Four-Point Bending Testing of 6-in. (150-mm), 12-in. (300-mm), and 16-in. (400-mm)-Diameter Kubota Earthquake Resistant Ductile Iron Pipes

Submitted to:

Mr. Toshio Toshima
Kubota Corporation

By

C. Pariya-Ekkasut
B.A. Berger
B. P. Wham
H. E. Stewart
T.D. O'Rourke
T.K. Bond

Cornell University
School of Civil and Environmental Engineering
Hollister Hall
Ithaca, NY 14853

April, 2017

Acknowledgements

The authors wish to recognize the excellent effort of Cornell graduate and undergraduate students that made these experiments successful. Namely, the contributions of Andrew Shakalis, Margaret Stack, George Howell III, Mia Stewart, Dara Karac, Maya Linden, and Charles Sanderson are gratefully acknowledged. The support from the Kubota Corporation is gratefully acknowledged, as are the welcomed discussions with and contributions of Toshio Toshima, Takeshi Hara, Naoto Itabashi, Keita Oda, and Yutaka Fujimoto from Kubota.

EXECUTIVE SUMMARY

Kubota Corporation has developed an earthquake-resistant ductile iron pipe (ERDIP), under the commercial name of GENEX®. Pressurized four-point bending tests were performed on nominal 6-in. (150-mm)-, 12-in. (300-mm)-, and two 16-in. (400-mm)-diameter sections of ERDIP. The purpose of these tests was to develop moment vs. rotation relationships for different sizes of ERDIPs.

The first leakage of approximately 0.1 gal/min (0.4 l/min) in the 6 in. (150 mm) pipe (T1) occurred at a rotation of 12.2 degrees and an applied moment of 520 kip-in. (58.8 kN-m). The leakage rate grew larger with increasing moment and joint rotation. At 14.3 degrees of joint rotation with an associated moment of 580 kip-in. (65.5 kN-m), the pipe had a significant leakage on the order of 7 gal/min (26.5 l/min). Significant leakage is defined as flow exceeding 7 gal/min (26.5 l/min), corresponding to 10,000 gal/day (38,000 l/day). The pipe reached the maximum moment of 630 kip-in. (71.2 kN-m) at a joint rotation of 16.6 degrees. The moment dropped rapidly, and the leakage stopped. The test was continued until the pipe reached 20.9 degrees of joint rotation without additional leakage. The pipe was unloaded and reloaded. The test was stopped when the pipe reached a rotation of 32 degrees.

In the 12-in. (300-mm) bending test (T2), the pipe reached the maximum moment 1,560 kip-in. (176 kN-m) at a joint rotation at 12.4 degrees. The test was continued until the pipe reached 20.5 degrees of joint rotation without leakage. The first leakage exceeding 8.3 gal/min (31 l/min) was observed at 19.3 degrees of joint rotation while the pipe was being unloaded.

Two bending tests, T3 and T4, were performed on 16-in. (400-mm) specimens. Test T3 was pressurized throughout the test. Test T4 was unpressurized until the rotation reached 8 degrees. The pipe then was pressurized. The rotational responses between specimens T3 and T4 are different. During the first 5 degrees of joint rotation, the unpressurized T4 pipe rotated to approximately 5 degrees under their own weights while a moment of about 270 kip-in. (30.5 kN-m) was required to cause the same amount of rotation for the pressurized T3 pipe. Test T3 had its first leakage of approximately 0.7 gal/min (2.6 l/min) at the maximum moment 2,700 kip-in. (305 kN-m) with a corresponding joint rotation of 17.5 degrees. The test was paused. Significant leakage on the order of 8.3 gal/min (31 l/min) occurred after lowering and raising internal pressure back to 80 psi (550 kPa). The test was continued. There was a rapid drop in moment at 18.9

degrees of joint rotation, corresponding to fracturing of the spigot. Specimen T4 reached its maximum moment of 2,400 kip-in. (271 kN-m) at a joint rotation of 13.6 degrees without leakage. The moment steadily declined, and the first leakage of approximately 0.05 gal/min (0.19 l/min) was observed at a joint rotation of 17.3 degrees and applied moment of 1,580 kip-in. (178 kN-m). Significant leakage on the order of 15 gal/min (57 l/min) occurred suddenly at an applied moment of 563 kip-in. (63.5 kN-m) and joint rotation of 20.7 degrees.

According to Kubota's guidelines, the maximum allowable deflection (rotation) of ERDIP for installation and seismic events are 6 and 8 degrees, respectively. The test results show that all sizes of the ERDIPs exceeded the allowable deflection and proportional limit without any leaks or pipe damage.

TABLE OF CONTENTS

Acknowledgements i
Executive Summary ii
Table of Contents iv
List of Figures v
List of Tables vi

Section			Page
1	Introduction and Organization		1
2	Four-Point Bending Tests		2
	2.1	Introduction	2
	2.2	Joint Description	2
	2.3	Testing Procedures for 6-in. (150-mm) T1, 12-in. (300-mm) T2, and 16 in. (400-mm) T3 ERDIP	2
	2.4	Calculation Approach	3
	2.5	Nominal 6-in. (150-mm) ERDIP T1	4
		2.5.1 Instrumentation	4
		2.5.2 Pressure	6
		2.5.3 String Pot Measurements	7
		2.5.4 Moment vs. Rotation	8
		2.5.5 Strains	10
	2.6	Nominal 12-in. (300-mm) ERDIP T2	10
		2.6.1 Instrumentation	10
		2.6.2 Pressure	11
		2.6.3 String Pot Measurements	14
		2.6.4 Moment vs. Rotation	14
		2.6.5 Strains	16
	2.7	Nominal 16-in. (400-mm) ERDIP T3	16
		2.7.1 Instrumentation	16
		2.7.2 Pressure	17
		2.7.3 String Pot Measurements	20
		2.7.4 Moment vs. Rotation	20
		2.7.5 Strains	20
	2.8	Nominal 16-in. (400-mm) ERDIP T4	23
		2.8.1 Testing Procedures for 16 in. (400-mm) T4 ERDIP	23
		2.8.2 Instrumentation	23
		2.8.3 Pressure	23
		2.8.4 String Pot Measurements	26

TABLE OF CONTENTS (continued)

Section		Page
	2.8.5 Moment vs. Rotation	26
	2.8.6 Strains	29
	2.9 Comparisons of Nominal 16-in. (400-mm) ERDIP T3 and T4	29
3	Summary	31
	References	33

LIST OF FIGURES

Figure		Page
2.1	Cut-Away View of ERDIP GENEX Joint	3
2.2	Cross-section of Instrumentation for 6-in. (150-mm) ERDIP Bending Test T1	5
2.3	Photo of 6-in. (150-mm) ERDIP Bending Specimen T1 before Testing	5
2.4	Internal Pressure vs. Joint Rotation for 6-in. (150-mm) ERDIP Bending Test T1	7
2.5	VSP Measurements for 6-in. (150-mm) ERDIP Bending Test T1	9
2.6	HSP Measurements vs. Rotation for 6-in. (150-mm) ERDIP Bending Test T1	9
2.7	Moment vs. Rotation for 6-in. (150-mm) ERDIP Bending Test T1	9
2.8	Photo of 6-in. (150-mm) ERDIP Bending Specimen T1 after Testing	10
2.9	Axial Strains in Central Portion for 6-in. (150-mm) ERDIP Bending Test T1	11
2.10	Cross-section of Instrumentation for 12-in. (300-mm) ERDIP Bending Test T2	12
2.11	Photo of 12-in. (300-mm) ERDIP Bending Specimen T2 before Testing	12
2.12	Internal Pressure vs. Joint Rotation for 12-in. (300-mm) ERDIP Bending Test T2	13
2.13	VSP Measurements for 12-in. (300-mm) ERDIP Bending Test T2	15
2.14	HSP Measurements vs. Rotation for 12-in. (300-mm) ERDIP Bending Test T2	15
2.15	Moment vs. Rotation for 12-in. (300-mm) ERDIP Bending Test T2	15
2.16	Photo of 12-in. (300-mm) ERDIP Bending Specimen T2 after Testing	16
2.17	Axial Strains in Central Portion for 12-in. (300-mm) ERDIP Bending Test T2	17
2.18	Cross-section of Instrumentation for 16-in. (400-mm) ERDIP Bending Test T3	18
2.19	Photo of 16-in. (400-mm) ERDIP Bending Specimen T3 before Testing	18
2.20	Internal Pressure vs. Joint Rotation for 16-in. (400-mm) ERDIP Bending Test T3	19
2.21	VSP Measurements for 16-in. (400-mm) ERDIP Bending Test T3	21
2.22	HSP Measurements vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T3	21
2.23	Moment vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T3	21
2.24	Photo of 16-in. (400-mm) ERDIP Bending Specimen T3 after Testing	22
2.25	Axial Strains in Central Portion for 16-in. (400-mm) ERDIP Bending Test T3	22
2.26	Cross-section of Instrumentation for 16-in. (400-mm) ERDIP Bending Test T4	24
2.27	Photo of 16-in. (400-mm) ERDIP Bending Specimen T4 before Testing	24

TABLE OF CONTENTS (completed)

Figure		Page
2.28	Internal Pressure vs. Joint Rotation for 16-in. (400-mm) ERDIP Bending Test T4	25
2.29	VSP Measurements for 16-in. (400-mm) ERDIP Bending Test T4	27
2.30	HSP Measurements vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T4	27
2.31	Moment vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T4	27
2.32	Photo of 16-in. (400-mm) ERDIP Bending Specimen T4 after Testing	28
2.33	Axial Strains in Central Portion for 16-in. (400-mm) ERDIP Bending Test T4	28
2.34	Moment vs. Rotation Comparisons for 16-in. (400-mm) ERDIP Bending Tests	30

LIST OF TABLES

Table		Page
2.1	Instrumentation for 6-in. (150-mm) ERDIP Bending Test T1	6
2.2	Instrumentation for 12-in. (300-mm) ERDIP Bending Test T2	13
2.3	Instrumentation for 16-in. (400-mm) ERDIP Bending Test T3	19
2.4	Instrumentation for 16-in. (400-mm) ERDIP Bending Test T4	25
3.1	Results of Four-Point Bending Tests	32

Section 1
Introduction and Organization

This report is submitted to Kubota Corporation (Kubota), and presents the results of pressurized four-point bending tests of nominal 6-in. (150-mm)-, 12-in. (300-mm)-, and two 16-in. (400-mm)-diameter sections of earthquake resistant ductile iron pipe (ERDIP), distributed under the commercial name of GENEX®. The purpose of the tests was to develop moment vs. rotation relationships for different sizes of ERDIPs and to characterize pipe joint performance with respect to leakage and structural integrity. An additional test was performed to investigate the effect of pressurization on a 16-in. (400-mm)-diameter pipe specimen following an initial 8-degree rotation under zero internal pressure. The work was undertaken in the Cornell Large Scale Lifelines Testing Facility, which is part of the Bovay Laboratory Complex at Cornell University.

The report is organized into three sections, the first of which provides introductory remarks and describes the report organization. Section 2 presents the instrumentation, test procedures, and test results for the bending tests. A total of four tests were conducted. The first three tests were performed on pressurized nominal 6-in. (150-mm), 12-in. (300-mm), and 16-in. (400-mm) ERDIP sections. The fourth test was a pressurized bending test of a nominal 16-in. (400-mm) pipe section after an initial rotation of 8 degrees with no internal pressure. Section 3 provides a summary of the testing and concluding remarks.

Section 2
Four-Point Bending Tests

2.1. Introduction

This section presents the results of four-point bending tests for nominal 6-in. (150-mm) (T1), 12-in. (300-mm) (T2), and 16-in. (400-mm) (T3) ERDIP test specimens. An additional test was performed on a 16-in. (400-mm)-diameter pipe specimen (T4), which was pressurized after an initial 8-degree rotation under zero internal pressure.

2.2. Joint Description

The bell of the Kubota ERDIP joint is equipped with a locking ring and a rubber gasket to prevent leakage. The spigot is inserted into the bell past the rubber gasket and the locking ring. The spigot has a special feature called a spigot projection that bears against the locking ring to resist pullout of the spigot from the bell. A cut-away view of the ERDIP joint is shown in Figure 2.1. Mechanical joint end caps with Kubota's G-link restraints were attached to the ends of the pipeline test specimens to allow for water pressurization. A nominal internal pressure of 80 psi (550 kPa) was applied throughout the bending test.

2.3. Testing Procedures for 6-in. (150-mm) T1, 12-in. (300-mm) T2, and 16-in. (400-mm) T3 ERDIP

The first three bending tests on 6-in. (150-mm) T1, 12-in. (300-mm) T2, and 16-in. (400-mm) T3 sections were performed as follows:

1) Install the pipe joint at a fully inserted position and level the pipe in the loading frame.
2) Check all instrumentation and data acquisitions systems.
3) Start data acquisition.
4) Fill the pipe with water and pressurize slowly, providing axial force sufficient to expand the joint.
5) Once the joint was fully opened, bleed air from the system and pressurize the pipe to approximately 80 psi (550 kPa).
6) Remove the temporary supports and lower the spreader beam onto the pipe.
7) Apply hydraulic actuator force to develop moment and rotation at the joint.

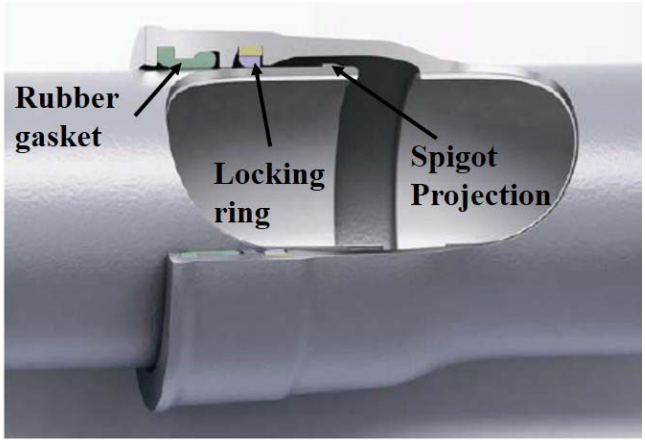


Figure 2.1. Cut-Away View of ERDIP GENEX Joint (courtesy Kubota Corp.)

8) If the actuator reached the limit of its stroke without indication of pipe failure, unload the pipe, and readjust the actuator and crosshead.
9) Apply hydraulic actuator force onto the pipe again until pipe failure.

2.4. Calculation Approach

The four-point load test set-ups for the 6-in. (150-mm) T1, 12-in. (300-mm) T2, and 16-in. (400-mm) T3 sections are presented in Figures 2.2, 2.10, and 2.18, respectively. For each set up the initial moment due to the self-weight of the pipe and water is calculated using a simply-supported beam approach, as follows

$$M_{distrib} = \frac{w l_t^2}{8} \quad (2.1)$$

where:

w = uniform load due to weight of the pipe and water, and

l_t = the total pipe length between the outer supports.

The additional moment applied to the central portion of the specimen, $M_{central}$, was calculated as

$$M_{central} = \frac{PL}{2} \quad (2.2)$$

where:

P = the applied load due to the weight of the spreader beam plus the load applied by the hydraulic actuator in the load frame, and

L = the distance between the load and support points.

The moments due to the pipe, water, and spreader beam weights are included in the moment vs. rotation calculations.

The joint rotation can be calculated by taking the difference between two vertical string pot measurement (VSPs) along the pipe, and dividing the difference by the pot separation distance. The arctangent of this result is the rotation of each side. The overall joint rotation is the sum of the two side angles, as follows

$$\theta_{Bell}\ (\text{degrees}) = \tan^{-1}\left(\frac{\text{difference between two bell VSPs disp.}}{\text{distance between centers of two bell VSPs}}\frac{180^{\circ}}{\pi}\right) \quad (2.4a)$$

$$\theta_{Spigot}\ (\text{degrees}) = \tan^{-1}\left(\frac{\text{difference between two spigot VSPs disp.}}{\text{distance between centers of two spigot VSPs}}\frac{180^{\circ}}{\pi}\right) \quad (2.4b)$$

$$\theta\ (\text{degrees})\ \text{overall} = \theta_{Bell}\ (\text{degrees}) + \theta_{Spigot}\ (\text{degrees}) \quad (2.5)$$

2.5. Nominal 6-in. (150-mm) ERDIP T1

2.5.1. Instrumentation

A cross-section of a nominal 6-in. (150-mm) ERDIP bending test setup T1 and instrumentation is shown in Figure 2.2. There were two temporary supports beneath the central loading points. The supports were used to level the test specimen and to support the self-weight of the pipe (including water for pressurized pipe) before vertical loading. Figure 2.3 is a photograph of the bending specimen before the test.

Table 2.1 lists the location, instrument type, and designation for the nominal 6-in. (150-mm) ERDIP bending test. The instrumentation consisted of string potentiometers (string pots) to measure horizontal displacements at the crown and invert of the joint, referred as HSPs. Vertical displacements along the length of the specimen were measured using seven vertical string pots (VSPs). The VSPs were used to determine the vertical deformation of the test specimen and to calculate the rotation at various locations along the pipe. Strain gages were installed to measure axial and bending strains in the DI pipe.

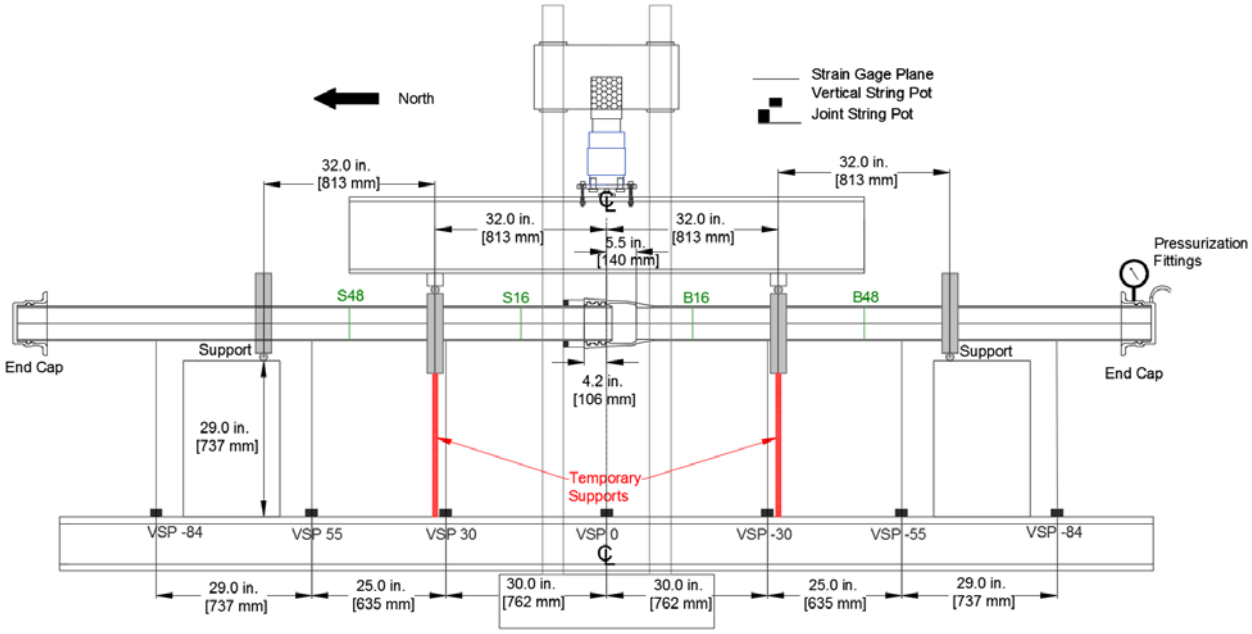


Figure 2.2. Cross-section of Instrumentation for 6-in. (150-mm) ERDIP Bending Test T1

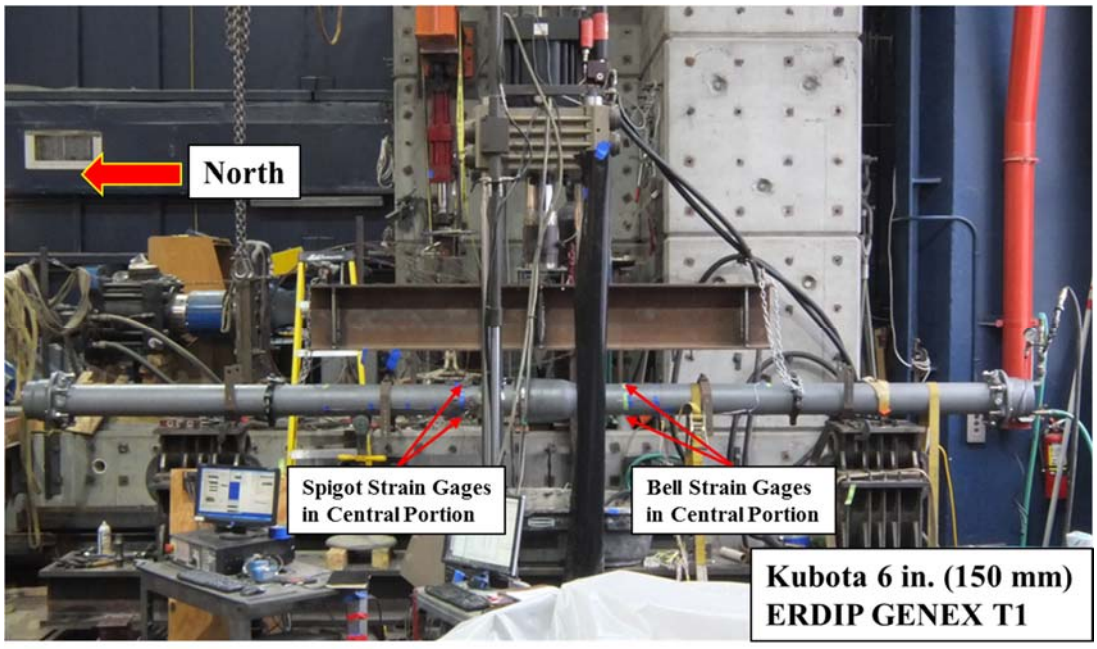


Figure 2.3. Photo of 6-in. (150-mm) ERDIP Bending Specimen T1 before Testing

Table 2.1. Instrumentation for 6-in. (150-mm) ERDIP Bending Test T1

Location	Instrument Description	Instrument Designation
-84 in. from Centerline	Vertical String Pot on Bell End	VSP-84
-55 in. from Centerline	Vertical String Pot on Bell End	VSP-55
-30 in. from Centerline	Vertical String Pot on Bell End	VSP-30
0 in. from Centerline	Vertical String Pot on Bell End	VSP 0
30 in. from Centerline	Vertical String Pot on Spigot End	VSP 30
55 in. from Centerline	Vertical String Pot on Spigot End	VSP 55
84 in. from Centerline	Vertical String Pot on Spigot End	VSP 84
4 in. from Centerline	Horizontal String Pot at Crown	HSP_C
4 in. from Centerline	Horizontal String Pot at Invert	HSP_I
-48 in. from Centerline	Axial Gage at Invert on Bell End	S48I
-48 in. from Centerline	Axial Gage at Crown on Bell End	S48C
-16 in. from Centerline	Axial Gage at Invert on Bell End	S16I
-16 in. from Centerline	Axial Gage at Crown on Bell End	S16C
16 in. from Centerline	Axial Gage at Invert on Spigot End	B12I
16 in. from Centerline	Axial Gage at Crown on Spigot End	B12C
48 in. from Centerline	Axial Gage at Invert on Spigot End	B48I
48 in. from Centerline	Axial Gage at Crown on Spigot End	B48C
Top Center	Load Cell	Load
South End Cap	Pressure Gage	Pressure

1 in. = 25.4 mm

2.5.2. Pressure

The specimen was initially set up at a fully inserted position. It was then pressurized with water to about 80 psi (550 kPa) while allowing the joint to extend fully in response to axial forces on the end caps. Figure 2.4 shows internal pressure vs. joint rotation from the bending test. During the initial application of moment corresponding to approximately 5 degrees rotation, internal pressure levels increased in response to volume reduction in the pipe. Thereafter internal pressure was adjusted continuously to maintain a nearly constant pressure for the rest of the test.

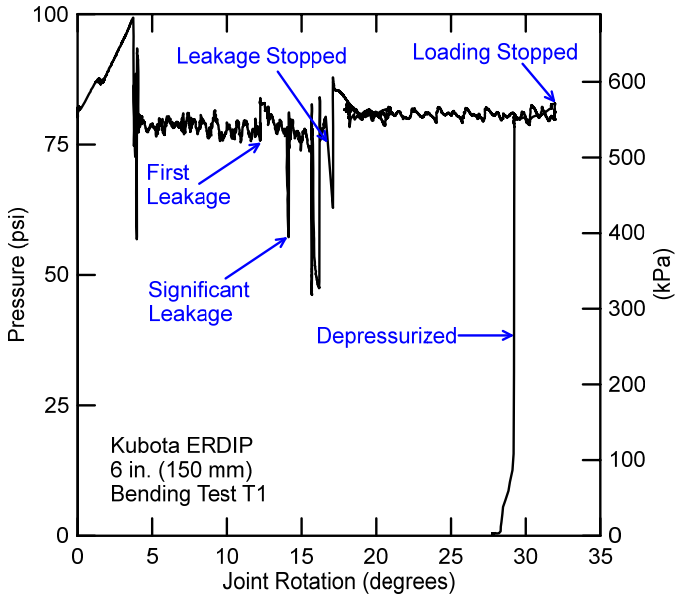


Figure 2.4. Internal Pressure vs. Joint Rotation for 6-in. (150-mm) ERDIP Bending Test T1

The first leakage of approximately 0.1 gal/min (0.4 l/min) was observed at 12.2 degrees of rotation, corresponding to a small fluctuation in pressure as shown in Figure 2.4. Due to safety requirements, direct measurements of leakage by collection of outflowing water at leakage locations around the joint were not performed. Estimates of leakage rates, however, were made by visual examination. Significant leakage is defined as flow exceeding 7 gal/min (26.5 l/min), corresponding to 10,000 gal/day (38,000 l/day). The leakage rate grew larger with increasing joint rotation. At 14.3 degrees of rotation, the pressure dropped to 60 psi (410 kPa), and the pipe leaked at a significant leakage rate of about 7 gal/min (26.5 l/min). The leakage stopped at 16.6 degrees of joint rotation, after which the pressure stabilized with very small pressure fluctuations. The test was stopped when the joint reached 32 degrees of rotation, as shown in the figure. The pipe was unloaded, thereby reducing the rotation to 29.2 degrees after which the pipe was depressurized.

2.5.3. String Pot Measurements

The spigot and bell side VSP measurements shown in Figure 2.5 indicate that there is good agreement between vertical displacement measurements at equal distances from the center point of the test. The continuous progression of these displacements is a further indication that the assumption of rigid body motion can be used in Equations 2.4 and 2.5 to determine rotations.

The horizontal string pots (HSPs) at the crown and invert of the pipe joint provide quantitative data for the evaluation of rotation. Figure 2.6 shows the HSP measurements vs. rotation. During the initial part of the test, the invert HSP displaced less than the crown HSP did, indicating that the pivot point of the joint was at the invert. The bell lip then deformed at the crown with the spigot breaking at approximately 16.6 degrees of joint rotation, corresponding to a rapid increase at the invert HSP. The pivot point then moved to the crown of the joint as indicated by higher displacement rate at the invert HSP than the crown HSP.

2.5.4. Moment vs. Rotation

The moment vs. rotation relationship is shown in Figure 2.7. The first leakage of approximately 0.1 gal/min (0.4 l/min) developed at a rotation of 12.2 degrees and an applied moment of 520 kip-in. (58.8 kN-m). The leakage rate grew larger with increasing moment and joint rotation. At 14.3 degrees of joint rotation with an associated moment of 580 kip-in. (65.5 kN-m), the pipe had a significant leakage on the order of 7 gal/min (26.5 l/min). When the pipe reached the maximum moment of 630 kip-in. (71.2 kN-m) at 16.6 degrees of rotation, the moment dropped rapidly, and the leakage stopped. The test was continued until the rotation reached 20.9 degrees of joint rotation without leakage, when the actuator reached the limit of its stroke.

As the pipe was unloaded to reset the actuator, it rebounded to 18.0 degrees of joint rotation. The actuator and crosshead were readjusted. The pipe was reloaded until it reached 32.0 degrees of joint rotation. The test was then stopped, and the pipe was unloaded. There was a residual joint rotation of 27.8 degrees after unloading. A photograph of the 6-in. (150-mm) bending specimen T1 after the test is shown in Figure 2.8. Substantial spigot deformation was observed after the test. Further investigation after taking the joint apart shows that the pipe broke at the crown of the spigot, corresponding with the rapid drop in moment during the first part of the test.

The test results show that the Kubota ERDIP 6-in. (150-mm) specimen accommodated more than 8 degrees of joint rotation and exceeded 12 degrees without leakage. The estimated leakage between 12.2 and 16.6 degrees of joint rotation varied from a minimum of 0.1 gal/min (0.4 l/min) to a maximum of 7 gal/min (26.5 l/min).

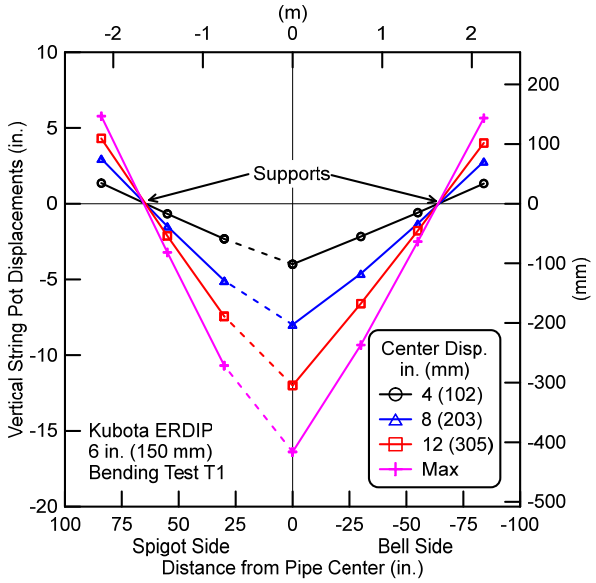


Figure 2.5. VSP Measurements for 6-in. (150-mm) ERDIP Bending Test T1

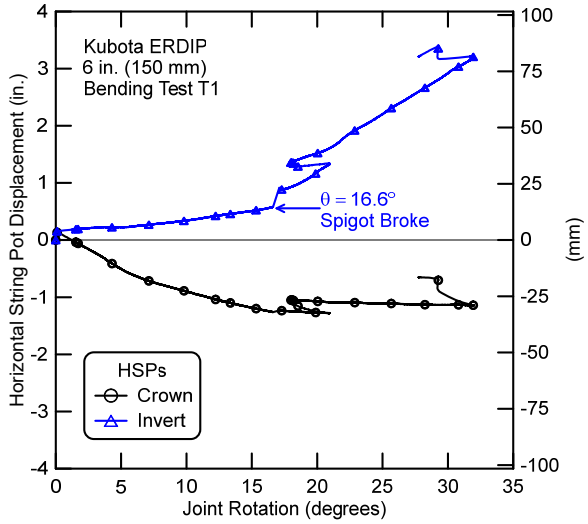


Figure 2.6. HSP Measurements vs. Rotation for 6-in. (150-mm) ERDIP Bending Test T1

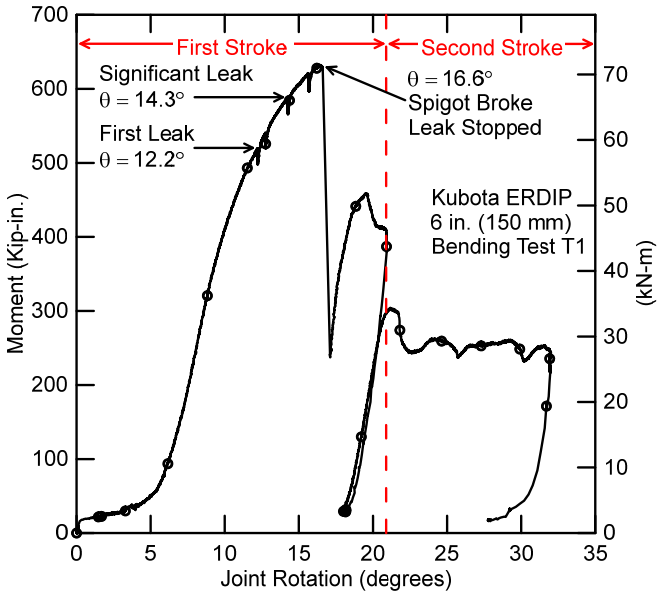


Figure 2.7. Moment vs. Rotation for 6-in. (150-mm) ERDIP Bending Test T1

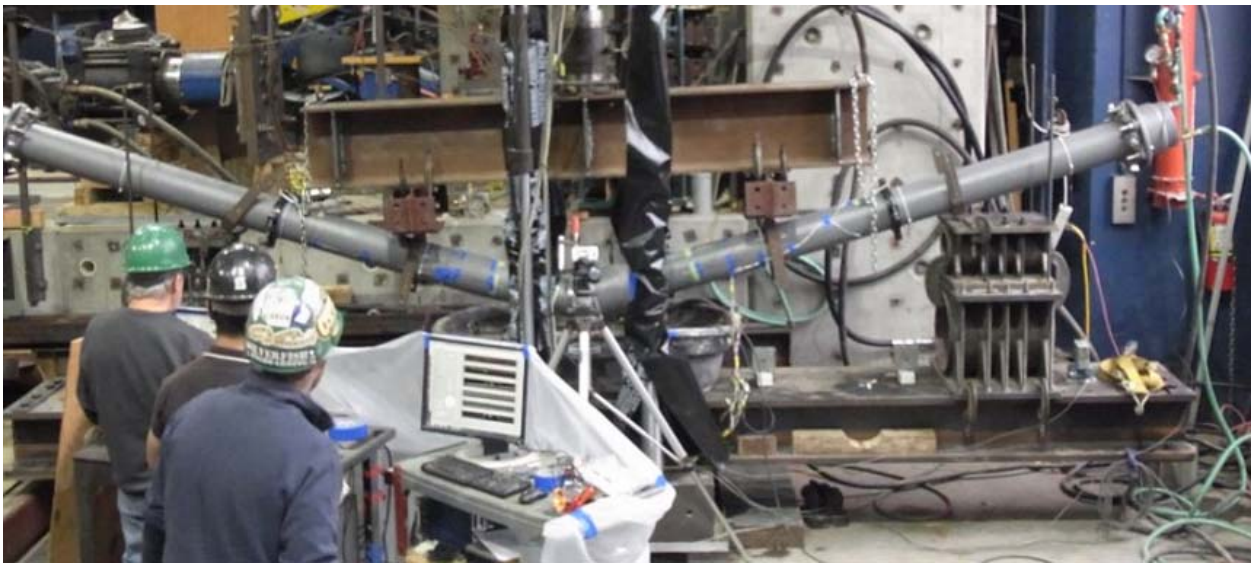


Figure 2.8. Photo of 6-in. (150-mm) ERDIP Bending Specimen T1 after Testing

2.5.5 Strains

Figure 2.9 shows the bell and spigot axial strains measured by strain gages in the central portion vs. joint rotation for the 6-in. (150-mm) specimen T1. The locations of the strain gages are shown in Figure 2.3. Based on tensile coupon tests performed at Cornell University (2016), the proportional strain limit of the ductile iron is 0.12% at a corresponding stress of 29.7 ksi (205 MPa), and the yield strain limit is 0.35% at a yield strength of 39.3 ksi (271 MPa), which is determined by the 0.2% strain offset method (ASTM, 2013). The spigot invert strain first reached the proportional and yield strain limits at 7.6 and 11.5 degrees of joint rotation, respectively. The strain measurements show that Kubota ERDIP 6-in. (150-mm) specimen accommodated rotation exceeding the ductile iron proportional and yield limits before first leakage at a joint rotation of 12.2 degrees.

2.6. Nominal 12-in. (300-mm) ERDIP T2

2.6.1. Instrumentation

Figure 2.10 shows a cross-section of the 12-in. (300-mm) ERDIP bending test T2. The test setup was similar to that for the 6-in. (150-mm) specimen T1. The differences are that the bell section and pressure gage station were moved to the north end, and the loading points were relocated for

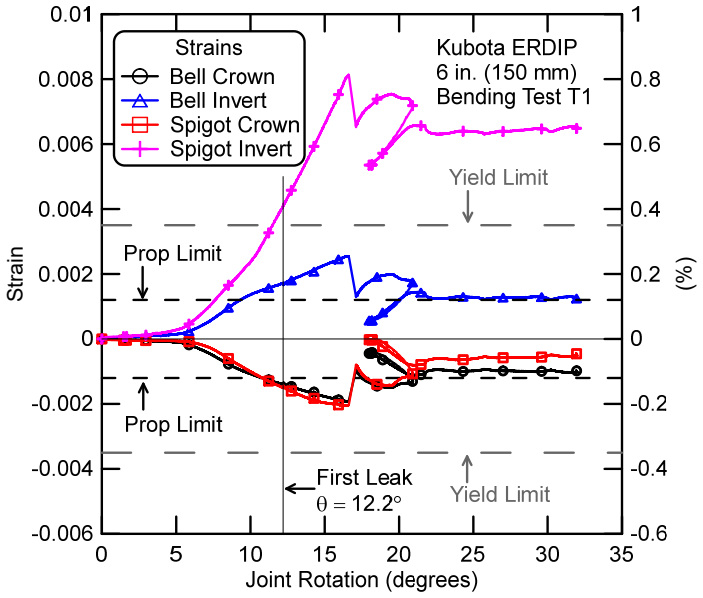


Figure 2.9. Axial Strains in Central Portion for 6-in. (150-mm) ERDIP Bending Test T1

the 12-in. (300-mm) specimen T2. Figure 2.11 provides a photo of the test setup. Table 2.2 lists location, instrument type, and instrument designation.

2.6.2. Pressure

The specimen was initially set up at a fully inserted position. It was then slowly pressurized with water to approximately 85 psi (590 kPa), while allowing the joint to extend fully in response to axial forces on the end caps. Figure 2.12 shows internal pressure vs. joint rotation. During the initial application of load to approximately 1 degree, internal pressure levels increased in response to volume reduction in the pipe. Thereafter internal pressure was adjusted continuously to maintain a nearly constant pressure until approximately 12.4 degrees, when the internal pressure dropped to 60 psi (410 kPa). The pressure recovered to 80 psi (550 kPa) for a short period and dropped again to about 40 psi (280 kPa) at a joint rotation of 13.5 degrees. However, the pressure immediately returned and stabilized at 80 psi (550 kPa). These two drops in pressure correspond to decreases in applied moment and represent abrupt changes in internal volume due to cracking of the spigot (as discussed in section 2.6.4). No leakage was observed during this event. The test was stopped when the joint reached 20.5 degrees of rotation. The first leakage was observed at 19.3 degrees of joint rotation while the pipe was being unloaded. The pressure was lowered and increased again to ensure that there was continuous leakage in the system. The leakage rate was

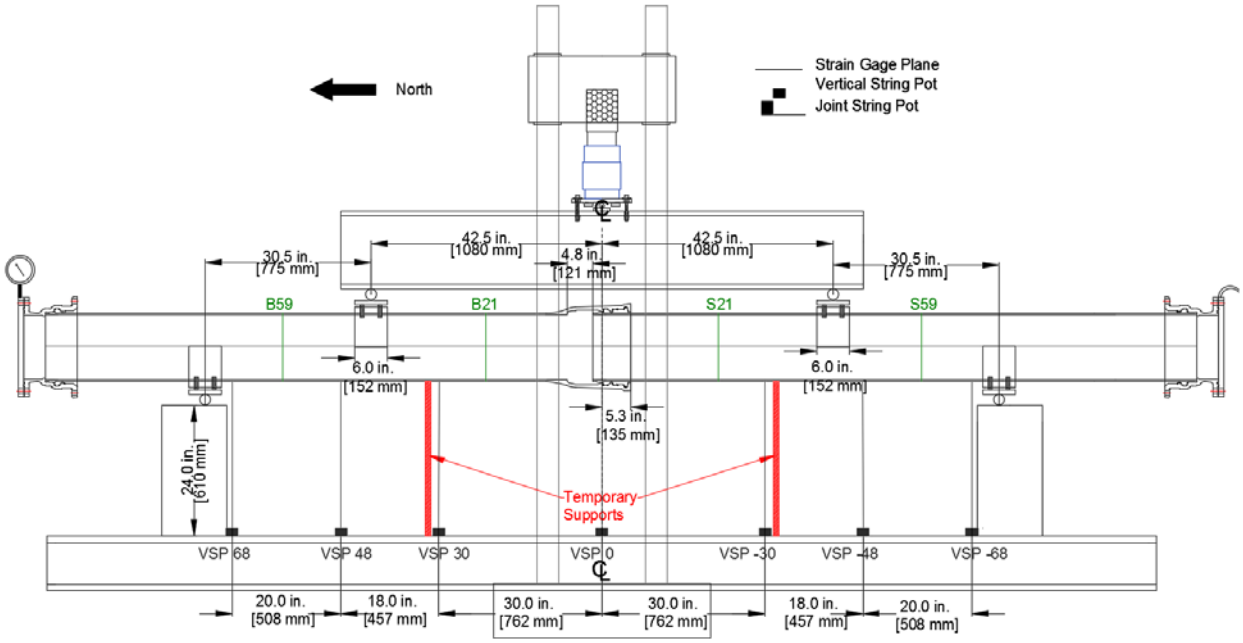


Figure 2.10. Cross-section of Instrumentation for 12-in. (300-mm) ERDIP Bending Test T2

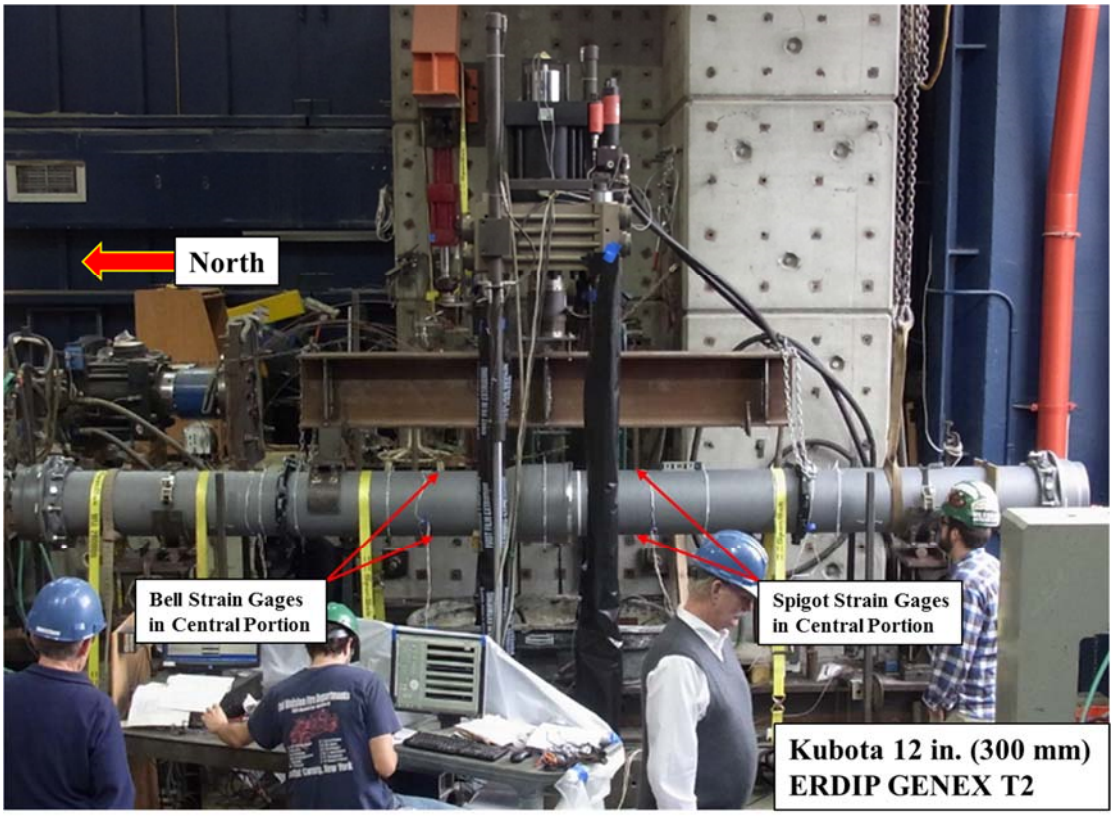


Figure 2.11. Photo of 12-in. (300-mm) ERDIP Bending Specimen T2 before Testing

Table 2.2. Instrumentation for 12-in. (300-mm) ERDIP Bending Test T2

Location	Instrument Description	Instrument Designation
-68 in. from Centerline	Vertical String Pot on Bell End	VSP-68
-48 in. from Centerline	Vertical String Pot on Bell End	VSP-48
-30 in. from Centerline	Vertical String Pot on Bell End	VSP-30
0 in. from Centerline	Vertical String Pot on Bell End	VSP 0
30 in. from Centerline	Vertical String Pot on Spigot End	VSP 30
48 in. from Centerline	Vertical String Pot on Spigot End	VSP 48
68 in. from Centerline	Vertical String Pot on Spigot End	VSP 68
5 in. from Centerline	Horizontal String Pot at Crown	HSP_C
5 in. from Centerline	Horizontal String Pot at Invert	HSP_I
-59 in. from Centerline	Axial Gage at Invert on Bell End	S59I
-59 in. from Centerline	Axial Gage at Crown on Bell End	S59C
-21 in. from Centerline	Axial Gage at Invert on Bell End	S21I
-21 in. from Centerline	Axial Gage at Crown on Bell End	S21C
21 in. from Centerline	Axial Gage at Invert on Spigot End	B21I
21 in. from Centerline	Axial Gage at Crown on Spigot End	B21C
59 in. from Centerline	Axial Gage at Invert on Spigot End	B59I
59 in. from Centerline	Axial Gage at Crown on Spigot End	B59C
Top Center	Load Cell	Load
North End Cap	Pressure Gage	Pressure

1 in. = 25.4 mm

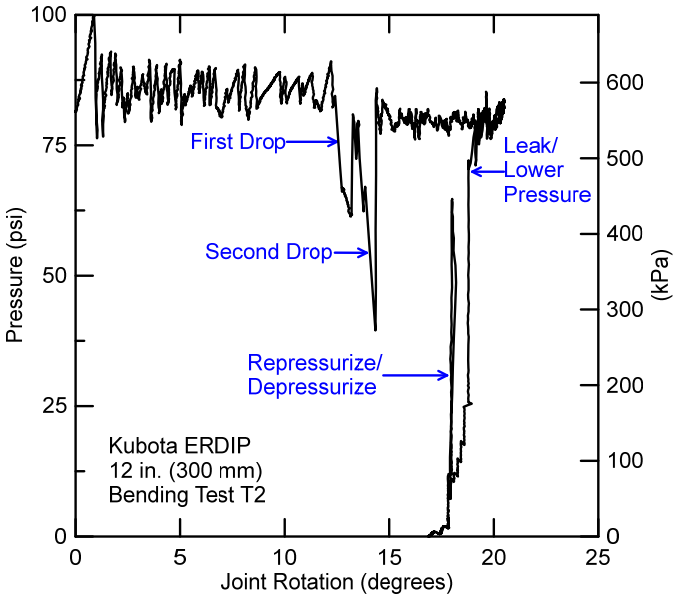


Figure 2.12. Internal Pressure vs. Joint Rotation for 12-in. (300-mm) ERDIP Bending Test T2

more than 10 gal/min (38 l/min), and the pipe was subsequently depressurized at 18.0 degrees of joint rotation.

2.6.3. String Pot Measurements

The VSP measurements on the pipe sections are shown in Figure 2.13. The spigot and bell side VSP measurements indicate that there is good agreement between vertical movement measurements at equal distances from the center point of the test.

Figure 2.14 shows the HSP measurements vs. rotation for the 12-in. (300-mm) specimen. During the initial part of the test, the invert HSP displaced less than the crown HSP did, indicating that the pivot point of the joint was at the invert. The bell lip then deformed at the crown, and the spigot was cracked at a rotation between 12.4 and 14.4 degrees, corresponding to a rapid increase at the invert HSP displacement. The pivot point then moved to the crown of the joint as indicated by the higher displacement rate at the invert HSP than the crown HSP.

2.6.4. Moment vs. Rotation

The moment vs. rotation test results are shown in Figure 2.15. The pipe reached a maximum moment of 1,560 kip-in. (176 kN-m) at a joint rotation at 12.4 degrees. The moment rapidly dropped to approximately 1,250 kip-in. (141 kN-m) and again to 480 kip-in. (54 kN-m) associated with cracking of the spigot. The test was continued until the pipe reached 20.5 degrees of joint rotation without leakage when the actuator reached the limit of its stroke. While the pipe was being unloaded, the first leakage of more than 10 gal/min (38 l/min) occurred at 19.3 degrees of joint rotation. There was a residual joint rotation of 16.8 degrees after unloading. A photograph of the bending specimen T2 after the test is shown in Figure 2.16. Further investigation after taking the joint apart shows that the pipe broke at the crown of the spigot corresponding to the rotations at which there was a rapid drop in moment. The test results show that the Kubota ERDIP 12-in. (300-mm) specimen accommodated more than 8 degrees of joint rotation without leakage. No leakage in fact was observed during loading of the pipe specimen to a rotation of 20.5 degrees.

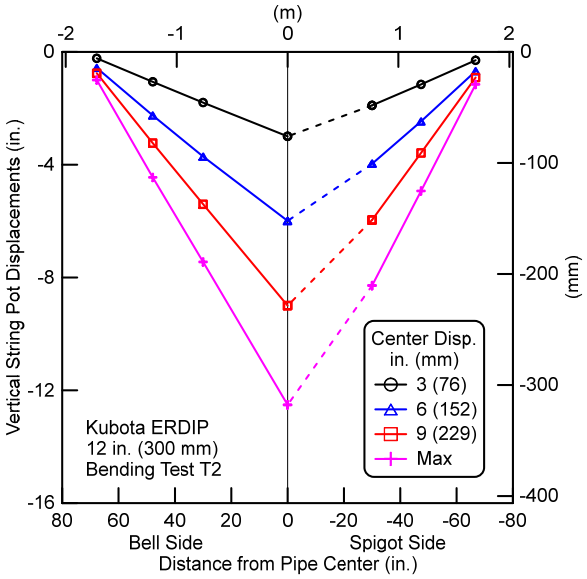


Figure 2.13. VSP Measurements for 12-in. (300-mm) ERDIP Bending Test T2

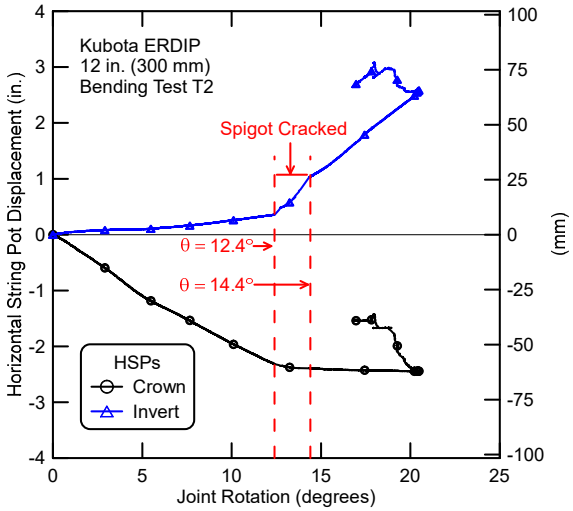


Figure 2.14. HSP Measurements vs. Rotation for 12-in. (300-mm) ERDIP Bending Test T2

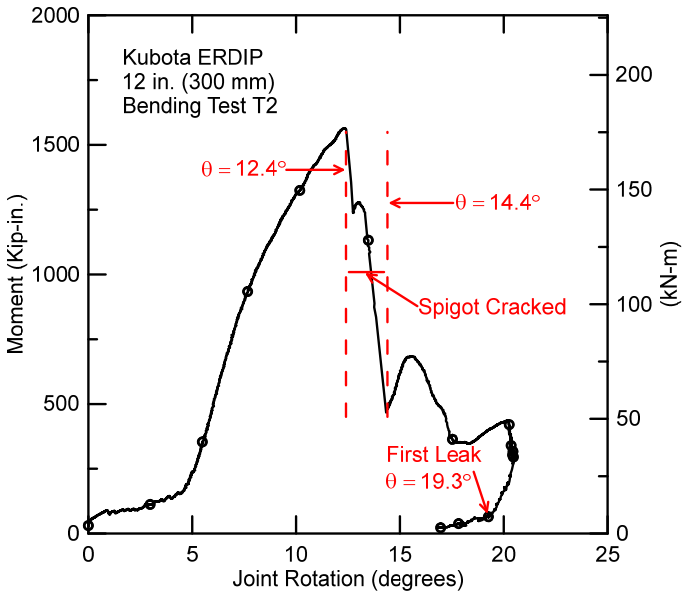


Figure 2.15. Moment vs. Rotation for 12-in. (300-mm) ERDIP Bending Test T2

Figure 2.16. Photo of 12-in. (300-mm) ERDIP Bending Specimen T2 after Testing

2.6.5 Strains

Figure 2.17 shows the bell and spigot axial strains measured by strain gages in the central portion of the test specimen T2 vs. joint rotation. The locations of the strain gages are shown in Figure 2.11. The spigot invert strain first reached the proportional (Cornell, 2016) and yield (ASTM, 2013) strain limits of the ductile iron at 7.3 and 11.5 degrees of joint rotation, respectively. The strain measurements show that Kubota ERDIP 12-in. (300-mm) specimen can accommodate rotation without breaking or leakage that exceeds the proportional and yield limits of the ductile iron pipe.

2.7. Nominal 16-in. (400-mm) ERDIP T3

2.7.1. Instrumentation

Figure 2.18 shows a cross-section of the first 16-in. (400-mm) ERDIP bending test, T3. The test setup was similar to that for the 12-in. (300-mm) specimen, although some VSPs were relocated so that they were closer to the loading points. Figure 2.19 provides a photo of the test setup. Table 2.3 lists location, instrument type, and instrument designation.

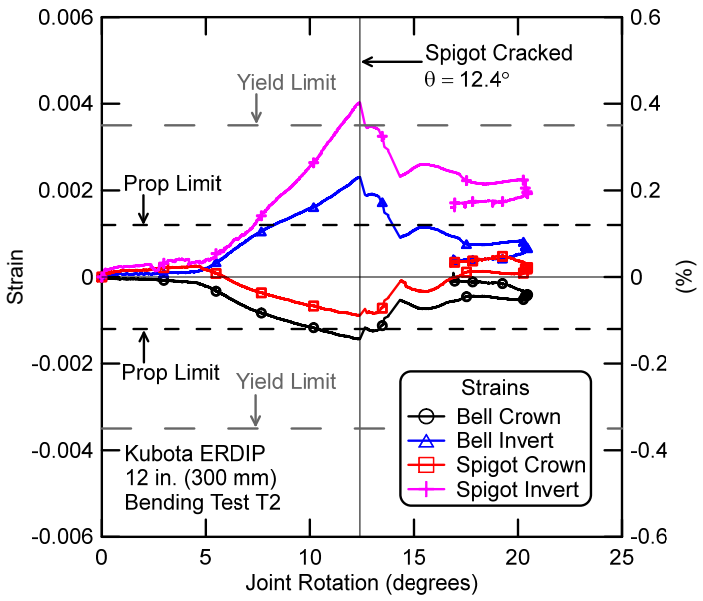


Figure 2.17. Axial Strains in Central Portion for 12-in. (300-mm) ERDIP Bending Test T2

2.7.2. Pressure

The specimen was initially set up at a fully inserted position. It was then slowly pressurized with water to approximately 85 psi (590 kPa) while allowing the joint to extend fully in response to axial forces on the end caps. Figure 2.20 shows internal pressure vs. joint rotation. Internal pressure was manually adjusted to maintain a nearly constant pressure during the test. The pressure dropped to 25 psi (170 kPa) when first leakage of approximately 0.7 gal/min (2.6 l/min) occurred at 17.5 degrees of rotation. When attempts were made to repressurize the pipe, additional leakage was observed at the crown of the spigot. The pressure fell again to approximately 17 psi (120 kPa), and significant leakage of at least 8.3 gal/min (31 l/min) was observed. The test was continued at an internal pressure of 80 psi (550 kPa) until 18.9 degrees of rotation, when the pipe suddenly broke with an attendant loss of pressure, indicating structural failure.

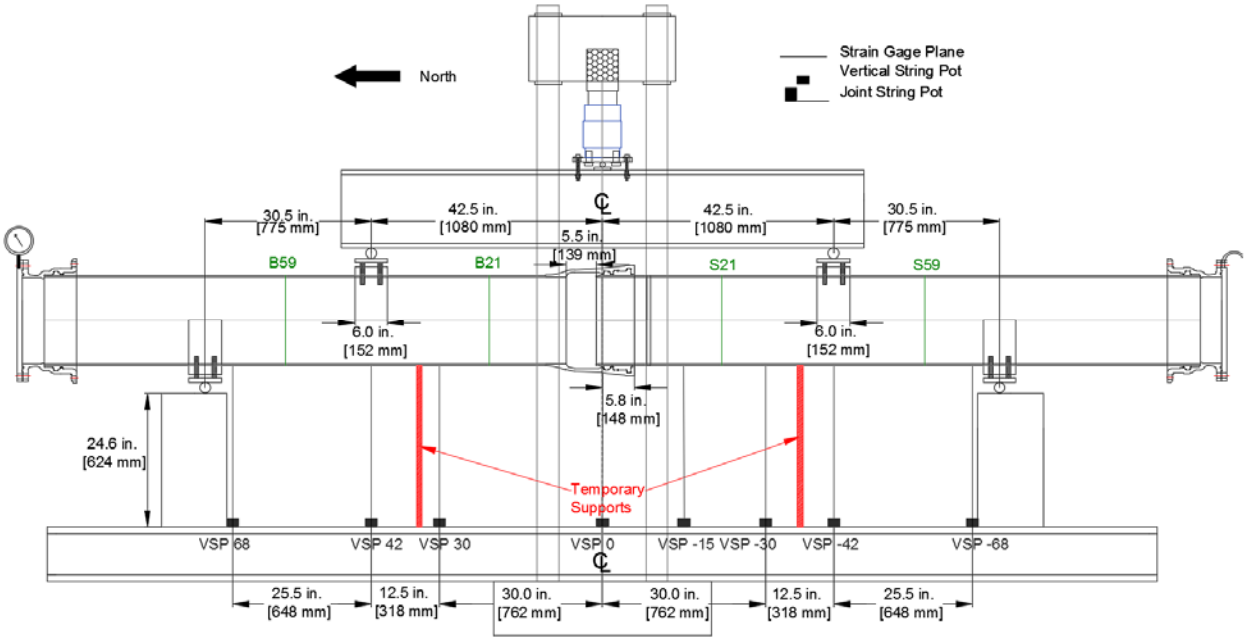


Figure 2.18. Cross-section of Instrumentation for 16-in. (400-mm) ERDIP Bending Test T3

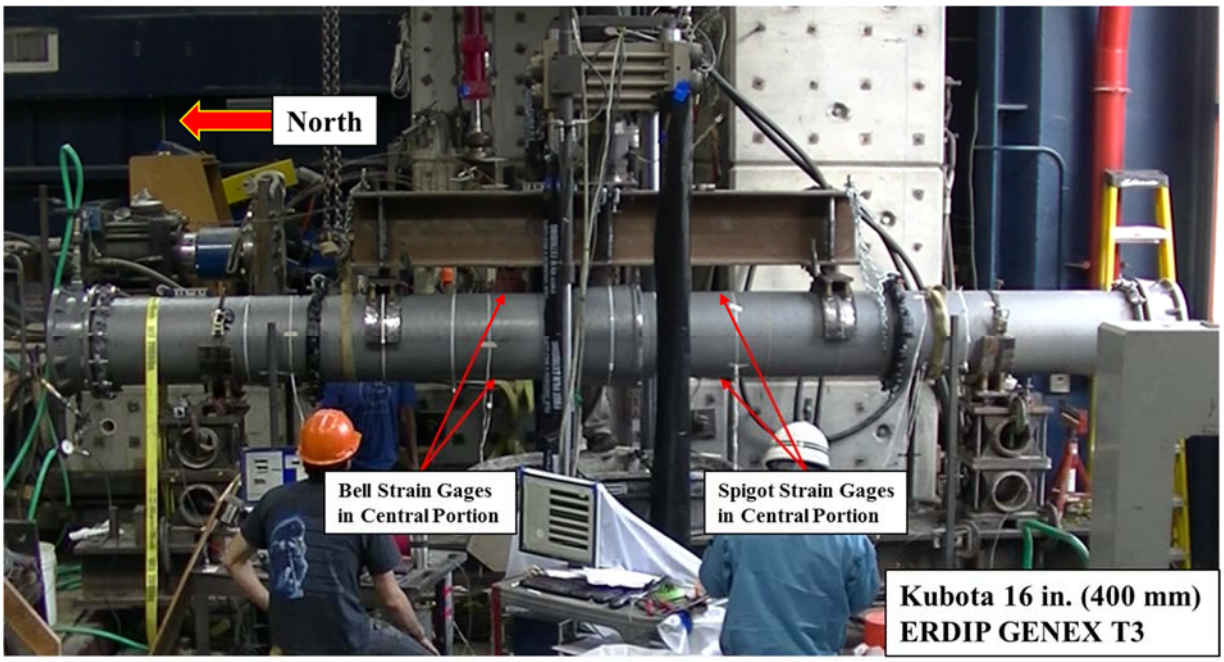


Figure 2.19. Photo of 16-in. (400-mm) ERDIP Bending Specimen T3 before Testing

Table 2.3. Instrumentation for 16-in. (400-mm) ERDIP Bending Test T3

Location	Instrument Description	Instrument Designation
-68 in. from Centerline	Vertical String Pot on Bell End	VSP-68
-42 in. from Centerline	Vertical String Pot on Bell End	VSP-42
-30 in. from Centerline	Vertical String Pot on Bell End	VSP-30
0 in. from Centerline	Vertical String Pot on Bell End	VSP 0
30 in. from Centerline	Vertical String Pot on Spigot End	VSP 30
42 in. from Centerline	Vertical String Pot on Spigot End	VSP 42
68 in. from Centerline	Vertical String Pot on Spigot End	VSP 68
6 in. from Centerline	Horizontal String Pot at Crown	HSP_C
6 in. from Centerline	Horizontal String Pot at Invert	HSP_I
-59 in. from Centerline	Axial Gage at Invert on Bell End	S59I
-59 in. from Centerline	Axial Gage at Crown on Bell End	S59C
-21 in. from Centerline	Axial Gage at Invert on Bell End	S21I
-21 in. from Centerline	Axial Gage at Crown on Bell End	S21C
21 in. from Centerline	Axial Gage at Invert on Spigot End	B21I
21 in. from Centerline	Axial Gage at Crown on Spigot End	B21C
59 in. from Centerline	Axial Gage at Invert on Spigot End	B59I
59 in. from Centerline	Axial Gage at Crown on Spigot End	B59C
Top Center	Load Cell	Load
North End Cap	Pressure Gage	Pressure

1 in. = 25.4 mm

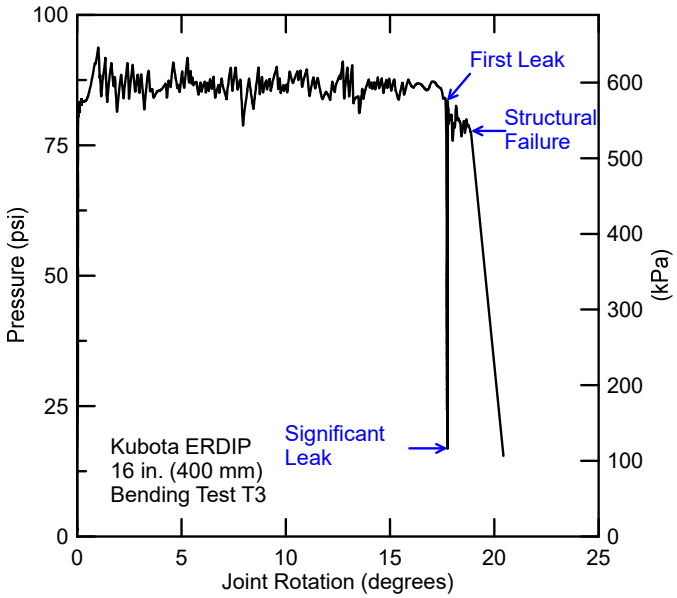


Figure 2.20. Internal Pressure vs. Joint Rotation for 16-in. (400-mm) ERDIP Bending Test T3

2.7.3. String Pot Measurements

The VSP measurements on the pipe sections are shown in Figure 2.21. The spigot and bell side VSP measurements indicate that there is good agreement between vertical movement measurements at equal distances from the center point of the test.

Figure 2.22 shows the HSP measurements vs. rotation. During the initial part of the test, the invert HSP displaced less than the crown HSP, indicating that the pivot point of the joint was at the invert. The spigot was in full contact with the bell when the crown HSP displacement began to flatten at about 16.5 degrees of joint rotation. At 18.9 degrees of rotation, the pipe failed, corresponding to a rapid increase of the invert HSP displacement.

2.7.4. Moment vs. Rotation

The moment vs. rotation relationship is shown in Figure 2.23. First leakage of approximately 0.7 gal/min (2.6 l/min) was observed at a maximum moment 2,700 kip-in. (305 kN-m) and associated joint rotation of 17.5 degrees. The test was paused, and the moment dropped slightly to 2,500 kip-in. (282 kN-m). As explained previously, the pressure was lowered and then raised back to 80 psi (550 kPa). At this point, another leak occurred at the crown of the spigot, resulting significant outflow of at least 8.3 gal/min (31 l/min) from the pipe. The test was continued, and at 18.9 degrees of rotation, the pipe broke and the moment dropped rapidly from 2,420 to 307 kip-in. (273 to 34.7 kN-m). A photograph of the bending specimen after the test is shown in Figure 2.24. Further investigation after taking the joint apart revealed that the pipe broke at the crown of the spigot, corresponding to leakage observed at the crown. The test results show that the Kubota ERDIP 16-in. (400-mm) specimen T3 accommodated more than 8 degrees of joint rotation, attaining a maximum rotation without leakage of 17.5 degrees.

2.7.5 Strains

Figure 2.25 shows the bell and spigot axial strains measured by strain gages in the central portion of the pipe vs. joint rotation. The locations of the gages are shown in Figure 2.19. The spigot invert strain first reached the proportional (Cornell, 2016) and yield strain (ASTM, 2013) limits at 9.3 and 14.8 degrees of joint rotation, respectively. The results show that the Kubota ERDIP 16-in. (400-mm) specimen T3 accommodated rotation exceeding the proportional and yield strain limits before the first leakage was observed at 17.5 degrees of rotation.

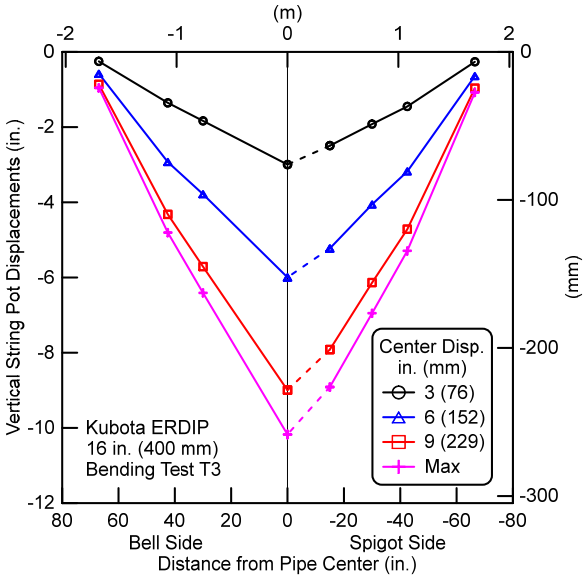


Figure 2.21. VSP Measurements for 16-in. (400-mm) ERDIP Bending Test T3

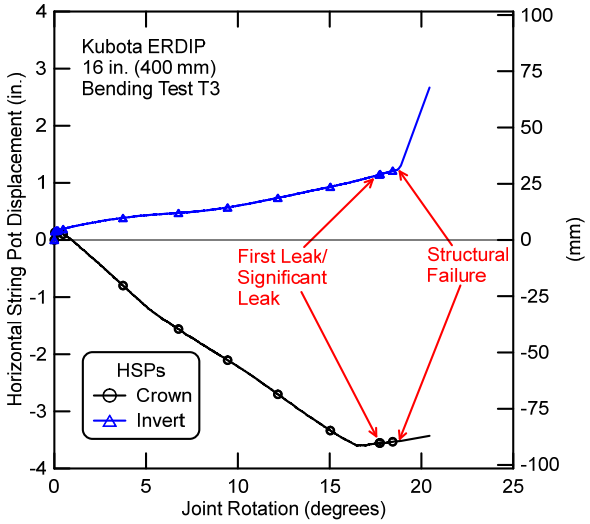


Figure 2.22. HSP Measurements vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T3

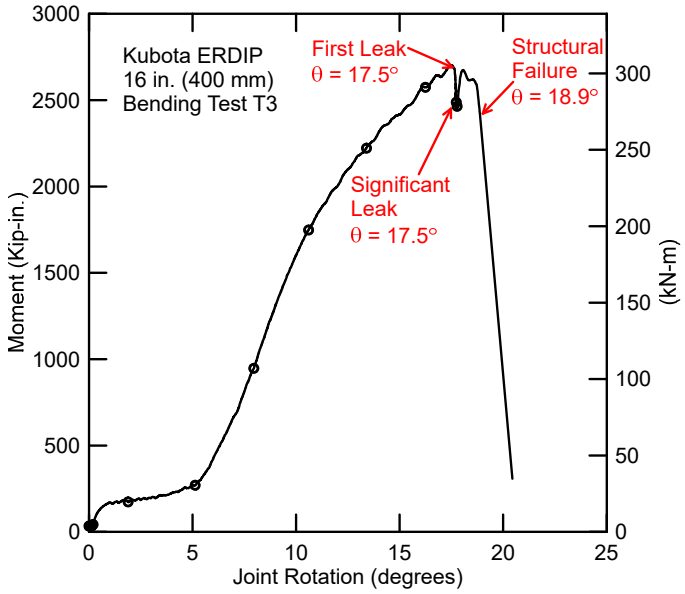


Figure 2.23. Moment vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T3

Figure 2.24. Photo of 16-in. (400-mm) ERDIP Bending Specimen T3 after Testing

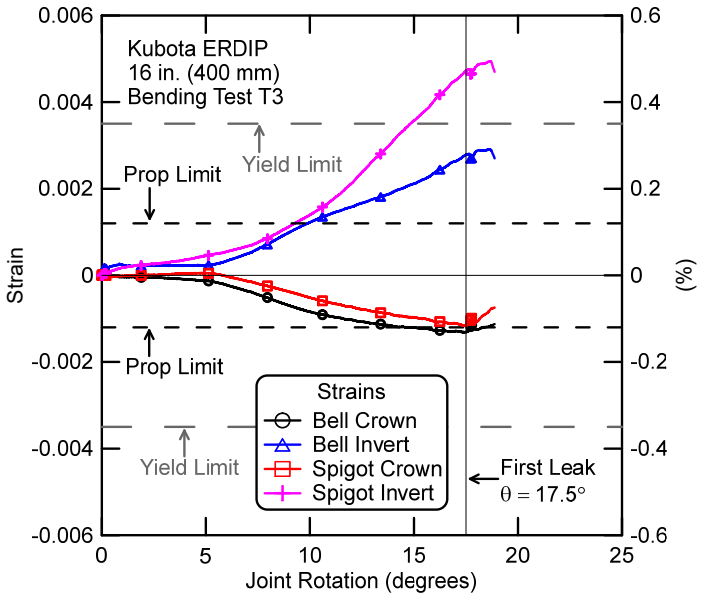


Figure 2.25. Axial Strains in Central Portion for 16-in. (400-mm) ERDIP Bending Test T3

2.8. Nominal 16-in. (400-mm) ERDIP T4

2.8.1. Testing Procedures for 16-in. (400-mm) T4 ERDIP

The second bending test of a nominal 16-in. (400-mm)-diameter specimen was performed as follows:

1) Install the pipe joint at the neutral position, referring as a location that allows 3.0 in. (75 mm) displacement for both tension and compression before internal contact in the pipe joint.
2) Level the pipe in the loading frame
3) Check all instrumentation and data acquisitions systems.
4) Begin data acquisition
5) Fill the pipe with water and bleed air from the system.
6) Remove the temporary supports and lower the spreader beam onto the pipe.
7) Apply the hydraulic actuator force to develop moment and rotation at the joint until 8 degrees of rotation is achieved.
8) Pressurize the pipe to 80 psi (550 kPa)
9) Apply hydraulic actuator force on the pipe until structural failure.

2.8.2. Instrumentation

Figure 2.26 shows a cross-section of the second 16-in. (400-mm) ERDIP T4 bending test. The test setup was similar to that for the first 16-in. (400-mm) specimen. Figure 2.27 shows the test setup before testing. Table 2.4 lists location, instrument type, and instrument designation.

2.8.3. Pressure

Figure 2.28 shows internal pressure vs. joint rotation. The specimen was set up at a neutral position and filled with water prior to the test. The pipe was not pressurized during the first 8 degrees of joint rotation. When the pipe reached 8 degrees, the pressure was raised to 80 psi (550 kPa). Internal pressure was manually adjusted to maintain a nearly constant pressure during the test. The pressure fluctuations at 14.4, 14.8, and 16.1 degrees of rotation, identified in the figure, were caused by abrupt changes in volume due to cracking of the spigot. First leakage of approximately 0.05 gal/min (0.19 l/min) occurred at 17.3 degrees of rotation. Significant leakage in excess of 15 gal/min (57 l/min) immediately occurred at a joint rotation of 20.7 degrees. The pipe was then depressurized.

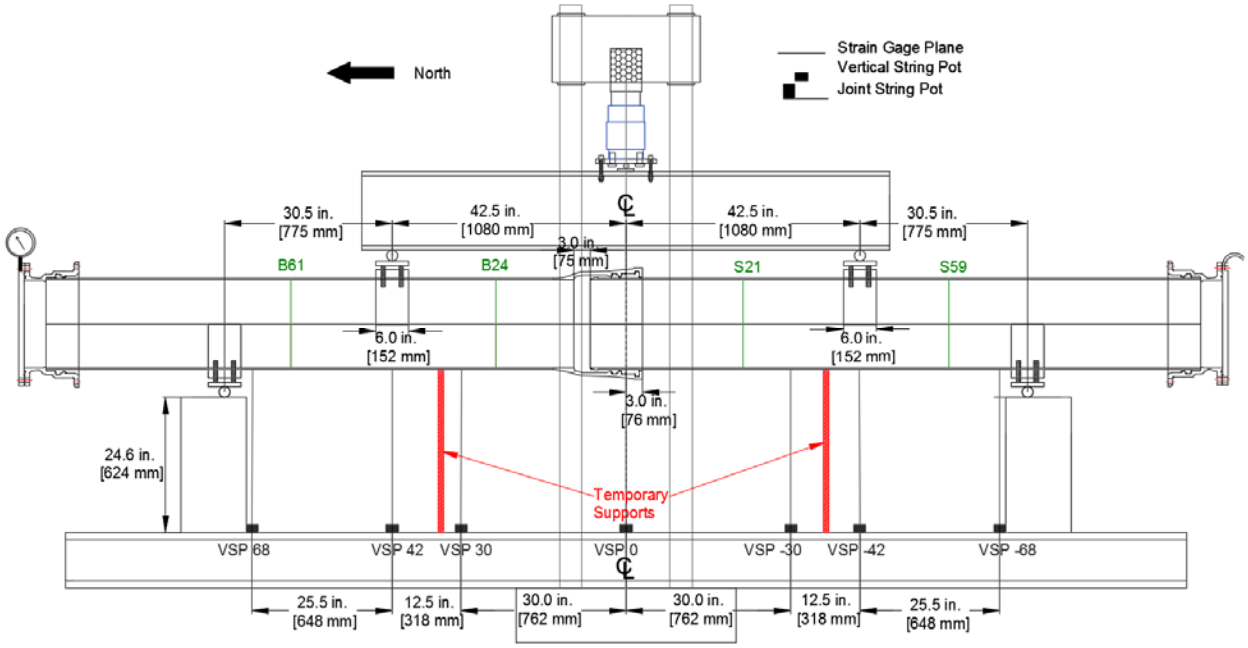


Figure 2.26. Cross-section of Instrumentation for 16-in. (400-mm) ERDIP Bending Test T4

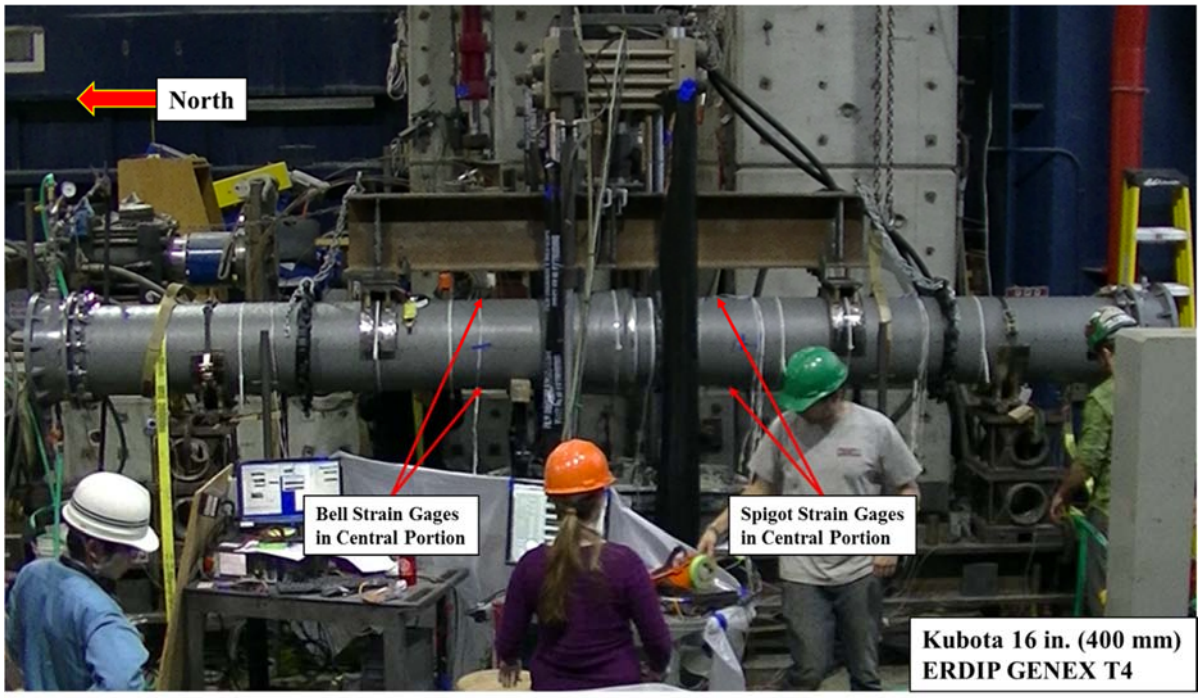


Figure 2.27. Photo of 16-in. (400-mm) ERDIP Bending Specimen T4 before Testing

Table 2.4. Instrumentation for 16-in. (400-mm) ERDIP Bending Test T4

Location	Instrument Description	Instrument Designation
-68 in. from Centerline	Vertical String Pot on Bell End	VSP-68
-42 in. from Centerline	Vertical String Pot on Bell End	VSP-42
-30 in. from Centerline	Vertical String Pot on Bell End	VSP-30
0 in. from Centerline	Vertical String Pot on Bell End	VSP 0
30 in. from Centerline	Vertical String Pot on Spigot End	VSP 30
42 in. from Centerline	Vertical String Pot on Spigot End	VSP 42
68 in. from Centerline	Vertical String Pot on Spigot End	VSP 68
3 in. from Centerline	Horizontal String Pot at Crown	HSP_C
3 in. from Centerline	Horizontal String Pot at Invert	HSP_I
-59 in. from Centerline	Axial Gage at Invert on Bell End	S59I
-59 in. from Centerline	Axial Gage at Crown on Bell End	S59C
-21 in. from Centerline	Axial Gage at Invert on Bell End	S21I
-21 in. from Centerline	Axial Gage at Crown on Bell End	S21C
24 in. from Centerline	Axial Gage at Invert on Spigot End	B24I
24 in. from Centerline	Axial Gage at Crown on Spigot End	B24C
61 in. from Centerline	Axial Gage at Invert on Spigot End	B61I
61 in. from Centerline	Axial Gage at Crown on Spigot End	B61C
Top Center	Load Cell	Load
North End Cap	Pressure Gage	Pressure

1 in. = 25.4 mm

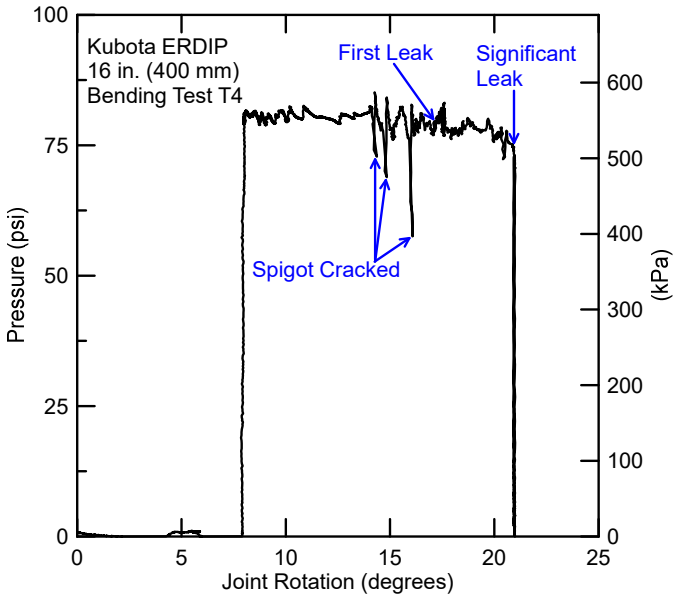


Figure 2.28. Internal Pressure vs. Joint Rotation for 16-in. (400-mm) ERDIP Bending Test T4

2.8.4. String Pot Measurements

The VSP measurements on the pipe sections are shown in Figure 2.29. The spigot and bell side VSP measurements indicate that there is good agreement between vertical movement measurements at equal distances from the center point of the test.

Figure 2.30 shows the HSP measurements vs. rotation. There was an initial horizontal displacement of 0.85 in. (22 mm), corresponding to the release of the central supports in the four-point bending test setup. Rotation of the joint to 5.6 degrees was measured under the pipe weight plus water. The spreader beam weight and hydraulic actuator force were applied until a joint rotation of 8 degrees was achieved. When the pipe specimen was pressurized to 80 psi (550 kPa), no additional joint opening was observed. Additional force was applied to the pipe until first leakage of 0.05 gal/min (0.19 l/min) and significant leakage of 15 gal/min (57 l/min) were observed at 17.3 and 20.7 degrees of rotation, respectively.

2.8.5. Moment vs. Rotation

The moment vs. rotation relationship is shown in Figure 2.31. The weight of the pipe plus water caused a joint rotation of 5.6 degrees. Additional moment was applied until the pipe reached 8 degrees of rotation at 358 kip-in. (40.5 kN-m). The test was paused, and the pipe was pressurized to 80 psi (550 kPa). There was no joint displacement during pressurization. The test was then continued. After a maximum applied moment of 2,400 kip-in. (271 kN-m) at a joint rotation of 13.6 degrees, the moment steadily decreased. The first leakage of about 0.05 gal/min (0.19 l/min) was observed at a moment of 1,580 kip-in. (178 kN-m) and a joint rotation of 17.3 degrees. The pipe continued to leak until significant leakage exceeding 15 gal/min (57 l/min) immediately occurred at a moment of 563 kip-in. (63.5 kN-m) and a joint rotation of 20.7 degrees. A photograph of the 16-in. (400-mm) ERDIP T2 bending specimen after the test is shown in Figure 2.32. Further investigation after taking the joint apart shows that the pipe fractured at the crown of the spigot, corresponding to the drop in moment shown in Figure 2.31. The test results show that Kubota ERDIP 16-in. (400-mm) specimen T4 accommodated more than 8 degrees of joint rotation and sustained a maximum rotation of 17.3 degrees without leakage.

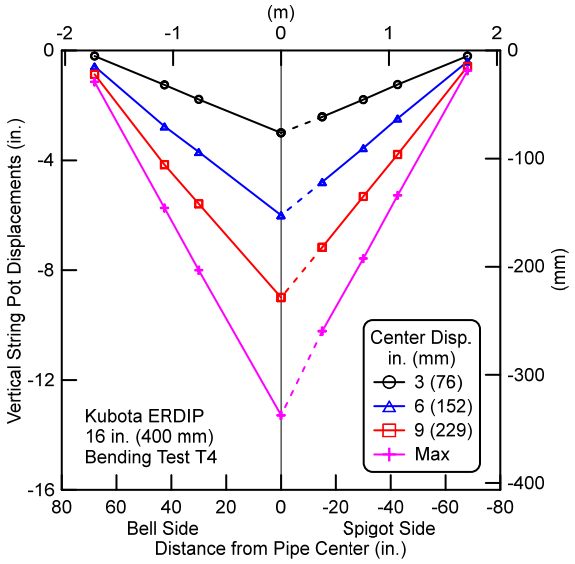


Figure 2.29. VSP Measurements for 16-in. (400-mm) ERDIP Bending Test T4

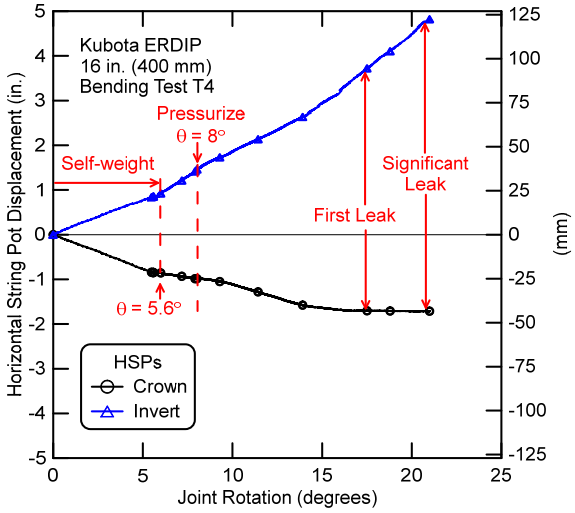


Figure 2.30. HSP Measurements vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T4

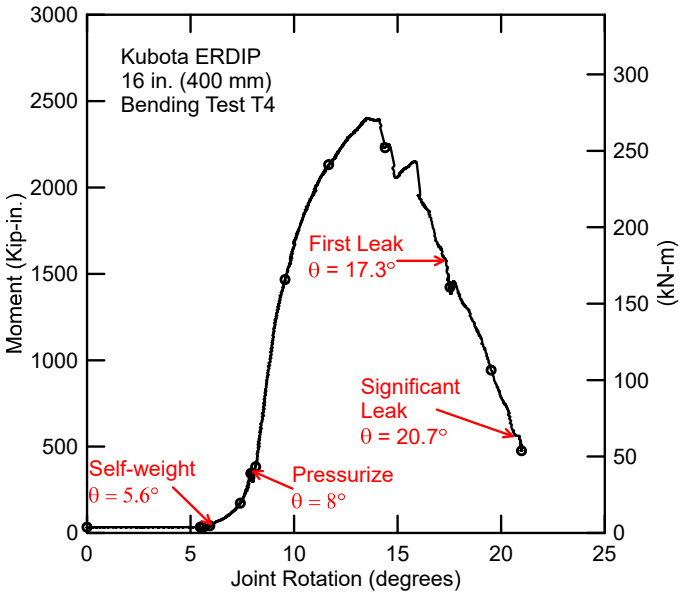


Figure 2.31. Moment vs. Rotation for 16-in. (400-mm) ERDIP Bending Test T4

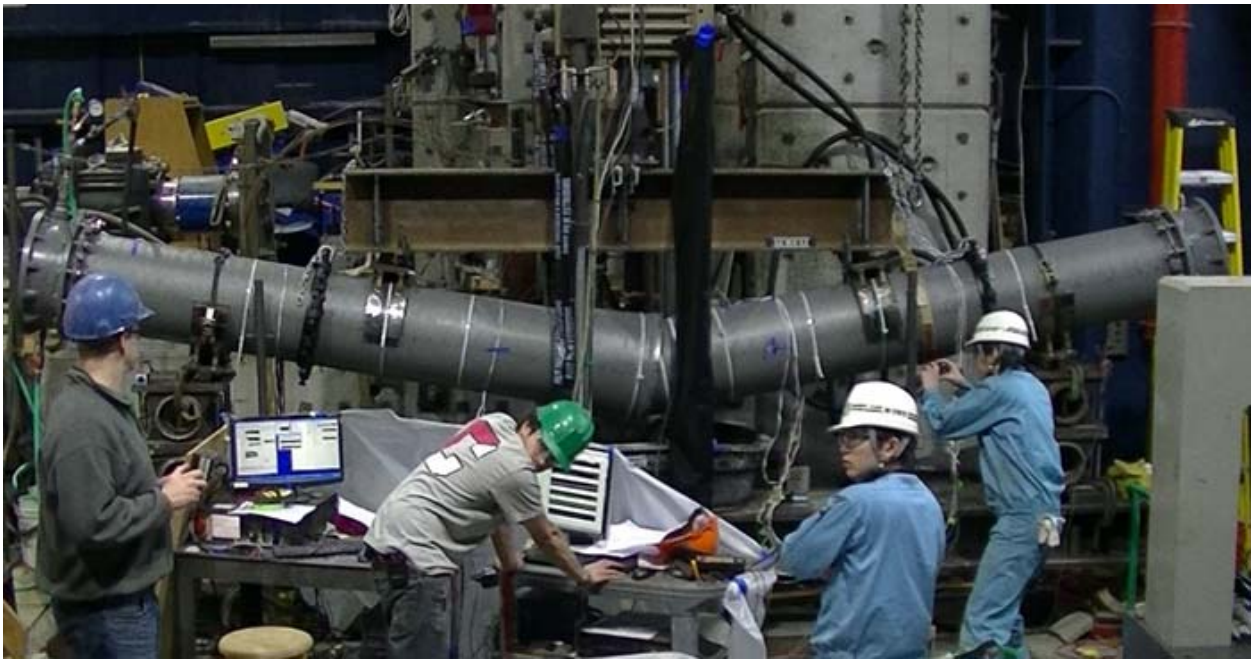


Figure 2.32. Photo of 16-in. (400-mm) ERDIP Bending Specimen T4 after Testing

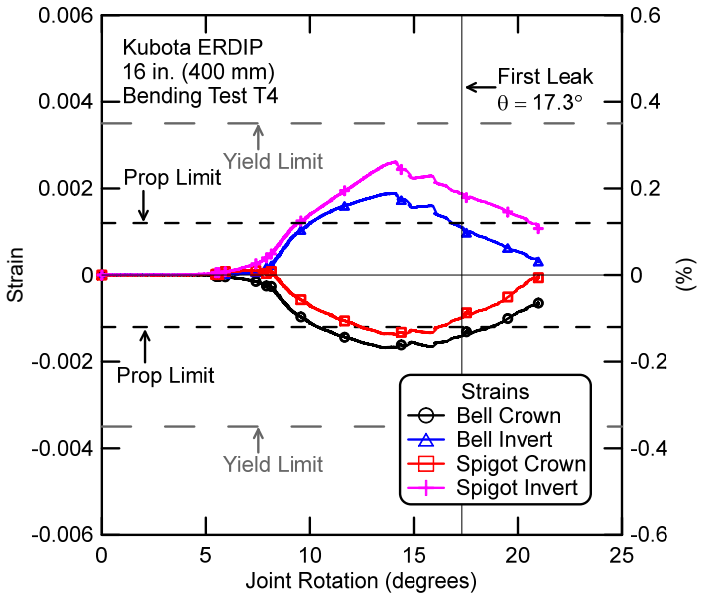


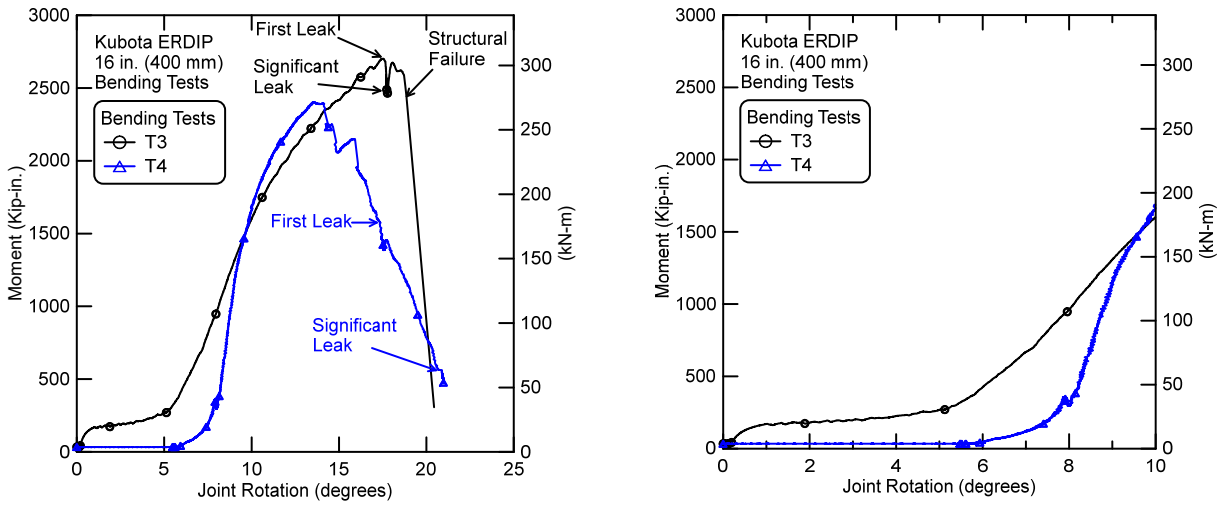
Figure 2.33. Axial Strains in Central Portion for 16-in. (400-mm) ERDIP Bending Test T4

2.8.6 Strains

Figure 2.33 shows the bell and spigot axial strains measured by strain gages in the central portion of the test specimen T4 vs. joint rotation. The locations of the strain gages are shown in Figure 2.27. The spigot invert strain first exceeded the proportional strain limit (Cornell, 2016) at a joint rotation of 9.5 degrees. However, no strains reached the yield limit (ASTM, 2010) during this test. The strain measurements show that the Kubota ERDIP 16-in. (400-mm) specimen T4 was able to accommodate rotation at strains exceeding the proportional limit before first leakage was observed at 17.3 degrees of rotation.

2.9. Comparisons of Nominal 16-in. (400-mm) ERDIP T3 and T4

The moment vs. rotation comparisons for the 16-in. (400-mm) are shown in Figure 2.34. The rotational responses between specimens T3 and T4 are different. During the first 5 degrees of joint rotation, the unpressurized pipe, T4, rotated approximately 5 degrees under its own weight. In contrast, a moment of about 270 kip-in. (30.5 kN-m) was required to cause the same amount of rotation for the pressurized pipe, T3. The maximum moments of bending tests T3 and T4 were on the order of 2,500 kip-in. (282 kN-m). The first leakage of both tests was observed at approximately 17.5 degrees. Significant leakage from specimen T3 occurred during depressurization and repressurization immediately after first leakage occurred. Specimen T3 failure occurred when the moment dropped rapidly at 19 degrees. The specimen T4 moment declined steadily after the maximum moment had been achieved at 13.6 degrees of joint rotation. After the first leakage was observed, specimen T4 continued to leak and reached a state of significant leakage at a joint rotation of 20.7 degrees.



a) Full Rotation Range

b) Up to 10 degrees

Figure 2.34. Moment vs. Rotation Comparisons for 16-in. (400-mm) ERDIP Bending Tests

Section 3
Summary

Results are presented for pressurized four-point bending tests of nominal 6-in. (150-mm)-, 12-in. (300-mm)-, and two 16-in. (400-mm)-diameter sections of earthquake resistant ductile iron pipe (ERDIP), distributed under the commercial name of GENEX®. The purpose of the tests was to develop moment vs. rotation relationships for different sizes of ERDIPs and to characterize pipe joint performance with respect to leakage and structural integrity. An additional test was conducted to investigate the effect of pressurization on a 16-in. (400-mm)-diameter pipe specimen following an initial 8 degree-rotation under zero internal pressure.

Table 3.1 summarizes moment and rotation data for each test. The first leakage of about 0.1 gal/min (0.4 l/min) in the 6 in. (150 mm) pipe (T1) occurred at a rotation of 12.2 degrees and an applied moment of 520 kip-in. (58.8 kN-m). The leakage rate grew larger with increasing moment and joint rotation. At 14.3 degrees of joint rotation with an associated moment of 580 kip-in. (65.5 kN-m), the pipe experienced significant leakage on the order of 7 gal/min (26.5 l/min). Significant leakage in this report is defined as flow exceeding 7 gal/min (26.5 l/min), corresponding to 10,000 gal/day (38,000 l/day). Loading continued and reached the maximum moment of 630 kip-in. (71.2 kN-m) at a joint rotation of 16.6 degrees. At this point the moment dropped rapidly, and the leakage stopped. The test was continued until the pipe reached 20.9 degrees of joint rotation without additional leakage. The pipe was unloaded and reloaded. The test was stopped when the pipe reached a rotation of 32 degrees.

In the 12-in. (300-mm) bending test (T2), the pipe reached the maximum moment of 1,560 kip-in. (176 kN-m) at a joint rotation of 12.4 degrees. The test was continued until the pipe reached 20.5 degrees of joint rotation without leakage. The first leakage of approximately 8.3 gal/min (31 l/min) was observed at 19.3 degrees of joint rotation while the pipe was being unloaded.

Two bending tests, T3 and T4, were performed on 16-in. (400-mm) specimens. The pipe in Test T3 was pressurized throughout the test. The pipe in Test T4 was unpressurized until rotation reached 8 degrees. The pipe was then pressurized. The rotational response of specimens T3 and T4 varies. During the first 5 degrees of joint rotation, the unpressurized T4 pipe rotated to approximately 5 degrees under their own weights while a moment of about 270 kip-in. (30.5 kN-m) was required to cause the same amount of rotation for the pressurized T3 pipe.

Table 3.1. Results of Four-Point Bending Tests

Test	First Leakage		Maximum Moment		Maximum Rotation
	Rotation	Moment	Rotation	Moment	
6 in. (150 mm) T1[a]	12.2°	520 kip-in. (58.8 kN-m).	16.6°	630 kip-in. (71.2 kN-m)	32.2°
12 in. (300 mm) T2[b]	19.3°	64 kip-in (7.2 kN-m)	12.4°	1,560 kip-in. (176 kN-m)	20.5°
16 in. (400 mm) T3[c]	17.5°	2,700 kip-in. (305 kN-m)	17.5°	2,700 kip-in. (305 kN-m)	17.5°
16 in. (400 mm) T4[d]	17.3°	1,580 kip-in. (178 kN-m)	13.6°	2,400 kip-in. (271 kN-m)	20.7°

[a] Leakage stopped at 16.6°

[b] First leakage when unloading after maximum rotation

[c] Significant Leakage at 17.5° and structural failure at 18.9°

[d] First leakage found after maximum moment

Test T3 reached first leakage of approximately 0.7 gal/min (2.6 l/min) at a maximum moment of 2,700 kip-in. (305 kN-m) and corresponding joint rotation of 17.5 degrees. The test was paused, after which significant leakage on the order of 8.3 gal/min (31 l/min) occurred after lowering and raising internal pressure back to 80 psi (550 kPa). The test was continued until the spigot cracked at 18.9 degrees of joint rotation, resulting in a rapid drop in moment. Specimen T4 reached its maximum moment of 2,400 kip-in. (271 kN-m) at a joint rotation of 13.6 degrees without leakage, after which the moment declined steadily. First leakage of about 0.05 gal/min (0.19 l/min) was observed at a joint rotation of 17.3 degrees and applied moment of 1,580 kip-in. (178 kN-m). Significant leakage on the order of 15 gal/min (57 l/min) occurred suddenly at an applied moment of 563 kip-in. (63.5 kN-m) and a joint rotation of 20.7 degrees.

According to Kubota's guidelines, the maximum allowable deflection (rotation) of ERDIP for installation and seismic events are 6 and 8 degrees, respectively. The test results show that all sizes of the ERDIPs exceeded the allowable deflection and proportional limit without any leaks or pipe damage.

References

ASTM International (2013). “Standard Test Methods for Tension Testing of Metallic Materials”, *ASTM Standards*. E8/E8M - 13a, 1 – 28.

Cornell University (2016). “Direct Tension and Split Basin Testing of 6-in. (150-mm)-Diameter Kubota Earthquake Resistant Ductile Iron Pipe” submitted to the Kubota Corporation, February, 2016.