SPE 163884

Development of a New CT Life Tracking Process

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This paper was prepared for presentation at the SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition held in The Woodlands, Texas, USA, 26–27 March 2013.

Abstract

A new process has been developed to track the life of coiled tubing (CT) strings. This paper documents the development of this process, including the material models and the software tools used by the process. The results of this process are a prediction of the CT life and diametrical change along the length of the CT. When the process is used for multiple CT strings, statistical metrics about the strings can be mined from a web based database.

Introduction

In the late 1980’s and 1990’s there were three major CT life prediction systems developed. These include:

1. Nowsco/BJ/Baker model – CIRCA™
2. Schlumberger / Tipton Engineering / NOV CTES models[5,6,7,8,11,14,18] – CoilLIFE and Achilles
3. Halliburton models developed by Dr. Valdimir Avakov[9], used by Halliburton and MEDCO FACT

These systems have served the industry well, significantly reducing CT failures due to fatigue. However, in recent years there have been significant changes in the services being performed with CT. New services, such as multi-stage fracturing of long horizontal wells, require larger CT diameters and higher pumping pressures than were typical before. These increases have raised the stress and stain levels experienced by the CT material. Stronger CT materials and improved manufacturing techniques have and are being developed to meet these increased demands. The number of fatigue related failures has increased in recent years, indicating that improvements are needed in the CT fatigue life prediction systems.

Additions and improvements have been made to these systems through the years, but the overall processes for developing and improving these systems have remained basically the same. There are usually a number of stakeholders included in these processes including:

- CT manufacture ring companies which provide fatigue test results and material samples
- Engineering firms that develop the fatigue models
- Software development companies which implement these models in the CT life prediction systems
- CT service companies which use the CT life prediction systems to monitor the life of their CT
- Software development companies which provide cloud storage and data mining services.

Often it takes many months and even years for improvements to the CT life prediction systems to be implemented because of the complexity of these processes.

This paper documents a new process for developing a CT life prediction system which attempts to reduce the number of stakeholders and streamlines this process. The intentions of this new process are:

- To give CT manufacturers control of the fatigue life and diametrical change calculation models. In some cases CT service companies may choose to provide their own models.
- To streamline the creating or modifying of models for new or modified CT materials. This enables new models to be provided quickly, possibly on a string by string or even strip by strip basis if desired.
- To enable the use of CT job data (real-time or batch) from any data acquisition system. Calculation modules can be provided to allow the fatigue calculations to be performed in the data acquisition systems or in the cloud
- To streamline the synchronization of the string data between the location and the cloud database via the internet.
- To provide web based database tools which enable mining of information from the cloud database

New Process

This process uses three major software components:

1. Material Model (MM) Creation – The CT manufacturing companies (and service companies if desired) are able to create models of the performance of various CT materials, with and without welds, using a fatigue data regression software package provided for this process. Each MM contains the information needed to calculate the predicted fatigue life and diametrical change. An additional calculation is being considered to predict ovality.
2. Life Tracking System (LTS) – The CT service companies use the LTS to track the CT fatigue life and diametrical change, during the life of each CT string. The LTS uses the MM and the string geometry along with the job data from a data acquisition system, to predict the current fatigue life and diametrical change.
3. Cloud Database (Cloud) – This entire process is centered around a database that is maintained through the internet on remote servers. When a new CT string is created, the string information including the MM and string geometry, are stored in the Cloud. The LTS synchronizes with the Cloud to obtain the string information, and to return the job information including the predicted fatigue life and diametrical change.

The process begins with the CT manufacturing companies developing the MMs required to perform CT life prediction calculations for their product. When the CT manufacturing company produces a new CT string, it places the MMs and the string information into the Cloud.

When the CT string is purchased by a CT service company, they synchronize their LTS with the Cloud to obtain the string information. The LTS is then used to calculate the predicted string life during the life of the string. Whenever the LTS is synched with the Cloud, the string information in the Cloud is updated.

Each of the stakeholders in this process, including the operating companies, may be able to mine data about the strings from the Cloud database. The CT manufacturing companies may use this data to estimate when a new string will be needed to replace an existing string. The CT service companies may mine the Cloud for statistical metrics about their strings. Operating companies may review the status of a string before it is used in one of their wells.

At the time of this writing, the CT manufacturing companies[22] are developing the MMs needed for this process. By the time the paper is presented the process is expected to be ready for field testing.

Material Model Creation

Development of MMs requires fatigue test data. Originally full-scale fatigue tests were performed[5,6,7,8 and 9] with a CT unit located at a test well. The CT would be cycled some distance (maybe 100 ft) into and out of the well repeatedly until a fatigue failure occurred. These tests where repeated with various internal pressures, CT materials, CT diameters and wall thicknesses. This type of testing was laborious, expensive and time consuming. Fatigue test machines[12] were developed which are used to test CT specimens more rapidly and less expensively. Each of the CT manufacturing companies now has one or more of these machines, and performs fatigue testing on a regular basis. The modeling challenge is to convert the resulting fatigue test data from these machines into a CT life prediction model.

The current MMs are composed of three types of curve fits, the baseline curve, the pressure curve, and the diametrical strain curve. Two different types of MMs are created, one for CT with welds and one for CT without welds. Each of these is discussed below. This paper does not attempt to give an exhaustive discussion of fatigue theory.

Baseline Curve

The baseline curve defines the fatigue performance of the CT with low internal pressure. Ideally there would be no internal pressure, but some pressure is needed to determine when a failure occurs. The Manson Coffin equation[1] is the industry accepted equation for low cycle fatigue.

$$\tfrac{1}{2}\varepsilon_a = \tfrac{1}{2}\varepsilon_{ae} + \tfrac{1}{2}\varepsilon_{ap} = \frac{\sigma_f^{'}}{E}\left(2N\right)^b + \varepsilon_f^{'}\left(2N\right)^c \tag{1.1}$$

This equation sums two components, the elastic and the plastic axial strain due to bending. The total axial strain is:

$$\varepsilon_a = \frac{r}{R} \tag{1.2}$$

The elastic and plastic components can be written in logarithmic form as:

$$\begin{gathered} \mathrm{Log}\left(\tfrac{1}{2}\varepsilon_{ae}\right) = \mathrm{Log}\left(\frac{\sigma_f^{'}}{E}\right) + b\,\mathrm{Log}\left(2N\right) \\ \mathrm{Log}\left(\tfrac{1}{2}\varepsilon_{ap}\right) = \mathrm{Log}\left(\varepsilon_f^{'}\right) + c\,\mathrm{Log}\left(2N\right) \end{gathered} \tag{1.3}$$

These equations are linear when plotted on a log/log plot as is shown in Figure 1. The cyclic axial strain versus cycles to failure curve, referred to here as the baseline curve, is the sum of these two curves. The endurance limit, which is approximately half of the ultimate strength, corresponding to 0.2% strain, is also shown in Figure 1.

The Ramberg-Osgood[1] cyclic stress strain curve can be plotted using the same parameters as are found in the Manson Coffin equation. The resulting curve is shown in Figure 2.

Pressure Curve

Once the baseline curve has been established, a pressure multiplier is calculated for each of the fatigue test points. The pressure multiplier is the number of cycles predicted by the baseline curve divided by the actual number of cycles for that point. The von Mises stress is also calculated for the fatigue test point, and divided by the yield stress to obtain the % stress. The pressure multiplier and the % stress are then plotted as is shown in Figure 3. Standard curve fitting techniques are then used to create either a polynomial or exponential curve fit. This curve is referred to as the pressure curve.

Once the number of cycles to failure with the pressure is calculated, this number (N) can be used in equation (1.1) to calculate the equivalent baseline strain. This equivalent baseline strain enables the plotting of all data points, with and without pressure, on one curve. It can also be used to perform rainflow cycle counting[3,4,20] of the fatigue events.

Tolerance Interval & Fatigue Model Curve

The baseline and pressure curves developed above combine to produce a fatigue prediction that passes through the center of the population of fatigue test points. A factor of safety has to be applied to this prediction to provide a safe working limit. A statistical interval called a "tolerance interval" is used to determine what is known as the "conservative-limit" which is applied to this fatigue prediction. The tolerance interval is similar to a probability interval, but it includes a degree of confidence in how well the fatigue test population represents the total population.

For this particular example with 516 fatigue test points, using a 95% confidence level for 95% coverage of the population, produced a conservative-limit of 59%. This conservative-limit is applied to the fatigue prediction curve to produce the final fatigue model curve. The fatigue model curve is shown in Figure 4.

Diametrical Strain Curve

The change in diameter of the CT during its life[12,15] is very complex. The CT tends to balloon when bent with high internal pressure and to get smaller (neck) when bent with a combination of tension and low internal pressure. The diametrical change per cycle is calculated for each fatigue test data point as follows:

$$DSPC = \frac{D_f - D_o}{ND_o} \tag{1.4}$$

The DSPC values are plotted versus a % stress term to create a diametrical strain curve. Several stress terms are used which include the three principle stresses and the axial strain, ε_a. Conventional curve fitting techniques are then used to create either an exponential or polynomial curve through the data points. Figure 5 shows a resulting curve for the 516 fatigue test points used in this example.

All of the data points in Figure 5 lie in the upper right quadrant. Currently there is no fatigue test fixture available which can perform fatigue tests while holding a tensile force on the sample. Tests performed in 1996 to determine the elongation[16] of CT also showed considerable necking of the CT. Future testing is being considered which will attempt to quantify this necking. For now the diametrical strain curve is mirrored into the lower left quadrant to allow some necking to be approximated.

Weld Fatigue Model

In 1994 and 1995 a joint industry project[13] was performed by CTES, L.C. to determine the fatigue life of welds. Testing was done on welds with the same wall thickness on both sides, and on "tapered" welds which had a change in wall thickness at the weld. Butt welds performed manually and with an orbital welder were tested, along with bias welds. The result of this project was a recommendation that the welds be derated by a certain percentage, which was different for each type of weld. Table 1 summarizes the results from this project.

Table 1 - Types and Numbers of Welds Tested

Type	Number Tested	Derating Factor
Plain Pipe (no weld)	117	None
Manual Weld	98	35%
Manual Tapered Weld	10	15%
Orbital Weld	50	45%
Orbital Tapered Weld	10	20%
Bias Weld	64	80%
Bias Tapered Weld	46	50%

These derating factors have been used since this project was completed. Until recent years, weld fatigue failures were infrequent. There is an industry perception of increased weld fatigue failures in recent years.

The data for the bias welds from this project were lumped together and an example weld MM was developed for them. This means bias welds from different manufacturers, using different CT materials, tapered and non-tapered. A 75%/75% tolerance interval was used because the JIP report makes it clear that there were poorly made welds included with those being tested. The resulting bias weld fatigue model is shown in Figure 6.

In a similar manner the manual and orbital weld data were lumped together and an example weld MM was developed for them using a 60%/60% tolerance interval. Figure 7 shows example fatigue curves using 3 MMs with the safety factors included. One curve is for 80-grade CT with no welds. The other two curves are for bias welds and butt welds. The weld fatigue curves are very different than a constant derating factor. They indicate that low pressure bending cycles cause much more fatigue damage to welds than they do to non-welded CT, while bending cycles at higher pressure cause proportionally less fatigue damage to welded CT.

These weld MMs were just a first, somewhat crude, attempt at trying to develop fatigue models for welds based on old data. New weld fatigue test datasets are being developed which will allow more accurate weld MMs to be developed.

Life Tracking System

The LTS is used on the CT unit to predict the current life of the CT string along its length. The inputs required by this system are:

- Material Model(s) for the string or strips within the string – discussed above
- String Information
- Reel Geometry
- Rig-up Type and Wellsite Geometry
- Job Data

The output from the system is the fatigue life and diametrical change prediction along the length of the CT string.

String Information

The string diameter, wall thickness versus length, weld locations, weld types and possibly strip yield strengths are included in the data supplied with the MM from the CT manufacturer.

Reel Geometry

The width, core diameter and flange diameter of the reel are used to calculate the bending R of the string on the reel. This R varies with each wrap of the string across the width of the reel. An example reel geometry and wrap calculation is shown in Figure 8.

Rig-up Type and Wellsite Geometry

The type of rig-up and the wellsite geometry are used to determine the radii of bending (R) and the location of the bend points along the length of the string as it is used for the job. An example is shown in Figure 9. There are several types of rig-ups including:

- Conventional – bending at reel and guide arch only
- Conventional with sag – if there is a significant distance between the reel and the injector, the CT may sag. Sagging of the CT between the reel and injector causes a reverse bending of the CT which exacerbates the fatigue. A catenary calculation (see Figure 10) is used to determine the amount of reverse bending.
- Big Wheel – some CT units use a big wheel style injector
- Big wheel with sag
- Parabolic arch
- Reel above injector

In most of these cases there is the possibility of having a straightener above the injector. A straightener[21] uses a reverse bend to remove the residual curvature from the CT. This reverse bend exacerbates the fatigue. A residual curvature calculation, shown in Figure 11, determines how much reverse bend is required to straighten the CT. This calculated reverse bend is then used in the fatigue calculation.

All of the bending curvatures (1/R) for a trip into and out of the well can be plotted. An example is shown in Figure 12. In this example the sag reverse bend was very small compared to the straightener reverse bend.

Job Data

Measured depth and pump pressure, typically from a data-acquisition system, are used either in real-time during each job, or in a batch mode after each job, to calculate the fatigue life and diametrical change along the length of the string. The data acquisition files are imported into the LTS,

Fatigue Life and Diametrical Change Output

Figure 13 shows an example fatigue life and diametrical change plot from the LTS. This plot is the primary output used by the CT service companies when studying the fatigue life of a string. It shows the change in fatigue life after the previous job, and then after this job, enabling the user to see the change in fatigue life due to one job. In some places the CT service company is able to charge the operating company a fatigue charge based on the change in fatigue life due to the job.

Based on this output, the CT service company may choose to modify the CT string, to move the areas with the highest fatigue to locations where they will receive less fatigue in future jobs. This may be done by cutting some length off of the end of the string, by reversing the string on the reel, or by cutting a highly fatigued section from the middle of the string.

Cloud Database

At the time of this writing the database which stores all of the data for this process on a web based server, referred to as the "Cloud", is under development. The data which are being stored in this database include:

- String information from the CT manufacturing company
    - Material models
    - String geometry material properties
- String information from the CT service company for each job performed using the string
    - Reel geometry
    - Rig-up type and wellsite geometry
    - Job data
    - Fatigue life and diametrical growth prediction after each job
    - Modifications to string – wall thinning, cutoff, weld added, string reversed
- String inspection information from inspection company

The necessary string data are synchronized with the LTS to enable fatigue predictions to be performed at the wellsite. If the string is inspected, the inspection data can be used to update the string diameter and wall thickness information.

Conclusion

A new process for developing CT life prediction models and applying them in the field has been developed and is being implemented. This process streamlines the development of new models, including weld fatigue models.

Nomenclature

D_f = final average diameter
D_o = original average diameter
DSPC = diametrical strain per cycle
E = Cyclic modulus of Elasticity
N = number of bending cycles to failure
r = outside radius, inside radius or mid wall radius of the CT
R = radius of curvature of bending
σ_f' = fatigue strength coefficient
b = fatigue strength exponent
ε_a = cyclic axial strain due to bending
ε_{ae} = cyclic elastic axial strain due to bending
ε_{ap} = cyclic plastic axial strain due to bending
ε_f' = fatigue ductility coefficient
c = fatigue ductility exponent

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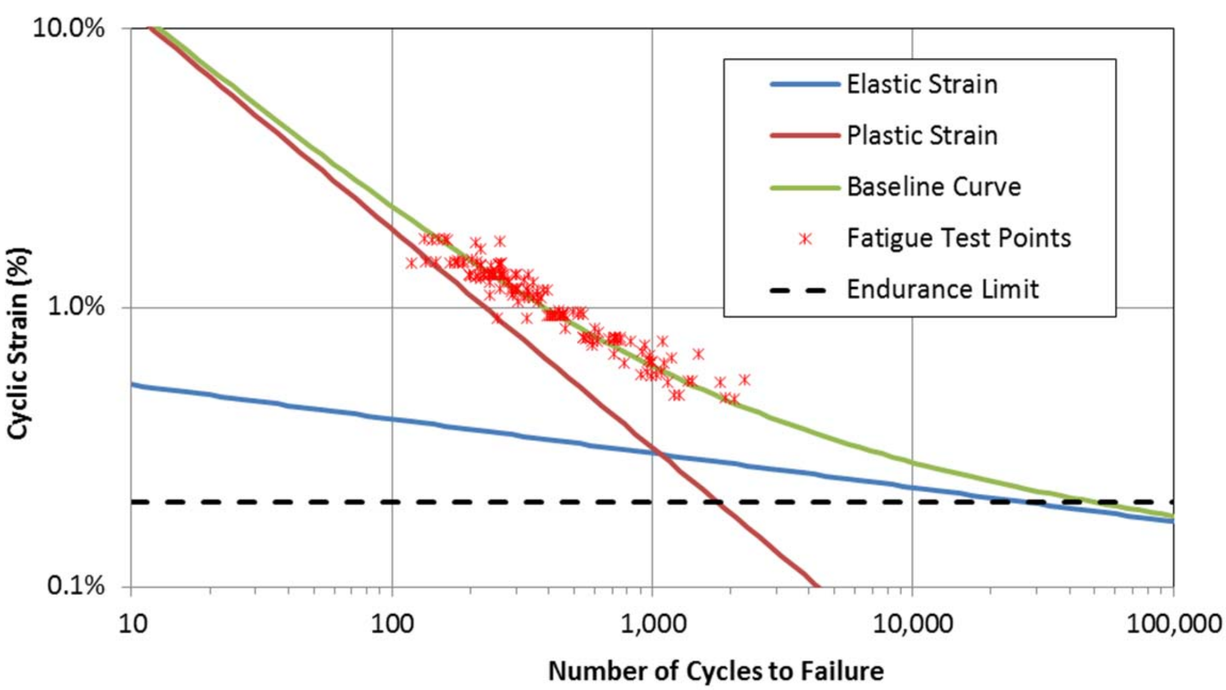


Figure 1 - Baseline Manson Coffin Curve with 143 Fatigue Test Points

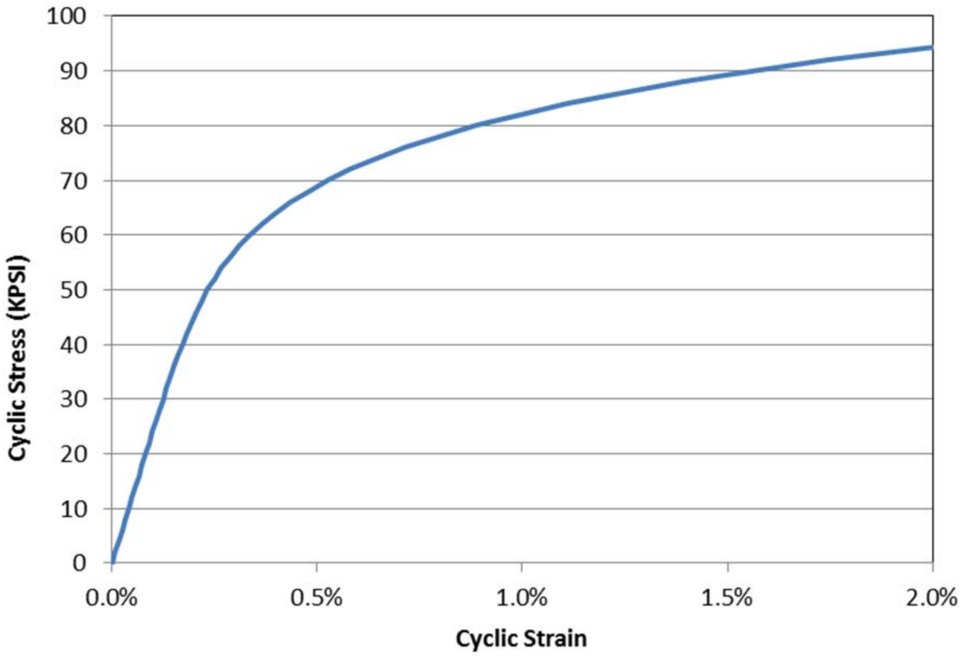


Figure 2 - Ramsberg-Osgood Cyclic Stress-Strain Plot

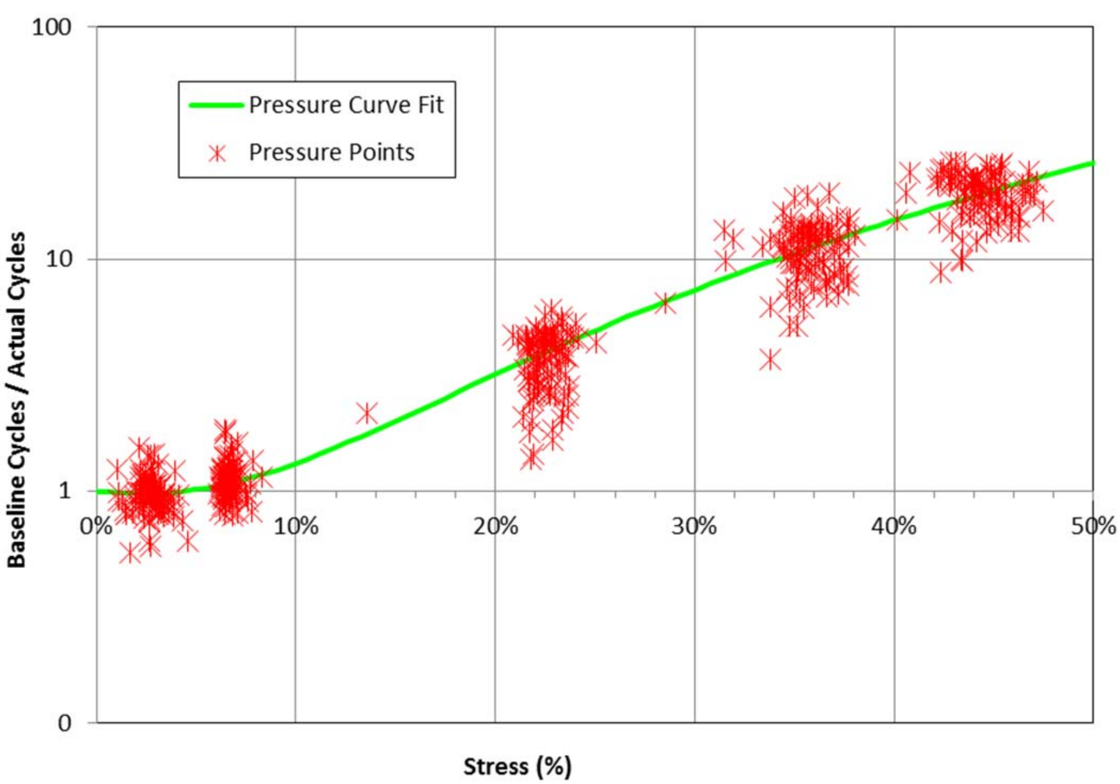


Figure 3 - Pressure Multiplier Curve Fit with 516 Fatigue Test Points

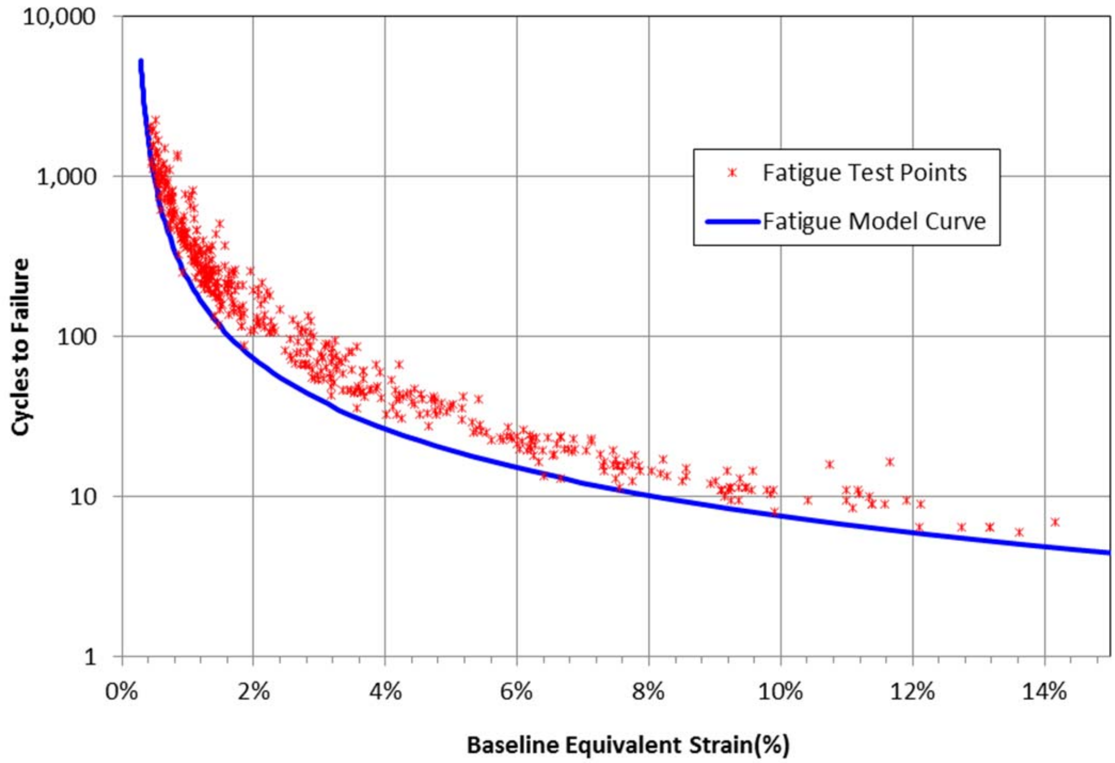


Figure 4 - Fatigue Model Curve with 516 Fatigue Test Points

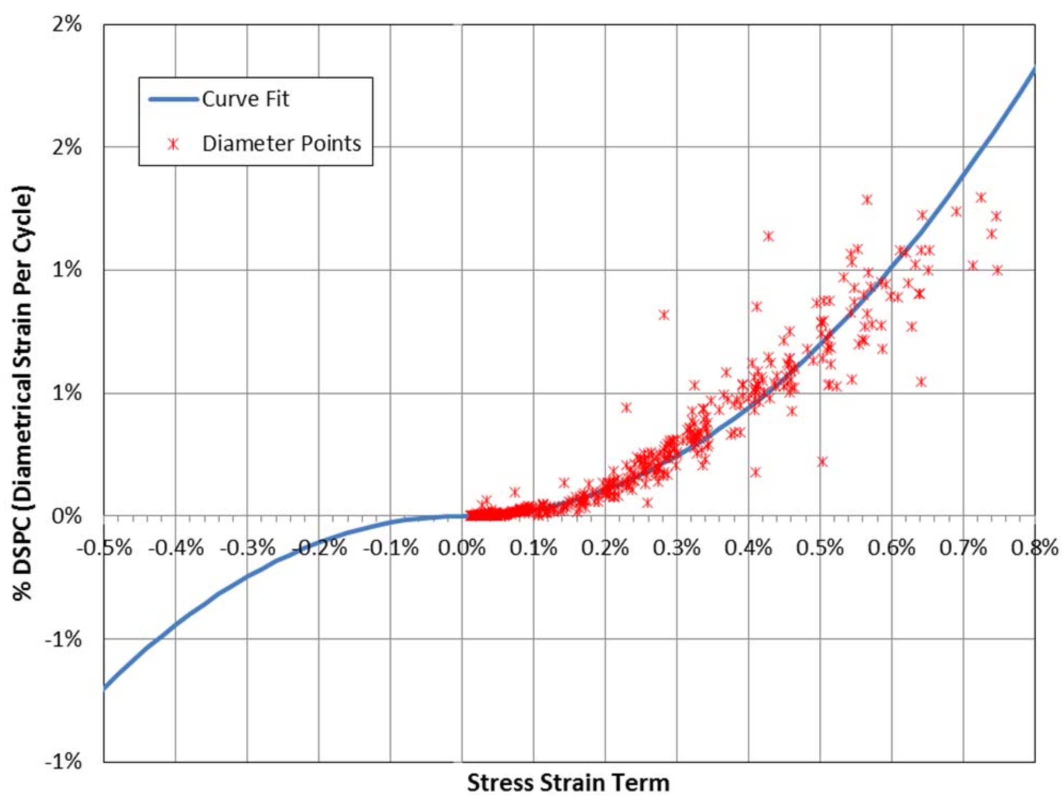


Figure 5 - Diametrical Strain Curve with 516 Fatigue Test Points

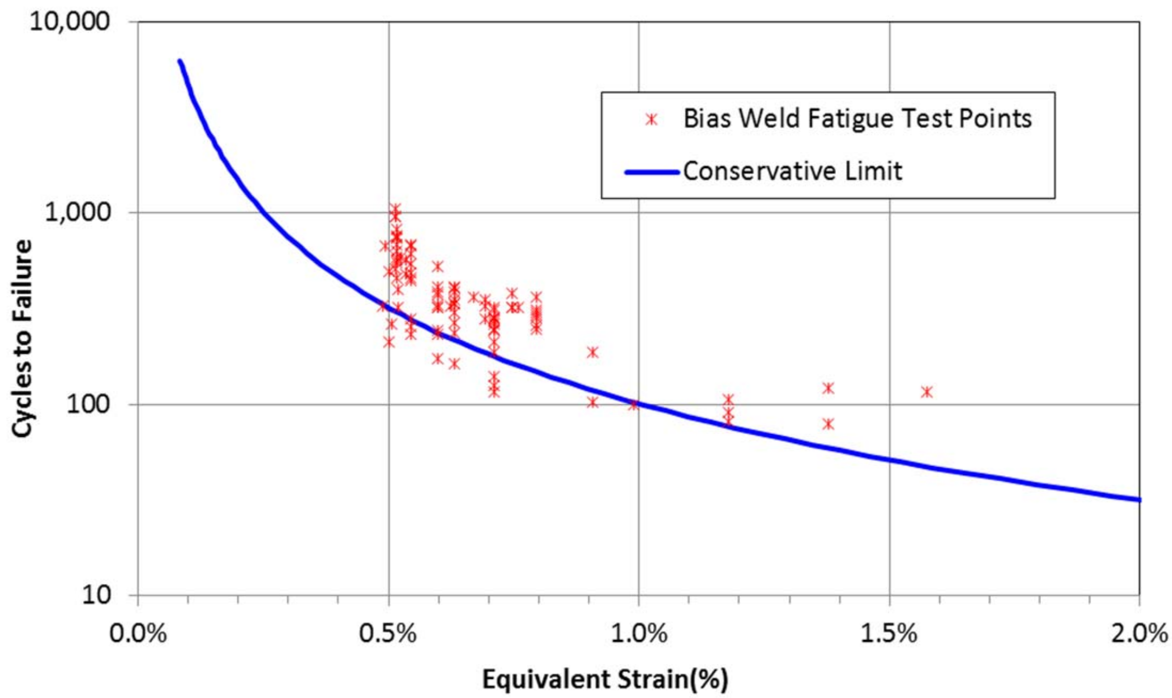


Figure 6 - Bias Weld Fatigue Model Curve

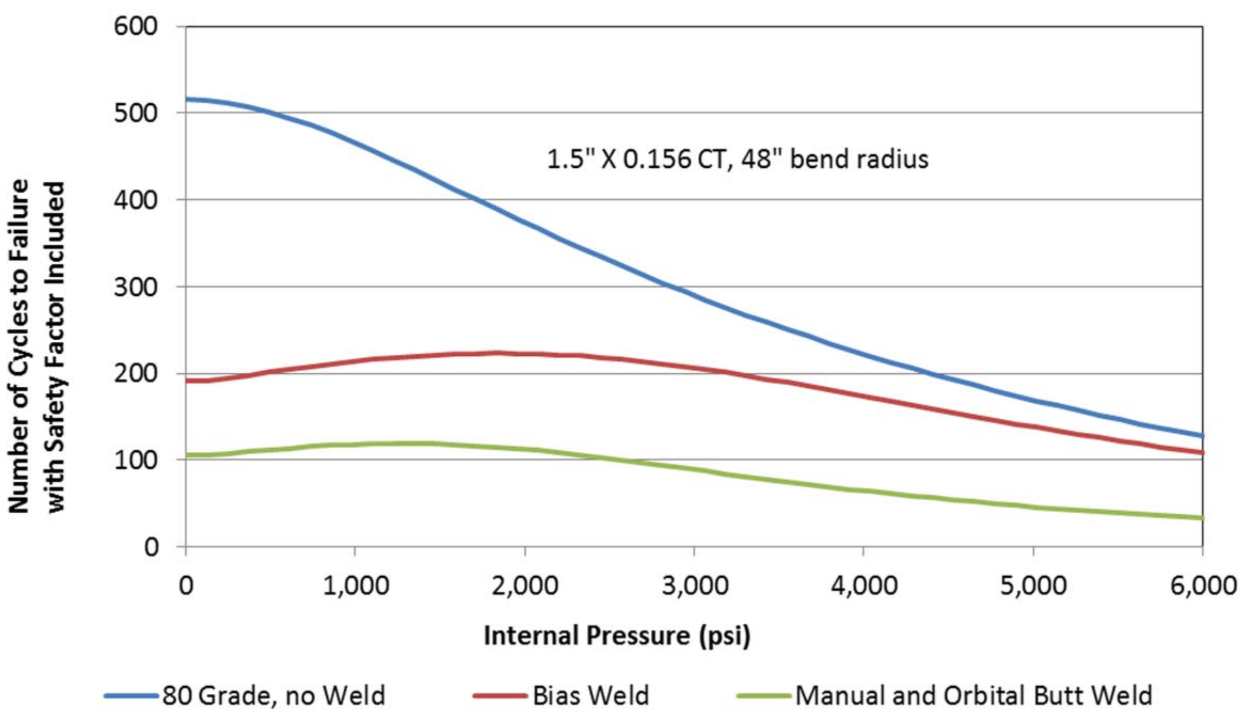
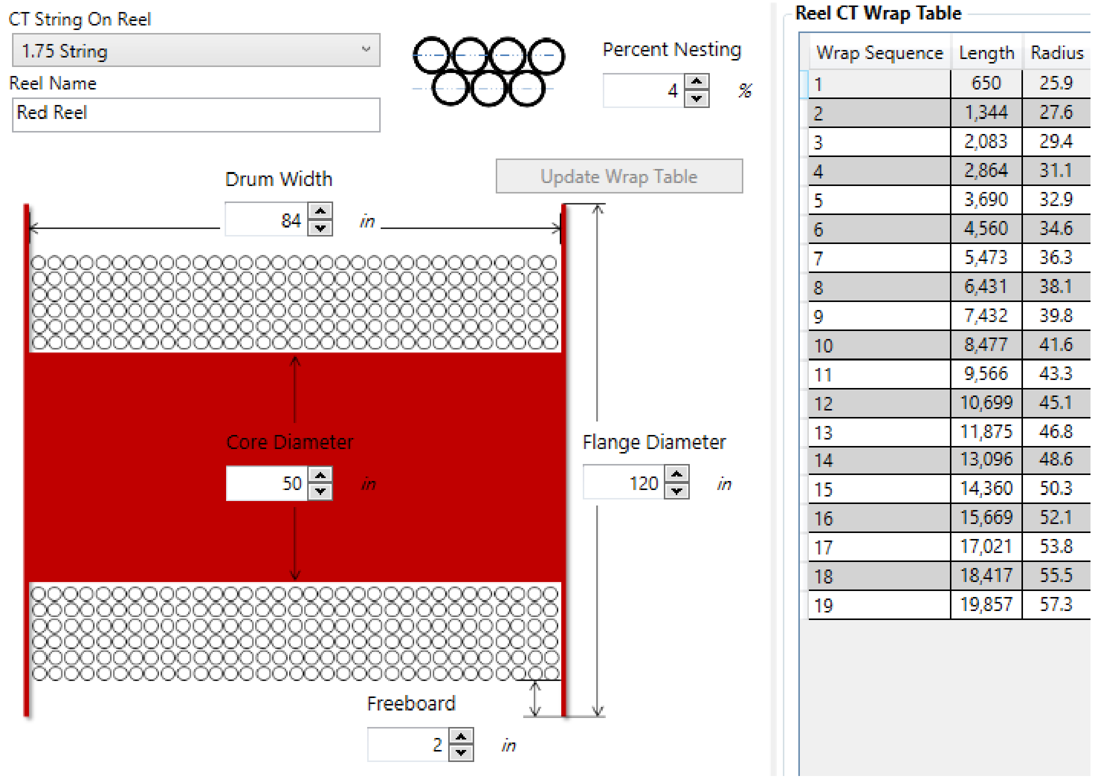


Figure 7 - Weld Fatigue Curves Compared to No Weld



Wrap Sequence	Length	Radius
1	650	25.9
2	1,344	27.6
3	2,083	29.4
4	2,864	31.1
5	3,690	32.9
6	4,560	34.6
7	5,473	36.3
8	6,431	38.1
9	7,432	39.8
10	8,477	41.6
11	9,566	43.3
12	10,699	45.1
13	11,875	46.8
14	13,096	48.6
15	14,360	50.3
16	15,669	52.1
17	17,021	53.8
18	18,417	55.5
19	19,857	57.3

Figure 8 - Reel Geometry and Wrap Table

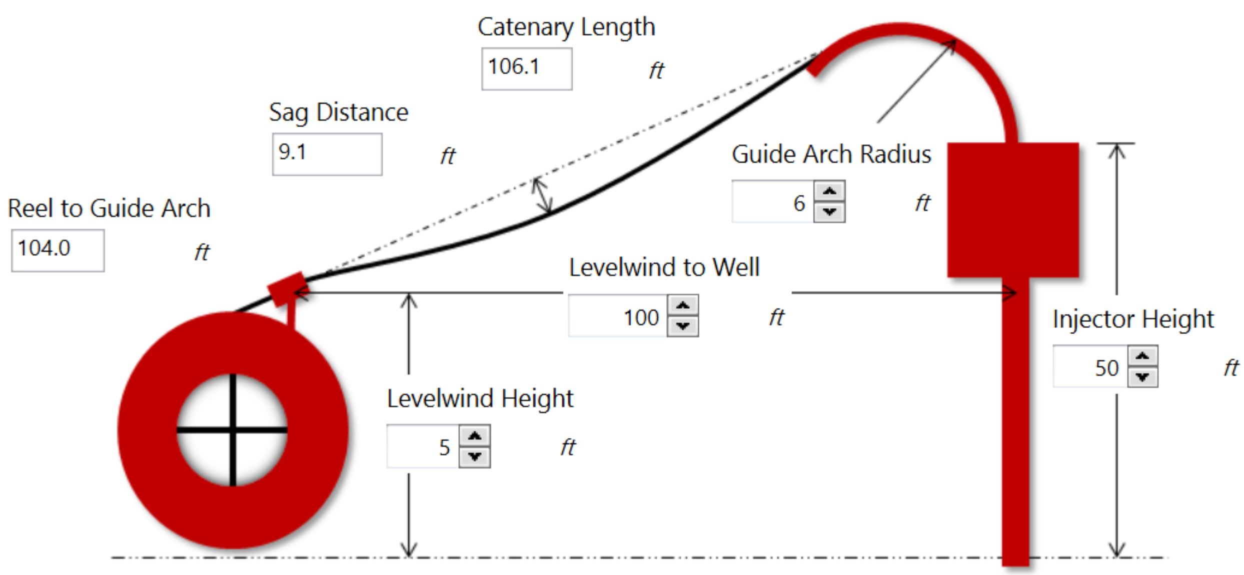


Figure 9 - Well Site Geometry

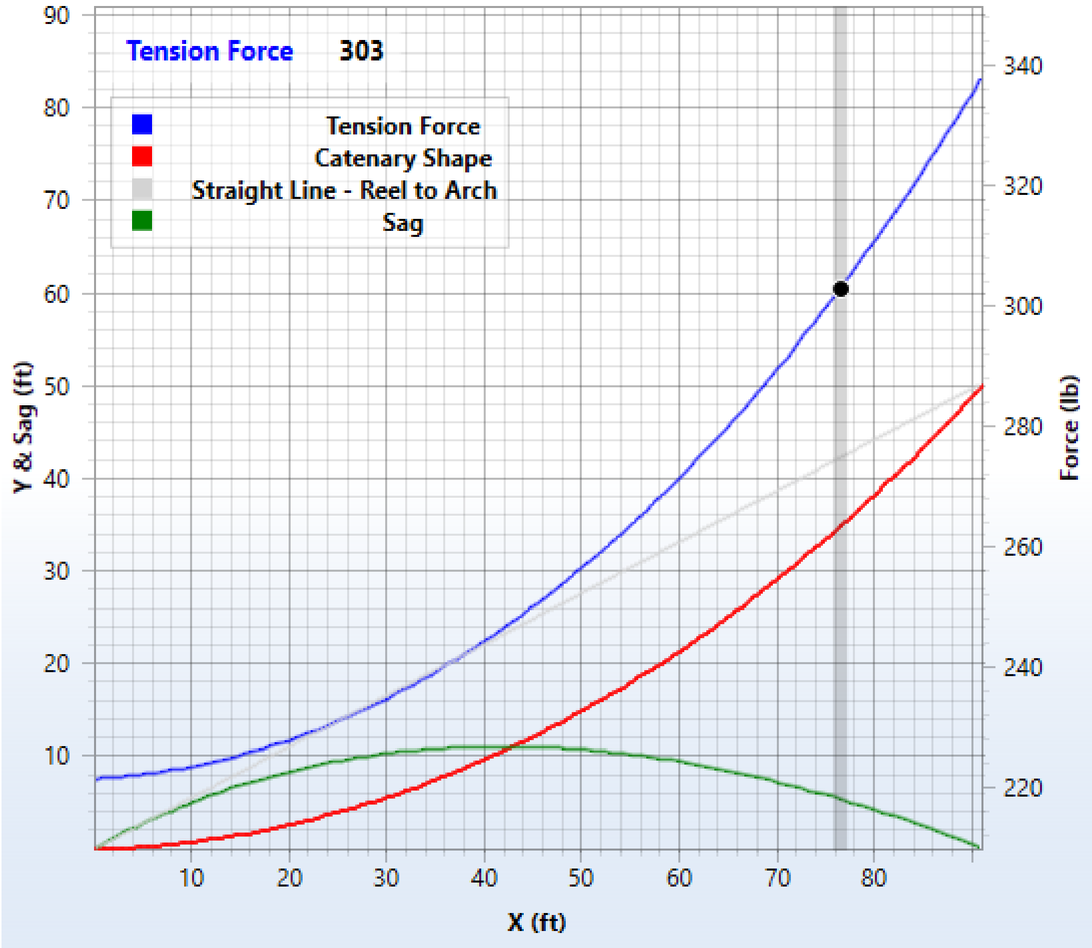


Figure 10 - Catenary Calculation for Reverse Bend due to Sag

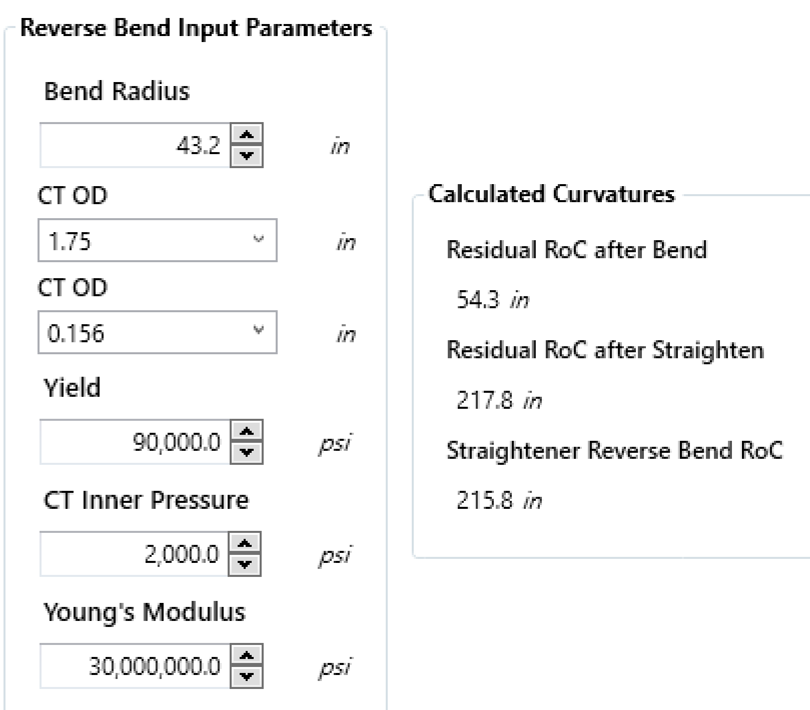


Figure 11 – Residual Curvatures and Reverse Bend in Straightener Calculations

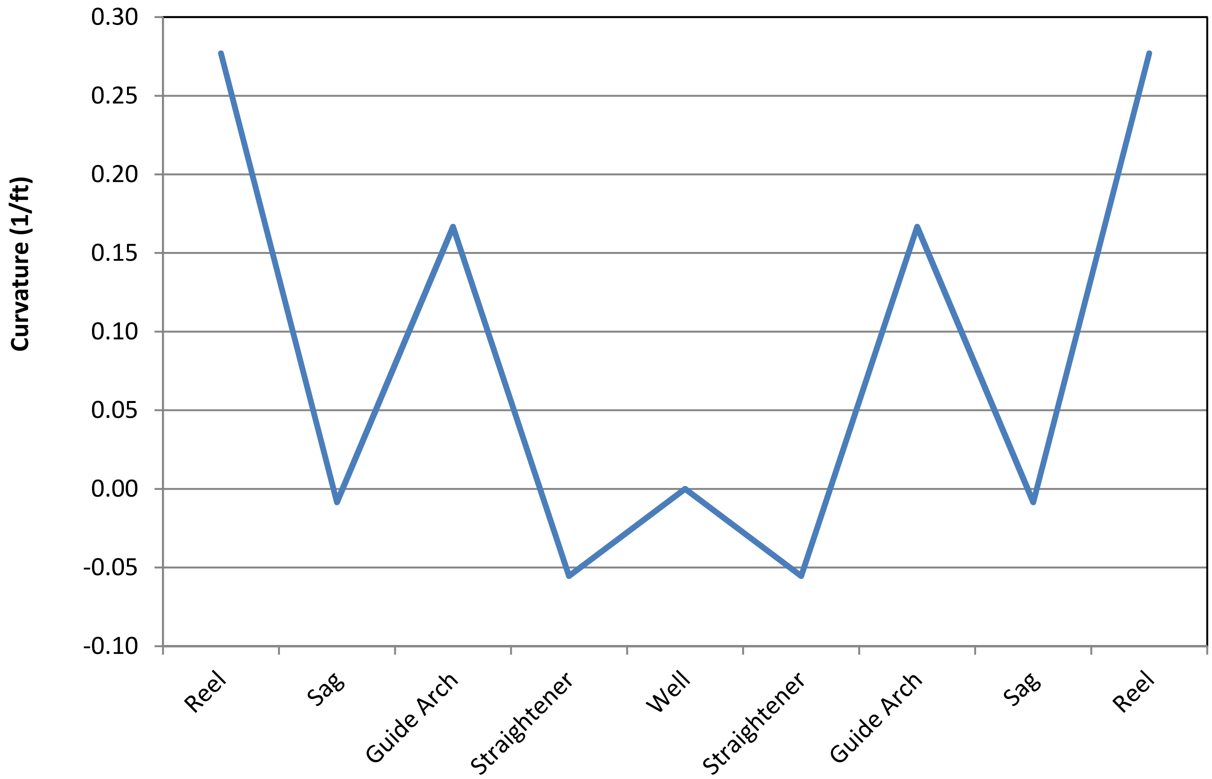


Figure 12 - Bend Curvatures for 1 Trip

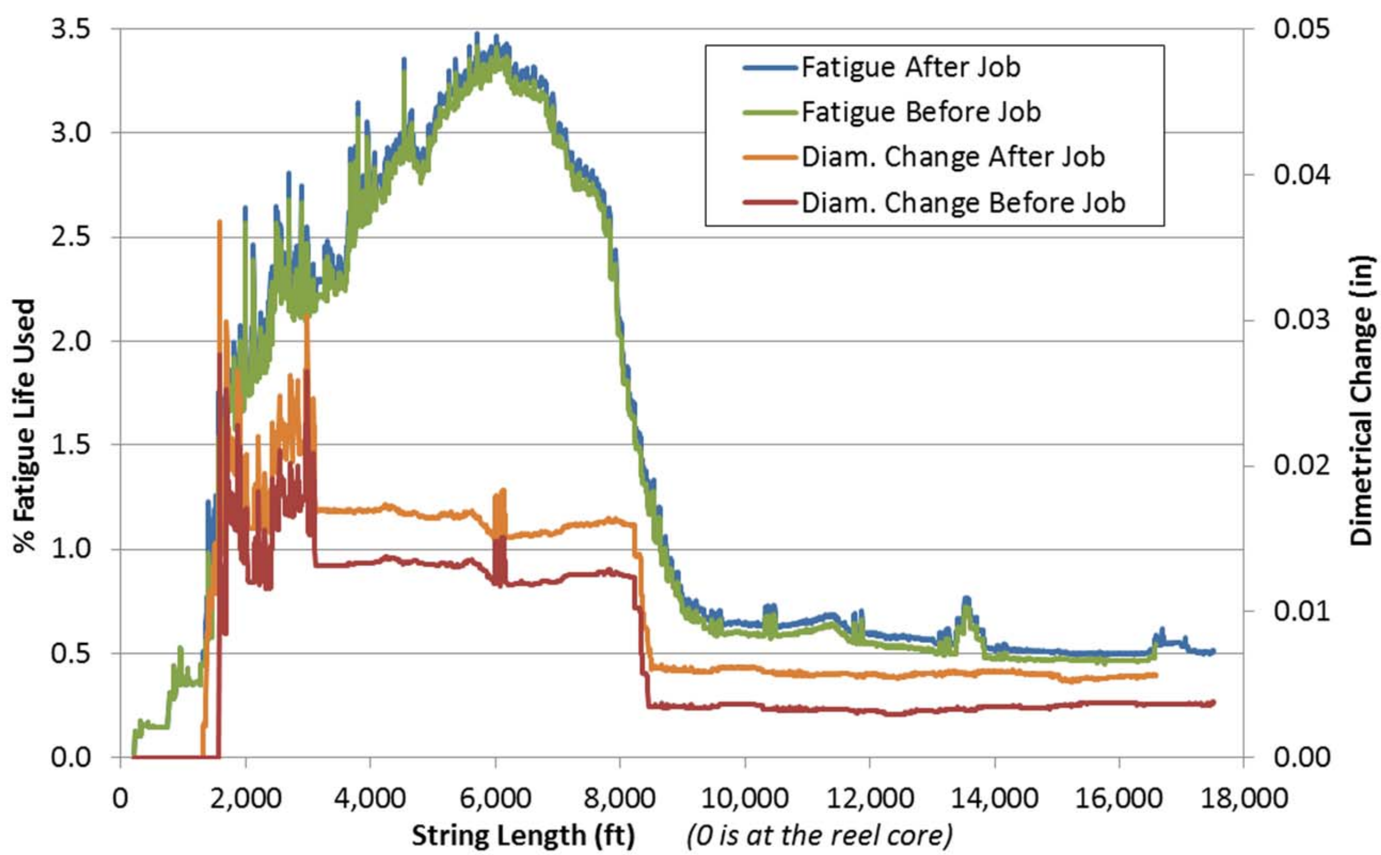


Figure 13 - Fatigue and Diametrical Change along the Length of the String