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NUMERICAL AND EXPERIMENTAL ASSESSMENT OF GIRTH WELDS INTERACTING WITH WRINKLE ANOMALIES

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Abstract

Two wrinkle-like features were discovered in two girth welds of an onshore, horizontal directionally drilled (HDD) 42-inch OD x 0.438-inch wall thickness, Grade X70 pipeline using a high resolution in-line inspection (ILI) tool. The HDD pipeline was buried at a depth of approximately 30 feet. The data from the ILI tool revealed a wrinkle feature encompassing the full circumference of the pipeline, in contrast to a traditional wrinkle, which typically encompasses a third to half the circumference. The high resolution ILI data was then used to generate a finite element model of the pipeline sections of interest to calculate stress concentration factors (SCFs) under combined loading conditions representative of buried transmission gas pipelines. The FEA results showed that stress concentration factors ranging from 1.03 to 7.5 existed in the pipeline section under certain loading conditions, which warranted additional assessment of the features.

In addition to the numerical analyses, full-scale experimental efforts were conducted to fabricate anomalies having characteristics similar to the ones found in the field on pipe sections of the same characteristics as those of the HDD pipeline. The wrinkle anomalies were generated by applying external compression loads in the lab, followed by pressure cycling representative of a 20 year service life, and burst testing.

This paper addresses these pipeline anomalies using both numerical and experimental methods, following the guidelines of the API-579-ASME-FFS-1 standard, which is used to evaluate if affected equipment is fit for continued service. In addition to the steps encompassed by API-579-ASME-FFS-1, elements of the Engineering Based Integrity Management Program, or EB-IMP® (IPC2008-64492), were also utilized in order to determine the operability of the pipeline, and the expected factors of safety relative to static strength, fatigue and crack propagation.

The conclusion from this study is that the wrinkle-like features by themselves (i.e., without cracks) do not pose an immediate threat to the actual pipeline considering that the testing survived 20 years of simulated cyclic pressure. However, the Sample did not survive the pressure ramp to 72% SMYS after pressure cycling, and it leaked via a circumferentially-oriented through-wall crack at 69% SMYS. This ultimately led to an appropriately scheduled replacement of the pipe section in question.

1. Introduction

This paper provides details on a study performed to evaluate the severity of wrinkle-like features located in girth welds that were detected during an in-line inspection run in an HDD section of a pipeline. The purpose of the study was to provide the information required for making a decision on the future operation of the pipeline and if the wrinkle-like features posed a threat to the integrity of the pipeline system.

Prior to this study a methodology was developed to assist gas and liquid transmission pipeline operators in evaluating the severity of pipeline defects as part of their overall integrity management programs. This methodology, known as the Engineering-Based Integrity Management Program (EB-IMP), integrates existing knowledge, analytical techniques, experimental methods, and engineering rigor to develop field-friendly tools to characterize and ensure pipeline integrity.

This EB-IMP program is based in part on the principles embodied in the API 579 Fitness for Service document. At its core, API 579 makes use of a three-level assessment process to evaluate the fitness for service of a particular component or system. Much of this work was driven by the needs in U.S. refineries; however, more recently B31.3, B31.4 and B31.8 and other standards governing pipelines and piping, and their safe operating envelope in existing equipment, have been incorporated into this methodology. Anomalies covered in this standard include dents,

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gouges, cracking, corrosion, and mechanical damage.

The EB-IMP is a five step process for evaluating pipeline imperfections. Figure 1 is a flow chart of the proposed process that builds on the basics of API 579, but expands the process by integrating testing (Level IV) and repair (Level V). This study proposes to conduct an assessment using both the Level III (numerical modeling via finite element analysis) and Level IV assessments (full-scale testing).

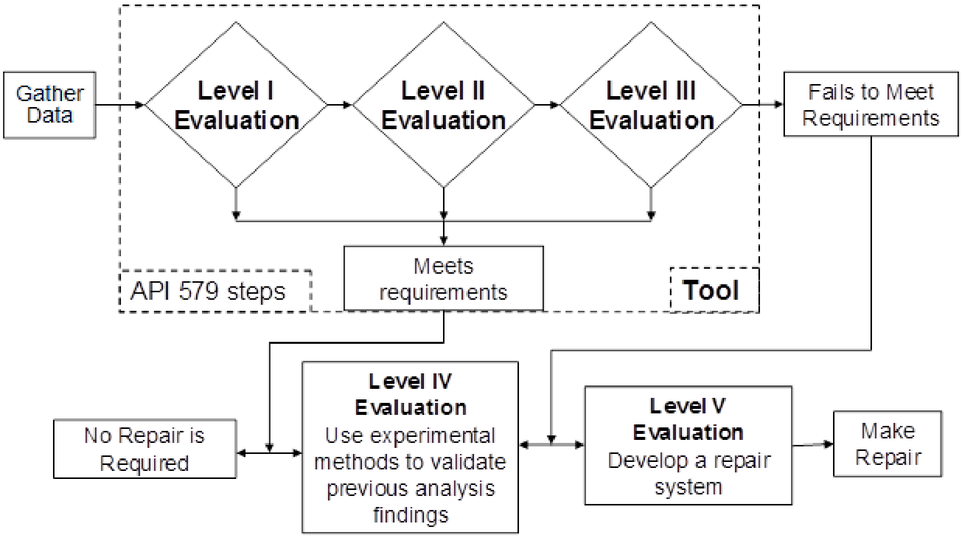


Figure 1. Elements of the EB-IMP process

2. Analysis Methods and Results

2.1. Use of In-Line Inspection Data to Evaluate Stresses in Wrinkle

The high resolution in-line inspection (ILI) data from a run that detected two wrinkle anomalies in a 42-inch OD X 0.625-inch wall thickness, Grade X70 pipeline was obtained. This data was converted into a finite element mesh, and several finite element analyses (FEA) were performed. The objective of the FEA was to assess the severity of the stresses that occur as a result of the presence of the wrinkle under various loading conditions. The loading conditions considered were:

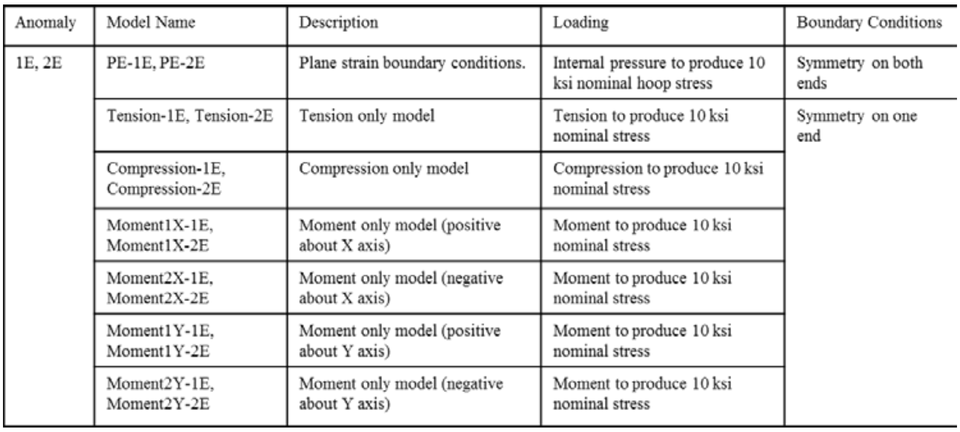
1. Pressure loading with plane strain boundary conditions (typical of buried pipelines)
2. Tension loading
3. Compression loading
4. Bending loading

From the loading conditions listed above, item 1 is the most common condition for a buried pipeline, and also the conditions that the HDD pipeline is likely subjected. In this condition, the interaction of the pipeline with the soil restricts axial deformation, which creates tensile axial stresses from Poisson effects that are equal to approximately 30% of the hoop stresses. These conditions are referred to as plane strain conditions. However, additional loading conditions such as compression, tension and bending may also affect the pipeline due to loads generated during installation, the straightness of the horizontally drilled hole, and other interactions with the environment. All of the loading conditions listed above were addressed independent of each other in order to quantify the stress concentration factor that each loading condition could contribute to the anomaly.

The finite element analyses consisted of 3D shell models where the anomaly was placed in the center of the modeled geometries. Stress concentration factors (SCF's) were calculated by taking the peak stresses at the region affected by the anomaly, and dividing the value by the appropriate nominal stress as described above. Table 1 summarizes the finite element loading conditions and boundary conditions considered for both anomalies. These anomalies are referred to as anomaly 1E and anomaly 2E; however, only anomaly 1E is discussed in this paper for brevity. All the analyses described in Table 1 above were performed with linear elastic material properties at ambient temperature.

Figure 2 shows the profile of anomaly 1E, as a function of axial and angular positions. The profile is defined as the change in the radial coordinate relative to a nominal OD of 42-inches.

Table 1. Summary of 3D shell FEA performed to assess SCF values



Anomaly	Model Name	Description	Loading	Boundary Conditions
1E, 2E	PE-1E, PE-2E	Plane strain boundary conditions.	Internal pressure to produce 10 ksi nominal hoop stress	Symmetry on both ends
	Tension-1E, Tension-2E	Tension only model	Tension to produce 10 ksi nominal stress	Symmetry on one end
	Compression-1E, Compression-2E	Compression only model	Compression to produce 10 ksi nominal stress	
	Moment1X-1E, Moment1X-2E	Moment only model (positive about X axis)	Moment to produce 10 ksi nominal stress	
	Moment2X-1E, Moment2X-2E	Moment only model (negative about X axis)	Moment to produce 10 ksi nominal stress	
	Moment1Y-1E, Moment1Y-2E	Moment only model (positive about Y axis)	Moment to produce 10 ksi nominal stress	
	Moment2Y-1E, Moment2Y-2E	Moment only model (negative about Y axis)	Moment to produce 10 ksi nominal stress	

Furthermore, a significant finding that came from analyzing the ILI data is that the wrinkle anomaly affected the entire circumference of the pipeline at that location. This is an important consideration, as wrinkle bends typically span a third to half of the circumference, and are created by bending moment loadings. In contrast, a wrinkle feature that spans the entire circumference was likely created due to significant compressive loads. Figure 3 shows the stress concentration factor (SCF) for plane strain conditions of anomaly 1E (model PE-1E), as a function of axial position, and select angular positions. Note that the largest SCF corresponds to the largest radial coordinate departure (126^{o} position). In addition, note that the profile at the 126^{o} angular position alternates between positive and negative values. The fact that the wrinkle goes inward and outward exacerbates the SCF at that location during pressure loading.

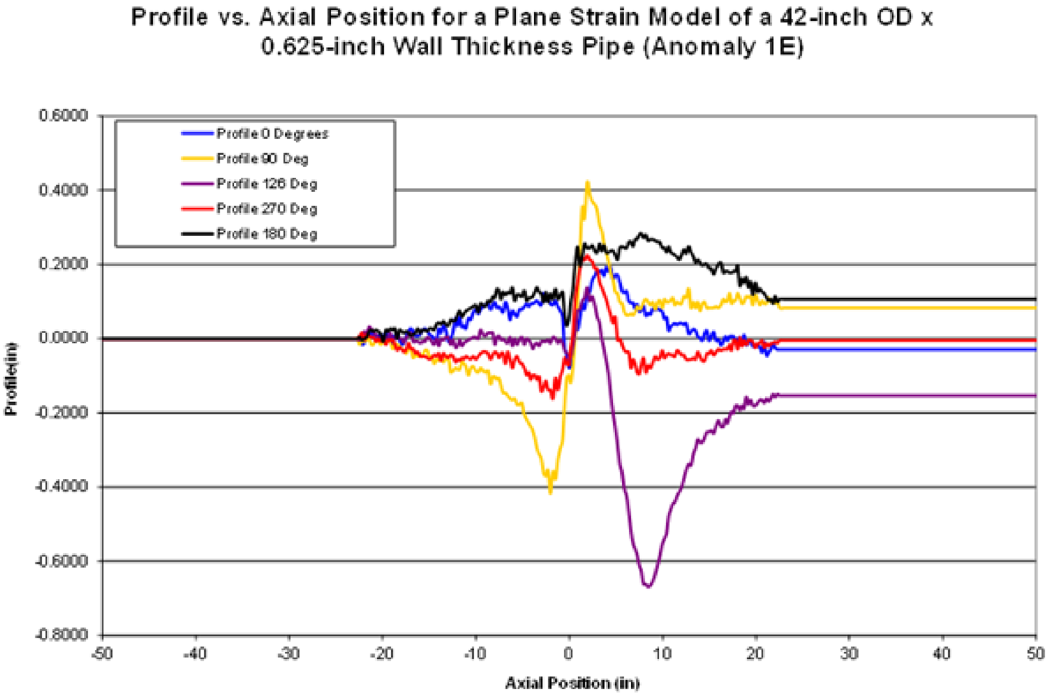


Figure 2. Radial profile of anomaly 1E vs. axial and select angular positions

Finally, Table 2 shows a summary of SCF's for anomaly 1E for all analysis cases. The presence of these high SCFs will have adverse implications in fatigue. While gas pipelines typically do not experience significant pressure or temperature cycles, over a period of time they will experience some level of cycling. Having an SCF of 6.53 and 7.5 on the OD and ID, respectively, implies that failure from low cycle fatigue may be a potential threat. In order to address the severity of this threat, full-scale testing on pipeline material was performed. The presence of interaction with a weld creates even greater concern.

The scope of the full-scale testing involved generating a wrinkle feature followed by pressure cycling and burst testing. An important consideration in generating this feature is that the lab-generated feature should impart similar

SCF's in testing having magnitudes similar to those encountered in actual field conditions. The lab-generated wrinkles were designed to only have an outward profile and be subjected to pressure end loads, while the field conditions have sections of an inward profile and do not have a pressure end load. However, the lab generated feature was subjected to similar stresses (i.e., similar SCFs) that were expected to occur in the field conditions in the pipeline.

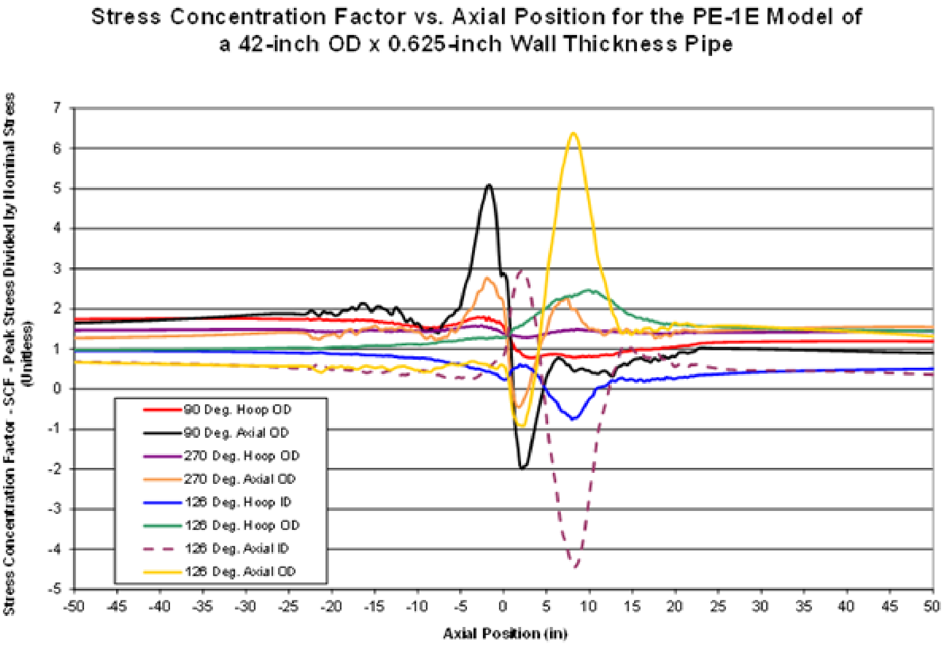


Figure 3. Stress concentration factor vs. axial position at select angular positions for model PE-1E

Table 2. Summary of SCF results for anomaly 1E

Anomaly	Model	SCF							
	[redacted]	Hoop ID		Axial ID		Hoop OD		Axial OD	
		Compressive	Tensile	Compressive	Tensile	Compressive	Tensile	Compressive	Tensile
1E	Plane-Strain	-0.80	2.27	-4.80	7.50	-0.40	2.51	-3.13	6.53
	Tension	--	--	-2.06	4.11	--	--	-2.06	3.80
	Compression	--	--	-4.22	2.19	--	--	-3.92	2.15
	Moment 1X	--	--	-4.10	2.40	--	--	-3.85	2.08
	Moment 2X	--	--	-2.43	4.00	--	--	-2.00	3.73
	Moment 1Y	--	--	-1.86	1.84	--	--	-2.14	2.11
	Moment 2Y	--	--	-1.85	1.84	--	--	-2.14	2.11

2.2. Development of Full-scale Testing Load Frame and Samples

The events that might have occurred during installation of the directional drilled crossing were of particular interest. It was concluded that the most logical scenario that could have contributed to the creation of the anomalies in the field were significant compressive loads generated during the process of installing the HDD. Loading associated with the use of an air hammer, a device used to dislodge stuck pipe, seemed the most probable source of loading.

Finite element analyses were performed to design a load frame that could apply large compressive loads on pipe sections to generate the required wrinkles. The objective in this phase of the project was to determine with a high degree of accuracy the loading required to generate the feature, as well as the required height to length ratio (h/L ratio) of the feature to have an axial SCF close to the FEA results representing the field conditions.

The analyses in this phase of the study consisted of applying a compressive load on a pipe section that would cause it to buckle in an axisymmetric sense (i.e. same geometry and loading around the pipe circumferentially). The estimated load required for this feature to generate is on the order of the load required to yield the cross-sectional area of the pipe in compression, approximately 5.7 million lbf for Grade X70 material. These finite element models in these analyses included nonlinear post-buckling behavior and plasticity.

To prevent possible instabilities associated with buckling during actual testing, including severe displacements or crushing of the pipe wall, the compression tests were designed to include 500 psi of internal pressure in the test Sample. This internal pressure provided stability to the wrinkle during generation of the anomaly during testing.

Figure 4 shows the FEA results of the load vs. radial displacement at the apex of the wrinkle as a function of pipe yield strength. An internal pressure of 500 psi is included for all results. Figure 4 also shows the load vs. axial displacement. These plots were generated as an aid to the full-scale testing work to determine how much axial deflection of the wrinkle (a measured quantity during testing) would produce the required radial displacement at the apex of the wrinkle to produce the same SCF estimated for the field conditions discussed previously.

The h/L ratio estimated to exist in the 1E anomaly is 0.04. However, the 1E wrinkle has a profile that alternates between inward and outward values, which increases this SCF relative to a wrinkle feature having only an outward profile. For these reasons, the h/L ratio for the experimental work was designed to be 0.10. Although the sought experimental h/L ratio is roughly 2.5 times larger than the one in the field, the experimental SCF was expected to be approximately equal to the SCF associated with the field conditions.

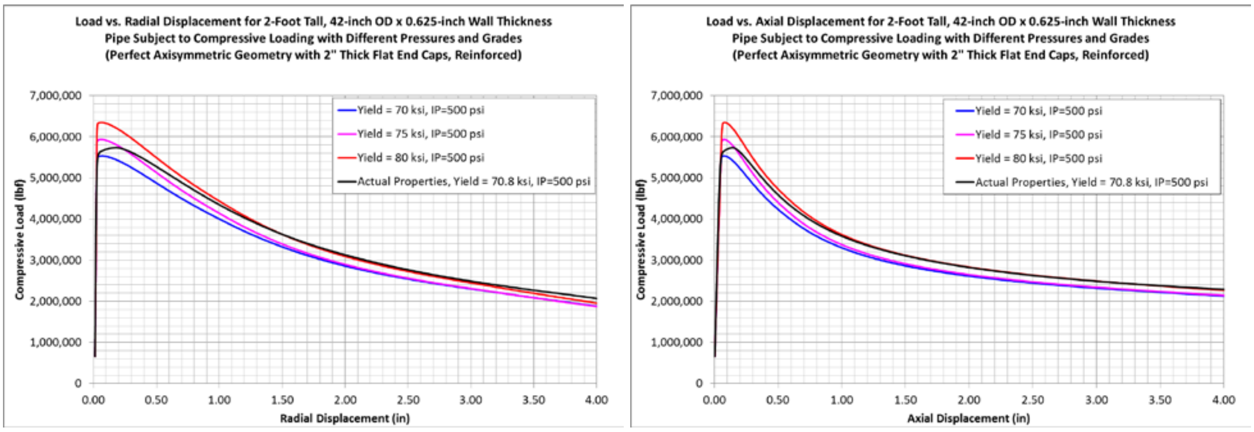


Figure 4. FEA calculated response of the pipe Samples during the wrinkle creation process

3. Testing Methods and Results

3.1. Sub-Scale Testing

Generating a wrinkle feature in the lab that ultimately had a SCF as close in severity as possible to the wrinkle in the field was an important task in the assessment of the HDD wrinkle anomalies. Sub-scale tests were performed prior to the full-scale tests with the intention of identifying unknown challenges that might exist in performing the full-scale tests. The sub-scale tests were also conducted to determine the degree of control that could be achieved during the creation of the wrinkle features. The FEA effort was also being pursued to validate this effort, as this type of test generating the wrinkle feature in this pipe size had not been performed previously to our knowledge. Four (4) Samples of 12-inch OD X 0.188-inch wall thickness[1], Grade X42 pipe sections were specified for fabrication. Three of the Sample lengths were 12-inches tall and one was 24-inches tall. Further, one of the Samples (12-inch tall) had a girth weld in the center of the Sample to capture the interaction of the girth weld with the anomaly being created.

The testing of the sub-scale Samples consisted of placing each Sample in a vertical load frame, where four hydraulic cylinders would lower a platen with a steel bar in the center to compress the Samples. The Samples were pressurized with water to 500 psi. During the wrinkle formation process, it was expected that the pressure inside the Sample would increase abruptly due to the compression of the Sample (i.e. reduced volume). Therefore, for each test an electronically-controlled automated pressure relief system was used to maintain the pressure in the Samples to as close to the 500 psi target pressure as possible. Figure 5 shows, for illustration, Sample 3 after testing was completed.

Results of the sub-scale testing showed that Sample 1 was compressed severely, while the compression levels for Samples 2 and 3 were reasonable. The purpose of Sample 4 was to verify the required length of the Sample to prevent wrinkles from forming at unwanted locations (omitted for brevity).

In order to validate the FEA methodology for the full-scale tests, another set of FEA analyses were performed using the sub-scale pipe size for the wrinkle creation prior to the sub-scale testing. The sub-scale finite element models were built as axisymmetric models. As such, they are limited in that they can only predict solutions that are also axisymmetric. As shown above with the sub-scale testing results, the wrinkles formed in a non-axisymmetric manner due to small variations in material properties, wall thicknesses, and other nuances that are absent in the idealized FEA models. Otherwise, the sub-scale finite element models are accurate (idealized) representations of the actual Samples that were tested.

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[1] 12.75-inch OD x 0.188-inch wall thickness has approximately the same D/t ratio as the 42-inch x 0.625-inch wall thickness pipe.

Figure 5. Sample 3 (girth weld in center) after sub-scale buckling test of 12-inch NPS pipe

3.2. Full-Scale Testing

The load frame design included 4 hydraulic cylinders having a load capacity of 2.25 million lbf each (9 million lbf total capacity). The pipe Sample was placed in between the circular plate and the top platen. The frame works by extending the hydraulic cylinders and loading the Sample in compression between the circular plate and the top platen, while the all threads react the load and are subjected to tension. Figure 6 shows photographs of the assembly of the frame with the Sample.

Figure 6. Assembly of load frame for full-scale testing

The instrumentation of the full-scale testing consisted of installing a total of 8 bi-axial strain gauges every 45^o around the circumference of the Sample approximately 0.5 inches away from the girth weld to measure the hoop and axial strains during the wrinkle creation. In addition, 4 displacement transducers were placed every 90^o around the circumference of the Sample to measure the axial deflections, and 2 displacement transducers were located 180^o apart near the girth weld to measure radial deflections. In addition, uniaxial strain gauges were placed on every other all-thread to monitor the tensile load in selected all-threads to ensure that they were not subjected to significant bending loads during testing due to misalignment of the equipment.

A pressure chamber that was made using pipe 20-inches in diameter and 20-feet in length was plumbed directly to the wrinkle Sample. This chamber was used as an accumulator to prevent pressure spikes once buckling in the test Sample had initiated.

A total of three (3) wrinkle Samples were fabricated, with the intent of testing only the Samples required to meet the SCF criteria as described earlier in this paper. Only one is described in this paper. The welding of the Samples' girth welds was performed according to the operating companies' approved and qualified welding procedure specification. Once the welding for all three Samples was completed, the welds were inspected and passed a radiography inspection according to API 1104.

Once the wrinkle was created, the flat end caps were removed, and approximately 9-feet of pup length on either side of the wrinkle Sample (24-inches in length) was welded. Strain gauges were installed at five (5) select locations, as well as three (3) displacement transducers equally spaced around the circumference for measuring axial deflection during pressure cycling. The Sample was placed the test pit was and connected to a cycling pump. The pressure was programmed to vary between 100 psi and 850 psi for 9,546 cycles. This cycling regime represents 20 years of service (954 cycles) with a factor of safety of 10. The experimental pressure ranges were determined based on an assessment of historical pressure data provided by the pipeline operator. Using historical pressure history data is an important part of assessing the integrity of damaged transmission pipelines. Even for gas transmission pipelines that do not typically experience a large number of pressure cycles, knowing the number of pressure cycles as a function of time is valuable information.

After the pressure cycling was completed, the next step in the testing was to perform a burst test with the holds shown below:

1. 10 minute pressure hold at 1,042 psi (50% SMYS)
2. 10 minute pressure hold at 1,500 psi (72% SMYS)
3. 10 minute pressure hold at 1,667 psi (80% SMYS)
4. 1 hour hold at 2,083 psi (100% SMYS)
5. Increase pressure to burst.

Figure 7. Sample to be pressure cycled in burst pit with pups, end caps and instrumentation.

3.3. Full-Scale Testing Results – Wrinkle Generation

Figure 8 shows the load (1 kip = 1,000 lbf) vs. axial displacement at the four different displacement transducers, as well as the full-scale finite element analysis results. Note that the drop in load and reload in the experiment was performed in order to visually inspect the wrinkle during the testing process. The final wrinkle geometry formed at the girth weld, 360° around the circumference, with some expected variation in profile.

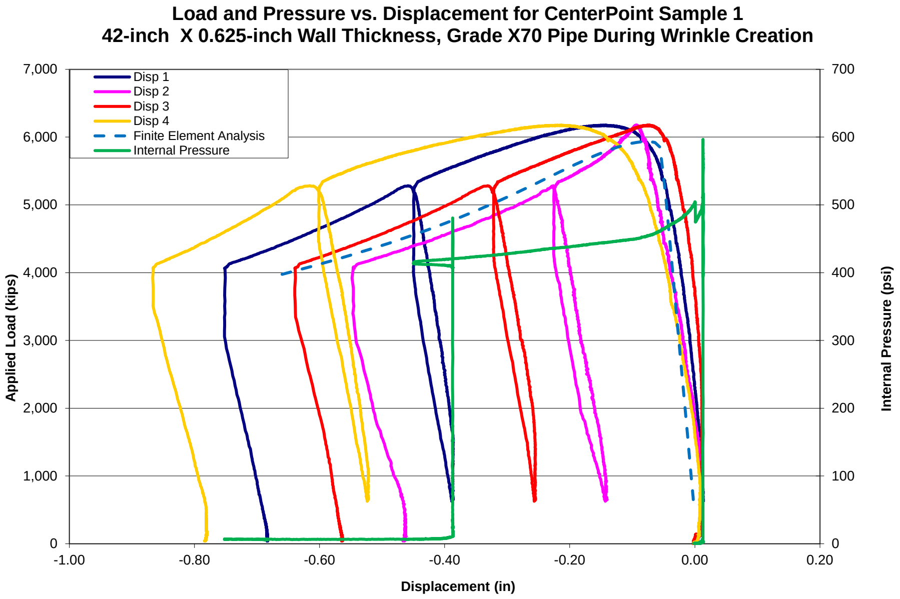

Figure 8. Load vs. axial displacement for Sample 1 and FEA results

Note that the displacements at each of the four experimental locations are not uniform relative to one another. This is due to variations in stiffness at the different locations around the circumference, which is due to slight differences in wall thickness and material properties. Also, note the similarities in the results with the FEA, both in the behavior as well as the magnitudes of the loads and displacements. As a point of reference, the maximum load predicted by the finite element model was 5,936 kips, whereas experimentally the maximum load was 6,177 kips, or a difference of approximately 3.9%. The discrepancy is likely due to variations in wall thickness around the Sample, as well as slight variations in material properties. The FEA work considers the material properties and the wall thickness to be constant and homogeneous. Also note that the material tests showed a small degree of anisotropy, or difference in material properties between transverse tensile tests and longitudinal tensile tests. The FEA models did not consider anisotropic material properties.

3.4. Full-Scale Testing Results – Pressure Fatigue Cycling

After the wrinkle testing was finished, the Sample was instrumented as previously described and pressure cycled from 100 psi to 850 psi for 9,546 cycles. This pressure range was determined from Miner’s rule calculations representing a 20-year service life with a factor of safety of 10.

Figure 9 shows the maximum pressure range history of the fatigue testing. Note that the maximum pressure range is initially 850 psi due to starting from a 0 psi pressure. It also shows the stress concentration factor as a function of cycle count. Similar to the pressure history plot, the SCF at the beginning of the cycling is initially higher due to the pressure starting from 0 psi. However, note how the SCF reduces to a value of approximately 7.0, which is approximately 55% lower than initially. In contrast, the pressure range reduced by approximately 13.3%. It is thought that the redistribution of residual stresses and strains contribute for this reduction in SCF after start-up conditions. In addition, this reduction in experimental SCF is likely very realistic given the expected shakedown to elastic action that likely occurred in the real pipeline.

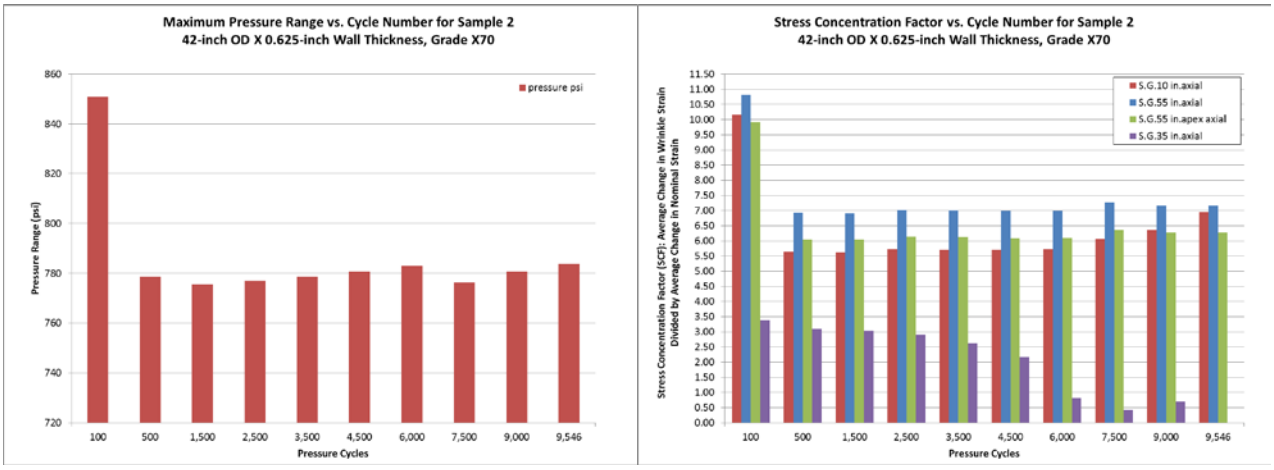

Figure 9. Pressure and SCF as a function of cycle count during pressure fatigue testing

3.5. Full-Scale Testing Results – Burst Testing

At the end of the pressure cycling, the lids from the test pit were removed. The planned testing procedure described earlier was then resumed.

After the first hold, the pressure was then being ramped to 1,500 psi; however, a significant leak formed at 1,434 psi, or 69% SMYS. The Sample was inspected and cracks on the order of 10 – 12 inches in length were found. Figure 10 shows the small puddle of water after pressure cycling was completed.

Figure 10. Leak during burst test after reaching 1,434 psi (photograph taken at approximately 15 psi).

4. Final Remarks

This paper has provided details on a study performed to evaluate damage to a 42-inch x 0.625-inch, Grade X70 HDD pipeline. During a high resolution ILI tool run two wrinkle-like features were detected near girth welds in the horizontally-drilled section of the pipeline. The primary aim of this study was to determine the extent to which the wrinkle-like features might reduce the integrity of the pipeline. The proximity of the features relative to girth welds, and their location in the HDD section of the pipeline, raised the level of interest to a greater degree than if the features occurred only in the base pipe in an area that could be more easily inspected.

A combination of analysis and testing techniques were used to quantify the level of severity associated with the wrinkle-like features. The purpose in conducting a joint analysis and testing effort was to achieve a higher level of confidence in simulating field conditions.

The main conclusion determined from this study is that the wrinkle-like features by themselves (i.e., without cracks) did not pose an immediate threat to the actual pipeline considering the testing survived 20 simulated years of life of pressure cycling at the same pressure range as the actual pipeline was operating at, with a factor of safety of 10 on cycles. However, the Sample did not survive the pressure ramp to 72% SMYS after the pressure cycles, and it leaked at 69% SMYS – note that the pipeline was operating at a significantly lower pressure than 72% SMYS. The existence of cracking ultimately led to a leak scenario, and therefore there was a fair amount of risk of leaving the pipeline in service for any significant period of time as the cracking could also exist in the actual pipeline. Inspection of the actual pipeline was performed and cracking was not detected. Based on these field findings, it was recommended that within the next 12 to 24 months that plans be made for conducting detailed inspection efforts to more accurately survey the potential damage. Of specific interest is the potential for cracks in the girth welds interacting with the wrinkle-like features, as these cracks may exist in the real pipeline from the postulated compressive loading that may have been applied during the creation of the wrinkle. Additionally, the potential for miscalling the severity of the wrinkle-like geometry should be addressed in the additional inspection effort to ensure that a conservative path plan forward is developed. Ultimately, the evidence of cracking after a simulated 20 years of pressure cycling, with a design margin of 10 on cycles, created enough concern to the operator that the pipeline was removed from service at an appropriately scheduled time in the future. Concerns related to accuracy associated with ILI technologies also contributed to the decision to remove the wrinkles from service.

The methods employed in this study can be applied to other scenarios encountered by pipeline operators to ensure good integrity decisions are made regarding high risk, challenging anomaly assessments.

5. References

[1] Scrivner, R. and Alexander, C., "Elements of an Engineering-Based Integrity Management Program," Proceedings of IPC2008 (Paper No. IPC2008-64492), 7th International Pipeline Conference, September 29-October 3, 2008, Calgary, Alberta, Canada.

[2] “Evaluating Damage to a HDD Pipeline”, Stress Engineering Services, March 2012.

[3] API 579-1 ASME FFS-1 Standard for Fitness-For-Service (2007) American Society of Mechanical Engineers, New York.

[4] API 1104: Welding of Pipelines and Related Facilities, 21st edition - American Petroleum Institute.