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DESIGN AND VALIDATION OF THE 16-INCH SCHEDULE 80 INTERFERENCE CONNECTION THROUGH NUMERICAL AND EXPERIMENTAL METHODS

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Abstract

A precision engineered controlled interference fit mechanical connector for joining steel pipe is evaluated in this paper. The primary advantage of such a connection is that the need for trained welders and radiographers is minimized, and the connection-joining process is accomplished very quickly with onshore and offshore production rates in the range of 25-30 connections per hour, and 15 connections per hour respectively. Use of these mechanical interference connections in the oil and gas industry began in the 1970s in the transportation of low pressure gas. Today, the implementation of this technology includes nominal pipe sizes ranging in size from 2-inch schedule 40, to 16 inch schedule 80, with the latter size being the subject of this paper. The usage of these connections varies from gathering and distribution systems, transmission lines, flowlines and other specialized applications both onshore and offshore.

This connection takes advantage of both the elastic and plastic properties of modern steel alloys, and therefore the design of a new connection size necessarily implies a rigorous process including numerical analyses and destructive testing for validation. This paper describes the use of finite element analysis (FEA) and full-scale testing of the connection under various internal pressures, tension and bending conditions as guided by ISO 13679:2002(E). The pipe size and type used in the program was 406-mm (16-inch) OD x 21.4-mm (0.843-inch) Wall Thickness, nominal Grade X52. The connection itself was monitored during make-up, simulated reeling, ISO Series B guided-testing and limit-load testing.

Details on the testing methods along with the analyses performed to evaluate the performance capabilities of the aforementioned interference connection are provided. The results of this testing program provided the data required to develop a performance envelope on the capacity of said connection size. In addition, the results obtained allow for estimating the applicability of this type of connection in future service conditions.

1. Introduction

Mechanical connectors have been used in oil and gas production for many years as an alternative to welding. Their primary advantage is that they minimize the need for welding, and all of the ensuing field NDT requirements, as well as eliminating the need for field applied protective coating of the joint. Production rates are increased and the number of required staff on location is reduced.

The concept behind the interference fit process is simple, but does require making the decision to use the connection early in the pipe procurement process. The first step is to prepare both ends of each pipe joint for the connection. This work can be performed at a pipe mill, or a coating facility. One end of each joint (Bell End) is cold formed by expansion into a bell shape by the insertion of a hardened steel mandrel. A liquid lubricant is used to prevent galling of the steel pipe surface. The opposite end (Pin End) is grooved and has a slight bevel applied to the end by a tapered roller. This operation is performed prior to any internal or external coating.

Once the pipe is delivered to the onshore location or offshore vessel, the joining press, along with a hydraulic power unit and automatic mixer, is used to join the pipe. For joint assembly, the pin OD and bell ID are coated with a thin film of a lubricant (catalyzed epoxy resin) to prevent galling of the pipe surface during joining. Once the lubricating epoxy cures to a solid, its lubricity properties and function cease to exist.

For onshore applications, the pipe is strung along the right-of-way (ROW) as would take place during a typical

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construction process involving welding. The joining press is transported along the ROW by a side-boom or other suitable transport vehicle. The power unit and automatic mixer are towed behind. At each connection, the bell and pin are centered between the unit's slips and the longitudinal hydraulic rams are used to pull the pin into the bell to a specified engagement length (depending on pipe size). The actual joining process requires a few seconds. The slips are released and the press is advanced to the next connection site. For offshore operations the same equipment is used; however, the press is stationary and the pipe moves through it to the tensioner. Whether work is done onshore or offshore, normal production rates of 25-30 connections per hour can be expected from a single press and a crew of 3-7, depending on pipe handling logistics. Figure 1 provides a photograph showing onshore installations using this interference fit connection process.

Figure 1. Onshore installations using the interference fit connection process

Full-scale testing work of the 406 mm (16-inch) OD X 21.4 mm (0.843-inch) Wall Thickness, Nominal Grade X52 interference fit connection evaluating comprehensive states of stress were carried out using the ISO 13679:2002(E) standard as a guideline[1]. This testing consisted of static strength combined loads, including bending, tension or compression, and internal pressure. The aforementioned stress states were evaluated using the defined load path[2] in stress-space per ISO 13679:2002(E). Lastly, after the static strength load paths were executed, the ultimate capacity of the joint was evaluated in tension, pressure, and combined tension, pressure and bending. As a validation step, a finite element analysis was compared to the experimental results during joining and tension to failure experiments.

2. Mechanics of the Interference Fit System

During belling, the internal diameter of the "bell pipe" is increased and the bell pipe is strain hardened so that its normal yield strength is shifted by isotropic and kinematic hardening. This property may require stress relieving of the bell end of the bell pipe under certain service conditions. The mandrel is sized so that the bell ID will be smaller than the pin OD, so that the degree of interference is controlled. This interference ensures that the pin will be placed in compression by the additional expansion of the bell during insertion. It is this compressive load applied over the joint engagement area in the presence of steel on steel friction that gives the connection its strength. The pipe properties of diameter, wall thickness, engagement length, coefficient of friction, and material grade define the system performance.

3. Tests Performed

A total of six (6) samples were included in this test program per Table 1. Of the six samples, three were instrumented during the make-up process as exemplars and compared to FEA results. The testing schedule for all six samples are included in Table 2. Load schedules for each sample were determined from material tensile testing, as well

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[1] The testing protocol was adapted by lowering the 95% von Mises equivalent stress envelope in stress space, to a different envelope. The final envelope was evaluated using Elastic-Plastic Finite Element Analyses, which modeled the belling and joining processes in detail. Otherwise, the trajectories of the testing load paths in stress space were the same as ISO 13679:2002(E). The details of the testing envelope are discussed in this paper.

[2] This load path imparts stresses that are much higher than the anticipated operating envelope.

as diameter and wall thickness measurements. The resulting test loads were calculated in relation the Actual Yield Strength (AYS) of each sample, using 95% of the nominal wall thickness, or the minimum wall thickness (whichever was less), in order to assure that the stresses in the pipe itself did not exceed the yield strength of the material during the ISO Series B testing.

Table 1. Pipe Size

Outer Diameter (mm {in})	Wall Thickness (mm {in})	Type	Grade
406 {16}	21.4 {0.844}	SMLS	X52(AYS of 71.5 ksi, Tensile Strength of 86.7 ksi)

Table 2. : Sample Matrix for Testing Program

Nominal Pipe Size	Sample Designation	Instrumentation During Make-up (Belling and Joining)	Reeling	ISO 13679: 2002(E) Series B	ISO 13679: 2002(E) Series B with Bending	Limit Load Testing
16-inch OD x 0.844-inch, Grade X52 (AYS of 71.5 ksi) Pre-qualification	1	Yes	No	No	No	Yes
	2	Yes	No	No	No	Yes
16-inch OD x 0.844-inch, Grade X52 (AYS of 71.5 ksi) Pre-qualification	LP1	Yes	Yes	Yes	No	Yes
	LP5	No	Yes	No	Yes	Yes
	LP3	No	Yes	Yes	No	Yes
	LP6	No	Yes	No	Yes	Yes

3.1. Make-Up of Joints

Prior to joining Sample 1, strain gages and circumferential displacement transducers were installed on the bell and pin as shown in Figure 2. During the joining operations, all measurements were recorded and monitored. Photographs of the joining operation for Sample 1 are shown in Figure 3 and Figure 4.

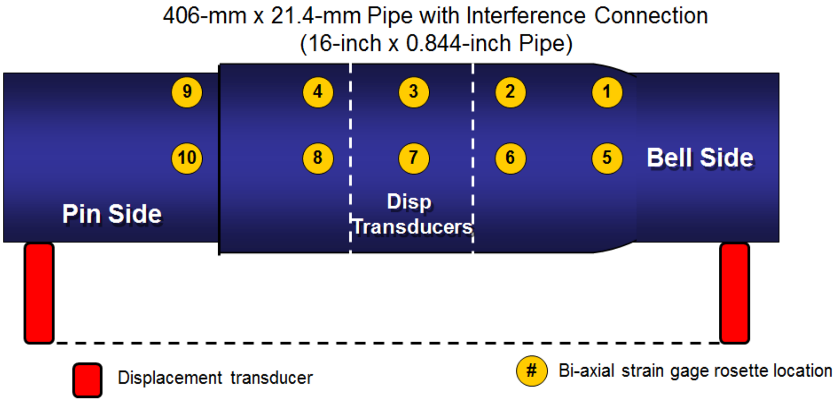

Figure 2. Instrumentation used for Samples 1, 2 and LP1 during the joining of the connection

Figure 3. Application of lubricating epoxy on Sample 1 prior to joining (406-mm OD x 21.4-mm Wall Thickness, Grade X52 (Actual Yield Strength of 71.5 ksi)).

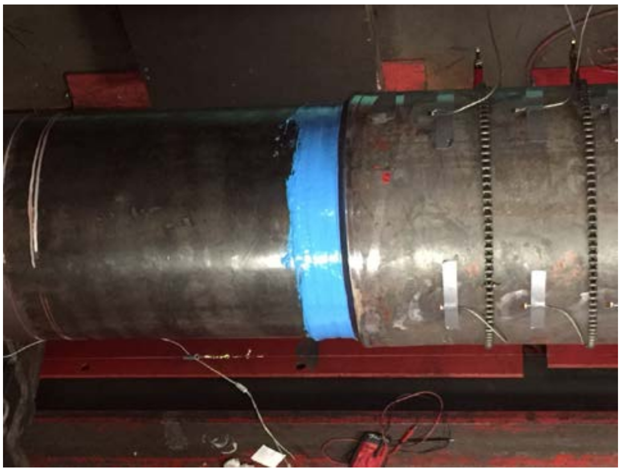

Figure 4. Joining operations for Sample 1 (406-mm OD x 21.4-mm Wall Thickness, Grade X52 (Actual Yield Strength of 71.5 ksi)).

3.2. Simulating Installation Testing (Reeling Test)

A bending reel test fixture was used to apply a fully-reversed bending load to generate bending strains of 2,500με. No axial loading was to be generated during this phase of testing. Four biaxial strain gages were installed on each end of each test sample to ensure that the proper bending strain was applied; additionally 4 biaxial strain gauges were installed in the transition region of the connection for future monitoring in the ISO tests. This is shown in Figure 5. Figure 6 shows a photograph of one of the samples in the reeling frame prior to the testing.

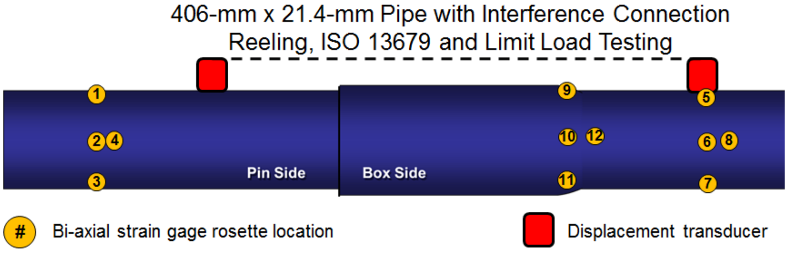

Figure 5. Strain Gage Locations for Simulated Installation Testing

Figure 6. Sample in the reeling frame (installation moment loading)

3.3. ISO 13679:2002(E) Test Loading (Pressure ± Axial Load ± Bending)

After Samples LP1, LP3, LP5 & LP6 were made-up, each was subjected to reeling followed by ISO 13679:2002(E) load testing, based on Table 7 and Table 8 of the same standard. Two samples (LP1 and LP3) were tested without bending, while the other two (LP5 and LP6) were subjected to bending during the ISO portion of the testing. Figure 7 shows the load points for samples LP1 & LP3, and LP5 & LP6. Figure 8 shows a typical sample in the load frame

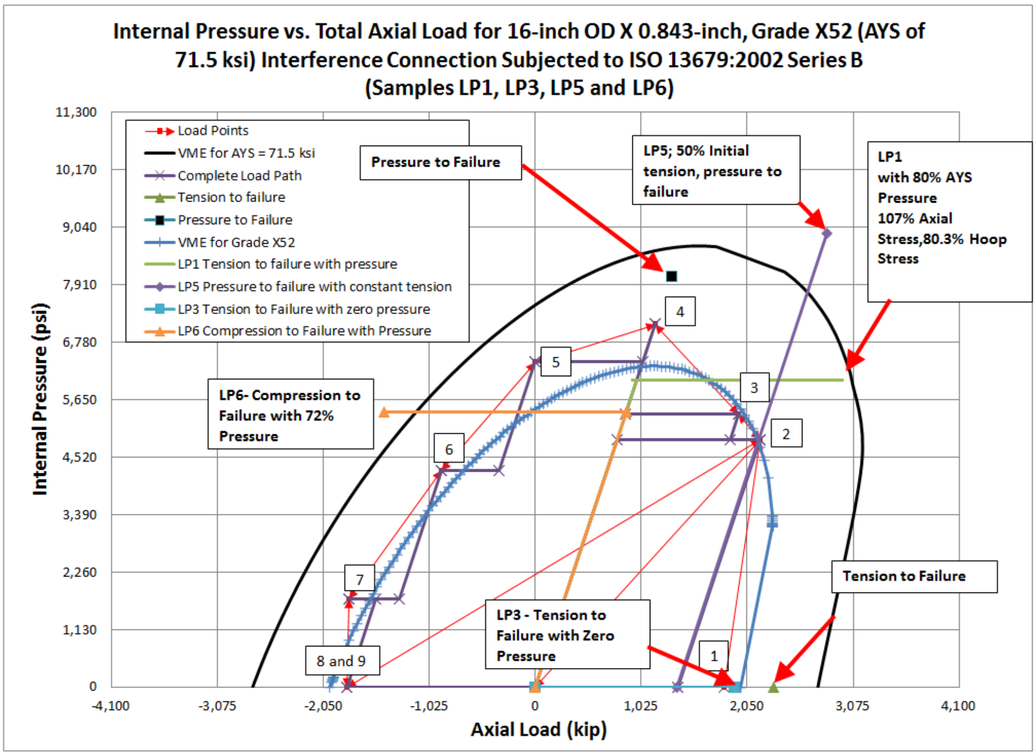

Figure 7. ISO Series B Load Plan (Samples LP1, LP3, LP5 and LP6)

Figure 8. Interference Connection Sample LP1 Prior to Testing

3.4. Limit Load Testing

Once the ISO 13679:2002(E) tests were conducted on the appropriate samples, each sample was tested (individually) to failure at various Load Points. Table 3 below shows the combination of loads considered for each sample.

Table 3. Description of Limit Load Stress Target – After the Loading Sequence in Figure 7 is performed.

Sample ID	Limit Load Specified
LP1	Tension to Failure with 80% AYS Hoop Stress by Internal Pressure
LP3	Tension to Failure with zero Internal Pressure
LP5	Pressure to Failure – 50% AYS applied Tension accumulating added Axial Stress by Pressure End Load
LP6	Axial Compression to Failure with 72% AYS Hoop Stress by Internal Pressure

4. Test Results

4.1. Sample Preparation and Make-up

As mentioned previously, Sample 1 was instrumented during the make-up phase of testing. Hoop and axial strains, as well as axial displacement, were measured during make-up.

During make-up, the maximum circumferential strain measured was approximately 8%. These measurements were taken by strain gauges, and confirmed by displacement transducers wrapped around the circumference, termed ‘Yoyos’. Further data-validation measurements compare favorably to hand calculations of the expected strains.

During the joining process, the pin pipe was marked at this axial position 360° around the circumference, and both belling and joining were monitored with cameras for visual confirmation of the appropriate insertion depths.

4.2. Sample Installation (Bending)

Following the make-up of samples LP1, LP3, LP5 and LP6, each was subjected to simulated installation testing in which a fully reversed bending moment, M_{in}, was applied to the samples. The target strains for each sample was 2,500 $\mu\varepsilon$, which corresponds to a radius of curvature of approximately 80 meters. For illustration, the actual strains generated during the application of this bending moment for sample 1 (LP1) are shown in Figure 9. All four samples successfully completed the installation phase of testing. Note that not all strain gages reached the 2,500 $\mu\varepsilon$ target at the same time. Moreover, some exceeded this value in an effort to achieve an average value of 2,500 $\mu\varepsilon$. This variation between strain gauge readings is due to variations in wall thickness, ovality and local differences in yield strength as well as the reeling mandrel not having the a radius of curvature of 80 meters.

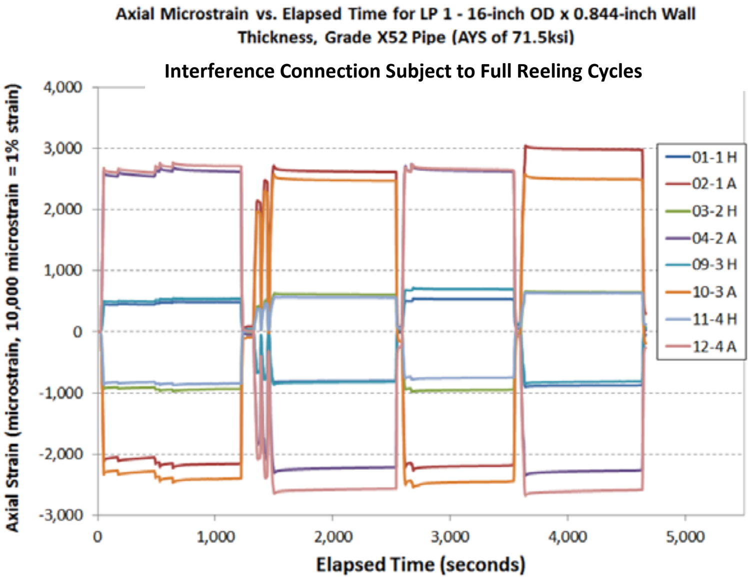

Figure 9. Installation Bending Strain vs Time for Sample 1 (LP1)

4.3. ISO 13679:2002(E) Testing

For ISO testing, samples LP1, LP3, LP5 and LP6 were subjected to the load steps described in the standard. These included internal pressure, axial loads, and bending. For illustration, the load history is shown for sample 1 in Figure 10. All four samples underwent ISO 13679:2002(E) testing without a leak being detected.

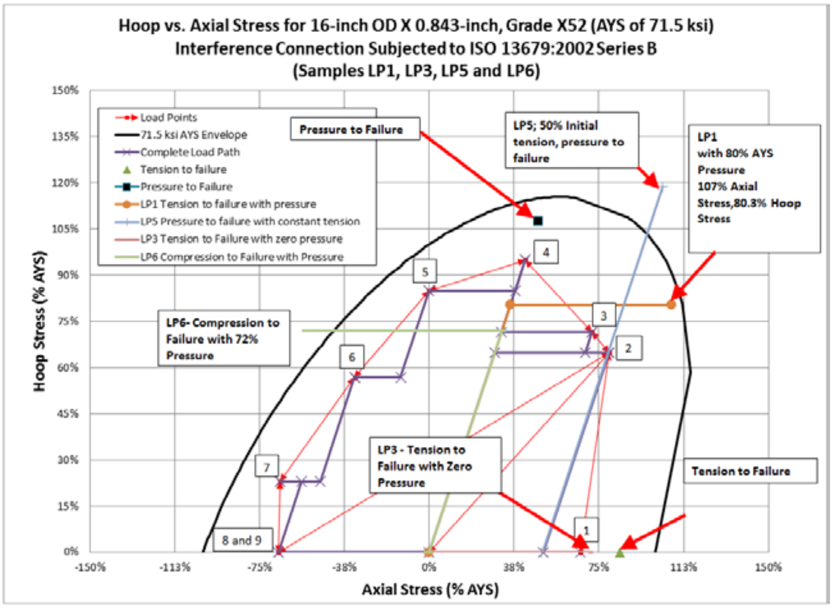

Figure 10. Stress State History for all Samples during and after ISO 13679:2002(E) Testing

4.4. Limit Load Testing Discussion

The final testing phase for Samples LP1 through LP6 was limit load testing to failure. Table 5 details the samples tested and their actual failure loads (presented as a percentage of Actual Yield Strength (AYS) of Sample LP1.

Table 5. Limit State Testing Results

Sample #	Limit Load Description	Hoop Stress (%AYS)	Axial Stress (%AYS)	von Mises Stress (% AYS)	Failure Mode
1	Tension to Failure	0% (0 ksi; 0 psi internal pressure)	84.1% (60.1 ksi)	84.1% (60.1 ksi)	Slippage between Pin and Bell
2	Pressure to Failure	107.6% (76.9 ksi; 8,085 psi internal pressure)	48.1% (34.4 ksi)	103% (73.6 ksi)	Burst of Pin Pipe (Pin pipe is suspected “True” X52 Material)
LP1	Tension to Failure with 80% AYS pressure	80.3% (57.42 ksi; 6,030 psi internal pressure)	107% (76.5 ksi)	104.7% (74.9 ksi)	Slippage between Pin and Bell
LP3	Tension to Failure with zero pressure	0%	70.5% (50.4 ksi)	70.5% (50.4 ksi)	Slippage between Pin and Bell
LP5	Pressure to Failure with 50% AYS Applied External Tension , plus pressure end load	118.8% (84.37 ksi; 8,924 psi internal pressure)	103.1% (73.7 ksi)	124.2% (88.9 ksi)	Slippage between Pin and Bell
LP6	Compression to Failure with 72% AYS constant Hoop Stress	73% (52.19 ksi)	-53.7% (38.4 ksi)	110.2% (78.8 ksi)	Yielding/Inelastic Buckling of Base Pipe

A few observations can be made from the limit state testing results. Sample LP1 failed at a higher axial load than Sample 1. This is due to the increased interference contact forces resulting from pin expansion during application of internal pressure. However, it is also noted that the connection failed just above 100% AYS, and not closer to the actual tensile strength of the pipe material. The reason for this is that as the pin pipe (in the connection) begins to yield, the bell pipe is also expanded, and contact pressure between the pin and bell is lost due to the softening of the material, and the joint separates. Note that the bell material had already experienced approximately 8% strain, so the ability of that material to sustain high loads had been greatly reduced. The connection process itself works because the pin pipe is still “largely elastic” and the degree of interference is controlled so that significant contact pressure in the vicinity of the yield strength of the pin material, (but still below significant permanent strain) is still present between the pin and bell.

In contrast, Sample 2 did burst at the pin pipe, suggesting that the pin pipe may have been closer to true X52 material (MTR data supported this discernment). So in effect, by over-matching the bell (with a higher yield strength material), the likelihood of failure by burst in the pin is much greater. However, analyzing in more depth, the comparison between Sample 2 and Sample LP5 shows that the latter failed at a von Mises stress of 88.9 ksi, compared to the verified tensile strength of 86.7 ksi, albeit by separation, or slippage between the pin and bell. This fact further supports Sample 2 pin pipe being closer to X52 material, and the failure of the connection being closer to its tensile strength – the nominal X52 tensile strength is approximately 66 ksi.

Samples 1 and LP3 were considered to have failed prematurely (before von Mises stresses reaching 90%-100% of AYS). An important trait of this type of connection is just as internal pressure increases the interference forces between the pin and the bell (up to a point), a lack of internal pressure makes the connection more vulnerable. The difference in performance between Sample 1 and LP3 is attributed to misalignment during the make-up process, as the actual equipment used to make up the connections had not been manufactured yet, and thus the amount of misalignment had not been minimized.

Lastly, the failure of Sample LP6 occurred at approximately 110% AYS von Mises stress, or 78.8 ksi. While the state of stress was farther away from the tensile strength of the material (86.7 ksi), the failure was not deemed a "catastrophic" failure, but instead inelastic buckling of the pipe.

Finally, Figure 11 below shows the comparison between the numerical analysis and prediction of the mandrel insertion, pin insertion and tension to failure loads for the maximum interference case. In the FEA, all portions of the connection joining process were modeled with Ramberg-Osgood material properties, using the tensile test results (AYS of 71.5 ksi, and tensile stress of 86.7 ksi). Differences between FEA and experimental results can be attributed to exact dimensions (i.e., degree of interference), coefficient of friction, and other factors being different.

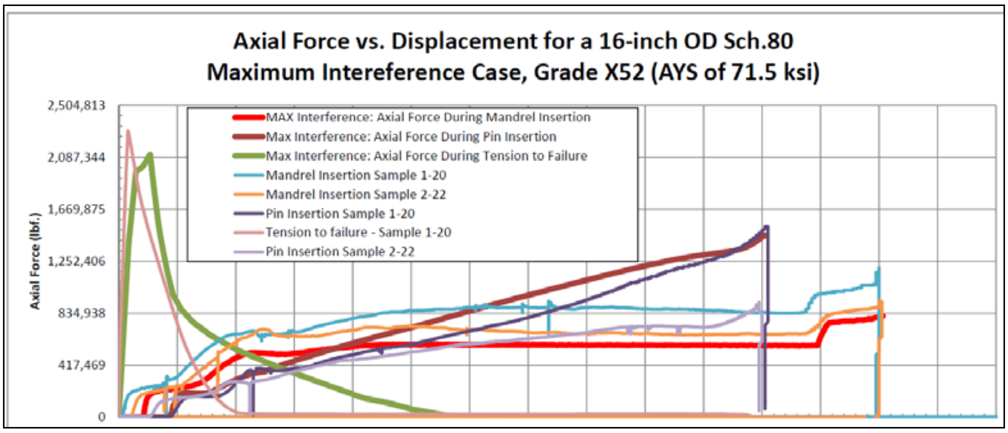

Figure 11. Load comparison between FEA and Experimental Results.

5. Conclusions

The primary aim of this study was to evaluate the performance of interference fit connections considering combinations of loading following the guidelines of the ISO 13679:2002(E) standard. All four (4) samples successfully completed the reeling and ISO tests prior to undergoing limit load testing. From this data, adequate loading and operating envelopes can be developed for the Schedule 80, 16-inch pipeline connections.

A summary of the observations from this study are listed below in no particular order:

- Interference connections are most vulnerable in tension loading conditions. These conditions are made more vulnerable if there is no internal pressure to increase the interference forces of the connection.
- Interference connections are energized by internal pressure – up to a point.
- The pressure to failure mode indicates that it is possible to fail at stresses very near the tensile strength of the material, although the failure is not necessarily a burst; in fact separation of the joint is more common.
- The connection is not as vulnerable to compressive loading as it is to tension loading. Note that samples LP1, LP3, LP5 and LP6 were subjected to the same states of stress prior to being tested to failure. In addition, LP5 and LP6 were subjected to bending stresses in lieu of higher direct tension loads, but the states of stress remained the same, suggesting that the connection can resist bending loads without adverse effects.
- When specifying pipe for interference fit connections, it is important to have a tight tolerance on material specification. Although the pin in Sample 2 is likely to be true X52 material, while its mating bell was closer to true X70, the stresses at failure were not qualitatively different from Sample LP5, where the actual stresses at failure were close to the tensile strength of the material. However, it is not clear the same results would have been obtained if the bell material was true X52 and the pin material was true X70.

- Design of pipeline systems with interference connections can be accomplished when the design and operating conditions are appropriately determined and the failure mechanisms are well understood.

6. Acknowledgements

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