Fatigue and Residual Strength of Fiber Tuglines

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Abstract - High performance synthetic ropes have been successfully used in the towing industry since the mid 1990's. Although many laboratory studies were conducted on the mechanical and physical attributes of the ropes, not too much was known on the long-term behavior of the ropes in field application. Samson Rope Technologies and DSM High Performance Fibers have undertaken a 2-year long joint program to collaborate field performance and in laboratory studies to establish a better understanding of retirement criteria of a rope in service. This report summarizes the study conducted on approximately 40 AmSteel Blue field-tested ropes made from Dyneema SK75 HMPE fiber. Detailed residual strength determination and laboratory analysis are discussed.

I. INTRODUCTION

Most applications of HMPE ropes are as a replacement for steel wire. Consequently, they are measured against that datum. The obvious fact is that strength of any rope will degrade from external factors. In reality, one cannot have both the ease of handling gained from using synthetic rope with the same or better toughness of steel. The best compromise is to assure maximum strength over the longest possible period.

Many factors attribute to the degradation of a new rope's strength [1]. Some of the factors, such as abrasion, can be visually inspected although the impact of abrasion to residual strength is very difficult to predict. Other factors, such as fatigue, are virtually undetectable and practical predictive measurements are unavailable. This study investigates five known factors, mechanical damage, winch drum compression, fatigue, shock loading, and twist, that adversely affect the rope's residual strength.

II. OBJECTIVE

To determine the relative contributions of factors that diminish rope strength over time and confirm residual strengths at different time/usage intervals.

III. SCOPE

The scope was limited to the AmSteel®-Blue main tow lines on single drum winches aboard tractor tugs in Long Beach/San Ramon Harbor, CA, Puget Sound, WA, and Valdez, AK. Rope sizes differed depending on the bollard pull of the tug.

IV. PROCEDURE

This study included laboratory inspection and analysis of approximately 40 separate break samples of AmSteel®-Blue rope made from Dyneema® SK75 fiber. Ropes ranged in size from 2-5/8" to 3-1/4" diameter and were actively used in the field aboard tugboats in vessel escort service. Duration of work exposure was between 800 and 2000 jobs, where the lines were subjected to many uncontrollable environmental forces. Sacrificial pendants were generally used for one year and main towlines were used for two years before testing. During the mainline's two year service, the lines were used for one year, end-for-ended, and used for another year.

Visual inspections and break test were performed on used AmSteel®-Blue lines, where all break tests were performed in accordance with CI-1500, "Standard Test Method for Fiber Ropes" [2]. All the ropes were tested using existing eye splices whenever possible to minimize the affects of a "used rope splice."

All the factors contributing to the loss in residual strength were isolated and tested using laboratory scale model testing at test laboratories.

A. Abrasion and cutting damage

Visual inspections were used to categorize and catalogue the degree of mechanical damage due to abrasion and cutting. Using this information, mechanical damage effects were estimated.

B. Shock loading

With the help of Harbor Marine Group and Portage Bay Marine, two tugboats were outfitted with data logging instrumentation on their force monitoring single drum winches. The force-time data was sampled over a period of three weeks and was used to compile the average and maximum forces for each day. Data for individual jobs were also captured to determine the magnitude of shock loading.

Upon determining the magnitude of the shock load (force per unit time), cycle testing was contracted to replicate the field measured shock loading rate. A standard sinusoidal loading rate and a less severe shock loading rate were used as comparators. Each rate was tested using the following procedure:

1. 1000 cycles between 5%-50% Min BS
2. 1000 cycles between 5%-60% Min BS
3. 1000 cycles between 5%-70% Min BS
4. 2000 cycles between 5%-80% Min BS
5. 1 cycle to 100% breaking strength
   BS=Breaking Strength

C. Tensile Fatigue

Fatigue tests were performed at NEL in East Kilbride, Scotland. A 5/16” diameter AmSteel®-Blue was tested in accordance with CI-1500 to determine the actual breaking strength of this scalar sample. Three cyclic control samples were then cycled between 5% and 75% of the previously determined breaking strength to determine the average total cyclic lifetime of the rope at 2 Hz until failure. Then one sample was cycled to 90% of the cyclic lifetime, three samples to 80%, and three samples to 30%. After the cycling was complete, the samples were tested to failure to determine the residual strength as a function of fatigue cycles/lifetime.

D. Drum Compression

To determine the effects of drum compression on residual strength, a scalar laboratory model of the winch/staple arrangement on the tractor tugs used in this study was constructed. The 13/16” diameter AmSteel®-Blue sample was wound on the drum under tension creating four layers on the winch drum. The working end of the rope was then passed around a pin and secured to a stationary bit. The winch drum then applied cyclic tension ranging from 5% to 60% of the actual breaking strength of the AmSteel®-Blue for 4160 cycles.

The rope was then sectioned into the following six distinct samples (See Figure 1):

1. Drum layer (inner most layer)
2. Second layer from the drum
3. Third layer from the drum
4. Fourth layer from the drum (outer layer)
5. Rope between the drum and the pin
6. Rope length just prior to and after the length in contact with the pin

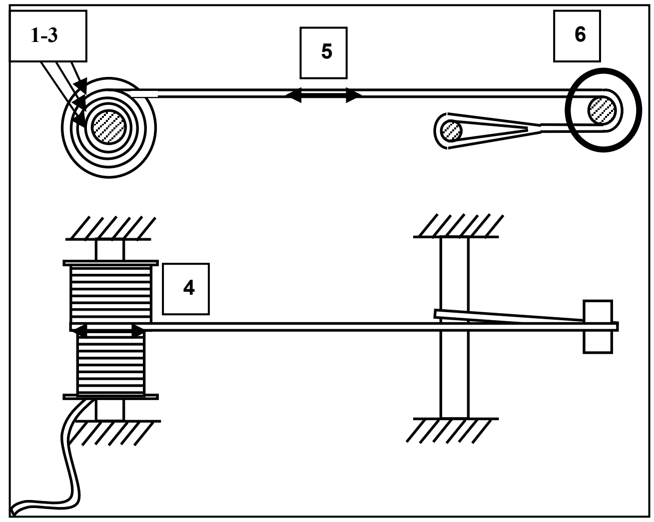

Fig. 1. Schematic of winch drum compression test.

Each one of these samples were spliced and tested in accordance to CI-1500 to determine the reduction of strength.

To investigate the effects of drum compression on the Dyneema fiber, a second drum compression test was performed on a Dyneema fiber 12 strand rope. The rope was wrapped around a cylinder 5 times and cycled to 50% of the rope breaking strength for 1000 cycles. The rope was then removed sectioned into 3 pieces, spliced, and tested to failure. The three samples were taken from the following areas:

1. Drum Layer
2. Fifth layer from the drum
3. Free end

Individual yarns from the three sections of the rope were also tested to failure in order to determine the effects of the compression at the fiber level.

E. Twist

Each towline was visually inspected for twist induced into the rope though normal towing operation. The degree of twist was recorded and normalized to the diameter of rope. The normalized twist levels were then replicated on 1” diameter AmSteel® and tested in accordance with CI-1500 to determine the breaking strength as a function of twist.

V. RESULTS

All ropes were tested to quantify the residual strength and are listed in Figures 2 and 3. The mainlines were sectioned according to Figure 4 and analysed accordingly. Due to insufficient data for the 3” and 3-1/4” diameter ropes, further data analysis focuses on the 2-5/8” diameter AmSteel®-Blue samples.

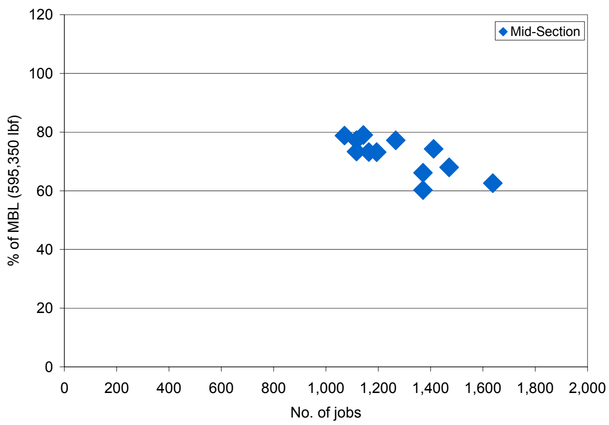

Fig. 2. Mainline Mid-Sections (8" circ.)

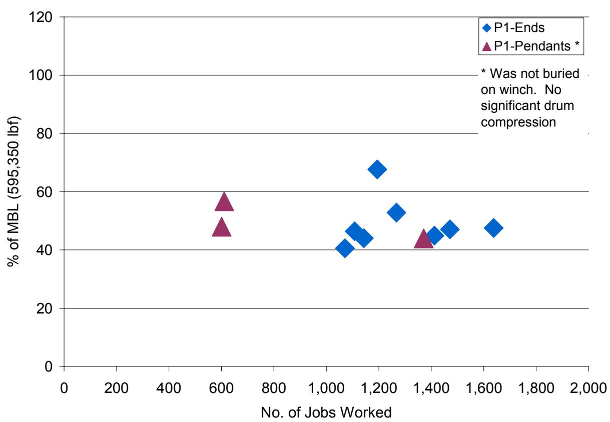

Fig. 3. Mainline Ends (8" circ.)

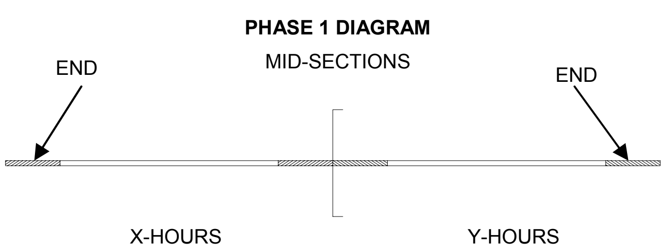

Fig. 4. Diagram of main line sectioning.

A. Abrasion and cutting

The effects of mechanical damage were estimated for all 2-5/8" diameter ropes. Figure 5 shows the estimated decrease in residual strength solely due to mechanical damage compared to the measured residual strength.

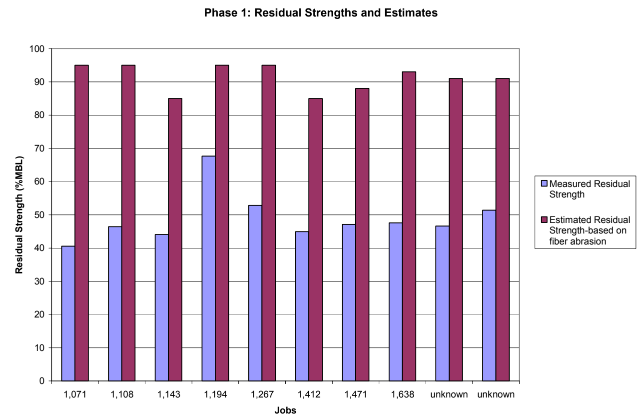

Fig. 5. Residual strength estimation based on abrasion

B. Shock loading

The data derived from the data logging instrumentation on the single drum winch is shown in Figures 6, 7, 8 and 9. Figure 6 shows over a three week time period the maximum load imparted on the winch is approximately 6% of the new rope's published minimum breaking strength. Figure7 shows the force time data taken from a single job, where the maximum force is approximately 18% of the new rope's published minimum breaking strength. The figure also shows many significant changes in load in very short periods of time. Two of these are shown in Figure 8 and 9. These charts show a loading rate of 53,000 and 50,000 lb(f)/sec, respectively.

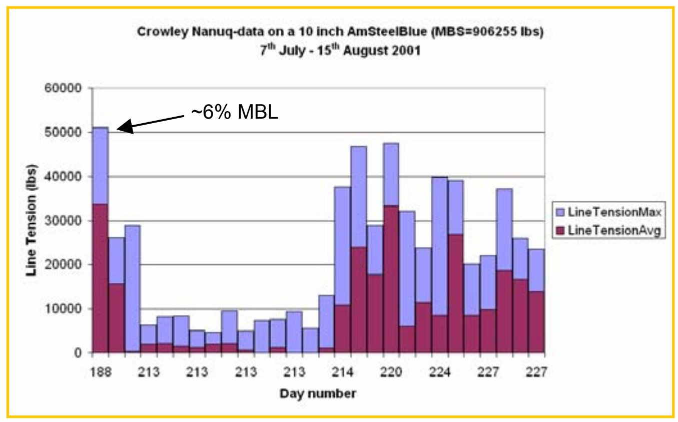

Fig. 6. Max. and Avg. forces measured over three weeks

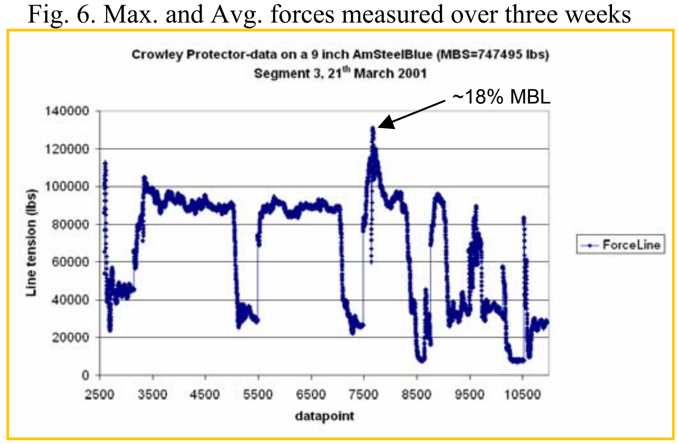

Fig. 7. Force/Time chart over a single job.

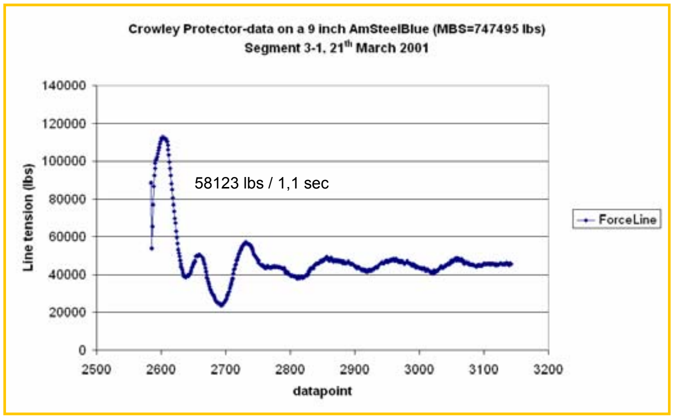

Fig. 8. Force/Time chart over a single shock event.

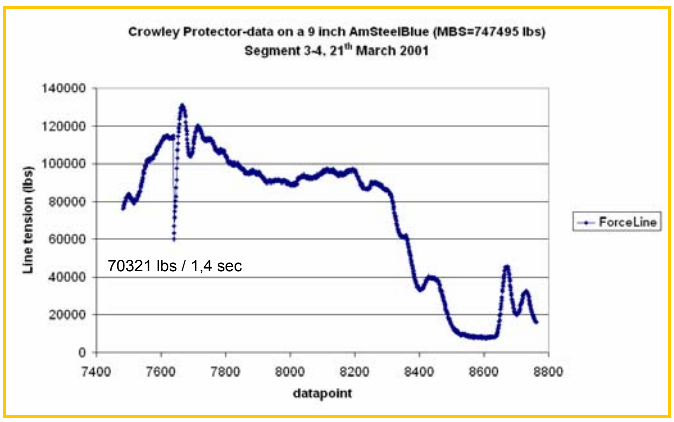

Fig. 9. Force/Time chart over a single shock event.

Scalar loading rates were then used in cyclic laboratory experiments to investigate the relative significance of these shock loads. Table 1 shows the residual strength after being subjected to cyclic testing.

TABLE 1.

Test 1	#cycles	Load cycle	Cycle time	Dwell Time (sec.)
	1000	5-50% BL	20 s.sine	0
	1000	5-60% BL	20 s.sine	0
	1000	5-70% BL	20 s.sine	0
	2000	5-80% BL	20 s.sine	0
	1	**Residual Strength=135% MBL**		
Test 2	#cycles	Load cycle	Cycle time	Dwell Time (sec.)
	1000	5-50% BL	3 s. sine	17
	1000	5-60% BL	3 s. sine	17
	1000	5-70% BL	3 s. sine	17
	2000	5-80% BL	3 s. sine	17
	1	**Residual Strength=139% MBL**		
Test 3	#cycles	Load cycle	Cycle time	Dwell Time (sec.)
	1000	5-50% BL	1,1 s. sawtooth	18.9
	1000	5-60% BL	1,4 s. sawtooth	18.6
	1000	5-70% BL	1,6 s. sawtooth	18.4
	2000	5-80% BL	1,8 s. sawtooth	18.2
	1	**Residual Strength=135% MBL**		

C. Tension Fatigue

The 5/16" diameter AmSteel®-Blue breaking strength was measured at 28,800 lbf. Then cyclic control sample was cycled between 5% and 75% of the measured breaking strength to failure, 426,600 cycles. Figure 10 depicts the data comprised from the 90%, 80% and 30% of the cyclic lifetime tests.

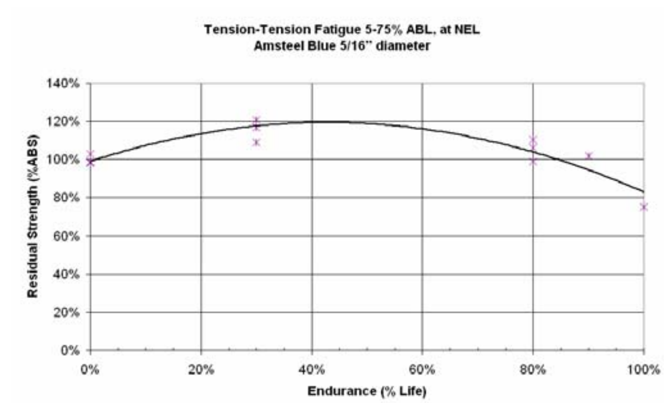

Fig. 10. Tension-Tension Fatigue

D. Drum Compression

The effects of drum compression on the residual strength of 13/16" diameter AmSteel®-Blue rope are shown in Table 2. Table 3 shows the effects of drum compression on Dyneema fiber rope and on the Dyneema fiber yarns (See Figure 1 for sample location information).

TABLE 2.

Sample Location	Load (lbf)	% Reference
Reference	69300	100
1	54692	79
2	53372	77
3	58542	84
4	58850	85
5	70224	101
6	67210	97

TABLE 3.

	Rope		Yarn	
Sample Location	Load (lbf)	% Reference	Load (lbf)	% Reference
reference	1386	100	102.3	100
Layer 1	1081.3	78	101.2	99
Layer 5	1379.4	99.5	96.8	94.5
Free End	1392.6	100.5	99	97

E. Twist

Most of the returned 2-5/8" diameter AmSteel®-Blue ropes had negligible twist, however on a few samples the twist levels were approximately 1 complete rotation per meter.

The laboratory tests on 1" diameter AmSteel®-Blue rope are shown in Figure 11.

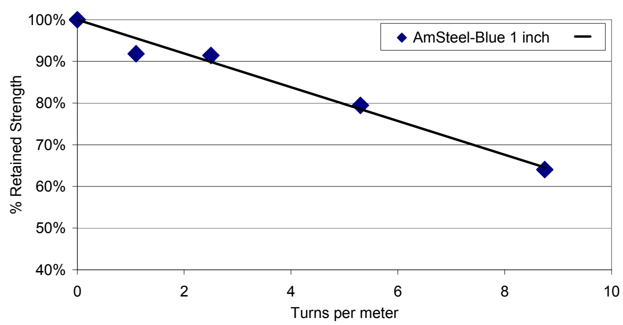

Fig. 11. Effect of twist on breaking strength

V. DISCUSSION

The residual tests performed on the AmSteel®-Blue tug lines, shows an average retained strength of approximately 45% (See Figure 3). This strength reduction is similar to those found in previous studies. However the mechanisms for strength degradation were not fully investigated [3, 4].

This strength appears to be independent of the geographical location of the tractor tug and the environmental stress attributed to these areas. It also appears to be independent of the number of jobs performed, however this most likely due to the lack of sufficient data between 0-1000 jobs and from 2000+ jobs. The decrease in residual strength can not be attributed to a single factor, but to a combination of the investigated mechanisms.

A. Abrasion

Abrasion damage based on the assessment techniques used in this study, appears to have some influence on the residual strength but not that significant. These cursory observations only give subjective, qualitative assessments of the degree of mechanical damage. It is believed the effect of abrasion has a more significant effect on residual strength. Therefore, further research by DSM-HPF and Samson appears promising to achieve more quantitative predictions of strength loss due to mechanical damage.

B. Shock loading

Sudden application of high loads (shock loading) can be in excess of the capability of the connecting system from vessels. Shock loading of either synthetic rope or steel wire has been historically documented as a significant cause of early failure in use [5]. Both steel wire and synthetic rope manufacturers advise against continuing to use ropes known to have been exposed to shock loads. Based on these data from the instrumented winches, the highest impact velocities were on the order of 0.02 to 0.04 metres per second, depending on the length of the line being used.

These strain rates are approximately 10 to 20 times higher than in most rope break tests standards. However after cycle testing at approximately the same rates as found in the field, the samples did not appear to be effected by these load rates. In fact the loading rates over the cycle schedule tested enhanced the ropes breaking strength, most likely from the optimization of load sharing between the rope's fibers/yarns. So it appears the load rates as measured on the winches are not significant enough to cause degradation to the rope or its fibers.

C. Tension Fatigue

As shown in the laboratory study up to 80% of the lifetime, tension fatigue is not a major factor in the residual strength of the AmSteel®-Blue ropes. Since laboratory studies used high load levels to accelerate the tests and most mainlines do not see the repeated loads in excess of 40% MBL, the lifetime of the mainlines are assumed to be orders of magnitude higher than the 426,600 cycles.

D. Drum Compression

Drum compression from laboratory studies contributes a 20% strength reduction to new rope. The compression strength reduction phenomena can also be observed in the mainline mid-sections, where the line is rarely subjected to other factors such as, abrasion, twist, or significant line tensions (See Figure 2). Laboratory testing shows that while a compressed rope has lost up to 20% of its strength, the rope yarns have retained essentially 100% of their original strength. Since there is no strength loss in the compressed rope yarns, it is believed that the compression in the rope, both in laboratory tests and the mainline mid-sections, leads to splicing inefficiencies and structural deformation.

Comparing the residual strength of the pendants that have never been compressed to the mainline ends that have been most recently been stored on the drum, the compression effect can not be differentiated from the other factors. The same is true when comparing the mainline ends which were most recently on the drum to the mainline ends that were most recently used and have regained their original shape (See Figure 3).

Once under tension most compressed areas on the line regain their original shape. It is assumed that since the fibers/yarns are not losing their strength, the regained shape has minimized the compression strength degradation.

Further investigation is needed to determine the effects of compression on residual strength.

E. Twist

Conventional wisdom acquired from many years of experience says that twist is bad [6, 7]. This is particularly true with cable lay constructions of both rope and wire, and its effects can also be observed in braided rope. From the visual inspections, most of the mainlines had between 0.5-1 twists per meter, which normalized to a 1" diameter equates to approximately 3 twists per meter.

From the effects of twist on residual strength data on the 1" diameter AmSteel®-Blue rope, the normalized 3 twists/meter shows a 10-15% decrease (See Figure 11). Twist in ropes can be actively and easily minimized. Furthermore, twist in a rope under tension should be avoided. The effect of twist in combination with tension fatigue of AmSteel®-Blue ropes is unknown and currently being investigated.

VI. CONCLUSIONS

AmSteel®-Blue ropes for tractor tug applications are subjected to a variety of mechanisms that can decrease its strength. From this application, the residual strength of the line appears to be dominated by drum compression and twist. The drum compression is significant when re-splicing the rope; however it is assumed that it has little impact during normal use. Furthermore it appears the magnitude of shock loading observed on the tugs is not significant to cause any fiber damage and the tension fatigue characteristics of the AmSteel®-Blue ropes is also not a significant factor. Abrasion assessment techniques need to be quantitative before any accurate determination of its effects on residual strength can be made.

VII. REFERENCES

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