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Slickline Fatigue Modeling and Tracking

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Abstract

This paper presents results of a joint industry project in which a slickline fatigue model and tracking system were developed. Two types of fatigue testing machines were developed, and a 3rd type is currently being developed. Results from testing with these machines, and the corresponding fatigue model are presented. The fatigue tracking system developed to use this model for monitoring reels of slickline in field operations is discussed.

Introduction

As the diameter of slickline (SL) increases, the amount of plastic fatigue which occurs when the SL is bent increases. This plastic fatigue phenomena is well known in the coiled tubing (CT) industry. CT fatigue modeling and tracking systems have produced significant cost savings and reductions in fatigue related failures since their introduction in the late 1980s. It is expected that use of a SL fatigue tracking system will have the following benefits:

- Extend life and therefore reduce cost of SL
- Improve safety – less likelihood of SL breaking at surface
- Reduce downtime and fishing operations resulting from SL failures
- Increase confidence in SL operations

A joint industry project was formed to develop the same type of modeling and tracking system common to CT, for SL. The following steps have been followed in this development process:

1. A SL fatigue test machine was developed that allowed tension to be applied to the SL while it was bent around sheave wheels.
2. Another, much simpler, SL fatigue test machine was developed which does not allow tension to be applied to the SL while it is being bent.
3. A plastic fatigue software model was developed which accurately reproduces the results from the two fatigue test machines.
4. A fatigue tracking system was developed to make this modeling capability usable for use in field operations
5. A commercial “briefcase” size version of the smaller SL fatigue test machine was developed for SL fatigue testing in the field.

6. A high tension version of the first SL test machine is currently being built, to determine the impact of high tension (near the breaking strength) events that sometimes happen in field operations on the fatigue life of the SL.
7. Field testing of the SL fatigue tracking system is currently being planned.
8. Additional types of SL will be tested and added to the system as required.

Slickline Fatigue Modeling

The maximum strain at the outer surface of the SL when it is bent is given by:

$$\varepsilon = \frac{d}{D} \tag{1.1}$$

Where:

ε	= strain (% strain)
d	= diameter of the SL (in)
D	= Bending diameter (in)

If the strain is set equal to the yield strain of the material:

$$\varepsilon_y = \frac{d}{D_y} = E\sigma_y \tag{1.2}$$

Where:

D_y	= Bending diameter at which yielding begins (in)
E	= Modulus of elasticity (psi)
σ_y	= Cyclic yield stress (psi)

Equation (1.2) can be solved for the bending diameter at which yielding begins:

$$D_y = \frac{dE}{\sigma_y} \tag{1.3}$$

The cyclic yield stress must be determined by fatigue testing, and will vary with the SL material. For one typical material σ_y = 140,000 psi. Assuming E = 30E6 psi and, the diameter at which yielding begins for typical SL diameters is given in Table 1.

d	**D_y**
in	*in*
0.092	19.7
0.108	23.1
0.125	26.8
0.140	30.0
0.160	34.3

Table 1 – Yield Bend Diameter for Various SL Diameters

Typical SL sheaves are 16” to 20” in diameter. Thus, in many applications, the SL material is being yielded with each bending cycle. This yielding significantly reduces the fatigue life.

A schematic for a typical well-site operation is shown in Figure 1. The “bending events” for a section of SL being run-in-hole (RIH) are numbered from 1 to 14. Of course these same bending events occur in reverse when the SL is being pulled-out-of-hole (POOH).

Assuming the drum and depth sheave diameters are 16”, the upper and lower sheave diameters are 20”, and the SL diameter is 0.125”, a strain diagram can be drawn for these bending events as is shown in Figure 2. All of the bending events are in the same direction (positive strain), except for bending event number 11, which occurs at the lower sheave. This type of bend is called a reverse bend or a “full reversal”. The fatigue damage done by a full reversal is significantly greater than the fatigue damage done from the other bending events. This difference is so great, that an argument can be made that only the full reversals need be considered in the fatigue modeling process. Since a full strain reversal happens at the lower sheave while RIH and again while POOH, a “trip”, in and out of a well produces two full strain reversals.

The fatigue modeling process involves summing the fatigue damage associated with each bending event, and using this damage summation to calculate the percentage of expected fatigue life used to this point. Empirical data from many fatigue tests is needed to develop these models. The theory used for this type of fatigue calculation has been well documented in CT fatigue references.

Slickline Fatigue Test Machines

Figure 3 contains a photo of the first SL fatigue test machine that was built. This machine uses 100 ft samples of SL, and requires about 6 hours to perform a test. The sample extends from one side of the storage drum, around the 3 sheaves, and back to the other side of the storage drum. Two sheave diameters are available, 16” and 19”, but only one 20” storage drum is available. An air piston pushes the center sheave towards the storage drum, causing tension in the SL. As the SL stretches, the piston extends. A sketch of this machine with its bending events is given in Figure 5, and the corresponding graph of the strain for each bending event is given in Figure 6. One full strain reversal (defined above) is produced at point 5, the center sheave, as the sample moves “forward” (from one side of the storage drum to the other side), and another full strain reversal when the sample moves backward.

Figure 4 contains a photo of the second SL fatigue test machine that was built. Figure 8 is the commercial version of the same machine. This machine holds a short sample of SL in a driven headstock on the right, and in a tailstock on the left, and performs a test in less than 30 minutes. The sample is held so that it has a constant radius of curvature. The SL sample is then rotated, and the number of revolutions to failure is counted. Each revolution performs one full strain reversal in the sample. The sample tends to get hot during the test. Some tests were run with the sample submerged in water to determine the impact of this heating on the test results.

Figure 7 contains a graph of the results of many tests on both machines for one particular type of SL, Bridon SUPA75, 0.125”. The number of full reversals to failure is shown versus the bending diameter. Note that for the case of the large test machine, the drum diameter is always constant at 20”. Only the sheave diameters change. The data for this large machine for various axial forces is shown with blue diamond data points. Interestingly, the variations in axial force did not cause a large difference in the fatigue results. As would be expected, there is significant scatter for the 19” sheave diameter case, and much less scatter for the 16” case. The data for the small rotating machine without cooling water are shown as red triangles, and the data with cooling water are shown as pink asterisks. The effect due to the cooling versus fatigue cycles to failure was minimal. More bending diameters were run with the small machine due to the ease of changing the bending diameter.

The solid lines in Figure 7 are the predicted failure lines from the fatigue model. The red line, for the small rotating machine, curves towards infinity as the bending diameter increases. The blue lines, for two different axial forces, show the model results for the large test machine. The bend at 20” is due to the unchanging drum diameter. For larger sheave bending diameters, the diameter of the drum becomes a larger factor in limiting the fatigue life.

Fatigue Tracking System

A SL fatigue tracking system was developed which reads data gathered by a data acquisition system on the SL unit for each job performed and calculates the remaining fatigue life. (Data acquisition systems are commercially available and are not part of this project). Figure 9 shows the main screen from this tracking system which lists all the jobs, cuts and re-spooling events that have happened with this SL. Figure 10 shows typical job data from a data acquisition system. Figure 11 shows the % Fatigue Life Used versus the SL length, the wraps on the drum, and the tension on the drum. This information makes it possible for informed decisions to be made about a particular SL such as:

- Should it be used for an upcoming job?
- Should it be spooled from one reel to another to move the maximum fatigued portion into a different position?
- Should some be cut off to move the position of the maximum fatigued section?
- Has it reached the end of its useful life?

If a commercial portable SL fatigue tester is used to test a sample of the SL in the field, a special function in the software, shown in Figure 12, can be used to determine what % of the fatigue life has been used for that particular sample.

Conclusions

A complete SL fatigue life tracking system has been developed which will provide the following benefits:

- Informed decisions can be made about how to maintain and when to scrap a reel of SL
- Cost savings due to longer usage of many SL reels
- Safety improvement due to less SL failures
- Cost savings due to less SL fishing operations

A commercial portable SL tester has also been developed which will enable better testing of SL samples in the field.

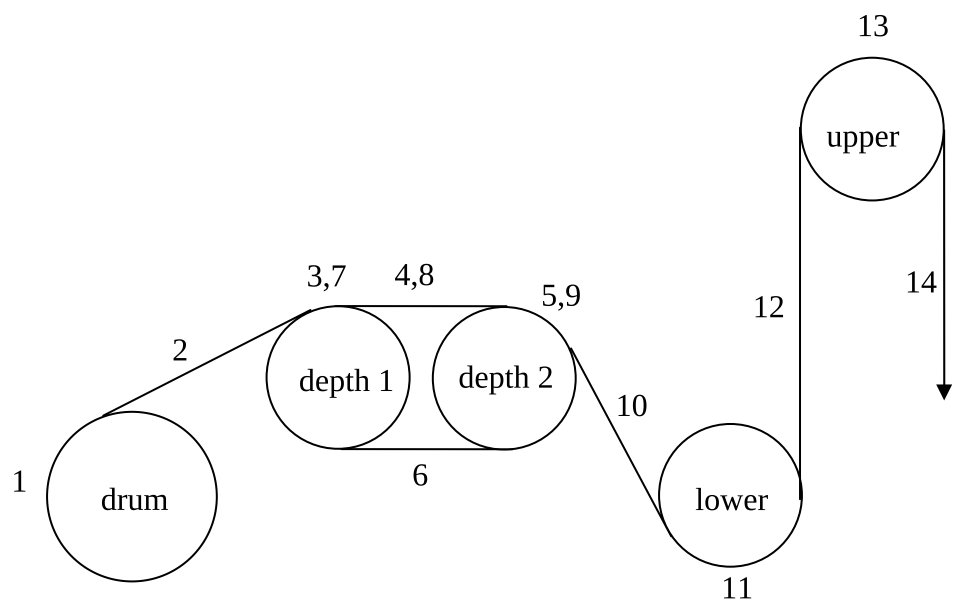

Figure 1 – Schematic of Typical Well-Site SL System

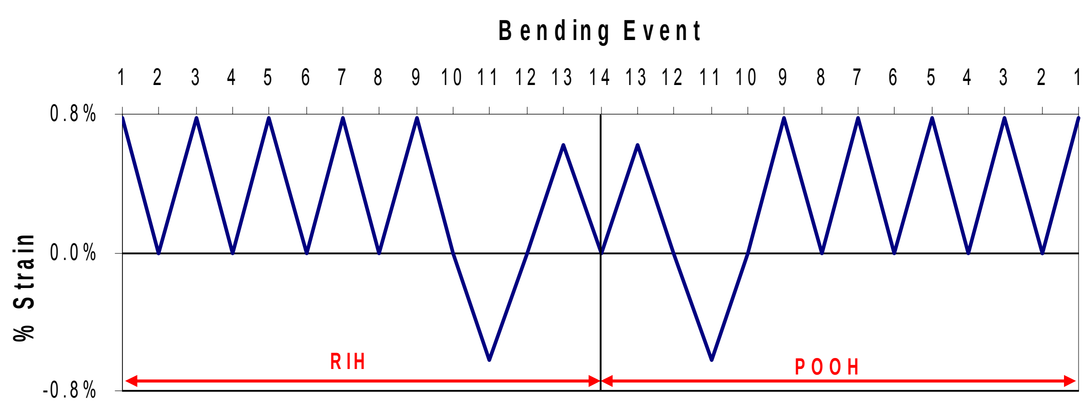

Figure 2 – Strain for each Bending Event in a Typical Well-Site SL System

Figure 3 – SL Fatigue Test Machine with Tension

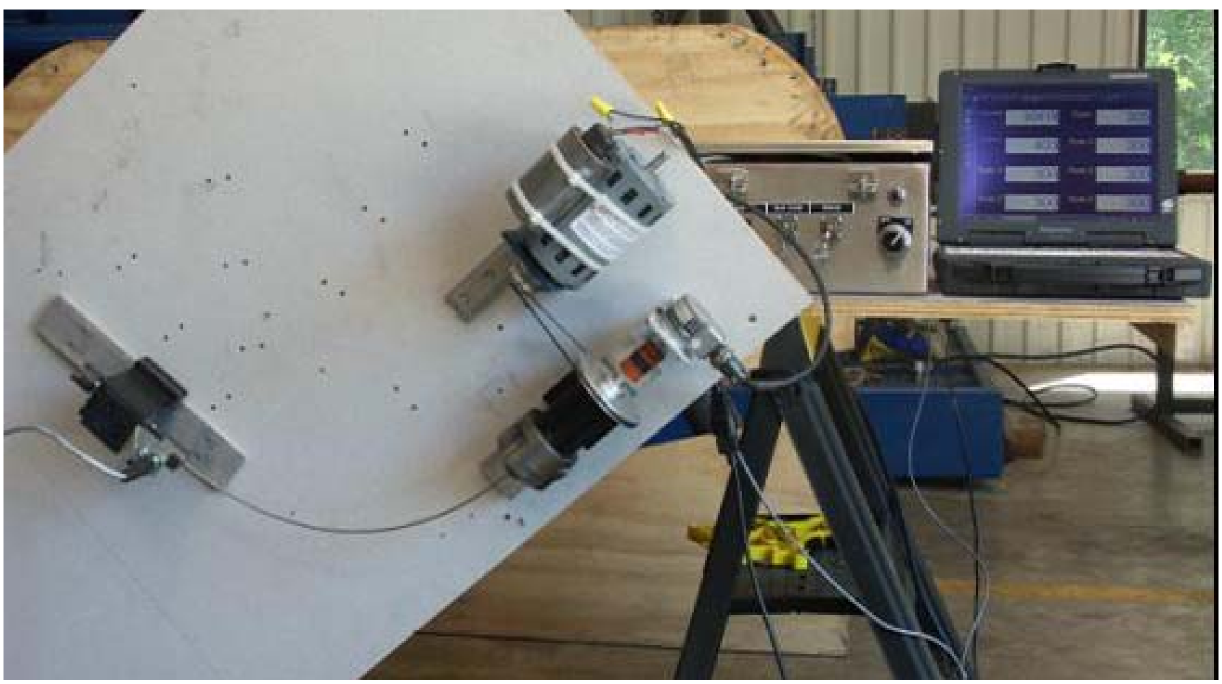

Figure 4 - SL Fatigue Test Machine without Tension

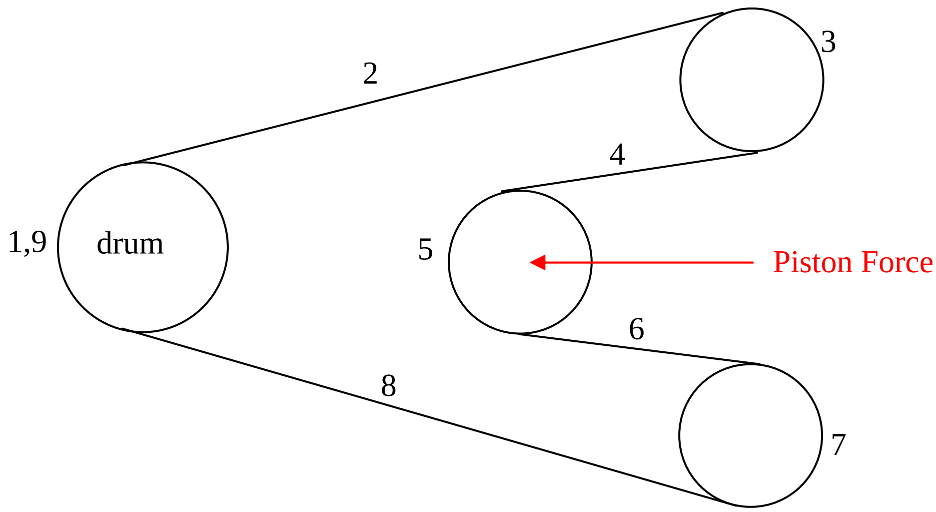

Figure 5 – Schematic of Large SL Fatigue Test Machine

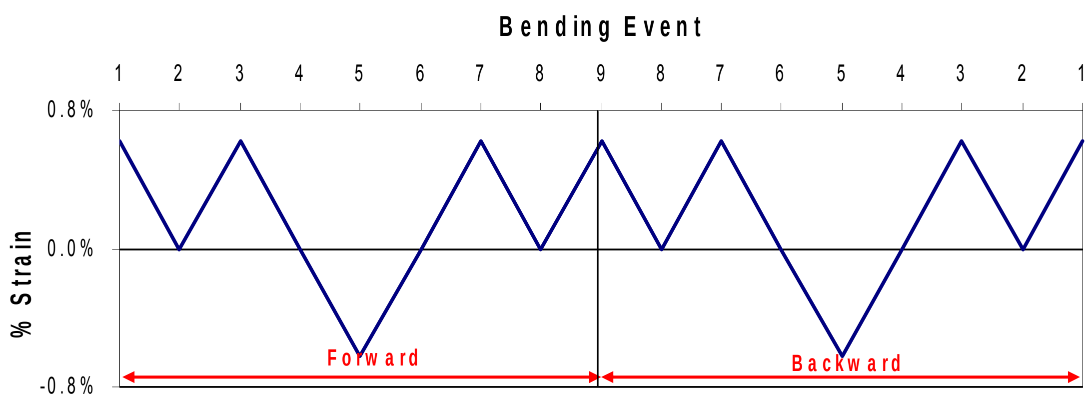

Figure 6 - Strain for each Bending Event for the Large SL Fatigue Test Machine

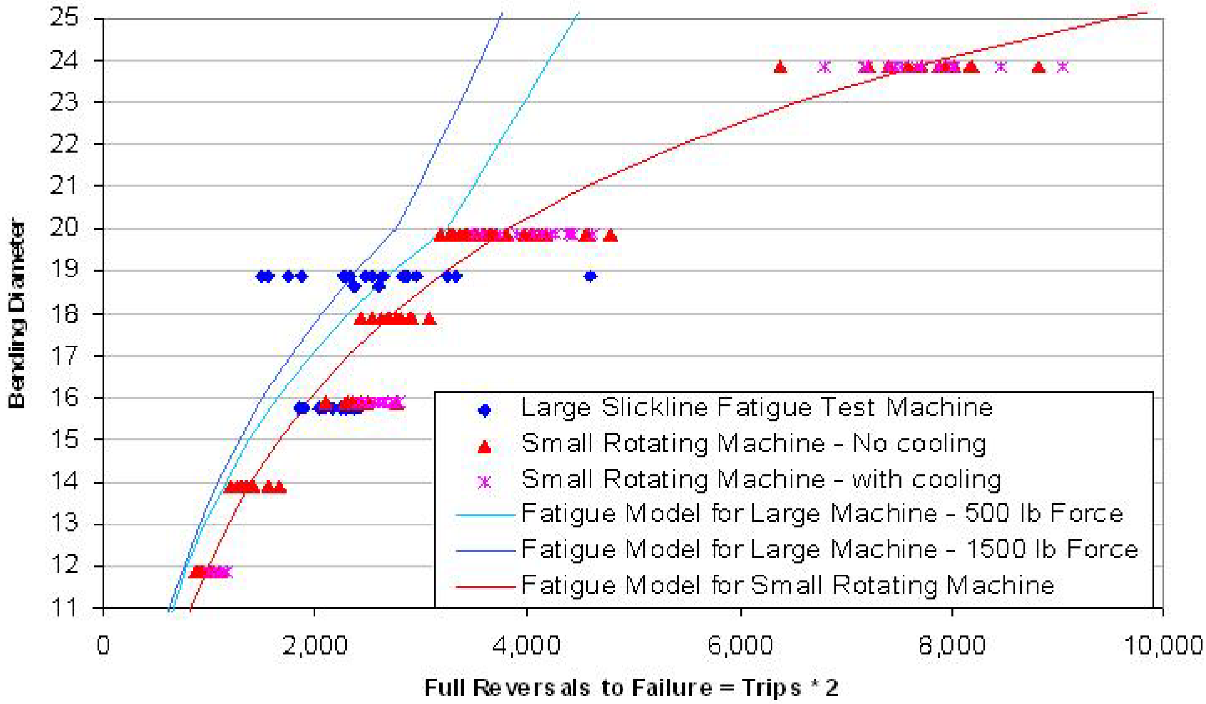

Figure 7 - Fatigue Test Data and Model Results for Bridon SUPA75 0.125"

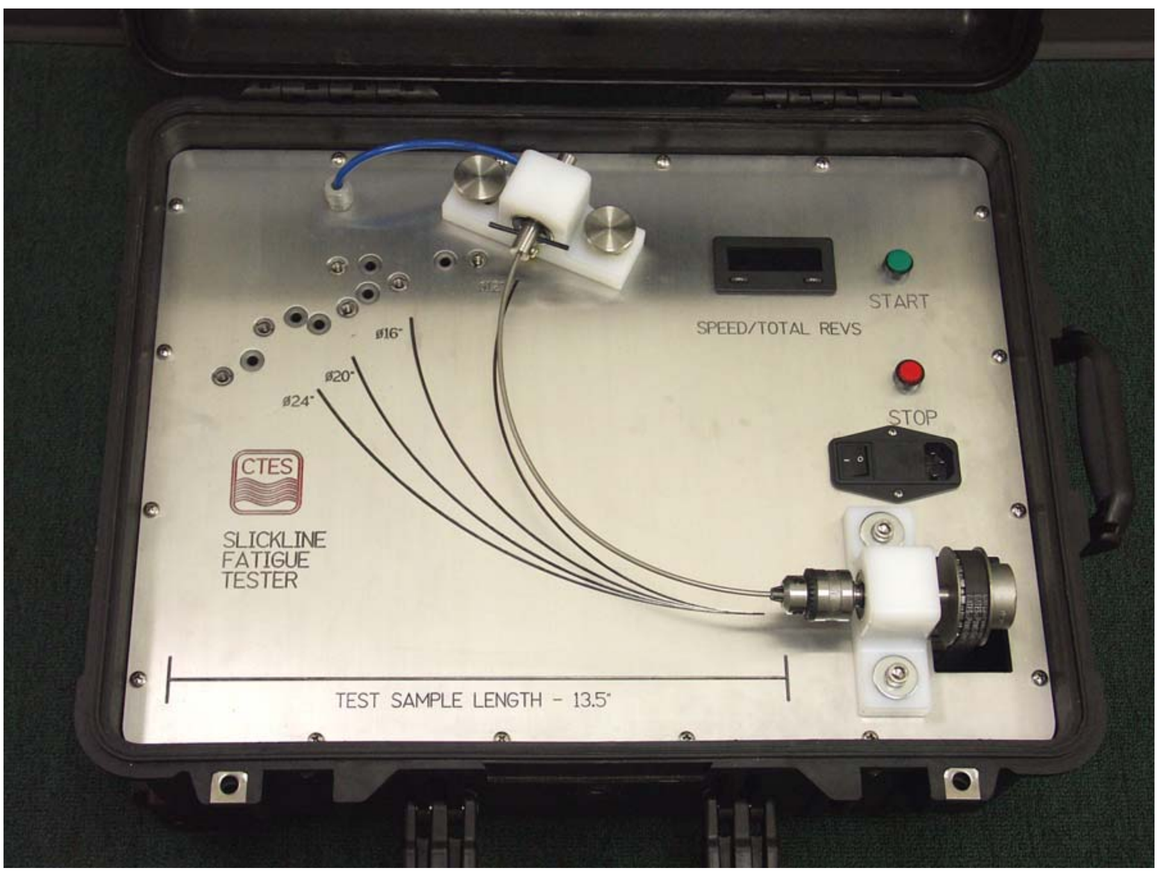

Figure 8– Commercial Portable SL Fatigue Tester

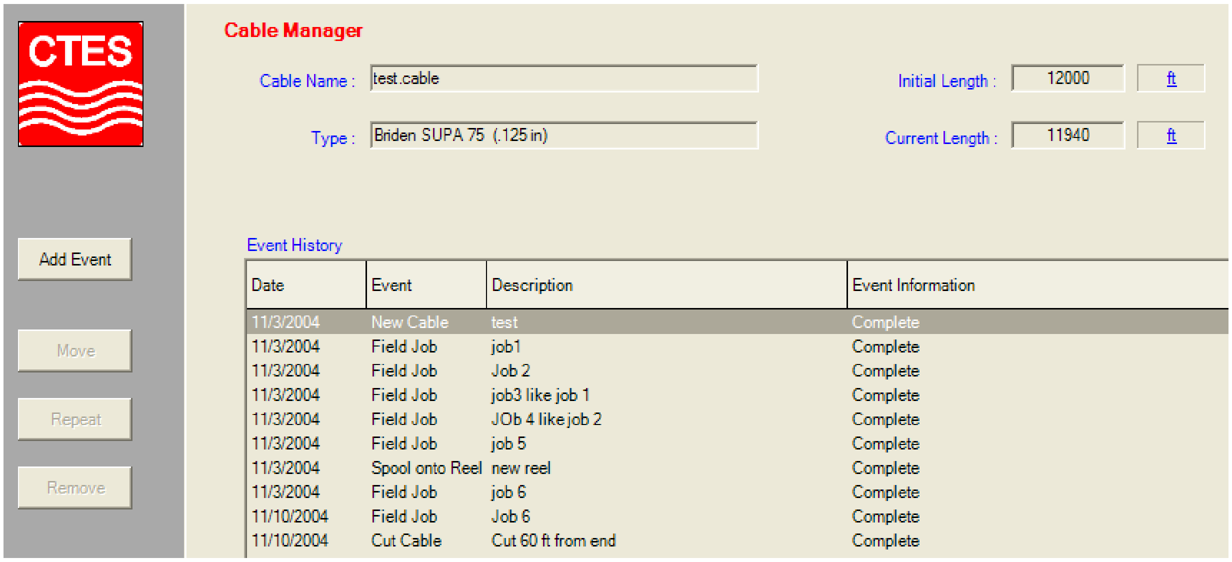

Figure 9 – Main Screen of Slickline Fatigue Tracking System

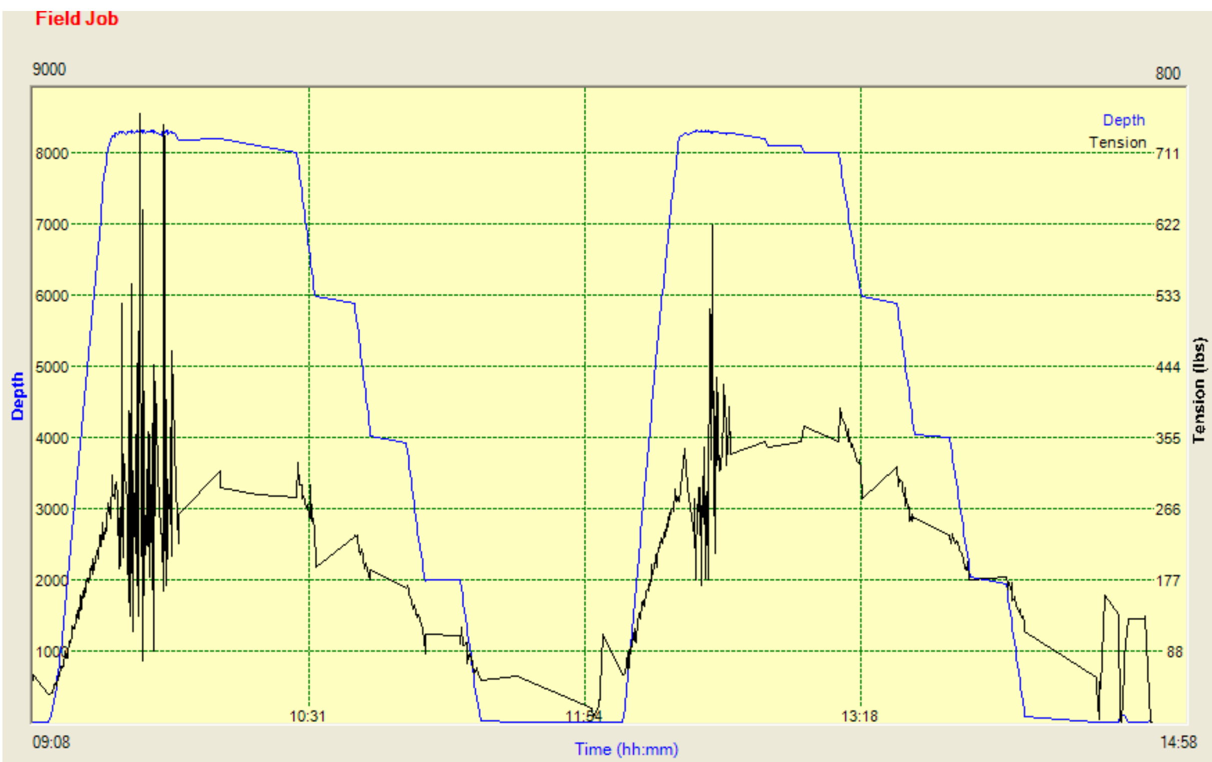

Figure 10- Typical Job Data from Data Acquisition System

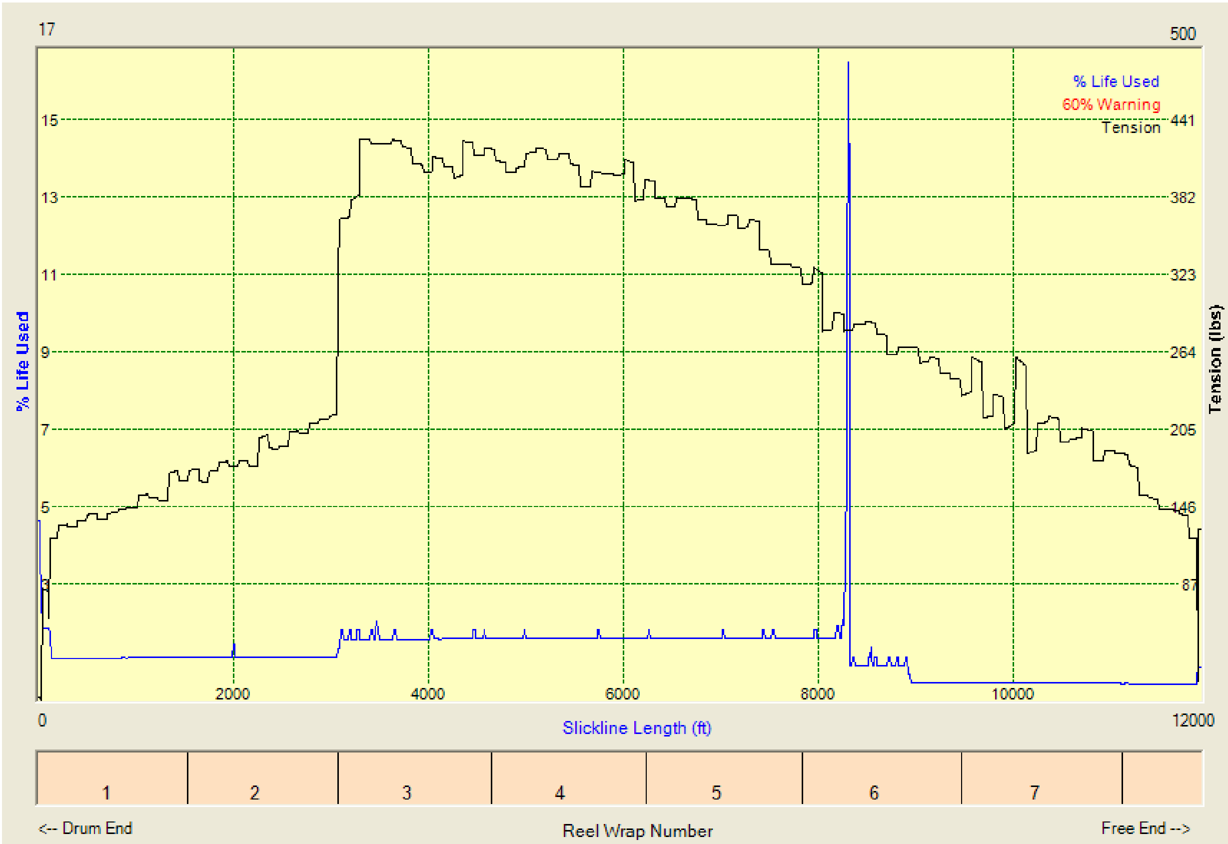

Figure 11 - %Fatigue Life Used and Tension vs Slickline Length

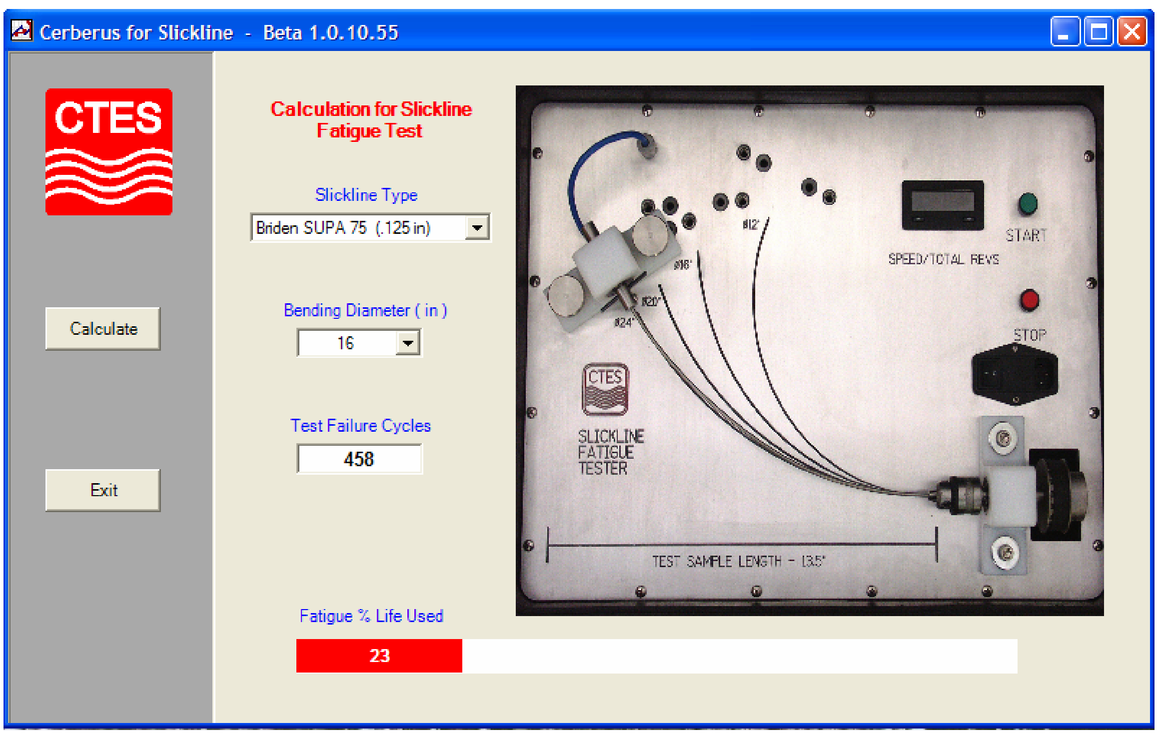

Figure 12 - %Fatigue Life Used for Field Test Sample