Mechanical Response of Steel Pipe Welded Lap Joints in Seismic Areas

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Abstract

Nonlinear finite element simulation tools are employed to investigate the bending capacity of internally-pressurized double-welded lap pipeline joints for a typical steel, with D/t value equal to 191.5. The study constitutes the first part of a comprehensive investigation on welded lap joints, which comprises both numerical simulations and experimental testing. The on-going research project is aimed at providing better understanding of welded lap joint behavior under extreme bending loading conditions, towards developing efficient design guidelines and safeguarding the structural integrity of steel water pipelines imposed to severe ground-induced actions. Herein, numerical work is presented, focusing on the global behavior of the lap joints, as well as on the value of local strains developed at critical locations. The present numerical results can be considered as preliminary, aiming at the efficient preparation and design of the upcoming experimental work.

INTRODUCTION

Large-diameter steel pipelines for water transmission, designed with AWWA M11, often employ welded lap joints. They are used instead of straight butt-welded full-penetration joints, because of their lower construction cost and their proven history of use. Welded lap joints require the forming a “bell” at the end of each pipe, which is constructed at the pipe mill through a mandrel that expands the end part of the pipe, so that the other end of the adjacent pipe segment, often referred to as “spigot”, is inserted and welded to the bell with a single or double full circumferential fillet weld, as shown in Figure 1.

The present paper describes numerical work, and is motivated by the need for determining deformation limits of welded steel pipelines for water transmission, constructed in geohazard (seismic) areas. In those areas, the pipeline may be subjected to severe permanent ground-induced actions, from fault rupture, liquefaction-induced lateral spreading, soil subsidence, or slope instability that may deform the pipe well beyond the stress limits associated with normal operating conditions, possibly well into the inelastic range of the steel material. In such a case, the structural performance of welded joints constitutes a key issue for safeguarding pipeline structural integrity with “no loss” of pressure containment.

Previous publications on the structural strength of welded lap joints has been directed towards determining their axial load capacity. Failures of such joints have been observed on the construction stage (Moncarz *et al.*, 1987; Eberhardt, 1990), as well as due to strong earthquake action (Meyersohn and O’Rourke, 1991; O’Rourke *et al.*, 1995; Lund, 1996;

Tutuncu, 2001). In welded lap joints, the stress path has an eccentricity due to the bell geometry (Figure 1) and, therefore, those joints are prone to buckling failure, also noted in medium-scale tests (Jones, *et al.*, 2004, Tutuncu and O'Rourke, 2006, Mason, 2006, Mason, *et al.*, 2010), and in axi-symmetric finite element analyses (Tsetseni & Karamanos, 2007). Full-scale experiments on the compressive capacity of 77.625-inch-diameter welded-lap pipe joints have been reported by Smith (2006), aimed at comparing the experimental strength with the joint efficiencies specified in ASME B&PVC VIII. Furthermore, tensile behavior of welded lap joints has been examined analytically using longitudinal strip models (Eidinger, 1999; Brockenbrough, 1990; Moncarz, *et al*., 1987), or experimentally on small-diameter (medium-scale) pipe specimens (Mason *et al.* 2011). Notable contributions on the practical use of welded lap joints, have also been reported by Watkins *et al*. (2006), van Greussen (2008), and Bambei and Dechant (2009).

On the other hand, despite the above publications on axially-loaded welded lap joints, the behavior of those joints under bending, has received much less attention. The first and only attempt to determine the bending behaviour of such joints has been reported by Karamanos *et al*. (2015), using advanced finite element simulation tools. In that work, the global response of those pipe joints was traced in terms of moment-curvature diagrams, and local strains were calculated at critical locations. It was observed that the local strains were substantially increased upon the occurrence of local buckling.

Motivated by the need to determine the strength and deformation limits of steel pipelines in seismic areas, a research program has been launched recently by Northwest Pipe Company, aiming at investigating the bending response of pressurized welded lap joints. The research comprises experimental testing on 24-inch nominal diameter pipes with diameter-to-thickness ratio value of 191.5, and it is supported by numerical calculations performed by the University of Thessaly, Volos, Greece. The present study reports initial finite element simulations on the bending performance of pressurized lap welded pipeline joints, to be used in the experimental program to be conducted soon.

In the present simulation, the pipe and the welded joint are modelled with finite elements, following the modelling procedure described in Karamanos *et al.* (2015). Numerical results are presented for plain steel pipes first, and subsequently, for double-welded lap joints under bending in the presence of internal pressure. Special emphasis is given on the evolution of local strain at critical locations, in an attempt to assess the structural performance of this joint against fracture.

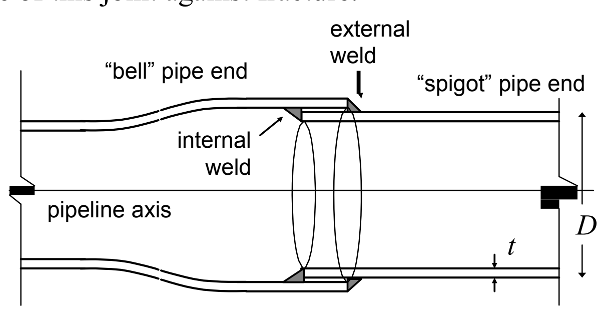

Figure 1. Configuration of a double-welded lap pipe joint.

NUMERICAL MODELING

The three-dimensional numerical model of welded lap joints using shell elements has been developed in finite element program ABAQUS/Standard accounts for elastic plastic behavior and uses four-node reduced-integration shell elements, and is similar to the one employed in Karamanos *et al*. (2015). Possible contact between the bell and the spigot parts is also taken into account. Furthermore, the two fillet welds are modelled considering a full-circumference ring with solid elements with a 45-degree triangular weld profile, as shown in Figure 2.

A finite element model is also developed for "plain pipe", i.e. pipe that does not contain a welded connection. This case can be regarded as representative for butt-welded pipe joints, assuming that butt welds restore fully pipeline continuity between two adjacent pipe segments; of course, special issues on butt-welded joints such as "high-low mismatch" imperfections are not considered herein.

For all cases analysed, the numerical model is 10-diameter-long, and the finite element mesh is considered quite dense in the area where buckling is expected, as described in Karmanos *et al*. (2015). Typical mesh for the lap joint model is shown in Figure 2. At the two ends of the pipe model, two "fictitious" nodes are introduced on the pipe axis, connected to the nodes of the end-section with appropriate kinematic conditions. The pipe is considered simply-supported at those two ends, and bending is applied with two opposite bending moments at the end nodes.

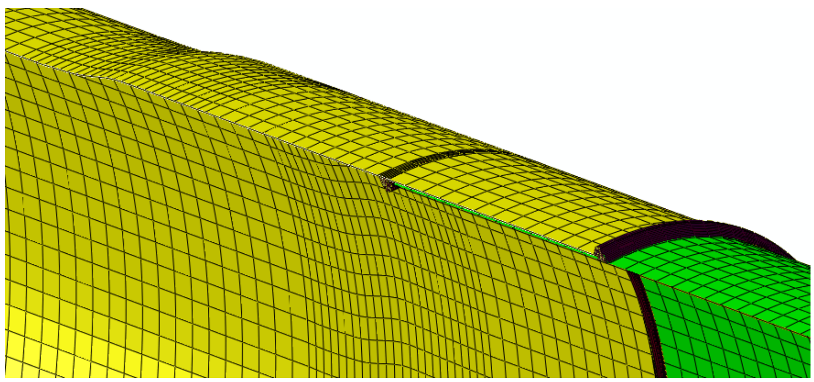

Figure 2. Finite element model for welded lap joint simulation; geometry of the double weld area.

Due to the large value of the diameter-to-thickness ratio, the primary mode of failure under bending is pipe wall bucking at the compression side. In plain pipes, to avoid numerical convergence problems in the nonlinear finite element analysis, an imperfection is assumed in the form of the first buckling eigen-mode of the pipe subjected to bending. The eigen-mode displacements are multiplied by an appropriate constant, so that the desired wrinkling amplitude w_0 is obtained. In the case of welded lap joints, consideration of such an imperfection is not used in the model, because it may not be necessary to obtain the post-buckling configuration.

NUMERICAL RESULTS

Results are presented for a steel pipe with diameter-to-thickness ratio D/t equal to 191.5. The pipe has a 25.75-inch diameter and a wall thickness equal to 0.1345-inch. The material of the pipe is ASTM 1011 grade 46 steel, and the stress-strain curve is shown in Figure 3. The yield stress is 317 MPa (46,000 psi), followed by a plastic plateau up to 1.5%

of strain, and subsequently, strain hardening occurs, with a hardening modulus equal to approximately 1/500 of Young's modulus.

The pipe joint is "double-welded" and the gap size between the bell and the spigot is constant around the pipe, with a value according to AWWA C200 provisions for maximum allowed tolerance of the joint. Moment-deformation relationships are determined for different values of internal pressure, and local strains are computed at critical locations, so that the possibility of joint failure is assessed.

Results for plain pipes

The response of plain pipes under bending, in the presence of internal pressure, is shown in Figure 4 in terms of moment-curvature diagrams. The reported value of curvature is computed as the ratio of the relative rotation of the two end sections of the pipe model over the model length and this can be regarded as a "global measure" of normalized rotation of the bent pipe segment under consideration. The values of bending moment are normalized by the fully-plastic moment $M_P = \sigma_Y D^2 t$, whereas the values of curvature are normalized by the "curvature-like" parameter $k_I = t$ [redacted] D^2 [e.g. see also Karamanos & Tassoulas (1996)].

The buckling shapes of this plain pipe for different levels of pressure is shown in Figure 5 and Figure 6. For zero pressure, a major buckle develops, as shown in Figure 5, located symmetrically with respect to the plane of bending, and several secondary or "side" buckles. This refers to a "diamond-shape" buckling pattern, typical for thin-walled shells subjected to compressive loading (Vasilikis *et al*., 2014, Karamanos *et al*., 2015).

The presence of internal pressure influences bending response. The corresponding moment-curvature diagrams in Figure 4 indicate an increase of bending capacity in the presence of pressure. The buckling shape in the presence of pressure, shown in Figure 6, are characterized by "diamond-shape" for small values of pressure and "bulging" for internally pressurized cylinders for larger amounts of pressure.

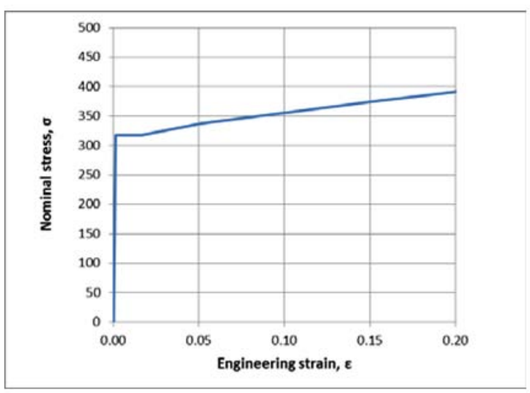

Figure 3. Stress- strain curve of ASTM 1018 grade 46 steel used in the present analysis; yield stress is equal to 317 MPa [46,000 psi].

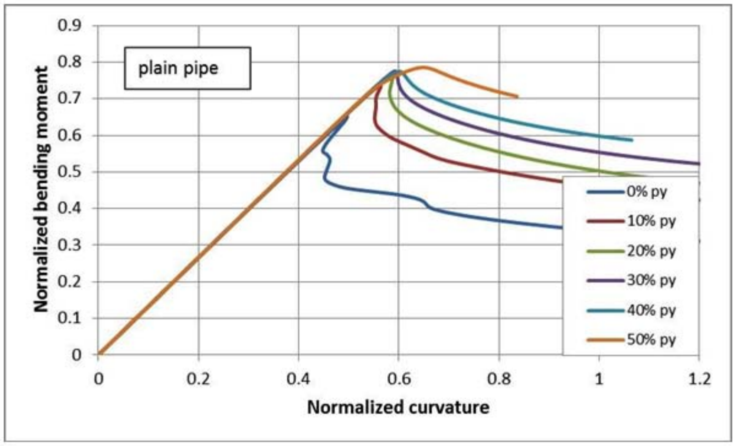

Figure 4. Bending response in the presence of internal pressure of pipe; initial wrinkling amplitude equal to 30% of pipe thickness ($D/t = 191$).

Results for welded lap pipe joints

The bending response of pipe segments containing welded lap joints is different than the response of "plain pipes". Welded lap joints, because of the bell geometry, introduce an initial geometric "imperfection", which under bending they are associated with significant deformation at the compression side of the pipe, in the form of localized wrinkling and folding. Upon occurrence of this pattern, the bending capacity of the welded pipe is significantly reduced. Figure 7 shows the response of double-welded joints compared to a plain pipe, in terms of the corresponding moment-curvature diagrams. The results show that the ultimate strength of the welded lap joint is lower than the capacity of the corresponding plain pipe for zero pressure. Figure 8 shows the deformed shape of an "double welded" pipe, subjected to bending in the absence of pressure; significant localized deformation occurs at the weld area, associated with "wrinkling" and "folding", and this local deformation is responsible for pipe failure and the reduction of structural strength.

Figure 9 shows the effects of internal pressure on the bending response of welded lap joints. The effect is similar to the one observed in plain pipes: the capacity increases when the level of internal pressure is raised. Furthermore, the wrinkling shape for higher levels of pressure is characterized by the "bulging" pattern, as shown in Figure 10, also observed in Figure 6 for plain pipes.

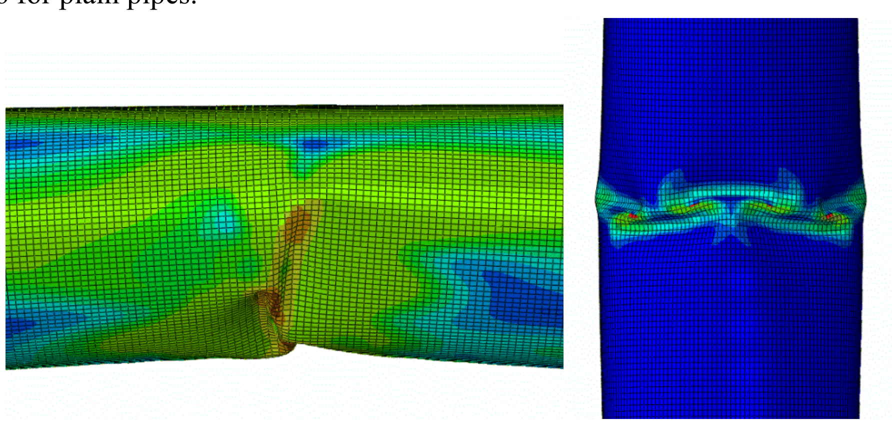

Figure 5. Plain pipe with D/t equal to 191 and initial wrinkling equal to 30% of pipe thickness.

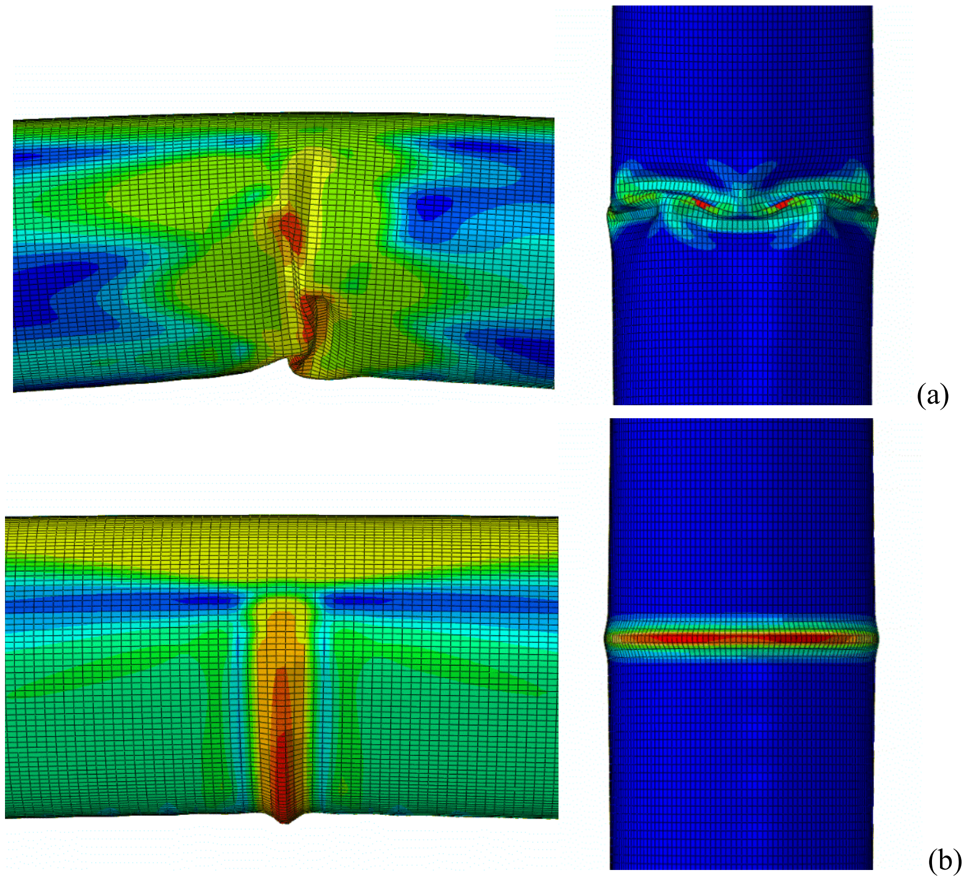

Figure 6. Buckling shape of a plain pipe in the presence of pressure (a) 10% of yield pressure, (b) 50% of yield pressure (D/t = 191).

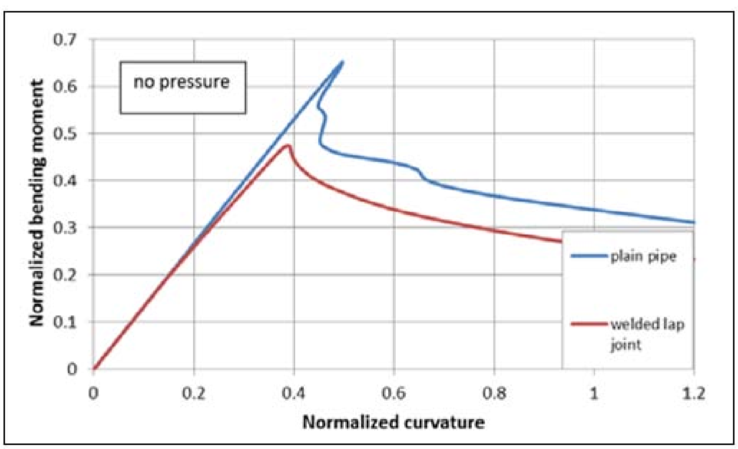

Figure 7. Moment-curvature diagrams for plain pipe and double-welded joints (D/t = 191, zero pressure).

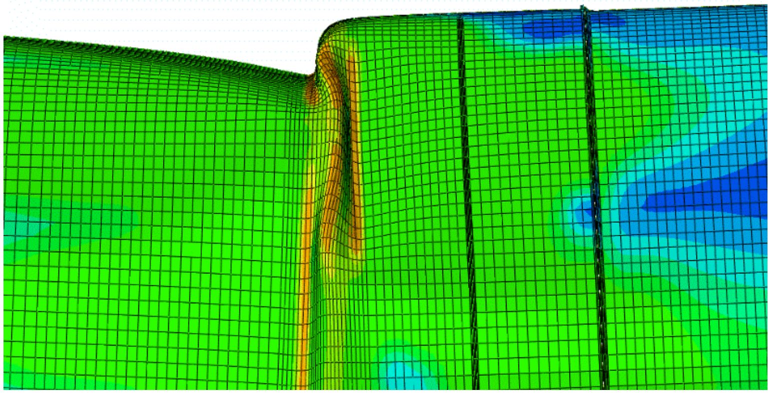

Figure 8. Deformed shape of a welded lap joint subjected to bending loading, characterized by localization of deformation; $D/t = 191$, zero pressure.

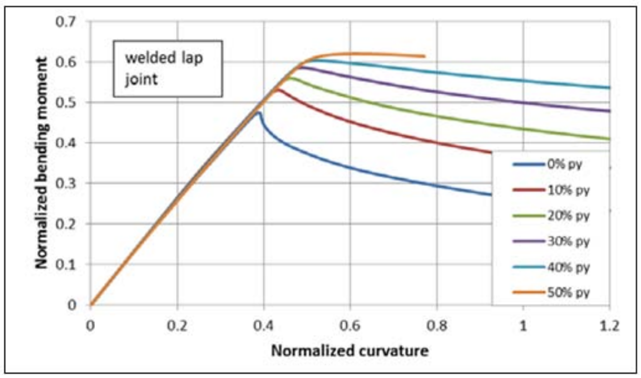

Figure 9. Effect of internal pressure on the bending response of double-welded lap joints ($D/t = 191$).

Local strains in buckled welded lap pipe joints

The above results focused on the global structural behavior of welded lap joints subjected to severe bending loading, in terms of the moment-rotation response of a finite length pipe segment, containing the welded lap joint. The “buckled shapes” depicted in Figure 8 and in Figure 10, constitute a limit state for the welded pipe. However, such a wrinkled shape may not be necessarily associated with immediate loss of containment; pipe material is quite ductile, capable of sustaining significant amount of deformation. Assessing the structural integrity of welded pipe joints against pipe wall fracture is also necessary. Towards this purpose, the analysis is continued beyond the maximum load, monitoring the evolution of local strain at critical locations. Three cases are considered for the double-welded pipe; one case is without pressure, referred to as “Case A”, the second case considers pressure 20% of yield pressure, referred to as “Case B” and third case considers internal pressure 40% of yield pressure, referred to as “Case C”. In Case A, the critical locations, at which maximum strain occurs, are shown in Figure 11, whereas the critical locations of the pressurized welded lap joints of Case B and Case C are shown in Figure 12.

The evolution of tensile strain at the above locations is shown in Figure 13, Figure 14 and Figure 15 for the three pressure levels under consideration. The results show that up to the maximum buckling load, the level of local strains is rather low. On the other hand, upon the occurrence of buckling, the value of local strains increases rapidly. This is attributed to local folding of the pipe in those locations. Soon after the maximum strength of the joint is reached, at a value of normalized curvature equal to about 0.4, the longitudinal strain increases rapidly and reaches values that in several instances may exceed 10%, which implies that, at this location, pipe wall may fracture. The situation is more critical in the vicinity of welds, where the material has lower ductility than the parent material. A thorough investigation of this issue requires experimental testing, and will be included in the subsequent stages of the present research.

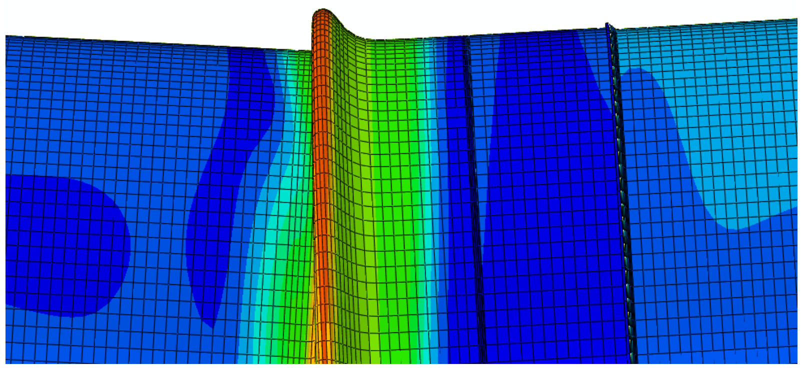

Figure 10. Effect of pressure on deformed shape of welded lap joint subjected to bending loading; compression side of the pipe (D/t = 191).

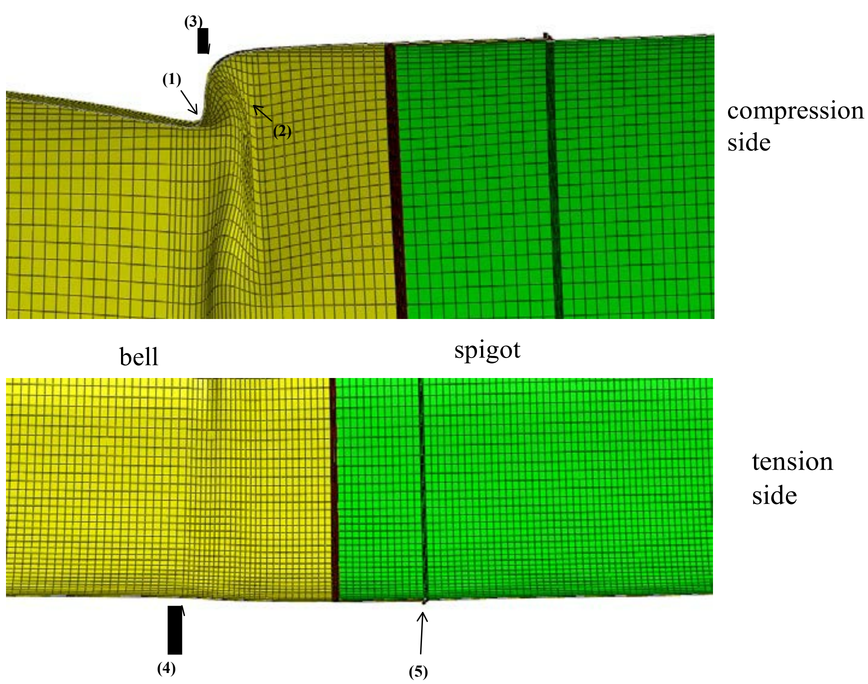

Figure 11. Critical locations in welded lap joints subjected to bending under zero pressure (D/t = 191).

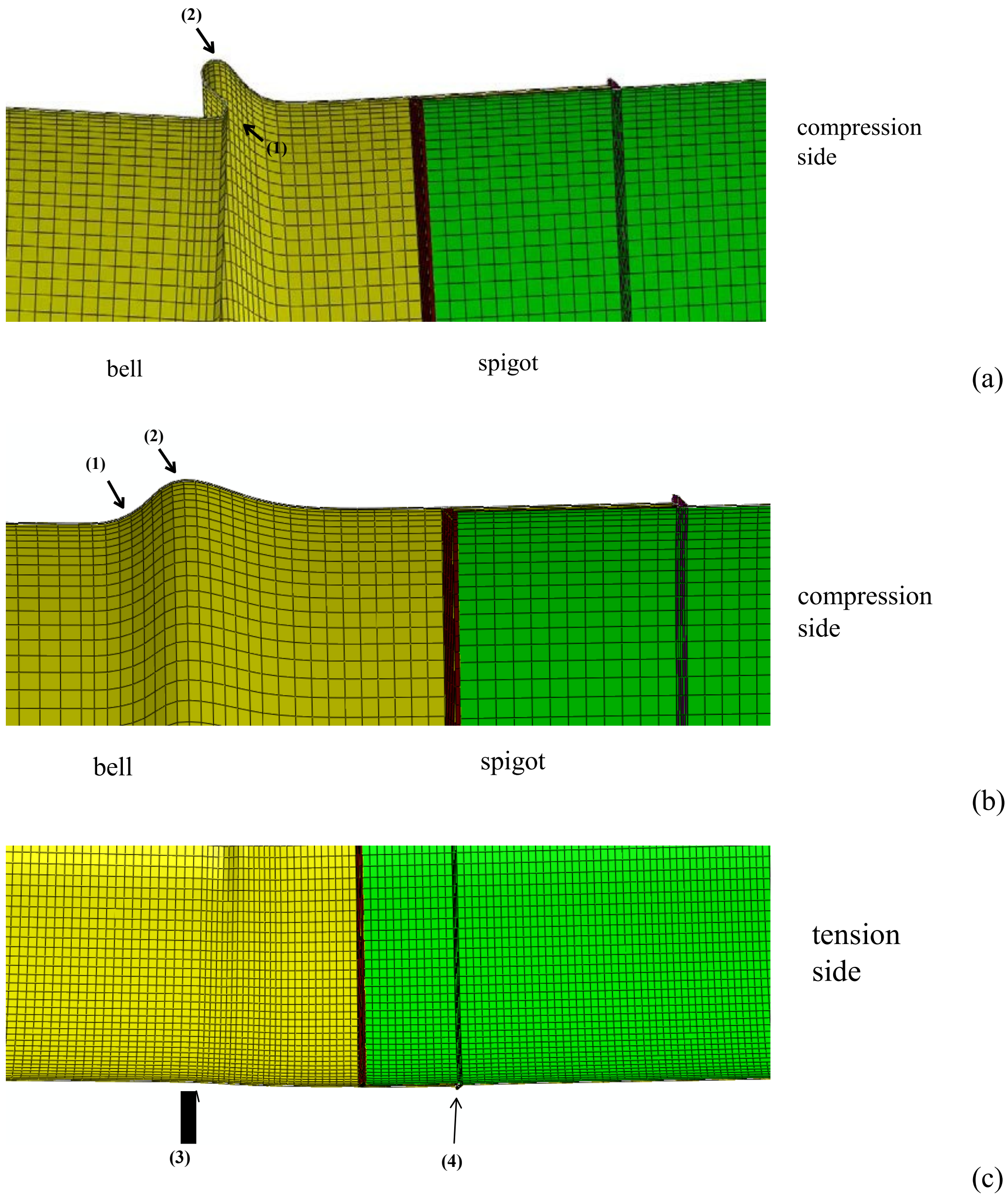

Figure 12. Critical locations in welded lap joints subjected to bending; (a) and (c) refer to pressure equal to 20% of yield pressure; (b) and (c) refer to pressure equal to 40% of yield pressure

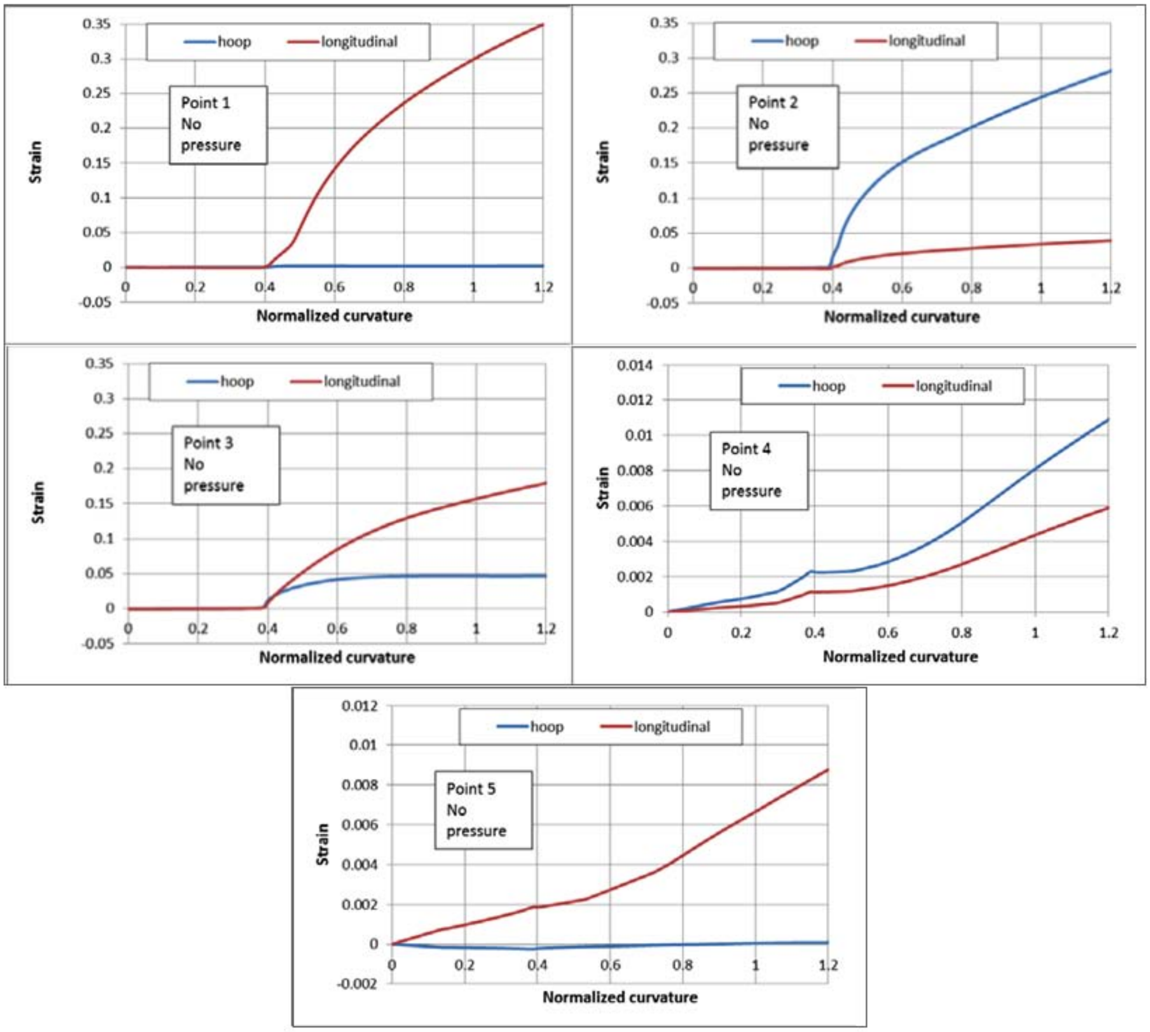

Figure 13. Evolution of local strain at the three critical locations of welded lap joints subjected to severe bending (D/t = 191; "double weld"; zero pressure).

DISCUSSION AND CONCLUSIONS

The paper presented numerical (finite element) results on the simulation of the structural performance of double-welded lap internally-pressurized joints under severe bending loading. It has been observed that the presence of internal pressure affects joint structural behavior and influences the value of local strains at critical locations. The most critical locations located are in the vicinity of the weld area (both on the compression and tension side of the bent pipe), as well as the ridge of the buckle (on the compression side of the bent pipe).

The finite element results indicated 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 they can be used in areas where severe ground-induced actions are expected, e.g. in fault crossings, in liquefaction areas and in areas of potential landslide. Comparison of bending results from welded lap joints with those from plain pipes, indicates that welded lap joints can be an efficient solution for steel pipelines, instead of butt-welded full-penetration joints. Nevertheless, experimental testing is currently being prepared, so that reliable deformation limits are determined for welded lap steel pipe joints.

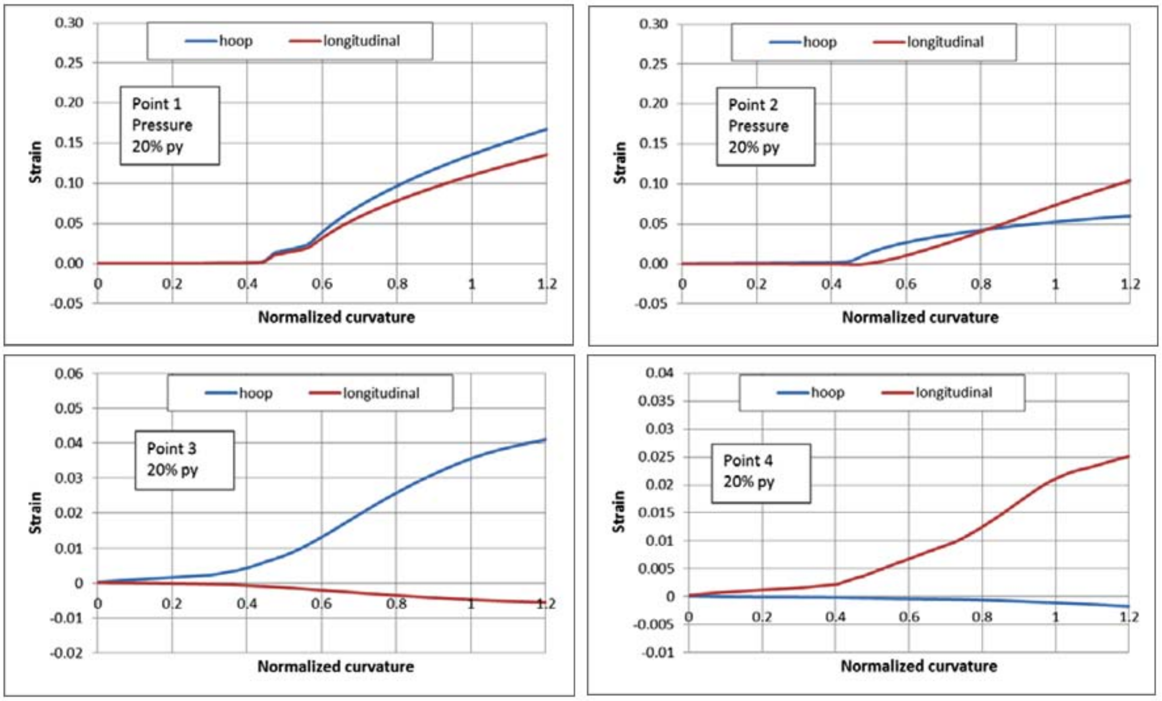

Figure 14. **Evolution of local strain at critical locations of welded lap joints subjected to severe bending (D/t = 191; "double weld"; internal pressure equal to 20% of yield pressure).**

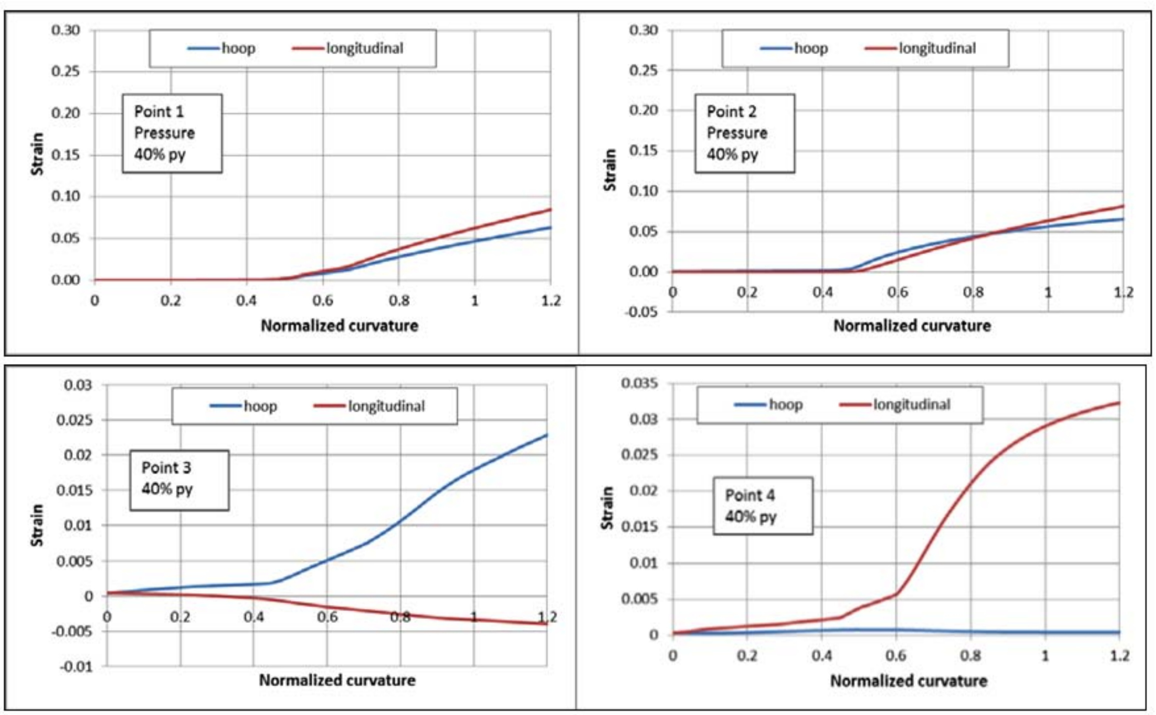

Figure 15. **Evolution of local strain at critical locations of welded lap joints subjected to severe bending (D/t = 191; "double weld"; internal pressure equal to 40% of yield pressure).**

It should be emphasized that the bending action considered constitutes an extreme external loading condition for the pipeline. Therefore, classical "stress-based design", based on stress allowables, as a percent of yield stress, may no longer be applicable. In such a case, consideration of large local deformations of the welded lap joint is necessary, to assess its deformation capacity.

Finally, based on previous publications of the authors (Karamanos *et al*., 2014, 2017), one should notice that in geohazard areas where low level ground movement is expected (e.g. areas with seismic wave shaking action), rubber gasketed joints can also be utilized. Gasket joints, used in combination with welded lap joints, can be used advantageously in the design of a pipeline in certain geohazard (seismic) areas.

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