# Analysis and Behavior of Steel Pipe Welded Lap Joints in Geohazard Areas

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# Abstract

Using advanced finite element simulation tools, which account for both geometric and material nonlinearities, the bending capacity of welded lap pipeline joints is investigated. Following the analysis of plain pipes, numerical results are reported for two steel typical grade 40 pipes, single-welded or double-welded, with D/t values equal to 150 and 240 respectively. Internal pressure effects are also examined, as well as the effects of bell-spigot gap. The results of the present study focus on the value of local strains developed at critical locations and are aimed at providing better understanding of welded lap joint behavior under extreme bending loading conditions. This may allow for the development of design methodologies in geohazard areas where welded joints are required, in order to safeguard the structural integrity of steel water pipelines imposed to severe ground-induced actions.

## INTRODUCTION

Welded lap joints are often used in large-diameter steel pipelines for water transmission (AWWA M11). They are used as an alternative to straight butt-welded joints in water conduits, because of their lower construction cost and proven history of use. Those joints are constructed through a mandrel at one end of a pipe segment and expanding it to create an expanded cross-section of the pipe, often referred to as the "bell", into which the other end of the adjacent pipe segment, often referred to as "spigot", is inserted. Figure 1 shows the configuration of a welded lap joint; the bell and spigot ends are connected with a single or double full circumferential fillet weld. For pipelines larger than 36 inches (914 mm) in diameter, internal welds are frequently used, which permit person entry. In some cases, both internal and external welds are also considered.

The present paper is motivated by the need for determining the deformation capacity of welded steel pipelines for water transmission, constructed in geohazard areas. In such areas, e.g. areas with significant seismic activity, the pipeline can be subjected to severe permanent ground deformations, resulting from fault rupture, liquefaction-induced lateral spreading and subsidence, or landslide action. Under those extreme loading conditions, the pipe deforms well beyond the stress limits associated with normal operating conditions, whereas the structural performance of welded joints constitutes a key issue for pipeline structural integrity. In such geohazard areas, the main action on the pipeline is bending loading.

Most of the work on the structural capacity of welded lap joints has been directed in the investigation of their axial loading capacity, recognizing that for – in such a case – one should take into account their post-yielding performance. Failures at the vicinity of such

joints have been observed either on the construction stage (Moncarz et al., 1987; Eberhardt, 1990), or after strong earthquake action (Meyersohn and O'Rourke, 1991; O'Rourke et al., 1995; Lund, 1996; Tutuncu, 2001). Because of the bell geometry, the stress path under axial compressive load has an eccentricity (Figure 1) and, therefore, an increase of longitudinal stress occurs, which may result in pipeline failure. Compressive tests on medium-scale specimens have been reported by the research group of Prof. T. D. O'Rourke at Cornell University (Jones, et al., 2004, Tutuncu and O'Rourke, 2006, Mason, 2006, Mason, et al., 2010). A finite element analysis of welded lap joints under axial compression has been presented by Tsetseni & Karamanos (2007), considering axisymmetric conditions. Full-scale tests on the compressive capacity of full-scale welded lap joints have been reported by Smith (2006), in an attempt to relate the experimental strength values with joint efficiency values, as reported in ASME B&PVC VIII. The tests specimens referred to 77.625-inch-diameter pipes with 0.323-inch thickness. It was concluded that the joint efficiency specified by the ASME code is quite conservative. The tensile response of welded lap joints has been examined analytically, based on longitudinal strip models (Eidinger, 1999; Brockenbrough, 1990; Moncarz, et al., 1987), or experimentally, with direct tension tests on small-diameter (medium-scale) pipe specimens (Mason et al. 2011). Finally, notable contributions on the practical use of welded lap joints, have been reported by Watkins et al. (2006), van Greussen (2008), and Bambei and Dechant (2009), Nevertheless, the mechanical behavior of welded lap joints under bending loading conditions, which is the major loading feature in geo-hazard areas, constitutes an open issue.

The study herein reports a finite element simulation of the structural performance of lap welded pipeline joints subjected to extreme bending loading conditions, resulting from those ground-induced actions, in the presence of internal pressure. Special attention is given on the geometry of lap joints, where the bell, the spigot and the weld cause non-uniform distribution of stress and deformation. Therefore, this welded connection can be regarded as an "initial imperfection" of the pipeline geometry from the "perfect cylinder" that may result in localization of deformation at the connection area, and reduce the structural capacity of the pipeline under bending.



Figure 1. (a) Configuration of a welded lap joint; (b) Detail of an internal welded lap joint in a 77-inch-diameter pipe [Smith, 2006]

In the present simulation, the pipe and the welded joint are modelled with nonlinear finite elements, capable of describing pipe joint deformation in a rigorous manner. The use of those advanced numerical tools is aimed at developing a "numerical testing laboratory", which can predict the structural behavior of welded lap joints in a reliable, yet cost effective manner. Numerical results are presented for plain steel pipes, and mainly for lap welded joints of steel pipes with diameter-to-thickness ratio values between 150 and 240, subjected to longitudinal bending and internal pressure. A comparison is also attempted with the mechanical performance of butt-welded joints, which are considered to restore the full continuity of the steel pipe, when are properly made per the AWWA C206 Field Welding Standard. Lap joints welds are considered as single-welded, mainly on the inside of the joint, or double-welded on both sides of the joint, and are subjected to bending loading. where the lap joint exhibits bulging and folding on the compressive side and stretching on the tension side. In the above cases, the effects of internal pressure of the welded pipe are considered, as well as the effects of the bell-spigot gap. Finally, the evolution of local strain at critical locations is monitored, in an attempt to evaluate the structural performance of those joints against fracture.

# NUMERICAL MODELS

A three-dimensional numerical model is necessary to account for the nature of the present physical problem. The model is developed in finite element program ABAQUS/Standard. Both the bell and the spigot are modelled with three-dimensional nonlinear four-node reduced-integration shell elements, which have been quite efficient in simulating buckling and post-buckling response of thin-walled cylindrical members (Vasilikis et al. 2014). Those elements can account for geometric nonlinearities, such as large deformations and buckling, as well as the nonlinear (inelastic) behavior of steel pipe material well beyond the elastic regime. To account accurately for possible contact between the bell and the spigot parts, the inner surface of the bell and the outer surface of the spigot are considered as reference surfaces of the shell model under consideration. In those surfaces, appropriate contact conditions have been imposed, which present penetration of one surface to the other, but allows for their separation. Furthermore, to account rigorously for the geometry of the weld, a full-circumference ring is modelled using solid elements with a 45-degree triangle, as shown in Figure 2. The triangular ring is connected to the bell and the spigot with appropriate kinematic conditions. The numerical model does not account for any symmetry, despite the fact that – initially – the deformation is symmetric with respect to the plane of bending. However, both the welded lap joint geometry and the buckling shape of the pipe are not symmetric, and therefore, a full three-dimensional model should be considered.

Two types of models are developed, one for "plain pipes", i.e. pipes that do not contain a welded connection, and one for pipes with welded lap connections. The former models can also be regarded as representative for butt-welded pipe joints as well, 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" or different material properties on each side of the joints, are not examined.

For each case analysed, the numerical model is 10-diameter-long, and the finite element mesh is considered quite dense in the area where buckling is expected. For the "plain pipe" models, a 2-diameter-long central section is modelled with a dense mesh, where the element size is equal to 1/200 of the pipe diameter, whereas the size of the elements in the circumferential direction is equal to 1/56 of the pipe diameter. It is noted that, from shell

buckling theory, a good estimate for the half-wave length in the axial direction of the pipe can be obtained from  $1.22\sqrt{Dt}$ . This means that for a pipe with D/t equal to 240, 16 elements are contained within each half-wavelength, a number which is considered very satisfactory for the purposes of the present analysis. A coarser mesh is considered for the pipe parts away from this central area. A typical mesh for "plain pipe" models is shown in Figure 3. 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, referred to as "kinematic coupling" in ABAQUS. The pipe model is considered simplysupported in those two ends, and bending is applied with two opposite bending moments at the end nodes. In the case of "welded lap joint" models, the welded connection is located in the middle of the pipe segment, and a section of pipe length equal to about 1.4 pipe diameters containing the welded lap joint is modelled with a dense finite element mesh, similar to the one used for the central section of the "plain pipe" models.



Figure 2. Finite element models for welded lap joint simulation; geometry of the weld area; internal weld (top) and double weld (bottom).



Figure 3. Typical finite element mesh of a "plain pipe" model; mesh is finer in the central section of the pipe, where buckling is expected to occur.

In the steel pipes under consideration, with diameter-to-thickness values higher than 150, the primary mode of failure under bending is bucking of pipe wall at the compression side. In plain pipes, to avoid numerical convergence problems in the nonlinear finite element analysis, an imperfection should be assumed so that transition to the buckled shape

is triggered. This imperfection is a wrinkling pattern, in the form of the first buckling eigenmode of the pipe subjected to bending, obtained through a bifurcation (linear buckling) analysis in ABAQUS, before the nonlinear analysis is performed, as shown in Figure 4a. The buckling eigen-mode (wrinkling pattern) is expressed in terms of nodal displacements, and before added to the cylinder geometry, it is multiplied by an appropriate constant, so that wrinkling amplitude  $w_0$  is controlled (Figure 4b). In the case of welded lap joints, consideration of such an imperfection is not necessary; the presence of the welded lap joint constitutes an "imperfection" for the pipe under bending.



Figure 4. (a) Wrinkling pattern used as initial imperfection in the analysis of plain pipes; (b) wrinkling amplitude  $w_0$ .

### NUMERICAL RESULTS

Two different steel pipes with different diameter-to-thickness ratio D/t are examined. The first pipe, denoted as "Pipe I", has a 56.25-inch diameter and 0.375-inch wall thickness (D/t equal to 150), whereas the second pipe, denoted as "Pipe II", has a 77.625-inch diameter and 0.323-inch wall thickness (D/t equal to 240). The material of both pipes is ASTM 1018 grade 40 steel (Smith, 2006), and the stress-strain curve is shown in *Figure 5*. The yield stress is 303 MPa (43,900 psi), as reported by Smith (2006), there is a plastic plateau up to 1.5% of strain, typical for structural steels, and subsequently, strain hardening occurs, with a plastic modulus equal to approximately 1/500 of Young's modulus.

Results for the effects of internal pressure and the influence of the gap size between the bell and the spigot are presented for lap joints. The results for welded lap joints refer to both "internal-welded" and "double-welded" pipe joints. For each case, the moment-deformation relationship is determined. Local buckling (bulging) and the subsequent folding of pipe wall due to excessive compression at the "intrados" of the bent pipe is simulated explicitly with the finite element solution. In addition, local strains are measured in critical locations for different levels of loading, so that the possibility of joint failure is detected.

## **Results for plain pipes**

The response of plain pipes under bending loading, in the absence of internal pressure, is shown in Figure 6a and Figure 6b, for Pipe I and Pipe II respectively, in terms of momentcurvature diagrams, for different values of initial wrinkling imperfection amplitude. 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  $k_I = t/D^2$ , following the relevant suggestion in Karamanos & Tassoulas (1996). The results show a significant reduction of structural strength for increasing amplitude of initial imperfection. This reduction is shown in graphical form in Figure 7a and Figure 7b. The buckling shape of those pipes is shown in Figure 8 and Figure 9, indicating the formation of a major buckle, 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).

The presence of internal pressure influences bending response. The corresponding moment-curvature diagrams for Pipes I and II are shown in Figure 10a and Figure 10b, indicating an increase of bending capacity in the presence of pressure. The buckling shape in the presence of pressure, shown in Figure 11, is characterized by "bulging", which is typical for internally pressurized cylinders.



Figure 5. Stress- strain curve of ASTM 1018 grade 40 steel used in the present analysis; yield stress is equal to 303 MPa [43,900 psi].



Figure 6. Moment – curvature diagrams for plain pipes for different values of initial imperfections; (a) D/t = 150; (b) D/t = 240.



Figure 7. Reduction of bending strength with increasing amplitude of initial imperfection for plain pipes; (a) Pipe I: D/t = 150; (b) Pipe II: D/t = 240.



Figure 8. Plain Pipe I with D/t equal to 150 and small initial wrinkling (amplitude equal to 10% of pipe thickness).



Figure 9. Plain Pipe II with D/t equal to 240 and small initial wrinkling (amplitude equal to 10% of pipe thickness).



Figure 10. Bending response in the presence of internal pressure of Pipes I and II; initial wrinkling amplitude equal to 30% of pipe thickness.



Figure 11. Buckling shape of a plain pipe in the presence of pressure (D/t = 240).

## Results for welded lap pipe joints

The bending response of pipe segments containing welded lap joints is different than the response of "plain pipes". The presence of a welded lap joint, because of the bell geometry, introduces an initial geometric "imperfection" in the pipe. Under bending loading, at the compression side of the pipe, the welded lap joint is significantly deformed, in the form of localized wrinkling and folding, reducing the bending capacity of the welded pipe with respect to the capacity of a plain pipe. Figure 12a and Figure 12b show the response of internally-welded and double-welded joints for Pipe I and Pipe II respectively, in terms of the corresponding moment-curvature diagrams. The results show that, in both cases, the ultimate strength of the welded lap joints is lower than the capacity of the corresponding plain pipe. Figure 13 shows the deformed shape of an "internal welded" pipe, subjected to bending; significant localized deformation occurs at the weld area, associated with "wrinkling" and "folding", and this local deformation responsible for pipe failure and reduction of structural strength. The shape of the deformed welded joint is quite similar to the ones shown in Figure 8 and Figure 9.



Figure 12. Moment-curvature diagrams for internally-welded and doubly-welded joints; (a) Pipe I, D/t = 150; (b) Pipe II, D/t = 240.

Figure 14 and Figure 15 show the effects of internal pressure on the bending response of welded lap joints. The effect is similar to the one observed for plain pipes: the capacity increases when the level of internal pressure is raised. Furthermore, the wrinkling shape for

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higher levels of pressure is characterized by the "bulging" pattern, as shown in Figure 16, also observed in Figure 11 for plain pipes. Finally, the results in Figure 17 show that the effects of gap size for the range of gap values considered are rather minimal. The maximum gap size is equal to 0.125 in, which is the maximum specified by AWWA C206.



Figure 13. Deformed shape of an "internal weld" lap joint subjected to bending loading, characterized by localization of deformation; Pipe I, D/t = 150, zero pressure.



Figure 14. Effect of internal pressure on the bending response; (a) internally-welded joints and (b) doubly-welded joints (Pipe I, D/t = 150).



Figure 15. Effect of internal pressure on the bending response; (a) internally-welded joints and (b) doubly-welded joints (Pipe II, D/t = 240).

# Assessment of welded lap pipe joints

The above results focused on the global mechanical 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 13 or in Figure 16, constitute a limit state for the welded pipe. However, such a wrinkled shape may not be necessarily associated with total failure and loss of containment. To assess the structural integrity of welded pipe joints against pipe wall fracture, it is necessary to proceed beyond the above analysis, monitoring the evolution of local strain at critical locations. The cases considered refer to Pipe I (D/t = 150) with "internal weld" and "double weld". Two cases are considered for "internal weld": one case is without pressure, referred to as Case A, and one with pressure 20% of yield pressure, referred to as Case B. In Case A, the critical locations, at which maximum tensile strain occurs, can be identified as follows, as shown in Figure 18a:

- (1) Compression side: pipe wall folding at the ridge of buckle (top surface).
- (2) Compression side: pipe wall folding at the ridge of buckle (bottom surface).
- (3) Compression side: weld connection at bell end.
- (4) Compression side: weld connection at spigot end.
- (5) Tension side: weld connection at spigot end.



Figure 16. Effect of pressure on deformed shape of welded lap joint subjected to bending loading; compression side of the pipe (D/t = 240; internal weld).



Figure 17. Effect of gap between the bell and the spigot on the structural performance of welded lap joints Pipe I at top; D/t = 150; and Pipe II at bottom; D/t = 240).

The evolution of tensile strain at the above locations is shown in Figure 19. The results show that up to buckling, the level of local strain is rather low. On the other hand, upon the occurrence of buckling, the value of local strains increases very rapidly. In locations (1) and (2), this is attributed to local folding of the pipe, whereas in locations (3), (4) and (5), the discontinuity due to the presence of the weld is responsible for this strain raise. Based on the numerical results, the maximum longitudinal strain is located at the ridge of the buckling, at location (1). Soon after the maximum strength of the joint is reached, at a value of normalized curvature equal to 0.33, the longitudinal strain increases rapidly and reaches values close to 10%, which implies that, at this location (3), because of significant displacement radial ("bulging").

Furthermore, the critical locations of the pressurized welded lap joint of Case B are shown in Figure 18b:

- (1) Compression side: pipe wall folding at the ridge of buckle (top surface).
- (2) Compression side: pipe wall folding at the ridge of buckle (bottom surface).
- (3) Compression side: weld connection at spigot end.
- (4) Tension side: weld connection at spigot end.

The results for the local strains are depicted in Figure 20. From the qualitative point-ofview, the numerical results are quite similar to the ones presented in Figure 19 for the unpressurized Case B. In this case, the tension side appears to be most critical.

Two cases are also considered for "double weld": Case C is without pressure, and Case D corresponds to pressure 20% of yield pressure. The corresponding critical locations, at which maximum tensile strain occurs, are shown in Figure 21 and are similar to the ones for Cases A and B and the evolution of local strains at those locations are shown in Figure 22 and in Figure 23.



Figure 18. Critical locations in welded lap joints subjected to bending Pipe I (D/t = 150; "internal weld"); (a) zero pressure and (b) pressure equal to 20% of yield pressure.



Figure 19. Evolution of local strain at the five critical locations of welded lap joints subjected to severe bending (Pipe I; D/t = 150; "internal weld"; zero pressure).

# **DISCUSSION AND CONCLUSIONS**

The present work reported the development of rigorous numerical (finite element) tools, which enable simulation of the structural performance of welded lap joints under severe bending loading. Both "internal weld" and "double weld" joints have been examined. It is found that the presence of internal pressure affects joint behavior and influences significantly the value of local strains at critical locations. The most critical locations are in the vicinity of the weld area (both in the compression and tension side), as well as the ridge of the buckle (in the compression side).

The finite element results indicated that welded lap joints subjected to bending, are capable of sustaining significant deformation (rotation) after the occurrence of buckling, without fracture and loss of containment. Therefore, 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. In those areas, welded lap joints can be an efficient solution, in comparison to butt-welded full-penetration joints. In geohazard areas where low level ground movement is expected, rubber gasketed joints can be utilized. More specifically,

used in combination with welded lap joints, the gasket joint can be used advantageously in the design of a pipeline in certain geohazard areas (Karamanos *et al.* 2014).

Finally, it should be emphasized that the bending action considered constitutes an extreme external action for the pipeline. Therefore, classical "stress-based design", which considers stress allowables, as a percent of yield stress, is no longer applicable. In such a case, a nonlinear analysis capable at simulating large local deformations of the welded lap joint is necessary.



Figure 20. Evolution of local strain at the four critical locations of welded lap joints subjected to severe bending (Pipe I; D/t = 150; "internal weld"; internal pressure equal to 20% of yield pressure).



Figure 21. Critical locations in welded lap joints subjected to bending Pipe I (D/t = 150; "double weld").



Figure 22. Evolution of local strain at the three critical locations of welded lap joints subjected to severe bending (Pipe I; D/t = 150; "double weld"; zero pressure).



Figure 23. Evolution of local strain at the four critical locations of welded lap joints subjected to severe bending (Pipe I; D/t = 150; "double weld"; internal pressure equal to 20% of yield pressure).

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### REFERENCES

- American Society of Mechanical Engineers (2010), *Boiler & Pressure Vessel Code*, Section VIII, Division 1, New York, NY, USA.
- 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 C200, Denver, CO, USA.
- American Water Works Association (2011), *Field Welding of Steel Water Pipe*, AWWA C206, Denver, CO, USA.
- Bambei Jr., J.H. and Dechant, D.A. (2009), "Welded steel pipe lap joints: An evolution.", *Proceedings of ASCE Pipelines 2009 Conference*, San Diego, CA.
- Brockenbrough, R. L. (1990), "Strength of Bell-and-Spigot Joints", *Journal of Structural Engineering*, ASCE, Vol. 116, No. 7, pp.1983-1991.
- Eberhardt, A. (1990), "108-in Diameter Steel Water Conduit Failure and Assessment of AWWA Practice", J. Perf. Constructed Facilities, ASCE, Vol. 4, No. 1, pp. 30-50.
- Eidinger, J. M. (1991), "Girth Joints in Steel Pipelines Subject to Wrinkling and Ovaling", TCLEE Monograph No. 16. Proceedings, 5th US Conference on Lifeline Earthquake Engineering, Seattle, WA, Aug. pp. 100-109
- Jones, S. L., O'Rourke T. D. and Mason, J. A. (2004), "Design of Welded Slip Joints in Pipelines for Compressive Loading", Proceedings, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August, Paper No. 1625
- Karamanos, S. A. and Tassoulas, J. L. (1996), "Tubular Members II: Local Buckling and Experimental Verification.", *Journal of Engineering Mechanics*, ASCE, Vol. 122, No. 1, pp.72-78.
- Lund, L. V. (1996), "Lifeline Utilities Performance in the 17 January 1994 Northridge, California, Earthquake", Bulletin of the Seismological Society of America, Vol. 86, No.1B, pp.S350-S361.
- Mason, J. A, O'Rourke, T. D., Jones, S., Tutuncu, I., (2010) "Compression Performance of Steel Pipelin.e with Welded Slip Joints", *Journal of Pipeline Systems-Engineering and Practice*, Vol. 1, No. 1, p., ASCE.
- Mason, J. A, O'Rourke, T. D, Jung, J. K. (2010), "Direct Tension Performance of Steel Pipelines with Welded Slip Joints", *J. Pipeline Systems-Engineering & Practice*, Volume 1, Issue 4, pp. 133-140.
- Meyersohn, W. D., and O'Rourke, T. D. (1991), "Pipeline Buckling Caused by Compressive Ground Failure During Earthquakes", *Technical Report NCEER-91-0001*, T.D. O'Rourke and M. Hamada, Eds., National Center for Earthquake Engineering Research, Buffalo, NY, pp. 471-487.
- Moncarz, P. D., Shyne, J. C. and Derbalian, G. K., (1987) "Failures of 108-inch steel pipe water main", *J. Perf. Constructed Facilities*, ASCE, Vol. 1, No. 3, pp. 168-187.

- O'Rourke, M. J., Liu, X. and Flores-Berrones, R., (1995), "Steel Pipe Wrinkling due to Longitudinal Permanent Ground Deformation", *J. Transportation Engineering*, ASCE, Vol. 121, No. 5, pp. 443-451.
- O'Rourke, T. D. and Bonneau, A., (2007) "Lifeline Performance Under Extreme Loading During Earthquakes," *Earthquake Geotechnical Engineering*, K.D. Pitilakis, Ed., Springer, Dordrecht, Netherlands, June, pp. 407-432.
- Smith, G. (2009), "Steel Water Pipe Joint Testing.", Proceedings of ASCE Pipelines 2006 Conference, Chicago, IL.
- Tawfik, M. S. and O' Rourke, T. D., (1985), "Load-carrying capacity of welded slip joints", J. Pressure Vessel Technology, ASME, Vol. 107, February, pp. 36-43.
- Tsetseni, S. and Karamanos, S. A. (2007), "Axial Compression Capacity of Welded-Slip Pipeline Joints", *J. Transportation Engrg*, ASCE, Vol. 133, No. 5, pp. 335-340.
- Tutuncu, I. (2001), "Compressive Load and Buckling Response of Steel Pipelines during Earthquakes", *Ph.D. dissertation, Cornell University*, Ithaca, NY.
- Tutuncu, I. and O'Rourke, T.D. (2006), "Compression Behavior of Nonslender Cylindrical Steel Members with Large-Scale Geometric Imperfections", *Journal of Structural Engineering*, ASCE, Vol. 132, No. 8.
- Van Greunen, J. (2008), "Seismic design of bell-and-spigot joints for large diameter steel pipe", *Proceedings of ASCE Pipelines 2008 Conference*, Atlanta, GA.
- Vasilikis, D., Karamanos, S. A., Van Es, S. H. J., Gresnigt, A. M. (2014), "Bending Deformation Capacity of Large-Diameter Spiral-Welded Tubes.", *International Pipeline Conference*, IPC2014-33231, Calgary, Alberta, Canada.
- Watkins, R. K., Card, R. J., Williams, N. (2006), "An investigation into the history and use of welded lap joints for steel water pipe.", *Proceedings of ASCE Pipelines 2006 Conference*, Chicago, IL.