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USING TESTING METHODS TO EVALUATE SUBSEA PIPELINE PERFORMANCE AND INTEGRITY

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

ABSTRACT
Evaluating the integrity of subsea pipelines involves a variety of tool and skill sets. Over the past several years there has been an increased interest in assessing the performance of pipeline systems using full-scale testing. Modes of testing have included full-scale bursting, pressure cycle fatigue, bending, and dropped object work. While lessons learned from prior experience and analysis are valuable, the role of testing in the evaluation process is receiving focused attention due to the critical nature of the subsea pipeline infrastructure.

This paper includes discussions on how testing has been used assist pipeline companies assess the integrity of their pipeline systems and components used to support pipelines. Specific emphasis is placed on helping the reader better understand what testing techniques are most appropriate and determining how to interpret and correlate the results into useful information for operating safe pipelines. Case studies are presented that include burst testing and pressure cycling anchor-damaged pipes, proof testing a riser cross-haul bucket tool, impact testing a pipeline protection system, and using burst testing to determine the limit state capacity of a pipeline.

INTRODUCTION
Like many aspects of engineering, integrity management is a combination of economics and safety, and few in the profession will argue that they are not linked. While experimental work has always played an important role in engineering, its importance is even greater considering the costs associated with lost production in pipeline systems. It is the author's observation that in many regards confidence achieved through successful testing provides engineers with critical knowledge required to make information decisions about how to maintain pipelines. When pipelines are damaged, the criticality of the decision-making process is at an all-time high.

This paper has been written to serve as a resource for engineers charged with the task of operating pipelines and pipeline systems. The topics of discussion include the philosophy of testing in terms of when testing is most appropriate. The sections of this paper include a *Background* section covering some of the different types of testing. And as discussed previously, the main focus of this study is a presentation on four case studies that include:

- Burst testing and pressure cycling anchor-damaged pipes
- Proof testing a riser cross-haul bucket tool
- Impact testing a pipeline protection system
- Burst testing to determine the limit state capacity of a pipeline.

A closing section provides comments on how the information presented in this paper can be used by pipeline operators as they face damage to their pipeline systems.

BACKGROUND
When designing a testing program for pipelines, the most critical element is to understand the potential failure modes. Provided below are the major defect classifications that typically arise when assessing damage to subsea pipelines.

- Plain dents
- Gouges
- Mechanical damage (dents with gouges)
- Wrinkles or kinks
- Ovality
- Corrosion

Onshore and offshore pipelines are subject to different failure modes, although the damage associated with dents and gouges is common to both. Work that involves evaluating pipeline damage is either reactive or proactive. The reactive evaluations are typically in response to a failure or incident that has occurred. A proactive response is one that involves evaluating the severity of a given defect before there is any particular need to a response. Both responses have their place. It is not possible to predict everything that will happen to a pipeline. However, it is apparent that as the pipeline industry marches through time knowledge is gained that permit appropriate responses to ensure the safe operation of pipelines. The operation of safe pipelines is at the core of integrity management,

There are several elements that are integral in any pipeline valuation. First, a review of the open literature and study of previous experience often provides insights on how pipelines respond to certain types of damage and the associated consequences. The second element group utilizes numerical modeling such as finite element analysis. One benefit in numerical modeling is the ability to evaluate the effects of different variables on the response of a pipeline to a specific type of damage. This often happens when no previous experience is available or engineers are resource-constrained in pursuing testing efforts. The third option involves experimental methods. It is the author's opinion that when practical and sufficient resources are available, testing should be part of any evaluation effort. If existing test data is not readily available, full-scale testing should be performed. Tests can either be destructive where test samples are taken to failure, or involve an increase in loading to a non-failure position where instrumentation measures the response of the sample to external loads.

Provided below are several types of tests that are often used in evaluating pipeline damage and integrity.

Burst Testing

Fundamentally pipelines are required to contain pressurized fluids. The primary basis of the pipeline design codes used in the United States (ASME B31.4 and B31.8 for liquid and gas pipelines, respectively) is hoop stress. In this regard, burst tests are a classic method for establishing the pressure integrity capacity of a given pipe. Additionally, it is possible to extend existing design margins by conducting extensive bursts tests on a given pipe to statistically evaluate geometric and material issues. In the past burst tests have been used to evaluate factors such as weld seam integrity, girth welds, dents, and gouges. In conducting burst tests, investigators are able to quantify the severity of the defect and determine the pressure at which failure will occur. As in all experimental efforts, the importance of statistical significance cannot be underestimated. When possible and practical, it is best to conduct multiple tests.

Pressure Cycle Fatigue Testing

While the failure mode for most gas and liquid pipelines is pressure overload, another contributor involves fatigue due to cyclic pressures. As the description implies, testing associated with pressure cycling involves connecting a sample to a pressure pump and apply pressure cycles at a specified pressure range. This typically involves a control unit with set-points at the lower and upper pressure levels.

Pressure cycles are typically applied for one of two reasons. The first simply involves applying pressure cycles to a test sample until failure occurs. The second option is to apply a specific number of pressure cycles to represent future service conditions. This usually involves evaluating pressure cycles data including frequency and range for a given period of time. This information is then used to generate loading conditions to represent future years of operation (e.g. 20 years).

Bend Testing

Offshore pipelines are subjected to loads other than just internal pressure. Examples where tension and bending are applied include the installation process off the back of a stinger where maximum strains occur at the overbend and sagbend. Additionally, thermal loads generate compressive stresses and consequent bending stresses associated with upheaval and lateral buckling.

Several testing systems have been designed to specifically simulate pipe bending. The first is a simulator designed to induce strains associated with the reeling or S-lay process. **Figure 1** and **Figure 2** include a schematic drawings and photograph of a bent pipe, respectively. As shown, this particular system induces a pure bending moment across the given pipe section. The second test set-up permits a pipe sample to be simultaneously subjected to internal pressure, axial tension, and bending using a four point bend set-up. A schematic and photograph are shown in **Figure 3**. This latter configuration is used extensively because of the ability to evaluate simultaneous loading and evaluate the effects of any particular loading variable.

CASE STUDIES

To demonstrate the effectiveness in using testing as a means for evaluating pipeline integrity management, four case studies are presented. Each of these case studies involved a particular issue with a pipeline system. The purpose in testing was to provide additional insights that either confirmed finite element analysis results or the testing results were used in and of themselves to make critical decisions about future pipeline operation.

Anchor Snag Damage to Subsea Pipeline

Subsea pipelines are subject to external damage. In recent years the active hurricanes in the Gulf of Mexico have caused significant damage to pipeline infrastructure as was evident in its aftermath. It is possible to classify post-hurricane damage to pipelines into two categories:

a. Direct damage due to hurricane or natural hazard that includes, loss of cover, exposed and spanned pipelines, pipelines that have moved significantly or strained because of mudslides and in extreme cases fully ruptured lines.
b. Secondary damage that includes damage from anchor drags, primarily from drilling vessels that go adrift during the hurricane. Anchor drags or snags produce significant damage on pipelines-like dents, gouges and cracks. Closer to the platforms, heavy objects can fall on pipelines and risers causing significant damage. DNV has produced a report that categorizes the damages seen after Katrina and Rita [1]. Results are provided in **Figure 4**.

The case study that is presented herein involves the Shell Ursa subsea gas pipeline that was damaged during Hurricane Katrina [2]. The Ursa TLP is located approximately 188 km (130 miles) southeast of New Orleans. It encompasses Mississippi Canyon blocks 808, 809, 810, 852, 853 and 854. The water depth averages approximately 1200 m (4,000ft). It is designed to process 150,000 bbl of oil and condensate, 400 MMcf of gas, and 50,000 bbl of produced water per day. Production from the platform is transported approximately 70 km (47 miles) via an 18-inch diameter oil pipeline and a 20-inch diameter natural gas pipeline, to the West Delta 143 platform.

Hurricane Katrina had significant operational impact on the assets in Gulf of Mexico. The Ursa gas pipeline suffered damage presumably from anchor drags. The damage was observed at a water depth of approximately 1000 meters. The pipeline was dented at the longitudinal seam weld (as seen in **Figure 2**). In addition, the line itself was displaced in the horizontal plane.

The Ursa gas export line is made of 500 mm (20-inch) OD x 18 mm (0.75-inch) WT, API 5L-X60 DSAW pipe. The maximum operating pressure of the line is 155 Bar (2200 psi), and external pressure is 95 Bar (1350 psi). At time of anchor dragging the line, it was operating at 77.4 Bar (1100 psi). The dent, shown in **Figure 5**, was in the range of 57 mm to 70 mm. (approximately 2 ¼ - 2 ¾ inches) deep.

In order to estimate the future performance of the damaged pipeline, full-scale testing was conducted. Dents were installed in 10-ft long pieces of 20-inch x 0.75-inch, Grade X60 pipe material. **Figure 6** shows the dent installation rig that was used to general dents that replicated the actual dent profile [3].

The primary purpose of the test program was to evaluate the integrity of the damaged pipe subject to loads including cyclic pressure and burst pressures. The test program involved several specific phases of testing that included the following:

- Dent installation including measurement of dent depth, loads, and dent profile
- Monitoring strain gages during indentation and pressure cycling
- Hydrotesting to a specified pressure level
- Fatigue testing nine dented samples
- Burst testing one dented sample.

Provided in **Table 1** is a summary of the fatigue test results. As noted, the minimum number of cycles to failure was 3,992 cycles, although the vast majority of the cycles to failure exceeded 10,000 cycles. Additionally, the burst test sample with the 2.5-inch dent in the seam weld burst at 6,419 psi (143% SMYS).

Using insights from the results of this test program, the operator was able to continue operation until an appropriate time when permanent repair options could be completed. By conducting and obtaining successful results, the decision was reached based on confidence achieved through statistically significant test data.

Proof Testing a Riser Cross-haul Bucket Tool

While the other case studies in this paper address issues specific to testing pipe, this particular case study provides results from a test program conducted on a device known as a cross-haul bucket. This device was used on an offshore platform for the pick up, cross haul, and hang off installation of the Independence Hub Steel Catenary Risers in MC 920 in 8000 feet of water depth. The objective in testing was to measure the load capacity of the cross-haul buckets and verify that they were fit for service [4].

Prior to testing, a test fixture was designed, evaluated, and analyzed. Because of the significant loads involved (i.e. 1064 mT (2,345 kips)), it was essential that every effort be made to ensure the safety of equipment and personnel. The test subjects included a 20-inch and a 10-inch / 8-inch, cross-haul buckets. Strain gages were applied to the lugs of the bucket samples to measure strain during loading. Loads corresponding to the flooded weight of the SCR with dynamic load factors were applied to the samples 15-degrees from vertical (8-inch bucket) and 22-degrees from vertical (20-inch bucket). A 625 mT (1,378 kips) load was applied to the three 10-inch / 8-inch cross-haul buckets and no significant through-wall yielding of the bucket was observed. For the 20-inch cross-haul bucket, a load of 1064 mT (2,345 kips) was applied and no significant through-wall yielding of the bucket was observed, indicating the buckets were adequately design for their intended service.

Figure 7 is a schematic of the test set-up, while **Figure 8** is a photograph showing the cross-haul bucket lifted prior to testing. Shown in **Figure 9** is the test set-up for the 10-inch/8-inch cross-haul bucket that includes the test fixtures and the vertically-positioned hydraulic cylinders. Both of the buckets were loaded to target levels. During testing the maximum von Mises stresses measured by the strain gages for the 8-inch/10-inch and 10-inch buckets were 38 ksi and 50 ksi, respectively. The maximum strain was very localized and only occurred at the bottom of the hole near the point of contact with the loading pin.

Figure 10 is a photograph of the Cross Haul Bucket during SCR installation. This test program was a critical part of the successful deployment of these devices as the results assured operational engineers that they could serve their intended purpose and safely lift risers from 8,000-ft water depths.

Impact Testing a Pipeline Protection System

One of the primary concerns for subsea pipeline involves damage from dropped objects. Using risk analysis modeling, it is possible to estimate the likelihood of impact, as well as the consequence of damage. A study was conducted to evaluate the effectiveness of a pipeline protection system (PPS) designed to protect a Chevron subsea 16-inch products pipeline off the coast of Angola in West Africa in approximately 400 feet of water beneath the South Nemba platform. The plan prior to the study was for platform upgrades to be made and concerns existed regarding the potential for dropped objects. Chevron specified that the PPS be designed to withstand a minimum impact of 3 MJ, with the possibility for extending this to 5 MJ. Full-scale testing played an integral role in evaluating the PPS. The work involved a combination of testing and analysis methods. Chevron developed the basic design of the PPS that included a large diameter upper (60-inch diameter) and a lower (72-inch diameter) half-pipe assemblies placed over the top of the 16-inch diameter pipeline. Preliminary analyses calculated the potential energy absorption capacity of the design considering variations in thickness of the PPS structural members. Using insights gained from the preliminary analysis, full-scale drop tests were performed on prototype PPS pieces fabricated from rolled and welded steel plate. These drop tests released a 23,850 lbs weight dropped from 25.2 feet, resulting in impact energies of 815 kJ. Significant deformation was inflicted to the PPS tests pieces during the drop tests; however, the 16-inch diameter pipe placed beneath the protection was untouched for all tests except the one that did not include the upper half-pipe shell.

Using insights gained from the quasi-static tests and preliminary finite element work, efforts were focused on full-scale drop tests. The drop tests used a forging weighing 23,850 lbs dropped from a height of 25.2 feet (measured from top of the PPS to dropped object center of mass) resulting in an impact energy of 815 kJ. A photograph of the dropped object is shown in **Figure 11**. <u>The primary objectives of the full-scale drop tests were to demonstrate several important elements:</u>

- Confirmation that the energy capacity predicted by the finite element analysis was accurate.
- Demonstrate the failure mode associated with collapse of the upper shell and that the PPS had sufficient rigidity to withstand the imparted impact loads.
- Observe the soil-structure interaction and assess the level of residual deformation in both the soil and PPS after impact.
- Use high speed data acquisition to capture displacement (i.e. velocity) and acceleration as functions of time.
- Assess the overall benefit of the Submar concrete mattress on energy absorption.

A total of four drop tests were performed. **Figure 12** provides a schematic showing the four different configurations. As noted, one of the test variables included location of impact relative to the internal reinforcing gusset. The four tests included the following configurations:

- Test #1 - Standard PPS with drop offset from gusset approximately 3 feet.
- Test #2 - Standard PPS with drop on top of gusset end.
- Test #3 - Standard PPS with Submar mat (drop at axial center).
- Test #4 - No upper shell PPS with Submar mat (drop at axial center).

Measurements played an important role in evaluating the overall response of the PPS design. Measurement devices included strain gages, displacement transducers, and accelerometers. **Figure 13** shows the location of the four displacement transducers. Also shown in this figure is the viewpoint used for the high speed video camera. From previous studies, SES knew the contribution that high speed video would have for assessing the overall response of the PPS test pieces to the impact loading. Studio Works of Houston, Texas was contracted to provide this service. High speed video was captured in digital format at a rate of 2,000 frames per second. This rate corresponds to a period of 0.0005 seconds for every captured image on the video. Digital video files (mpeg format) were produced after testing was completed that included a counter showing elapsed time during the period of impact.

Figure 14 is a photograph showing the set-up for the full-scale testing. As shown, a gantry crane capable of lifting objects to heights up to 35 feet was used. The spacing between the gantry jacks was deemed sufficient to prevent contact with the dropped object after impact. The PPS test pieces were also oriented in such a way as to increase the likelihood that their post-impact response would direct them away from the gantry crane jacks.

Figure 15 through **Figure 18** provide photographs for Tests #1 through #4, respectively. The following observations are made in viewing the visual aspects of the drop tests:

- Tests involving the full PPS design (Tests #1, #2, and #3) demonstrate that the design had sufficient rigidity to prevent the prevent damage to the pipe.
- The PPS design without the upper shell (Test #4) clearly demonstrates the importance of the upper shell. Contact with the pipe was made in this test.
- The Submar mats act to distribute load to the overall PPS structure as shown in comparing the less severe damage shown in **Figure 17** (Test #3) to more extensive damage observed in **Figure 15** (Test #1).

The full-scale testing results presented in this paper were used to validate finite element models. Using numerical models that integrated the effects of soil and interaction with the PPS, the study verified that the proposed design could indeed protect the 16-inch pipeline from impact energies up to the target level of 5 MJ.

Determining the Limit State Capacity of a Pipe

Prior to commissioning a pipeline company wanted to verify the performance of their subsea 18-inch x 0.75-inch, Grade X65 pipe material. Two full-scale tests were conducted: one whose focus was on the DSAW seam weld, while the intent of the second was to evaluate the integrity of a girth weld. Strain gages were also installed on the pipes and monitored continuously during testing.

Figures 19 and **20** are photographs showing the test set-up. **Figure 21** provides maps showing the locations of the strain gages. **Figure 22** plots the strain gages results for the girth weld test sample. **Figures 23** and **24** are photographs showing the failure in the base pipe and girth weld test samples, respectively. It is significant to note that both of these failures resulted in a classic "fish mouth" appearance characteristic of a ductile overload condition.

The base pipe sample failed at a burst pressure of 7,473 psi (1.38 times SMYS and 2.0 times MAOP). The second sample, the girth weld sample, failed at the center of the sample after achieving a pressure of 7,437 psi (1.37 times SMYS and 2.0 times MAOP). The longitudinal seam and girth welds did not contribute to the failures in either of the two test samples.

After testing, a cross-sectional view of the failure from the base pipe test sample was made. What is observed in **Figure 25** is a classic cup and cone fracture associated with ductile tensile overload. The 0.75-inch nominal wall necked down to be less than 50 percent of the original wall thickness, further demonstrating the level of ductility associated with the failure.

The results of this test program demonstrated the integrity of both the base pipe and the girth weld that were fabricated for this testing effort. Additionally, this program demonstrates how engineering testing methods can be used to evaluate the integrity of pipe materials including girth welds.

CONCLUSIONS

This paper has provided discussions and insights on how testing methods are used to validate the integrity of subsea pipelines. Studies were conducted on both new pipe, as well as pipe that had been damaged in some form.

Much of the work that is done on subsea pipelines involves numerical modeling analysis. While there is obvious benefit in conducting analytical studies, the importance of experimental verification cannot be underestimated. This is even more important when considering integrity management issues where decisions regarding future operation of a damaged pipeline are to be made. Additionally, properly-designed experiments can validate specific data sets within a numerical model. Once this is achieved, the analyst can proceed with confidence in using the models to evaluate more general conditions.

REFERENCES

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[2] Technical Report, MMS Report No: 448 14183 Rev-1, Det Norske Veritas.

[3] D. Raghu, R. Swanson, and C. Alexander, (May 2008), "Methodology to Establish the Fitness for Continued Service of a Hurricane Damaged Export Pipeline in 1000 m of Water," Paper No. OTC-19653-PP, 2008 Offshore Technology Conference, May 5–8, 2008, Houston, Texas.

[4] Alexander, C., Mekha, B., Hogan, M., Rager, B., and Kumar A., (June 2008), "Design, Manufacture, Testing, and Deployment of a Cross Haul Bucket for the Independence Hub", Paper No. OMAE2008-57598, The 27th International Conference on Offshore Mechanics and Arctic Engineering, June 15-20, 2008, Estoril, Portugal.

[5] Alexander, C.R., Manimala, Y., Stubbs, L., and Spikula, D., "Evaluating the Performance of a Pipeline Protection System to Prevent Damage to Subsea Pipelines from Dropped Objects," Paper No. IOPF2008-903, Proceedings of the ASME International Offshore Pipeline Forum, October 29-30, 2008, Houston, Texas.

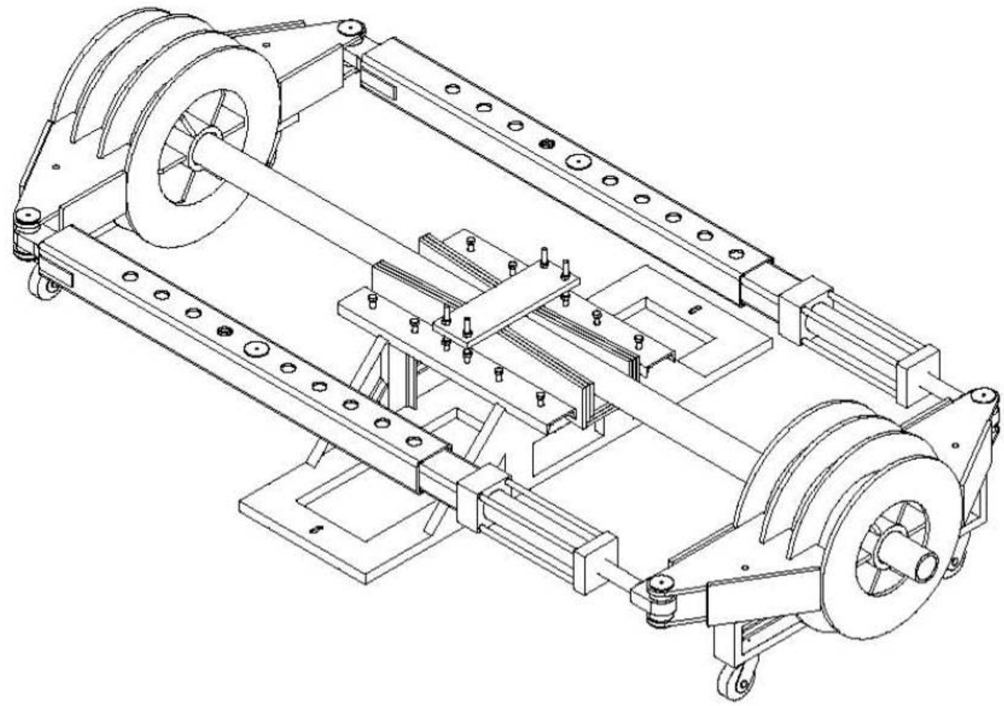


Figure 1 – SES pipe strain simulation machine [1]

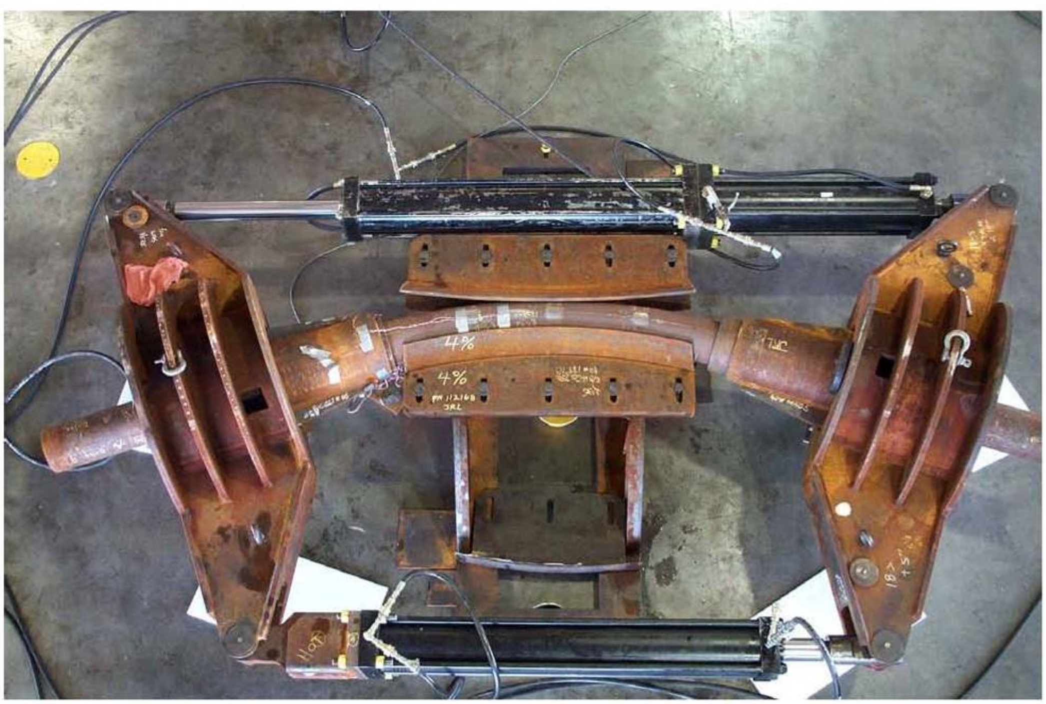


Figure 2 – Photograph of pipe bent to simulate 4 percent bending strain [1]

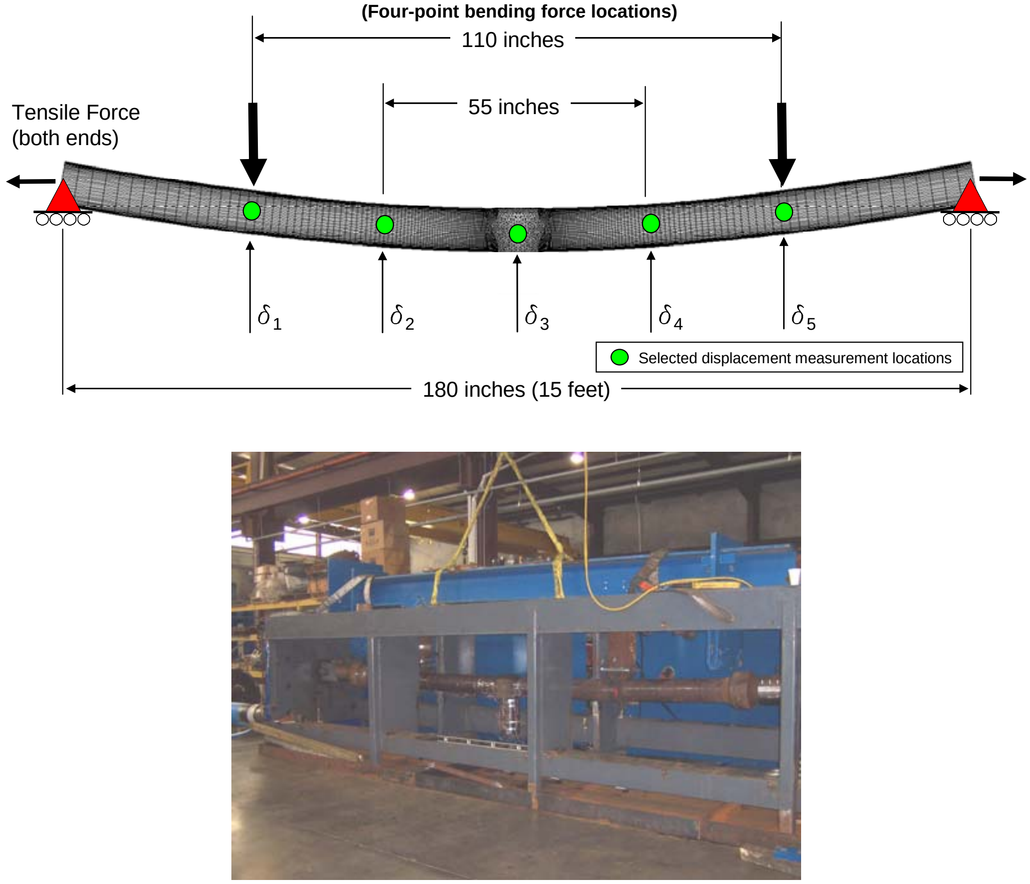


Figure 3 – Schematic and photograph of four point bending test set-up

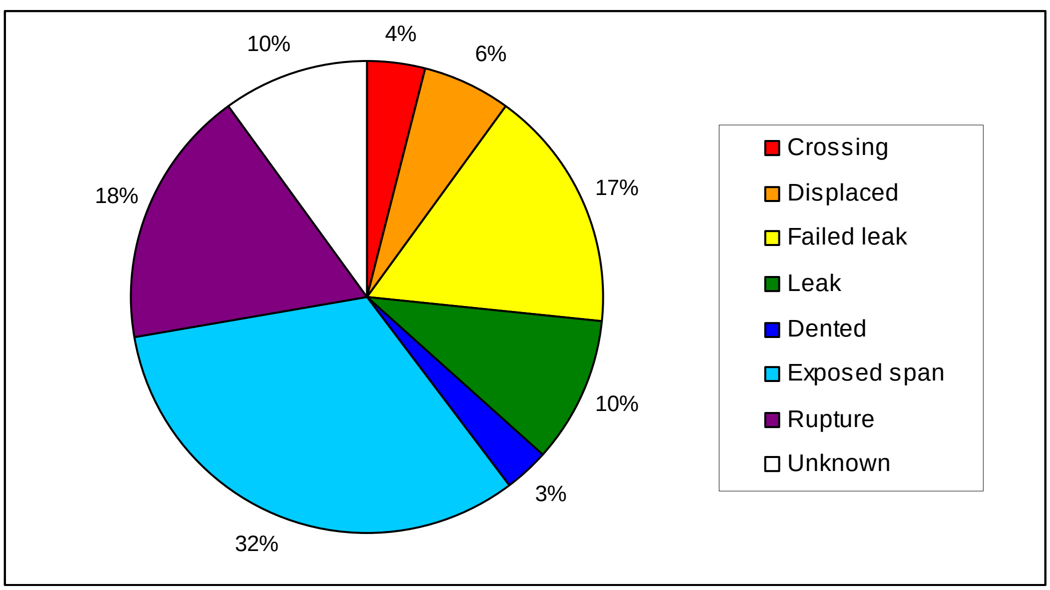


Figure 4 – Damage inflected from Katrina and Rita per DNV report [2]

Figure 5 – Photograph of dent in 20-inch Shell URSA gas pipeline [3]

Figure 6 – Photograph of dent installation rig [3]

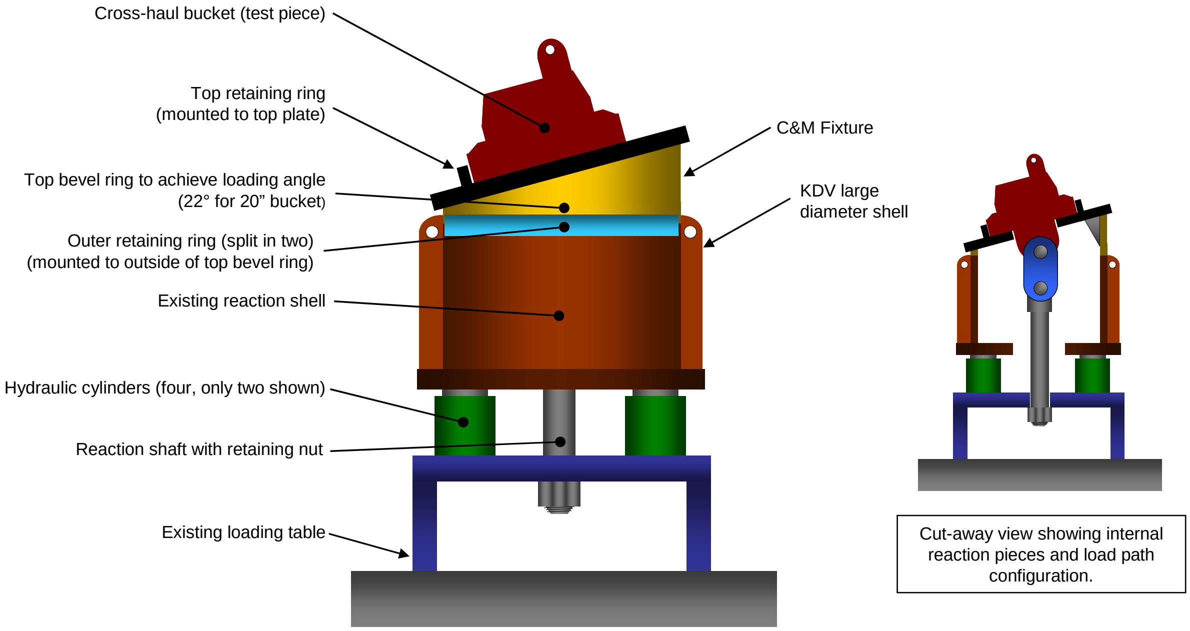


Figure 7 - Diagram of cross-haul bucket test set-up [4]

Figure 8 - Assembled cross-haul bucket and reaction shaft [4]

Figure 9 - Test set-up for the 10-inch / 8-inch cross-haul bucket [4]

Figure 10 – Cross Haul Bucket during SCR Installation [4]

Figure 11 – Photograph of weight serving as dropped object [5]

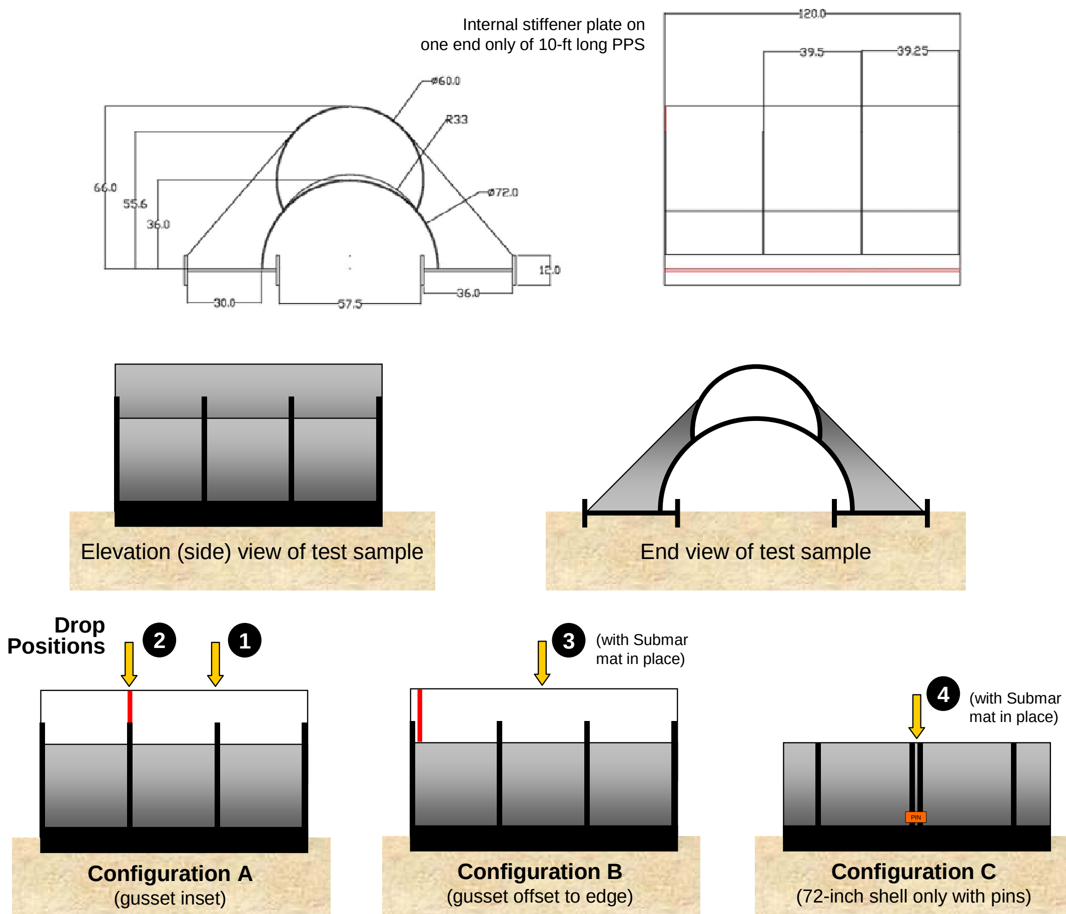


Figure 12 – Schematic diagram showing four drop test configurations [5]

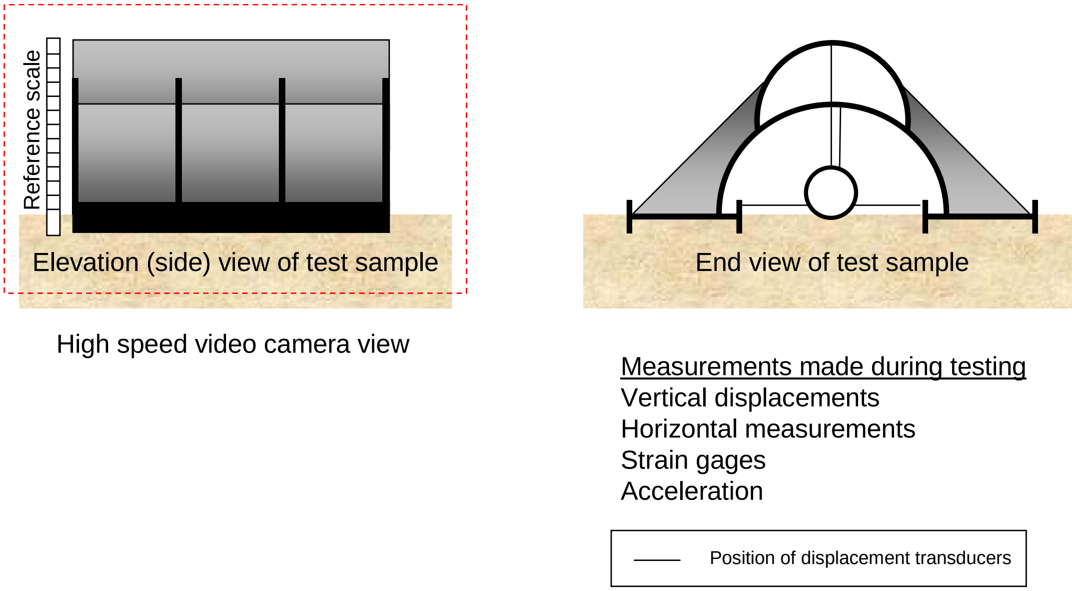


Figure 13 – Measurements devices used in full-scale drop testing [5]

Figure 14 – Photograph showing gantry jack crane used to drop weights [5]

Figure 15 – Photographs from Test #1 drop test [5]

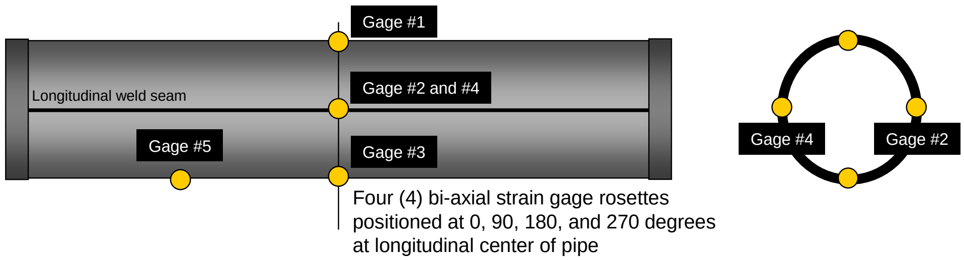
Figure 16 – Photographs from Test #2 drop test [5]

Figure 17 – Photographs from Test #3 drop test [5]

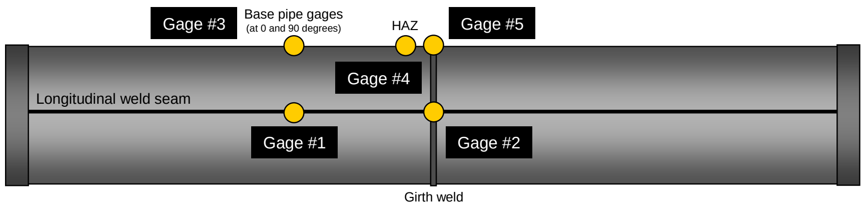
Figure 18 – Photographs from Test #4 drop test [5]

Figure 19 – Burst test set-up showing pipe enclosure and concrete blocks

Figure 20 – Inside view of test sample in pipe enclosure



Sample #1 – Test of base pipe only



Five (5) bi-axial strain gage rosettes installed on girth weld test sample (one on longitudinal weld crown, one on girth weld crown, one in HAZ of girth weld, and two placed on the base pipe) to measure hoop and axial strains

Sample #2 – Test of girth weld

Figure 21 – Maps showing locations of strain gages on test samples

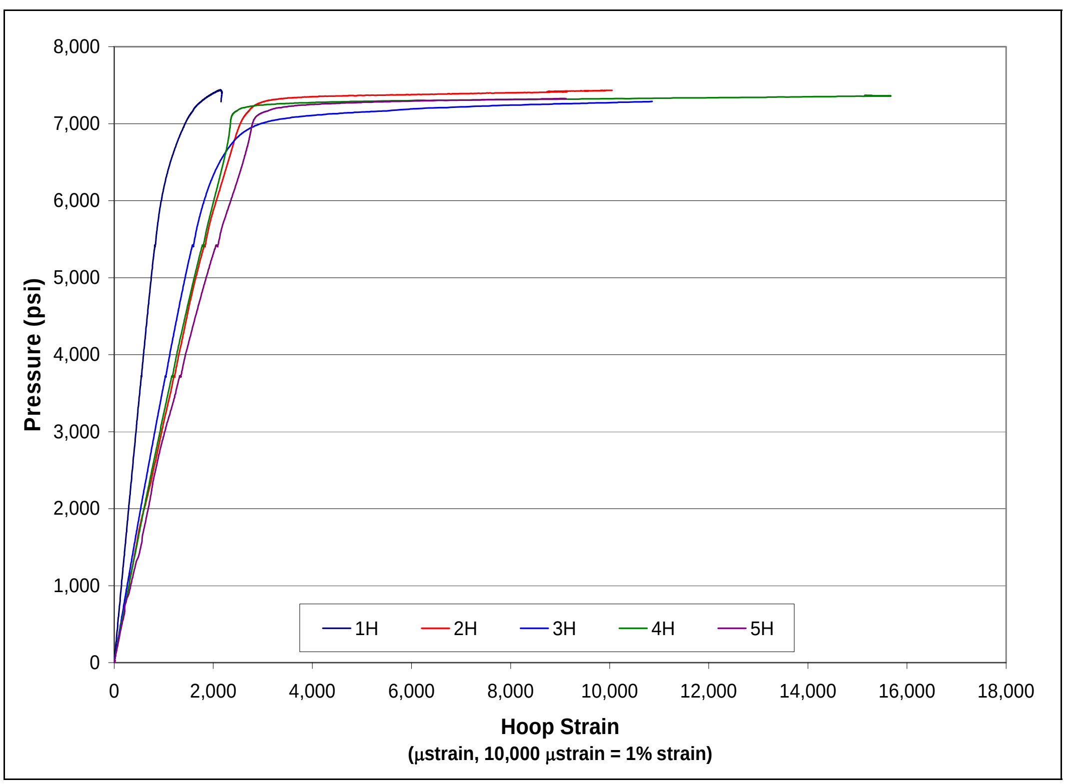


Figure 22 – Hoop strain measured in the girth weld test sample
(refer to **Figure 21** for strain gage location numbers)

Figure 23 – Failure in the base pipe sample

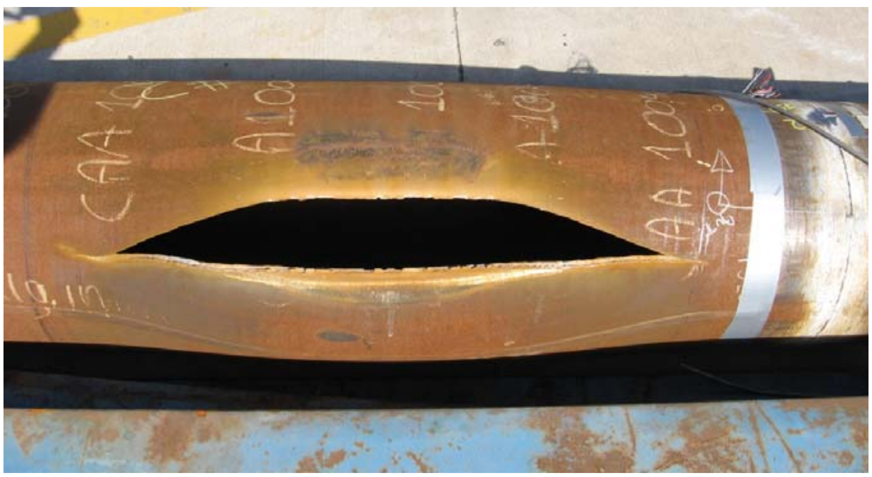


Figure 24 – Failure in the girth weld sample

Figure 25 – Cross-sectional view of the base pipe test sample after failure

Table 1 – Denting and Cyclic Pressure Results for URSA pipeline study [3]

Specimen	Length (ft)	Max Dent Depth (in)	Max Dent Force (lbs)	Cycles to Failure	Remarks
1	8	3.037	357,104	43,721	Hydrotest Pressure: 2200 psi Mean Pressure: 1700 psi Pressure Range: ±300 psi
2	8	3.699	412,155	3,992	Hydrotest: 2200 psi (30 min) Mean Pressure: 1300 psi Pressure Range: ±600 psi
3	13	2.46	386,433	48,175	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±400 psi
4	16	2.53	392,985	10,000	No Hydrotest Mean Pressure: 1300 psi Pressure Range: ±600 psi
5	8	2.67	399,688	7,316	Hydrotest: 2200 psi (30 min) Mean Pressure: 1300 psi Pressure Range: ±600 psi
6	8	2.65	398,471	8,489	Hydrotest: 1500 psi (20 min) Mean Pressure: 700 psi Pressure Range: ±600 psi
7	8	2.98	412,800	8,488	Hydrotest: 1500 psi (20) Mean Pressure: 700 psi Pressure Range: ±600 psi
8	8	2.71 (@ 180°)	N/A	20,721	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±600 psi (failure occurred in weld seam)
9	8	2.77	N/A	11,200	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±600 psi (sharper dent profile)