Finite Element Analysis of Steel Lap Welded Joint Behavior under Severe Seismic Loading Conditions

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ABSTRACT

The present paper extends the experimental and numerical research presented at the ASCE 2018 conference. The paper is numerical, based on a shell finite element simulation of the welded lap joint subjected to internal pressure and structural loading, which accounts for the bell formation process, the corresponding residual stresses, and the presence of initial (geometric) imperfections of the cylindrical pipes. Previous numerical simulations of the experiments presented in the 2018 conference, have shown a very good comparison between the numerical results and test data. The present paper has the following two purposes: (a) extend the numerical results for the case of axial compression loading, in addition to the case of bending; and (b) examine the effects of pressure on the mechanical response of welded lap joints. Towards the above purposes, two 24-inch nominal diameter pipes with thickness equal to 0.135 in. and 0.25 in. will be considered, similar to those tested in the prior experiments. The pipes contain welded lap joints with single and double weld and are pressurized first to a certain level (up to 50% of yield pressure) and subsequently, they are subjected to either axial compression or bending, well into the plastic regime of the steel material. The numerical results are used for elucidating some interesting issues of welded lap joint behavior under severe axial and bending deformation, allowing for determining the ultimate load deformation capacity of those joints in geohazard and seismic areas, where severe ground-induced actions are expected, towards minimizing the risk of failure.

INTRODUCTION

Large-diameters steel water pipelines are often constructed with welded lap joints instead of butt-welded joints, due to their lower construction cost. The welded lap joints consist of a "bell" cold-formed at the end of each pipe segment, using an expanded mandrel so that the end of the adjacent pipe segment, often referred to as "spigot", is inserted and welded to the bell through a single or double full-circumferential fillet weld, as shown in Figure 1.

The present paper is motivated by the need of understanding the mechanical behavior of welded lap joints subjected to severe bending or axial loading conditions. An initial attempt to investigate the mechanical response of welded lap joints under bending has been reported by Karamanos *et al*. (2015, 2017b), using advanced finite element models, which takes in to account the manufacturing process of the bell. An extensive literature review on the structural strength of those joints can be found in those two papers, and is not repeated herein for the sake of brevity. The structural response of welded lap joints under extreme conditions, consists an important issue for safeguarding welded steel pipelines integrity for water transmission against seismic-induced actions. In areas with high potential seismic activity, the pipeline may be subjected to severe permanent ground-induced actions, such as fault rupture, liquefaction-induced lateral spreading, soil subsidence, or slope instability, which may deform the pipe well beyond the stress limits associated with normal operating conditions. The seismic design framework of water pipelines has been described recently by Karamanos *et al.* (2017a), while the important issue of pipe-soil interaction in buried steel pipelines has been examined, experimentally and numerically in the course of a large international project (Sarvanis *et al.* 2017). Using this framework, the deformation capacity and strength of welded lap joints consists a vital issue of steel water pipeline integrity that requires further investigation.

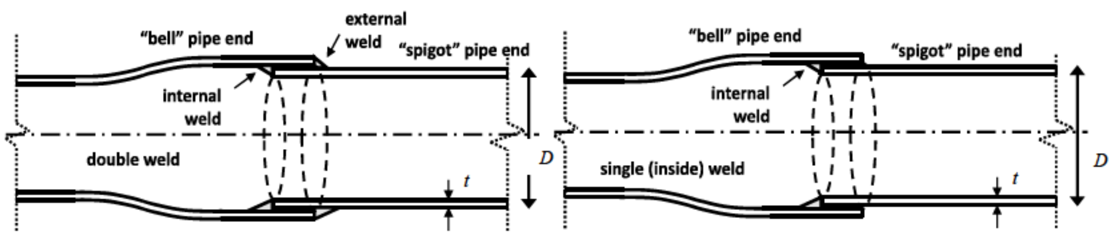

Figure 1. Schematically configuration of the three types of lap pipe joint.

Table 1. All analyzed cases.

weld type	double				inside				plain pipe			
load	pure bending		compression		pure bending		compression		pure bending		compression	
thickness (in)	0.135	0.25	0.135	0.25	0.135	0.25	0.135	0.25	0.135	0.25	0.135	0.25
Pressure (% P_y)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-	-	-	-
	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	-	-	-	-
	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	-	-	-	-
	-	0.5	0.5	0.5	0.5	-	0.5	-	0.5	0.5	0.5	0.5

The present research effort aims at expanding the experimental and numerical results presented by Keil et al. (2018) and Chatzopoulou et al. (2018) in the ASCE 2018 Pipelines Conference. The paper is numerical and instigates the effect of the internal pressure, up to 50% of yield pressure, in the structural performance of welded lap joints both in bending and axial loading. Two different pipes are analyzed in this paper. The first pipe has 25.75-inch outer diameter, and thickness equal to 0.135in. The second pipe has the same outer diameter but its thickness is equal to 0.25in. The steel grade of the pipes is ASTM A1011 SS GR36 and ASTM A1018 SS GR40, respectively. All analyzed cases are tabulated at Table 1.

DESCRIPTION OF THE NUMERICAL MODEL

The numerical model employed for this research effort is described in detail in Chatzopoulou *et al.* (2018) and it is outlined here for the sake of completeness. The model consists of three (3) main parts, a pipe with a bell configuration, a straight pipe (spigot) and the welds, as shown in Figure 2. The model employs four-node, reduced-integration shell finite elements, referred to as S4R, for the pipes and 8-node solid "brick" elements for the two fillet welds, the mesh is shown in Figure 3, the total length of the model is 120 inch. Two (2) different cases of pipe joint are examined in the present study the "double-welded", and the "single/interior-welded" joint. The gap size between the bell and the spigot is constant around the pipe and is equal to 0.05 inch, which is within the AWWA C200 requirements. The reader is referred to Keil *et al.* (2018) and Chatzopoulou *et al.* (2018) for more information related to joint geometries.

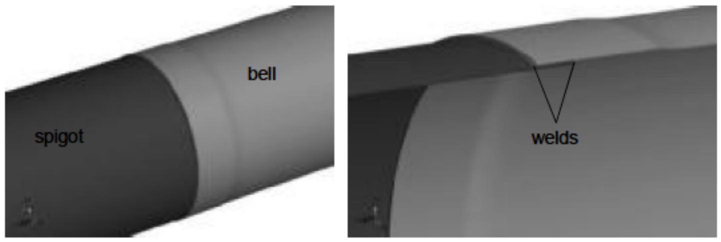

Figure 2. Finite element model of a welded lap joint; geometry of the double-welded area of the joint.

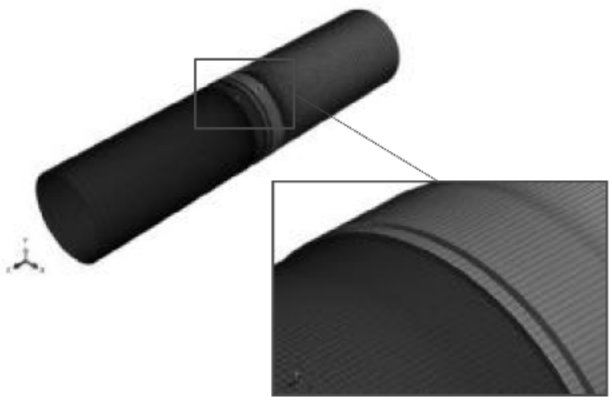

Figure 3. Finite element mesh used in the numerical simulation.

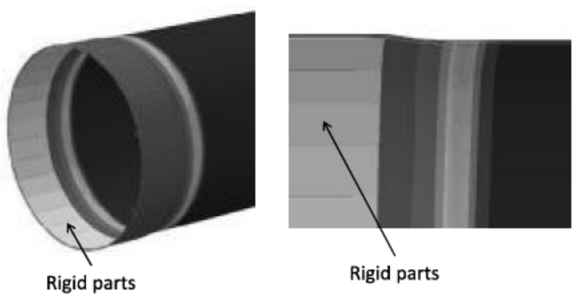

Figure 4. Simulation of bell expansion using mandrels.

Initially bell expansion is simulated. The bell configuration is achieved by expanding the pipe end, using an appropriate mandrel (rigid body) that moves outwards at the radial direction as shown in Figure 4. After bell formation, the spigot and the bell are connected with the weld parts using appropriate kinematic constraints, which ensure the continuity of the geometry. Two reference points, located at each end of the model, are employed, which are coupled, in all six (6) degrees of freedom, in order to apply the desirable boundary conditions. In the case of pure bending, the rotation is induced at both far ends of the model as shown in Figure 5. In the second case, for the case of compression, the axial displacement is induced at the end cross section of the bell side, while the end cross section of the spigot side remained fixed, as shown in Figure 6.

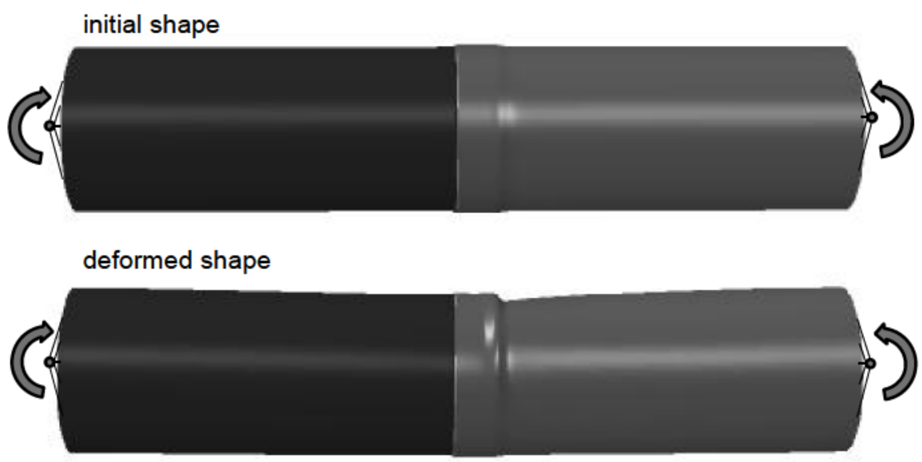

Figure 5. Schematic representation of induced rotations at the two far ends of the model.

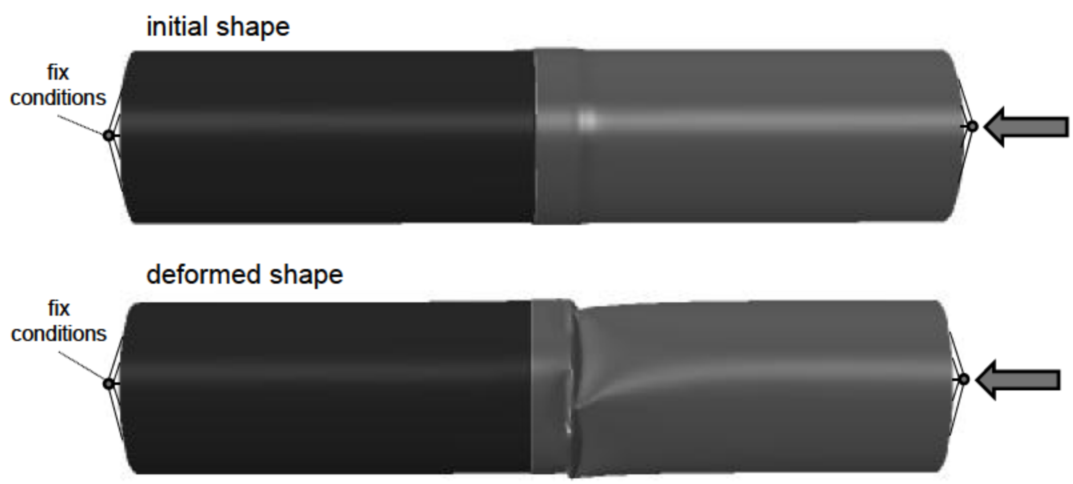

Figure 6. Schematic representation of induced axial displacements at the two far ends of the model.

NUMERICAL RESULTS

The results obtained from the numerical models presented above are for axial load with respect to axial deformation and for bending moment with respect to curvature. The axial force and the bending moment have been normalized using the yield force and the plastic bending moment respectively. The normalized axial deformation is equal to $\varepsilon/\varepsilon_I$, where ε is a global axial strain equal to the applied displacement over the total length of the examined pipe ($\varepsilon = \Delta L/L$) and ε_i is equal to t/D. Moreover, the normalized curvature is equal to k/k_I, where k equal to twice the applied rotation over the total length of the examined pipe, and k_I is equal to t/D^2.The normalized numerical results are presented in Figure 7 to Figure 11, for all analyzed cases. The increasing of internal pressure result in increasing of structural strength of the joints under consideration since it result to higher maximum bending moments and higher axial forces. Furthermore, plain pipes (without joint) are examined against pure bending in order to compare the strength of the welded lap joints with the strength of the pipe. The results show a reduction of the structural strength of the joints with respect to the pipe under pure bending was less than 20% in all examined cases.

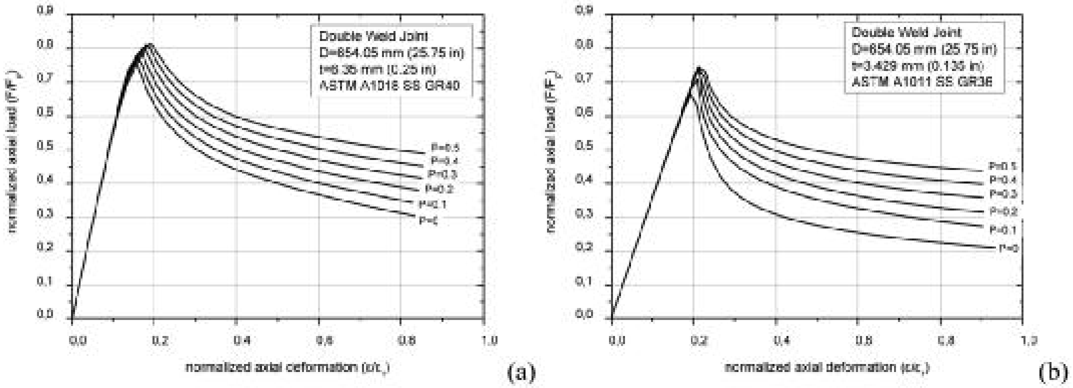

Figure 7. Normalized axial load versus normalized axial deformation for different internal pressure levels of double weld joint; (a) thick pipe 0.25 in.; (b) thin pipe 0.135 in.

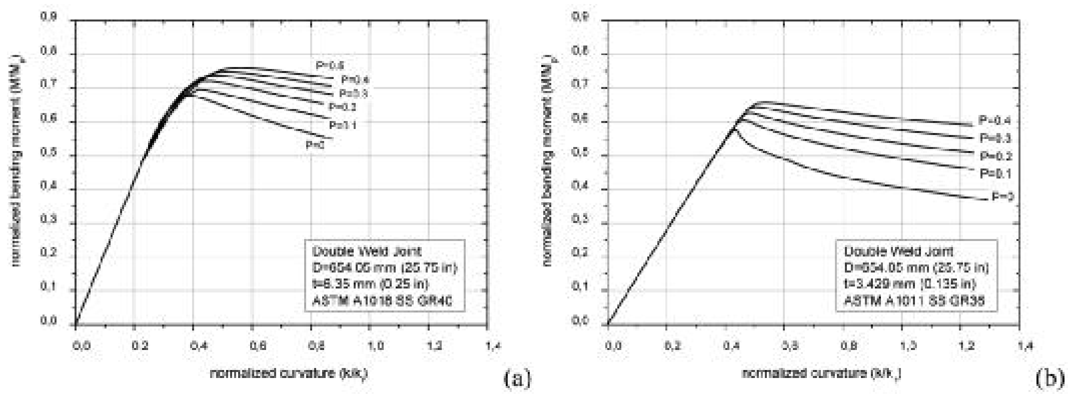

Figure 8. Normalized bending moment versus normalized curvature for different internal pressure levels of double weld joint; (a) thick pipe 0.25 in.; (b) thin pipe 0.135 in.

Apart from the ultimate strength of the lap joint, the presence of internal pressure affects also the buckling mode as shown in Figure 12 to Figure 17. In the case of the thin pipe the buckling mode has a "diamond" shape in absence of internal pressure for both bending and axial compression, whereas, it has an axisymetric shape in the case of the thick pipe. The corresponding deformed shapes, for the case of the double-welded thin pipe with zero internal pressure are illustrated in Figure 12 to Figure 15. The buckling shape of a welded lap joint of both thick and thin pipes seems to be unaffected by the presence of internal pressure despite the fact that the strength of the joints increases, as shown in Figure 16 and Figure 17.

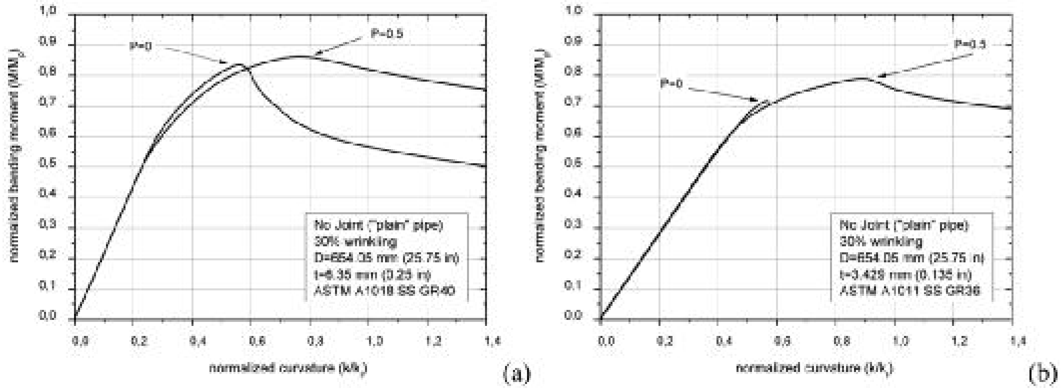

Figure 9. Normalized bending moment versus normalized curvature for two different internal pressure levels of plain pipe; (a) thick pipe 0.25 in.; (b) thin pipe 0.135 in.

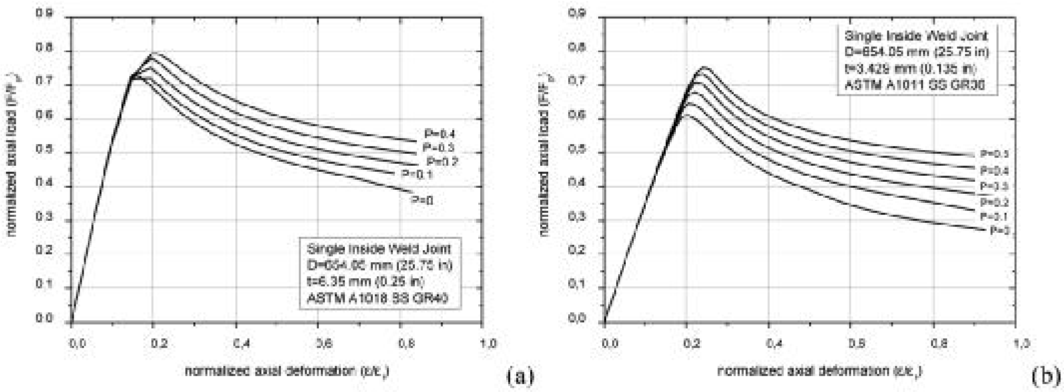

Figure 10. Normalized axial load versus normalized axial deformation for different internal pressure levels of single inside weld joint; (a) thick pipe 0.25 in.; (b) thin pipe 0.135 in.

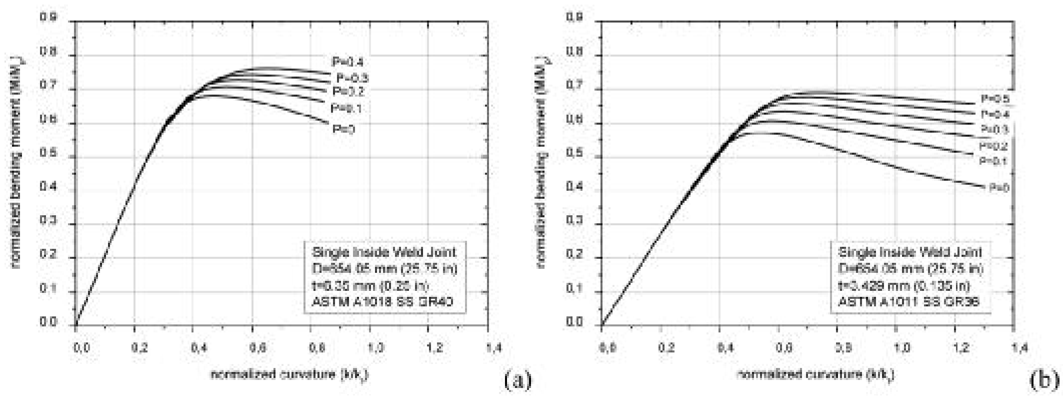

Figure 11. Normalized bending moment versus normalized curvature for different internal pressure levels of single inside weld joint; (a) thick pipe 0.25 in.; (b) thin pipe 0.135 in.

CONCLUSION

The parametric study presented in the present paper constitutes a step forward for understanding the mechanical behavior of welded lap steel pipe joints. In particular, the effect of internal pressure, up to 50% of yield pressure, on the mechanical response of lap welded joints has been examined numerically using a finite element model, which has been verified against experimental data elsewhere. The cases considered in the present paper refer to two different loading patterns, namely pure bending and axial compression. Furthermore, two different pipes have been considered with double weld and single-inside weld. The numerical results indicate that, in all cases, increasing the internal pressure level results in the increase of both bending and axial force capacity of the joint under consideration. In most cases, the maximum bending moment or maximum axial force sustained by the pipe joints range between 60% and 80% of the corresponding nominal full-plastic values. Furthermore, these values are about 80% of the maximum bending moment or maximum axial load that the corresponding plain pipe can sustain. The results from the present study, as well as from the two companion papers presented in ASCE 2018 Pipelines conference support the argument that welded lap joints are suitable for use in demanding pipelines applications, such as seismic/geohazard areas.

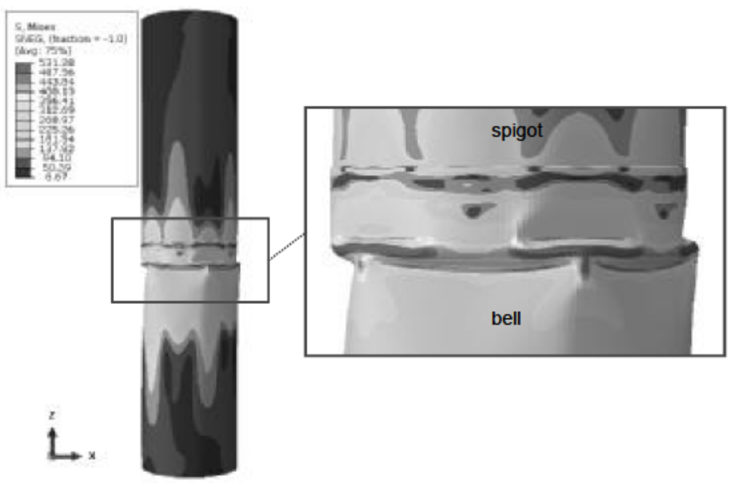

Figure 12. Deformed shape of double-welded thin pipe subjected to compression loading with zero internal pressure.

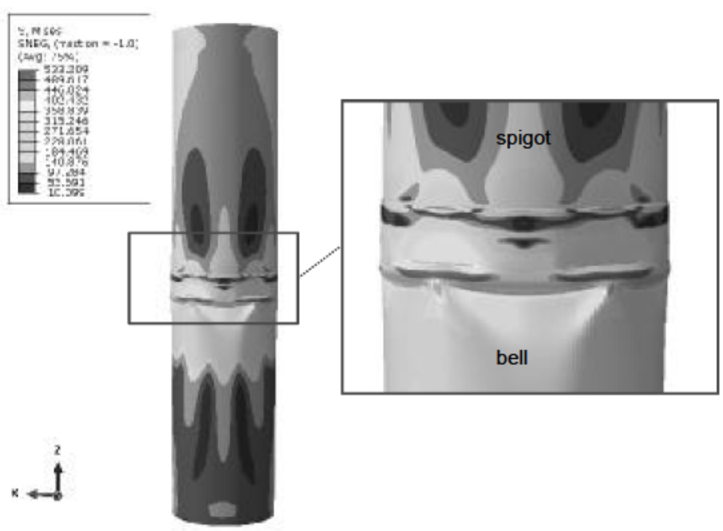

Figure 13. Deformed shape of double-welded thin pipe subjected to bending moment with zero internal pressure.

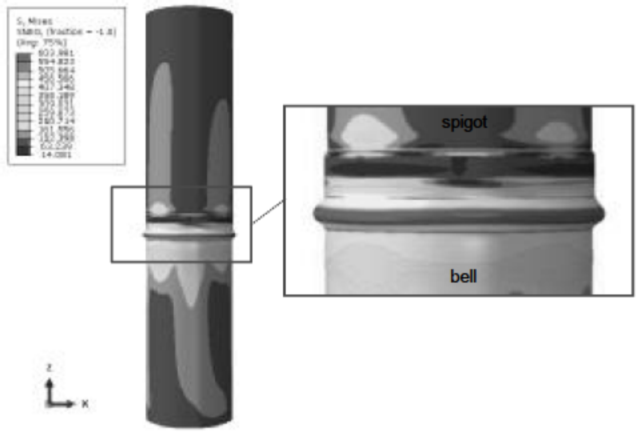

Figure 14. Deformed shape of double-welded thick pipe subjected to compression loading with zero internal pressure.

Figure 15. Deformed shape of double-welded thick pipe subjected to bending moment with zero internal pressure.

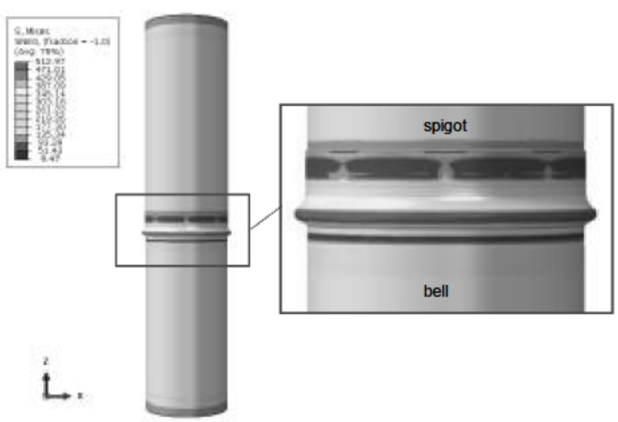

Figure 16. Deformed shape of double-welded thin pipe subjected to compression loading with internal pressure 50% of yield pressure.

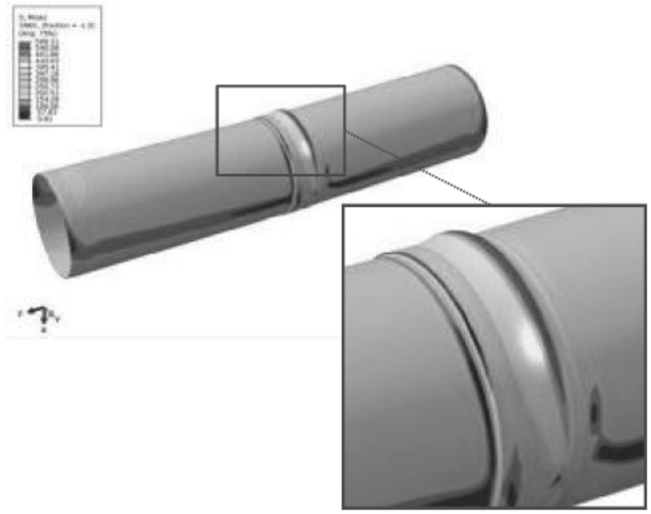

Figure 17. Deformed shape of double welded thick pipe subjected to bending with internal pressure 50% of yield pressure.

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