Numerical Simulation of Steel Lap Welded Pipe Joint Behavior in Seismic Conditions

Giannoula Chatzopoulou[1]; Dimitris Fappas[2]; Spyros A. Karamanos[3]; Brent D. Keil[4]; and Richard D. Mielke[5]

[1]Univ. of Thessaly, Volos, Greece. E-mail: gihatzop@uth.gr
[2]Univ. of Thessaly, Volos, Greece. E-mail: dfappas@uth.gr
[3]Univ. of Thessaly, Volos, Greece; Univ. of Edinburgh, Scotland, U.K. E-mail: spyros.karamanos@ed.ac.uk
[4]Northwest Pipe Co., Vancouver, WA, USA. E-mail: bkeil@nwpipe.com
[5]Northwest Pipe Co., Vancouver, WA, USA. E-mail: rmielke@nwpipe.com

ABSTRACT

The present paper reports numerical calculations which complement experimental work reported in the companion paper entitled "Experimental Results of Steel Lap Welded Joints in Seismic Conditions", also presented in ASCE 2018 Pipelines Conference. Nonlinear finite element simulation tools are employed to investigate the bending capacity of internally-pressurized welded-lap 24-in-diameter pipeline joints, considering two thicknesses (0.135 in and 0.250 in). The work presented in this paper: (a) simulates numerically the seven large-scale experiments presented in detail in the companion paper; (b) elucidates some interesting issues of welded lap joint behavior under severe bending deformation. In the final part of the paper, based on the above experimental and numerical results, a discussion is offered on the design of welded lap joints in pipelines constructed in seismic areas.

INTRODUCTION

Welded-lap joints, sometimes referred to as "bell and spigot" joints, have been employed extensively in large-diameter steel pipelines for water transmission instead of straight butt-welded full-penetration joints. As shown in Figure 1, the "spigot" is inserted and welded to the "bell" with a single-interior, single exterior or double full-circumferential fillet weld. Their use has been motivated by their ease of installation, lower construction cost, and proven history of use; these joints have been shown to be very efficient in traditional pipeline design, where internal pressure is the main design parameter. On the other hand, the strength and deformation capacity of these joints can be challenged in seismic areas, where the pipeline joint is usually subjected to excessive bending action in the presence of internal pressure. Joints are subjected to severe loading, which could threaten pipeline structural integrity. An extensive literature review on this topic is presented in previous publications of the authors (Karamanos ***et al***. 2015; 2017)

The present research is motivated by the need for determining the allowable deformation limits of welded steel pipelines for water transmission, constructed in geohazard (seismic) areas where fault rupture, liquefaction-induced lateral spreading, soil subsidence, or slope instability may induce significant deformation in the pipe. In particular, the structural performance of welded joints constitutes a key issue for safeguarding pipeline structural integrity with no loss of pressure containment.

The work presented herein is part of a large-scale research program, launched recently by Northwest Pipe Company, aimed at determining the strength and deformation limits of steel pipelines in seismic areas. In particular, the research focuses on the bending response of internally-pressurized pipes with welded lap joints, constructed according to AWWA C206 provisions. The research comprises experimental full-scale testing on 24-inch nominal diameter pipes, and it is supported by numerical calculations. The experiments have been performed by Northwest Pipe Co. and have been presented in the companion paper entitled *“Experimental Results of Steel Lap Welded Pipe Joints in Seismic Conditions*”, also presented in ASCE 2018 Pipelines Conference (Keil *et al*., 2018).

The work presented herein is numerical, and complements the experimental work reported in the companion paper. The numerical work has a dual purpose: (a) to simulate numerically the large-scale experiments on 24-inch-diameter welded lap joints; (b) to elucidate some interesting issues of welded lap joint behavior under severe bending deformation. The pipe and the welded joint are modelled with finite elements, enhancing the modelling procedure adopted in previous publications by the authors (Karamanos *et al*. 2015; 2017).The comparison with the experimental results concerns the maximum bending load capacity, the failure mode, and the displacements and strains at key locations.

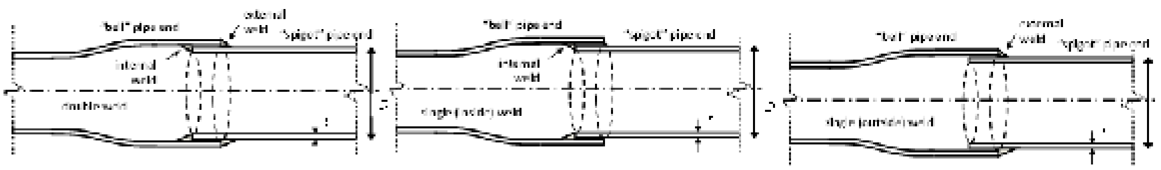


Figure 1. Configuration of welded lap pipe single-interior, single exterior or double lap welded pipe joints.

NUMERICAL MODELING

Finite element model

The pipes under consideration have a 25.75inch outer diameter and their wall thickness is equal to either 0.135 inch or 0.250 inch. The material specific for the pipe with wall thickness equal to 0.135 inch is ASTM A1011 SS GR36 steel, whereas the material speciation for the pipe with wall thickness equal to 0.250-inch is ASTM A1018 SS GR40 steel. The axial stress-strain curves of the two materials used in the present analysis are shown in Figure 2.

For the simulation of welded lap joints, numerical models are developed in the commercial finite element software ABAQUS/Standard, which is capable of accounting for elastic-plastic pipe behaviour, as well as abrupt changes of pipe geometry, due to local buckling formation. Four-node, reduced-integration shell finite elements, referred to as S4R, are employed for simulating the pipe, while 8-node solid “brick” elements are used for the two fillet welds using a 45-degree triangular weld profile, as shown in Figure 3 and in Figure 4. In the latter figure, the bell dimensions are also shown.

Three cases of pipe joint are examined in the present study “double-welded”, “single/interior-welded”, and “single/exterior-welded”. 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 bell and spigot joint geometry are shown in Figure 4.

The first step for the present analysis is the expansion of the pipe end, in order to form the bell. In this step, analytical rigid surfaces are used, as shown in Figure 5, which move in the radial direction, causing expansion of the pipe end. After bell formation, the spigot part and the bell part are connected using appropriate kinematic constrains; a “tie” is used to connect the spigot and the welds, and a “rough contact” with “no separation” is employed to connect the bell with the welds.

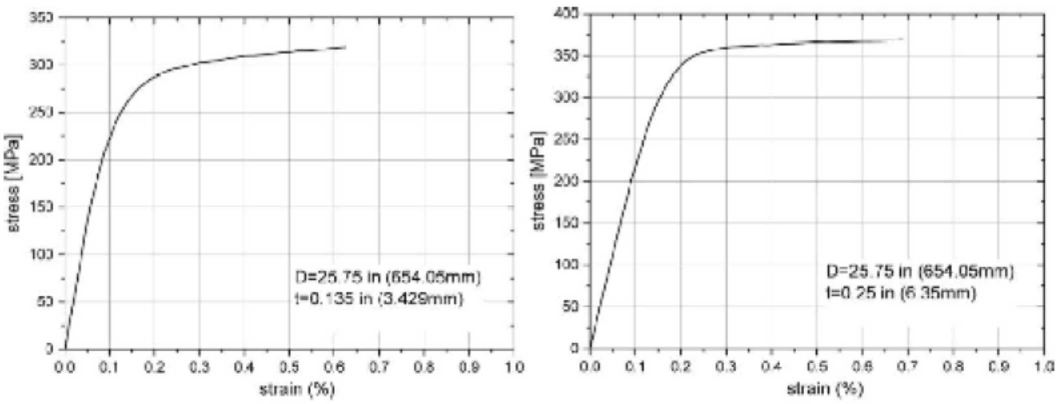


Figure 2. Axial stress vs. strain material curves for the pipes analyzed.

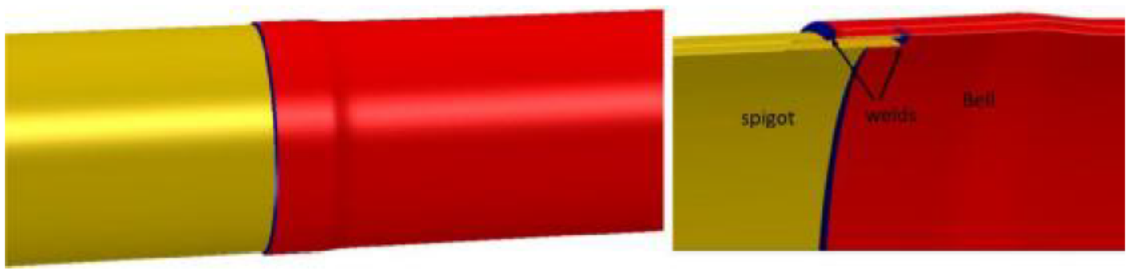


Figure 3.Finite element model of a welded lap joint; geometry of the double-welded area of the joint.

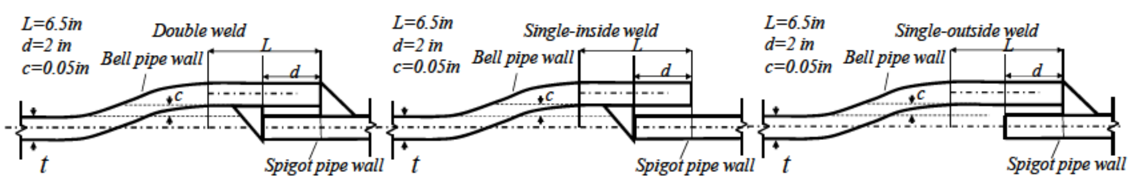


Figure 4. Configuration of the bell and spigot geometry.

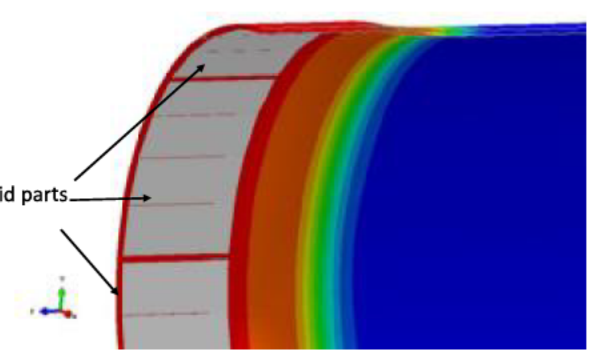


Figure 5. Finite element model for a welded lap joint simulation; geometry of the double weld area, showing the rigid part that moves in the outward radial direction for bell formation.

Simulation of the four-point bending test

For simulating pipe joint structural performance under internally-pressurized four-point bending conditions, the numerical model of Figure 6 was developed. This symmetric four-point bending loading consists of two transverse forces (from two hydraulic actuators), acting at the pipe specimen ends. The specimen is supported by two straps near the middle and the lap joint is located exactly at the middle of the pipe. The two straps are simulated with analytical rigid surfaces that "embrace" the pipe and are connected with beam elements hinged at both ends, as shown in Figure 7. Interaction between the pipe outer surface and the straps is imposed with a tangential friction coefficient equal to 0.2. At the two ends of the pipe model, two fictitious nodes are introduced on the pipe axis, and are connected to the nodes of the end-section with appropriate kinematic conditions. These fictitious nodes are used for applying the load from the hydraulic actuators. The hydraulic actuators are limited to 36" of stroke or displacement.

The analysis considers the presence of internal pressure in the specimens. Pressure is applied first in one step up to the desired level (nearly 40% of the nominal yield pressure P_{ij}). Subsequently, while keeping the pressure level constant, displacement at the two reference nodes at the pipe ends are gradually increased, simulating the four-point loading pattern in a displacement-controlled scheme, well beyond the formation of local buckling.

Table 1. Specimen description.

	diameter (in)	thickness (in)	D/t ratio	pressure (bar)	weld type
1-AD	25.75	0.135	191	11.72	double weld
2-ASO	25.75	0.135	191	11.72	single (outside) weld
3-ASI	25.75	0.135	191	11.72	single(inside) weld
4-PP	25.75	0.135	191	11.72	plain pipe (no weld)
5-BSI	25.75	0.250	103	22.41	single (inside) weld
6-BSO	25.75	0.250	103	22.41	single (outside) weld
7-BD	25.75	0.250	103	22.41	double weld

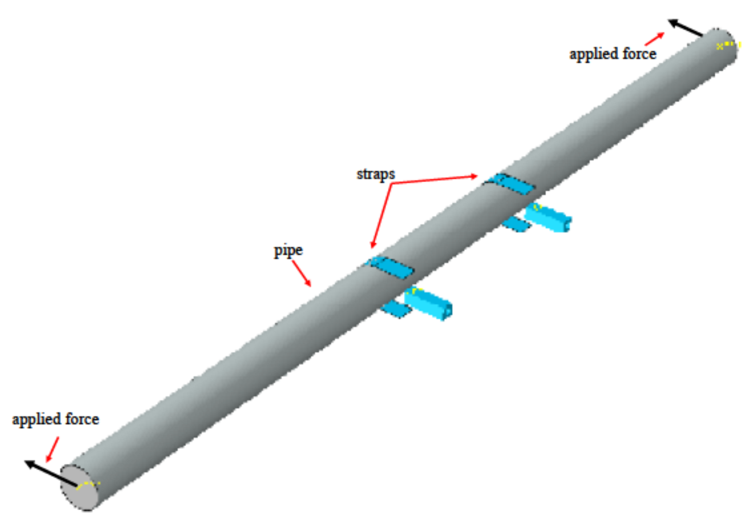


Figure 6. Numerical model of testing setup for four point bending test.

Using the above model, seven four-point bending tests are simulated, as shown in Table 1. Four tests refer to pipes with diameter-to-thickness ratio (D/t) equal to 191, referred to as "0.135 in walled pipes", and three tests refer to "0.250 in walled" pipes (D/t=103).

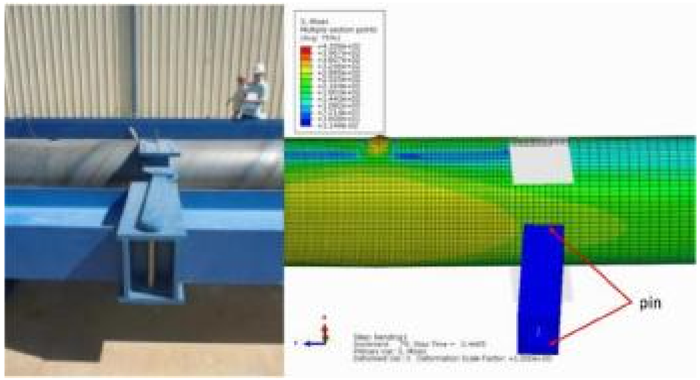


Figure 7. Details of the test setup and the respective numerical model.

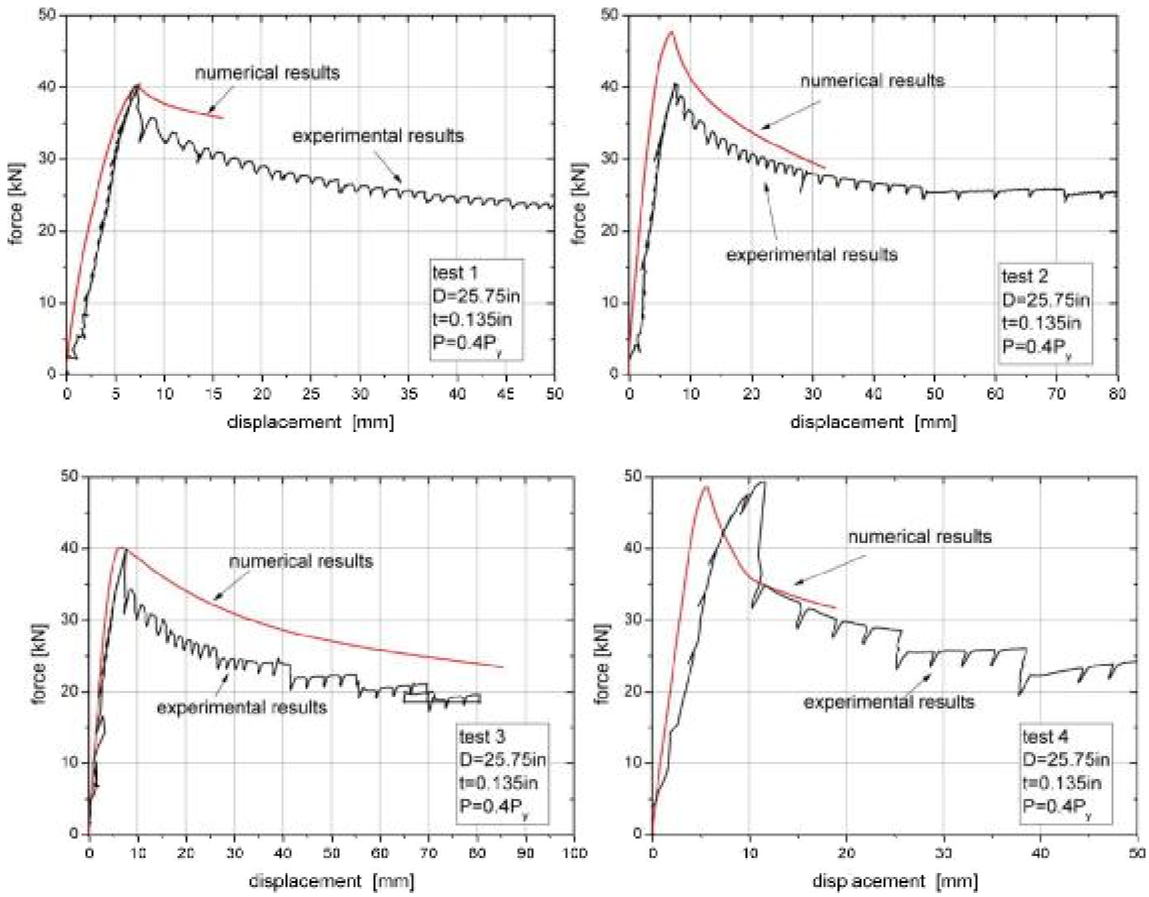


Figure 8. Force vs. midspan displacement plots for welded-lap joints in thin-walled pipes (D/t=191).

Figure 9. Buckled shape of double-weld lap joint; Test 1 (D/t=191).

Figure 10. Buckled shape of single (outside) weld lap joint; Test 2 (D/t=191).

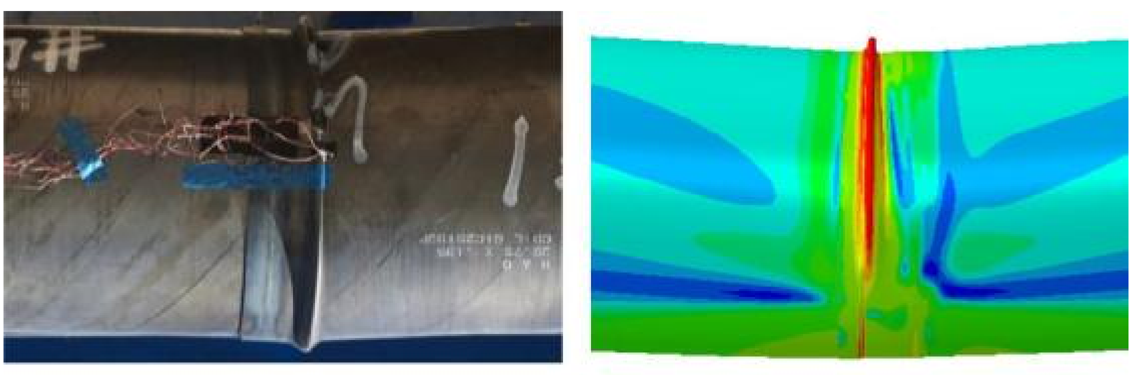
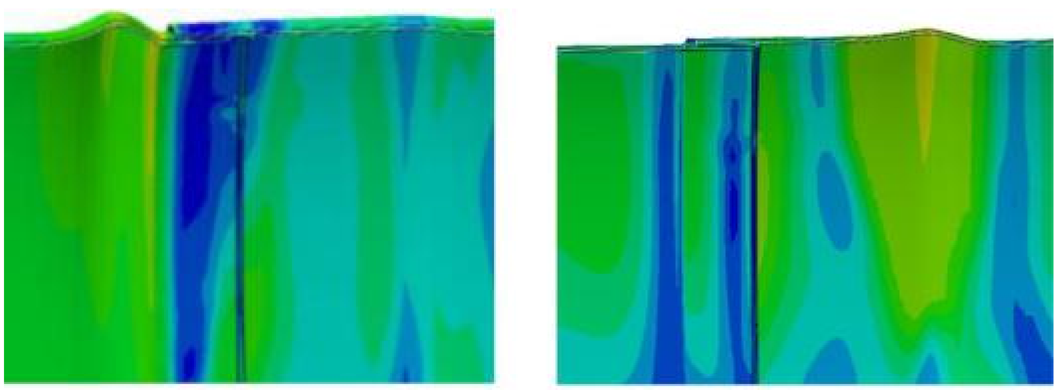


Figure 11. Buckled shape of single (inside) weld lap joint; Test 3 (D/t=191).

NUMERICAL RESULTS

The bending response of pipe segments containing welded lap joints is different than the response of plain pipes, as shown numerically in previous investigations on this topic reported elsewhere (Karamanos et al. 2015; 2017), as well as in the companion paper (Keil et al., 2018). In welded lap joints, because of the bell geometry, an initial geometric "imperfection" is introduced, which, under bending, is often associated with significant local deformation at the compression side of the pipe in the form of localized wrinkling and folding. This behavior is a key aspect for the welded lap joint structural performance and will be discussed in the following paragraphs.

Figure 12. Buckled shape of a no-joint (plain) pipe; Test 4 (D/t=191).



(a) (b)

Figure 13. Deformed (buckled) shape of a double weld joint; (a) with initial imperfection and (b) without initial imperfection (D/t=191).

The comparison between numerical and experimental results is shown below (buckled) in terms of force-displacement diagrams and deformed shapes. In addition, some representative force-strain diagrams, referring to strain at specific locations at the lap-welded joint, are reported. Overall, the comparison between experimental and numerical results agrees well, and the finite element model employed in the present study is capable of predicting not only the load-displacement response, but also the deformed shape of the joint and the local strains with good accuracy.

Results for welded-lap joints in "0.135 in-walled" pipes (D/t=191)

For the case of pipes with a diameter-to-thickness ratio (D/t) equal to 191, numerical and experimental results for double, inside, and outside welds are presented in Figure 8, together with the results from the plain pipe. The comparison between experimental and analytical agrees well for initial slope, maximum load, and shape of the post-buckling branch of the curve. The buckling shape for the pressurized specimens is shown in Figure 9 through Figure 12. For the cases of double-weld (AD-test1) and single-outside weld (ASO-test2), buckling occurs at the spigot, while for the case of single-inside weld (ASI-test3) buckling appeared at the bell. At this point, it is important to mention that the buckle location is quite sensitive in the presence of initial imperfections. More specifically, while simulating Test 1 (in which failure occurred at spigot), a wrinkling imperfection has been included in the initial pipe geometry to enable the buckle to occur at the spigot. If this imperfection were not imposed, buckling would have occurred at the bell, as shown in Figure 13. The sensitivity of buckling location to the presence of initial imperfection is an open issue to be investigated in the continuation of the research.

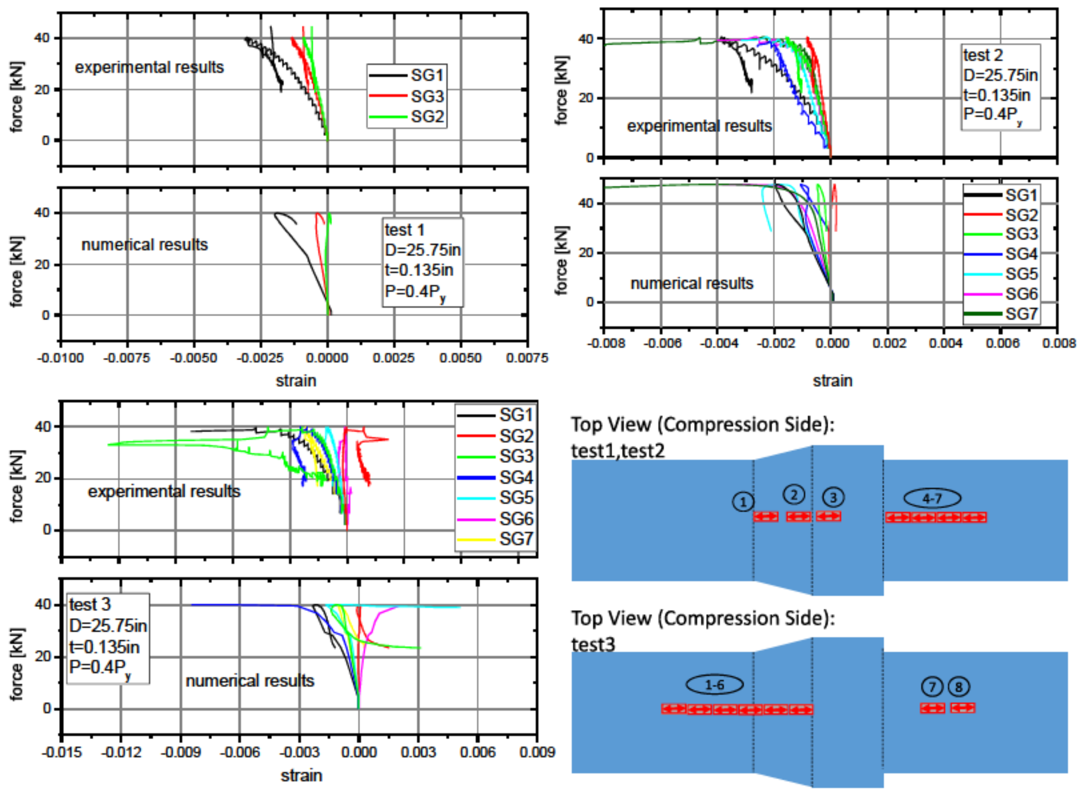


Figure 14. Force vs. strain plots for welded lap joints in thin-walled pipes (D/t=191).

In Figure 14, the force vs. strain diagrams for the three cases are presented and show good agreement with the experimental measurements. The results show the maximum load and the displacement at which a buckle occurred is close for the three joint cases examined, verifying the experimental results.

Results for welded-lap joints in "0.250 in-walled" pipes (D/t=103)

The case of 0.25" pipes with diameter-to-thickness ratio D/t equal to 103 was also examined. The experimental and numerical results are compared in terms of load vs. displacement diagrams Figure 15, and their comparison indicates very good agreement. For test 7, only the maximum load is available from the experimental results. The buckling shape in the presence of internal pressure is shown in Figure 16 through Figure 18 for tests 5, 6, and 7, respectively. For the cases of double weld and single-inside weld, buckling occurred at the bell, while for the case of outside weld, a buckle occurred at the spigot. In Figure 19, the force vs. strain plots for test 5 are presented, and the comparison between numerical and experimental results is quite satisfactory.

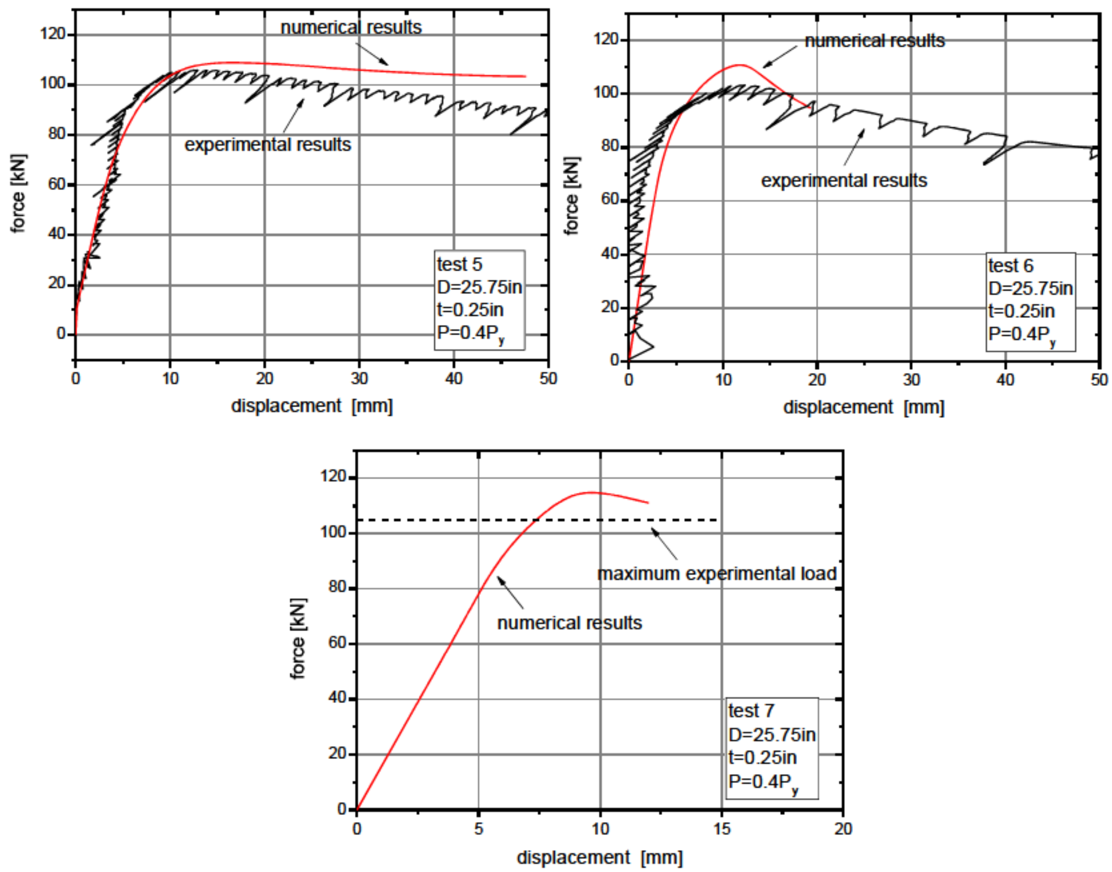


Figure 15. Force vs. displacement plots for lap joints (D/t=103).

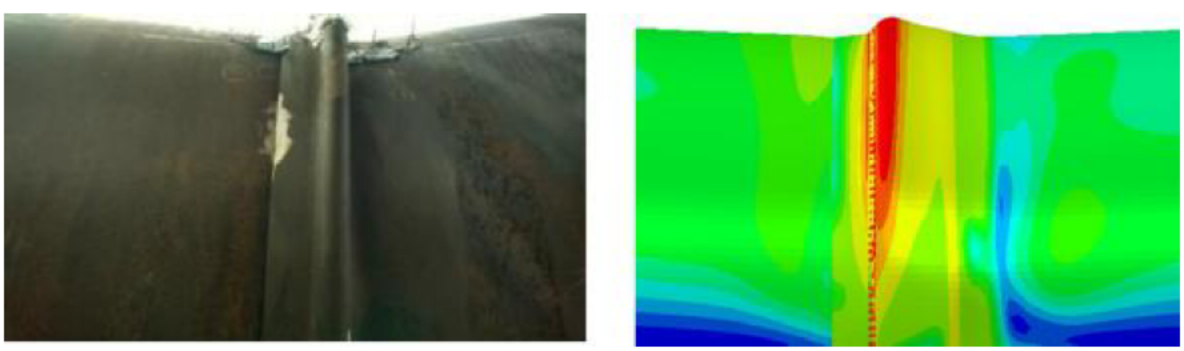


Figure 16. Buckled shape of a single (inside) weld lap joint; Test 5 (D/t=103).

DISCUSSION AND CONCLUSIONS

The present paper reports numerical (finite element) results simulating the structural performance of welded lap internally-pressurized joints under severe bending loads, complementing the experimental work reported in a companion paper (Keil et al. 2018)

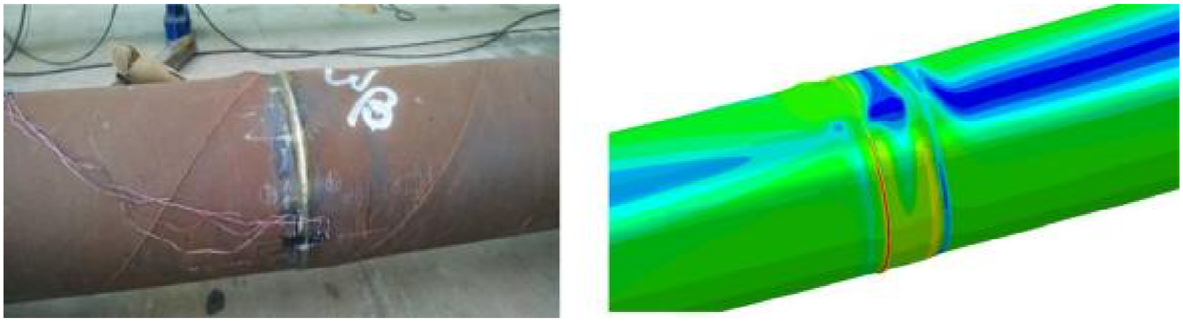


Figure 17. Buckled shape of a single (outside) weld lap joint; Test 6 (D/t=103).

The finite element results are in very good agreement with the test data, and verify that welded lap joints subjected to bending are capable of sustaining significant deformation (rotation) after the occurrence of buckling. This is a good indication that welded lap joints, if properly constructed according to the provisions of AWWA M11 and C200 can be used in areas where severe ground-induced actions are expected, such as fault crossings, in liquefaction areas, and in areas of potential landslide. Comparison of the bending test results from welded lap joints to those from plain pipes indicates that welded lap joints can be an efficient solution for steel pipelines instead of butt-welded full-penetration joints in seismic areas.

Figure 18. Buckled shape of a double weld lap joint; Test 7 (D/t=103).

It should be emphasized that the bending action induced by geohazard action is an extreme loading condition for the pipeline. Therefore, classical stress-based design procedures, based on allowable stresses as a percent of yield stress, may no longer be applicable. In such cases, consideration of large local deformations of the welded lap joint is necessary, well beyond the elastic regime of the steel material, to assess its deformation capacity.

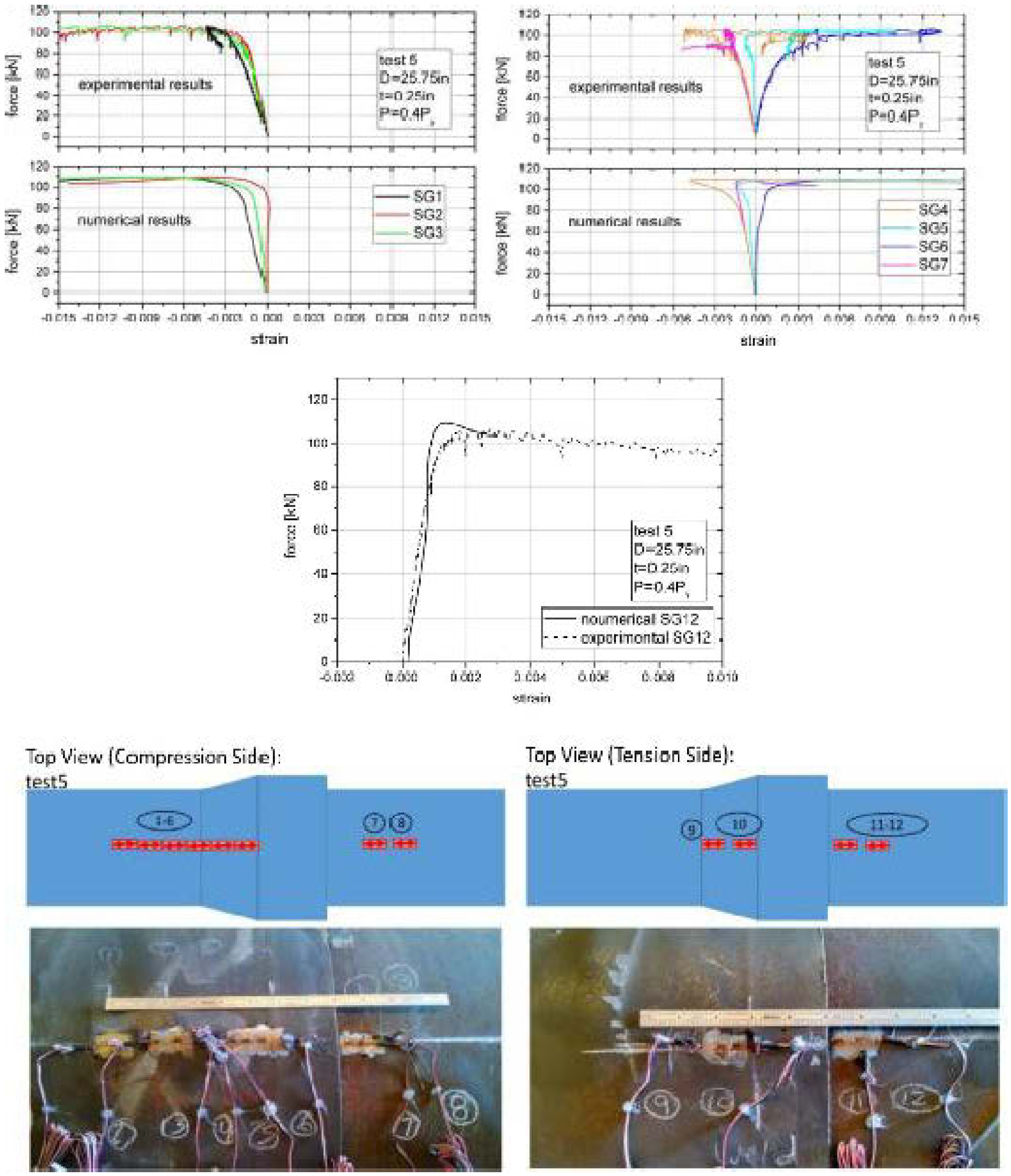


Figure 19. Force vs. strain diagrams for a single-weld lap joint; Test 5 (D/t=103).

REFERENCES

American Water Works Association (2004), *Steel Pipe – A Guide for Design and Installation*, AWWA Manual M11, Denver, CO, USA.

American Water Works Association (2012), *Steel Water Pipe – 6 in. and Larger,* AWWA Standard C200, Denver, CO, USA.

American Water Works Association (2013), *Field Welding of Steel Water Pipe,* AWWA Standard C206, Denver, CO, USA.

Karamanos, S. A., Koritsa, E., Keil, B. and Card, R. J. (2015), "Analysis and Behavior of Steel Pipe Welded Lap Joints in Geohazard Areas", *ASCE Pipelines Conference,* Paper No. 413, Baltimore, Maryland, USA.

Karamanos, S. A., Koritsa, E., Keil, B. Card, R. J. and Pappa, P. (2017), "Mechanical Response of Steel Pipe Welded Lap Joints in Seismic Areas", *ASCE Pipelines Conference,* Paper No. 227, Phoenix, Arizona, USA.

Karamanos, S. A., Sarvanis, G. C., Keil, B. D. and Card, R. J. (2017), "Analysis and Design of Buried Steel Water Pipelines in Seismic Areas", *ASCE Journal of Pipeline Systems Engineering & Practice,* Vol. 8, No. 4, Article Number: 04017018.

Keil, B. D., Gobler, F., Mielke, R. D., Lucier, G., Sarvanis, G. C., and Karamanos, S. A. (2018), "Experimental Results of Steel Lap Welded Pipe Joints in Seismic Conditions", *ASCE Pipelines Conference*, Paper No. 386906, Toronto, Ontario, Canada.