Hazard Resilience Evaluation of US Pipe Ductile Iron TR-XTREME™ Joints: 4-16 in. (100-400 mm) Diameter Pipe

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SUMMARY

US Pipe has developed a hazard resistant ductile iron (DI) pipe joint, called the TR-XTREME™ Joint. Sections of 6-in. (150-mm) pipes with TR-XTREME™ joints were tested at Cornell University to 1) evaluate the stress-strain-strength characteristics of the DI, 2) evaluate the bending resistance and moment-rotation relationship of the joint for two positions of the locking clip segments, 3) determine the capacity of the joint in direct compression and tension, 4) investigate the axial soil resistance and pull-out capacity of the pipe-joint when buried in soil with and without a polywrap covering, and 5) evaluate the capacity of a 6-in. (150-mm) DI pipeline with TR-XTREME™ joints to accommodate fault rupture using the Cornell full-scale split-basin testing facility. Sections of 12-in. (300-mm)- diameter pipes with TR-XTREME™ joints also were tested at Cornell University to 1) evaluate the bending resistance and moment-rotation relationship of the joint for two positions of the locking clip segments, and 2) determine the capacity of the joint in direct tension. Finite element (FE) analyses were performed for 4- through 16-in. (100- through 400-mm)-diameter pipelines with TR-XTREME™ joints to show how these sizes of pipelines would respond to large-scale split-basin tests, similar to the one conducted on the pipeline with 6-in. (150-mm)-diameter joints. Detailed information about the testing and test results is provided in two reports that cover the 6-in. (150-mm) joint tests (Cornell, 2015a) and the 12-in. (300-mm) joint tests and FE results (Cornell, 2015b).

It should be noted that the term “rotation” in this report is equivalent to “deflection” as used commonly in the field and commercial pipeline information. Test results are summarized for tensile stress-strain-strength characteristics, bending test results, direct joint compression and tension, axial soil/pipe resistance, pipeline response to fault rupture, and significance of test results under the headings that follow.

Tensile Stress-Strain- Strength Characteristics

The tensile test data for the DI specimens taken from the pipe with TR-XTREME™ joints show similar tensile stress vs. strain characteristics as specimens taken from DI pipe with the TYTON JOINT®. Given this similarity, there should be little to no difference in the mechanical performance of the DI pipe with the TR-XTREME™ joints relative to other U.S. Pipe DI pipe with similar geometric characteristics. Improvements in the casting and pipe fabrication associated with other U.S Pipe DI are expected to result in pipeline response to large ground deformation that either equals or exceeds the TR-XTREME™ pipe response.

Bending Test Results for 6-in. (150-mm) Pipe Joints

Four-point bending tests were performed to evaluate the moment vs rotation relationships of the 6-in. (150-mm) TR-XTREME ™ joints when the locking clips were at the 3 and 9 o´clock positions (Test A) and the 12 and 6 o´clock positions (Test B). Test A was able to sustain an applied moment of 515 kip-in. and an average rotation of 8.6 degrees as shown in Figure 1 before leakage or failure of the bell. Test B failed at an applied moment of 480 kip-in. (7% lower than Test A) and at an average rotation of 9.1 degrees (6% higher than Test A).

Figure 2 shows the moment-rotation results for tests A and B on the 6-in. (150-mm)-diameter. There is no significant moment – rotation difference for the two tests. The test results show that moments in the range of the proportional limit, M_{prop}, and the yield moment, M_{yield}, were associated with loss of pressure and pipe leakage. Stress concentrations related to spigot-bead contact with the restraining clips are a likely source of local deformations leading to leakage at such moments.

Direct Compression and Tension for 6-in. (150-mm) Pipe Joints

The setup for the compression test is shown in Figure 3. Compression testing showed that the 6-in. (150-mm) TR-XTREME™ joint was able to accommodate axial loads to a compressive level at about the DI proportional limit. After this stress level was reached, progressive bending and local distortion of the pipe occurred. Axial loads of roughly 350 kips (1555 kN) were applied to the joint. These results were similar to those from the four-point bending tests in which local deformation developed and subsequent leakage occurred after moments, corresponding to the proportional limit, were applied.

Two tension tests were performed on the US Pipe with 6-in. (150-mm) TR-XTREME™ joints. As illustrated in Figure 4, Tests T1 and T2 reached a maximum force of 83 kips (369 kN) at 2.75 in. (69.6 mm) of axial displacement and an axial load of 78 kips (347 kN) at 2.72 in. (69.1 mm) of joint displacement, respectively. The joints began to leak at openings of 3.3 and 3.5 in. (83.8 and 88.9 mm) for T1 and T2, respectively. The overall behavior of T1 and T2 was nearly identical.

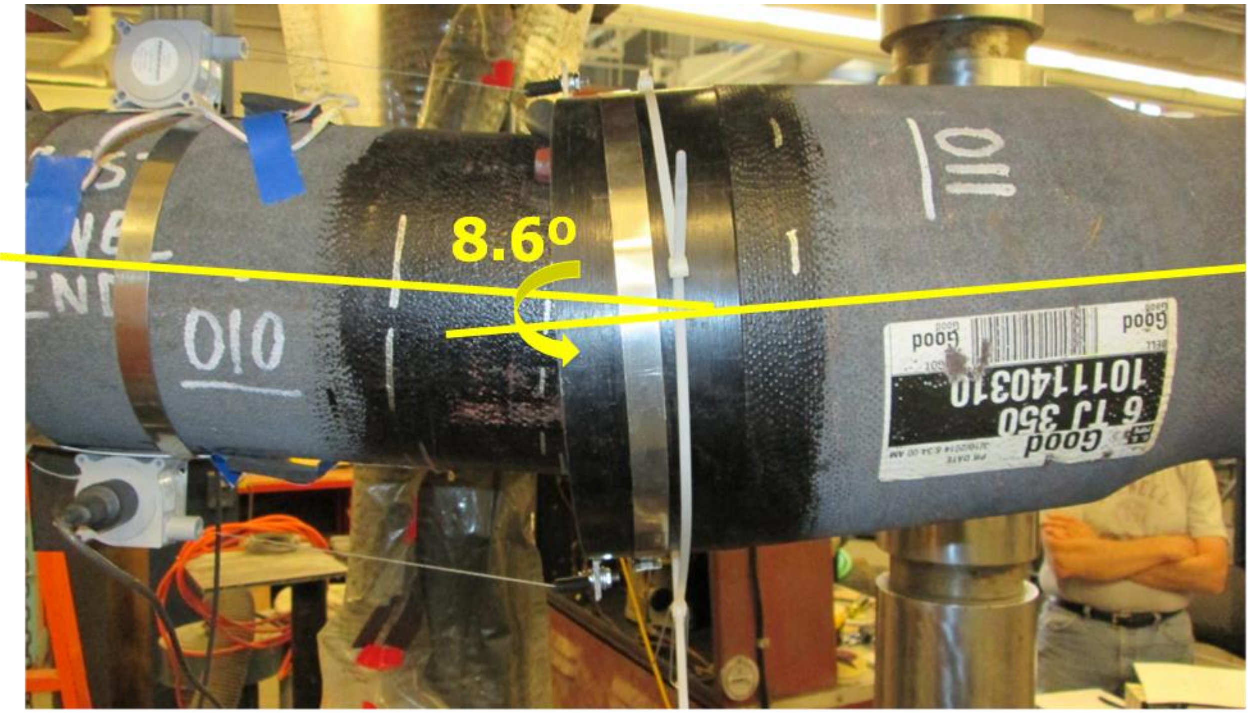


Figure 1. Joint Rotation in Test A; 6 in. Pipe

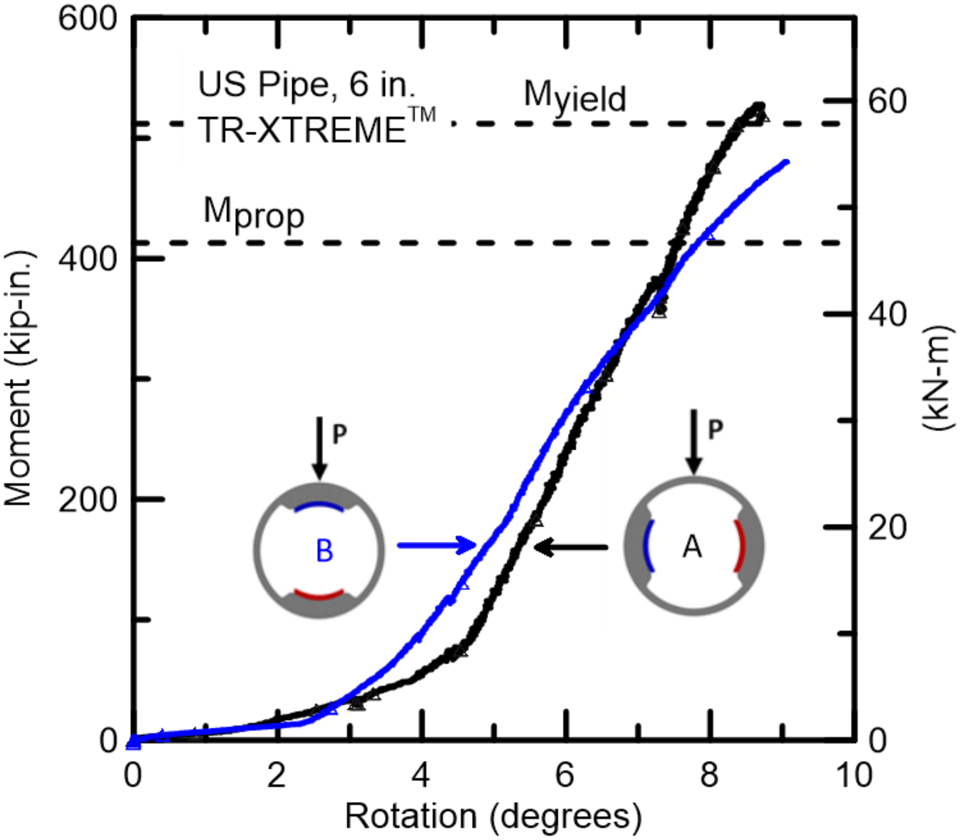


Figure 2. Moment-Rotations for Tests A and B; 6 in. (150 mm) Pipe

Figure 3. Photo of 6 in. Pipe Compression Test

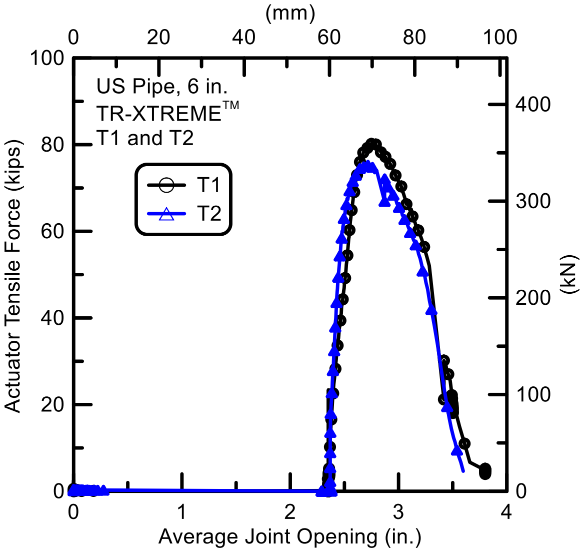


Figure 4. Tensile Force vs. Average Joints Opening for Tests T1 and T2

The onset of leakage was caused by forces generated between the spigot bead and restraining clips that deform the spigot inward a sufficient distance to allow the bead to slip past the clips, with attendant loss of water pressure. Similar to the compressive and four-point bending test results for the US Pipe TR-XTREME™ joint, leakage occurred in the tensile tests when localized strains resulted in irrecoverable deformation. In this case, those strains are circumferential, and the irrecoverable deformation was reflected in shortening of the spigot diameter caused by forces between the spigot bead and clips.

Axial Soil/Pipe Resistance for 6-in. (150-mm) Pipe Joints

Figures 5 and 6 show pipe in direct soil contact and covered with polywrap, respectively, in preparation for axial soil resistance tests. The axial soil resistance tests confirm axial slip of the 6-in. (150-mm) TR-XTREME™ joint under conditions in which sufficient soil/pipe shear resistance is mobilized either side of the joint to exceed the force required to initiate joint slip. Once the spigot bead engages the clips that, in turn, engage the bell mouth, additional resistance to pullout is mobilized from soil reaction at the bell as it is pulled through the soil. The test results provide excellent data with which to quantify the axial pullout loads and displacements when there is relative movement between the adjacent soil and pipelines with 6-in. TR-XTREME™ joints.

The test results show that the polywrap reduced the axial pullout force by about 15% or more at displacements exceeding 4 in. (102 mm) when compared with unwrapped pipe under similar burial conditions. The reduced axial force is caused by the lower interface resistance between the soil and polyethylene wrap when compared with the interface resistance between soil and ductile iron pipe.

There is less than 10% difference between the ultimate pullout forces associated with the flat and curved ends of the bell oriented towards the direction of movement. The force vs. displacement data show that the ultimate pullout resistance is mobilized more rapidly when the flat end of the bell is oriented toward the direction of movement, thus contributing to a stiffer reaction.

Fault Rupture Effects on Pipeline with 6-in. (150-mm) Pipe Joints

Figure 7 shows a plan view of the test setup at the Cornell Large-Scale Lifelines Facility for generating fault rupture across a 39-ft (11.9-m)-long, five-piece section of a 6-in. (150-mm) DI pipeline with TR-XTREME™ joints. The pipe had four joints, equally spaced about a 50° fault.

Figure 5. Pipeline in Direct Contact with Soil

Figure 6. Pipeline Prepared with Polywrap

The pipe was placed on a bed of compacted partially saturated sand, aligned, instruments checked, and then backfilled with compacted sand to a depth of cover of 30 in. (762 mm) above the pipe crown. The pipe was pressurized to approximately 80 psi (552 kPa). The test basin's north section was displaced along a 50º fault at a rate of 12 in. (305 mm) per minute. At a fault displacement of roughly 19.0 in. (483 mm) there was an audible "pop," the pipe lost pressure, as shown in Figure 8. The 19.0 in. (483 mm) fault displacement corresponds to 12.2 in. (310 mm) of axial extension of the test basin and pipe. Following excavation, a fracture was observed at the west springline of the bell of the south joint.

The test measurements confirm that the pipeline was able to accommodate successfully fault rupture through axial displacements and rotations at all four joints. Moreover, the measurements provide a comprehensive and detailed understanding of how the movement was accommodated at each joint, the sequence of movements, and combined axial pullout and rotation at each joint. The combined joint pullout displacements are 12.2 in. (310 mm), which exceeds the sum of the 2.3 in. (58.4 mm) spigot insertion length for all four joints. On average, the spigot at each joint pulled from the bell on the order of 3.05 in. (77 mm), thus confirming that significant additional pullout occurs beyond the slip required for the spigot bead to make contact with the restraining clips. This type of additional pullout capacity was observed at comparable levels of movement during previous tension testing of TR-XTREME™ joints. The maximum rotation measured at the joints closest to the fault was nearly six degrees, thus demonstrating the ability of the joints to sustain significant

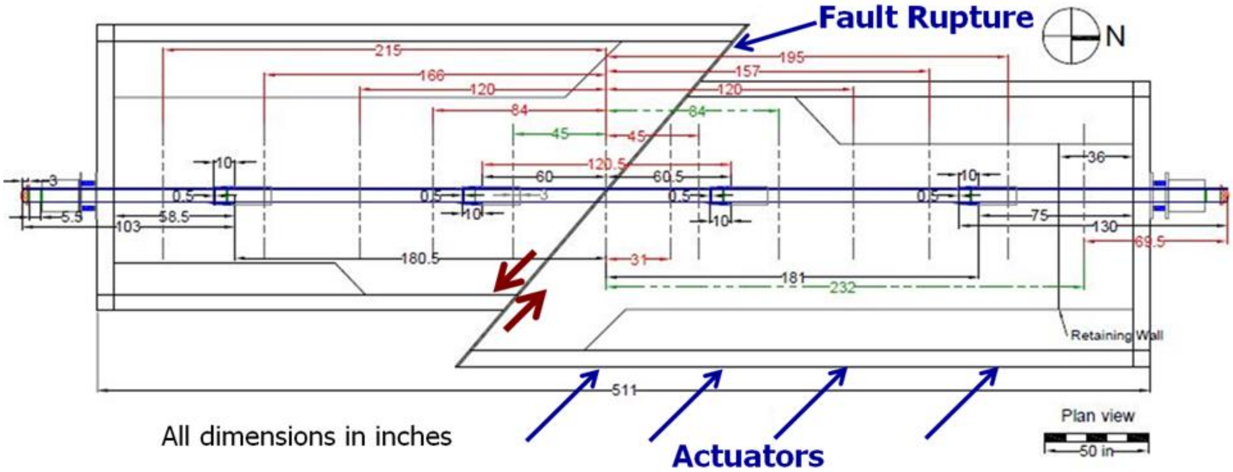


Figure 7. Plan View of Large-Scale Split-Basin Test for Fault Rupture Intersecting US Pipe Ductile Iron Pipeline

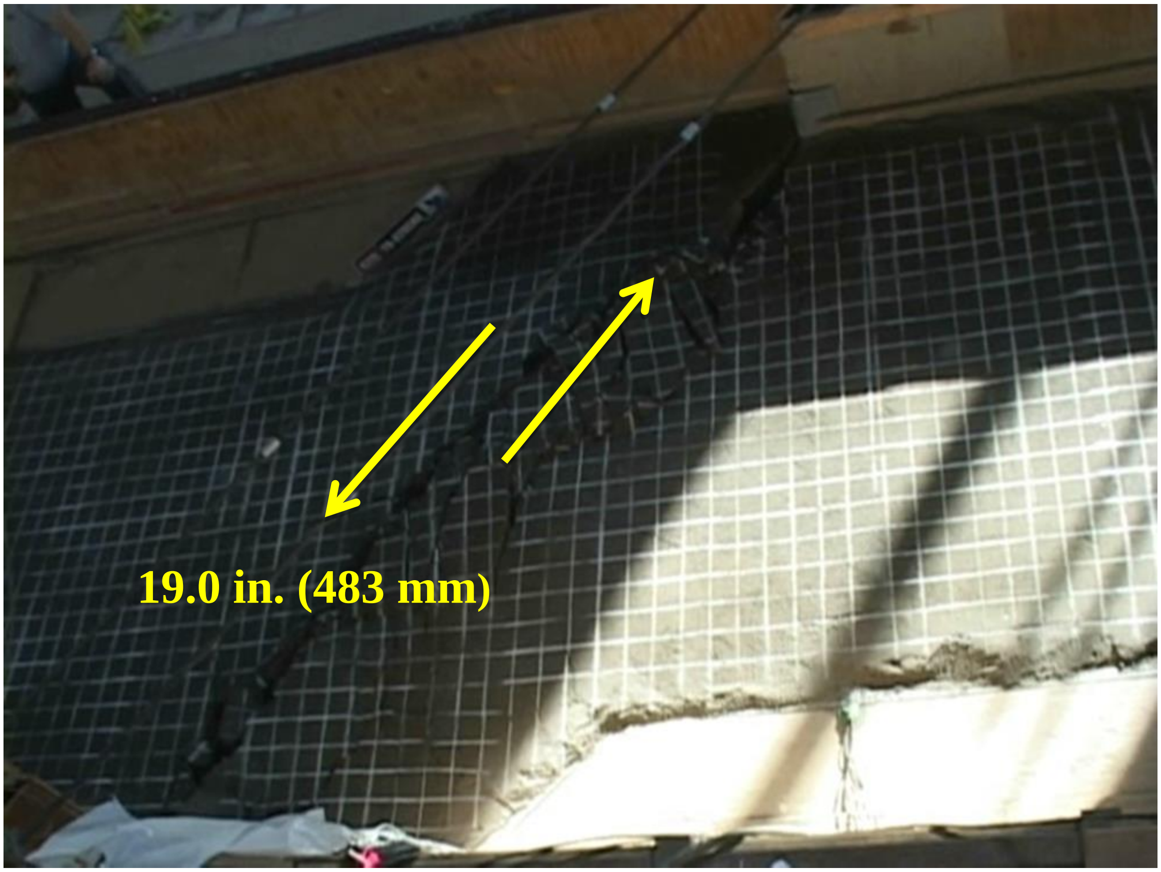


Figure 8. Fault Rupture at Pipe Failure

levels of combined axial pullout and rotation. The maximum stresses in the pipeline, corresponding to the largest pipeline deformation, were well within the elastic range of pipeline behavior.

The 6-in. (150-mm) pipeline with TR-XTREME™ joints was able to accommodate significant fault movement through axial pullout and rotation of the joints. Fault rupture simulated in the large-scale test is also representative of the most severe ground deformation that occurs along the margins of liquefaction-induced lateral spreads and landslides.

Bending Test Results for 12-in. (300-mm) Pipe Joints

Four-point bending tests on 12-in. (300-mm) pipes were performed to evaluate the moment vs. rotation relationships of the TR-XTREME™ joints when the locking clips were at the 3 and 9 o´clock positions (Test A) and the 12 and 6 o´clock positions (Test B). Both pipes were pressurized to 80 psi (552 kPa). First leakage was observed at a moment of 565 kip-in. (64 kN-m) and an average joint rotation of 6.5 degrees for Test A. The leakage stopped after depressurization to approximately 60 psi (414 kPa). The pipe was re-pressurized to 80 psi (552 kPa) and did not leak again until a rotation of 10.3 degrees. The first leakage of Test B was detected at an applied moment of 350 kip-in. (40 kN-m) and 4.8 degrees of average joint rotation. The average rotation at first leakage for the two tests is 5.6 degrees.

The joints were able to sustain substantially higher moment and rotations beyond moment and rotation at first leakage. The maximum leakage of Test A occurred at an applied moment of 1770 kip-in. (200 kN-m) and an average joint rotation of 15.9 degrees. The test was terminated without significant damage or dislocation at the joint. The maximum leakage of Test B was observed at an applied moment of 1240 kip-in. (140 kN-m) and an average joint rotation of 11.0 degrees. The test was terminated when the restraining clips at the invert slipped out of the joint.

The moment vs. rotation relationships for the two tests are similar to a rotation of approximately 10 degrees. Higher moments were mobilized at smaller rotation angles when the clips were positioned closer to the 12 and 6 o’clock positions in alignment with the applied load. The maximum moments developed in both tests were well below both the proportional limit moment, M_{prop}, and the yield moment, M_{yield}.

Direct Tension for 12-in. (300-mm) Pipe Joints

Figure 9 shows the tensile force vs. average joint opening for two direct tension tests performed on 12-in. (300-mm) TR-XTREME™ joints. Both tests began with the spigot fully inserted in the bell. As the pipe was pressurized, the spigot was displaced from the bell seat at approximately 6 psi (41 kPa) internal pressure. The slip was 2.43 in. (61.7 mm) and 2.27 in. (57.7 mm) before the weld bead became engaged with the restraining clips for Tests 1 and 2, respectively. Tests 1 and 2 reached a maximum force of 220 kips (977 kN) at 2.83 in. (71.9 mm) of axial displacement and a maximum axial load of 259 kips (1150 kN) at 2.92 in. (74.2 mm) of joint displacement, respectively. The onset of leakage is caused by forces generated between the spigot bead and restraining clips that crack the bell circumferentially. The joints began to leak at openings of 2.84 and 2.99 in. (72.1 mm and 75.9 mm) for Tests 1 and 2, respectively. After the weld bead on the spigot made contact with the clips, an additional movement between 0.4 and 0.7 in. (10 mm and 18 mm) was required to generate leakage at the joint.

The maximum axial load of 259 kips (1150 kN) in Test 2 is more representative of the axial load capacity of the 12-in. (300-mm)-diameter US Pipe TR-XTREME™ joint and should be used for the best estimate of maximum load capacity for direct axial loading. The maximum axial load caused cracking of the pipe bell. Given an initial slip of 2.27 in. (57.7 mm) to engage contact between the spigot bead and restraining clips, an additional movement of approximately 0.65 in. (16.5 mm) was required to initiate cracking of the bell and leakage at the joint.

Finite Element Simulations

Two-dimensional (2D) finite element (FE) analyses were performed for 4-, 6-, 8-, 12-, 14-, and 16-in. (100-, 150-, 200-, 300-, 350-, and 400-mm)-diameter DI pipelines with TR- XTREME™ joints using soil, pipe, and test dimensions consistent with the large-scale split basin test performed at Cornell University for a 6-in. (150-mm)-diameter pipeline. All pipeline dimensions used in the FE simulations are consistent with those for thickness Class 53 available from US Pipe, and the DI material properties are consistent with those of pipe commercially available from US pipe tested in previous Cornell research.

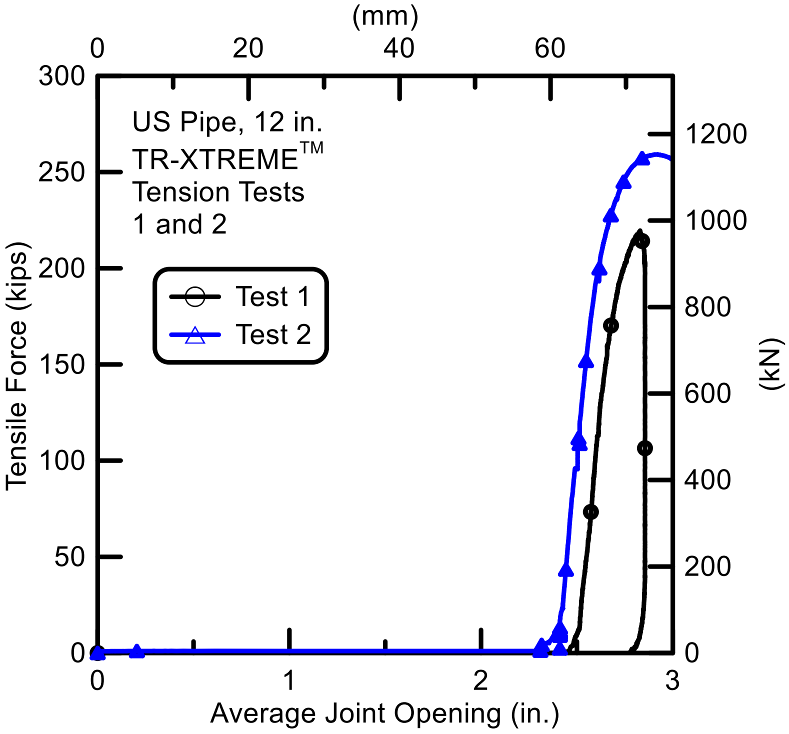


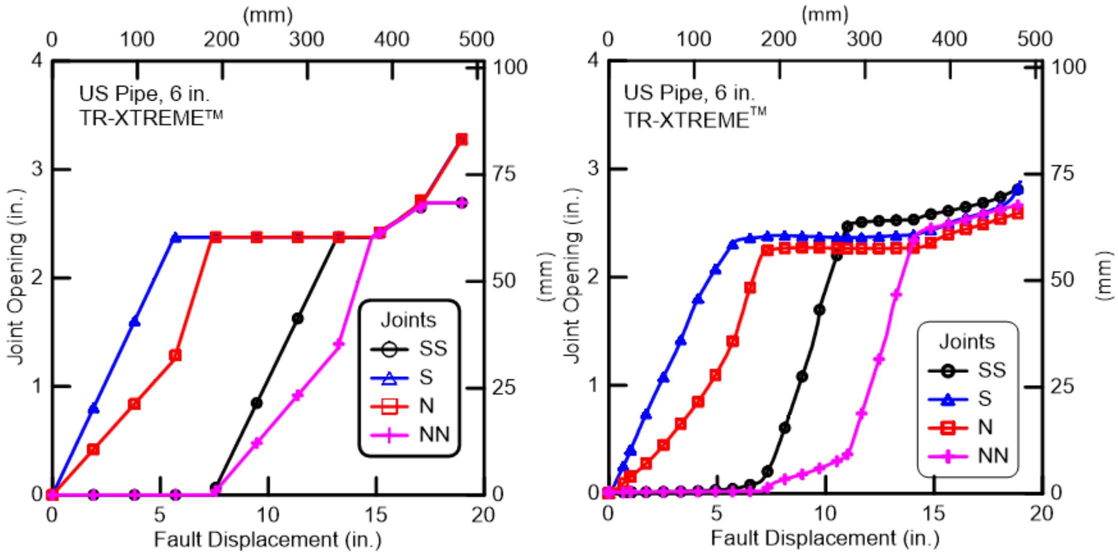
Figure 9. Tensile Force vs. Average Joint Opening for Tests 1 and 2

The FE simulations agree very closely with those of the 6 in. (150 mm) pipeline used in the large-scale split basin test performed at Cornell University. Figure 10, for example, shows that the measured and simulated opening vs. fault displacement at each joint is virtually the same when the FE and experimental results are compared for the large-scale split basin test. This type of comparison confirms that the numerical simulations are accurate representations of the full-scale testing of the US Pipe TR-EXTREME™ jointed pipelines, and provides confidence in the numerical approach when applied to the range of pipe sizes covered in this work.

Based on the test results presented in this report, as well as previous results from large-scale Cornell tests, a scaling procedure was developed to calculate the moment vs. rotation and force vs. pullout relationships for joints with different diameters. Pipelines of 4 and 8 in. (100 and 200 mm, respectively) diameter were scaled with respect to the behavior exhibited by the 6 in. (150 mm) specimens, while pipelines of 14 and 16 in. (350 and 400 mm, respectively) were scaled relative to the results for the 12 in. (300 mm) specimen. The FE simulation results for joint opening vs. fault displacement and joint rotation vs. fault displacement, respectively, are entirely consistent with axial and bending tendencies for all sizes of pipe considered in this study.

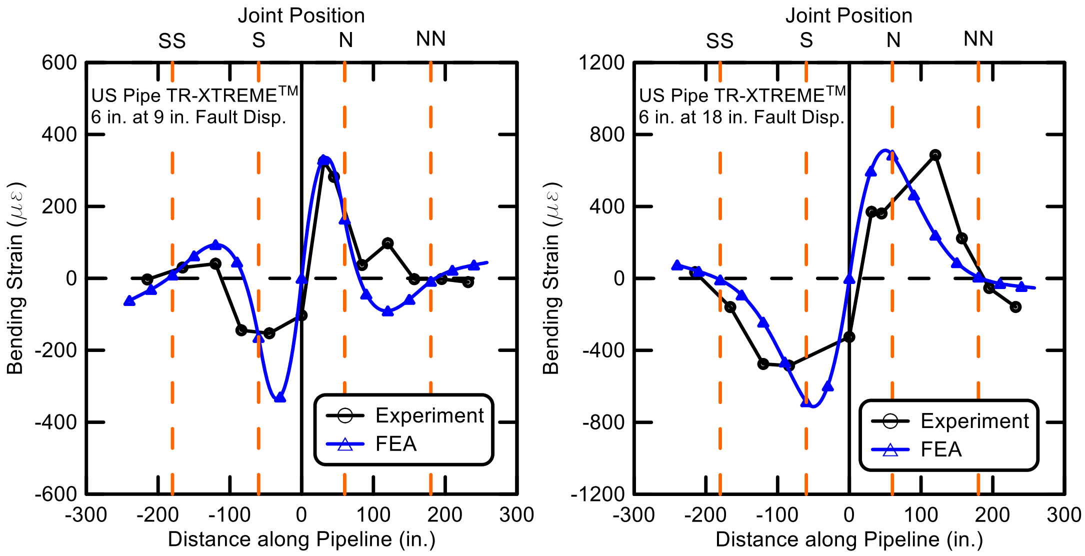
The FE simulations show similar distributions of axial strain for each of the smaller and larger pipe size categories. Maximum axial strain occurs at the location where the pipeline crosses the fault. Maximum axial strains are approximately 490 με and 580 με for 4-, 6- and 8-in. (100-, 150-, and 200-mm)-diameter pipelines and 12-, 14- and 16-in. (300-, 350-, and 400-mm)-diameter pipelines, respectively.

Figure 11 shows favorable agreement between the FE bending strains (FEA in Figure 11) and those measured in 6-in. (150-mm) pipeline during the large-scale split-basin test. The FE bending strains at various locations along the pipelines are provided for 9 in. (225 mm) and 18 in. (450 mm) of fault movement, and show that the bending strains increase in inverse proportion to pipe diameter. As the diameter increases, pipe segments between joints behave more like rigid pipe lengths so that the bending distortion decreases. In all cases the maximum stress from the FE results is below the DI proportional limit stress, thus indicating linear stress vs. strain behavior for all pipe sizes. The maximum axial and bending strains from the FE simulations for 6-in. (150-mm)-diameter pipe compare well with the measurements of maximum axial and bending strains obtained during the previous large-scale split basin test at Cornell, thus providing confidence in the FE results.



a) Finite Element Results b) Full-Scale Test Results

Figure 10. Joint Opening vs. Fault Displacement for 6-in. (150-mm)-Pipes



a) 9 in. (225 mm) Fault Offset b) 18 in. (450 mm) Fault Offset

Figure 11. Comparison of Measured and Analytical Bending Strains

Significance of Large-Scale Test and Finite Element Simulation Results

It should be recognized that the amount of tensile strain that can be accommodated by pipelines with TR-XTREME™ joints will depend on the axial separation between the pipeline joints. The 6-in. (150-mm) pipeline used in the large-scale split-basin test was able to accommodate 12.2 in. (206 mm) of axial extension, corresponding to an average tensile strain of 2.61% along the pipeline. The FE results presented in this report show similar performance for all sizes of pipelines between 4 in. (100 mm) and 16 in. (400 mm). Such extension is large enough to accommodate the great majority (over 99%) of liquefaction-induced lateral ground strains measured by high resolution LiDAR after each of four major earthquakes during the recent Canterbury Earthquake Sequence (CES) in Christchurch, NZ (O'Rourke et al., 2014). These high resolution LiDAR measurements for the first time provide a comprehensive basis for quantifying ground strains caused by liquefaction on a regional basis. To put the CES ground strains in perspective, liquefaction-induced ground deformation measured in Christchurch exceed those documented in San Francisco during the 1989 Loma Prieta earthquake (e.g., O'Rourke and Pease, 1997; Pease and O'Rourke, 1997) and in the San Fernando Valley during the 1994 Northridge earthquake (e.g., O'Rourke, 1998). They are comparable to the levels of most severe liquefaction-induced ground deformation documented for the 1906 San Francisco earthquake, which caused extensive damage to the San Francisco water distribution system (e.g. O'Rourke and Pease, 1997; O'Rourke et al., 2006).

The test results and FE simulations presented in this report confirm that the TR-XTREME™ joints are able to sustain without leakage large levels of ground deformation through axial displacement and rotation. The test results are directly applicable to the performance of nominal 4-in. (100-mm) to 16-in. (400-mm)-diameter US Pipe DI pipelines with TR-XTREME™ joints.

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