Experimental Results of Steel Lap Welded Pipe Joints in Seismic Conditions

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ABSTRACT

Welded lap joints are commonly used in large-diameter steel pipelines for water transmission. Their structural performance constitutes a key issue for safeguarding pipeline structural integrity with no loss of pressure containment, required even after a severe seismic event. Full-scale experiments are presented herein, and are part of an extensive project sponsored and coordinated by Northwest Pipe Co. on the structural performance of welded lap joints under severe ground-induced (seismic) actions. In the companion paper "Numerical Simulation of Steel Lap Welded Pipe Joint Behavior in Seismic Conditions" numerical simulation of the experiments are presented. The paper describes a series of large-scale experiments on welded lap joints in 25.75 in outside diameter steel pipes, with wall thickness of 0.135 in (3 specimens) or 0.250 in (3 specimens). The specimens were internally pressurized to 40% of yield pressure, and then subjected to four-point bending. Measurements of the bending load, characteristic displacements, and local strains at the joint area are reported. In all tests, the welded lap joints tested were capable of sustaining remarkable bending deformation, without any loss of pressure containment. This behavior supports the argument that welded lap joints, if appropriately constructed, can be used in seismic areas where severe and permanent ground-induced actions in the pipeline may occur.

INTRODUCTION

Welded lap joints are employed in large-diameter steel water pipelines instead of butt-welded full-penetration joints, because of their ease of installation, lower construction cost, and their proven history of use. They require the forming of a "bell" at the end of each pipe segment. The bell is manufactured at the pipe mill by expanding the end of the pipe so that the end of the adjacent pipe segment, often referred to as the "spigot", is inserted and welded into the bell with a single or double full-circumferential fillet weld, as shown in Figure 1.

The present research effort is motivated by the need for safeguarding the structural integrity of welded steel pipelines for water transmission, constructed in geohazard (seismic) areas. In those seismic areas, the pipeline may be subjected to severe and permanent ground-induced actions from fault rupture, liquefaction-induced lateral spreading, soil subsidence, or slope instability. Any of these actions may deform the pipe well beyond the stress limits associated with normal operating conditions, possibly well into the inelastic range of the steel material. 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, both experimentally and numerically, by Sarvanis *et al.* (2018). In this framework, the deformation capacity and strength of welded lap joints comprise a crucial issue that requires further investigation. A first attempt to examine the mechanical response of welded lap joints under bending loads have been reported by Karamanos *et al.* (2015, 2017b), using advanced finite element simulation tools. The reader is referred to those two papers for an extensive literature review on the structural strength of welded lap joints.



Figure 1. Schematic configuration of a double-, internal-, and external welded lap pipe joint.

The present work is part of a large-scale research program, launched by Northwest Pipe Company, aimed at determining the strength and deformation limits of steel pipelines in seismic areas, with specific focus on the bending response of welded lap joints. This paper reports experimental results, whereas numerical simulations are reported in a companion paper, "Numerical Simulation of Steel Lap Welded Pipe Joint Behavior in Seismic Conditions", also presented at the ASCE 2018 Pipelines Conference (Chatzopoulou et al., 2018).

The present paper describes a series of six large-scale experiments on welded lap joints in 25.75 inch diameter steel pipes, three specimens have a wall thickness of 0.135 in, while the other three specimens have a wall thickness of 0.25 in. Moreover, in the thin-walled specimens, the material is ASTM A1011 SS GR36, while in the thick-walled specimens, the material is ASTM A1018 SS GR40. The specimens were end-capped, internally pressurized to about 40% of the yield pressure, and subjected to four-point bending. In each group of specimens having a given wall thickness, the welds were "internal", "external", or "double", so that all cases were examined. A 0.135 in thick plain pipe specimen (with no joint) was tested under the same loading conditions, for comparison purposes. Measurements were obtained for the bending load, three characteristic displacements, and local strains at the joint area.

EXPERIMENTAL SETUP

The tests were performed in Adelanto, California at the Northwest Pipe Company plant. The experimental setup, shown in Figure 2, was contained within a rectangular self-reacting frame with dimensions of 651 in \times 172 in (16.5m \times 4.36m). Each pipe specimen had a total length equal to 52 feet (15.85 m), and was loaded at the ends by two actuators of total load capacity equal to 45 klbf (200 kN) (Figure 3a). Two metal straps served as intermediate supports, providing the reactions, as shown in Figure 3b. The actuators and the metal straps were pinned at both ends, allowing the pipe to rotate freely at those locations. The distance between the two straps, corresponding to the length of constant bending moment, was equal to 120 inches (3.048 m).

The bending tests were performed with constant pressure applied inside the pipe. Pressure was applied first at a level of 40% P_y. Maintaining constant internal pressure and using the two hydraulic actuators, a horizontal displacement was applied at the two ends of the pipe specimen as shown in Figure 3a. The metal straps (Figure 3b) restricted the horizontal displacement so that a four-point bending scheme was achieved. In Figure 4, the initial and deformed shapes of the

pipe are depicted.



Figure 2. Experimental setup for four-point bending tests.



Figure 3. Details of the experimental setup; (a) pipe end with hydraulic actuator; (b) metal straps at the intermediate support locations.



Figure 4. Undeformed (a) and deformed (b) specimen in test 2.

The load applied by the actuators was recorded along with the pipe deflection at three points around the lap joints: midspan and two locations 24 inches (0.61 m) on each side of the midspan, using the wires and displacement transducers shown in Figure 5a. Moreover, local strains within the area of each lap joint were measured at both the tensile and the compressive side of the pipe using strain gauges (Figure 5b). Seven tests were performed in total, six tests with welded lap

joints, and one test with a plain pipe to serve as a reference case. Details of the test specimens are tabulated in Table 1. Two different wall thicknesses were considered, 0.135 inch (3.429 mm) and 0.250 inch (6.35 mm), and all possible weld patterns for the lap joints (double, single-internal and single-external) were examined for each thickness. The geometric details of the welded lap joints used in the experiments are presented in Figure 6.



Figure 5. Instrumentation of the test specimens; (a) wires and displacement transducers; (b) strain gauges at the joint area.



Figure 6. Geometric details of the welded lap joints used in the experimental program.

EXPERIMENTAL RESULTS

The experimental results in terms of force-displacement diagrams are presented in Figure 7 and Figure 8 for tests 1, 2, 3 (0.135 in D/t = 191) and tests 5, 6 (0.250 in D/t = 103) respectively.

In Figure 7, test 4 (plain pipe) is presented as a reference case. The curve for test 7 could not be obtained due to the fact that the deflection measurements were not recorded due to an issue with the recording system. A brief summary of the experimental results can be found in Table 2, while in Figure 9 the position of local buckling for all lap-joints is reported. The occurrence of local buckling at either the bell or the spigot indicates that the buckle location might be sensitive to initial material and geometric imperfections. Furthermore, the bend angle at the end of the test is computed from the displacements of the end sections and offers a useful global measure of total pipe deformation. In all cases, the bend angle was equal to about 40° when the hydraulic actuators reached the end of their stroke with the pipe and joint maintaining complete containment, which is a remarkable value and indicates an impressive deformation capability.

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	Test	Thickness (inch)	D/t	Pressure level (bar)	Weld details	
	1-AD	0.135	191	11.72	double weld	
Ī	2-ASO	0.135	191	11.72	single (outside) weld	
	3-ASI	0.135	191	11.72	single (inside) weld	
	4-PP	0.135	191	11.72	without joint/plain pipe	
	5-BSI	0.250	103	22.41	single (inside) weld	
	6-BSO	0.250	103	22.41	single (outside) weld	
	7-BD	0.250	103	22.41	double weld	

Table 1. Details of the test specimens (outer pipe diameter is 25.75 in).

Tests 1, 2, 3 and 4 correspond to 0.135 in wall pipe with D/t = 191, and presented in Figure 7. The three lap-joint specimens exhibit a very similar structural response in both elastic and post-buckling region. There is a difference in terms of maximum force between those three tests and test 4 (plain pipe), which is attributed to the lap weld. Furthermore, in the cases of joint-pipes there exists a less abrupt reduction of load in the post-buckling branch due to the presence of the joint.

Test	weld details	Position of buckle	Maximum force (kN)	Bend angle at full stroke of the hydraulic test rams
1-AD	double weld	spigot	40	38.5°
2-ASO	single (outside) weld	spigot	41	44°
3-ASI	, single (inside) weld bell		40	44.2°
4-PP	plain pipe	plain pipe 700 mm away from midspan		44.4°
5-BSI	<i>-BSI</i> single (inside) weld		107	43.3°
6-BSO	single (outside) weld	spigot	104	-
7-BD	double weld	bell	105	43.4°

 Table 2. Experimental results.



Figure 7. Load vs. midspan deflection data plotted for tests 1, 2, 3 (welded joints) and 4 (without a joint) for 0.135 in-walled pipes (D/t = 191).



Figure 8. Load vs. midspan deflection data plotted for tests 5 and 6 for a 0.250 in wall pipe; maximum force measured in test 7 shown.



Figure 9. Position of local buckle; (a) test 1-AD, (b) test 2-ASO, (c) test 3-ASI, (d) test 5-BSI, (e) test 6-BSO, (f) test 7-BD.







Figure 11. Load vs. strain diagrams plotted for test 2 (D/t = 191, single-outside weld).



Figure 12. Load vs. strain diagrams plotted for test 3 (D/t = 191, single-inside weld).



Figure 13. Load vs. strain diagrams plotted for test 5 (D/t = 103, single-inside weld).

In Figure 10 through Figure 14, local strains are presented in terms of applied load for each test. Tensile and compressive strains measured at different locations in the vicinity of the joint are plotted against the applied load. The experimental results indicate that the lap joints are capable of sustaining a significant amount of local strain. In some cases, tensile strain exceeded 2% without any loss of pressure containment. Given the fact that the strain gauge nearest to the weld is located at a distance of approximately 0.5 inch from the weld toe, it is expected that the local strain at the weld toe is significantly higher than the measured strains. However, measurements of this very local weld toe strain were not possible in the present work due to limitations with the physical size of the available strain gauges. Moreover, it is important to notice that the experimental results for the three cases of lap joints (double, single-internal, and single-external) in terms of force vs. displacement diagrams and induced strains are quite similar. All tests demonstrated that the welded lap joints under consideration were capable of sustaining remarkable bending deformation, without any loss of pressure containment. This result indicates that welded lap joints can be used in pipeline applications in seismic areas where severe and permanent ground-induced actions are expected.



Figure 14. Load vs. strain diagrams plotted for test 6 (D/t = 103, single-outside weld).

CONCLUSIONS

The present paper reports experimental results of the structural performance of internallypressurized, welded lap joints, subjected to four-point bending. Two different values of wall thickness were examined; 0.135 inch (3.429 mm) and 0.250 inch (6.35 mm). All possible lap joint weld patterns (double, single-internal and single-external) were tested for each thickness. In addition, a pipe without any joint (a plain pipe) was tested under bending for comparison purposes. In all tests, the welded lap joints were capable of sustaining remarkable bending deformations without any loss of pressure containment. All specimens buckled at either the bell or spigot side, but were able to deform significantly at bending angles exceeding 40 degrees. The significant deformation capacity of the welded lap joints indicates that those joints, if constructed properly, can be employed in seismic areas where severe and permanent ground-induced actions are expected.

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