SPE-189948-MS

Rotation and Diameter Growth of Coiled Tubing

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This paper was prepared for presentation at the SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition held in The Woodlands, TX, USA, 27-28 March 2018.

Abstract

The fact that coiled tubing (CT) rotates when used is not currently included in CT fatigue models. The CT also experiences diametrical growth and elongation. Almost all fatigue testing is done without rotating the CT sample. Diameter growth models based on these fatigue tests have over predicted the amount of diametrical growth.

This ongoing work has already shown that rotation affects the fatigue life. Fatigue life calculations without rotation are usually conservative. It has also shown that rotation does not explain the over prediction of diametrical growth. It is currently believed that the axial force (weight) in the CT causes elongation and a diametrical decrease, which reduces the diametrical growth. It is also possible that the injector chains cause some reduction in diameter. The fatigue/plasticity model being developed will attempt to answer more of these questions. This paper presents fatigue testing with rotation and with varying pressures, which is being used to validate the model. Lab measurements made with a rotation measuring device are also presented.

Introduction

CT Rotation

When CT is manufactured, a continuous strip of steel is rolled so that the edges come together to form a tube. The two edges are welded together at the top of the tube, causing a continuous seam weld. After the welding process there is a seam weld anneal process, in which the seam weld is heated and then cooled. The CT tends to twist or rotate between the welding station and the seam weld annealing station. For the rest of this paper the term "rotate" will be used when referring to this twisting motion. Care must be taken to prevent the CT from rotating too far, making the seam weld annealing ineffective. Figure 2 shows pictures of the seam welding, weld bead removal and then the seam annealing.

Figure 1—CT Air Cooling and First Spooling

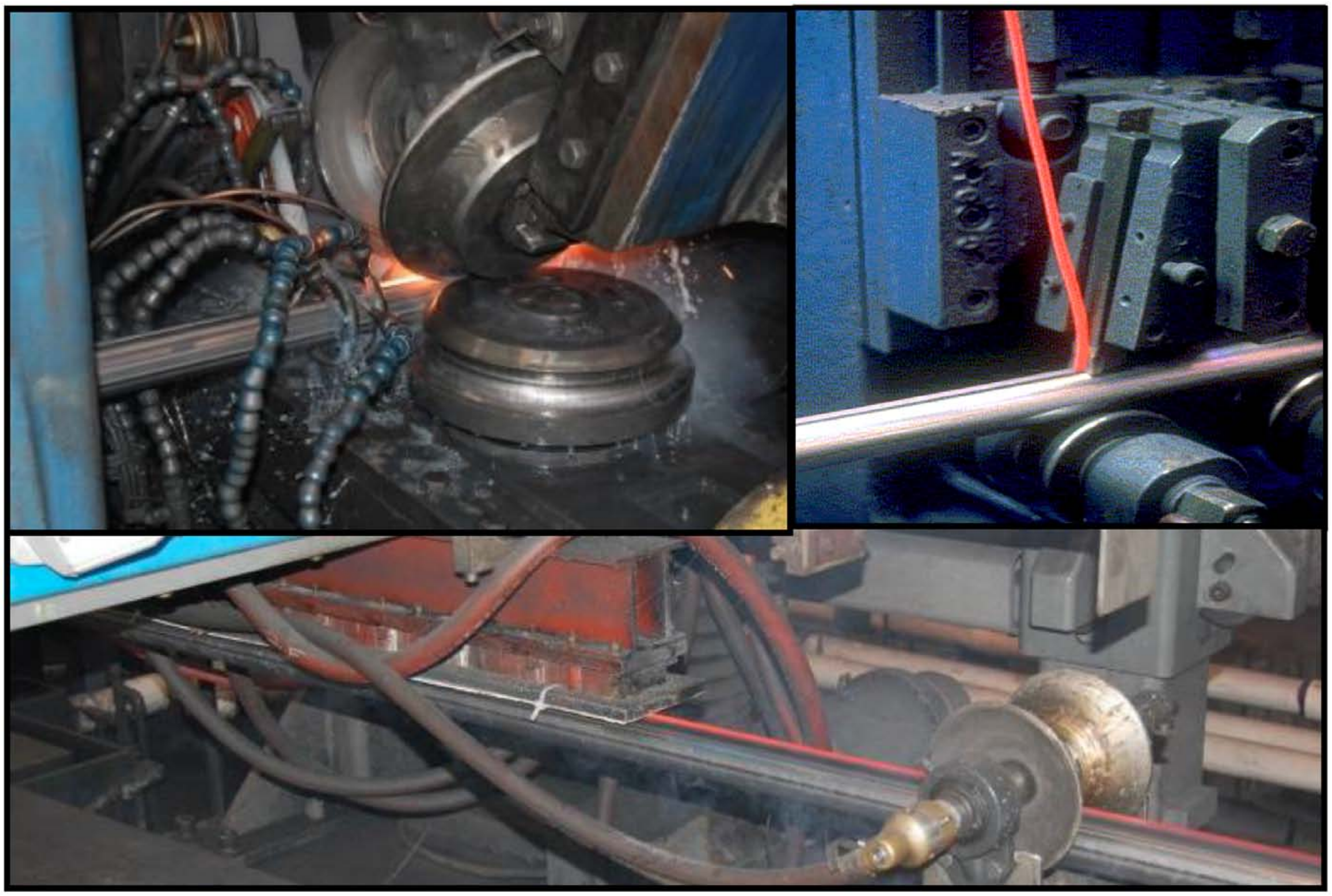

Figure 2—CT Seam Weld, Removal and Annealing

After the seam annealing, final heat treatment and sizing, the CT air cools for a significant distance (see Figure 1) before being spooled onto a reel for the first time. Over that distance the CT rotates. Once on the reel the rotational position of the seam weld varies.

Reference 5 documents testing that was done using a laboratory device, dubbed an ROMD (rotational orientation measuring device), shown in Figure 3. Reference 5 "Test 1" showed that the location of the seam weld for new 2″, 13,538 ft string, new from the manufacturer, oscillated 30 to 40 degrees. There are conjectures, but no one knows for sure why this rotation occurs.

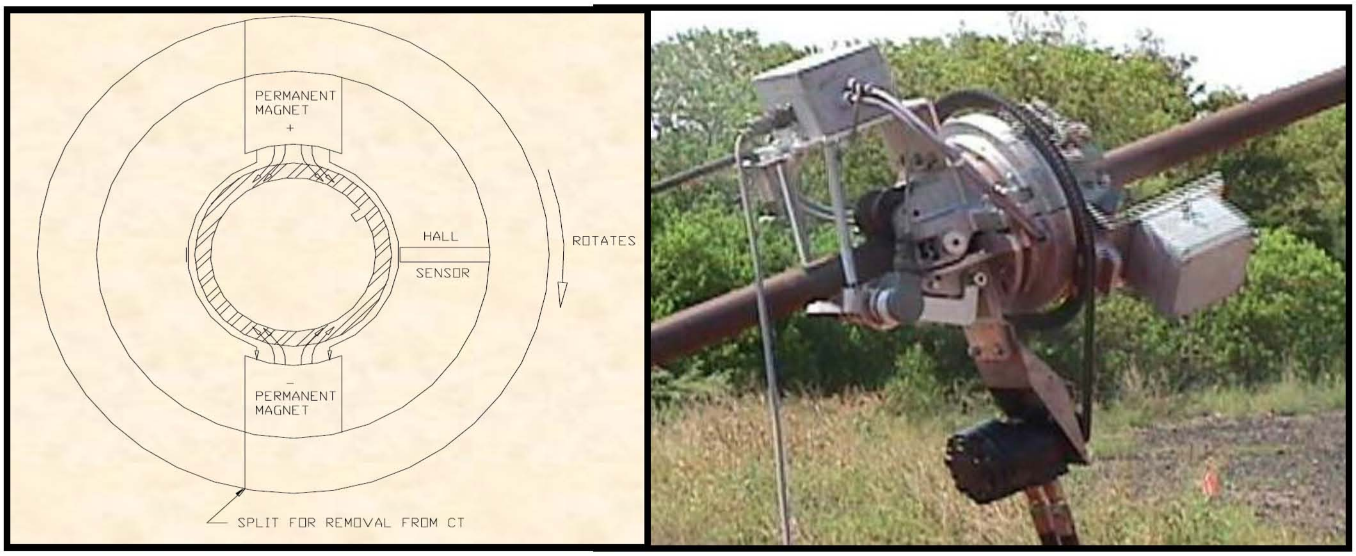

Figure 3—Rotational Orientation Measuring Device from Reference 5

Reference 5, "Test 2", documents testing that was done on a test well to measure the rotational orientation of the seam weld as a used CT string was run into a test well to 5,054 ft, and back out again. As is customary, pull tests we run while running into the hole (RIH), by pulling up 100 ft at every 1,000 ft depth increment. Results from this test are shown in Figure 4. The first graph shows the rotational orientation of the seam weld when RIH (blue) and the orientation when pulling out of hole (POOH) in red. The second graph shows the difference between these two sets of values (RIH and POOH). From these graphs the following observations can be made:

- For the first 2,300 ft there were 2 complete revolutions. The POOH measurements are similar to the RIH measurements. The difference in the measurements averaged only 6 degrees, but the maximum reached 40 degrees.
- From 2,300 ft to 3,400 ft the CT which was RIH had 1 complete rotation, with a period of 1,100 ft. However, when that same section of CT was pulled out of the hole it had 2 complete rotations in this section with an average period of 550 ft!
- From 3,400 ft to 5,000 ft there were 10 complete rotations of the CT, with an average period of 160 ft. The direction of rotation was the same direction that torque from a drilling motor would rotate the CT, causing one to wonder if this string may have been used for drilling at some point. Of course, at 5,000 ft, the RIH and POOH measurements agree. As the string was POOH, the POOH measurement begins to deviate gradually from the RIH measurement, until it reaches a maximum of 100 degrees in this section. Most of this section of the string rotated an average of 60 degrees while in the hole.

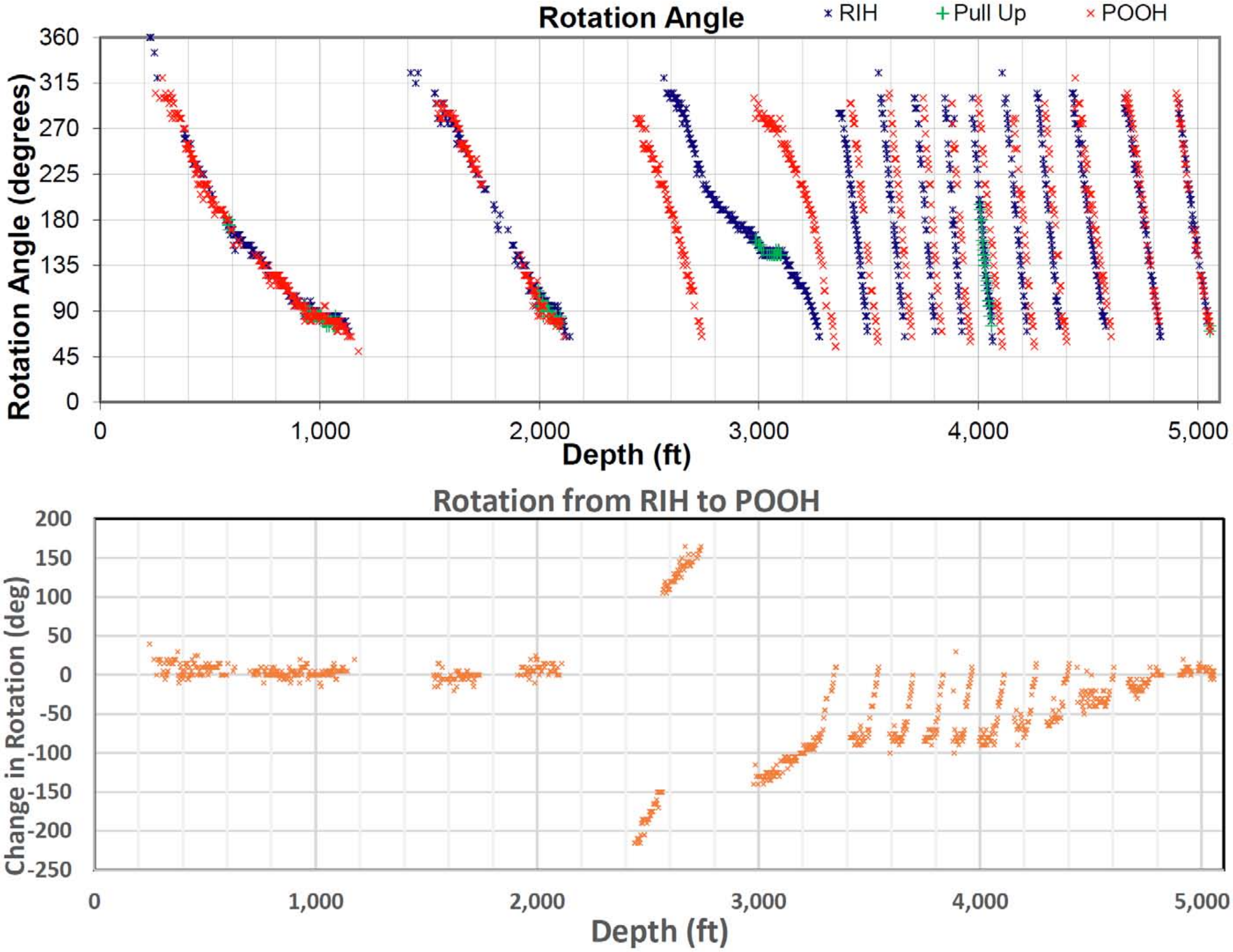

Figure 4—Results from ROMD Test in Test Well

Based on these results, and undocumented stories from the field, we know the CT rotates during manufacturing, during spooling, and during field operations. The cause of the rotation is not understood. But the fact that rotation has occurred effects the fatigue life and possibly the axial and diametric changes (elongation and ballooning) that occur in the string (references 1,2,3). This work looks at the effect of rotation on fatigue life and diameter growth.

CT Diameter Growth

The diameter growth of CT has been studied, measured and modeled for as long as the fatigue life has been studied. CT life models like the Cerberus™ model, predict the diameter growth based upon diameter growths measured during fatigue testing. However, the predicted diameter growth tends to be larger, than the diameters measured in the field. The following are things which could cause the diameters measured in the field to be less than the diameters predicted by the models:

- CT rotation
- Variations in pressure inside the CT (fatigue tests are typically performed at 1 pressure)
- Tension in the CT in the well
- Reel back tension – tension in the CT while being bent on surface

A second aspect of this work was to try and determine which of these things is significant to diameter growth.

Twenty years ago, Radovan Rolovic studied CT deformation for his PhD at the University of Tulsa (reference 1). A product of that work was a software model, now called CoilPerformance, which Radovan was kind enough to provide the authors for this work. Unfortunately, CoilPerformance does not contain the newer materials used for this testing, and thus cannot be expected to be accurate for specific tests. However, comparisons are made that show it is similar to measured results.

Effect of Rotation on Fatigue Life

Fatigue Model Development

Fatigue life models calculate the fatigue life used with each bending event. Historically models focus only on the point of maximum strain, which is either the top or bottom surface of the CT. The axial strain is given by the following equation:

$$\varepsilon_a = \frac{r}{R} \tag{1.1}$$

Where r is the radius of the CT and R is the radius of bending. The fatigue models use this axial strain, the stresses caused by internal pressure, and axial force, to calculate the fatigue life used.

A modified fatigue model was developed which divided the cross-section of the CT into 72, 5-degree elements. For each element the radius r is the radius from the centerline of bending of the cross-section to the element. As the CT rotates, the elements rotate about the centerline, and r changes. Figure 6 shows the non-amplified axial strains (using r to the inside surface) for a single element which starts at the top of the CT. All of the CT bending events are to a 48″ radius. The CT is rotated 10 degrees each trip in and out of the well. There are 3 bending cycles in a trip.

Figure 5—Fatigue Test Machine and 10 deg Rotation Samples

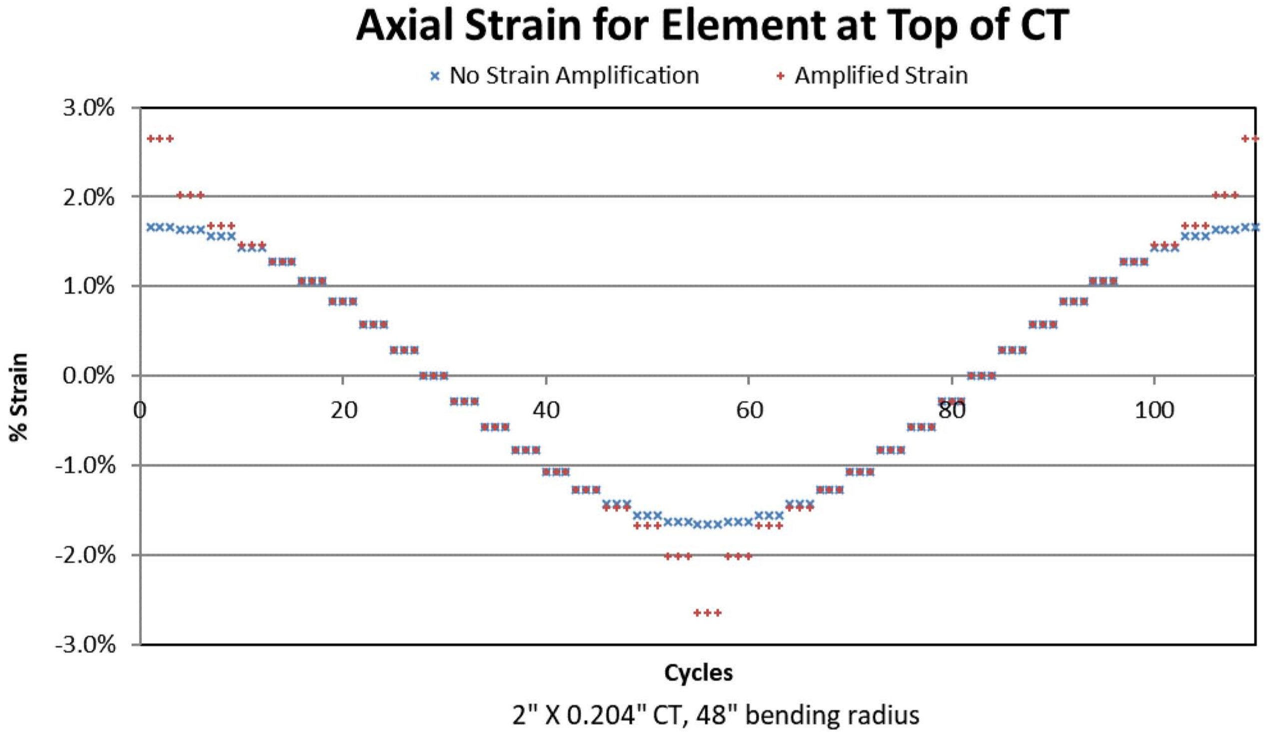

Figure 6—Axial Strain for Element Starting at the Top, Rotating 10 deg each trip

In reference 5, and initially in this work, these axial strains were used to calculate the fatigue life. However, the fatigue life predictions tended to be longer than the fatigue life measured in rotation fatigue tests. This was due to the fact that the strain range was varying with rotation. As Figure 6 shows, at some rotational locations the strain ranges for the cycle are positive (tensile), and at other rotational locations the strain range is negative (compressive). These strain reversals (switching from positive to negative strains) cause more fatigue damage to the material than repeated strains in the same range. Known methods such as Rainflow Cycle Counting were implemented to correct this problem, but were not effective. A method was developed in which an amplified axial strain was used, especially at the higher strains. This method more accurately matched the fatigue test results.

There is a worst-case scenario which has not been tested. In this worst-case the CT would rotate 180 deg per trip. The above amplified axial strain method shows the fatigue life would only be 34% of the fatigue life without rotation. It seems extremely unlikely that this type of rotation could ever occur.

Fatigue Tests

Fatigue tests with rotation are difficult and time consuming. All the testing for this paper was done with 2″ outer diameter by 0.204″ wall thickness, TS-90 CT with, using a 48″ bend radius and 7,000 psi internal pressure. For a baseline, 5 tests were performed with no rotation. Results from this testing are shown in Table 1.

Table 1—Results from Fatigue Tests with Rotation

Degrees per rotation	0	10	30
Cycles between rotations	NA	3	9
Samples tested	5	20	3
Fatigue Cycles to Failure			
Min of	105	150	134
Average cycles to failure	111	167	144
Max cycles to failure	118	187	159
Model Prediction	117	165	152
Diameters at Failure (in)			
Minimum	2.281	2.366	2.352
Average	2.318	2.385	2.369
Maximum	2.355	2.405	2.385
Average dia. growth per cycle (in)	0.0029	0.0023	0.0026

No Rotation. When there is no rotation, the current fatigue model accurately predicted the cycles to failure. Figure 8 shows the fatigue around the cross-section for all the cases. The fatigue life reached 100% at the top and bottom. For the 5 tests done, 1 failed at the top and 4 failed at the bottom. Failures at the top or bottom tend to be random.

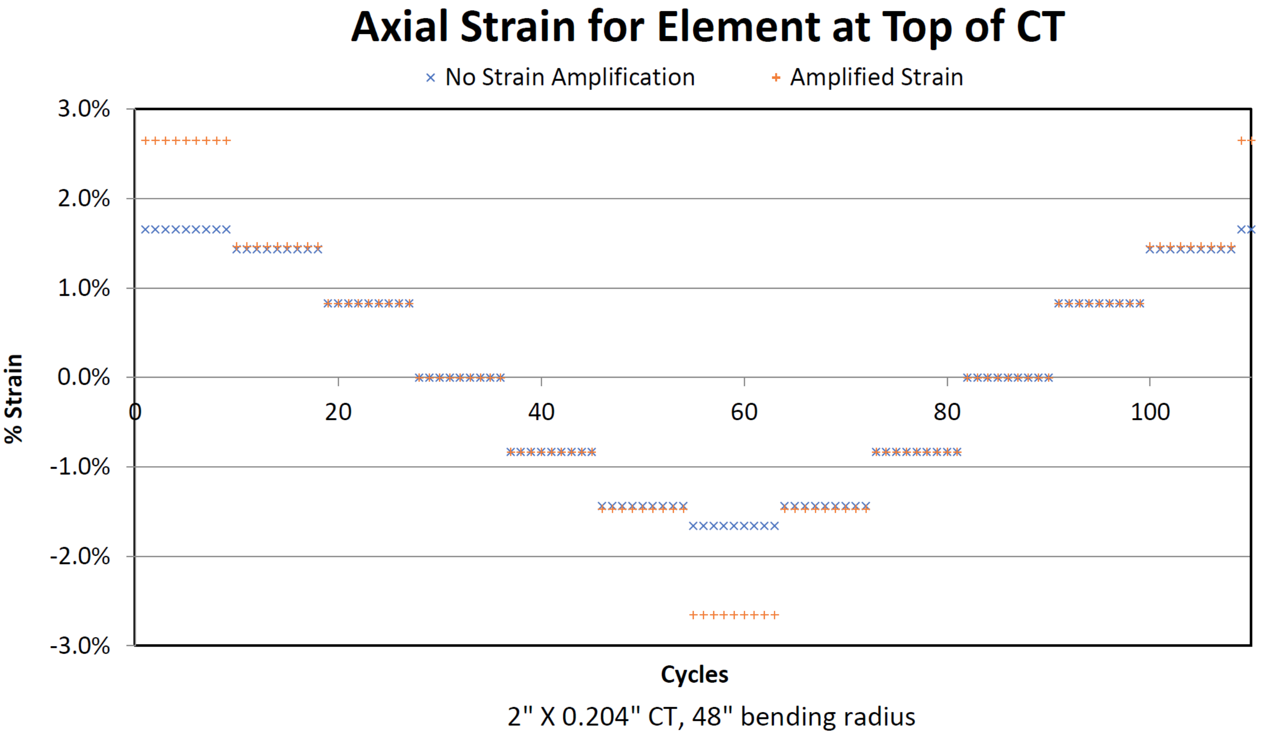

Figure 7—Axial Strain for Element Starting at the Top, Rotating 30 deg Every 3 Trips

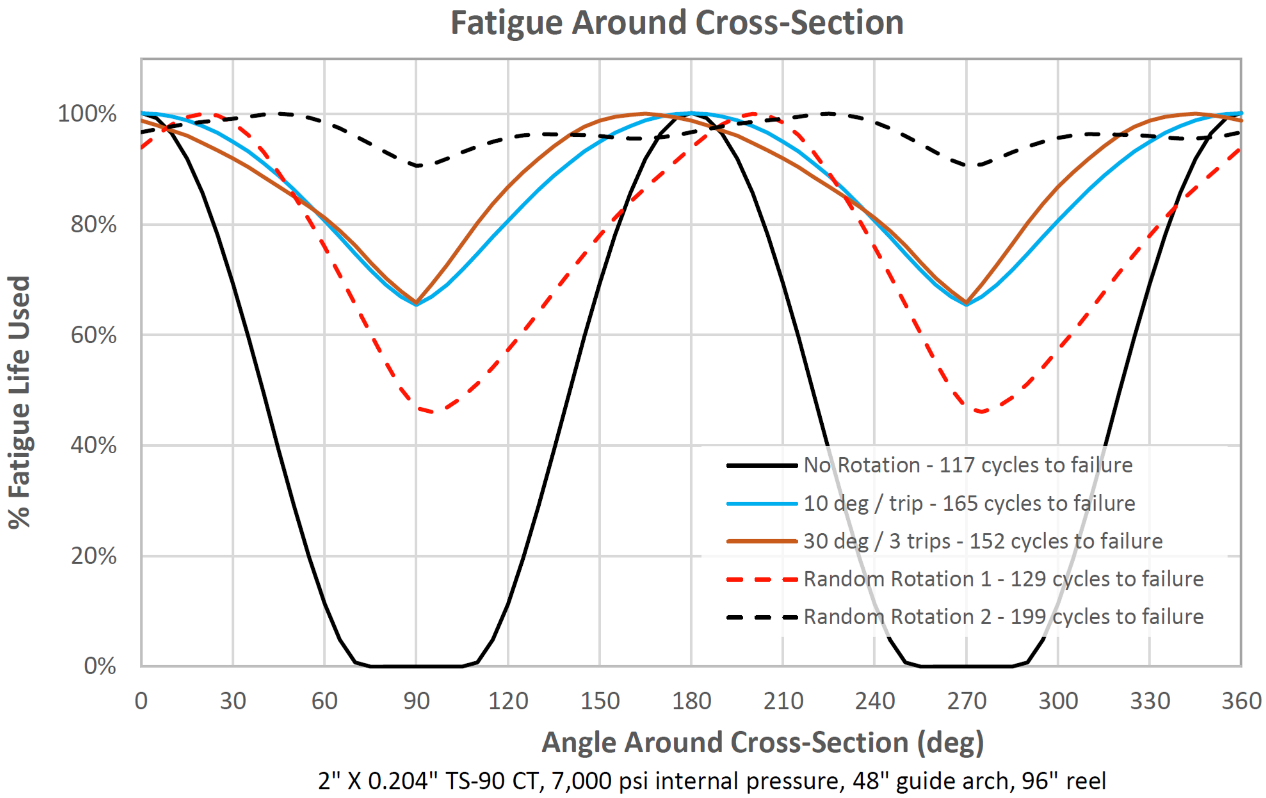

Figure 8—Fatigue Around Cross-Section for Various Rotations

Rotation 10 deg / Trip. Figure 5 shows the fatigue test machine and samples marked with lines each 10 degrees. Every 3 cycles the sample was rotated and a green dot was painted on the line. After 36 rotations the dots started to overlap. Figure 6 shows the axial strain for each cycle for one element located at the top of the CT sample. The fatigue life increased by 50%, from 111 cycles to 167. The amplified axial strains are also shown. With these amplified strains the model predicted 168 cycles to failure.

Rotation 30 deg / 3 Trips. A second set of rotation fatigue tests were done in which the sample was rotated 30 deg every 9 cycles (3 trips). Figure 7 shows the axial strains for the element which started at the top of the CT. The average number of cycles was 144 and the amplified strain model predicted 146 cycles.

Random Rotation. Random rotation every trip was modeled using the amplified strain model. Since the rotation was random, the results for each modeled test were different. Two modeled tests are shown in Figure 8, one with 129 cycles to failure and the second with 199 cycles to failure. These were the max and min cases from several modeled tests.

CT Diameter Growth

Effect of Rotation on Growth

Does the rotation of the CT effect the diameter growth? According to the average diameters at failure shown in Table 1 for tests with and without rotation, it would appear that rotation causes the growth to increase. However, these tests each had a different number of cycles to failure. Considering the average diameter rate or growth per cycle (shown in the same table), the rotation reduced the rate of diameter growth. In the two cases with rotation, the growth rate is 80% and 89% of the growth rate without rotation. Thus, it would seem that rotation actually slows the rate of growth, but the effect is not large.

CoilPerformance was used to model these same tests, with and without rotation. It predicted that the diameter rate of growth for the two rotation cases would be 91% and 86% of the case without rotation.

Effect of Varying Pressure on Growth

Radovan found in his work that varying the internal pressure affected the diameter growth. Figure 9 is an example from his thesis (reference 1) which shows that the diameter grows when there is high internal pressure and shrinks when the internal pressure is low. It also shows that the CoilPerformance model can calculate the growth and shrinkage. Note that when the pressure is high, the growth continues. When the pressure changes from high to low, there is initially significant shrinkage, but then that shrinkage tapers off and the diameter remains fairly constant until there are more high-pressure cycles.

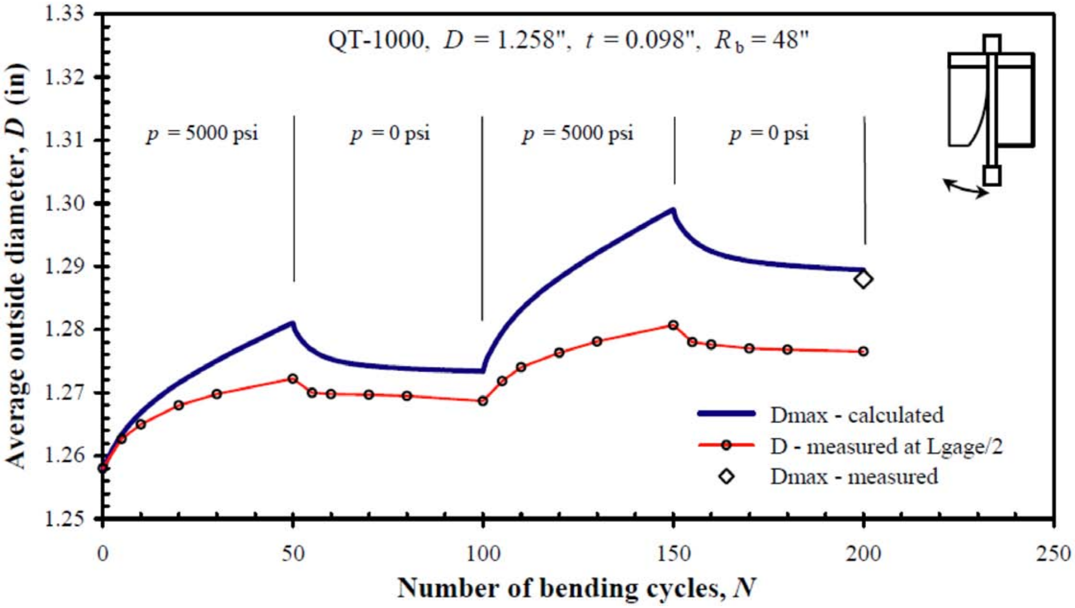

Figure 9—Calculated and Measured Diameter Growth with Varying Pressure from Reference 1

Similar tests were performed in conjunction with the fatigue testing discussed earlier, again using the 2″ × 0.204″ TS-90 CT cycled with 48″ radius of curvature. In the first test, the CT was cycled 6 times with 7,000 psi internal pressure, and then 6 times with zero internal pressure. The diameter was measured at the end of each 6 cycles. The test was performed 3 times, but one test wasn't used because of an error. The results for the 2 tests are shown in Figure 10, compared to the current model prediction. Again, when there is 7,000 psi pressure the diameter grows. When there is no pressure the diameter decreases. It is interesting that the measured diameters almost reach the model prediction when fatigue failure occurs. However, in the middle of the life, the difference between the actual diameters and the model prediction is over 100%.

Another set of 4 tests were performed in a similar manner, this time with 30 cycles at 7,000 psi and then 30 cycles at 0 psi, to see if the decrease in diameter was asymptotic. The results of these tests are shown in Figure 11. The decrease in diameter was greater with the first few 0 pressure cycles. The diameter continued to decrease for the full 30 cycles at 0 pressure. Again, at the end of the test the diameters were close to the current model predictions. But in the middle of the tests the current model over predicted the diameter growth by over 100%

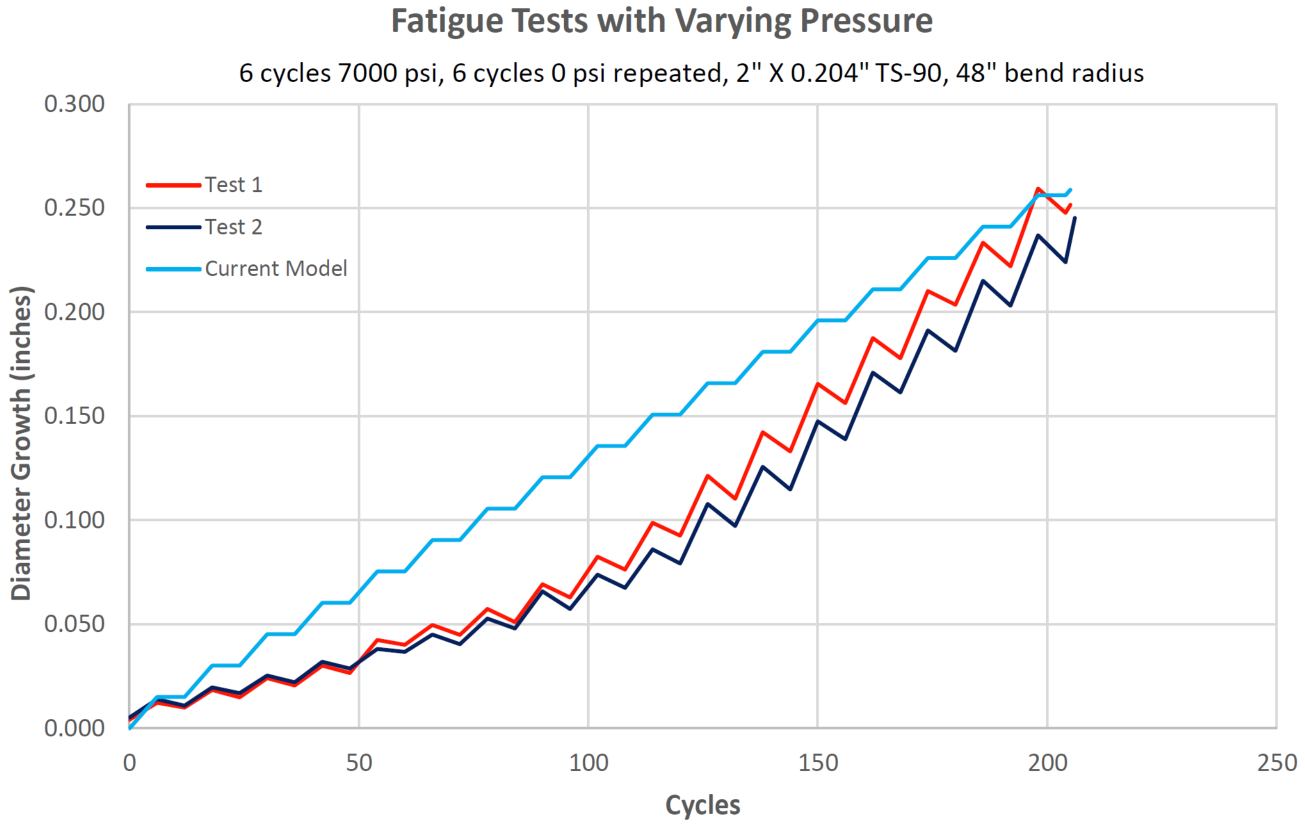

Figure 10—Varying Pressure Tests - Alternating 6 Cycles with Pressure, 6 Cycles Without

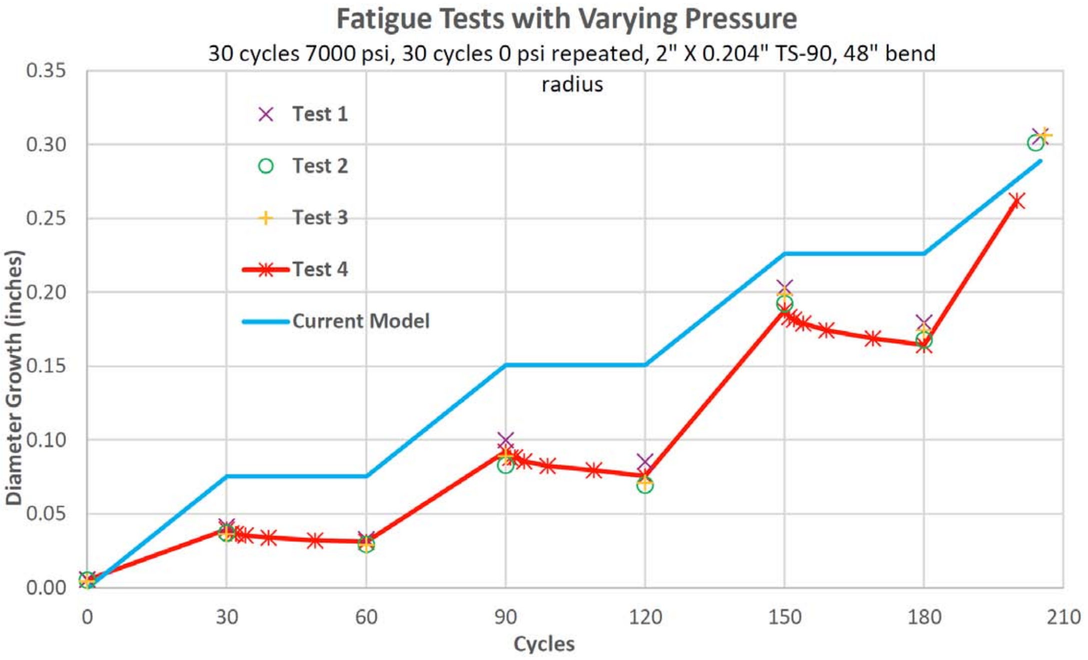

Figure 11—Varying Pressure Tests - Alternating 30 Cycles with Pressure, 30 Cycles Without

Effect of Tension in the CT

The hanging "weight" of the CT below the injector chains is usually the maximum tension the CT experiences when being run in and out of a well. Sometimes this weight can be significant, possibly as much as 80% of the yield strength of the CT. Tension causes pipe to decrease in diameter, or to "neck". The decrease in diameter that this tension causes was studied using Radovan's CoilPerformance model for

HS-90 CT. A tension of 0%, 40% or 80% of the yield force was applied once per trip. Figure 12 shows the results of this study. The tension does cause a decrease in diameter, but that decrease is basically recovered on the next bend cycle. For the 40% yield force case, the diameter remained basically the same as the no tension case. For the 80% yield force case, the first trip did cause a decrease in diameter, but after that difference the diameter follows the no tension case. Note that 40% of the yield force would be a normal "weight" seen in field operations. 80% is very high and would rarely be seen.

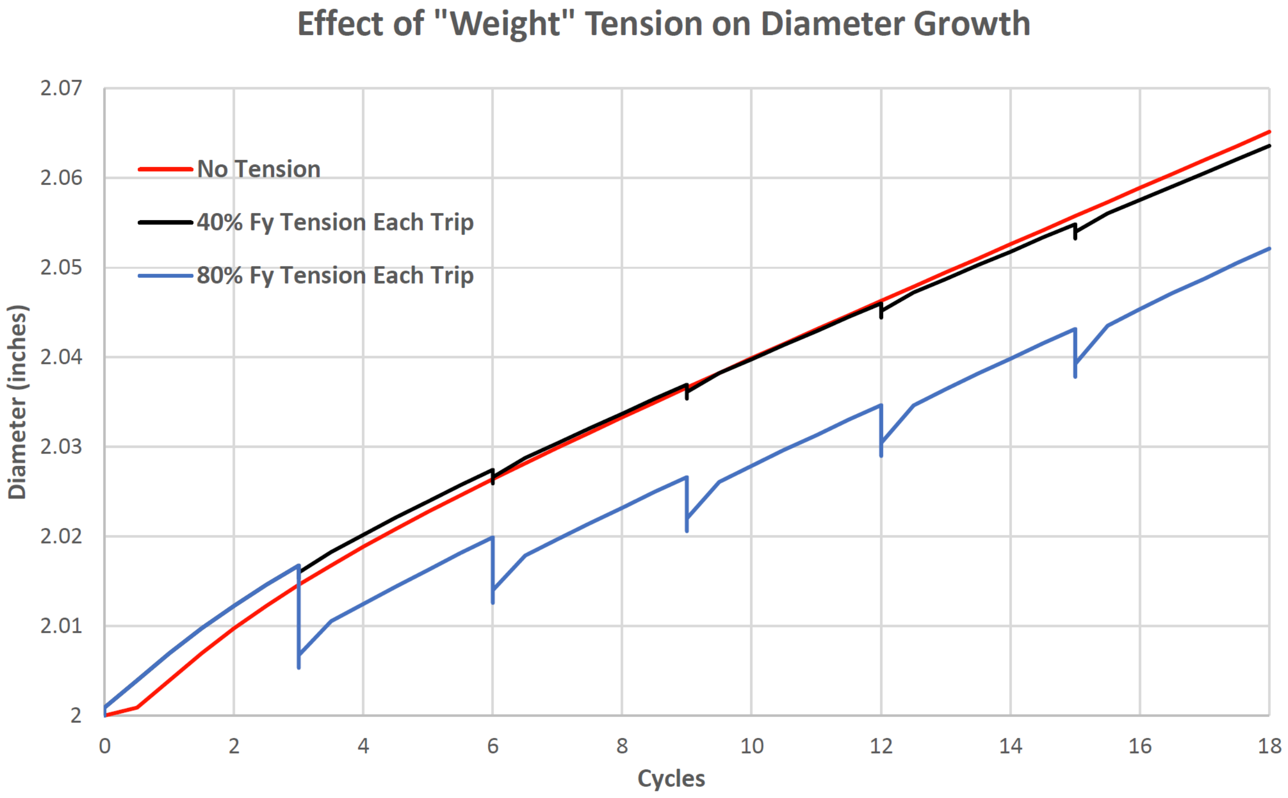

Figure 12—Diameter Change due to Tension Caused by "Weight" in Well

Based on these results it appears that the tension that occurs in the well has little impact on the diameter growth.

Effect of Reel Back Tension

Reel back tension is the tension the tension in the CT between the reel and the injector. This tension is necessary to keep the CT from "springing" off of the reel. Since this tension is in the CT when it is being plastically bent at the reel and at the guide arch, it was felt that this tension, though small, might cause the CT to "neck" to a smaller diameter. Again, CoilPerformance was used to model this RBT for HS-90.

Figure 13 shows the results from this model for 0 and for 5,000 lb RBT. Again, there is a difference in diameter for the first bending cycle, but after that the diameter difference remains constant. Based on this result it appears RBT has little impact on diameter growth.

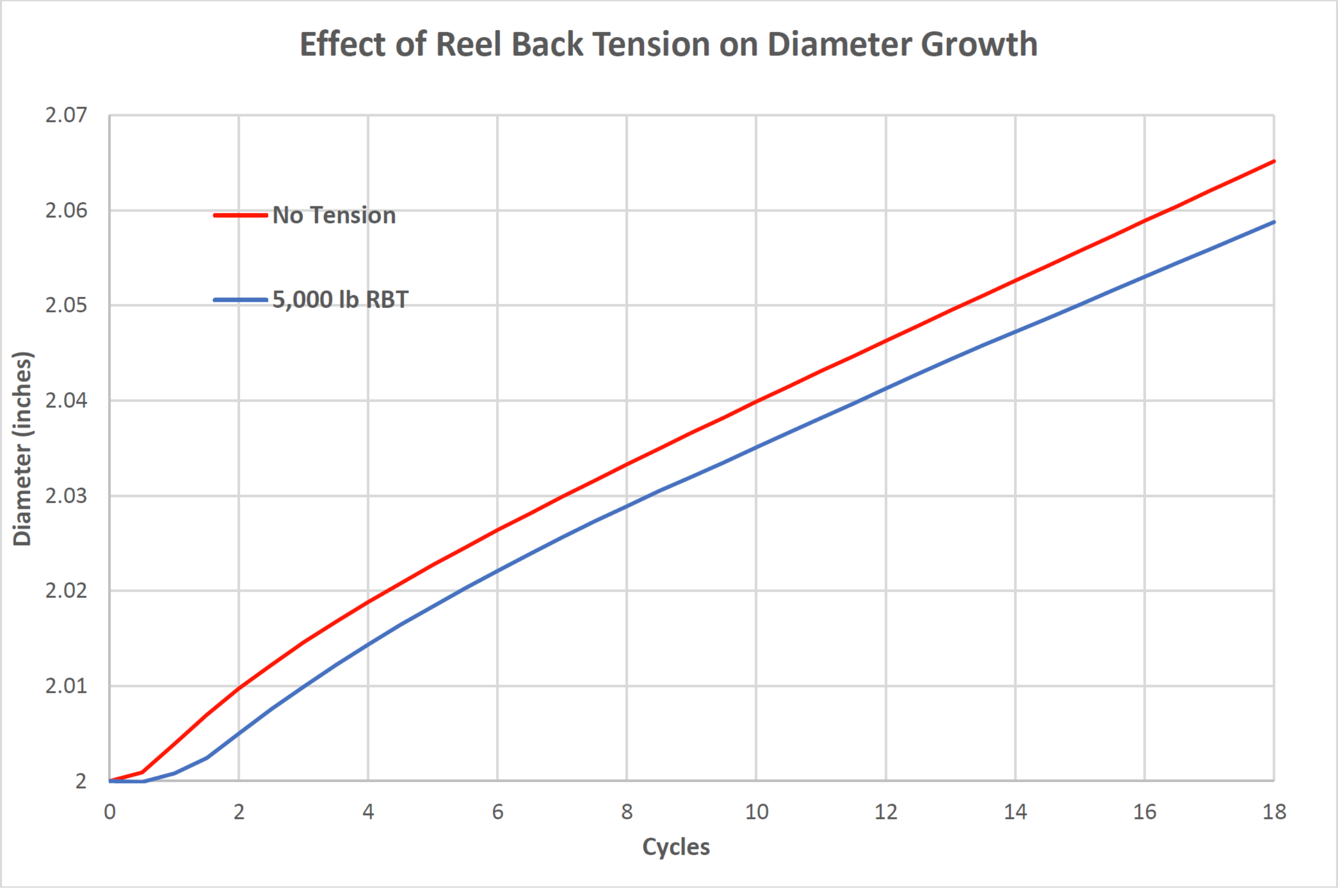

Figure 13—Diameter Change due to Reel Back Tension

Conclusions

Rotation Fatigue life

The rotation of the CT during its life does affect the fatigue life. The worst case tends to be the case without rotation, which means the current fatigue models (which assume no rotation) are conservative. An amplified strain fatigue model was able to model the two rotation test cases presented. Many more fatigue tests with rotation are needed to develop an accurate fatigue model that includes rotation.

Without a measurement of the CT rotational orientation during CT operations, a fatigue model that accurately modeled the effect of rotation would be useless. Efforts are being made to develop a commercial version of the ROMD described here.

CT Diameter Growth

Four possible causes of the measured diameters in the field being less than the diameters predicted by current models have been examined. The varying pressure inside the CT causes the most significant reduction in diameter after the diameter increased due to internal pressure. Rotation of the CT has a much smaller impact. Tension due to weight, and RBT have a minimal impact.

Acknowledgements

The authors wish to thank Radovan Rolovic for the use of his CoilPerformance model, and Jason Oil and Gas for providing the fatigue tests presented.

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