Residual Strength Testing of Dyneema®, Fibre Tuglines

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SYNOPSIS: This programme was performed to identify the mechanisms that diminish rope strength over time and confirm residual strengths at different time/usage intervals, and was designed to verify established rope retirement guidelines. In order to better understand the time for retirement of a rope from service, Samson Rope Technologies and DSM-HPF have spend considerable resources to describe rope behaviour in both the field and in laboratory simulations. In order to do this, it is imperative to understand the effects of mechanical damage as well as quantifying the extent of physically applied loads during use. This study included laboratory inspection and analysis of approximately 40 separate break samples of AmSteel®-Blue rope made from Dyneema® SK75 fibre. Ropes ranged in size from 64mm to 80mm diameter and were actively used in the field aboard tugboats in vessel escort service. Duration of work exposure was between 800 and 2000 hours of working time over a period of two years. Samples were tested at certified, independent testing facilities. The laboratory scale model testing was also performed at well-known test laboratories in Europe and North America. The data from the break tests were then analysed using statistical methods to assure data conformity. For predictive assessment, a statistical model was then created to describe the anticipated strength retention over time. The values obtained were used to better predict the retained strength at a specified time or duration of use.

BACKGROUND

AmSteel®-Blue ropes are 12-strand ropes made from Dyneema® SK75 fibre. The fibre is strong, compared to other synthetic fibres, it is also resistant to cutting and abrasion. External forces and actions affect long-term durability. These ropes have proven instrumental in improving the ergonomics of towing and mooring in the maritime arena. For equal diameters, these ropes have the same strength as steel wire but weigh less than 1/8th as much.

UNDERSTANDING ROPE EXPOSURES

Several factors can contribute to the strength degradation of towlines (1):

- Abrasion and cutting damage: 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. This is best accomplished through proper application, due care and protection. Chafe gear and pennants are used to prevent these ropes from being prematurely retired due to mechanical damage. Follow-up research by DSM-HPF and Samson is taking place and looks promising to achieve better predictions of strength loss due to mechanical damage.

- Compression on the winch drum: HMPE ropes are relatively soft and compliant. While this is a good ergonomic trait, the ropes can be compressed from their relatively round shape into a new shape. This compression is a minor drawback and the rope will return to its original shape through working and handling of the rope.

There is disagreement as to how much this compression activity can result in permanent strength loss.

- Line twist: Conventional wisdom acquired from many years of experience says that twist is bad (2.3). This is particularly true with cable lay constructions of both rope and wire. Our 12 strand and 8 strand constructions are balanced ropes. Thus, the effects of twisting are not so pronounced. Our testing has concluded that the amount of twist experienced in the field does not greatly affect these HMPE ropes. However, when twist is introduced, it can cause uneven wear on the strands.

- 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(4). Both steel wire and synthetic rope manufacturers advise against continuing to use ropes known to have been exposed to shock loads. Crowley Marine Services contracted with the Harbor Marine Group and Portage Bay Marine to instrument the winches of three tugs in order to get real-time data. The data were then reviewed to determine peak loads and the loading rates in actual use. Based on these data from the Crowley tugs, 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. After an extensive search, DSM-HPF found a rope test bed that had strain rates similar to those encountered in the towing operations. After performing a number of cycles in accordance with OCIMF's TCLL test, the ropes showed a residual strength of 135 per cent. This is comparable to the residual strength results seen in other TCLL with the lower strain rates normally used. These results at extreme high load levels (80 per cent) indicate that shock loading is not an issue when due diligence is exercised in the tug operations. In addition, inspection and testing of used ropes show that the internal Dyneema® yarns that were not exposed to abrasion and mechanical damage had a residual strength of 85 to 90 per cent of original strength.

LIFE OF HMPE:

The above items all can contribute to either longer or shorter life of a rope. If the factors are minimised, safe usage is prolonged; if exaggerated, lifetimes can be expected drop dramatically. In order to establish Retirement Guidelines of HMPE ropes, it is necessary to understand the many factors involved that can reduce that rope's life expectancy. Compared to steel wire, all synthetics are more vulnerable to cutting, and are less heat-resistant than steel wire. It is known that HMPE ropes do have excellent chemical resistance to most chemicals, and are UV resistant.

Residual Strength Testing

- Objective: Obtain data to develop retirement criteria to be used by Crowley Marine Services to gauge when a rope should be removed from service.

- Procedure: Pennants were generally used for one year and main towlines were used for two years before testing (main 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. All break tests were performed in accordance with ASTM 04268- 93, 'Standard Test Method for Testing Fiber Ropes' (5). It was agreed by all parties in advance that the residual strength should be adjusted to reflect rope strength loss separate from mechanical damage.

- Results: The results of residual strength tests are shown in Table 1 opposite.

Table 1

Residual Strength of Ends of Main Towlines

Boat	Class	Line size (mm)	Jobs	Hours	Residual strength %	Mech. Damage %	Total Residual strength %
Guard	Protector	72	589	874	88	2	90
Guard	Protector	72	589	874	49	7	56
Admiral	Harbor	64	1071	1327	41	5	46
Guide	Harbor	64	1108	1194	46	10	56
Scout	Harbor	64	1143	1244	44	15	59
Master	Harbor	64	1164	1090	50	10	60
Protector	Protector	64	1172	1476	52	8	60
Guide	Harbor	64	1194	1109	68	10	78
Admiral	Harbor	64	1267	1685	53	5	58
Tioga	Harbor	64	1371	1394	60	7	67
Scout	Harbor	64	1412	1605	45	15	60
Master	Harbor	64	1471	1704	47	12	59
Protector	Protector	64	1603	1995	51	8	59
Tioga	Harbor	64	1638	1811	48	7	54
Leader	Harbor	64	unknown	unknown	51	9	60
Leader	Harbor	64	unknown	unknown	47	9	56
Nanug	PWS	80	612	-	Pending	Pending	Pending
Tanerig	PWS	80	319	-	Pending	Pending	Pending
Nanug	PWS	80	328	-	Pending	Pending	Pending
Tanerig	PWS	80	319	-	Pending	Pending	Pending

Residual Strength of Pennants

Boat	Class	Line size (mm)	Jobs	Hours	Residual strength %	Mech. Damage %	Total Residual strength %
Tanerig	PWS	80	313	813	55	10	65
Nanug	PWS	80	346	868	62	6	68
Scout	Harbor	64	601	642	48	11	59
Master	Harbor	64	611	690	57	9	66
Tioga	Harbor	64	1371	1394	44	12	55

Residual strength of Midsections of Main Towlines

Boat	Class	Line size (mm)	Jobs	Hours	Residual strength %	Mech. Damage %	Total Residual strength %
Guard	Harbor	72	589	874	89	0	89
Guard	Harbor	72	589	874	104	2	105
Admiral	Harbor	64	1071	3271	79	5	84
Master	Harbor	64	1117	1340	73	6	79
Scout	Harbor	64	1143	1244	79	4	83
Guide	Harbor	64	1164	1090	73	5	78
Guide	Harbor	64	1194	1109	73	5	78
Admiral	Harbor	64	1267	1685	77	5	82
Tioga	Harbor	64	1371	1394	66	4	70
Scout	Harbor	64	1412	1605	74	4	78
Master	Harbor	64	1471	1704	68	6	73
Toga	Harbor	64	1638	1811	63	4	66
Leader	Harbor	64	unknown	unknown	84	3	86

OVERALL STRENGTH RETENTION

Midsections are defined as samples that were taken from either the actual midpoint or at least 65 metres in from the end of the line. The results of the more than 40 inspections and break tests provided the following values for (average) strength retention of the lines:

Main Line Midsections:	**81**% of original strength
Main Line Ends:	**61**% of original strength
Pennants:	**63**% of original

Effects of Winch Drum Compression

The test results were further sorted and analysed to examine the strength retention of the (end-for-ended) towlines for the sections that were:

- Against the winch drum then worked	**59**% of original strength
- Worked then put against the drum	**61**% of original strength
- Midsections	**81**% of original strength
- Pennants	**60**% of original strength

Comparison of Used vs. New AmSteel®-Blue Rope

All ropes, except one, had been end-for-ended. The purpose of testing this line prior to "ending" was to investigate whether there was strength loss in the line due to compression and deformation of the line against the winch drum. Below is a comparison of the strength loss of an end-for-ended 64mm diameter AmSteel®-Blue to that of a non-end-for-ended line:

	'Ended' vs. 'not ended'
- Against the winch drum then worked	**59**% vs. **88**%
- Worked then put against the drum	**61**% vs. **54**%
- Midsections	**81**% vs. **95**%

Comparison of these test results indicates that there is strength reduction of approximately 12 per cent before the line is end-for ended, caused by a compressive compaction of rope and deformation on the winch drum.

Laboratory Studies

In order to better understand the influences on deformation of rope construction and transverse compression forces generated from translation of high tensions on the drum, two scale experiments have been performed by DSM-HPF.

A laboratory test on a small diameter (3mm) braided Dyneema® construction with five layers on a drum showed that after 1000 cycles at 50 per cent of its breaking strength the end on the drum has lost 20 per cent of its strength while the upper layer showed a minimal loss. The loss in strength could not be explained by the loss in yarn properties.

t = 1000 cycles	**Braid**	**Yarn**
1. Drum layer 1	78%	99 %
2. Drum layer 5	99.5 %	94.5 %
3. Free end	100%	97 %

In the other study, DSM-HPF used 20mm AmSteel®-Blue in a scale model of the tugline system. After cycling this rope for 4190 cycles at 60 per cent of its breaking strength (31,500 kg = 100 per cent), residual strengths were determined for several positions:

- Bottom Drum Layer	**79**%
- Middle Drum Layer	**77**%
- Top Drum Layer	**84**%

Based on the results of these tests, it appeared that there could be as much as 20 per cent reduction in strength on the end of the line that contacted the surface of the drum and a 15 per cent reduction in the third and fourth layer wrapped around the drum.

Although the percentages of the used non-end-for-ended line were for one test, only, the results suggest that the observed 12 per cent strength reduction is significantly lower than findings from laboratory scale model testing performed by DSM-HPF. It is suspected that in this model test, the loading used for winding the drum was too low.

Effects of shock loading:
In a study on the effect of shock loading on 20mm AmSteel®-Blue, which DSM-HPF performed at Kinectrics in Toronto, Canada, the OCIMF Thousand Cycle Load Level Test (6) protocol was used. Results of TCLL tests at fast cycle times, equivalent to the determined impact velocities experienced by Crowley tugs, showed to be comparable to TCLL tests at normal cycle times. This indicates that actual use shock loading occurring during harbour towing operations is not affecting the strength of the rope.

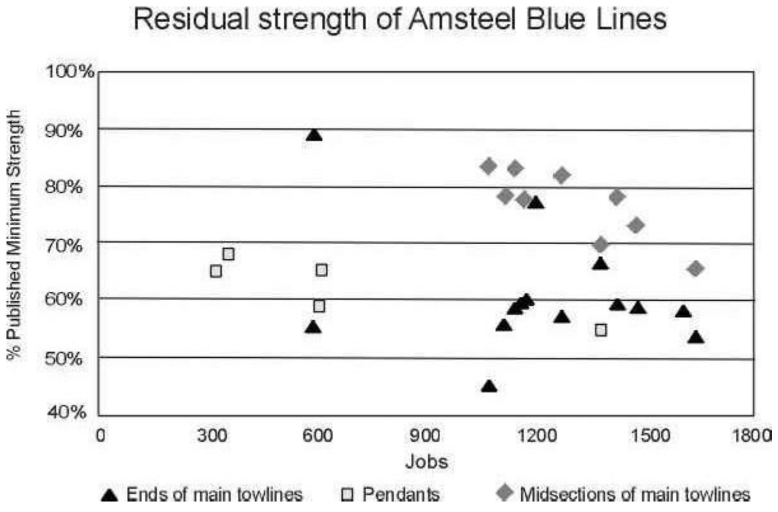
	Sine	**Sine**	**Saw- Tooth**
	t = 20 s.	t = 3 s.	t = 1.1 -1.8 s.
1000 at 5-50%BL	0.003 m/s	0.020 m/s	0.05 m/s
1000 at 5-60%BL	0.004	0.024	0.05
1000 at 5-70%BL	0.004	0.029	0.05
2000 at 5-80%BL	0.005	0.033	0.06
Break strength	134%	139%	135%

The effect of shock loading was further examined in a laboratory test on Dyneema® yarns. In this test tenacity, elongation at break and modulus properties were determined at strain rates ranging from 0,05 %/s to 400 %/s at temperatures between -60°C to 100°C. The properties were rather constant in the temperature range and strain rates representative to towing jobs.

Statistical Analysis:
All break test data were put into a statistical matrix to determine correlation coefficients and tests -the data were reviewed and compared using a variety of methods, such as Durban-Watson, Single Linear Regression (SLR) and Multiple Linear Regression (MLR). Confidence level using number of jobs as the dependent variable and residual strength as the independent variable yields an R-Square value of 0.9395. This is a very high value, which verified that all coefficients in the model were statistically significant.

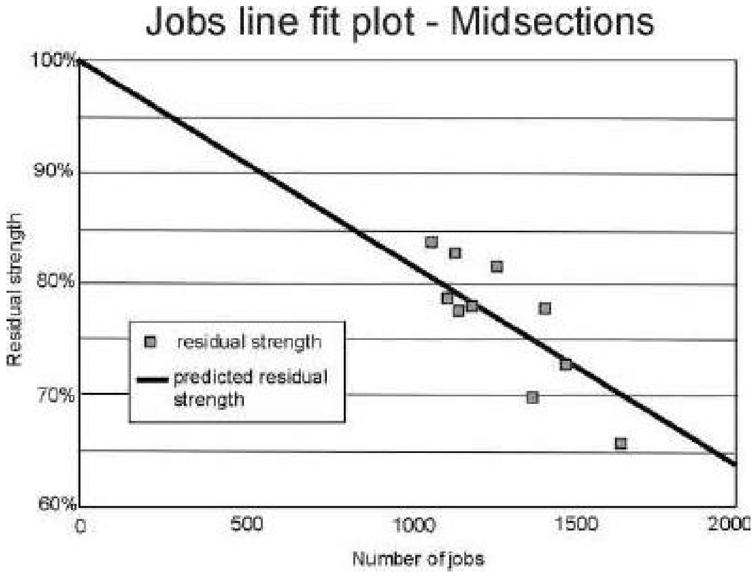
The statistics become better as the data group grows and is better defined. We will continue to enlarge the existing database over the next several years. Figure 1 shows the graphical display of the values from Table 1.

Figure 1



The number of samples in each group is small. However, there was determined to be small statistical difference within the rope categories separate from 'pennants'. In fact, the correlation of the midsections of the ropes was excellent. This allows the predictive model of midsection life as shown in Figure 2. It makes sense that the ends do not correlate as well. They are exposed to a variety of damages due to cutting, abrasion and such. The cumulative effects of these damages can only be estimated through a detailed inspection and internal yarn inspections.

Figure 2



The suggested retirement criterion now in use is jobs, rather than hours, or years. This has the additional advantage of allowing crews to schedule the replacement of components or preventative activities such as end-for-ending of lines or cropping damaged ends and splicing of new eyes.

As a result of the statistical analysis portion of the programme, we have instituted the model and continue to grow the database. We have also begun a secondary test program using test ropes for further validation and definition of the premise. The secondary test specimens are 15m long and are deployed between the pennant and tow hawser. We have put these seven identical 64mm diameter test specimens aboard seven identical tugs in the same type of service. The variables have, as much as possible, been eliminated:

- All ropes and fibres were extensively tested and monitored through the manufacturing process

- All 7 specimens, plus a 'control' assembly were fabricated from the same Dyneema® SK75 AmSteel®-Blue rope

- Eyes on all 8 specimens were spliced by the same person

- No re-splicing of used rope will be required

- All specimens will be break-tested under strictly controlled protocol at the same location by the same operators, on Samson's new 500-tonne test machine

- Final rope condition will be inspected and documented individually by two parties

CONCLUSIONS:

Based on the testing performed over the past two years, both the pennants and the main towlines are retaining more than 60 per cent of their initial strength at the set retirement age. Time intervals are approximately one year for pennants and two years for tow hawsers.

Abrasion and cutting damage has averaged 5-10% wear (total internal and external abrasion), which may account for a strength loss of 5-10%. It has now been determined that compression from the drum accounts for a strength loss of 10- 12%. Several lines that were tested had moderate to severe twist, up to 1.5 turns per foot, which resulted in damage to about 10% of the total fibre in the rope. Line twist of 1 to 1.5 turns per foot equates to a 15-20% strength reduction. Abrasion and compression alone can account for 15-20% strength loss. If the line has also been twisted, the combination of these three factors could account for up to 40% strength reduction.

In DSM-HPF's laboratory testing of the scale model of the tugline system, there did not appear to be a significant reduction in strength on the worked side of the rope, so this might indicate that next to abrasion, shock loading might also be a factor. In a TCLL-test set-up actual use shock loading during harbour towing operations showed to have no effect on the residual strength of the rope.

Degradation of the fibre does not appear to be a contributing factor to the strength loss of the main lines. Samples of used ropes have been sent to DSM-HPF for analysis and the strands and yarns taken from the tuglines show almost no abrasion damage. However, the rope yarns out of the pennant do show higher levels of abrasion damage (broken filaments). These broken filaments would correspond to recorded lower strengths.

All materials will lose strength over time as they are subjected to repeat fatigue cycling. However, the cumulative effect on the residual strength of a fibre (or rope construction) is directly influenced by three primary factors:

- The magnitude of the load

- The number of cycles

- The speed at which the load is applied

The testing performed by both DSM-HPF and Samson Rope Technologies indicates that Dyneema® fibre has excellent resistance to cyclic fatigue, even when tests are performed well in excess of the OCIMF TCLL cycle times. The resistance of Dyneema® to both high magnitude loads and an extensive number of load cycles has been proven in laboratory testing. The resistance of Dyneema® to much higher strain rates has also been proven on yarns.

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