Improving Bend-over-Sheave Fatigue in Fiber Ropes

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Abstract- **One of the limitations of synthetic fiber ropes in industrial uses has been the premature wear of these materials when subjected to continuous bend-over-sheave fatigue. While one-way passage over sheaves is not generally damaging, repeated back-and-forth movement over one part of the rope, as in heave compensation units, can lead to damaging heat buildup and unexpected failure modes. This report details the results of bend-over-sheave fatigue testing on 18 mm diameter fiber ropes conducted at Cortland Cable Company. Cycles-to-failure data is presented for the fiber materials, coatings, and constructions tested to date. Fatigue life was significantly improved by fiber blending and with specialty coatings, resulting in a new braided rope design specifically optimized for bending fatigue (BOB). The BOB design was found to have a significant CTF advantage over aramid constructions and steel wire currently in use today. The importance of test parameters such as sheave design and cycle rate is highlighted.**

INTRODUCTION

Many applications involving rope require the passage of the rope over sheaves of one kind or another. Synthetic fiber ropes are not particularly damaged by periodic one-way passage over these sheaves, however repeated or continuous back-and-forth cycling over one spot on the rope can create rapid heat build-up and unforeseen damage mechanisms. This test program was initiated as a way to generate a broad array of bending fatigue data on small-scale 18 mm (3/4”) synthetic ropes subjected to continuous bending over a 230 mm (9”) diameter sheave. The purpose of the test program was to develop a new braided rope design that could compete with aramid wirelay and steel wire rope in cyclic bending applications

BACKGROUND

The advantages of synthetic fiber ropes over wire ropes have been documented extensively, as in [1]. The light weight, absence of corrosion, and low stiffness drive the use of fiber ropes in place of wire rope in many applications in a variety of industries. Recently fiber ropes made from polyester (PET) and HMPE have begun to replace large-diameter wire ropes for mooring permanent and temporary platforms in the petroleum industry [2-3].

The fatigue life of fiber ropes under tension-tension loading has been the subject of much recent study, e.g. [4], and the fatigue performance has proven to be as much as an order of magnitude higher than that of steel wire rope. However, one application where wire ropes have continued to outperform synthetics is in cyclic bending fatigue over sheaves (CBOS). This is one of the most common applications of wire ropes, in familiar end-uses such as cranes, elevators, and pulling lines.

Historically fiber ropes were not able to displace wire rope in over-sheave applications, even if the CBOS fatigue life had been equivalent. Synthetics could not match the strength of wire so any replacement would require larger sheaves and other hardware. In addition, high bearing pressures and relative motions during bending caused fiber-to-fiber abrasion that was not apparent from looking at the exterior of the rope. While also true of wire rope (with the added complication of corrosion), inspection criteria in fiber ropes were not as well developed as in wire.

The first application of large synthetic fiber ropes to bend-over-sheave applications came after the development of aramid fibers (e.g. Kevlar®). These were the first high-performance synthetic fiber (HPF) ropes that could match the strength of steel, so that a size-for-size replacement could be made without increasing the size of winches and sheaves. Although the CBOS performance of aramid wirelay ropes did not quite meet the specifications of wire rope, the advantages of having the synthetic line (most notably safety, low weight, and corrosion resistance) drove the end-user away from wire rope. The result was the US Navy’s deep-sea salvage lifting lines, all-aramid fiber ropes in a helical wirelay jacketed construction.

This paper will discuss the development of a new HPF-based rope product specifically targeted at CBOS applications. This new technology is based on the use of fiber blends and specialty coatings. The development testing also revealed new insights into the effects of test and material parameters such as material type, design factor, sheave diameter, test speed, and rope size. CBOS tests have demonstrated that new products developed using this technology can meet or exceed the CBOS fatigue performance of wire ropes. Better fatigue life coupled with the inherent advantages of weight and environmental stability should continue to drive the replacement of wire ropes with synthetics in CBOS applications.

EXPERIMENTAL

Ropes were cycled over mild steel sheaves as shown in Fig. 1 so that a rope length of one-half a sheave circumference (in the center of the rope) was subjected to two bend cycles (straight-bent-straight-bent-straight) per machine cycle. This area of the rope is called the “double-bend-zone” or DBZ, and in this case was approximately

Fig. 1. CBOS Test Frame at Cortland Cable

400 mm in length. On either side of the DBZ was a roughly 360 mm length subjected to only one bend cycle (straight-bent-straight) per machine cycle – the "single bend zone" or SBZ.

Sheaves used in these tests had a sheave tread diameter of 230 mm (9.0") and a sheave groove diameter of 20 mm (0.79"), 5% greater than the nominal rope size. The test machine was cycled at a rate of 360 machine cycles per hour. Some experiments were conducted to quantify the effect of varying sheave tread diameter, sheave groove size, and cycle rate.

Rope surface temperatures were measured periodically during the testing by holding a thermal probe against the rope in the center of the DBZ with the machine stopped. Temperatures measured using this technique ranged from 35-45 ^{o}C during cycling.

All ropes were 12-strand single braid construction, designed to precisely meet an 18 mm (0.75") diameter specification. Actual breaking strengths of these ropes ranged from 31 to 38 metric tons. The following fiber materials, coatings, and constructions were tested during the testing:

Fibers:	HMPE (Dyneema® SK-75, Spectra® 1000, Plasma®), LCP (Vectran® HS 1500)
Coatings:	Polyurethanes PG, PN, PP, PB, PR
Designs:	12-strand (A) and braided variants B, C, D

DATA TREATMENT

In order to compare the results of testing at different conditions, a basic theoretical treatment of test parameters was sought. One normalizing equation comes from the wire rope industry, and is derived by making a simplistic assumption about the static bearing stresses on a sheave under load,

$$BearingStress \cong \frac{2T}{D \cdot d} \qquad (1)$$

In this case T is the tension in the rope, D is the sheave diameter, and d is the rope diameter.

By now dividing both sides by the ultimate strength of the material (U), we get the Drucker-Tachau bearing pressure ratio [5],

$$\beta \equiv \frac{2 \cdot T}{U \cdot (D \cdot d)} \qquad (2)$$

which has been used for many years to normalize wire rope CBOS test data. By dividing through top and bottom by d^2 we get

$$\beta \cong \frac{2\left(\frac{T}{d^2}\right)}{U \cdot \left(\frac{D}{d}\right)} \qquad (3)$$

On recognizing that T/d^2 should be linearly related to the stress in the rope material, and assuming that failure should occur when the stress exceeds U, then we can replace part of the equation (removing arbitrary constants) to get a "Normalized Sheave Pressure" or NSP, defined as

$$NSP \equiv \frac{\%MBL}{\left(\frac{D}{d}\right)} \qquad (4)$$

where %MBL is the load in the rope expressed as a percentage of its minimum rated breaking load. The inverse of the NSP has also been used by investigators to normalize CBOS data, e.g. the "Life Factor" used by Gibson[6].

Note that because of the inherent non-linearity in rope structures as well as other factors affecting breaking strength, the assumptions that lead to Eq. 4 are not strictly correct. However, the NSP should provide some predictive capability for a particular rope design (constant size, material, and construction) over a range of sheave diameters and stress ranges. This parameter can also provide quick comparisons between different materials and constructions.

In order to test the NSP as a normalizing parameter, two sets of experiments were conducted. In one set two ropes were subjected to CBOS fatigue loaded to a tension of 9% of the MBL at a D:d ratio of 24:1. In the second set the tension was 4.5% of the MBL at a D:d of 12:1. Both had NSP values of 0.38. Both experiments averaged around 40,000 cycles-to-failure, indicating that the NSP is a useful normalization tool for predicting performance over a range of loads and sheave diameters.

RESULTS

The effect of sheave groove radius was investigated at the request of a specific end user. The results showed a strong preference for a tightly fitting groove matched to the diameter of the rope, as shown in Fig. 2.

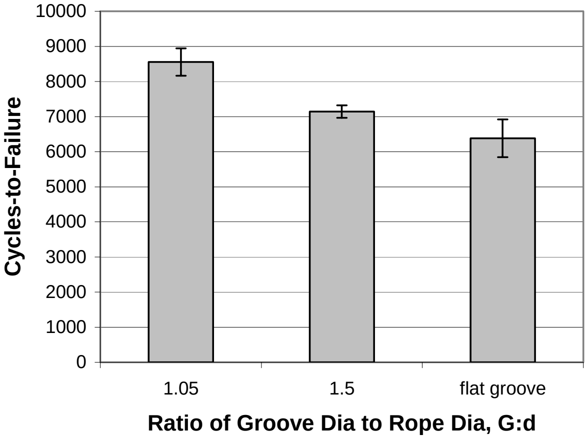

Fig. 2. Effect of Groove Diameter

Several minor constructional variations were also compared as part of the testing. The results are shown in Fig. 3. Some variants were found to significantly increase the life of the ropes.

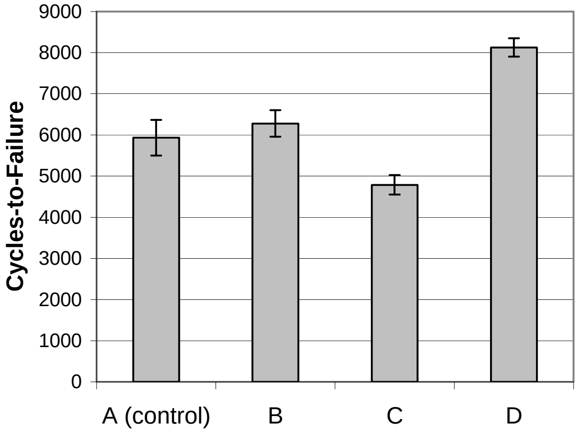

Fig. 3. Effect of Construction Variation

The next set of specimens demonstrated the strong effect of coating materials on CBOS fatigue life. Three out of the four advanced coatings tested enhanced the fatigue life substantially (see Fig. 4).

It was found that increasing the machine cycle rate beyond a certain point had a detrimental effect on HMPE fatigue life. At the highest rate tested (720 cph), the CTF rating dropped by nearly 50%, as shown in Fig. 5. Cycle rate should always be specified in testing of fiber ropes in bending fatigue.

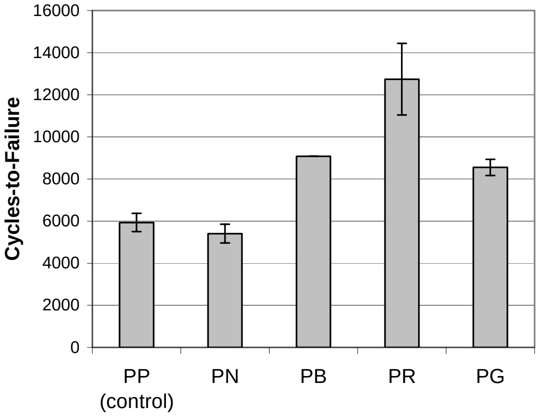

Fig. 4. Effect of Advanced Coatings

The data shown in Fig. 5 suggests that internal heating of HMPE fiber ropes may influence the mechanism of failure. Assuming that the rate-sensitive failure mode is evidence of a creep rupture phenomenon, then blending with a high-temperature low-creep fiber might extend the life of the rope by preventing creep rupture induced by cyclic heating. This was verified by testing. Fig. 6 shows that blending high-temperature (Vectran® LCP) and low-temperature (HMPE) fibers can have a significant synergistic effect on CTF results. LCP fiber was chosen over aramid in this study because of its demonstrated superior flex fatigue life [7].

As a result of the initial experiments detailed here as well as more extensive follow-on experiments, a rope design was developed which is optimized for CBOS service. This rope, a 12-strand braid optimized for bending fatigue (BOB), utilizes the best coatings, blend ratios, and constructional variants identified during these experiments. Figure 7 shows the BOB results along with other test results selected from the present study.

In order to compare BOB results to other fiber ropes used in CBOS applications, one aramid cable-lay rope were also tested in the program. Figure 7 shows the much better fatigue life of the BOB product compared with both aramid cable-lay and aramid wirelay [8] constructions.

Figure 7 also shows data from Lang Lay steel wire rope

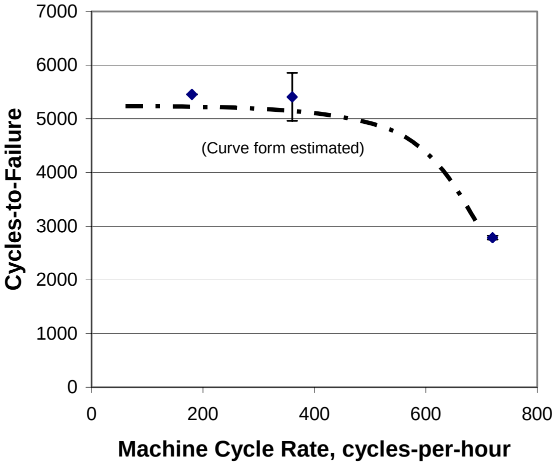

Fig. 5. Effect of Cycle Rate

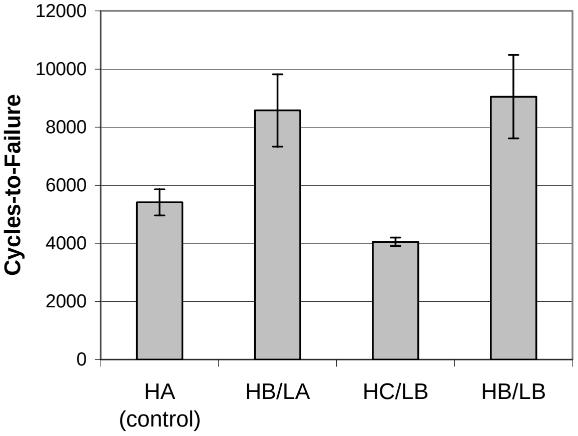

Fig. 6. Effect of Addition of LCP Fibers

in the same size range as tested here [9]. This data was obtained from other sources, and shows that specialty wire rope is still a benchmark for CBOS performance. It should be noted however, that specialty Lang Lay wire rope produces extremely high torque and is difficult to work with, and most end users utilize standard lay constructions. The performance of these regular lay wire ropes is far below that of Lang Lay, and consequently far below that of the BOB construction.

As with wire ropes and other materials, an NSP value of 0.2 or less is recommended where exceptionally long life is required for the design.

No pathological examinations or analysis of damage mechanisms were performed in this phase of the study.

Note that the testing utilized during this test program is worst case, continuous cycling at constant amplitude over one spot on the rope structure. Most real world applications will have a stochastic variation of load and amplitude over a much larger area of affected rope surface. Thus the actual CTF in service will likely be orders of magnitude higher than shown here. Worst-case testing can serve as a useful comparison of the relative stability and robustness of fiber ropes constructions to fatigue damage.

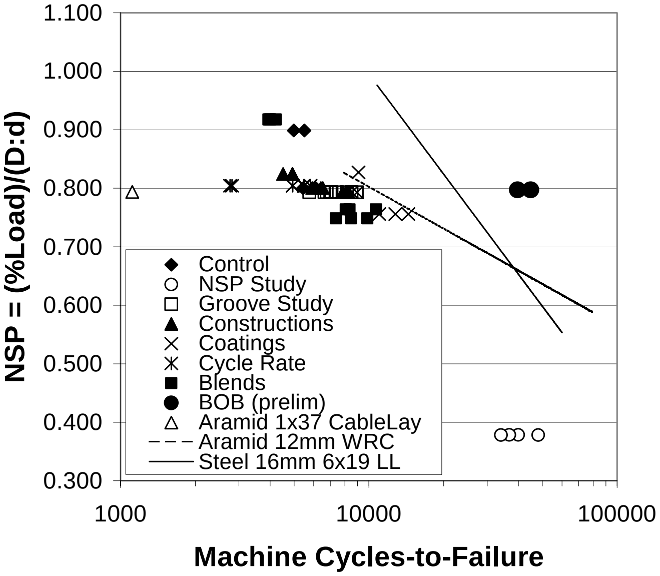

Figure 7. Summary of Bend-over-Sheave Data

CONCLUSIONS

This study demonstrated dramatic improvement (up to 5x) in cyclic bend-over-sheave (CBOS) fatigue life in fiber ropes based on the use of advanced fibers such as LCP and HMPE. The use of fiber blends and/or advanced coatings also helped to improve fatigue life. Further improvements are likely to be found with additional testing around the best candidates identified to-date. The following conclusions were reached during the study:

Performance in CBOS applications depends on a variety of factors, including but not limited to fiber type, design factors, sheave design, cyclic test speed, and rope size.

The normalized sheave pressure (NSP) parameter, obtained by dividing the %load by the D:d ratio, is useful in combining data from comparable rope materials and sizes when a reasonable range of sheave sizes and design loads are encountered.

Under design conditions typical of fiber rope systems, new rope designs can meet or exceed the CBOS fatigue life of Lang Lay wire rope.

Ropes optimized for CBOS service based on new fiber materials and constructions can significantly outperform older fiber rope designs based on aramid fibers in wirelay configurations.

Combining the best results of the experiments in this study has led to the development of a new rope design, specifically optimized for CBOS fatigue life. This rope design, Braid-Optimized-for-Bending or (BOB), is beginning to replace wire and aramid in a variety of applications.

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