# Abrasion and Residual Strength of Fiber Tuglines

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## Abstract:

High performance synthetic ropes have been successfully used in the towing industry for ship assist and vessel escort since the mid 1990's. Samson Rope Technologies and DSM Dyneema undertook a 2-year long joint program combining field performance and in laboratory studies to establish a better understanding of retirement criteria of synthetic fibre ropes. Phase I of this study was presented at ITS 2002 [1]. Important observation was made to understand the long term behaviour of HMPE ropes used in tug assist application up to 1700 jobs. In this Phase II program, the short term rope behaviour was studied. This 1-year study put 7 working line pendants on Harbour Class Tractor tugs to evaluate their residual strength, where each of the pendants experienced in between 100 and 1200 jobs. Detailed residual strength determination and laboratory analysis are discussed to determine the relative importance of different contributing factors that adversely affect rope strength in the field. This report combines and concludes the 1 and 2-year studies conducted on approximately 50 AmSteel® Blue field-tested ropes made from Dyneema SK75 HMPE fibre.

## Introduction:

AmSteel®-Blue ropes for tractor tug applications are subjected to a variety of mechanisms that can decrease its strength, specifically abrasion, tensile fatigue, shock loading, drum compression, and twist [2]. From previous studies on the long term rope behaviour, the residual strength of the line appeared to be dominated by drum compression and twist. The drum compression was significant when re-splicing the rope; however it is assumed that it had little impact during normal use. Phase I also revealed that the magnitude of shock loading observed on the tugs and the tension fatigue characteristics of the AmSteel®-Blue ropes were not significant factors contributing to the strength reduction of the ropes. The Phase I study did not find a strong correlation between the residual strength and abrasion damage; however the analytical technique for determining the extent of the abrasion damage was elementary and purely qualitative. A new technique has been developed to quantitatively estimate the degree of damage to the rope due to discontinuous fibres caused by external and internal abrasion and other mechanisms.

## Objective:

To determine the short term behaviour of HMPE tug working lines and relate the findings to strength reduction mechanisms, specifically abrasion. And to develop an analytical technique to determine strength reduction associated with discontinuous fibre.

## Scope:

The scope was limited to the AmSteel®-Blue main tow lines on single drum winches aboard tractor tugs in Long Beach/San Ramon Harbour, CA, and Puget Sound, WA.

## Procedure:

Phase II program included laboratory inspection and analysis of 7 separate samples of AmSteel®-Blue. . They were 64mm diameter and were actively used in the field aboard tugboats in vessel escort service. Duration of work exposure was between 100 and 1200 jobs, where the lines were subjected to many uncontrollable environmental forces.

Visual inspections were performed on used AmSteel®-Blue lines followed by break tests in accordance with CI-1500, “Standard Test Method for Fiber Ropes” [3]. All the ropes were tested using existing eye splices.

These ropes were produced in the same production run to maximize the property consistency. In order to eliminate the strength reduction typically attributed to splicing a used rope, the pendants were manufactured and fabricated to standard rope specimen lengths with eyes on each end. This pendant was placed in service between the tugs mainline and their sacrificial pendant, therefore seeing much of the same loading and conditions as the Phase 1 mainline ends (See Figure 1).

**Figure 1. Mainline assemblies for Phase 1 and 2.**

### *Abrasion study*

Visual Examination: The entire length of the test pendant was inspected to identify (and mark) any areas that appeared to have a higher degree of wear (i.e. abrasion), damage (i.e. cut or pulled strands) or melting or fused fibers. These are most likely be the weakest areas of the line and detailed inspections were performed at these points. If there were no areas with noticeably more wear, a “representative” spot in the line was used for inspection.

To get an accurate measure of the rope’s strength at the areas marked (the “high damage” area or “representative area”), individual strand analysis was performed on 3-4 “S” strand crowns and 3-4 “Z” strand crowns. Each of the 12 strands of the rope are made up of a number of smaller “1st twist strands” (See Figure 2). These 1st twist strands are layered when they are twisted together to form the large strand. The total number of 1st twist yarns were counted and catalogued, as were the total number of “outer surface” yarns. Each of the “outer surface” yarns were compared to a relatively undisturbed “inner” yarn to estimate the diameter change for each strand. With the average diameter reduction of the “outer surface” yarns, the strength reduction can be calculated.

**Figure 2. Strand Diagram showing the possible 1st twist yarn configuration.**

Generally there is not much of a diameter reduction on the inner yarns since they are protected from external surface phenomena by the outer strands, however they will most likely exhibit some “fuzzing” from internal (strand-on-strand) abrasion. Internal abrasion is typically estimated to be about 5-10% strength loss.

The total residual strength estimate is calculated using a weighted average fiber loss of the “outer surface” yarns and the “inner” yarns for each strand.

Yarn Testing: After the break tests were completed, undisturbed sections from two pendants were analyzed. Like the detailed abrasion estimation technique, the yarn analysis was performed on the rope in the area deemed most damaged from visual inspection. For this analysis, a single strand was removed from the braid and its overall length was approximately one “braiding period” (Figure 3). The single strand was then separated into its 1st twist components (Figure 2). The yarns were then placed on a tensile testing apparatus and pulled to failure.

**Figure 3. Rope Diagram show Braiding period used on yarn tensile testing.**

## Results:

### *Residual Strength Testing*

All the pendants were tested to determine their residual strength as a function of the number of job worked. Figure 4 illustrates the effects of the number of jobs on the lines residual strength. Combining the Phase 1 and 2 results adequately describes the behaviour of HMPE mainlines for tractor tugs over a two year period (Figure 5), showing initial strength reduction followed by levelling off.

**Figure 4. Results from Residual Strength Testing on Phase 2 Pendants**

**Figure 5. Residual Strength of all mainlines and pendants tested in Phase 1 and 2.**

### *Abrasion Study*

Visual Examination: The effects of mechanical damage were estimated for all the Phase 2 pendants. Figure 6a and 6b shows the estimated decrease in residual strength solely due to mechanical damage compared to the measured residual strength. Figure 6a represents the estimations made from Phase 1 techniques and Figure 6b represents the estimations made from the procedure outlined in the Abrasion Study section.

**Figure 6a. Residual Strength Estimation from detailed abrasion analysis.**

**Figure 6b. Residual Strength Estimation from detailed abrasion analysis.**

Yarn testing: The effects of discontinuous fibres in the strand's yarns were measured for both the 300 and 1200 job pendants. The residual strength of the yarns were averaged and placed into categories based on their position in strand (See Table 1). Based on the condition of the strands, see Figure 7, there were many 1st twist yarns that had zero fibres available for tension testing.

Table 1. Residual Strength of Yarns from used Phase 2 Pendants

| Number of Jobs | Strength (%) of Yarns | | | Average Yarn Strength (%) (26 yarns) | Rope strength (%MBL) |
|---|---|---|---|---|---|
| | Centre (2 yarns) | Middle (9 yarns) | Outside (15 yarns) | | |
| 300 | 87 | 78 | 65 | 71 | 70 |
| 1250 | 47 | 31 | 12 | 21 | 42 |

**Figure 7. Dismantled Rope strands showing the effects of damaged yarns.**

## Discussion:

The HMPE mainlines' residual strength from Phase 2 testing appears to be dependant on the number of jobs performed (Figure 4). This short term behaviour study on HMPE mainlines is characterised the by gradual strength reduction. This strength reduction continues until approximately 600 jobs, where it then plateaus. These losses and subsequent plateau should not be significantly affected by drum compression or twist as previously determined in the Phase 1, as neither was observed during the visual inspection of the Phase 2 samples. Comparing the combined data to studies performed by A. Street and J. Hooker, there appears to be common mechanisms causing the strength reduction regardless of the location and equipment used for the studies [4] [5].

The combined data produced from the short term and long term testing, corresponds to other studies made on HMPE rope in tug applications (See Figure 5) [1]. From the test data of AmSteel® Blue, the strength drop is appreciable after a few hundred jobs. After approximately 600 jobs the rope's residual strength is indistinguishable from a rope that had been used for more than 1700 jobs. One possible explanation for this phenomenon would be abrasion. Since abrasion is primarily a surface phenomena and the strength of the rope is directly proportional to the volume of continuous fibre able to support tension, the discontinuous fibres due to abrasion damage would contribute a fixed strength decrease.

Analysing the basic curvature of Figure 5, the location of the sample used for testing appears to be irrelevant. The Phase 1 mainline ends and pendants appear to seamlessly interconnect to the Phase 2 pendants forming a single continuous curve. The standard length of line used during ship escort, berthing and un-berthing was approximately 30 meters, which would correspond to the following rigging arrangements as shown in Figure 1:

- Phase 1: 13 meter out board pendant and 17 meters of mainline
- Phase 2: 13 meter outboard pendant, 13 meters Test Pendant and 4 m of mainline

The outboard pendant typically is characterized as the sacrificial end intended to take the abuse of the client ship's chocks, especially if the client ship is using wire rope. However from the combined data, the sacrificial pendant has nearly identical residual strength to the mainline and to the Phase 2 test pendant with similar jobs. If the client's chocks were indeed causing tremendous abrasion and cutting, a similar phenomenon must be present near the tug's winch and in the free rope between the tug and ship's chock. In this study the mainline assembly was passed though a stainless steel clad staple prior to being sent to the client ship. These staples were smooth, rust-free, and devoid of any burrs or scoring, which would minimise the effects of external abrasion and cutting on the rope that are traditionally seen at the client ship's chock. Therefore the dominate mechanism causing local fibre failure likely originated from other surface phenomena.

*Abrasion Study*

Visual Examination: The cursory examinations used in Phase 1 were insufficient to produce any conclusion on the effects of abrasion and other strength reduction mechanisms that produces discontinuous fibres. The new analytical technique is based on the assumption that a personal judgment based on visual examination alone would be able to ascertain the residual strength of the HMPE mainline.

Using the technique outlined in the detailed abrasion examination procedure, the residual strength was estimated by counting the number of continuous fibres in all twelve strands. This technique estimated the strength reduction in the 1000 and 1200 jobs very close to the actual test result (Figure 6). This indicates for these lines the amount of continuous fibres available for loading was a good indication of the rope's strength and the other factors, drum compression and twist, presented in Phase 1 are either a mechanism attributing to discontinuous fibre or are less important than originally believed. Since the degree of external abrasion from rope contact points on the tug and client vessel is assumed to have minimal effects on the residual strength, other factors that could cause localised fibre failure resulting in a discontinuous fibre should be investigated, specifically the effects of small sand, silt, and salt crystals concentrated in the rope's body under cyclic loading and the effects of bending fatigue at the vessels points of contact

Yarn Testing: To further investigate the effects of discontinuous yarns on the residual strength, yarn analysis was conducted on two test pendant samples. The 300 job test pendant's yarns were estimated to have an average residual strength of 71%, which was similar to the value measured for the actual rope (70%). Conversely the average residual strength of the yarn from the 1200 job test pendant (21%) was far below the tested value of the rope (42%). Therefore discontinuous yarns can support more load in rope form due to strand twisting and braiding than they can support in their basic yarn form. This can be related to an end-for-end (long) splice in the mid span of the rope, where each end is essentially a collection of discontinuous fibres that have the potential to support 100%

of the rope's minimum break strength as determined by CI-1500. In this example the distance between the two ends is greater than the critical length of discontinuous fibre at which the rope can sustain significant loading. Even though the 1200 job pendant's strand was estimated to have 50% of the breaking strength of the rope, it is possible that the distance between discontinuous fibres was greater than the critical length of the rope. For braided rope the critical length is a function of the twist levels in the yarn and the strand and the helix angle of the braid and is unknown for twelve-strand Dyneema.

Figure 7 shows many of the discontinuous fibres originate on the outside surface of the rope as depicted by the soiled (brown) sections. This would substantiate the surface phenomena strength reduction assumption but does not shed light as to the mechanism.

## Conclusions:

AmSteel® Blue ropes used for Tug mainlines and pendants a subjected to many factors that decrease the rope strength. From Phases 1 and 2 testing it appears the dominant strength reduction mechanism is from discontinuous fibre. However the combined effects of tensile fatigue, shock loading, twist and drum compression can not be overlooked, as they can create or accelerate localised fibre failure.

The overall length of the sacrificial pendant should be re-evaluated to incorporate the test data to date. Since the sacrificial pendant has approximately the same residual strength as the mainline and the intermediate test pendant, the benefits of reducing the damage on the longer mainline are unattained in its current length. Sacrificial pendants should be at least 26 meters overall length to get the maximum preservation of the longer mainline.

By describing the rope's behaviour as a function of its usage, application specific retirement criteria can be developed. Furthermore this type of information can be used to initially size a tug's mainline so it can meet or exceed regulatory requirements if used correctly. The information in this study is based solely for the construction of rope used, the tug's bollard pull, and the operating conditions. Projection or prediction of behaviour of ropes subject to other application or environment should not be made based on this study.

## References:

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