FATIGUE MECHANISMS AND RESIDUAL PROPERTIES OF POLYESTER ROPES

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ABSTRACT

A first study has been conducted to compare modulus properties between textile yarn and rope. A good agreement has been found between yarn and rope for both loading to failure in a rested condition after cyclic loading and in cyclic loading.

There are large differences in modulus response between loading in a rested condition after cyclic loading and cyclic conditions. This is most likely due to changes in the polymer as a result of visco-elastic effects where the time dependent extension recovery does not have time to recover in cyclic loading.

In the 48 million cycle fatigue test, internal abrasion between strands was found to be significant. No other forms of fatigue mechanisms were found. This enables the designer to understand the potential mechanisms that may operate in long life applications around 20 to 30 years. It should be noted that this fatigue life is far greater than steel and well beyond that required for offshore moorings.

In contrast a lower helix angle rope showed no internal abrasion for the same test conditions, but 12 million cycles. Rope lay angle is a very important rope design parameter for long term applications and if correctly specified could design out or minimise effects of internal wear.

INTRODUCTION

Many studies have been conducted on measuring the mechanical properties of both yarn and rope and a reasonable understanding has been reached on the effects of frequency, load range, mean load and loading history. However, in comparison, little work has been conducted on understanding the relationship between yarn and rope properties.

This paper presents two different topics, modulus and fatigue but is conveniently based on the same yarn grade and rope source so a valid comparison of properties could be made. It is very difficult to find such data and this is one of the first attempts in making such a comparison for fatigued samples and under cyclic loading.

For modulus, a comparison of the properties between textile yarn, around 0.3mm diameter, which is the basic building component of sub-ropes and rope has been conducted. The modulus properties for textile yarn and rope, both in loading to break has been studied. The textile yarn was removed from fatigued tested rope. The new rope was cycled 10 times and then loaded to break. Also, the same comparison has been conducted for textile yarn and rope under cyclic loading.

The other topic concerns the fatigue effects in a long term cyclic load test of a 6t sub-rope to 48 million cycles which is the largest number of cycles ever conducted on a rope of this size and length. A study was conducted on the damage mechanisms and measurement of residual strength of the yarns in the rope. Also examined was a 5t parallel strand rope cycled to 12 million cycles at the same test loads.

DATA SOURCE

The textile yarn data was derived from a 250t parallel strand rope that had been subjected to a severe test matrix of 17 runs comprising 64.5 hours and 23,732 cycles (ref 1.) simulating harsh environment 100 year storm conditions. Yarn samples were removed from the rope in a manner that preserved the twist as the yarn existed in the rope. This simulated as near as possible the geometrical condition of the yarn in the rope. The textile yarn is the same grade as that used in the 6t sub-rope (ref 2) data described below.

The 6t sub-rope data was derived from fatigue tests conducted on polyester 3-strand sub-rope samples of 2m nominal pin to pin length. The nominal break strength of the sub-rope was 6 tonne and the average Actual Breaking Strength (ABS) of three samples was 61.94 ± 2.59 kN which represents a coefficient of variation of ± 4%. The ropes were conditioned with 10 cycles 1% to 50% of break load before the break test. The long term 48 million fatigue test sample was tested at 20% mean and 20% load range based on this average ABS. The modulus data was based on a fatigue test conducted at 40% mean load and 15% load range. The samples were un-jacketed and supplied with spliced terminations and soft eyes protected with UHMWPE cloth. The spools used were made of stainless steel with a flat profile and were 60 mm in diameter by 25 mm deep. Based on a calculated rope diameter of 11.8 mm the D/d ratio was 5:1.

Finally, an examination and yarn tests were conducted (ref 3) from a 5t polyester parallel strand rope spliced sample 2m nominal pin to pin length that was fatigue tested 12 million cycles unfailed at 20% mean and 20 % load range.

TEST METHODOLOGY

Textile yarns were tested in accordance with ASTMD 885 and extension was measured using an optical extensometer on the clear gauge length (500mm) to remove grip effects.

For the 5t rope, 6t sub-rope and 250t rope, three test machines of 50, 100 and 1000 kN load capacity were used and the ropes being tested were fully immersed in tap water. Fresh water was used at the start of each test but was not normally changed during the course of testing. For the long running fatigue sample the water was changed periodically during the course of testing. The fatigue tests were conducted at a frequency of 1-4 Hz. There was no measurable heat build-up within this frequency range at the test loads considered.

The 6t fatigue results (ref 2) presented in this paper were part of a broader test programme, for which the objective was to demonstrate the capability of undertaking long life fatigue tests in preparation for a new JIP (ref 4) into the durability of polyester rope.

Modulus calculated on the basis of machine crosshead movement using full size ropes, in general, tends to be slightly higher than that produced using an extensometer attached directly to the rope, at least after the rope has bedded-in. This difference is due to there being more material in the splice regions which effectively increases the stiffness within these regions.

The rope modulus data obtained during break testing was based on machine crosshead movement whereas the cyclic modulus was derived from an extensometer of approximately 1m gauge length.

MODULUS PROPERTIES – YARN TO ROPE

RESULTS and DISCUSSION

In this discussion, since effect of frequency has been well proven to be effectively negligible (ref 5, 6, 7, 8, 9) the terms for slow loading to break and wave period or dynamic loading have been avoided. The test data being compared is described as either break test or cyclic data.

Figure 1 shows a comparison of the 6t sub-rope load/extension curve in loading to break for a new rope break test, after 10 conditioning cycles, against a break test after a 15 million cycle 40% mean 20% load range fatigue test. Importantly, it can be seen that after 15 million cycles around 8% strength loss had occurred. It should also be pointed out that this sample underwent simulated storm runs including stochastic loading to assess modulus behaviour. Therefore, a loss in strength is not surprising. The curves superimpose up to around 50% of break load and then the deviate up to break. It is an indication that the 10 conditioning cycles prior to break is sufficient to remove most of the bedding-in and thus the curves match up to 50%. The deviation from 50% load to break is most likely due to structural bedding-in of both rope and splices.

The same data is shown in figure 2, but converted into a modulus/extension curve. A curve has been drawn through the data to illustrate the trend. Clearly, the modulus curves superimpose up to 4% but then the new rope reduces in modulus and then increases up to break. This is not a characteristic of polyester and confirms the effect is due to structural bedding-in that alters load sharing across rope components.

As removed from the cyclic loaded 250t rope, three sets of textile yarn were loaded to break and are shown superimposed over the rope data as shown in figure 2. There were actually ten samples tested and all gave the same trend. The test conditions are similar for both yarn and rope in that the they are break tests and have been cyclic loaded and rested. Since the yarn carries different stresses than the sub-rope due to the effect of geometry or helix angle, the textile yarn modulus has to be corrected using the following relationship

Rope modulus = Yarn modulus x $\cos 2^{4.75}$ where 2 = helix angle

The yarn and rope data now both show the characteristic polyester material behaviour with a first modulus peak at low extension, followed by a trough at around 2% extension and then a second modulus peak before the modulus reduces again up to break.

The behaviour of the yarn is different to the fatigued rope after 6% extension. An explanation to this behaviour is provided.

The yarn data compares very closely to the rope over the extension range 2% to 6%, but deviates either side. Firstly, we can examine the deviation up to the trough. Due to differences in test techniques and bedding-in effects for the textile yarn compared to the 6t sub-rope, the datum zero on the extension axis will be different. If the rope curve is moved to the right to allow for this difference, then the match is very close up to around 6% extension as shown in figure 3.

Secondly, we can now explain the deviation in modulus between fatigued yarn and fatigued rope from around 6% extension to break. There is a downward shift in the 2^{nd} peak of the 6t sub-rope, which has had considerably more fatigue cycles than the 250t rope. This downward shift may be due to fatigue damage at the polymer level.

Lastly, there is a difference in the break extension between yarn at around 10.5% and rope at around 9%, which is 86% of yarn. Take the datum on the textile yarn break load at 100%. The 6t sub-rope has a strength efficiency of around 85% of the textile yarn. The difference between the break extension matches the tensile efficiency and explains the deviation. Note that the slope is similar from the second peak to break for both yarn and rope. This indicates that the underlying polymer behaviour is being replicated in both yarn and the rope.

In cyclic loading a different response was found. Figure 4 shows a 750t polyester parallel strand rope cyclic loaded at 0.5%, 1% and 1.8% extension range. The textile yarn data is also shown, but for loading to break. Clearly, the curves are showing different response under the different loading conditions. The rope under cyclic loading shows a constant, linear modulus response over the imposed extension range whereas the yarn shows a decreasing modulus with increasing extension. This is a polymer effect and is most likely due to the delayed elastic recovery effect that under cyclic conditions does not have time to recover. In comparison as shown in figure 2 after cyclic loading and recovery, the two peak modulus behaviour returns in both rope and yarn. However, when yarn data under cyclic loading at 0.6% extension range is included as shown in figure 4, the fit is within 8% of the rope data at similar strain range. From this we can deduce that both textile yarn and rope undergo similar modulus changes in cyclic loading.

EXAMINATION AND YARN STRENGTHS OF 12 and 48 MILLION FATIGUED TESTS

RESULTS and DISCUSSION

This examination was conducted on a 6t sub-rope that was fatigue tested to 48 million cycles at 20% mean and 20% load range based on the average ABS of 61.94kN. This is the same material and sub-rope as used for the modulus tests described above. To keep the subject in perspective, it should be noted that this test was very severe in that a steel wire rope would have failed at around 1 million cycles.

One strand failed in the eye at the tangent contact on the spool as shown in figure 5. No further examination of this eye was conducted since the damage was done, more could be learnt from examining the opposite end eye that was still intact as shown in figure 6. A single layer of Dyneema cloth was wrapped in a spiral direction around the eye. The Dyneema cloth had not worn through on the stainless steel spools. When the cloth was removed as shown in figure 7 the eye had severe abrasion damage around the contact on the spool with the maximum damage on the rope in the sliding zone at the tangent contact on the spool. The outside layer of yarn in the strand had virtually completely worn through. A close up photograph in figure 8 revealed abrasion failed filament ends. It can also be seen that there was negligible inter-strand abrasion in this same region. There was some rust deposit on the strand and it was suggested this may have accelerated the abrasion. However, the absence of inter-strand abrasion proves this theory not to be possible.

A high D/d ratio of 5/1 had been used for the spool and this had resulted in a high axial induced rope strain creating a sliding motion on/off the spool. The single layer of Dyneema cloth would promote sliding at the interface between the sub-rope and the cloth. Since Dyneema has a better wear performance than polyester, the polyester had preferentially worn. As previously found (ref 10), two layers of Dyneema cloth would prevent such damage since the coefficient of friction Dyneema on Dyneema is lower than Dyneema on polyester. Thus, the sliding interface would be between the cloth where any abrasion, if it ever occurs, would not be sacrificial since this is non axial load bearing component.

It is clear that the combined effect the single cloth layer and the high D/d ratio had caused the abrasion damage.

There was significant inter-strand abrasion along the entire midspan length between splices. A typical region is shown in figure 9 where the lay has been opened to reveal the strand contact. A close up photograph of the abrasion damage is shown in figure 10 where the broken ends of the filaments are a few millimetre long. Before these broke and protruded out of the rope, they would have been under the strand-on-strand contact region where the pressure is highest. Also, the slip motion between strands is highest at the line contact between strands where the abrasion damage occurs.

Strands were removed from three different regions of the test strop, the eye, splice and midspan. In each strand there are outer yarns and inner yarns which were separated. Twenty textile yarns were removed from each of the inner and outer layer yarns. The textile yarn strength measurements are summarised in table 1 for the three regions of the test strop. The midspan region outer textile yarn had strengths varying from 27% to 81% and an average 52% residual strength. The coefficient of variation is high at 31% and is indicative of severe damage. Along with the visual examination, this confirms the damage was due to inter-strand abrasion. The core yarn residual strengths vary from 86% to 103% with an average of 93%. The coefficient of variation is fairly low at 6% when compared to new virgin yarn at around 2-3%. Since a small loss will occur in removing and all the associated handling, it could be deduced that the core yarn has lost virtually no strength. Thus, is not surprising since creep rupture at 30% peak load would not have reduced strength and at 10% minimum load there should be no axial compression. The only other possible mechanism is internal wear and inner yarns are well protected from inter-strand abrasion.

The splice region shows much the same story, except that the core yarn is showing a significant strength reduction. This may be due to the higher contact pressures that exist within the splice region. Further investigation would be required to confirm the cause of strength loss.

Yarns were tested from the inner layer of the strand in the unfailed eye and found to be very low 16% residual strength. It is clear that this eye was close to failure.

A calculation of rope strength was conducted using the realisation method from yarn strength as shown in table 2 taking into account the different strengths of the yarns in the inner and outer layers. The midspan region and splice gave similar residual rope strength at 63% and 62% respectively. It is clear that the residual strength was fast approaching the peak cyclic tension of 30% of break load and the rope would not have lasted much longer.

A fatigue test (ref 3) conducted on a 5t polyester parallel strand rope to the same test loads as above was stopped after 12 million cycles. An examination of the rope revealed no inter-strand abrasion at all in either splices as shown in figure 11 or clear rope in figure 12. In table 3 the textile yarn average residual strength was very high at around 90%, although there was some early indication of fatigue damage with some yarns significantly down in strength to 57%. In contrast, a large number of yarns exceeded 100% and as high as 107%, so there is there is clearly no internal abrasion. This raises an important question, why the difference in internal abrasion compared to the 48 million cycle test? The 48 million cycle sub-rope had a significantly higher helix angle of around 13 degrees compared to the 12 million cycle sub-rope in the rope. It is believed that the higher inter-strand contact pressure and slip had caused the abrasion damage in the 48 million cycle test and was not due to the extra cycles. Certainly there will be a relationship between mean load, load range, helix angle and contact pressure and slip. These tests indicate that there is a cut off where no internal abrasion will occur with cycles providing the slip and pressure is sufficiently low.

CONCLUSIONS

A preliminary understanding of the modulus behaviour has been established between textile yarn and rope. This applies to a wide range of scale from rope sizes 6t to 250t break load.

In a loading to break test after fatigue testing, modulus compares closely between yarn and rope up to around 6% extension. From around 6% extension up to break there is a downward shift in the second peak for the rope that had far less fatigue cycles which may be due to fatigue damage at peak loads of 55%. Further work would be required to establish the reason for this effect and an understanding of this fatigue mechanism.

Modulus under cyclic loading for rope does not compare with modulus under break test for textile yarn. This is due to changes that in modulus between loading to break and cyclic conditions that occur in both yarn and rope. When similar cyclic conditions for textile yarn and rope are compared the modulus is in good agreement.

A single layer of cloth in the eye is inadequate to protect the rope from abrasion against a spool fitting. Two layers of low friction cloth are required in eye. For the spliced eye spool fitting D/d ratio should be not be too high otherwise excessive slip and abrasion will occur.

In the 48 million cycle fatigue test, inter-strand abrasion was significant on the outer layer yarn in the strand. This affected the complete rope length including splices. There was no evidence of axial compression, internal wear or creep rupture damage on the inner yarns that had lost virtually no strength. The rope residual strength was around 62% and failure was imminent in this fatigue test.

In the 12 million cycle fatigue test, there was no internal abrasion since the sub-ropes in this rope have significantly lower helix angle. Rope lay angle is a very important parameter for reducing effects of internal wear in long term fatigue applications like deepwater mooring of permanent production facilities.

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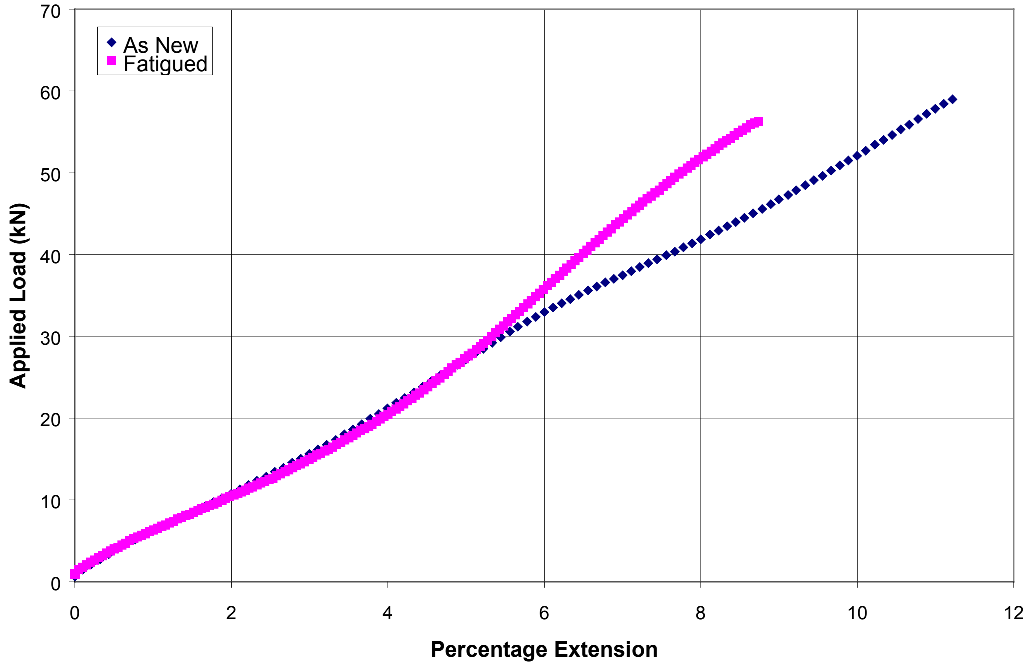

Figure 1. 6t sub-rope load/extension curves to break for new rope (after 10 conditioning cycles) and after fatigue testing

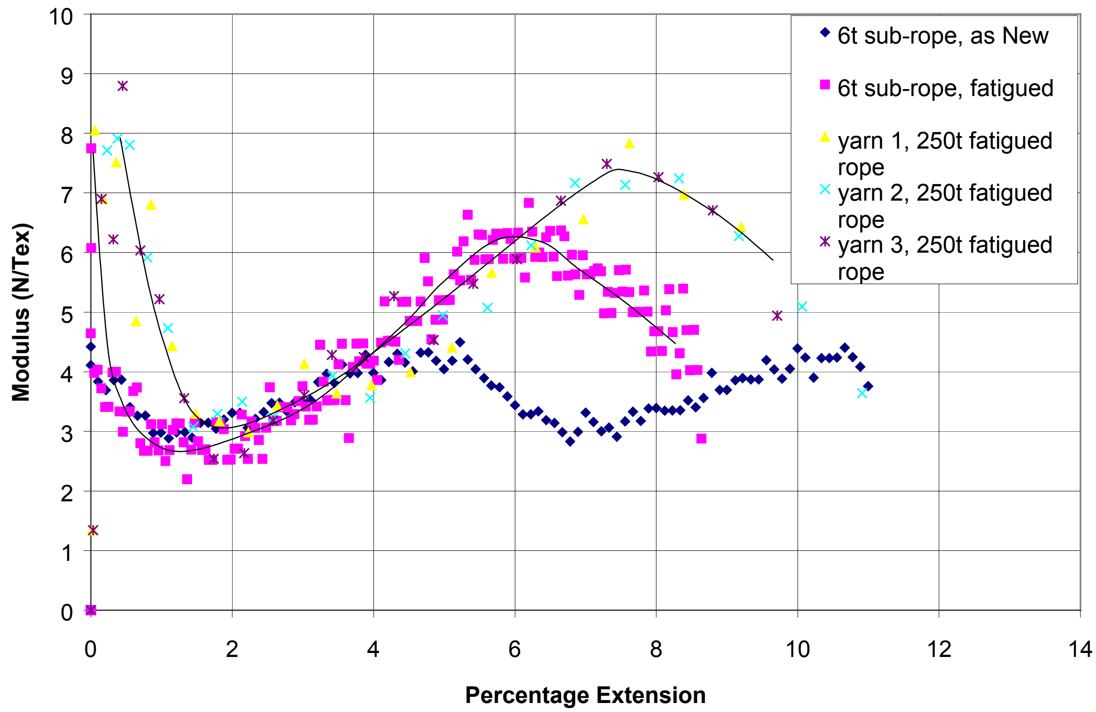

Figure 2. As figure 1, but including textile yarn removed from fatigued rope

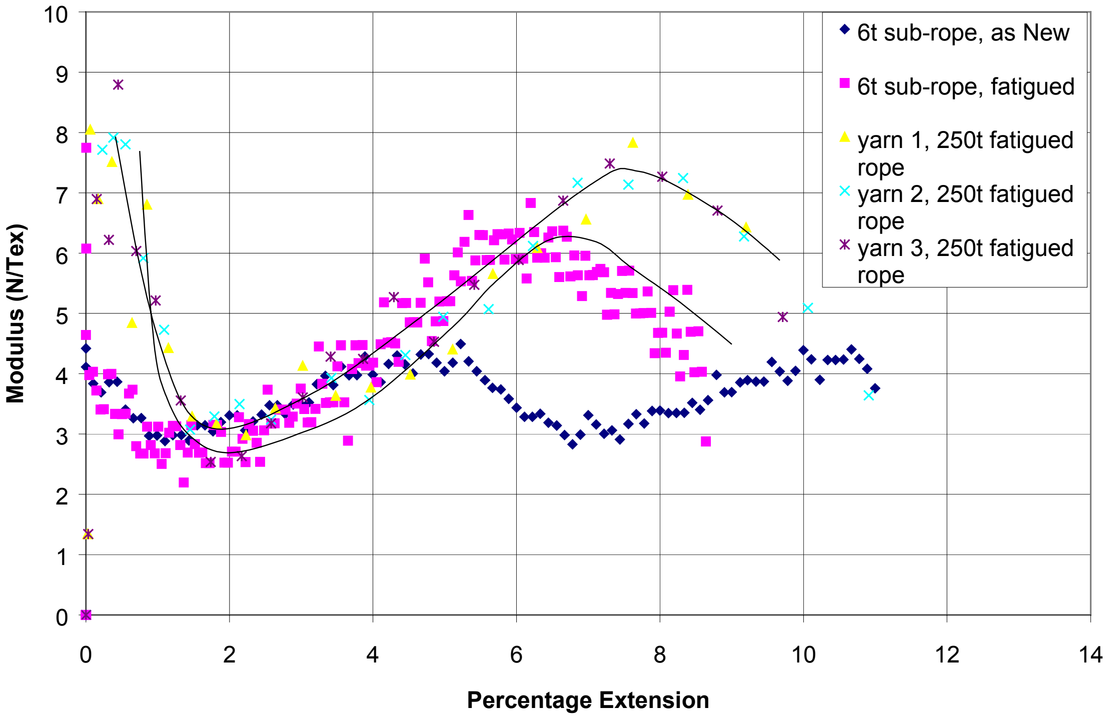

Figure 3. As figure 2, but rope curve offset on extension axis

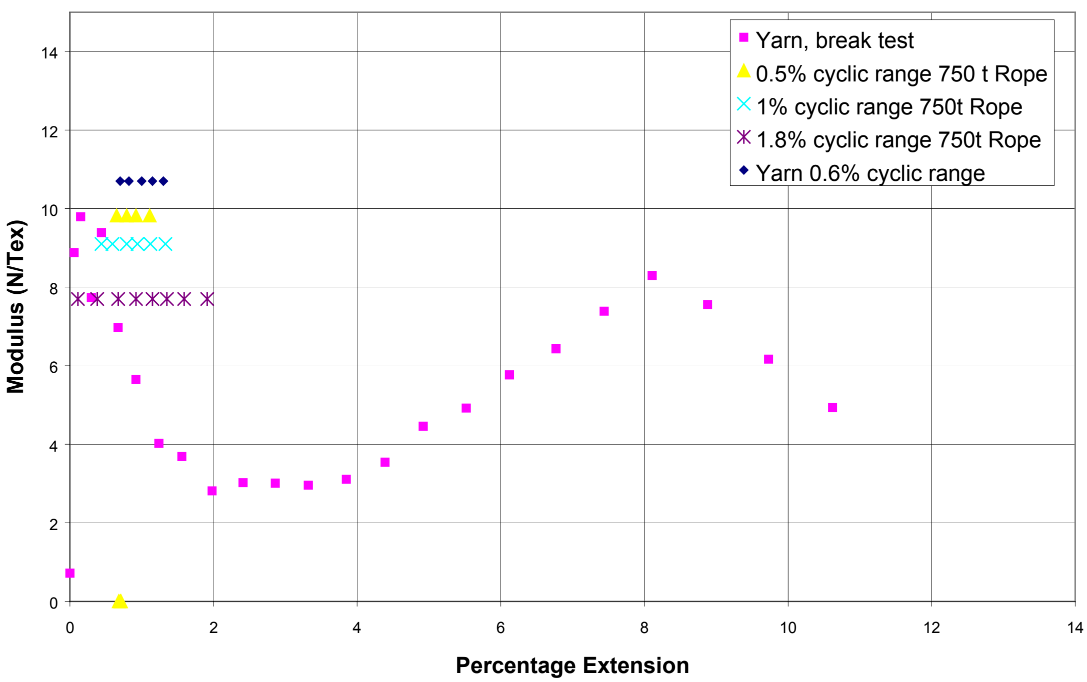

Figure 4. 750t rope modulus in cyclic loading compared to textile yarn modulus in break test and cyclic loading

Figure 5. One strand failed at the tangent contact of the eye on the spool

Figure 6. Intact eye with single layer of Dyneema cloth wrapped in a spiral direction around the eye. The Dyneema cloth had not worn through on the stainless steel spools.

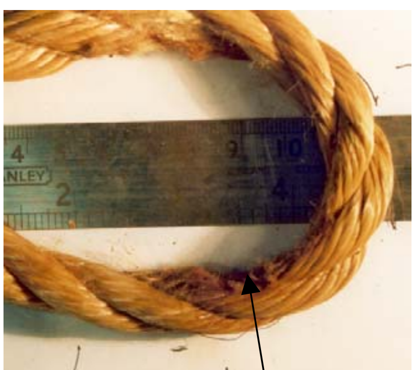

Figure 7. When the cloth was removed as shown in figure 6, the eye had severe abrasion damage around the contact on the spool with the maximum damage on the rope in the sliding zone at the tangent contact on the spool. The outside layer of yarn in the strand had virtually completely worn through.

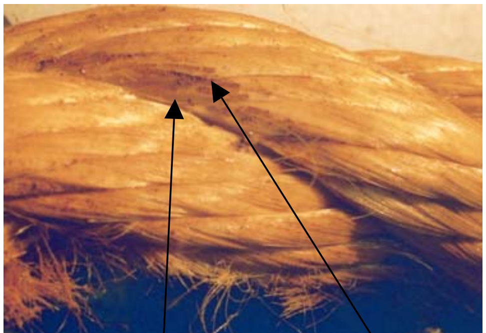

Figure 8. A close up photograph of figure 7 revealed abrasion failed filament ends. It can also be seen that there was negligible inter-strand abrasion inter-strand at this same region. There was some rust deposit on the strand and it was suggested this may have accelerated the abrasion. However, the absence of inter-strand abrasion proves this theory not to be possible.

Figure 9. There was significant inter-strand abrasion along the entire midspan length between splices. A typical region is shown where the lay has been opened to reveal the strand contact.

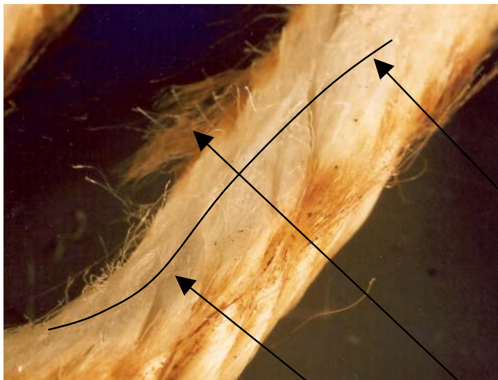

Figure 10. A close up photograph of the abrasion damage shown in figure 9 where the broken ends of the filaments are a few mm long. Before these broke and protruded out of the rope, they would have been under the strand-on-strand contact region where the pressure is highest (the slightly darker region). Also, the slip motion between strands is highest at the line contact between strands where the abrasion damage occurs

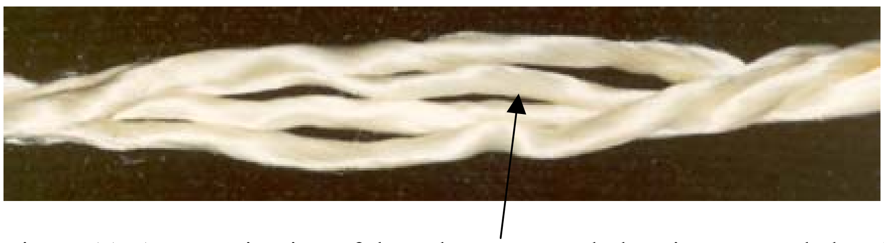

Figure 11. An examination of the sub-rope revealed no inter-strand abrasion at all in the clear rope

Figure 12. An examination of the sub-rope splice revealed no inter-strand abrasion at all in the clear rope

POSITION	MIDSPAN OUTER	MIDSPAN CORE	SPLICE OUTER	SPLICE CORE	EYE INNER
	%	%	%	%	%
NUMBER	RESIDUAL	RESIDUAL	RESIDUAL	RESIDUAL	RESIDUAL
1	75	98	52	84	61
2	27	88	56	90	45
3	68	94	50	92	46
4	54	86	44	93	54
5	48	86	40	96	53
6	66	88	64	85	69
7	43	103	52	47	40
8	57	91	52	84	66
9	55	93	47	82	52
10	35	91	86	88	46
11	34	88	62	87	73
12	73	92	63	69	75
13	81	91	42	84	59
14	60	99	40	76	78
15	35	102	50	83	76
16	46	98	47	81	56
17	63	101	44	92	47
18	49	94	78	86	75
19	31	90	44	75	69
20	31	89	72	86	88
MEAN	52	93	54	83	61
STD. DEV	16	5	13	10	13
CV %	31	6	23	12	22

Table 1. Textile yarn test results from 48 million cycled 6t sub-rope

REGION	MIDSPAN	SPLICE	EYE
NUMBER OUTSIDE YARNS	11	11	11
OUTSIDE YARN AVE STRENGTH kgs	8.4	8.8	0
AGGREGATE YARN STRENGTH kgs	2772	2904	0
NUMBER INSIDE YARNS	4	4	4
CENTRE YARN AVE STRENGTH kgs	15.2	13.5	10.0
AGGREGATE YARN STRENGTH kgs	1824	1620	1200
AGGREGATE YARN STRENGTH IN ROPE	4596	4524	1200
CALCULATED ROPE STRENGTH kgs	3956	3894	1033
% RESIDUAL ROPE STRENGTH	63	62	16

Table 2. Calculated rope strength by yarn realisation for the 48 million cycled 6t sub-rope

	'S' TWIST STRAND	'S' TWIST STRAND
	('Z' TWIST YARN)	('Z' TWIST YARN)
NUMBER	% RESIDUAL STRENGTH	% RESIDUAL STRENGTH
1	84	101
2	80	105
3	106	102
4	101	103
5	100	89
6	105	103
7	107	103
8	104	105
9	99	96
10	57	95
11	90	85
12	76	94
13	74	91
14	78	85
15	77	87
16	83	89
17	102	73
18	106	70
19	70	80
20	102	79
MEAN	90	92
STD. DEV	15	11
C. OF V. %	17	12

Table 3. Textile yarn residual strength from 5t parallel strand sub-rope after 12 million cycle fatigue test