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USE OF LIMIT ANALYSIS METHODS TO ASSESS ELEVATED STRAINS DURING INSTALLATION OF TEES IN DEEPWATER PIPELINES

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ABSTRACT

With trends for installing subsea pipelines and flowlines in deeper water conditions, designers and contractors are being forced to address the potential for high strain conditions during pipelay operations. Conventional analysis methods, even those based on strain, are often difficult to implement because questions arise regarding acceptable design strain conditions. To address this particular shortcoming, limit analysis methods can be applied. Limit analysis involves loading a structure, either through analysis or testing, to the point where unbounded displacements occur. The load at which this occurs is defined as the lower bound collapse load (LBCL). Using the LBCL, designers can determine appropriate design loads based on a specified safety design margin.

This paper provides discussions using limit analysis methods and applications for deepwater pipelay activities. Of particular interest are a series of analyses and full-scale tests performed on a tee assembly prior to installation in the Independence Hub field using a stinger. The intent is to provide industry with an alternative analysis methodology to properly size and design piping and components subjected to high strain loading during installation.

PROJECT BACKGROUND

The Independence Subsea Project is a Gulf of Mexico development involving fifteen (15) subsea natural gas wells tied back via seven (7) main flowlines to a floating host platform in Mississippi Canyon 920 (MC 920), known as the Independence Hub. A map of the field is shown in Figure 1.Two of these flowlines transit a distance of over 45 miles each to collect produced natural gas from the Vortex, Jubilee, and Cheyenne developments. The flowlines are connected to each other via a pigging loop at the most distant development, Cheyenne possesses In-Line Sleds (ILSs) at the Jubilee and Vortex locations in order to collect production at those mid-line points. Each ILS contains one branch tee connection for current use and one spare tee connection for future utilization. The flowlines are fabricated from 8-inch and 10-inch nominal diameter pipes and installed by the S-Lay method. Details relevant to the ILSs are provided in Table 1. Figure 2 shows the tee assembly prior to deployment over the stinger.

The objective of the analysis and testing efforts discussed in this paper was to determine the acceptable strain limit of the tee assembly that is an integral part of the ILS.

INTRODUCTION AND TEST METHODS

Prior to performing testing on the 8-inch block tee, analysis of the component was completed using finite element methods. By understanding the mechanics of the loading, the test set-up replicated the analysis loads based on the loads expected during installation. The loading combination used in the analysis phase involved the load conditions specified below. Figure 3 provides a schematic of the analysis loading configuration.

- Axial tension load of 330 kips
- Shear load at roller of 35.8 kips
- Bending moment of 130.9 kip-feet

Because the total bending moment is influenced by the vertical shear force at the roller, the maximum total applied bending moment applied at the center of the tee is 286.3 kip-feet. This was calculated by adding the bending moment of 130.9 kip-feet to the moment induced by the shear load, V, as shown in the following equation. It was this maximum bending moment that was the target value for the test program. The length L is the total length of the tee assembly modeled in the finite element analysis.

$$M_{total} = \mathrm{M}_{\mathrm{bending}} + \left(\frac{\mathrm{V}}{2}\right)\cdot\left(\frac{\mathrm{L}}{2}\right) = (130.9\ \mathrm{kip\text{-}ft}) + \left(\frac{35.7\ \mathrm{kips}}{2}\right)\cdot\left(\frac{208.5\ \mathrm{in}}{2}\right) = 286.3\ \mathrm{kip\text{-}ft}$$

A one (1) million lbs. capacity tension load frame was fitted with an I-beam to permit the application of bending loads. A four-point bending set-up was selected because of the ability to generate a relatively uniform bending across a given section of the piping assembly. Figure 4 is a schematic showing the imposed loading on the test assembly with overall dimensions. The attached piping was heavy wall 8-inch nominal diameter pipe (8.625-inch x 0.950-inch, Grade X65).

As shown in Figure 4, a vertical downward bending force was applied to the test assembly at two positions, along with the application of an axial tension force. Vertical displacement of the sample was measured using displacement transducers as functions of axial position at five (5) selected points. This information was used to monitor displacement of the tee as well as calculating the radius of curvature. As loading on the test sample was increased, the radius of bending curvature is effectively reduced resulting in greater bending strain in the test sample. Also measured was the axial displacement of the test sample due to tension loading.

Strain gages were installed at select locations on the test assembly. Figure 5 provides an overall schematic of the gage locations. Numerous gages were installed in the vicinity of the block tee, as well, as gages that were installed along the length of the run pipes. The objective was to monitor strain as a function of position considering tension and bending loads. Figures 6 through 9 are photographs showing different views of the test set-up.

In addition to strain and displacements, hydraulic ram pressures (using pressure transducers) were monitored for the vertical bending cylinders as well as the axial tension cylinders. These pressures were then converted to bending forces and axial tension forces. The bending moment on the test sample is calculated by multiplying the distance from the end of the sample to the point of load application (40 inches or 3.33 feet) by the applied bending force. As an example, with a bending force of 10 kips the corresponding bending moment is 33.3 kip-feet. All electronic measuring devices were connected to a data acquisition system where data was recorded at 1 scan per second.

The basic steps involved in testing are outlined below.

1. Start the data acquisition system in order to record data. Record data at 1 scan per second.
2. Apply loading in the following sequence to achieve the following conditions (based on finite element results):
    a. Axial tension of 330,304 lbs (applied first)
    b. Achieve intended bending moment using hydraulic cylinders to achieve design strain limit of 0.38 percent posed by Pegasus during the analysis phase of work
    c. Strain in the pipe was monitored continuously during testing to ensure that the proper bending moment is applied.
3. Once the above load state is achieved, hold the loading for 5 minutes and observe strain distribution in the test assembly.
4. To obtain failure loading (or the lower bound collapse load), increase the upward displacement of the two hydraulic cylinders (four-point bending) to the point of failure. The reaction force will be monitored to determine the corresponding applied bending moment.

TEST RESULTS

Once all testing was completed including the recording of data, post-processing of the results was required. In generating plots and figures using the collected data, it is important to note that the primary aim in testing was to determine acceptable design strains (and loads) for the pipe lay installation process. Using this information, Pegasus International and its clients could be assured that adequate safety margins exist to prevent damage to the equipment during installation considering loads associated with the Lorelay stinger configuration.

The following sets of data were processed along with a brief description of principal observations.

- Axial bending strains at select locations in the test assembly (limit load plot)
- Axial bending strains along the length of the test assembly
- Maximum principal strains in the vicinity of the block tee
- Bending force versus vertical displacement along length of test assembly

Axial Bending Strains in Test Assembly (Limit Load Plot)

The primary purpose in performing the test program was to experimentally determine the lower bound collapse load for the test assembly. This was done by incrementally increasing the bending load until unbounded displacements occurred (e.g. large increases in strain/displacement with minimal increases in load/stress). Limit analysis is typically performed using finite element models; however, it is also possible to obtain this value experimentally.

Figure 10 plots bending moment as a function of axial strain for gages placed along the length of the test assembly. As noted in this plot, the lower bound collapse load is evident in the response observed for Rosette #R11 that is located 45 inches from the circumferential weld line. The bending moment corresponding to the lower bound collapse load is 993 kip-feet. Another set of data plotted in Figure 10 show data for the applied bending force in kips. It should be noted that the **bending moment** is calculated by multiplying the **bending force** by the moment arm of 40 inches (3.33 feet).

Included in Figure 10 are horizontal lines corresponding to different design load levels. These include the following:

- Lower Bound collapse load (993 kip-feet bending and 298 kips bending force)
- Allowable design load (573 kip-feet bending and 172 kips bending force)
- Expected installation loads (286 kip-feet bending and 86 kips bending force)

Axial Bending Strains along the Length of the Test Assembly

Axial strain gages were installed along the length of the pipe where the intent was to monitor strain as a function of axial position. **Figure 10** shows data for six axial strain gages that were positioned from the circumferential weld line out to 45 inches, which was almost at the point where bending loads were applied. The following maximum strains were extracted:

- Gage R17 (on weld): 2,375 με
- Gage R16 (2 inches from weld): 6,812 με
- Gage R1 (6 inches from weld): 3,282 με
- Gage R13 (25 inches from weld): 10,579 με
- Gage R12 (35 inches from weld): 5,665 με
- Gage R11 (45 inches from weld): 13,138 με

The non-uniformity is likely due to interactions considering geometric effects (like the weld line) as well as points of loading associated with the hydraulic cylinders. One point of consideration is the exponential decay in bending moment that results with the application of tension loading. Figure 10 is plot of this relationship. The calculated maximum nominal strain due to bending and tension for the lower bound collapse load is approximately 10500 microstrain (or 1.05 percent). The calculation is shown in the following equation using loads actually applied during testing.

$$\varepsilon_{total} = \varepsilon_{\text{tension}} + \varepsilon_{\text{bending}}$$

$$\varepsilon_{total} = \frac{T}{A \cdot E} + \frac{\mathrm{M} \cdot \mathrm{R}}{\mathrm{E} \cdot \mathrm{I}}$$

$$\varepsilon_{total} = \frac{330{,}000\,\text{lbs}}{(22.9\,\text{in}^2)\cdot(30E6\,\text{psi})} + \frac{(11.9E6\,\text{in - lbs})\cdot(4.3125\,\text{inches})}{(30E6\,\text{psi})\cdot(171.2\,\text{in}^4)} = 1.05\,\text{percent}$$

where:

ε	Strain (unitless, in/.in)
T	Axial tension force (lbs)
A	Cross-sectional area of pipe (in^2)
E	Young's modulus for steel (psi)
M	Applied bending moment (in-lbs)
R	Outside radius of pipe (inches)
I	Moment of inertia (in^4)

IMPLICATION OF RESULTS

In reviewing the information contained within this report, the most fundamental data acquired was the lower bound collapse load. From this value an appropriate design condition was established and compared to existing installation loads. As a review consider the following bending moment and force values:

- Lower Bound collapse load (993 kip-feet bending moment and 298 kips bending force)
- Allowable design load (573 kip-feet bending moment and 172 kips bending force)
- Expected installation loads (286 kip-feet bending moment and 86 kips bending force)

The allowable design load is calculated using the methods of the ASME Boiler & Pressure Code, Section VIII, Division 3 that includes rules for designing to account for material plasticity using limit analysis methods. A design margin of 1.732 is applied to the lower bound collapse load in determining the design load (i.e. multiplying the collapse load by 0.577). From the design load, it is clear that the expected installation loads are approximately 50 percent of the design load. These results clearly demonstrate that the block tee assembly is adequately designed for the intended installation requirements.

An additional series of comments is warranted in reviewing results from the previous finite element analysis (FEA), which have not been discussed extensively in this paper. Figure 11 is a finite element plot showing strains in selected regions of the model. As noted, the strain magnitudes in the run pipe vary from 0.35 percent in the main body of the pipe to 0.52 percent in the vicinity of the tee block weld. Although there is some variability in the strain magnitude in the pipe measured during testing, it is clear in viewing the test data (such as those plotted in Figure 10) that the majority of strain gages measured strain between 0.2 and 0.4 percent. This is consistent with the finite element results. Additionally, the design strain limit of 0.38 percent posed during the analysis phase of testing is within the range of values measured experimentally and calculated analytically.

CONCLUSIONS

This report has provided detailed information on the test program performed for Pegasus International on the 8-inch block tee assembly. The work was performed by Stress Engineering Services, Inc. for Pegasus International with the intent of qualifying loads expected during installation of pipe using the Allseas Lorelay pipe lay barge. The Lorelay has a stinger radius of 73 meters (240 feet). Installation loads were calculated during previous analyses using finite element methods and found to include a tension of 330 kips and an applied bending moment of 286.3 kip-feet. The results of this test program confirm the accuracy of finite element analysis results previously provided.

Because the expected design loads are 50 percent of the allowable design load, it is clear that the block tee and piping assembly are adequately designed for the intended installation loads. Although a visual inspection of the welds does not indicate the presence of cracks, a non-destructive evaluation was not been performed. Using the information contained within the report involving the destructive testing of the 8-inch block tee, installation of the pipe can continue as planned without any reason to believe that the system will not perform as originally intended.

REFERENCES

[1] ASME, Boiler and Pressure Vessel Code, Section VIII, Division 1, *Rules for Construction of Pressure Vessels*; Section VIII, Division 2, *Rules for Construction of Pressure Vessels, Alternative Rules*; and Section II, Materials, Part D, Properties, The American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016.

[2] Kalnins, Arturs, WRC Bulletin 464, *Guidelines for Sizing of Vessels by Limit Analysis*, August 2001, Welding Research Council, Inc. Three Park Avenue, New York, NY, 10016.

Table 1 – In-line Sled Details

ILS Description	Flowline / Branch Pipe Size	Water Depth	Installer	Nominal Lay Tension	Nominal Pipe Strain
Vortex East	Two 10-in x 8-in	8,345 feet	Allseas Solitaire	278 Tonnes	0.34%
Vortex West	Two 8-in x 8-in	8,345 feet	Allseas Lorelay	164 Tonnes	0.29%
Jubilee East*	Two 10-in x 8-in	8,635 feet	Allseas Solitaire	258 tonnes	0.34%
Jubilee West	Two 8-in x 8-in	8,635 feet	Allseas Lorelay	170 tonnes	0.29%

<u>NOTE:</u> The Jubilee East sled transitions the flowline from 10” to 8” resulting in lower max tension compared to Vortex east.

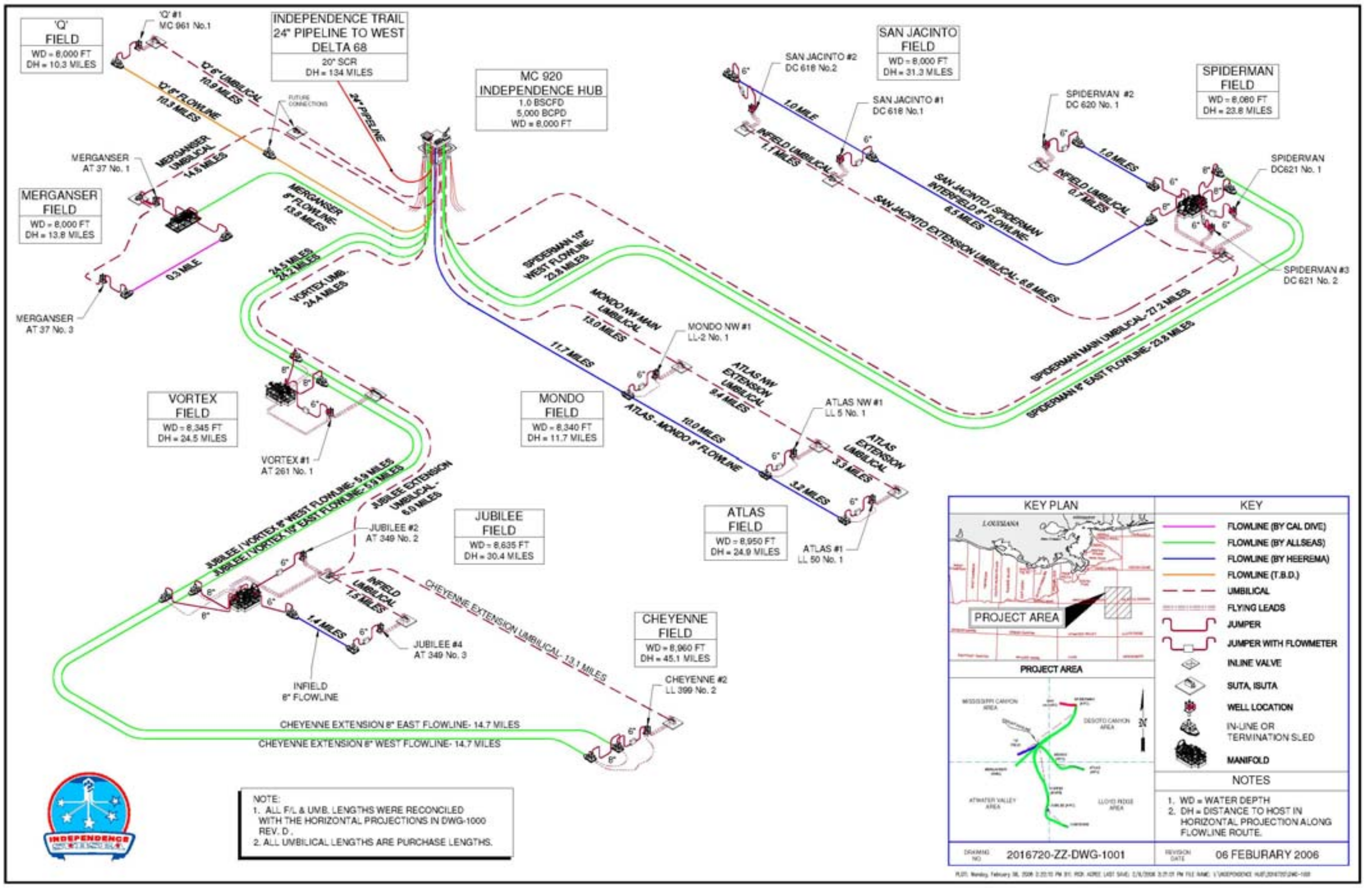

Figure 1 – Map showing layout of the Independence Hub field

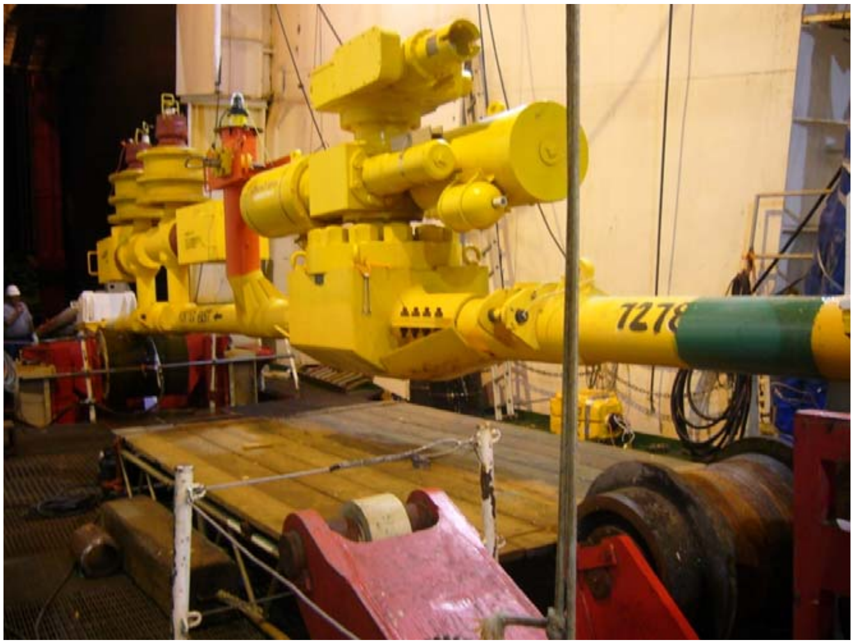

Figure 2 – Tee assembly including shroud structure prior to going over stinger

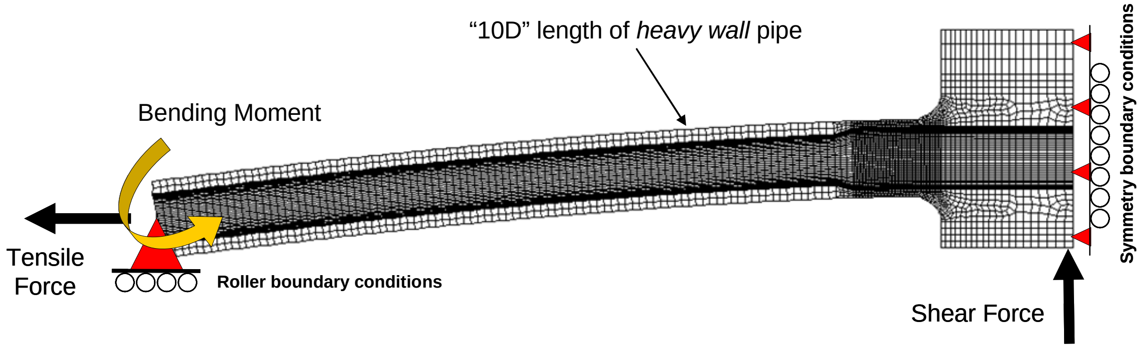

Figure 3 – Schematic diagram of finite element analysis bending model

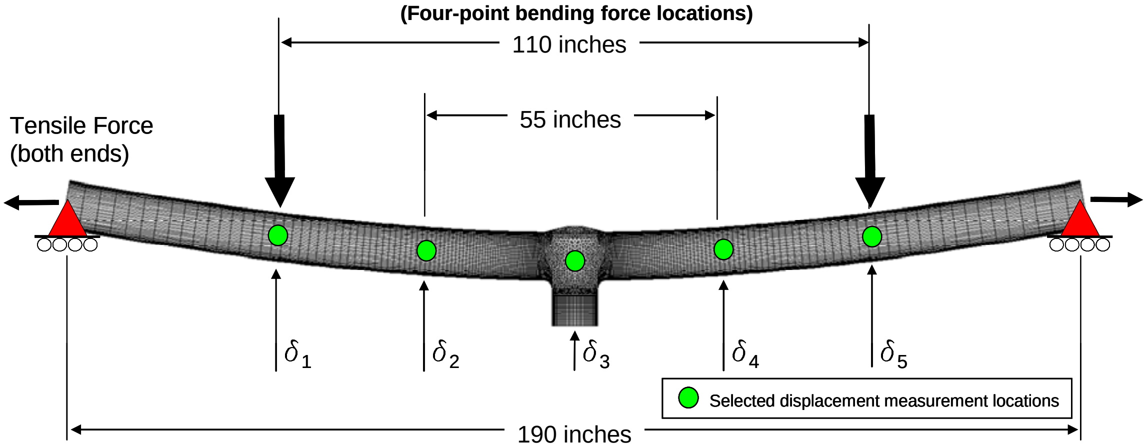

Figure 4 – Set-up for four-point bend test

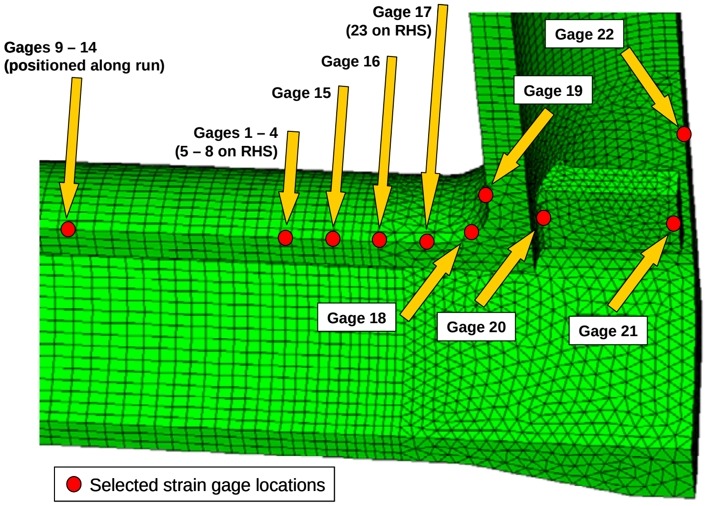

Figure 5 – Location of strain gages near block tee

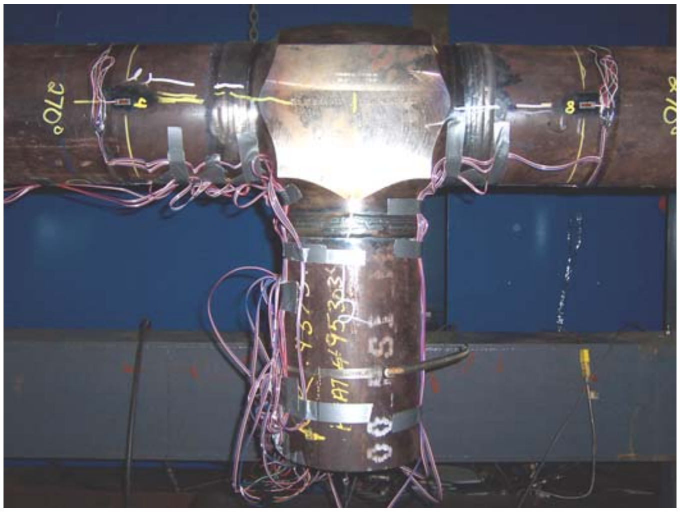

Figure 6 – Close-up photo of tee showing installed strain gages

Figure 7 – Photo showing end fixture and bending support structure

Figure 8 – Photo from center of sample showing bending fixture

Figure 9 – Photo showing overall view of test assembly
(blue I-beam on top used to provide reaction support to bending cylinders)

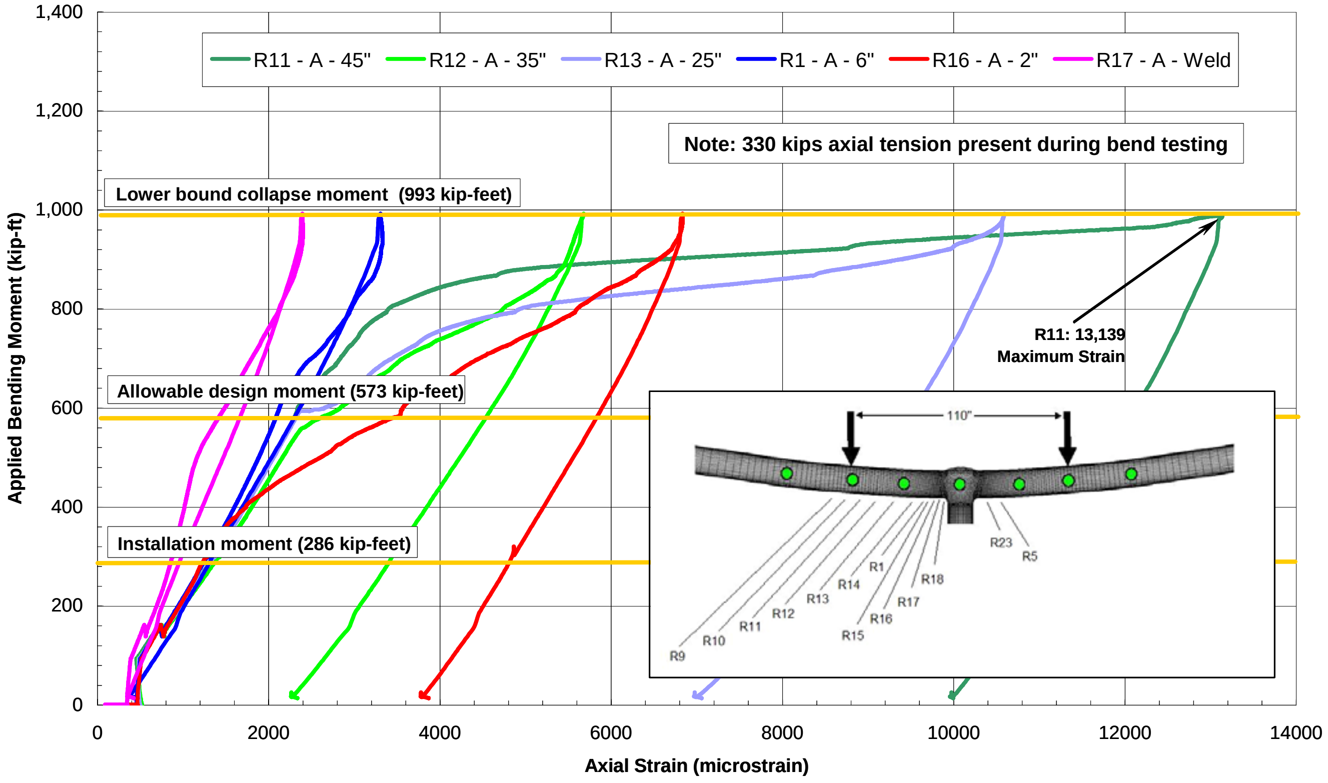

Figure 10 – Limit analysis plot showing bending moment versus axial strain
(note: 10000 microstrain equals 1 percent strain)

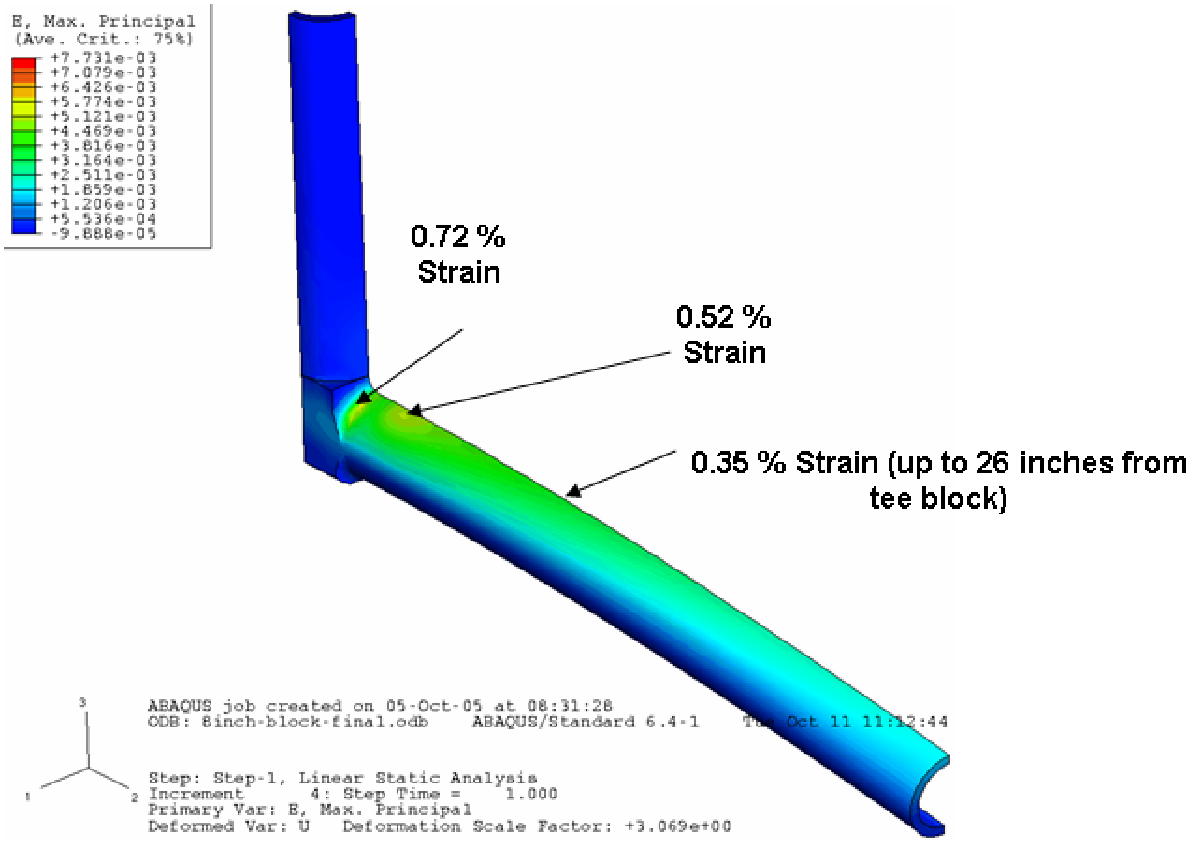

Figure 11 - Maximum principal strain FEA contour plot for 8 inch block tee