Steel Water Pipe Joint Testing

By Greg Smith

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Abstract

Steel water pipe in the municipal industry has typically been designed with either restrained or non-restrained joints, (typically rubber gaskets). Restrained joints are required where thrust at elbows, tees, laterals, wyes, reducers, valves, and dead ends. These joints are restrained by welding, harnessing and blocking. Most typical are the welded slip joint, because of its flexibility, ease in forming and laying, watertight quality and its ability to make small angle changes at each joint.

The efficiency of the welded slip joints and rubber gasket joints has been tested by numerous manufactures for internal pressure. The pipe barrel will usually fail by exceeding the elastic limit of the steel prior to leaking or failure of the joint. This is due to the increased section modulus of the joint configuration and stress orientation.

The ASME, recommends applying joint efficiencies of 0.45 and 0.55, respectfully for single and double-fillet lap welds and 0.9 for butt-welded pipe. The full-scale tests done by Thompson Pipe and Steel Company (1984) showed efficiencies in the 0.83 to 0.76 range for lap welded pipe. The unpublished tests at Consolidated Western Steel (1958) revealed efficiencies at nearly 1.0 for lap welded joints. Joint efficiency values are sometimes used to calculate shell thickness for buried pipelines. The question arises, what do these efficiencies mean, and how should they used in design of welded joints?

Introduction

To get a better understanding of the performance of the lap welded joints, Northwest Pipe Company performed full-size joint testing on several lap weld joint configurations. Strain gauges, strategically place at each joint were used to determine stress levels at typical operating pressures, and to eventual joint failure. Two test specimens were prepared, see figure 1, each specimen had six different joint configurations.

Both test pipe specimens were 77.625” OD x 0.323” wall thickness (D/t=240) and approximately 47 feet long. Each specimen had six identical joints fabricated and internally welded to simulate typical field construction. One lap-welded joint was welded both in and out for comparison purposes.

Test pipe specimen (A), was left open ended and cement mortar lined. Test specimen (A) was tested in a hydro tester to simulate unrestrained ends. The ends of the hydro tester were sealed with internal rubber gaskets, which have some flexibility to allow movement at the ends of the pipe. Specimen (A) would also provide data on the performance of cement mortar lining in extreme pressure situations.

Test pipe specimen (B), was prepared identically to test specimen (A), but was not cement mortar lined, and had test heads welded to each end. Test specimen (B) was tested under pressure and the test heads introduced an axial thrust on the pipe joints (biaxial). See Figure 1

Testing of pipe to bursting has been performed on full-scale pipes for many years and the results have always shown yielding of the pipe barrel (elastic failure of the parent metal shell) before yielding of the joints. This elastic failure of the barrel often is the driving load (biaxial loading) which creates the bending stress to the joint causing actual joint failure.

Test Specimens

The test specimen cylinders were manufactured to AWWA C200, spiral-welded pipe specifications, using ASTM 1018 grade 40 steel. The actual yields were tested to be 44,000psi for specimen (A) and 47,300psi for specimen (B). The joints were fabricated by circumferentially cutting the pipe into 6.75-foot sections, fabricating the joints and then hand welding the joints back together in the same manner that would be typical for field installations. Hand welding on each joint was performed using Lincoln 71 outer shield wire. All strain gauges were Vishay tee rosette, CEA-06-250UT-350, placed perpendicular to the pipe axis.

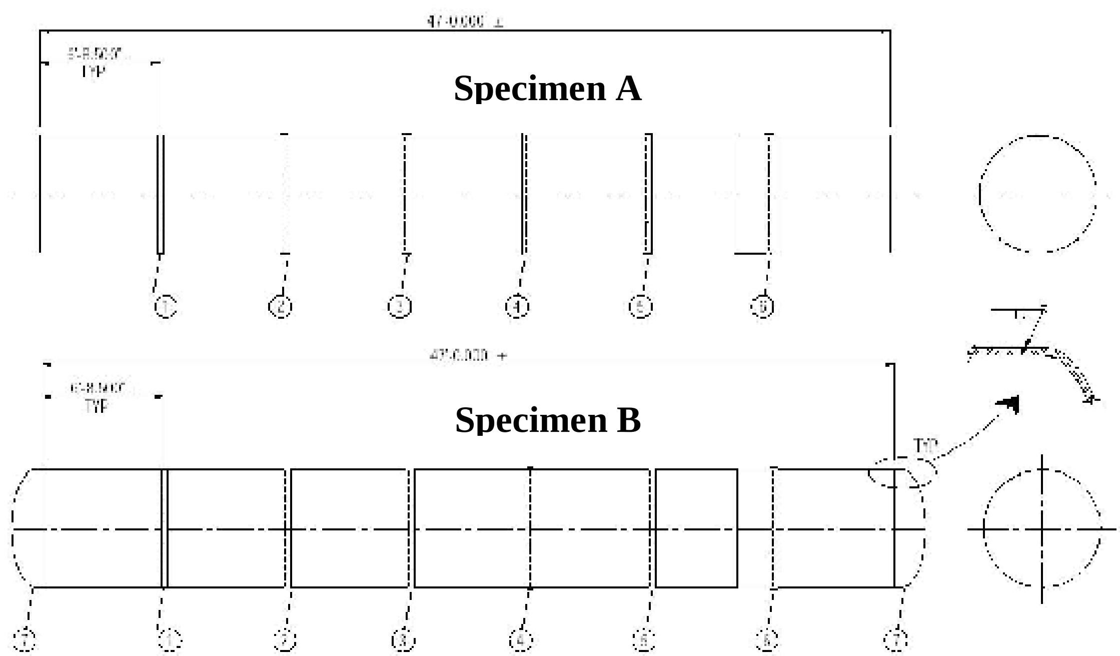


Figure 1

Joint #1 (Butt Joint)

Joint #1 was a complete penetration butt weld joint, fabricated with a 30-degree bevel and a 1/16" land. The joint was fabricated with a 0.125-inch plate back-up bar, tack welded to the outside diameter of the pipe, to support the root pass. The strain gauge was located directly in the center of the butt weld with the back-up bar removed a distance of two inches either side of the gauge. See Figure 2. This section represents the standard butt weld, which is assumed to have the highest joint efficiency.

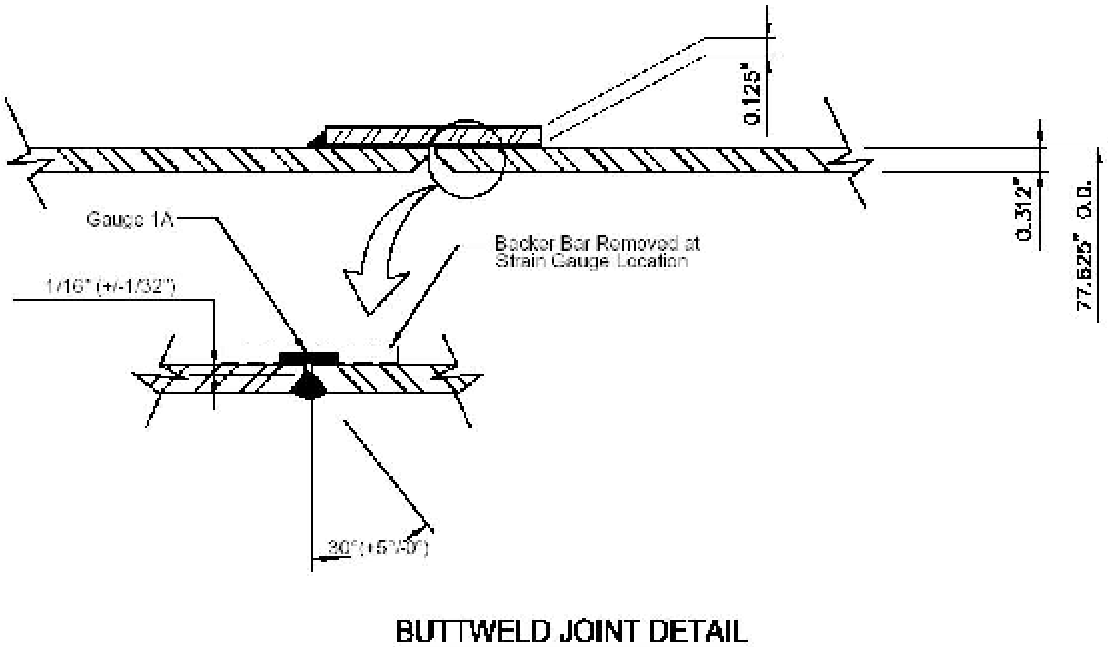


Figure 2

Joint #2 (Single lap)

Joint #2 was a bell and spigot joint, welded with a full penetration single inside fillet weld. The engagement of the spigot into the bell was 2.25 inches and the annular gap between the bell and spigot was 0.063 inches equally spaced around the circumference. Strain gauges were placed at three locations on the outside of the joint, at the location of the internal weld and at the center point of the expanded bell. See Figure 3 and Photo 1. This section represents the typical lap weld joint found in most large diameter steel pipeline projects with a tight tolerance between the bell and spigot.

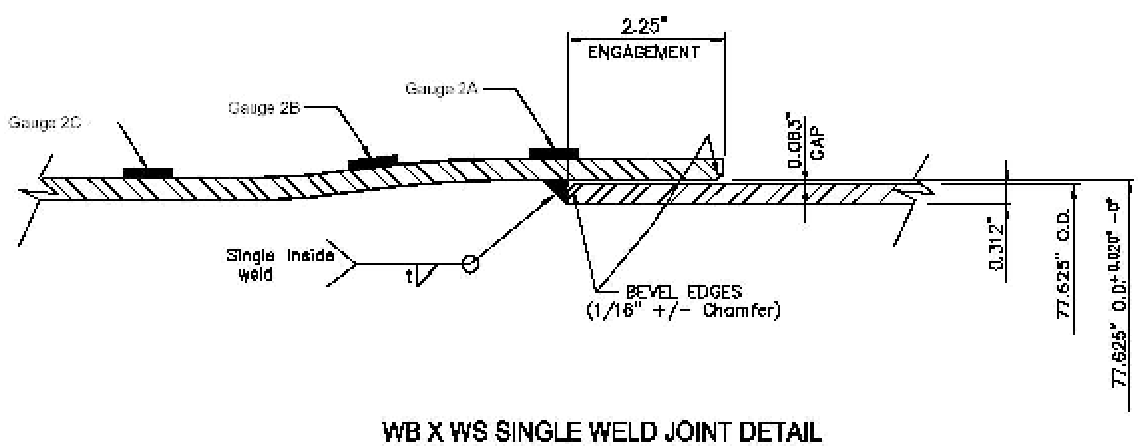
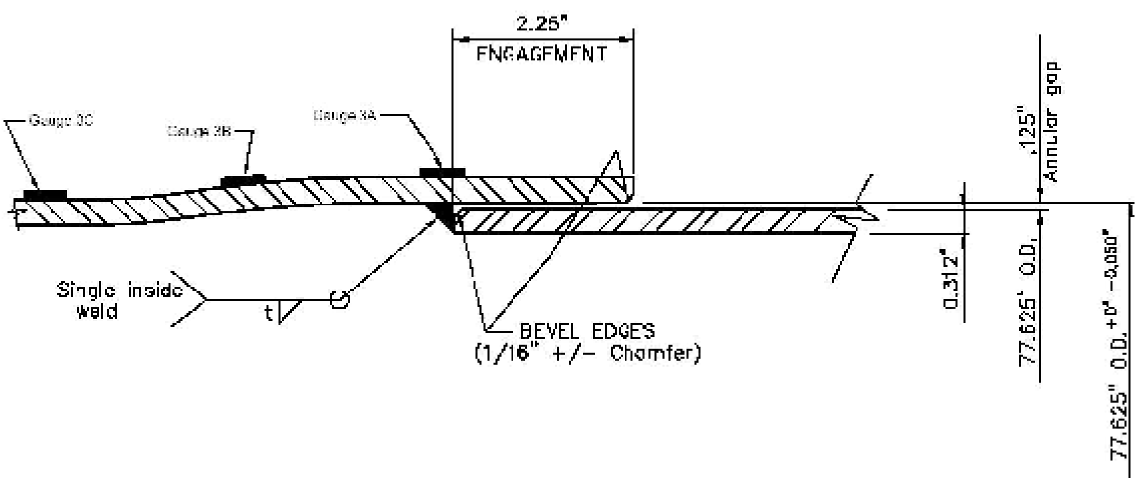


Figure 3

Photo 1

Joint#3 (Single Lap with Large Gap)

Joint #3 was similar to joint #2 with the exception of the larger gap on the annular space between the bell and spigot. The gap was the maximum allowed by AWWA C200 for this type of joint (0.127 inches) equally spaced around the circumference. All other physical characteristics of this joint were equal to joint #2. See Figure 4. This section represents a typical lap weld joint with a larger annular space between the bell and spigot, which is assumed to have the lowest efficiency due to the eccentric geometry.

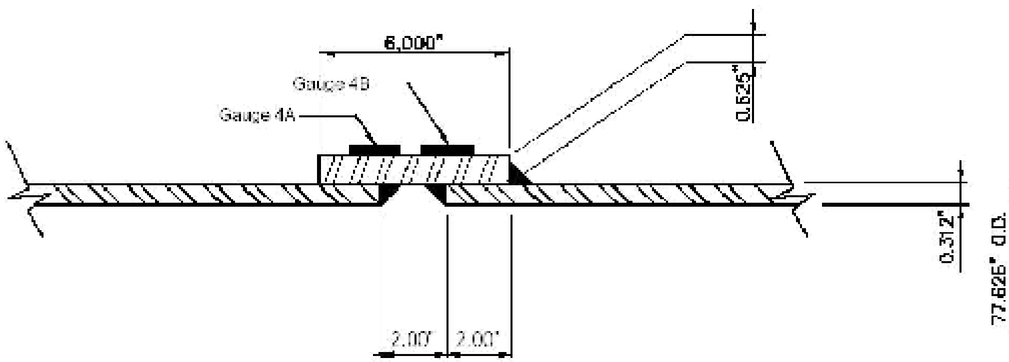


WB X WS SINGLE WELD W/GAP JOINT DETAIL

Figure 4

Joint #4 (Modified Bell)

Joint #4 was a modified bell and spigot joint, created by welding a 0.625-inch plate to the inside and outside of the pipe end forming a bell on the end of the pipe. The inside closure weld used was a single filet. Strain gauges were located on the outside of the pipe at the location of the two inside welds, and as close as possible to the outside weld. See Figure 5. This section creates the easily field-constructed bell and spigot joint but removes the curvature in shaping the bell and provides a stiffer bell section.

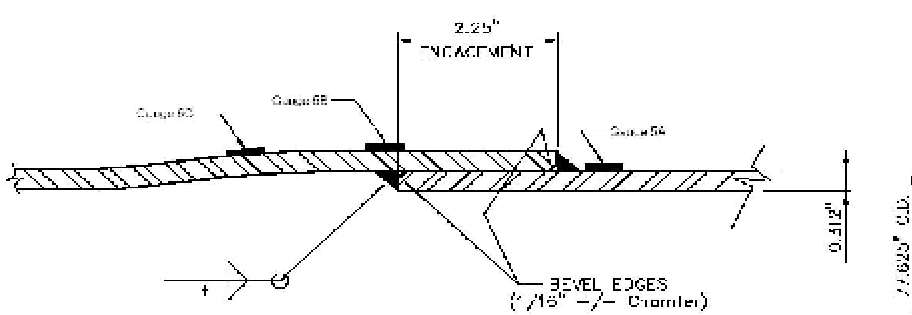


MODIFED BELL JOINT DETAIL

Figure 5

Joint #5 (Double Weld Lap)

Joint # 5 was a bell and spigot lap weld joint with the same dimensions as joint #1 with welds on both the inside and outside of the pipe. This configuration had strain gauges on the outside of the pipe at the curvature of the bell, over the inside weld and at a point as close as practical to the outside weld. See Figure 6. This joint will provide comparison data between the single and double welded lap joints.

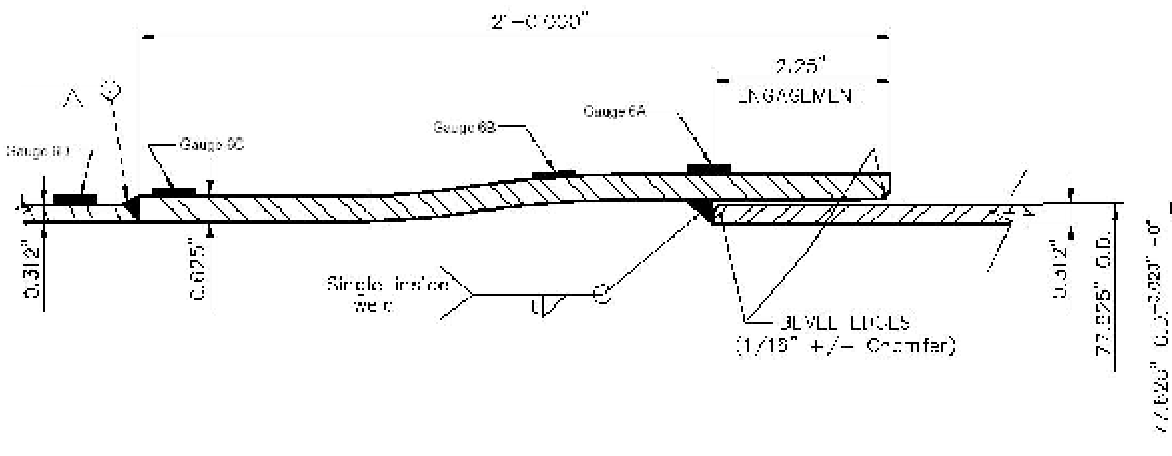


WB X WS DOUBLE WELD JOINT DETAIL

Figure 6

Joint #6 (Reinforced Bell)

Joint #6 was a straight spigot and a bell section made from 0.625-inch plate, 2 feet in length. Strain gauges were placed on either side of butt weld of the pipe cylinder and the heavy wall bell plate, at the curvature of the bell shape and at the location of the inside weld. See Figure 7. This section creates the curvature of the bell section with much heavier gage steel to compare the strain of the curved sections.



WB X WS SINGLE WELD REINFORCED JOINT DETAIL

Figure 7

Testing Procedures

A total of 30 strain gauges were installed on each specimen. Each gage was a general-purpose two-element 90-degree rosette with exposed solder tabs. The gage measured one-half inch by three-quarters inch with 350-Ohm resistance. Gauges were strategically located at each joint and at a neutral section of pipe between two joints, (neutral control) away from the spiral welds. A total of six wires were soldered to each rosette (three per side) and then wired to connector plugs (two per gauge) for connection to the recording instrument. Data was collected and analyzed on a Strainsmart 5000 and continually gathered at ten records per second.

The testing procedure consisted of filling each specimen with water and pressurizing the containers to three levels of pressure. Internal pressure of 100psi, 200psi and 300psi were held as closely as possible with the testing equipment. These pressures correspond to 12,000psi, 24,000psi and near yield stress for the test specimen. Continual pressure was difficult to maintain on the unrestrained specimen due to some leakage at the rubber seals at the ends. The recorder could only accommodate twenty connections at a time and with thirty connections for each specimen, it was necessary to test each specimen twice. The control gauges (located on pipe barrels, away from joints and seam welds) were used as the reference for comparison of joint strain measurements on each specimen and between specimens. Comparisons of all joints to the strain on the control gauges were quite easy. All joint comparisons were therefore referenced to the calculated maximum principal stress of the control gauge. After both specimens were tested for internal pressure, the unrestrained specimen was tested by longitudinal compressive loading (simulating a seismic event), to measure performance of joints to one another, as compared to the reference control gauge. See Photo's 2 and 3.

For the purpose of this paper, joint efficiency is defined as the maximum principal stress at the control gauge divided by the maximum principle stress at a gauge location. Although this is a very simplified methodology, it becomes quite significant in practical testing of full-scale samples where the performance limit of the straight pipe barrel governs the limiting performance of the pipeline system.

Photo 2

Photo 3

Unrestrained Test Data

Gauge Location	Maximum Principal Stress (psi)	Joint Efficiency	Maximum Principal Stress (psi)	Joint Efficiency	Maximum Principal Stress (psi)	Joint Efficiency
Control	12,000	1.00	24,000	1.00	46,900	1.00
1A	15,200	0.79	29,700	0.81	43,200	1.09
2A	6,600	1.82	20,300	1.18	32,000	1.47
2B	10,800	1.11	22,000	1.09	34,500	1.36
2C	10,900	1.10	21,400	1.12	30,900	1.52
3A	6,700	1.79	17,700	1.36	27,600	1.70
3B	13,000	0.92	23,400	1.03	37,900	1.24
3C	13,700	0.88	24,400	0.98	40,500	1.16
4A	3,300	3.64	8,100	2.96	16,800	2.79
4B	4,200	2.86	9,900	2.42	19,700	2.38
5A	3,700	3.24	11,100	2.16	24,700	1.90
5B	6,500	1.85	13,800	1.74	26,300	1.78
5C	11,000	1.09	22,500	1.07	41,100	1.14
6A	-400	30.00	-300	80.00	6,800	6.90
6B	-2,300	5.22	450	53.33	7,700	6.09
6C	-1,100	10.91	3,600	6.67	13,700	3.42
6D	5,700	2.11	14,300	1.68	28,300	1.66

Chart 1

Restrained Test Data

Gauge Location	Maximum Principal Stress (psi)	Joint Efficiency	Maximum Principal Stress (psi)	Joint Efficiency	Maximum Principal Stress (psi)	Joint Efficiency
Control	12,000	1.00	24,000	1.00	30,300	1.00
1A	22,400	0.54	43,500	0.55	63,800	0.47
2A	9,100	1.32	19,500	1.23	26,600	1.14
2B	4,400	2.73	9,820	2.44	13,600	2.23
3A	3,100	3.87	8,500	2.82	12,500	2.42
3B	-400	30.00	60	400.00	1500	20.20
4A	13,000	0.92	25,600	0.94	32,400	0.94
4B	-1700	7.06	-6,500	3.69	-6,400	4.73
4C	-3400	3.53	-10,500	2.29	-10,500	2.89
5A	3,000	4.00	13,500	1.78	19,100	1.59
5B	3,500	3.43	10,700	2.24	14,500	2.09
5C	-3,700	3.24	-4,100	5.85	-2,400	12.63
5D	3,200	3.75	13,500	1.78	19,500	1.55
6A	11,000	1.09	20,800	1.15	25,800	1.17
6B	-2,000	6.00	400	60.00	2,500	12.12
6C	400	30.00	1,900	12.63	2,700	11.22
6D	-4400	2.73	-5,500	4.36	-5,000	6.06

Chart 2

Testing Results

The strain measurements are recorded by the data recorder and were reduced to maximum principal stress values and tabulated. The data for the internal pressure testing are shown in Chart 1 and 2. The pressure was brought to just beyond yield for the unrestrained testing and below yield for the restrained testing. There was no detectable permanent deformation on either specimen after the tests were completed. The gauge on the butt weld (1A) for the restrained specimen had stress, which was larger than the control stress. These readings were not consistent with the original hypothesis of the butt weld being the most efficient joint. The gauge on the butt weld was removed and replaced with a new gauge to verify the original readings. The test was rerun and the same readings were obtained. It was concluded that the readings were correct for this gauge. The AWWA standard for steel pipe has a minimum wall thickness calculated to 50% of the minimum yield. For these test specimens the corresponding design pressure would be 168psi, based on the 0.323-inch wall thickness.

Joint #1 (Butt Joint)

This joint had very surprising results. On the unrestrained pipe the stress levels were very close to the control gauge stresses. The butt weld joint does have a section geometry that is extremely close to the straight pipe section, other than the backup bar which was cut back at the gauge location. However the stress readings on the restrained specimen were consistently almost twice the value of the control gauge on the bare cylinder. The gauge was located directly on the weld where there is some alloying between the parent steel and the welding rod, which might explain some stress differential. This alloying in the weldament however is a combination of two metals with very similar yields, tensile and elongation. This author assumes the large increase in strain is due more to a bending hinge at the weld due to a potential geometric peak rather than a material inconsistency. The butt weld joint had higher stresses than any location of any other of the joints tested in the unrestrained or restrained pipe specimens. This joint had the least efficiency of all tested gauge locations

Joint #2 (Single lap)

On the unrestrained test the gauge at the weld (2A), had the least recorded stress of the three gauges on this joint. The equivalent wall thickness at this location is double that of the bare pipe and the stress at the 100psi level was nearly half the control stress. As the internal pressure increases the efficiency does go down. The restrained joint measured higher strains at the weld location than in the bell section. It is assumed the axial load tends to straighten the bell creating slight compression on the outside of the bell cross section. All strains for this joint were lower than the control strain at the neutral location on the pipe.

Joint #3(Single Lap with Large Gap)

On the unrestrained test gauge at the weld (3A), the lowest stress again was at the weld and the bell readings were similar to the control gauge. This was consistent at all pressure levels. The restrained tests were also consistent with joint 2, in that the bell section strains were lower than the welds. The bell stress for on the restrained test was much lower for this joint due to the larger gap, which creates a greater moment on the section. It must be assumed that the compression load on the outside of the bell section also creates a larger tension stress on the bell ID. All the measured strains on this joint are lower than the control gauge.

Joint #4 (Modified Bell)

The gauges at this joint were both placed over an interior weld; (4A) was over the double weld section and (4B) over the single weld end. The unrestrained test measured strain very similar for both joints, which were lower than the single weld lap joints. This is assumed due to the heavier wall thickness at the weld location. The restrained test created a hinge effect at the double weld and put the single weld in a compression load. The higher pressures did have a slightly higher stress at the double weld location than the control for the restrained test.

Joint #5 (Double Weld Lap)

The unrestrained test gauge readings on the plate close to the exterior weld were much lower than the control strains due to the double plate thickness of this double lap welded joint. The stresses away from the joint bell were very similar to the control readings. The gauge reading over the interior weld was about one half the control strains which, was consistent with the most lap welded joints. The restrained test gauge readings were lower than the unrestrained, which was consistent with all the joints except the butt joint. The gauge at the bell for this joint was externally in compression at the lower internal pressure as the cylinder expanded at a greater rate than the stiffer double welded joint. At the higher pressures the stress was in tension, but at much lower levels than the control section.

Joint #6 (Reinforced Bell)

The heavy plate used in the construction of this joint had the least measured stress of all the testing for internal pressure. The gauge reading on the thinner cylinder at the weld was close to half the control due to the added stiffness of the weld to the heavier plate. The gauge readings at the weld for the unrestrained specimen were the lowest of all the lap weld joint weld locations. The readings on the weld gauge for the restrained specimen was nearly as high as joint #4, the other heavy thickness joint.

Internal Pressure Test Conclusions

The butt weld joint #1 had the highest stress readings and the lowest joint efficiencies for all the joints tested in every test pressure for both the restrained and unrestrained specimen. In general the principal maximum stress on the weld locations for lap welded joints were lower than the stresses on the bell sections for all the unrestrained test readings. In contrast, the readings on the welds were higher than the bells for all the restrained test readings. The biaxial loading of the restrained specimen induced higher stresses, but nothing close to the stress in the steel cylinder for all normal operating pressures. Internal pressures creating stresses closer to the yield of the steel did generate efficiencies lower than the normal operating pressures. In no case was there efficiency less than unity except the butt weld joints and the lap weld joint, with the larger gap on the unrestrained specimen, and the butt weld and modified bell on the restrained specimen. The test data supports the fact that lap welded joint configurations have less stress at the joints than the pipe itself for internal pressure.

Cement Mortar Lining Tests

The unrestrained test specimen was cement mortar lined per AWWA C205 and the joints were repaired internally per AWWA C206. After the internal testing of this specimen the internal lining was inspected for damage. The normal operating pressure for a pipeline with this diameter and wall thickness would be 166psi with an allowable surge to 275psi. The internal pressure actually peaked beyond 400psi. The internal lining did suffer some hairline cracking circumferentially at each joint repair. There was also some minor longitudinal hairline cracking sporadically throughout the machine-lined portion of the pipe. In no case was there any spalling or crack that would require any repair based on AWWA criteria. It is assumed that all this type of cracking would heal autogenously if present on a cement mortar lined pipeline. See Photo 3.

Photo 4

Compression and Tension Testing

The test results for the internal testing revealed the cylinder in a straight configuration to have more stress than the joints. The increased section modulus resists stress from internal pressure and longitudinal strain developed by the dished heads on the restrained pipe specimen. To further test the stress levels under longitudinal compression and tension, to simulate potential external loads that could be subjected to pipeline i.e. seismic events, it was hoped to compress the unrestrained specimen and pull apart the restrained specimen. Unfortunately pulling apart a specimen of this size and strength was beyond the mechanical capabilities of the manufacturing facility. However we could compress the unrestrained pipe to failure in the hydro tester. This test would be a one-time shot where the weakest joint or section would fail.

The hypothesis was that the lap joint with the larger gap between the bell and spigot would fail first due to instability of the wall and collapse in a tradition buckling configuration rather than instability of the entire shell causing axial bending. The recording equipment could only monitor twenty connectors or ten gauges at one time. The ten gauges chosen for the compression test were 1A, 2A, 2B, 3A, 3B, 4A, 5B, 5C, 6C, and the control gauge on the bare cylinder.

The first test was terminated when due to irregular cuts at the pipe ends, large critical stresses were created and one end buckled. The pipe ends were then reinforced with a 0.625-inch thick butt strap welded true to the pipe axis to insure a equalized compressive force on the circumference of the pipe shell. The compression test then resulted in a classical buckling generated at the joint #3 (single lap with large gap), which compressed the entire length of the pipe, by 3.0-feet. The buckling was isolated to only the one joint and resulted in a accordion type failure which spalled all the cement mortar lining off the shell only at the failed joint. It did not fail in a mushroom fashion as might be expected.

The fact that the pipe had no internal pressure at the time of the collapsing may attribute to the classical rather than mushroom type failure. There was no visual damage to any other portion of the test specimen both interior or exterior. Chart 3 shows the maximum stress at the test gauges at several time intervals during the compression testing. The actual collapse of joint #3 occurred at approximately 1558 seconds yet the joint retained enough strength to continue to exert further stress on the remainder of the joints. It was unexpected to see the double welded joint measure stress equal or higher to the large gap joint up to collapse. The buckling occurs in a random wrinkle around the pipe perimeter and it is not possible to predict if a gauge is on a wrinkle (tension or compression section), or in a neutral stress area.

The recorded strain on joint #5 was higher than expected and actually exceeded yield. Close visual inspection revealed some flattening of the bell but no damage to the interior lining. There was no tearing or cracking of the steel or weld that could be visually inspected. The specimen was hydrostatically tested after the collapsing and did not leak when subjected to 300psi internal pressure. The only conclusion from this test was that the weakest joint failed first and due to extreme strains, buckled as predicted and yet retained enough strength to not leak and transfer stress to the other joints. A pipe collapse of this nature would not be performance limiting to a pipeline. See photo 4 and 5. The collapsing testing was performed with no internal pressure, which makes it more susceptible to buckling. A pressurized pipeline subjected to the same external compressive force would have a much greater resistance to this type of buckling.

Photo 5

Photo 6

Collapse Test Stresses versus Time

Gauge Location	1390 sec.	1410 sec.	1420 sec.	1500 sec.	1532sec.	1556 sec.	1558 sec.	1559 sec.	1560 sec.	1580 sec.	1588 sec.
Control	-250	-70	980	1,700	2,800	2,900	4,000	3,900	3,800	3,500	3,600
1A	-1,300	-1,300	-1,100	-360	-9	-1,100	-3,100	-4,000	-4,500	-6,500	-5,800
2A	120	700	2,700	4,100	7,300	8,500	14,000	15,400	15,900	18,300	17,600
2B	-250	550	1,800	2,500	3,700	3,950	6,500	6,800	6,700	6,400	6,100
3A	1,300	6,300	11,300	14,900	27,100	34,000	49,700	84,800	145,000	135,400	117,500
3B	-350	1,300	2,800	3,800	6,300	7,600	12,100	1,600	17,500	15,200	21,800
4A	290	160	180	540	1,900	2,900	10,400	12,800	14,100	18,400	18,700
5B	980	7,000	12,800	17,200	30,300	38,700	45,000	48,700	50,500	56,400	54,100
5C	1,700	330	650	1,240	3,000	3,700	3,700	3,700	3,700	3,700	3,600
6C	480	2,800	5,400	7,500	14,800	20,600	24,000	25,900	26,800	30,800	30,400

Maximum Principle Stress
Chart 3

Summary

The testing measured actual strain at six joint locations on two test specimens rated for a operating pressure of 166psi. The data that was recorded for internal pressure at the lap joints created less strain than the bare steel cylinder. The butt-welded joints had more strain than the bare steel cylinder and the lowest efficiency for internal pressure. The stress was higher on the restrained specimen than the unrestrained. Collapsing the unrestrained test specimen with no internal pressure required considerable force and though it did damage the lining, the structural integrity remained. Based on the test data there was no limiting of the pipe performance due to internal pressure for any of the lap joints. The collapsed pipe specimen showed that the fine-grained, fully killed steels, from continuously cast slabs can withstand severe deformation and still hold pressure and transmit stress on steel pipes. It can be assumed that based on these test results, most published joint efficiencies for lap welds are much too conservative. Designers of steel pipes in seismic areas using lap joints should expect any damage to be isolated to a local joint area. The resultant damage, as shown in these tests, will not limit the purveyance of needed water.

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