Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2011
June 19-24, 2011, Rotterdam, The Netherlands

OMAE2011-50209

ZAP-LOK® CONNECTION TESTING AND AXIAL STRENGTH DESIGN

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ABSTRACT

Zap-Lok® is a pipe joining technology which relies on radial-interference elastic strain and surface friction to join pipes. The connection consists of a “bell” (expanded end) into which a “pin” (the straight end of the adjoining pipe) is forcefully inserted to provide an interference fit (See Figure 1). Joining is accomplished via a specialized hydraulic joining press provided by Zap-Lok® which grips both pipe sections and forces them together. A thin layer of the patented epoxy is applied internally to the bell end, and externally to the pin end, to provide lubrication for the insertion. The joining operation takes approximately ten seconds. Both the bell and the pin are formed to specified tolerances per specification by Zap-Lok® technicians, and may be done in the field or shop. Typical applications include gathering and distribution systems, transmission lines and specialized pipe installations on land and offshore.

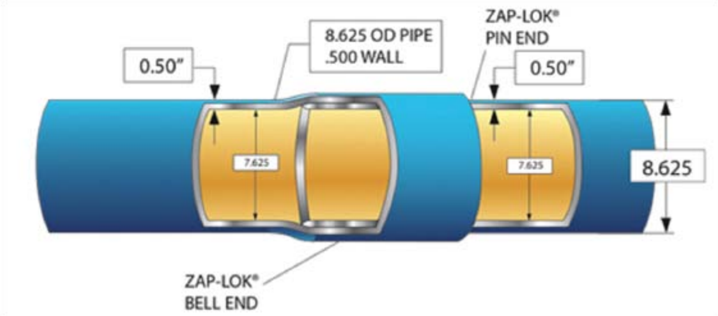


Figure 1: Typical Zap-Lok® Connection

Of particular interest is the ability to withstand corrosive products with the application of an internal coating that does not sustain damage during the joining operation. To qualify this technology for use extensive testing and analyses was performed. We found that:

- In sour service applications the plastic deformation of the bell necessitated a heat treatment to insure that the connection remained NACE compliant.
- The axial strength capacity was found to be somewhat less than that of a welded joint.
- Burst capacity of the joint was robust.
- The joint did not leak even after several cycles of significant plasticity.
- Fatigue performance of the joint rivaled that of a lower-end girth weld. (i.e. F2 S-N curve)

A design method was developed to correctly account for the axial strength using basic ASME-type design concepts. In this presentation we summarize the connection mechanics, testing results, analytical models and design method for the Zap-Lok® connection.

INTRODUCTION

An extensive review of testing and analyses of Zap-Lok® connectors revealed that the connector can separate under extreme loadings affecting the axial integrity and potentially the burst capacity. Three focus areas for design are:

- Burst Limit State. This limit focuses on the pipeline connection ability to contain pressure. For Zap-Lok® connections often this limit state occurs by pullout of the inserted pin pipe from the bell (instead of a fish-mouth tearing of the pipe wall). Figures 2 and 3 show examples of these two pressure containment losses.
- Axial Strength Limit State: This limit focuses on the ability of the pipeline connection to maintain axial

integrity. For the Zap-Lok® joint this limit state results in pullout of the inserted pin pipe from the bell.
- Leak after Bending: This limit state looks at the potential for the Zap-Lok® connector to leak after severe bending deformations.

This paper focuses on the appropriate design method for the new 10” design Zap-Lok® connectors (10.75” OD, 0.5” w.t. 15” insertion). Although the traditional Zap-Lok® insertion length for a 10” pipe is 13”, based on preliminary analyses, the insertion length of the connector was set to 15” to enhance the connector performance. Zap-Lok® provided access to several previous testing programs and ETC (Chevron Energy Technology Company) has provided guidance to two testing programs recently completed at Stress Engineering Services, Houston TX.

Figure 2: Pressure Containment Loss: Pull-out

Figure 3: Pressure Containment Loss: Fish-Mouth Burst

PREVIOUS TESTING FROM ZAP-LOK®

A significant amount of testing and analyses of the Zap-Lok® connection can be found in [4][5]. For some special cases the connection can be shown to meet the B31 series of ASME code requirements, although in general the axial strength will be somewhat lower than a welded connection. This decrease in axial capacity is the focus of this paper, and will require the designer to account for this by providing additional margin to typical ASME-type design equations. In summary:

- Overall the connections achieve strength levels that are comparable to welded joints.
- The burst limit state often involves separation of the connections, not a fish mouth opening that occurs with welded pipes. This implies a lower capacity for pressure containment than a welded joint.
- No axial strength testing of the Zap-Lok® connector had been performed for 10” and larger pipe connections.

FINITE ELEMENT WORK FOR 12” ZAP-LOK®

A reputable contractor with expertise in pipeline design performed the initial finite element analyses for the standard 12” Zap-Lok® connector (13” insertion length). Although from the report the analyses and the assumptions used appeared reasonable at the time, extensive review of this works and the actual ABAQUS model revealed deficiencies that made the results inaccurate. Some of these modeling errors are summarized:

- Mandrel misalignment
- X-52 stress-strain curve too strong
- $\mu_{friction}$= 1.0, too high
- Linear 8-noded bricks and tetrahedral elements 1-layer thick
- Bell head improper constraints
- Linear geometry
- Incorrect axial loads for pressure
- Excessive artificial viscosity

The model was subsequently modified correcting all of the errors. Figure 1 shows the comparison of the final deformed shapes and Von-Mises stress states. Note that the incorrect version shows excessive deformation and plasticity outside of the bell in the pin end of the joint.

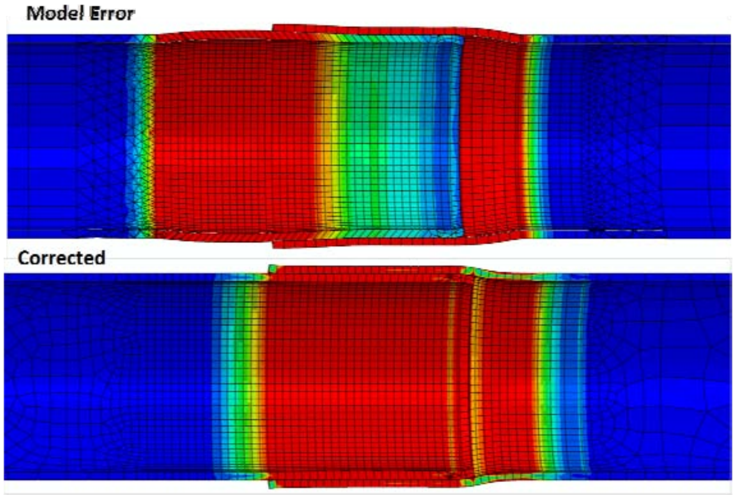


Figure 4: FEA models with Von-Mises Stress Contours

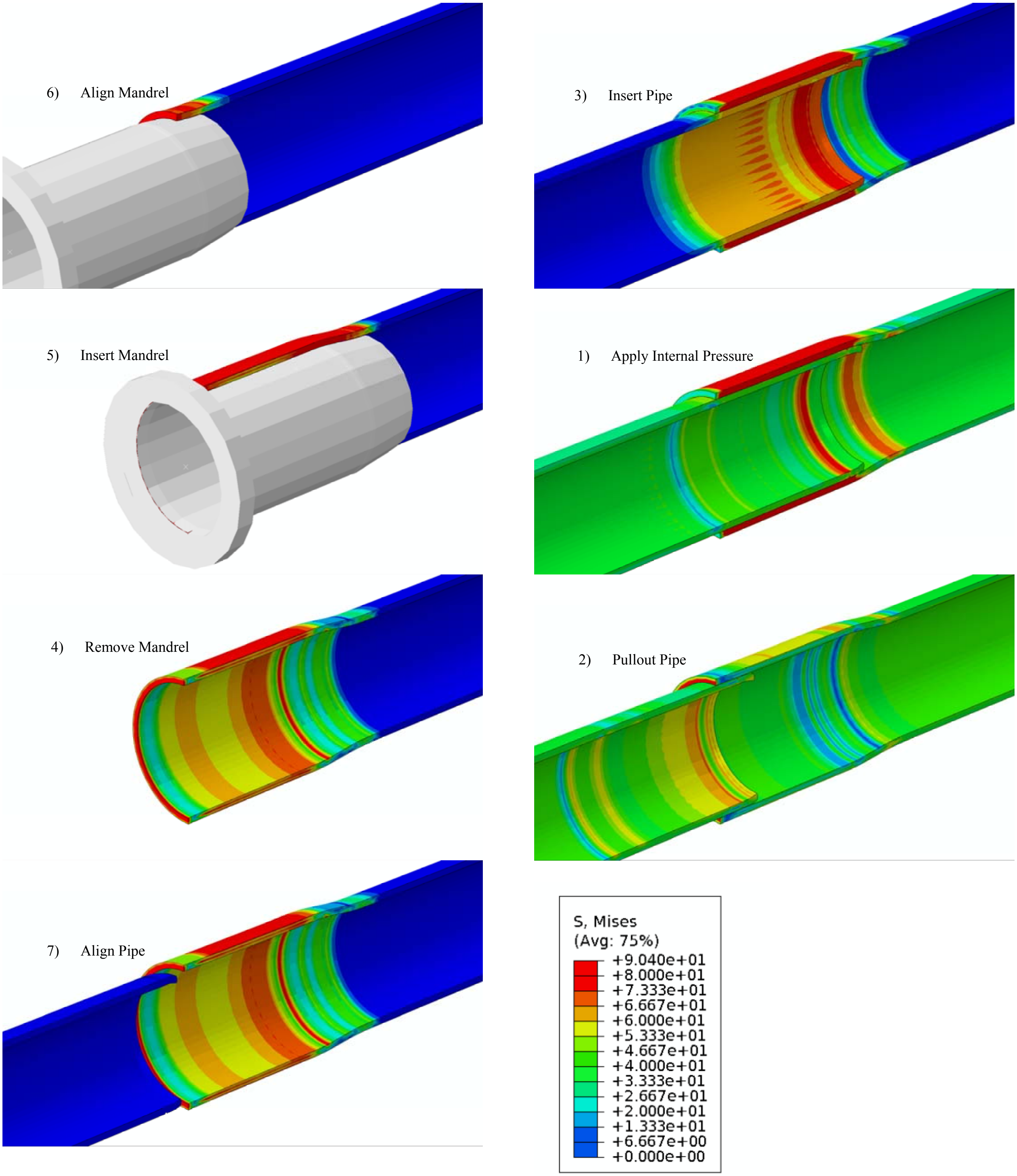


Figure 5: FEA models with Loading Steps: von_Mises Stress in ksi

For complicated analyses, even a reputable contractor can end up with analyses errors that at first may not be apparent.

Figure 5 shows typical FEA steps taken to model the connection formation, internal pressure and subsequent pulling out of the connector to get axial capacity. Figure 6 shows stress strain curves used for the 12” pipe FEA runs. A Ramberg-Osgood fit of X-52 specified minimum properties was used.

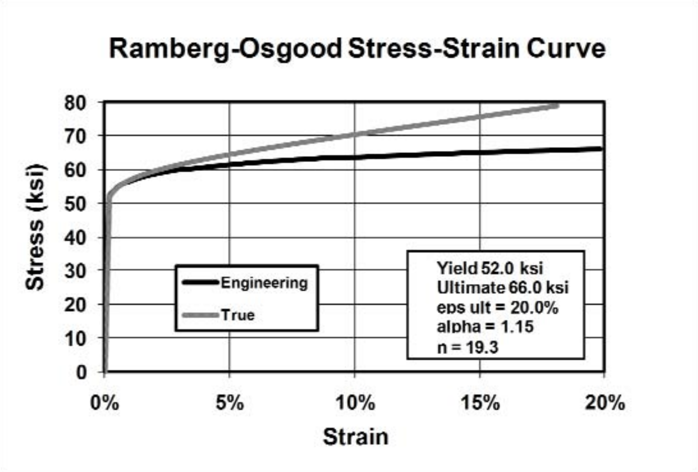


Figure 6: X52 Stress-Strain Curve

Figure 7 shows the results of several finite element analyses. Each FEA result is shown as a black filled circle, with an dark blue connecting graph line. The 12” pipe (12.75 in OD, 0.5” w.t.) standard insertion length (13”) was used. Note that this was the geometry used for the first set of ETC tests. Also shown on Figure 3 are the von-Mises yield surface for the combined hoop and tensile stress state. Here the stress state is idealized using a plane-stress approximation assuming through-thickness radial stress = 0. Three von-Mises surfaces are shown: 1) Using SMYS=52ksi, 2) Using SMTS=66ksi, and 3) using a flow stress equal to the average of SMTS and SMYS of 59 ksi.

Figure 7 also shows the loading sequence for the FEA runs involving the application of tension beyond the end-cap loads. The grey “Burst” arrow is the stress state loading for a simple burst test where the axial loads are due to pressure end-cap effect only. The other colored arrows show a loading sequence where: 1) pressure is increased, and then 2) at a given hoop stress the pressure is held constant while axial tensile loading is applied to failure. For the FEA models, the pressure and end-cap loadings are increased and then at the given pressure, the pressure is held constant and displacements are increased till a peak tensile load is obtained. This peak tensile load is the ordinate value plotted in the figure (black dots-dark blue curve) for the FEA results. As shown, the tensile capacity of the Zap-Lok® joint FEA model is lower than the von-Mises yield surface, although the burst capacity nearly reaches the SMTS based von-Mises surface. Also note that a simplified model is shown that approximates the axial tension dominated capacity well for hoop stresses up to about 70% of SMYS. The development of this simplified model is detailed in the Annex.

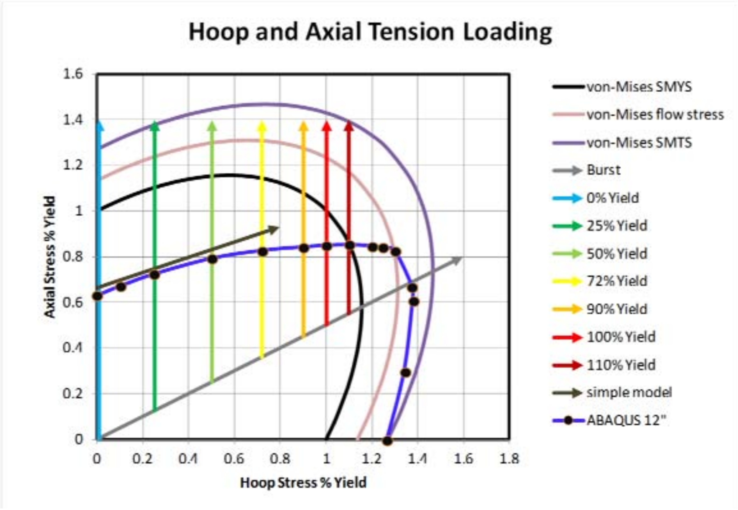


Figure 7: 12” FEA Results

Figure 8 shows the same 12” FEA results with a simulated welded pipe analyses. For the welded pipe simulation, the pipe body was simply modeled without the Zap-Lok® connection. Since usually the weld is overmatched, failure will occur in the weaker pipe body. As shown, the hoop capacity of the Zap-Lok® FEA model connection matches the weld model (pipe body failure) well, but the axial capacity of the 12” Zap-Lok® connection is nearly ½ of the weld model.

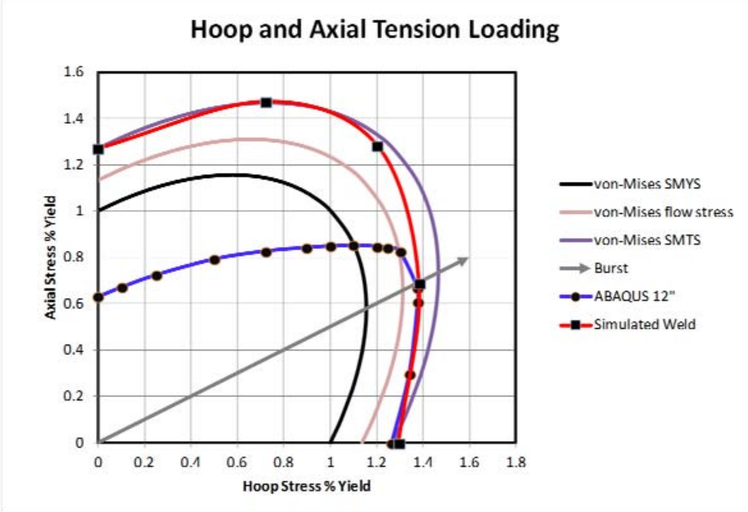


Figure 8: Zap-Lok®-welded connection comparison

From these analyses we can conclude that:

- Zap-Lok® matches the axial strength performance of welded pipes at hoop stresses above the flow stresses.

- The standard 12” Zap-Lok® connection (13” insertion length) is significantly weaker in the axial direction than welded pipes for hoop stresses less than the flow stress.
- A robust FEA model of the Zap-Lok® connector can be used to identify relative performance parameters.

SOUR SERVICE EVALUATION

Sour service testing was carried out on materials from 12” and 10” diameter Zap-Lok® joints. The sour service evaluation included the following:

1. Hardness and Microstructural evaluation of the pin and bell sides of Zap-Lok joints.
2. NACE TM0177 Method “A” testing of bell (most highly strained) material in the as formed condition as well as in the heat treated condition.
3. Modified NACE TM0177 testing of full sections of Zap-Lok® bell material in a 4 point bending configuration.

The Hardness and microstructural analysis found no evidence of local straining on the contact faces of the bell and pin which suggested that a bulk materials sour service qualification would be representative.

Sub-size NACE Method “A” tensile bars were machined from actual Zap-Lok® bells. The tensile samples were oriented transverse to the direction of the pipe (hoop stress orientation), due to the large amount of hoop strain imparted to the material during the forming process. Samples were stressed to 90 AYS which was determined by pulling triplicate cross weld tensile samples.

Sour service testing included samples obtained from as-fabricated and heat treated (according to NACE MR0175) bells. During this testing program, only samples which had not undergone heat treatment, cracked. Note that all virgin material was previously qualified for sour service using the same test methodology. Samples which had not undergone heat treatment failed the sour service testing. Testing in the 4-pojnt bend arrangement did not yield cracking in any test, but this is attributed to the small amount of material which is actual stressed in the 4-point bend testing.

FIRST SET OF ETC TESTS AT STRESS ENGINEERING SERVICES

Early 2008, a series of bending tests on 12” pipes (OD 12.75”, w.t. 0.5” with standard 13” insertion length) was performed. The objective of these tests was to assess the leak integrity of the Zap-Lok® connector after severe bending cycles simulating installation. The results showed that the Zap-Lok® connector did not leak even after severe bending cycles that included significant pipe wall plasticity. A burst test was conducted after the severe bending on one sample. This sample burst in the fish-mouth mode (See Figure 3), without separation of the connection. No tension tests were performed. From these tests we can conclude that:

- Severe multiple cyclical bending strains did not affect the leak integrity of the Zap-Lok® connection.
- The burst capacity (after severe plastic bend straining) of a single specimen was equal to that of a welded pipe.

Figure 9: 12” Zap-Lok® Burst Test with Connection Separation.

SECOND SET OF ETC TESTS AT STRESS ENGINEERING SERVICES

In 2009, two Zap-Lok® samples left over from the first ETC tests were burst tested at Stress Engineering Services. These two left over samples did not receive the bending strains that the single burst test from the first ETC tests had undergone. These two burst tests burst at about 90% of SMTS hoop stress, consistent with the FEA results in Figures 7 and 8. The failure mode was that of connection separation. Figure 9 shows the pin-end of one of these samples after burst. Note that post burst, each end of the zap-lok connector became a missile, impacting the end of the containment structure which was filled with wood for energy absorption. The figure dramatically shows the destruction of the wood at the end of the containment structure.

ETC and Zap-Lok® put together a testing program to quantify the axial capacity with the focus of quantifying the axial capacity under different loading conditions for design. Since initial use will involve 10” pipes, the testing focused on obtaining similar pipes. Three 40ft 10” X52 pipes (10.75” OD, 0.5” w.t.) were obtained. Forecasting the possible use of heat treating the cold-worked bell for future sour service usage, 8 of the specimen bells were heat treated. The standard insertion length of 12” was extended to 15” to increase the axial capacity. Figure 10 shows a typical burst test set-up and Figure 11 shows the axial test setup.

Figure 10: Burst Test Setup for 10” Zap-Lok® in covered pit

Figure 12 shows typical axial load vs. displacement for the 72% AYS hoop stress test for both the standard insertion depth (12”) and the elongated insertion depth (15”). As expected the longer insertion depth has a higher axial capacity, 890 kips, compared to the standard insertion depth of 771 kips. Note that the FEA simulation (15” insertion) has an axial peak of 776 kips, and overall behaves similar to the elongated insertion length test results.

Figure 13 summarizes all of the 10” test results. Again, the von-Mises surface for the combined hoop and tensile stress states are shown. Four von-Mises surfaces are shown: 1) using AYS=59.4ksi, 2) using ATS=78.4ksi, 3) using a flow stress equal to the average of ATS and AYS of 68.9 ksi, and 4) using a 90% AYS von-Mises surface (for information). Note that AYS is actual yield stress and ATS is actual tensile stress. These von-Mises curves show the failure surface for the combined stress states of tension and hoop.

Figure 11: Axial Tensile Test Setup with internal pressure for 10” Zap-Lok®

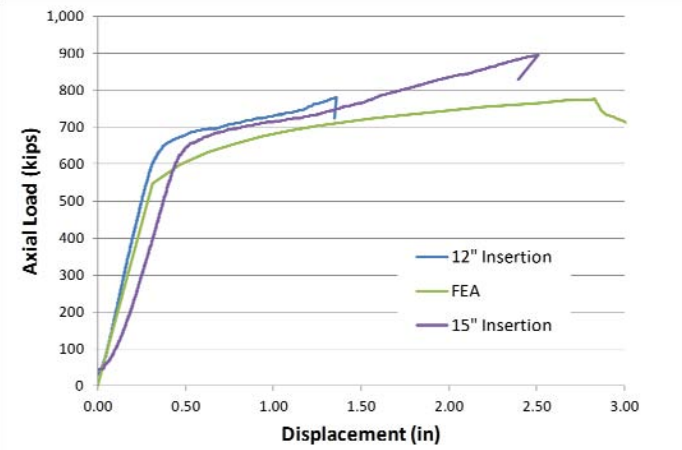


Figure 12: 10” Zap-Lok® 72% AYS Hoop Stress

In the figure, the black circles are the heat treated (long, 15”) bells, the diamonds are the non-heat treated (long, 15”) bells, and the triangles are the standard insertion length non heat-treated (standard, 12”) bells. The dark blue line connects the (long, 15” bells with heat treated) data. The colored arrows show the loading sequence used: 1) first the specimen is pressurized, and then 2) the axial loading is applied while holding the pressure steady. Note that Figure 12 resembles Figure 8, but with a significant increase in normalized axial capacity. Also note that the simple model predicts the axial capacity very well for axially dominated loading, up to 120% or the normalized hoop stress.

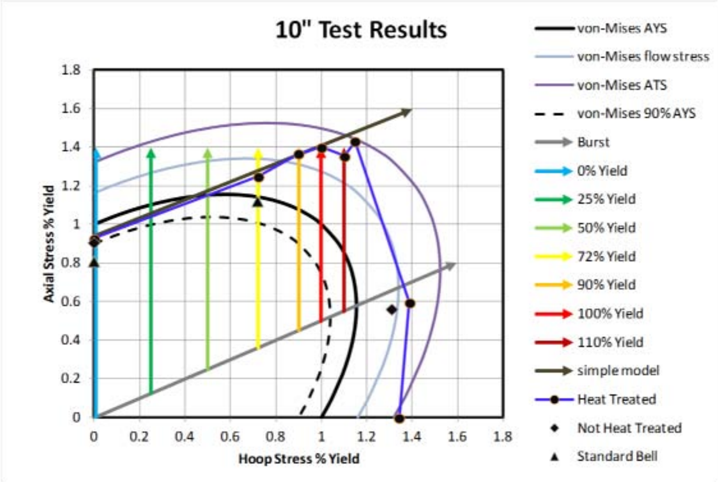


Figure 13: 10” Zap-Lok® with 15” Insertion Length Test Results

FINITE ELEMENT WORK FOR 10” ZAP-LOK®

Figure 14 shows the Abaqus FEA model results together with the testing results. Longitudinal stress-strain curves of the heat treated bell was used in the model (AYS=59.4ksi, ATS=78.4ksi). The FEA model predicts the axial capacity of the test fairly well for the predominantly axial loadings, however, for the predominantly pressure loads, the FEA over-predicts the pipe capacity. This may be due to anisotropy in the pipe steel, with slightly higher properties in the hoop direction than the longitudinal direction.

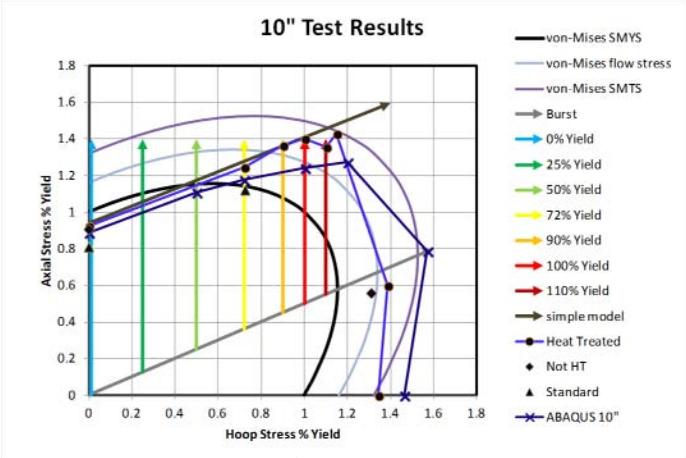


Figure 14: 10” Zap-Lok® with 15” Insertion Length Test Results and FEA results

DESIGN GUIDANCE FOR THE AXIAL PULL-OUT LIMIT STATE

The use of the flow stress von-Mises interaction surface as the basis for axial pull-out capacity is proposed. This gives a reference axial capacity beyond yield, allowing for some hardening, but below the ultimate tensile. Using the test data we get: Axial capacity of pipe = 1.16 AYS, and test results of 0.925 AYS at zero internal pressure. The factor to apply to allowable stresses due to axial loading to keep the same margin is then: 0.925/1.16 = 80%.

The test data from the two programs show that bending integrity is not affected for very high plastic strains, and the pressure containment is near that of a virgin pipe. The limiting stress state is then the total axial loading, excluding the bending.

The results reported here are specific to the 10.75” OD pipe with the 15” insertion length. To keep the same margin against axial pull-out in terms of stresses, the allowable longitudinal stress due to axial loading is then modified by the 0.80 factor. Then standard design codes including (but not limited to) ASME B31.3, B31.4, B31.8 ([1][2][3]) can be used with the following restriction:

$$S_{LT} = 0.8(S_A) \qquad (1)$$

Where:

S_{LT}: The longitudinal tensile stress calculated for straight pipe due to pressure and external loads acting in tension along the axis of the pipe. Longitudinal stresses due to bending moments on the pipe are not to be included. The tensile loads used to calculate these longitudinal tensile stresses shall be the resultant the tensile loads due to all sources of loads (e.g., thermal expansion, dead weight, wind, seismic, etc.). Occasional loads such as wind and seismic do not need to be considered to act concurrently with other occasional loads unless the code requires consideration of concurrent action.

S_A: The allowable stress established by the applicable piping code for the loading condition specified.

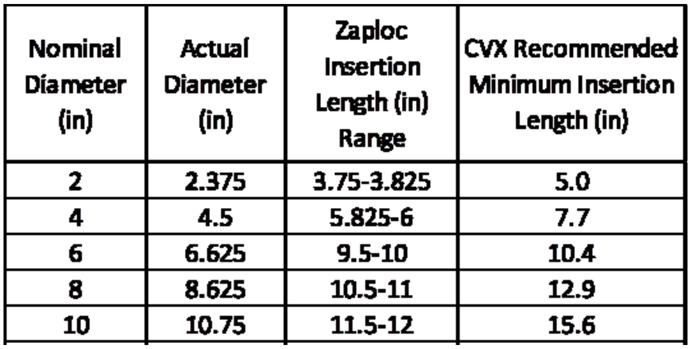
Thus the only restriction for this Zap-Lok® connector is that the total axial load divided by the cross section (i.e. average cross-sectional tensile stress) must be less than 80% of the code allowable stress. In addition, Zap-Lok® limits the hydro-test pressure to a hoop stress 90% of SMYS. This application is limited to non-sour and non-cyclic installations.

RECOMMENDED INSERTION LENGTHS:

By setting the total friction generated axially in the Zap-Lok® connection equal to the yield tension capacity of the virgin cross section, we can generate a simple equation for the insertion length required of the connection in the absence of internal pressure:

$$L_{insertion} = \frac{(d_o - t)}{2\mu} \qquad (2)$$

Where d_o is outside diameter, t is the virgin pipe wall thickness, and μ is the coefficient of friction in between the pipes. Zap-Lok® has previous experience and data that shows μ=0.37. Calibrating this model to our test data we find that the total 15 inch length does not contribute, but instead about 2 inches worth of engagement is effectively lost. This can explained through the loss of interference contact at the flare of the outer pipe and at the inside pipe where the d_o is crimped to facilitate insertion. The recommended insertion lengths that correspond to the design recommendations in this memo are summarized in the following table:



Nominal Diameter (in)	Actual Diameter (in)	Zaploc Insertion Length (in) Range	CVX Recommended Minimum Insertion Length (in)
2	2.375	3.75-3.825	5.0
4	4.5	5.825-6	7.7
6	6.625	9.5-10	10.4
8	8.625	10.5-11	12.9
10	10.75	11.5-12	15.6

Table 1: Recommended Insertion Lengths for Zap-Lok® Connectors.

Table 1 is preliminary and offered mainly for guidance. These values assume that:

1. 93.85% of the yield load will be generated in the connector prior to pull-out. (From the simple models in figures 5 and 6)
2. Two inches worth of insertion does not contribute to friction.
3. The design guidance offered in this memo is followed.

Actual pull-out testing is recommended whenever significant deviations from the analyses parameters presented is encountered.

It is important to note that for typical pipelines, the axial loadings are not critical, and are often significantly lower than the design limits. Then through the use of the equation for insertion length calculation (2), a smaller insertion length could be justified for axial loads that are significantly smaller than the design limits. If the resulting insertion lengths are significantly less than the tabulated values in Table 1, a validation testing program is recommended.

ACKNOWLEDGMENTS

Special thanks to Dr. Chris Alexander of Stress Engineering Services for his role in testing and discussions.

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ANNEX A

ZAP-LOK SIMPLIFIED AXIAL STRENGTH MODEL

This annex describes the simplified model for the prediction of axial strength capacity of an interference fit pipe with internal pressure. First we start with an interference fit that produces yield level hoop stresses in both the bell and the pin. The interference pressure between the bell ID and the pin OD is then:

$$p_{interference} = \frac{\sigma_{yield} t}{r_o}$$

where:

$p_{interference}$ is the interference pressure
σ_{yield} is the actual yield stress of the pipe
t is the wall thickness of the virgin pipe
r_o is the outside radius of the pin

Integrate this pressure over the contact area, and multiplying this by the coefficient of friction gives the total axial load due to interference only:

$$T_{interference} = \frac{\sigma_{yield} t}{r_o} \mu_{friction} L \pi d_o$$

where:

$T_{interference}$ is the axial capacity
$\mu_{friction}$ is the coefficient of friction
L is the insertion length
d_o is the outside diameter of the pin

For the application of internal pressure, a simplifying assumption is applied: half of the pressure is carried by the bell and half is carried by the pin. Then the pressure between the bell and the pin is approximately one-half of the total internal pressure. The integration of this pressure (half of the internal pressure) over the contact area gives an increase in axial carrying capacity:

$$\Delta T_{pressure} = \frac{p_{internal}}{2} \mu_{friction} L \pi d_o$$

where:

$p_{internal}$ is the internal pressure
$\Delta T_{pressure}$ is the increase in axial capacity

The total axial capacity is then:

$$T = T_{interference} + \Delta T_{pressure}$$

$$= \frac{p_{internal}}{2} \mu_{friction} L \pi d_o + \frac{\sigma_{yield} t}{r_o} \mu_{friction} L \pi d_o$$

$$= \left(\frac{p_{internal}}{2} + \frac{\sigma_{yield} t}{r_o}\right) \mu_{friction} L \pi d_o$$