Fatigue Curves for Polyester Moorings - A State-of-the-Art Review

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Abstract

The gathering momentum for the use of polyester ropes for long term production system moorings in deep water has instigated a thorough review of their fatigue performance. The traditional view of designers has been to use spiral strand steel wire rope T-N curves to assess the fatigue performance of polyester ropes on the basis that available evidence indicates that the latter's fatigue performance is superior to spiral strand wire rope. The authors have examined all the available fatigue testing data and the proposals for polyester specific T-N curves and have identified a number of issues pertinent to the derivation of fatigue design data for fibre ropes and propose an improved design curve.

This paper systematically identifies the various issues and proposes a rational way of including the available data (including runouts) for the development of a T-N curve for polyester ropes. The new data was used to re-visit the fatigue life and reliability for an example West of Shetland FPSO moored using polyester ropes (Ref.1).

Introduction

Synthetic fibre ropes have undergone a rapid testing and development phase over the last five years through a number of Joint Industry Projects (Ref. 2,3,4 and 5) and other studies. Ref. 2 is a recently launched JIP which utilises the latest materials with marine finish, terminations and rope designs.

Due to their good behaviour in fatigue, testing fibre ropes to quantify their fatigue life can be an expensive process and individual tests at loads representative of FPS conditions are predicted to run for man-years even when accelerated several fold. Thus, most fatigue testing has been conducted at high load levels and accelerated rates to produce data within reasonable time and budget.

This paper will review the data to show the true potential of polyester fatigue life and to provide a realistic design T-N curve.

Terminated Rope Breaking Strength

Rope strength is defined as Minimum Breaking Strength (MBS) with terminations and is guaranteed by the manufacturer. The average measured breaking strength will typically be 10% higher based on the most recent technology.

As shown in Table 1, a material, rope and termination review of the public domain data shows considerable scatter in the margin of ABS (Actual Breaking Strength) over MBS between –7% to +36%. This illustrates that care needs to be taken in analysis of data when selecting the basis of rope strength and that a common basis for strength can reveal new information. The column titled theoretical ABS is calculated from the yarn content to give the theoretical strength of the rope to allow for terminations, variability (manufacture of rope, not terminations) and obliquity (effect of the lay angle). This gives a strength expected using a well made, designed and terminated rope with a high quality fibre. This now gives a margin well within 10% for the spliced ropes, with the exception of number 5 for which the terminations may not be reflecting the true potential of the rope. All the resin socket and barrel and spike terminations are giving strengths well below the true potential of the rope.

The variability in these terminated rope strengths affects fatigue life as discussed in the next section.

Fatigue Life

The fatigue data points are shown in Table 2.

Data points 1, 2, and 3 from Ref. 6 are from well-designed ropes and terminations and tested fully immersed (except for 1 which was tested at such a low frequency, hysteresis heating effects were negligible). However, it should be noted that even these data points are from older technology from the mid 1980's and further improvement in materials and terminations have been made. Theoretical break strength matches well with measured ABS. Thus fatigue loads are realistic relative to both rope and termination and to fibre stresses expected in FPS applications. Data point 4 is of similar pedigree to 1, 2 and 3. Data point 5 is similar, but the higher 15% margin of strength indicates that the termination could be improved or the ropemaker has been conservative in the design by increasing fibre content.

Data point 6 was from the same rope used in Ref. 8, but the termination was designed and made by TTI. Computer modeling was used to design the splice to ensure optimum stress transfer from tucked to rope strands. Tapering down to filament diameter (approx. 20 microns) in the critical end of splice area was conducted to avoid any stress concentrations. Tension was applied at all stages of splicing to ensure consistent length between components. Such methods can be realistically applied at full scale and are easier since the components are considerably larger compared to a small 50kN rope. Also, the scaling effect will permit larger component diameter for the final stages of tapering whilst maintaining the same contact pressure. Theoretical and actual strength compare very well. Visual examination of the rope and terminations showed no sign of internal abrasion and residual strength tests on the textile yarns showed 90% retained strength compared to control yarn removed from the new rope.

Data points 7 through 38 were all tested in the Tethers 2000 JIP in the early 1990s (Ref. 5). The rated MBS for the ropes was calculated on a constant stress basis to ensure that terminations, materials and rope constructions could be compared. Although that is a correct methodology for a comparative study it is not relevant for the establishment of a design T-N curve for deepwater mooring where data from all available experiments from many different sources must be put on a common footing before being taken into account.

Data points 10, 11, 16, 20, 24, 25, 26, 27 and 30 that gave termination failures had resin socket and barrel and spike terminations that gave low strength compared to theoretical. Examining data point 11 in more detail from Table 2 reveals that at 65% of measured ABS the cycles to failure was 156,980 which is unrealistically high. In comparison data point 41 gave 200 cycles for a similar percentage load level which is in the expected region. It becomes clear that the low static strength has affected the fatigue results and that these points should be rejected since they underestimate fatigue life as termination design and fitting procedures have changed considerably. For example, current resin socket designs use different cone angles. Furthermore, no tensioning of strands was conducted during resin socketing. It should be noted that recent resin socket designs have been improved and further testing has been conducted as discussed in Ref. 9 and 10.

Data points 32, 35, 36, 37 and 38 were tested with a water spray mechanism that did not provide sufficient cooling to prevent hysteresis heating. All these points should be excluded from analysis.

From Ref. 11, data points 39 to 47 use the latest fibre, rope and termination and were tested fully immersed. Only data point 39 should be excluded since it failed on the tangent contact of the spool in the eye. Although this point was not included in the analysis, it should be noted that this is the highest number of cycles that a fibre rope has been tested and at a high load range.

In summary, from the tests taken to failure, data points 10, 11, 16, 20, 24 to 31 and 35 to 39 can be rejected because of the shortcomings discussed above. This leaves data points 2, 3, 15, 17, 18, 19 and 40 to 47, which can be selected for analysis as they are of good quality and known to have been tested immersed, gave clear failures and had terminations relevant to best practice. All the run-outs (except 32 which was not tested fully immersed) have been selected for analysis by the maximum likelihood method as discussed in the next section. Regression analysis based on the theoretical ABS gives the true potential fatigue life of well designed and terminated ropes.

However, in practice there may be range of termination efficiencies and the engineer should use the regression curve against measured ABS. It must however, be noted that the measured ABS will not be available at the design stage and some specified break strength or catalogue break strength or MBS will have to be used in design calculations. Reference to Table 1 shows that when ropes are properly designed, the use of MBS will indeed provide a further conservatism in the calculated fatigue life.

Regression Analysis

Although they offer additional information on the fatigue behaviour of the rope, the run-out tests have usually been omitted in the regression analysis used to derive the T-N curves. In order to take advantage of the valuable information implicit in the runouts, the maximum likelihood method (Ref. 12) has been used in the regression analysis. A clear description of the method may be found in Ref. 12 or Ref. 13.

In general, given a mix of failure and non-failure experiments, the method of maximum likelihood can be used to fit a probability distribution to the experimental outcome. Assuming that the outcome of the experiment is measured by the random variable x, the likelihood function (L) can be written as:

$$L = \prod_i f_X(x) . \prod_j \left[1 - F_X(x)\right]$$

where f is the probability density function of x, F is the cumulative density function of x, i is an index denoting failure tests, and j is an index denoting non-failure tests.

The procedure used to derive the slope and intercept of the T-N curve using the maximum likelihood method was taken from Ref. 13. The regression was performed for 8 different cases assuming that tension range is the independent variable. These 8 regressions were performed in order to evaluate all possible combinations (2^3) of the effects of the data selection, the use of the run-outs and the choice of the ABS (calculated or measured) in the T-N curve derived.

The resulting design T-N curves (mean - 2 x standard deviation, σ) are presented in Figure 1 along with the design curves for chain (Ref. 14 and 15), six-strand wire rope (Ref. 14), spiral strand wire rope (Ref. 14) and previous derivations for polyester (Ref. 16 and 17). The T-N curve definition used in this paper is the following:

$$\mathrm{Log}_{10}(N) = -M.\mathrm{Log}_{10}(R) + k$$

where N is the number of cycles to failure, R is the ratio of tension range to measured or calculated ABS as noted and k is the ***design*** T-N curve intercept (i.e. mean - 2σ) . The calculated values of M, k and σ are presented in Table 3 for all combinations studied.

Fatigue Analysis and Reliability

The calculated T-N curves were used to re-visit fatigue life and reliability for a West of Shetland FPSO moored in 1000m of water using polyester ropes (Ref. 1). The mooring system used was a combination of 1500 tonnes break strength polyester rope and 1870 tonnes break strength chain. The results for all the T-N curves given in Table 3 are presented in Table 4.

The first and most important conclusion of the analysis is that whichever polyester T-N curve is used in the fatigue and reliability model, the fatigue life and probability of failure after 20 years of exposure are at least 3 orders of magnitude greater than the chain in the same model. The model was also run for equivalent spiral strand and six-strand wire ropes, and the results confirm the conclusion of the Engineers' Design Guide (Ref. 16) that it is conservative to use the spiral strand wire rope T-N curve to evaluate the fatigue life of polyester ropes.

The results also show that the selection of the data, mainly the exclusion of the non-best practice termination failures, improves the expected life of the rope significantly.

As expected, the inclusion of the run-outs in the regression analysis increases the scatter of the curve, which has a negative effect on the reliability results. However, the mean T-N curve including the run-outs is above the one calculated excluding the run-outs. This has a positive effect on the fatigue reliability results. In Table 4, it can be noticed that the inclusion of the run-outs improves the fatigue life for curves number 3/4, 5/6 and 7/8 but decreases the expected life for curves 9/10. This is due to the fact that the increase in standard deviation (σ) which is quite considerable, dominates over the increased mean ($k+2\sigma$) of the T-N curve.

Conclusions

A systematic review of all available fatigue test data for polyester ropes has been performed. This review critically examined the suitability of these data for inclusion in T-N curve derivation. Such a critical review highlighted compelling reasons for neglecting a number of fatigue test data which had previously been included in other analyses of data. The primary reason for neglecting the data was the recognition that some of the termination failures which occurred would not have occurred if current best practice had been applied as would be the case for the design of actual ropes. Some other points were neglected because of lack of sufficient attention having been paid to mitigating the effects of hysteresis heating by immersion in water during the tests.

Although a number of previously used test data were neglected, maximum likelihood method has been used to properly include the information gathered from runouts which have previously not been taken into account except in Ref. 12. Furthermore, recent results (Ref. 11) have been added to the body of useable experimental data thus providing a total set of 29 data points. This is the most comprehensive and carefully filtered set of data used in any analysis of fatigue behaviour of polyester ropes to date.

The resulting T-N design curve for use in design analysis of polyester mooring systems is as follows:

$$\mathrm{Log}_{10}(\mathrm{N}) = -13.46.\mathrm{Log}_{10}(\mathrm{R}) - 0.587$$

$$\sigma = 1.177$$

This curve corresponds to the regression analysis in which the data have been selected, the run-outs have been included and the stress range is calculated using the measured ABS. (polyester case 10 in Table 3). The proposed design curve is plotted in Figure 1.

It was concluded in Ref. 1 that the fatigue performance of a polyester mooring system is governed by the chain segments of the chain-polyester-chain line rather than by the polyester segment. This conclusion is further reinforced by the findings of this paper which shows consistently better performance by the polyester segment (against chain), regardless of whether all data available from polyester fatigue testing is used indiscriminately or as is recommended, the relevant data points are used in T-N curve derivation.

It has also been demonstrated that the fatigue behaviour of polyester rope is better than that of spiral strand wire rope and again, this conclusion is valid regardless of whether selected or all data are used in T-N curve derivation.

It must be remembered that the nondimensionalising parameter for stress range used is ABS. A designer is rarely in possession of the ABS and is generally working with MBS. The ratio of ABS/MBS is around 1.1 and thus the use of MBS in the design stage to nondimensionalise the stress range will result in a conservative calculated fatigue life by a significant margin.

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Legend l	Ref.. No.	Construction Generic Construction	Construction Termination Type	Rated MBS (kN)	Measured Mean ABS (kN)	Margin ABS/MBS %	Theoretical ABS KN	Margin Calc/ABS %
1	6	PSC	SPL	980.0	1156.5	18.0	1108	-4.2
2	6	PSC	SPL	980.0	1156.5	18.0	1108	-4.2
3	6	PSC	SPL	980.0	1156.5	18.0	1108	-4.2
4	7	PSC	SPL	53.6	57.2	6.7	62	8.4
5	7	PSC	SPL	53.6	58.7	9.5	67.8	15.4
6	8	PSC	SPL	50.0	66.6	33.3	66.1	-0.8
7	5	PSC	RS	49.0	45.6	-7.1	66.1	45.0
8	5	PSC	RS	49.0	45.6	-7.1	66.1	45.0
9	5	PSC	RS	49.0	45.6	-7.1	66.1	45.0
10	5	PSC	RS	49.0	45.6	-7.1	66.1	45.0
11	5	PSC	RS	49.0	45.6	-7.1	66.1	45.0
12	5	PYC	RS	49.2	46.6	-5.2	67.3	44.3
13	5	PYC	BS	49.2	53.6	9.1	67.3	25.4
14	5	PYC	RS	49.2	46.6	-5.2	67.3	44.3
15	5	PYC	BS	49.2	53.6	9.1	67.3	25.4
16	5	PYC	RS	49.2	46.6	-5.2	67.3	44.3
17	5	PYC	BS	49.2	53.6	9.1	67.3	25.4
18	5	PYC	RS	49.2	46.6	-5.2	67.3	44.3
19	5	PYC	BS	49.2	53.6	9.1	67.3	25.4
20	5	PYC	BS	49.2	53.6	9.1	67.3	25.4
21	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
22	5	WRC	SPL	49.1	66.6	35.8	67.1	0.7
23	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
24	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
25	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
26	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
27	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
28	5	WRC	SPL	49.1	66.6	35.8	67.1	0.7
29	5	WRC	SPL	49.1	66.6	35.8	67.1	0.7
30	5	WRC	RS	49.1	47.6	-3.1	67.1	41.1
31	5	WRC	SPL	49.1	66.6	35.8	67.1	0.7
32	5	WRC	SPL	1177.0	1528.0	29.8	1560.9	2.2
33	5	WRC	SPL	49.1	63.9	30.3	67.1	5.0
34	5	WRC	SPL	49.1	63.9	30.3	67.1	5.0
35	5	WRC	SPL	1177.0	1528.0	29.8	1560.9	2.2
36	5	WRC	SPL	1177.0	1528.0	29.8	1560.9	2.2
37	5	WRC	SPL	1177.0	1528.0	29.8	1560.9	2.2
38	5	WRC	SPL	1177.0	1528.0	29.8	1560.9	2.2
39-47	11	PSC	SPL	58.9	61.94	5.2	83.2	7.5

Table 1. Terminated polyester rope strengths

Key: PSC: Parallel Strand Construction; PYC: Parallel Yarn Construction; WRC: Wire Rope Construction
SPL: Splice Termination; RS: Resin Socket; BS: Barrel and Spike

Legend	Ref.. No.	Cyclic Period Seconds	Load Range %MBS	Measured Load Range %ABS	Calc. Load Range %ABS	Testing Condition	Cycles To Failure	Failure Location	Run-out (cycles)
1	***6***	***5.0***	***29.5%***	***25.0%***	***26.1%***	***PREWETTED***			***2000000***
2	**6**	**10.5**	**82.6%**	**70.0%**	**73.1%**	**IMMERSED**	**914**	**unknown**	
3	**6**	**10.5**	**59.0%**	**50.0%**	**52.2%**	**IMMERSED**	**61376**	**unknown**	
4	***7***		***21.3%***	***20.0%***	***18.5%***	***IMMERSED***			***1000000***
5	***7***		***21.9%***	***20.0%***	***17.3%***	***IMMERSED***			***1000000***
6	***8***		***30.0%***	***22.5%***	***22.7%***	***IMMERSED***			***12000000***
7	***5***	***0.5***	***60.0%***	***64.6%***	***44.5%***	***IMMERSED***			***1000000***
8	***5***	***0.5***	***55.0%***	***59.2%***	***40.8%***	***IMMERSED***			***1000000***
9	***5***	***0.5***	***50.0%***	***53.8%***	***37.1%***	***IMMERSED***			***1000000***
10	5	0.5	70.0%	75.3%	51.9%	IMMERSED	290	termination	
11	5	0.5	60.0%	64.6%	44.5%	IMMERSED	156980	termination	
12	***5***	***0.5***	***40.0%***	***42.2%***	***29.2%***	***IMMERSED***			***1000000***
13	***5***	***0.5***	***45.0%***	***41.3%***	***32.9%***	***IMMERSED***			***1000000***
14	***5***	***0.5***	***45.0%***	***47.5%***	***32.9%***	***IMMERSED***			***1000000***
15	**5**	**0.5**	**70.0%**	**64.2%**	**51.2%**	**IMMERSED**	**30270**	**middle**	
16	5	0.5	60.0%	63.3%	43.9%	IMMERSED	65340	termination	
17	**5**	**0.5**	**60.0%**	**55.0%**	**43.9%**	**IMMERSED**	**185890**	**middle**	
18	**5**	**0.5**	**50.0%**	**52.8%**	**36.5%**	**IMMERSED**	**208910**	**middle**	
19	**5**	**0.5**	**55.0%**	**50.4%**	**40.2%**	**IMMERSED**	**389580**		
20	5	0.5	50.0%	45.8%	36.5%	IMMERSED	708010	termination	
21	***5***	***0.5***	***45.0%***	***46.4%***	***32.9%***	***IMMERSED***			***1000000***
22	***5***	***0.5***	***40.0%***	***29.5%***	***29.2%***	***IMMERSED***			***1000000***
23	***5***	***0.5***	***40.0%***	***41.3%***	***29.2%***	***IMMERSED***			***1441190***
24	5	0.5	55.0%	56.7%	40.2%	IMMERSED	390	termination	
25	5	0.5	70.0%	72.2%	51.2%	IMMERSED	550	termination	
26	5	0.5	60.0%	61.9%	43.9%	IMMERSED	680	termination	
27	5	0.5	50.0%	51.6%	36.6%	IMMERSED	770	termination	
28	5	0.5	70.0%	51.5%	51.2%	IMMERSED	2180	end of splice	
29	5	0.5	50.0%	36.8%	36.6%	IMMERSED	12350	end of splice	
30	5	0.5	50.0%	51.6%	36.6%	IMMERSED	37550	termination	
31	5	0.5	45.0%	33.1%	32.9%	IMMERSED	75880	end of splice	
32	5		20.0%	15.4%	15.1%	SPRAY			940000
33	***5***	***0.5***	***50.0%***	***38.4%***	***36.6%***	***IMMERSED***			***1000000***
34	***5***	***0.5***	***55.0%***	***42.2%***	***40.2%***	***IMMERSED***			***1000000***
35	5	6.7	70.0%	53.9%	52.8%	SPRAY	780	middle	
36	5	10	60.0%	46.2%	45.2%	SPRAY	15920	back of eye	
37	5	3.3	50.0%	38.5%	37.7%	SPRAY	49640	back of eye	
38	5	6.7	50.0%	38.5%	37.7%	SPRAY	138300	back of eye	
39	9	0.33	21	20	18.6%	IMMERSED	47699530	tangent eye	
40	***11***	***0.25***	***21***	***20***	***18.6%***	***IMMERSED***			***14819730***
41	**11**	**0.67**	**74**	**70**	**65.1%**	**IMMERSED**	**200**	**middle**	
42	**11**	**0.67**	**63**	**60**	**55.8%**	**IMMERSED**	**150**	**tail of splice**	
43	**11**	**1**	**53**	**50**	**46.5%**	**IMMERSED**	**844880**	**tail of splice**	
44	**11**	**0.5**	**42**	**40**	**37.2%**	**IMMERSED**	**1666680**	**tail of splice**	
45	**11**	**0.5**	**42**	**40**	**37.2%**	**IMMERSED**	**4159790**	**tail of splice**	
46	**11**	**0.5**	**37**	**35**	**32.6%**	**IMMERSED**	**4480730**	**tail of splice**	
47	**11**	**0.5**	**42**	**40**	**37.2%**	**IMMERSED**	**5215850**	**middle**	

Table 2. Fatigue data points (Selected points in **bold,** selected runouts in ***bold italics***)

Description					M	k	σ
Chain API – Ref. 14					3.36	2.568	
Chain JIP – Ref. 15					3.00	2.975	0.319
Six Strand – Ref. 14					4.09	2.364	
Spiral Strand – Ref. 14					5.05	2.220	
Polyester	1	API – Ref. 17			9.0	0.875	0.408
	2	EDG – Ref. 16			9.42	0.981	
	3	All Data	Calculated ABS	Without Runouts	9.76	-1.277	1.081
	4	All Data	Calculated ABS	With Runouts	12.33	-2.122	1.227
	5	All Data	Measured ABS	Without Runouts	8.76	-0.264	1.059
	6	All Data	Measured ABS	With Runouts	10.08	-0.742	1.390
	7	Selected Data	Calculated ABS	Without Runouts	13.34	-0.982	0.711
	8	Selected Data	Calculated ABS	With Runouts	14.54	-1.250	0.760
	9	Selected Data	Measured ABS	Without Runouts	14.42	-0.705	0.740
	10	Selected Data	Measured ABS	With Runouts	13.46	-0.587	1.177

$\text{Log}_{10}(N) = -M.\text{Log}_{10}R + k$ (k design as opposed to k mean)

Table 3. T-N Curves

Curves		Fatigue life (years)	Probability of failure @ 20 years
Chain API		53	N/A
Chain JIP		N/A	$1.96\ 10^{-1}$
Six Strand		258	N/A
Spiral Strand		2694	N/A
Polyester	1	938000	$< 10^{-15}$
	2	2570000	N/A
	3	26750	$1.52\ 10^{-4}$
	4	32340	$1.63\ 10^{-5}$
	5	40920	$4.13\ 10^{-5}$
	6	166100	$1.36\ 10^{-4}$
	7	21800000	$< 10^{-15}$
	8	70820000	$< 10^{-15}$
	9	209300000	$< 10^{-15}$
	10	65360000	$1.85\ 10^{-10}$

Table 4. Fatigue Life and Fatigue Reliability Results

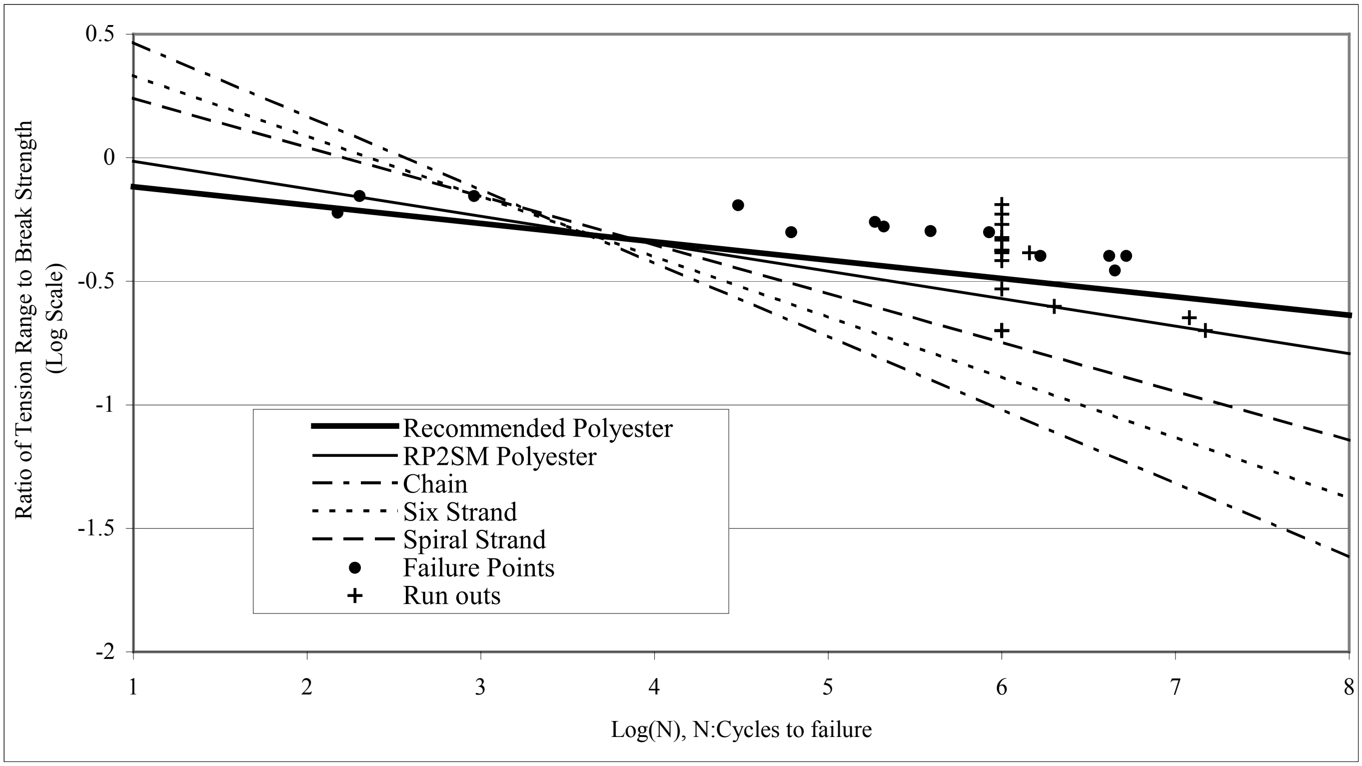

Figure 1. Polyester Rope Fatigue Data and Design Curve