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Large-Scale Testing Methodology to Measure the Influence of Pressure on Tensile Strain Capacity of a Pipeline

Paulo C. Gioielli[1], Karel Minnaar[1], Mario L. Macia[1], Wan C Kan[2]

[1]ExxonMobil Upstream Research Company, Houston, Texas, USA
[2]ExxonMobil Development Company, Houston, Texas, USA

ABSTRACT

Strain capacity of a welded pipeline is usually characterized using uni-axial tests such as curved wide plate test. However, the difference between the responses of a wide plate test and a pressurized pipe has not been fully established. Six pressurized and un-pressurized full-scale tests with machined flaws have been conducted to determine the influence of pressure on the tensile capacity of a pipeline. Experimental techniques and results showing the effect of pressure on the strain capacity of the pipe and tearing resistance of the flaws are presented. It has been demonstrated that pressure can significantly reduce the measured strain capacity.

KEY WORDS: Pipelines, strain capacity, full-size testing, tearing resistance, effect of pressure.

INTRODUCTION

Pipelines are often operated in regions where large ground deformations are possible. For example, large ground deformations may occur in seismic regions where a pipeline crosses a fault line or in arctic regions where the pipeline is subjected to large upheaval or subsidence ground movements that occur when the ground freezes or thaws.

The strain capacity of a welded pipeline is usually characterized using uni-axial tests such as the tensile wide plate test [Hukle, Horn, Hoyt, and LeBleu, 2005]. It has been shown that the wide plate tests can be used to estimate the strain capacity of a pipe without pressure. However, the differences between the responses of a wide plate test and pressurized pipe have not been fully established.

ExxonMobil has conducted a test program consisting of six pressurized and un-pressurized full-scale tests with machined flaws to determine the influence of pressure on the tensile capacity of a pipeline. This paper describes the experimental techniques and the results of this test program. Results showing the effect of pressure on the strain capacity and tearing resistance are also presented. It has been demonstrated that pressure can significantly reduce the measured strain capacity.

TESTING PROGRAM

The effect of pressure on strain capacity of pipelines was assessed in a testing program consisting of 3 pairs of full size strain capacity tests (6 tests). One specimen of each pair was tested with virtually no internal pressure while the other was tested with internal pressure to generate hoop stresses equal to 80% of the pipe material yield stress. Electro Discharge Machining (EDM) was used to cut notches in each specimen. The first pair of specimens had notches at the pipe material, which ensures uniform tensile properties in the test and simulates an equally matched weld, these specimens will be labeled 0% overmatch, in this paper. The second and third pairs contained notches at the center line of the girth welds. Based on yield strength, the girth weld was 5% stronger than the pipe material for the second pair (5% overmatch) and 20% stronger than the pipe material for the third pair (20% overmatch).

All specimens were axially pulled to failure under strain control, while the following data were digitally recorded: load, overall pipe elongation, localized strains, crack mouth opening displacement, and internal pressure. Additionally, the 5% and 20% overmatch tests were monitored using acoustic emission (AE) and full field strain cameras. Details of the specimen configuration, instrumentation, and testing procedures are given next.

Specimens

The specimens were fabricated using X65 Electric Resistance Welded (ERW) pipes with 325 mm (12.75”) outside diameter (OD) and 14.3 mm (0.562”) wall thickness (WT). EDM notches were placed on the OD of all specimens. All notches were machined 3 mm deep by 50 mm long. Figure 1 shows the EDM notch profile.

The first pair of specimens (0% overmatch) was made of plain pipes (without girth welds) with 10 EDM notches machined in each pipe. The 10 EDM notches were machined at five longitudinal locations along the OD of the pipe with 2 notches placed 180° apart at each location (away from the ERW seam weld). The notches at adjacent locations along the pipe length were staggered 90°. Figure 2 shows the notch placement for the 0% overmatch specimens. The other specimens contained a single

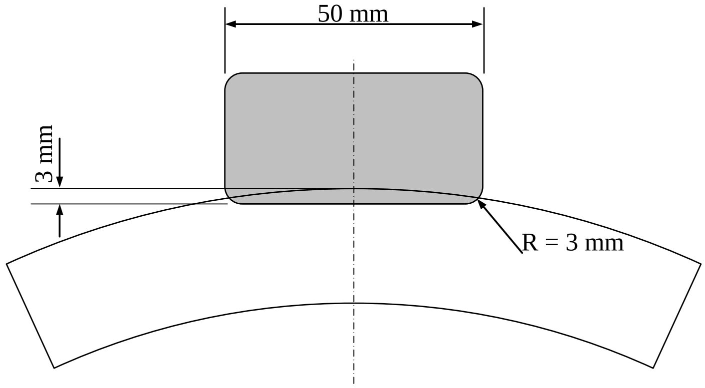

Figure 1. Profile of the EDM notches.

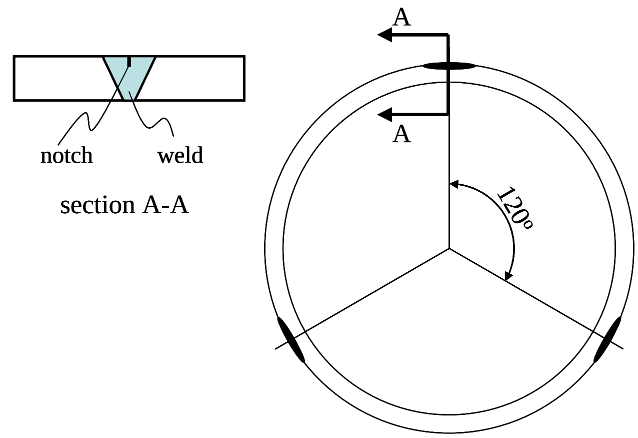

Figure 3. Notch placement for the 5% and 20% overmatch specimens.

girth weld with 3 notches at the weld centerline, placed 120° apart. Figure 3 shows the notch placement for the 5% and 20% overmatched specimens.

Mechanical properties (yield strength, ultimate tensile strength, and uniform elongation) were measured for the pipe and weld materials. Table 1 presents these properties.

All specimens were welded with end caps serving a dual purpose: (1) to hold internal pressure; (2) to allow application of axial tensile loads. The caps were designed to resist a minimum of 42 MPa (6 ksi) internal pressure and to resist an axial force sufficient to cause failure of the pipe being tested.

Instrumentation

The specimens were instrumented to collect the following data: load from the load cell, overall pipe elongation from two linear variable displacement transducers (LVDT's), biaxial strain measurement from multiple strain gages, crack mouth opening displacement from clip gauges, and internal pressure. Figure 4 shows the strain gage and LVDT locations.

The instrumentation used during these tests was intended to provide enough data to characterize the progression of tearing ahead of the machined notches during the test. In a companion paper, this information is used to develop a tearing resistance curve for the pipe tested [Minnaar, Gioielli, Macia, Bardi, and Kan, 2007]. Loads, crack mouth opening displacements (CMOD), and flaw sizes are required to generate a tearing resistance curve. Monitoring the growth of flaw size during the test is the most challenging measurement. Standard flaw sizing techniques, such as electrical potential drop and elastic unloading compliance, present additional challenges when applied to full size tests. Both techniques were tried. After the first set of tests, the elastic unloading compliance technique was selected because it provided more accurate results. Equations correlating flaw size with elastic compliance were generated using finite element analysis (FEA).

Additionally the 5 and 20% overmatched specimens were instrumented with full field strain cameras and acoustic emission (AE). The full field strain measurement is accomplished with pairs of cameras taking stereopair images of a pattern imprinted on the pipe surface to continuously monitor the development of strains over the surface of the pipe [Schmidt, Tyson, Galanulis, Revilock, and Melis, 2005]. This technique allows local inhomogeneities in the strain pattern to be identified. This information allows local variations in material properties to be identified and enables verification of finite element models by ensuring the models capture the experimentally observed variations in strain fields. AE monitoring was used to identify the point during the test at which ductile tearing initiated. Figure 5 shows a specimen in the testing frame highlighting AE transducers, full field strain cameras, and other instrumentation.

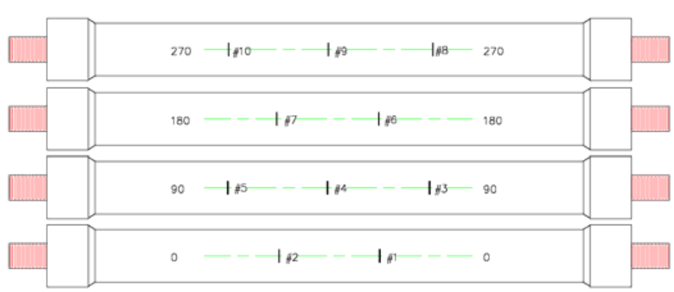

Figure 2. Notch placement for the 0% overmatch specimens

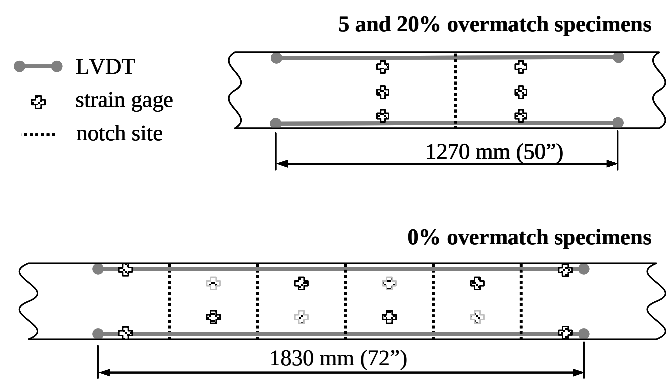

Figure 4. Sketch of specimen showing placement of LVDTs and strain gages.

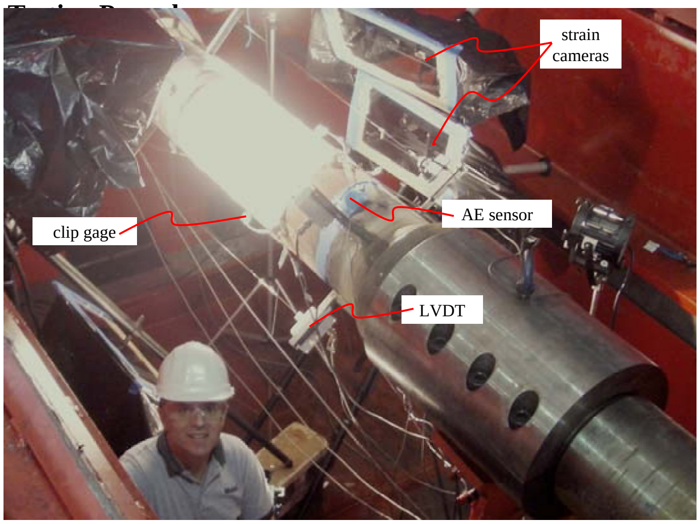

Figure 5. Picture showing the non-pressure, 5% overmatch specimen before the test.

Testing Procedure

The 0% overmatched specimens were tested using a 17.8 MN (4 million pound) capacity load frame while the other specimens were tested using a 26.7 MN (6 million pound) capacity load frame. Since all specimens failed below 17.8 MN, the only advantage of the larger frame was the increased space for the placement of the full field strain cameras that were used with this test frame.

All specimens were filled with water. The non-pressurized specimens were pressurized to a nominal 1 MPa (150 psi) for leak detection while the other specimens were tested at 39 MPa (5,700 psi), creating hoop stresses equivalent to ~80% of the pipe material yield strength. The data recording system was activated before pressure was applied. All tests were performed at room temperature.

The specimens were pulled in tension to failure under strain control. Between 20 and 40 elastic unloading cycles were applied to measure the CMOD elastic compliance. During each cycle, the load was decreased by an amount sufficient to decrease the axial stress by approximately 138 MPa (20 ksi). These unloads are large enough to effectively monitor crack growth, but do not result in significant fatigue crack extension.

After testing, fractography was performed on each notch included in each specimen. Notches that were not completely exposed by failure of the specimen were cut out from the test specimen and exposed by fracture after cooling with liquid nitrogen. Initial and final flaw sizes were measured and used to verify the flaw sizes generated from the elastic compliance calculation.

Material Properties

Tensile tests were performed according to ASTM E8-04. Fracture Mechanics tests were performed in all materials according to ASTM 1820-06. Table 1 shows the Yield Strength (σ_y), Ultimate Strength (σ_{uts}), Elongation (EL), and Crack Tip Open Displacement (CTOD). The specimens used to characterize the girth welds were taken from companion welds made using the same welding procedures used for fabricating the full scale test specimens.

Table 1. Small-scale mechanical properties.

Material	σ_y		σ_{uts}		EL	CTOD
	MPa	ksi	MPa	ksi	%	Mm
Pipe	562	81.5	631	91.5	30	0.52
Weld #1	677	98.1	804	117	28	0.41
Weld #2	589	85.4	644	93.4	31	0.39

RESULTS AND DISCUSSION

The pipe strain capacities were calculated from the total LVDT displacement, at the moment of failure, divided by the initial LVDT length. The failures for the 0 and 5% overmatched specimens were defined by the first leak resulting from through wall tearing from a notch. The 20% overmatched specimens failed outside the weld, and the strain capacities were measured at maximum applied load. Table 2 shows the measured strain capacities.

The specimens that failed by tearing from the notches exhibited a significant reduction in strain capacity from the addition of internal pressure. The failure strain for the 0% and 5% overmatch cases were 44% and 47% lower with pressure than without pressure. The effect of pressure was less pronounced on the specimen pair with failure occurring outside the weld. Only a 16% decrease in strain capacity from the addition of pressure was observed in the pair of tests with 20% overmatch.

The moderate decrease in strain capacity for the specimen that failed by tensile instability of the pipe away from the notch is not surprising. Established deformation plasticity theory, based on effective stress, accurately predict the reduction in the strain to plastic collapse as a result of biaxial loading [Nadai 1950]. However, the larger decrease in tensile strain capacity for the specimens failing by ductile tearing from the notches cannot be explained by simple metal plasticity models. The test data demonstrate that biaxial loading can have a significant effect on tearing fracture.

Strain capacity as function of overmatch is plotted in figure 6. As expected, increasing overmatch increases strain capacity. With increasing overmatch, there is a transition from failure caused by tearing of a weld flaw to a plastic collapse failure of the pipe away from the weld, which has occurred between 5% and 20% overmatch for the materials tested in this study. The transition between weld and pipe failure may occur at different levels of overmatch depending on internal pressure, flaw/pipe geometry, and other pipe/weld material properties, such as, tearing resistance and strain hardening.

Table 2. Measured strain capacity showing effect of pressure and overmatch.

Specimen Overmatch	Strain Capacity		Reduction due to Pressure
	Pressure	Non-pressure	
0% (plain pipe)	1.9%	3.4%	44%
5%	1.9%	3.6%	47%
20%	4.6%	5.5%	16%

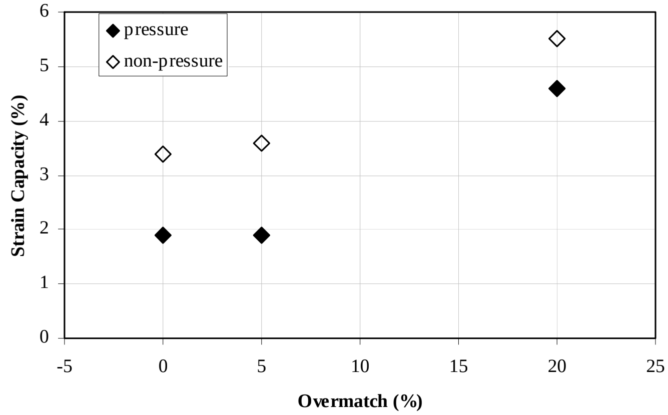

Figure 6. Measured strain capacity as function of overmatch.

Figure 7 shows the load vs. displacement for the non-pressurized, 0% overmatch specimen and the pressurized 5% overmatch specimen, including the elastic unloading cycles. The other specimens followed similar load displacement trends.

Figure 8 shows the tearing resistance for both 0% overmatch specimens. Similar tearing resistance curves were obtained for the non-pressure and pressure specimens. In addition, a resistance curve measured using a small scale fracture single edge notched bend (SENB) specimen is plotted to allow for a direct comparison of full-scale and small scale resistance. The tearing resistance curve for the 20% overmatch specimens was not measured because these specimens failed outside the weld with virtually no tearing at the notches. By the time this paper was written, the analysis to generate tearing resistance curve for the 5% overmatch specimens were not complete.

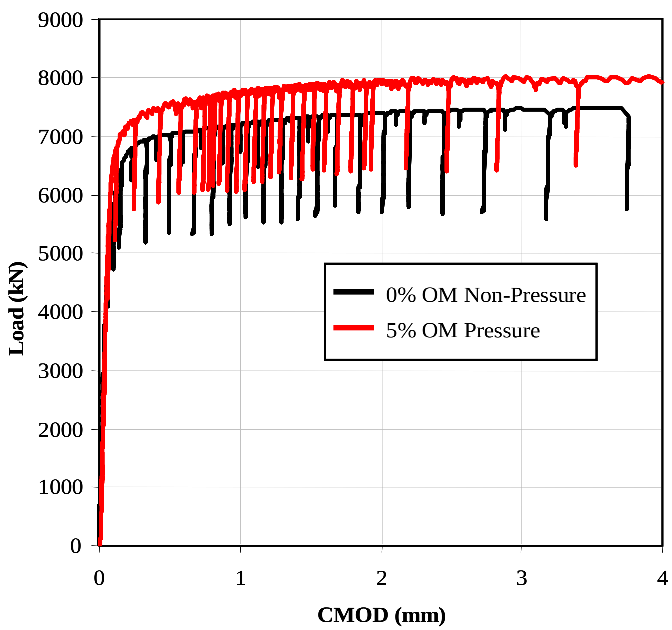

Figure 7. Load vs. CMOD for 0% overmatch (OM) un-pressurized and 5% OM pressurized specimens

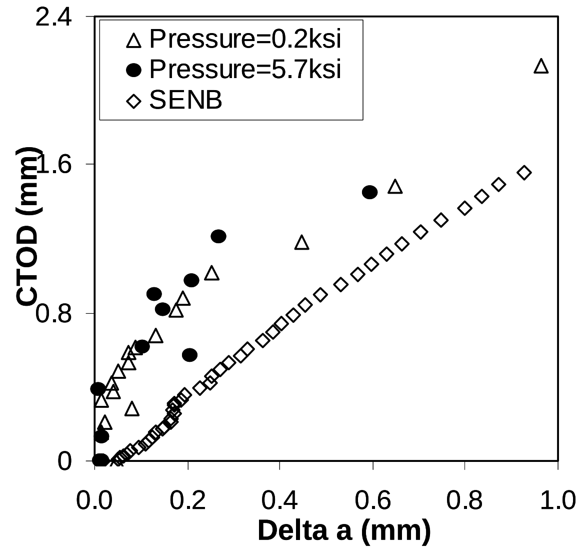

Figure 8. Measured tearing resistance curves from the 0% overmatch specimens compared to small scale test result.

CONCLUSIONS

A test methodology to evaluate the effect of pressure on strain capacity and to measure the resistance curve on full-size specimens has been successfully developed.

For specimens with a low level of weld overmatch, with failure caused by weld flaw tearing, significant reduction in strain capacity was caused by internal pressure.

The effect of pressure on strain capacity was minimized when the failure was cause by plastic collapse of the pipe.

The pressure does not seem to affect the tearing resistance curve, such that the influence of pressure on the strain capacity can be explained by the increased fracture mechanics driving force due to pressure.

The methodology to measure tearing resistance using full-size specimens can be applied to pipe sections, such as wide plate test specimens. However additional tests would be required to confirm that the tearing resistance measured is not different than the equivalent full-size configuration.

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