



Seismic Strengthening of Large Diameter Steel Waterline with Advanced Composites

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ABSTRACT

This paper presents the results of full scale testing of water supply pipelines to evaluate their response to earthquake-induced axial forces in both the as-built and strengthened state, using fiber-reinforced polymer (FRP) wrap applied at welded slip joints. Pipeline specimens of welded slip joints of nominal 300, 810, and 910-mm diameter, with diameter-to-thickness ratios (D/t) ranging from 48 to 250 were fabricated and supplied by the Los Angeles Department of Water and Power for compression, tension, and earthquake simulation testing at Cornell University. The paper presents the results of full-scale testing for all sizes of pipe in the program, and compares them with the results of numerical simulations using the software, ABAQUS. The numerical and experimental results are shown to compare favorably. The paper also compares the full-scale test results for as-built and FRP-strengthened specimens. The FRP wrap increases the compressive capacity of the joints from 30 to 100% depending on D/t , weld properties, and characteristic of the FRP strengthening.

Introduction

Recent experience with severe earthquakes in California show the impact of compressive ground deformations on water supply trunk and distribution pipelines, (O'Rourke, 1998; O'Rourke and Jeon, 2000). For example, damage from the 1994 Northridge earthquake resulted in 1,013 repairs in the water distribution system. There were 74 major repairs in the large diameter (> 600 mm) trunk lines, with over 60% due to compressive deformation at welded slip joints (WSJs). Moreover, out of 11 repair locations on the Los Angeles Aqueducts No. 1 and 2 operated by LADWP, 4 involved either circumferential cracks or compressive buckling at welded slip joints. Damage to the Foothill Feeder, from the 1994 Northridge earthquake, operated by the Metropolitan Water District (MWD) occurred near Jensen Filtration Plant at a welded slip joint of 85-in. (2160-mm) diameter steel pipeline. Most steel water trunk and transmission pipelines are constructed by connecting adjacent pipe segments at a WSJ. A WSJ is made by inserting the cylindrical end of one pipe into the bell end of an adjoining pipe, and applying a fillet weld around the circumference at this junction. The bell end is fabricated by expanding a mandrel inside one end of a steel pipe. The curvilinear shape of the bell and eccentricity associated with the welded connection reduces the compressive capacity of the cylindrical pipe due to the WSJ.

To evaluate both the compressive and tensile capacity of WSJs, full-scale tests were performed through the Multidisciplinary Center for Earthquake Engineering Research (MCEER) at Cornell University and Taylor Devices, Inc. of North Tonawanda, NY. Pipeline specimens of WSJs of nominal 300, 810, and 910-mm (12, 32, and 36 in.)

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diameter, with diameter-to-thickness (D/t) ranging from 48 to 250 were fabricated and supplied by LADWP.

As part of the work, the effects of externally applied FRP wraps were investigated. The FRP wraps were applied by Fyfe-Watson Inc., North Tonawanda, NY, and Master Builders, Inc., Columbus, OH. Details of the testing and test results are provided by Mason (2005). This paper describes compressive and tensile loading tests, and provides select test results. The compression tests results are for unreinforced and reinforced WSJs specimens strengthened with FRPs at the WSJ.

Pipeline Construction.

In general, a steel water distribution system is constructed of pipe segments either approximately 20 or 40 ft. (6 or 12m) long. Each piece is joined together with couplers that integrate the segments into a system. For steel pipelines, at least 3 options exist to create the coupler for the individual pieces: 1) direct abutting of adjacent ends of two pipe segments with 1 complete circumferential weld, 2) an exterior steel sleeve that extends over the ends of both abutting pipes, with a complete circumferential weld for each pipe (that is, 2 complete circumferential welds per coupler), and 3) a coupler that is factory formed directly in the pipe wall that becomes an expanded connector, a bell housing, to accept the adjacent pipe spigot end, with a complete circumferential weld, (that is, 1 complete circumferential weld per coupler), also known as the welded slip joint coupler. The majority of pipe installed in the Los Angeles system are the 3rd type: the welded slip joint (WSJ). A bell housing of a welded slip joint is constructed by inserting a mandrel into one end of a pipe segment and expanding it to create room for the insertion of the straight end of an adjoining pipe. Thus, each piece of pipe segment has a prismatic spigot end and the other end with an expanded bell housing. The ease of field construction makes these joints preferable in water delivery systems over more costly joints, such as the girth-welded joints, the 2nd type listed previously. Understanding the behavior of welded slip joints under compression, tension, and cyclic loading, and reinforcing them to accommodate these loading conditions, is critical for the post-earthquake emergency services and fire-fighting capabilities needed in urban areas affected by earthquakes.

Full-Scale Test Results for Compressive Loading.

Prior experimental studies to this work have shown that typical large diameter pipelines can accommodate axial strains on the order of 0.4% to 0.6% prior to the onset of local buckling for the experimental specimen. Guidelines for the seismic design of oil and gas pipeline systems (Committee on Gas and Liquid Fuel Lifelines, 1984) point out the relatively low values of compressive strain that can trigger buckling. They are typically an order of magnitude less than the level of tensile strains that can be sustained by modern steel pipelines. Compressive deformation, therefore, represents the most severe type of loading imposed on welded steel pipelines during an earthquake. The experimental results presented provide unique full-scale experimental evidence to clarify

the compressive load capacity for cylindrical water trunk and transmission lines (Mason, 2006).

Compressive load tests were performed on the smaller diameter (300mm) specimens with the 2670kN (600 kip) loading devices at Cornell University. The larger diameter specimens (810 and 910mm) as well as the cyclic and tensile loading of the smaller (300mm) diameter specimens required higher capacity equipment with the ability for dynamic application of loads. To perform the high capacity compressive and tensile tests, the equipment at Taylor Devices, Inc. was used. Figure 1 shows a photograph of this equipment. There are two basic loading configurations for this system: 1) 6700kN (1500 kip) load at 1000mm/s (40 in./s), or 2) 3400kN (750 kip) load at 1800mm/s (70 in./s) velocity, with a ± 500 mm (20 in.) stroke for both cases. Seismic records of 1.5 minutes duration can be applied.

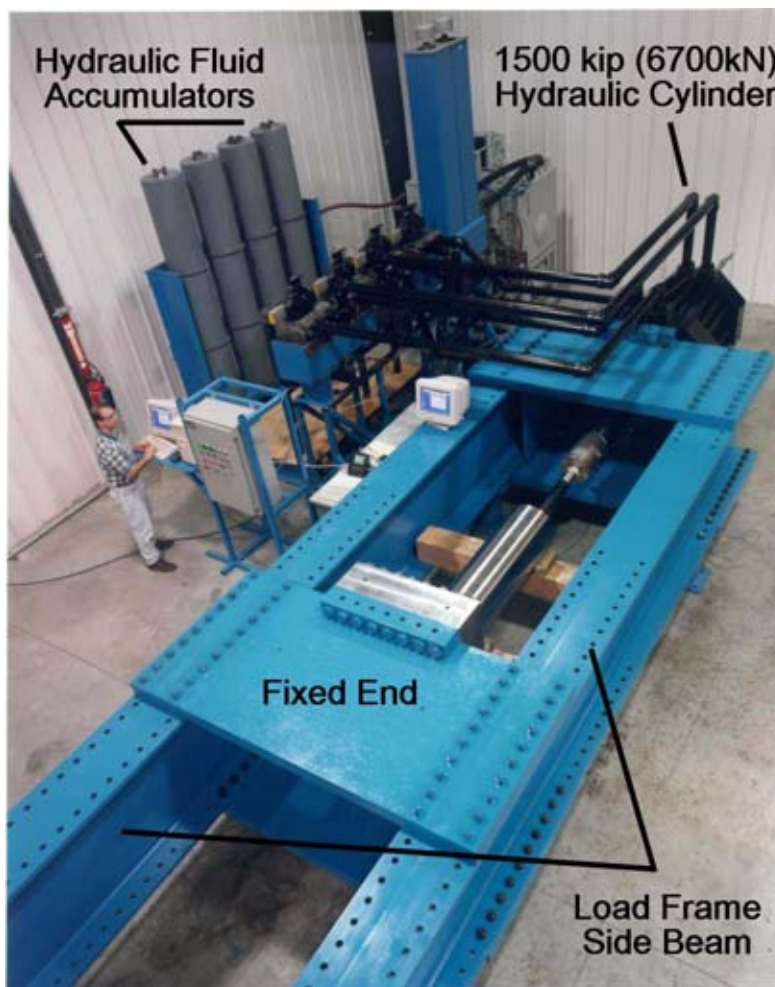


Figure 1. 6700kN (1500kip) Load Frame.

Figure 2 shows a 910mm (36 in.) diameter specimen in the loading frame at the Taylor Devices facility where compressive loads as high as 4510kN (1014 kips) were applied.

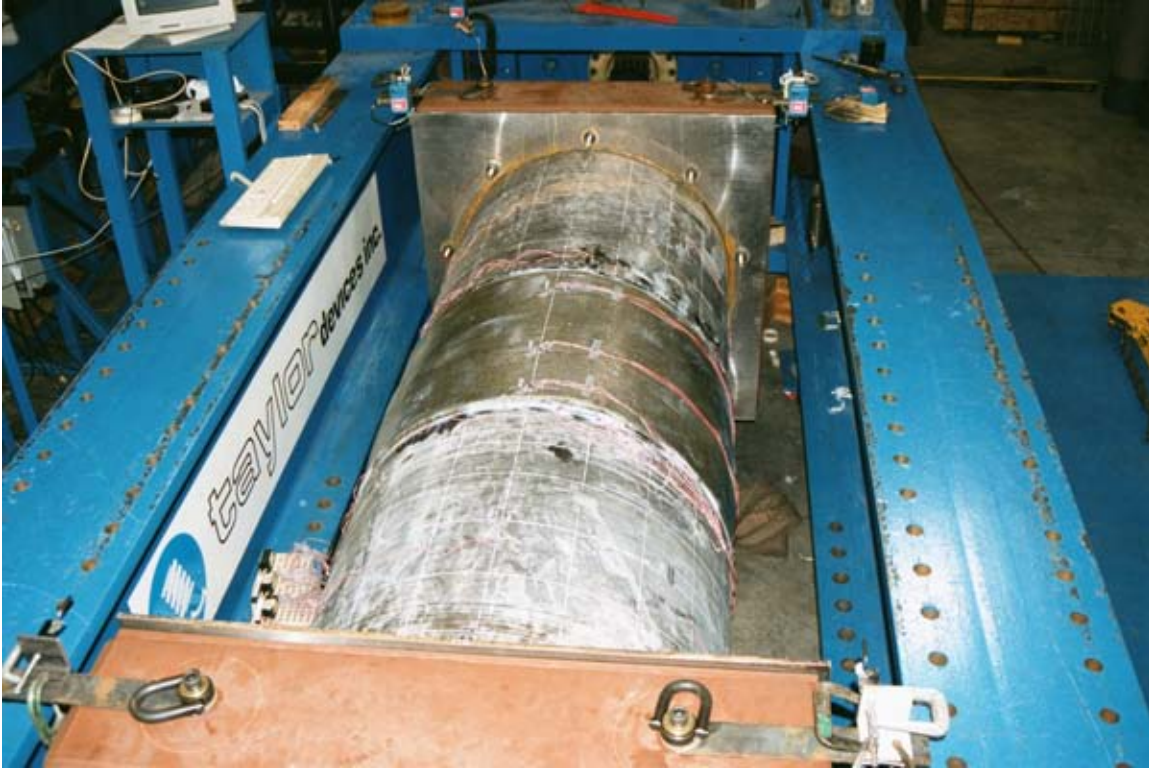


Figure 2. 910mm Diameter Strengthened Specimen in Load Frame.

Compression Loading of As-Built Pipeline with WSJ.

A brief summary of a representative laboratory test of an unreinforced welded slip joint pipe specimen is presented. Both 32 in. (810mm) and 36 in. (910mm) diameter pipe specimens were tested. The 36 in. (910mm) diameter specimens are typical “as-built” specimens for municipal water distribution systems. The diameter to wall thickness (D/t) ratio for the two diameters was approximately 245 and 145, respectively. The 32 in. (810mm) diameter specimens were constructed specially for this testing program to investigate the performance of pipelines having large diameter-to-pipe wall thickness (D/t) sections. The experimental data are compared with the results of FEA and linear elastic models.

The preparation of three of the five specimens in this sequence of tests involved the removal of the interior mortar at the ends of the pipe specimen. The existing gap between adjacent liners at the WSJ was left as delivered with approximately 3.0 in. (75mm) of open space between the ends. Two 32 in. (810mm) diameter specimens were prepared for testing with the gap at the WSJ of the interior liner filled with a non-shrink grout. The liner that was removed for attachment of the end plates to the pipe was replaced with a similar type of grout. The filling of the liner at the WSJ and replacement of mortar at the ends created a continuous liner within the specimen. Testing specimens with and without cement mortar at the WSJ allowed for an evaluation of stress transfer between the steel pipe wall and interior mortar, as well as the strengthening effect of the mortar. The continuous liner specimen results are not presented here.

The axial load vs. displacement plot of Specimen 36.10 is presented in Figure 3. The specimen responded in a linear elastic manner to a proportional limit load (PLL) of 670 kips (2980kN). A peak load of 747 kips (3320kN) was measured at a displacement of 0.0968 in. (2.54mm). The test specimen buckled at approximately 64% of the FEA maximum for a straight pipe specimen and 62% of theoretical yield load capacity. The FEA-WSJ model results tracked the experimental results to near peak response (98%), after which buckling occurs. The measured post-peak load vs. displacement data plot slightly higher than the FEA results.

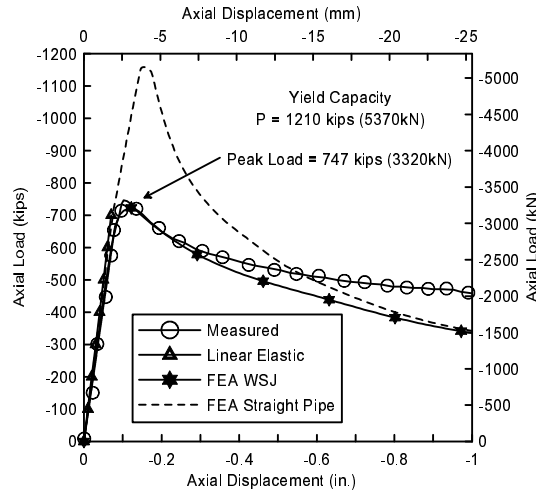


Figure 3. Specimen 36.10. Complete Load versus Displacement.

Compression Loading of Pipeline with Strengthened WSJ.

A brief summary of one laboratory test for one of the reinforced welded slip joint pipe specimens is presented. Both 32 in. (810mm) and 36 in. (910mm) diameter pipe types were tested. The reinforcement was constructed from epoxy saturated carbon fiber fabric (FRP) placed manually around the welded slip joint region. The 36 in. (910mm) diameter specimen was a typical “as-built” specimen for municipal water distribution systems. The 32 in. (810mm) diameter specimens were constructed specially for this testing program to investigate the performance of large diameter-to-pipe wall thickness (D/t ratio) pipes.

Figure 4 presents the load vs. displacement plot for Specimens 36.6 FW with FRP reinforcement, Specimen 36.10 with no reinforcement, FEA models of straight and WSJ pipe, and linear elastic pipe model. Figure 5 shows the same information at an expanded scale. Specimen 36.6 FW, a strengthened specimen, was tested to a peak load of 1015 kips (4515kN) at a displacement of 0.150 in. (3.81mm). The specimen failed by circumferential local buckling 6 in. (150mm) from the FRP wrap in the straight pipe section of the spigot end. This load corresponds to 91% of the yield load capacity of a cylindrical pipe section. In both figures, the good correlation of the FEA model response for both the unreinforced WSJ and straight pipe models is evident. The FEA unreinforced WSJ model tracks the performance of the test specimen past peak load displacement to

approximately 0.25 in. (6mm) displacement. The FEA straight pipe model tracks the strengthened specimen performance to approximately 900 kips (4000kN) load, at which point the buckling deformation of the test specimen exceeds the FEA model. The close correspondence in load vs. displacement between Specimen 36.6 FW with FRP wrap and the FEA straight pipe model shows that FRP strengthening promotes performance similar to that of a straight pipe.

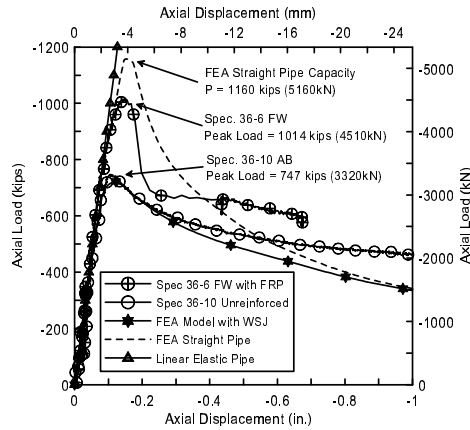


Figure 4. Performance Comparison for Specimen 36.6 FW and 36.10.

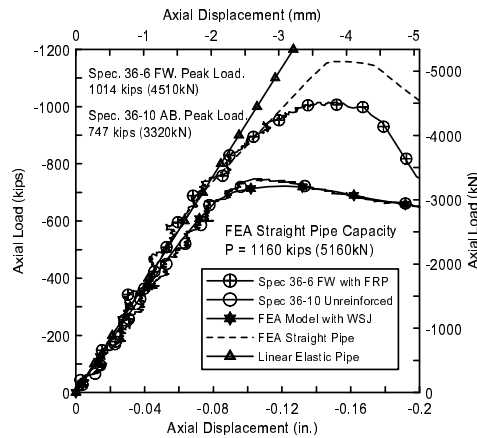


Figure 5. Performance Comparison for Specimen 36.6 FW and 36.10. Expanded Scale View.

Full-Scale Test Results for Tension Loading.

A brief summary of one of the tension tests procedures and results for steel water pipelines that were tested to failure is presented. These pipes were approximately 12 in. (300mm) diameter, 6 ft (1.83m) long with 0.25 in. (6mm) thick wall. Each pipe had an exterior welded slip joint (bell and spigot connection) centered in the specimen length. The exterior cement coating was removed, while the interior cement liner was left in-place. Experimental and numerical results are compared for the performance of the full-scale pipe specimen with respect to finite element models and a theoretical prismatic tube.

As an example of the testing process for Specimens 12.3 and 12.5, Figure 6 shows the load sequence for Specimen 12.3. The first two recorded episodes were related to the attachment of the specimen into the load frame for this particular test. Episode 1 shows compression being applied to the specimen. This was due to the advancement of the ram onto the test specimen during the initial attachment. The fixed end was attached first, with the load end bolts loose. The ram end was then moved to just touch the pipe. Then the bolts at the load end were tightened. Episode 2 shows the release of the compression on the specimen from the ram advancement. A slight compressive correction was applied in an attempt to establish a null load state prior to full testing. This resulted in a slight compression load over-shoot, as seen in Episode 3. Episode 4 was a series of three small load-unload cycles to test and check the data recording equipment. The first test load cycle, Episode 5, involved loading of the specimen to approximately the proportional limit load. The proportional limit load for Specimen 12.3 was approximately 320 kips (1420kN), based on tension coupon tests. The specimen was then partially unloaded to approximately 100 kips (450kN). Episode 6 was loading the specimen to peak load of 580 kips (2580kN). Episode 7 was the necking of the prismatic section of the pipe at peak load until complete failure of the section.

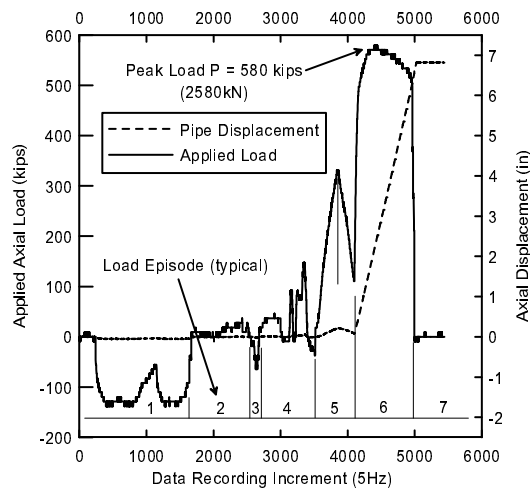


Figure 6. Specimen 12.3. Load Episode Displacement Plot.

Figure 7 shows the response of Specimen 12.3 for the complete test. The specimen was loaded to the approximate proportional limit load (PLL) of 320 kips (1420kN). It was then unloaded to approximately one third of the PLL. Then, the second and final tensile loading cycle began from this load state. The specimen was tested to a peak load of 580 kips (2580kN) at a displacement of 2.20 in. (55.9mm), equivalent to 97% of the ultimate tensile stress determined from tensile coupon tests. After the peak load, necking of the specimen progressed in the spigot portion of the specimen until complete fracture at a displacement of 6.8 in. (170mm). Figure 8 is an expanded scale version of Figure 7.

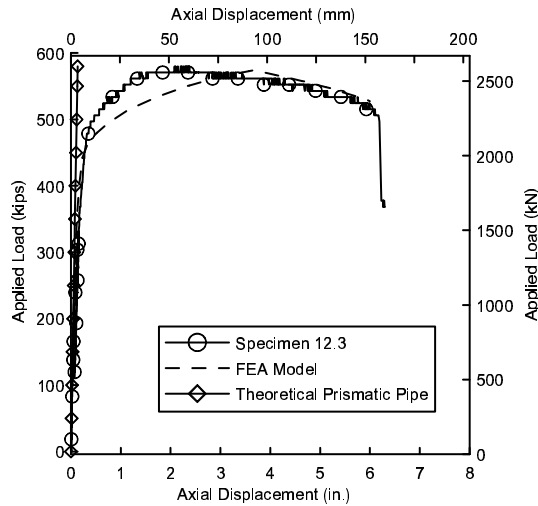


Figure 7. Specimen 12.3. Load-Displacement and FEA Plot. Maximum Displacement.

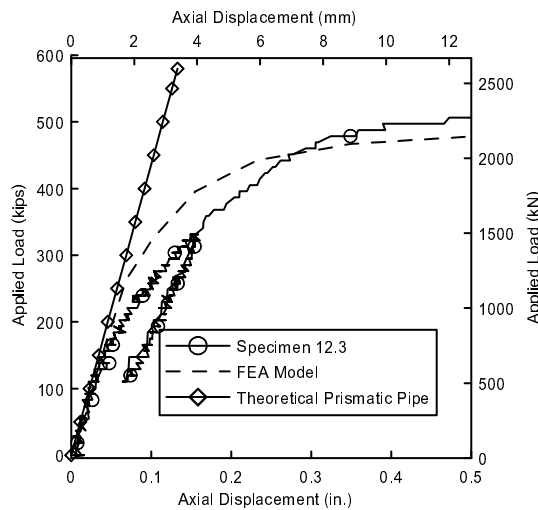


Figure 8. Specimen 12.3. Load-Displacement and FEA Plot.
0.5 in. (12mm) Displacement

Figure 9 shows the complete failure of Specimen 12.3 due to fracture near the mid-section of the spigot end. The interior liner can be seen at the bottom of the pipe. This was crushed due to the decrease in diameter during necking.

Figure 10 shows the elongation deformation of Specimen 12.3 in terms of strain. The axial strain was calculated as the measured amount of elongation between adjacent planes which were marked on the exterior of the pipe divided by the original separation distance between them, i.e. a 4 in. (100mm) gage length. The circumferential strain was calculated as the measured amount of reduction in circumference divided by the original circumference for each measurement plane. At the failed end, the spigot end, the local longitudinal strain was approximately 28% with an associated decrease in circumference of approximately 10%. At the opposite end (i.e., longitudinal position of 8 in. (200mm) to 12 in. (300mm)) the longitudinal strain was approximately 16%, with an associated decrease in circumference of approximately 3%. In the region of the bell housing there was approximately 3% longitudinal strain with small change in circumference.



Figure 9. Specimen 12.3. Fractured Pipe.

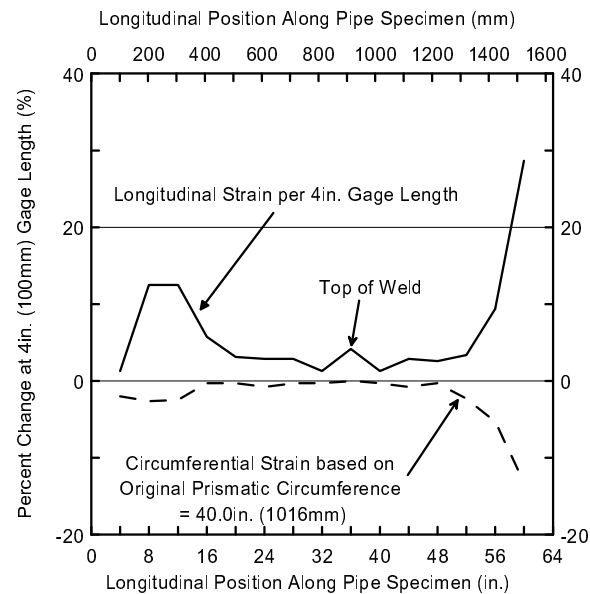


Figure 10. Specimen 12.3. Measured Axial and Circumferential Strain.

Conclusions

This paper presents the results of full-scale testing of water supply pipelines to evaluate their response to earthquake-induced axial forces in both the as-built and strengthened state, using fiber-reinforced polymer (FRP) wrap applied at welded slip joints (WSJs). Pipelines specimens with WSJs, of nominal 300, 810, and 910-mm diameter and diameter-to-thickness ratios (D/t) ranging from 48 to 250, were fabricated and supplied by the Los Angeles Department of Water and Power for compression, tension, and earthquake simulation testing. Numerical simulations using the software,

ABAQUS, were performed for compressive and tensile testing. The numerical simulations were performed for deformations sufficiently large to mobilize fully the nonlinear properties of the steel and geometric nonlinear buckling at WSJs. The numerical and experimental results are in close agreement. The paper also compares the full-scale compressive test results for as-built and FRP-strengthened specimens. The FRP wrap increases the compressive capacity of the joints from 30 to 100%, depending of D/t, weld properties, and characteristics of the FRP strengthening. A major finding of the work is that the application of a properly designed and installed FRP wrap to a WSJ restores the compressive capacity of the pipe to that of a straight cylindrical pipe section.

Insofar as the authors are aware, these experiments represent the first full-scale tests to tensile failure of steel pipelines with WSJs. As such, they provide a unique experimental database for evaluating analytical models and for quantifying our engineering assumptions about behavior under extreme conditions in the field. Even though the specimens involved WSJs, failure did not occur in the vicinity of the circumferential welds, but rather in the body of the pipe at roughly two diameters from the WSJ. The experiments therefore demonstrate that the WSJs, fabricated with good workmanship, can provide for full strength and ductility under axial elongation.

Acknowledgments

This research was supported by the Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY and the National Science Foundation, whose assistance is gratefully acknowledged. The collaboration and support of LADWP is deeply appreciated, and in particular thanks are extended to Glen Singley, Craig Davis, Charlotte Rodriquez of LADWP, and LeVal Lund, formerly of LADWP. The authors also acknowledge Doug Taylor and his engineering staff at Taylor Devices, Inc. for providing access to his test equipment and facility. Thanks are also given to Ron Watson, Ed Fyfe, and the technical staff at Master Builders, Inc.

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