of high modulus polyethylene (HMPE) have increasingly influenced marine markets over the past decade. These lines have comparable tensile strength to steel-wire ropes for a given diameter and their density is lower than that of water. This means a considerable reduction in line weight and buoyant lines. HMPE ropes are as stiff as steel resulting in similar elongation characteristics. In addition, the chemically-inert nature of the fiber allows for long-term exposure to water and other compounds without fear of damage. Therefore, synthetic ropes offer significant advantages in line-handling, weight reduction, and chemical care.

As braided HMPE ropes continue to be used in new markets, questions regarding inspection criteria have arisen. While steel cable has been used in many industries for well over a century, synthetic rope lacks the same experience. Without comparable levels of experience, many industry standards which specify proper use of steel-wire rope do not include similar recommendations for HMPE lines.

Steel-wire rope has a long history of use in marine industries. Use has expanded to a wide variety of specific applications since early implementation leading to a high level of confidence based on experience. This long history of use and development has revealed many types of failure modes, issues affecting steel wire performance, and/or safety. These observations have since fueled the wide range of product and industry standards on wire rope production, use, inspection, and discard criteria used today. Limitations, failures, performance, and deterioration of steel wire have become more predictable with continued use and experience in handling.

### *B. Goals of Investigation*

This investigation into the effect of wear on synthetic rope strength aims to improve inspection methods available for HMPE lines. Current practice typically requires a synthetic rope expert to complete an onsite inspection before delivering qualitative judgment on remaining rope life. This leaves industries that utilize HMPE lines dependent on each individual specialist's experience. Furthermore, very little standardization exists within the rope industry in terms of quantifying levels of wear and damage or criteria for retirement. In addition, this type of qualitative analysis does not translate into numerical estimates on residual strength. By investigating specific types of wear experienced by synthetic ropes in the field, we will demonstrate how various observable modes of rope wear/damage affect rope strength.

In order to complete such a study, it was necessary to create a more standardized way to discuss rope damage. Until now, depending on the industry and even the individual user, the way a damaged rope is described can be subjective. Labeling a rope as "severely damaged" could describe drastically different levels of wear. Depending on the observer, a "severely damaged" line may refer to a rope that has only a few broken filaments, creating a slightly fuzzed appearance with little or no effect on strength, or a rope which has already parted and retains no strength. The creation of a visual comparison tool allows synthetic rope users to better communicate the amount and type of damage their lines have seen. The standardized wear/damage grading scale thus allows manufacturers, users, and inspectors to speak a common language, reducing miscommunication and thus increasing productivity and safety.

## II. Methodology of Investigation

### *A. Common Forms of Damage to HMPE Ropes*

Synthetic ropes can be exposed to numerous types of damage depending on their use. Exposure to particular types of failure varies with industry and application. Some of the potential concerns that HMPE fiber ropes may be susceptible to include the following:

- Abrasion – Mechanical wear resulting in broken filaments across a wide area of the rope.
- Cutting – Mechanical damage localized on a particular strand or collection of nearby strands.
- Bending fatigue – Weakening of the rope caused by repeated cycles of loading and unloading.
- Tension-tension fatigue – Weakening of the rope due to repeated cycles of loading and unloading.

- Overload – Applying loads near the ultimate strength of the line through shock or gradual loading which can cause broken internal filaments.
- Creep – Permanent elongation of the rope caused by static loading for an extended period of time.
- Ultraviolet degradation – Weakening of the caused by extended exposure to ultraviolet light.

### *B. Mechanical Wear Focus*

Of the above forms of damage, abrasion and cutting are the most common forms observed throughout in applications where HMPE lines are currently utilized. In any situation that brings a rope into contact with another surface, and even itself in some cases, there is a potential for abrasion or cutting to occur. Therefore, this study focuses on how rope strength is affected by damage caused through mechanical wear.

Both abrasion and cutting result in broken filaments of HMPE fiber in the rope. Abrasion is characterized as a low density of broken filaments distributed across a larger volume of rope, both along the length of the rope as well as among the various strands at any position along the rope. Cutting is characterized as a highly concentrated density of broken filaments localized on one or several strands at one particular position on the rope. Abrasion results in a more balanced type of wear that potentially affects rope strength differently than concentrated fiber damage caused by cutting.

Retirement criteria due to the effects of mechanical wear are generally provided by the manufacturer of a given synthetic rope product. The Cordage Institute, a non-profit association of fiber rope manufacturers and suppliers, has specified standard inspection and retirement criteria for fiber ropes of various constructions. The published international guideline CI 2001-04 "Fiber Rope Inspection and Retirement Criteria" includes specific criteria for use with single braid lines [1]. In regards to both external abrasion and cutting damage, the Cordage Institute guideline suggests retirement of the rope as the best action where there is "10% loss of fiber cross-section in whole rope or in an individual strand cross section." While this document provides direction for the retirement of HMPE lines, it depends on having a scheduled and well documented inspection program in place. In many applications an individual using an HMPE line will not have access to a record of inspection history that would document the required diameter measurements under specific reference loads. Without this history, a guideline to retire after a reduction of 10% of fiber cross section is impossible to implement.

## III. Theory of Steel Wire Mechanical Damage

Steel-wire rope retirement due to mechanical damage, like extreme abrasion and/or wire breaks, is largely based on the loss of metallic cross-sectional area and, therefore, loss of strength. The relationship between the contribution of individual load-bearing rope parts (core and outer strands) and the total metallic cross-sectional area of a wire rope dictates the distribution of load within a steel-wire rope construction.

The outer strands contribute to the steel-wire rope's total metallic area, as well as the total strength. Therefore, a steel-wire rope's total strength is determined by the specific strand construction, the number of outer strands within the construction, and the size of the outer wires. The outer wires may account for a substantial part of the total cross-sectional area of a steel-wire rope, depending on the type of construction and core.

Only a portion of each outer strand's wires are visible to inspection at the rope's outer surface. By increasing the number of outer strands, this visible area may be further reduced. Additionally, as the number of outer strands increases in a construction the diameter of the outer wires will become smaller, reducing contribution to the total metallic area and impact on the steel-wire rope's strength. An increase in the wire rope's outer strands also increases the core's importance as a larger percentage of the total strength is contributed by the internal strands.

Several standards specify discard criteria and values for steel-wire rope based on construction, core type, and application. A thorough inspection of steel-wire rope must include diameter measurement. Any decrease in diameter may be caused by external abrasion, internal wear, or other contributing factors which affect the condition of the wire rope. Visual inspections must also be made over a specified length to determine the number of visible broken wires. The number of visible broken wires, the nature of the breaks, and their location within the construction must be carefully assessed in accordance with the discard criteria in order to determine safety and usability.

The steel-wire rope's outer surface condition may not always be fully representative of the internal wire rope condition as the presence of internal wear and/or fractured wires will not necessarily be evident by examining only the visible load-bearing outer wires of the outer strands. The discard criteria and values in standards are determined in an attempt to account for this and allow the safe use of wire ropes up to point of discard. Although, when the rope construction allows, an internal wire rope examination should be carried out to better assess the condition of a steel-wire rope.

## IV. Abrasion of HMPE Ropes

### *A. Definition of Abrasion*

Abrasion damage develops along synthetic strands through contact with surfaces of varying levels of roughness, often while under load. This type of damage is a form of mechanical wear resulting in broken filaments along a section of rope. The high efficiencies of HMPE lines are, in part, due to the highly anisotropic nature of the material; the polymer chains are oriented substantially in the direction of the filament. This results in the desired increase of strength-to-weight ratio as the strength of the material acts axially down the length of the rope. However, this also results in a material that is weaker off axis and thus may be more susceptible to harm from external contact than a steel wire, which is significantly more isotropic. In addition, an HMPE filament has a diameter of 10 microns making each individual filament more vulnerable to damage.

It is important to note that this type of wear can develop both externally on the exposed surface of the rope and internally between the rope strands/yarns. External abrasion

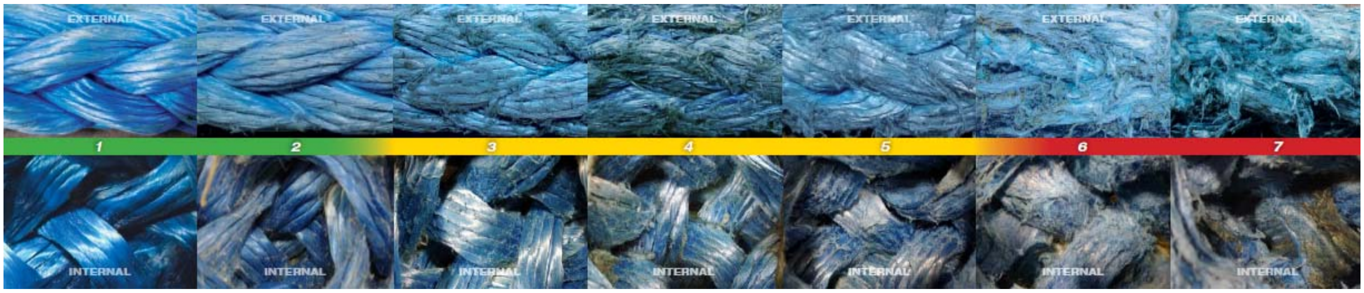

Fig. 1. Visual comparator tool illustrating the seven levels of internal and external abrasion.

develops when the rope comes in contact with rough surfaces in the working environment and is obvious to those who handle the line. Internal abrasion develops as strands move relative to one another within the rope construction and can be less obvious to the untrained eye. Therefore, frequent inspections of both the internal and external surfaces of the rope are recommended. The resulting appearance of abrasion damage is a general “fuzz” along the strands where filaments have broken and been brushed away from the body of the rope.

Abrasion rates can be controlled through proper use and maintenance of equipment with which the line comes into contact. External abrasion will develop more quickly in situations where the line is exposed to rough surfaces while under load. Similarly, the rate at which internal abrasion develops progresses when a rope is subject to increasingly severe bends or when rough particulate, such as gravel, intrudes into the rope’s structure.

As an HMPE fiber rope begins to abrade, the broken filaments can provide a barrier that protects the unbroken filaments from a portion of the damaging contact. This can be observed as the rate of accumulated abrasion damage decreasing over time.

### B. *Method of Abrasion Study*

The nature of abrasion damage on synthetic fiber ropes renders steel-wire rope inspection methods impractical. Abrasion damage on steel-wire rope generally results in a loss of material from the outer wires. This is easily measurable either as a reduction in diameter or roundness (asymmetrical wear). As the filaments of a rope break, the frayed fiber will tend to stay attached (for some period of time at least) to the body of the rope. These frayed ends will also tend to have larger void volumes between adjacent filaments. For these reasons, a simple diameter measurement will not show this loss of material the same way that it might in the case of an abraded steel rope. The diameter of a braided synthetic line is dependent on the tension applied. A change in rope diameter by as much as 10% can be observed based on the load history of the line. Therefore, measurements taken of the same rope with and without tension applied will indicate different levels of strength.

When volume measurements appear inconclusive a more useful method is required. A one-inch diameter rope can be made up of over a million individual HMPE filaments making a method of counting the total number of broken fibers impractical. Instead, a visual comparison approach was taken; similar to methods used successfully to measure other complex phenomena, such as surface roughness. Photographs of used 12-strand HMPE rope samples were collected and organized from lowest to highest levels of abrasion. Included were images of both internal and external abrasion. From these criteria, a series of seven pictures for each type of abrasion were chosen to evenly span the range of potential damage. Fig. 1 is an illustration of the visual comparison method used to determine abrasion levels.

Based on this visual scale, a rope sample can be compared to a range of internal and external abrasion criteria and receive a numerical ranking. This would be a consistent way to communicate the visual appearance of abraded ropes across various industries and inspectors. In addition, this scale provides a way to relate levels of internal/external abrasion to residual strength of damaged rope samples.

Utilizing five years of well documented test results on rope samples used in a variety of applications, a correlation was made between abrasion level and residual strength. The study was limited to one rope product in particular: AmSteel®-Blue, a 12-strand single braid, 100% Dyneema® rope. The majority of samples tested were used as commercial marine mooring and tug tow lines. The process required an initial screening of the test reports to ensure that abrasion damage was the predominant factor causing the reduction in rope strength. In a significant number of cases, inspection of the test samples showed other damage modes in addition to abrasion such as cutting, melting, compression and severe twist. Other factors that caused disqualification from the sample pool include abnormal break locations, non-standard testing methods, and poor documentation of testing and/or line condition. The result was the elimination of 75% of the test results as they did not clearly document abrasion as the sole cause of strength.

Visual ranking was then applied to the remaining pool of 51 test sample reports that indicated abrasion as the only source of strength reduction. These tests were documented with multiple pictures of the internal and external conditions of the rope. Every report used in this evaluation had images taken of the most severe abrasion observed on the sample. Six synthetic rope experts were presented the visual comparator with sample images from each report and asked to rank internal and external abrasion for each. The experts were instructed to choose the images showing the most damaged section of line for each sample upon which to make their ranking. The resulting data was a collection of 306 observations with values for sample residual strength, internal abrasion level, and external abrasion level.

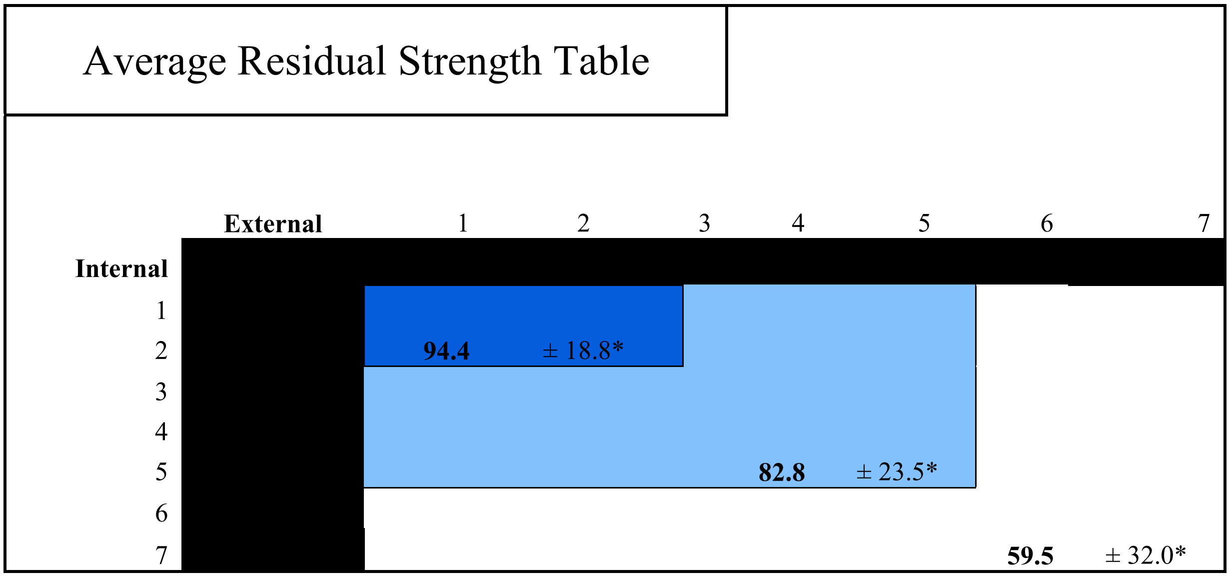


Fig. 2. Illustration of the 3 bin strength percentages with tolerance limits base on K values for 90% Confidence / 90% Population

By limiting the investigation to the one particular construction of rope, the AmSteel®-Blue product, we reduce the number of uncontrolled variables. Each of the 12-strands making up the braid is composed of Dyneema® fiber twisted together. Depending on the diameter of the product, these strands may be made up of a single bundle of twisted fiber or a collection of multiple twisted yarns. The final rope is coated with an abrasion resistant urethane formula designed to improve wear life. The twist ratio, yarn/strand size, coating, and braiding angle can vary between different HMPE ropes. These constructional changes can have a drastic effect on many characteristics of the rope. For example, by lengthening the braid angle the strength efficiency can be increased. However, this will result in a looser rope construction that may be more susceptible to wear. The findings from this investigation are therefore valid only for this particular product.

### C. *Analysis of Findings*

Evaluation of the collected information begins with a study into how the data is organized. Each data point gathered from this investigation falls into one of 49 separate states. Each distinct state is defined by two numerical values ranging from 1 to 7. The first value placed on the sample observed was based on the level of internal abrasion as visually identified by the expert. The second defining value represents the observed sample's external abrasion.

On average, a data set of 300 points with 49 potential states would result in six residual strength data points per state. In reality, the data is organized less uniformly among the states. For example, the state defined by a value of "1" for external abrasion and "7" for internal abrasion has no data points. This indicates a strong correlation between internal and external abrasion, which makes an application resulting in a rope exhibiting the highest level of internal abrasion without any visible external abrasion difficult to imagine.

In order to correlate rope strength to abrasion state with a tighter tolerance interval, higher sample counts per state are needed. Thus various separate states were combined. This investigation looked at combining the data into three, five, and seven collections of data, or bins. The method used to combine states sorted them based on their largest ranked abrasion type. For example, the state defined by an internal abrasion value of 3 and level 5 external abrasion would be sorted into the same bin as the state defined by an internal abrasion ranking of 5 and external abrasion value of 4 as level 5 is the highest damage level in both cases. After determining the number of samples per bin in each arrangement, statistical means for each bin, and standard deviations, tolerance limits were calculated. These were based on a 90% confidence on 90% of the total population falling within the limits. Due to the relatively small number of data points collected, the 3-bin arrangement provides the tightest tolerances as the number of samples per bin allows for a lower statistical "K" value, where "K" represents the statistical multiplier based on sample size, and similar standard deviations. The abrasion comparison tool was not modified to only show these three levels in the interest of maintaining higher resolution when tracking rope wear. As more data is collected in later studies, this may lead to a higher resolution model in the future.

As Fig. 2 shows, the bins were arranged such that the highest damage level was 2, 5, and 7. By using all 306 data points developed by the experts' visual analysis of test reports, between 60 and 120 residual strength results were arranged in each bin. The graph shown in Fig. 3 illustrates the average percentage of strength retention for samples in each bin with their tolerance limits. This shows a clear decrease in strength as either internal or external abrasion levels increase. In addition, the lower tolerance limits provide a level of confidence in the strength lost in a used rope based solely on the level of abrasion. Through a visual ranking of a level 2 abrasion ranking of a used AmSteel®-Blue line, you can state with 90% confidence that the rope's strength is above 75.6% of new rope strength.

## V. CUTTING OF HMPE ROPES

### A. *Definition of Cutting Damage*

Another type of mechanical damage that HMPE lines can experience is the complete, or partial, cutting of strands. Unlike

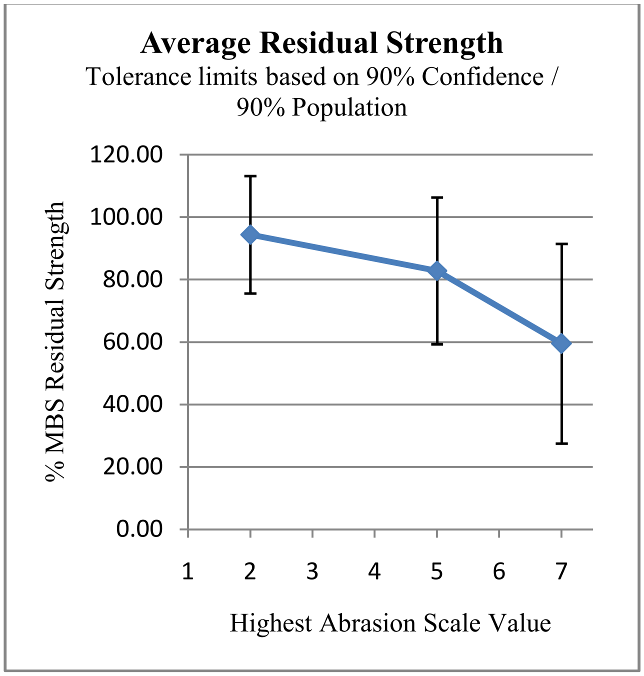


Fig. 3. Graph illustrating the average strength retention for results in each bin.

external abrasion, cutting refers to extremely localized damage where a significant percentage of the filaments in a rope are severed in a single location. This causes strength loss due to the overall decrease in fiber content as well as an unbalancing of the twist levels in the rope. For this reason, it is important to ensure that a rope does not come in contact with any sharp surfaces, especially while under significant tension.

When deciding whether or not to retire an HMPE line, the separation of localized damage becomes an important factor. Cutting two adjacent strands has a greater impact on the rope strength than cutting two strands on opposite ends of the rope. This is due to traction between adjacent strands leading to transfer of tension and load sharing. This study attempted to quantify not only the effect on strength that the number of cut strands has, but the effect of their separation distance as well.

*B. Method of Cut Strand Study*

The first challenge in the testing procedure is maintaining a consistency in the amount of damage applied. Each target strand to receive cutting damage must receive the same percentage of fiber reduction. The result of using this construction is that there is no way to count out an exact number of fibers in groupings of less than an entire strand. Therefore, all damage inflicted on the testing samples is in units of entire cut strands. This study investigated tensile strength of new rope with controlled cutting damage inflicted. Specimens were tested with a single cut strand as well as two cut strands, both adjacent and separated. The separation between cut strands was measured in lay lengths, where a single lay length is defined as the distance for a strand to make one revolution around the axis of the rope.

As opposed to generalized abrasion, cutting damage is isolated in location as well as in time. That is, cutting of a rope or strand generally occurs as a singular event. In the event that a rope is cut during use, the question is whether it can continue to be used or if it needs to be retired. To simulate this, the test method used involved cycling the rope 10 times to 50% of the rope's published minimum breaking strength, relaxing the sample, applying the required damage, and then pulling directly to break. This simulates a scenario where the rope has been used for some time before being damaged. Once the damage is inflicted and discovered, during the relaxed phase of testing, the question becomes, "What is the rope's current strength?" By pulling the rope immediately to break after it has been damaged, the instantaneous strength loss of the used rope can be determined.

Various lengths and sizes of ropes were used in this investigation. All testing where multiple strands were cut on a single sample rope involved the cutting of two strands of the same twist. This was theorized, and shown in testing, to cause the most severe loss in strength due to the unbalancing of the rope. The three phases of testing are outlined below:

- 3/8" diameter samples, short separation lengths
- 3/8" diameter samples, long separation lengths
- 1" diameter samples, short separation lengths

Due to test bed limitations, testing could not be performed on large diameter ropes at long lengths. Thus testing was done to thoroughly investigate the effects of cutting on small diameter samples first. Once a relationship was identified, larger diameter samples could be investigated within the range of capabilities and compared to verify that the strength retention trends are similar for both sizes of rope as the two sizes are manufactured by slightly different methods. The small size has all of the fiber in a strand together in a single twist stage, while the larger rope strands are made up of multiple first twist yarns twisted together.

*C. Analysis of Findings*

Testing results showed significant effects of cutting damage on residual rope strength. As shown in Table 1, damaged samples were found to have lower average strengths than the undamaged samples. All damaged sample strengths were compared to the average tested strength for the new rope samples.

| **Sample Size** | **Cut Strand Test Results** | | |
|---|---|---|---|
| | *Single Cut* | *2 Cuts (no separation)* | *2 Cuts (separated)* |
| 3/8" (short) | 92.3% | 76.4% | 83.1% |
| 3/8" (long) | 87.1% | 82.3% | 98.7% |
| 1" | 79.1% | 65.4% | 76.3% |

Table 1. Average residual strength of damaged rope samples as compared to tested average new rope breaking strength.

Contrary to initial thinking, as the separation between two points of damage inflicted to the rope is increased the average breaking strength of the sample will not approach that of a sample with a single point of damage. This is due to the rope always failing at the weak point with the lower strength value. In the case of a normal distribution of breaking strengths measured for the same construction of rope with a single weak point, roughly half of the samples will break higher than average and half will break lower. With a situation involving two independent potential failure points, the point with a lower breaking strength will cause the sample to break first. The result is that the wear points that statistically would break above average are only witnessed when both points are above average. The strength will approach a slightly lower value and the standard deviation in the average will be less than that of a sample with a single weak point. As shown by the probability density curves in Fig.5, this drives the overall average for the rope breaking strength down without any interaction taking place between the two cut strands.

Varying the separation distance for the small diameter samples did not show a statistically significant effect on the rope breaking strength. As is evident in Fig. 6, changing the length from two to 10 lay lengths did not change the breaking strength significantly. However, initial findings on small diameter sample testing shows a trend towards the theoretical

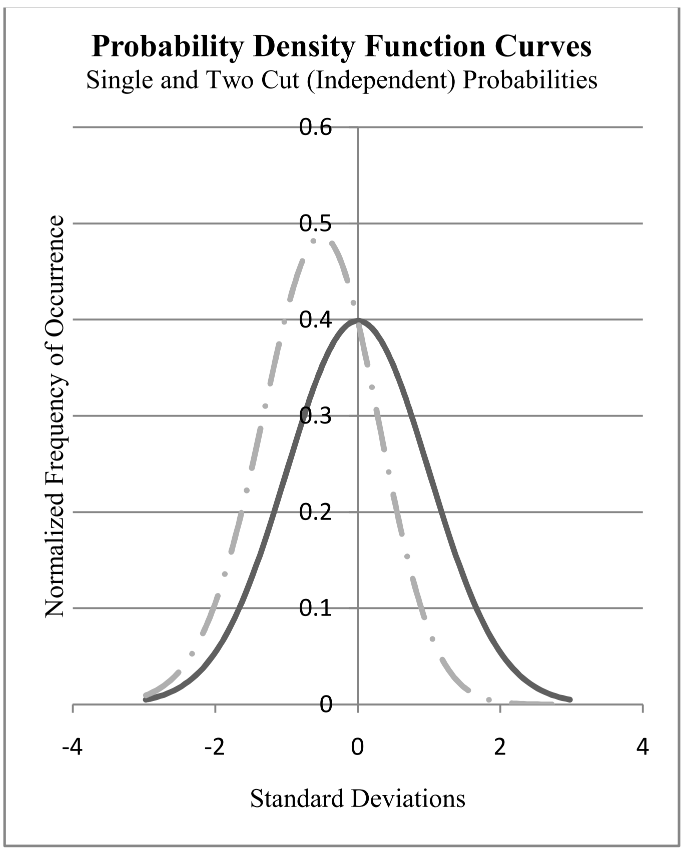


Fig. 5. Solid curve is a normalized probability density function (PDF) for a normal distribution (the average breaking strength of samples with a single cut strand is assumed to follow this distribution) while the dashed curve is the resulting PDF for the average strength of a sample with two independent weak points.

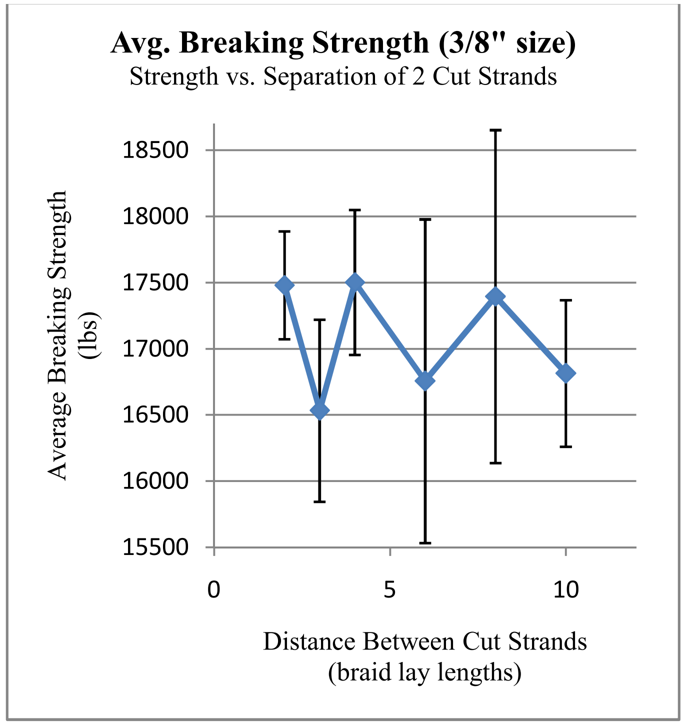


Fig. 6. Comparison of average strength based on cut separation with error bars indicating 95% confidence in the mean.

mean expected based on the statistical model. The average breaking strengths found for samples with two separated damage locations are all higher than the strength of ropes with two adjacent cut strands. It is apparent that there has been an increase in breaking strength of the rope by adding some amount of separation between the strands with inflicted damage.

Testing on the one-inch diameter samples showed a similar trend in the effect of separation on residual strength. The results shown in Fig. 7 illustrate the change in average breaking strength for the lines with multiple cut strands as compared to those with a single cut. The samples with separated cuts had a consistent six lay lengths between each of the locations where damage was inflicted. Three samples were tested for each condition to determine the average.

One variation that was apparent with the different diameters was the percentage of breaking strength lost due to cutting damage. On the small diameter samples a single cut strand resulted in an average breaking strength almost 10% lower than that of the undamaged samples. The average strength observed when two adjacent strands were cut was almost 25% less than that of the control samples. In the one-inch diameter testing, average breaking strengths for the single and two adjacent cut tests were 20% and 35% less than the control average respectively. This shows a significantly higher effect of cutting damage on the strength of the larger diameter rope.

Investigations into the long separation length on small diameter samples did not provide any useful information. Testing showed an unacceptable amount of variation. In an effort to reach longer sample lengths, testing was performed on

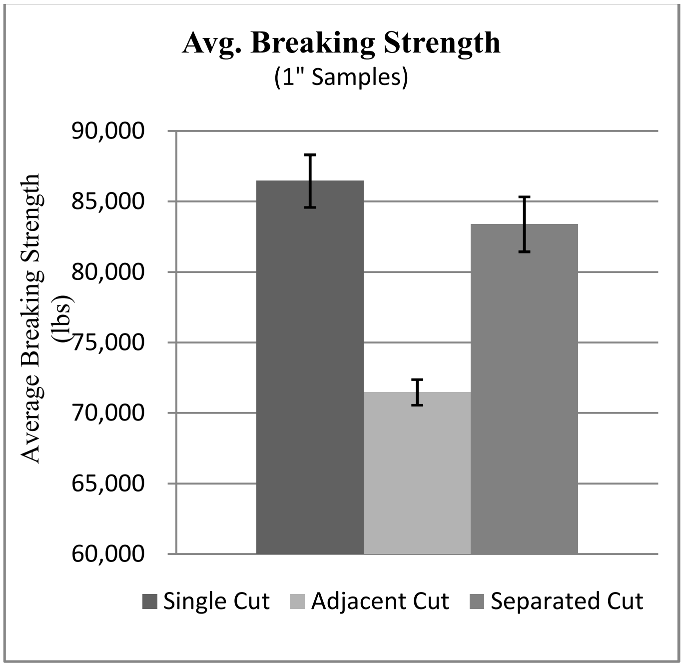


Fig. 7. Comparison of average breaking strengths for various levels of cutting damage.

a machine test-bed with a load capacity much higher than the strength of the ropes. As such, there may have been a resolution and accuracy issue in the testing equipment that accounted for the spurious results.

## VI. Conclusions

This investigation has provided valuable insight into the inspection methods and criteria for HMPE ropes affected by mechanical wear. However, further testing will continue to improve the understanding of strength loss in used fiber ropes. Moving forward, residual testing of abraded lines will be evaluated based on the visual inspection tool and added to the data collected in this study. By continually analyzing these results we can better understand how the visual appearance of abraded HMPE lines correlates to residual strength.

Future investigation will focus on the combination of these two mechanical wear modes as well. The testing plan deliberately separated these two wear modes to make consistent and repeatable measurement possible. This required the disqualification of any testing reports that show evidence of both abrasion and cutting damage for this investigation. However, these test reports can be used in a future mixed mode model investigation.

Residual strength of used rope needs to be estimated for retirement and safety. In many applications accurate records of usage is unattainable and therefore effective inspection and retirement criteria should be independent of service history. By testing abraded samples from the field we were able to correlate visual ranking of abrasion-to-strength without relying on usage records. Using the methods developed in this study we have the ability to make strength estimates without requiring destructive testing.

## References

[1] Cordage Institute, Fiber Rope inspection and Retirement Criteria, http://www.ropecord.com/cordage/publications/CI2001.pdf, 2001-2004, pp. 27-29 (Appendix C).