

## **EVALUATING ANCHOR IMPACT DAMAGE TO THE SUBSEA CANYON CHIEF PIPELINE USING ANALYSIS AND FULL-SCALE TESTING METHODS**

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### **ABSTRACT**

This paper presents findings from a study conducted as part of a joint industry effort involving engineers from Williams Midstream, Stress Engineering Services, Inc., GL Noble Denton, and Saipem America. The purpose of this study was to evaluate the severity of damage inflicted to Williams' subsea 18-inch x 0.875-inch, Grade X60 Canyon Chief Gas Export Pipeline due to an anchor impact at a water depth of 2,300 feet. The phases of work included an initial assessment after the damage to the deepwater pipeline was detected, evaluating localized damage via finite element analysis based using in-line inspection data, full-scale destructive testing including burst tests, and final efforts included the design and evaluation of a subsea-deployed repair sleeve. The study included modeling Saipem's repair sleeve design accompanied by full-scale destructive testing. Strain gages were used to measure strain in the reinforced dent beneath the sleeve, that were then compared to prior results for the unrepaired dent test results.

The work associated with this study represents one of the more comprehensive efforts conducted to date in evaluating damage to a subsea pipeline. The results of the analysis and testing work provided Williams with a solid understanding on the behavior on the damage inflicted to the pipeline and what level of performance can be expected from the repaired pipeline during future operation. After the engineering analysis and testing phases of this work were completed, the deepwater pipeline was repaired

information included ROV video footage, in-field measurements using ROV-assisted tools, and in-line inspection data that provided the three-dimensional geometry of the dent. A photograph is provided in Figure 1 was taken using an ROV showing the geometry of the dent. As observed in this figure the coating was relatively intact, although the in-line inspection tool did detect metal loss in the vicinity of the dent. Figure 2 includes a sonar image of the bend in the pipeline, which was overlaid with scale circles used to provide an estimate of the radius of bend. As shown, the radius of the bend was between 35 and 80 feet.

After the initial inspection efforts were completed, Williams contracted the services of Stress Engineering Services, Inc. to perform an assessment of the pipeline damage. Finite element analysis, along with and full-scale destructive testing were used to evaluate the damage inflicted to the 18-inch x 0.875-inch, Grade X60 Canyon Chief Gas Export Pipeline. At the time of the incident, the operating pressure was 1,450 psi (25% SMYS), while the maximum allowable operating pressure (MAOP) is 3,600 psi (62% SMYS). Multiple defects were detected in the pipeline and measured during the in-line inspection, some involving dents with combined metal loss. From among the identified defects the most severe dent defect was selected and evaluated for further study. The assessment included detailed modeling, as well as full-scale destructive testing. In a parallel effort, Williams retained the services of Saipem America to assist in the design, assessment, construction, and deployment of a repair sleeve.

The main focus of the testing program was to experimentally quantify the severity of damage inflicted to the pipeline by the anchor snag. The limited finite element modeling supported the experimental work, primarily to size the indenter geometry. In-line inspection data provided by Rosen was used to generate a representative dent defect including the associated metal loss. The repair sleeve, designed by Saipem America, was tested as part of the program, with results being compared between the reinforced and unreinforced dent geometries to evaluate the effectiveness of the repair.

The sections of this paper that follow provide details on the finite element modeling work, experimental assessment efforts, and design/fabrication/deployment of the sleeve technology to reinforce the damaged Canyon Chief pipeline. The authors of this paper were able to participate in all phases of this project, spanning the initial assessment of the dent in question after its discovery to actually designing and deploying the repair technology.

### **INTRODUCTION**

The Williams Canyon Chief 18-inch diameter pipeline was hooked by an anchor in late 2005 at a depth of 2,300 feet. The resulting damage pulled the pipeline laterally 1,500 feet from its original path. Inspection efforts using ROVs at the time of the accident indicated that the pipeline was not leaking. However, in the interest of safety, the pipeline pressure was lowered to approximately 800 psi (15% SMYS, pressure, where SMYS is the Minimum Specified Yield Strength of the pipe material) and allowed to continue operation while a remediation method was developed (the repair was made at a reduced pressure). The intent after remediation work was completed that the pipeline would be returned to the full 3,200 psi (55% SMYS) operating pressure.

A minimum level of information was available; however, the clearly-defined objective from Williams was to develop a reinforcing solution to restore integrity to the damaged pipeline that involved a dent having material loss in a bent section of pipe. Sources of

## FINITE ELEMENT MODELING

An in-line inspection conducted by Rosen detected the presence of multiple dents, including one having a depth of 7.4 percent of the outside diameter of the pipe. Additionally, this dent damage included a localized metal loss having a depth of 11 percent of the pipe's nominal wall thickness. A total of 16 dents were evaluated using finite element analysis (FEA), although the primary focus was a 7.4 percent deep dent, identified by Rosen as Dent ID 339968. Figure 3 provides a stress contour plot from the finite element analysis for the dented region at a pressure of 100% SMYS (hoop stress of 60,000 psi). As noted in Figure 3, the maximum principal stress is 221.4 ksi, corresponding to a stress concentration factor of approximately 3.7. FEA was also used to calculate stresses in the sleeve and also estimate the level of strain reduction in the dented region due to the presence of the sleeve. Figure 4 is a schematic diagram showing the layout for this particular FEA model, while Figure 5 plots strains in the dented region with and without reinforcement. As observed in this latter figure, the sleeve acted to reduce strain in the dent by a factor of approximately 5 at a pressure of 1,450 psi (25% SMYS).

An FEA model was also constructed of the pipeline-grout sleeve system and determined that expansion of the pipeline due to increased internal pressure would apply an expansion force through the grout that the sleeve would see as an internal pressure of 750 psi. However, it was recognized that the seals in the sleeve would not see a pressure due to expansion of the pipeline. Instead they would only see the pressure of the cement grout during injection. Therefore, it was accepted that some leakage of the seals during the hydrotest could be allowed. The grout sleeve itself is not a pressure-containment but is simply a strong-back for the grout. This fact simplified sealing of the sleeve on the pipeline and allowed a novel end seal arrangement. This arrangement kept the corners of the end seals at the horizontal split line pulled back away from the pipeline until after the sleeve was closed around the pipe.

## TESTING METHODS AND RESULTS

In addition to the finite element modeling work that was used to evaluate the relative severity of the dent, experimental investigations were undertaken to determine the relative severity of the dents with metal loss and also evaluate the feasibility of the proposed repair solutions. While the primary focus of the experimental work involved full-scale destructive testing, sub-scale testing using smaller diameter pipe was also conducted to evaluate the level of reinforcement provided by select filler materials that had to be deployed from a boat to the repair being made at a water depth of 2,300 feet.

The sections of this paper that follow provide details on the testing methods and results associated with the sub-scale and full-scale tests, respectively.

### Sub-Scale Testing Efforts

Several sub-scale tests were performed using 8-inch nominal diameter pipe material to evaluate the performance of two load-transfer filler materials in a cold water environment. The sub-scale tests were designed to address the following questions that were raised during the early phases of this project.

- Is it possible for a filler material to effectively fill the annulus between the outside surface of the pipe and the inside of the sleeve?
- Will a cement-filler material properly reinforce the dent within the clamp, especially in light of concerns in using an epoxy filler

material that might not cure in deep water 40 degree F condition?

- How much reinforcement is actually provided by a steel clamp (i.e. how much will the steel sleeve reduce strain in the dented region)?
- Will the cement filler material properly cure in a cold-water subsea environment?

Figure 6 shows the cross-section of bolt-on sleeve for sub-scale testing. The sub-scale test, while Figure 7 is a schematic diagram showing set-up for sub-scale dry test with repair sleeves. Figure 8 shows strain range measurements and the associated stress concentration factors from the sub-scale tests.

A total of five full-scale burst tests were conducted that included a range of defect types including dents and material losses. Figure 9 is a schematic diagram showing layout for the different test samples. The purpose in conducted burst tests involving the different dent/gouge combinations was to address the potential defect severity that might exist in the pipeline. All measurement devices have an inherent uncertainty and in-line inspection tools are no exception. Williams Midstream and Stress Engineering Services Inc. evaluated the range of damage scenarios, especially with regards to metal loss in the dent, and determined that the four following defects best represented the potential damage that might have been inflicted to the pipeline. All dents involved a 7.4% deep dent (measured as a percentage of the pipe's outside diameter), while all groove and gouge depths are measured as a percentage of the pipe's nominal wall thickness.

- Sample #1: Dent with 11% deep axial groove
- Sample #2: Dent with 21% deep axial gouge
- Sample #3: Dent with 11% deep axial gouge
- Sample #4: Dent with 11% deep circumferential groove

Prior to denting, longitudinally-oriented EDM notches were installed in Samples 1 through #3, while an axisymmetric groove was machined in Sample #4 to simulate metal loss in the dented region of the pipe (in the absence of actual data, a gouge length of 6 inches was used). The most severe defect involved the dent with a 21% deep V-notch metal loss. One of the five tests involved the pipe being reinforced using the repair sleeve designed by Saipem (the defect in this pipe sample was the most severe combination: a 7.4% deep dent with a 21% gouge). As with the unrepaired samples, strain gages were placed near the dent beneath the repair to measure stresses due to internal pressure loading. Cyclic pressure was also applied to all unreinforced and reinforced samples prior to burst testing to simulate future years of service.

The minimum failure pressure for any of the burst tests was 9,485 psi (2.6 times the Maximum Allowable Operating Pressure of 3,600 psi and 6.5 times the current operating pressure of 1,450 psi). In this sample the hoop strain in the base pipe at 3,600 psi was measured to be 1,226  $\mu\epsilon$  (microstrain, where 10,000  $\mu\epsilon$  equals 1 percent strain), while the maximum hoop strain was measured to be 11,166  $\mu\epsilon$  located 2 inches axially from the center of the dent. Figure 10 is a photograph showing the burst test for Sample #2 (21% deep axial gouge). Of the unreinforced dents, this is the only one that failed in the dented/gouged region. Listed below (and provided in Table 1) is a summary of the burst test results, including results for the reinforced pipe sample.

- Sample #1 failed at 9,485 psi (163% SMYS)
  - Dent with 11% deep axial groove
  - Failed in seam weld (away from dent)

- Sample #2 failed at 9,739 psi (167% SMYS), only failure to occur in the dent defect
  - Dent with 21% deep axial gouge
  - Failed in dent/gouge area
- Sample #3 failed at 9,986 psi (171% SMYS)
  - Dent with 11% deep axial gouge
  - Failed in seam weld (away from dent)
- Sample #4 failed at 9,530 psi (163% SMYS)
  - Dent with 11% deep circumferential groove
  - Failed in seam weld (away from dent)
- Repaired sample failed at 9,486 psi (163% SMYS)
  - Dent with 21% deep axial gouge
  - Failed in base pipe outside of repair

In contrast to the unreinforced samples where the maximum hoop strain was measured to be 11,166  $\mu\epsilon$ , the maximum hoop strain in the reinforced dent was measured to be 1,060  $\mu\epsilon$  (located 6 inches axially from the center of the dent). The significance of this comparison is that the Saipem sleeve was effective in reducing strain in the dented region to levels equivalent to those associated with hoop strains measured in the undamaged base pipe. Figure 11 is a photograph showing the burst test for the repaired sample. Note that the failure occurred on the base pipe outside of the reinforcing sleeve.

## FIELD DEPLOYMENT

The analysis and testing efforts were fundamental in supporting the design and deployment of Saipem's grouted repair sleeve. The parameters that were studied in the prior phases of work were an integral part in determining what and how would be installed subsea. The sections below provide in-depth discussions on the various phases of work associated with the design and deployment of the sleeve. The pipeline was operating at approximately 900 psi at the time that the sleeve was installed.

## Grout Sleeve Design

An ROV-installable grout sleeve design was developed that would accept the full range of bend radii of 35 to 80 feet. The 28 inch inside diameter of the sleeve was selected to provide a minimum of 3 inches of grout around the pipeline at the minimum estimated radius. The ends of the sleeve were then cut at an angle to match the likely exit angle of a 45 foot radius. Openings in the end plates were also offset to improve the fit on the pipeline. The sleeve was then split horizontally so that vertically-positioned, cone-head screws would provide an ROV-friendly method of closing the sleeve around the pipeline. It was recognized that the center of gravity of a horizontally split sleeve would change significantly as the sleeve opened and closed. In order to minimize this effect, the spreader bar connecting legs were attached at specific positions with one pair of legs attached to the top half of the sleeve and one pair attached to the bottom half of the sleeve. This articulated arrangement moved the spreader bar horizontally as the sleeve opened and closed.

To hold the sleeve closed 48 screws required. A special torque wrench was designed to tighten the screws using an ROV. After the sleeves were made up, the grout fill pipe was mounted in the bottom center of the bottom half of the sleeve. The top half of the sleeve incorporated three ROV-operated vent valves. During grout filling, water inside the sleeve was forced out of the vent valves. When the ROV observed good, clean grout exiting the vent, that valve was closed. This method allowed confirmation that the sleeve was completely filled with cement grout.

## Deployment Plan

It was also recognized that the most critical time during an offshore operation is the time when the crane or lowering line on the vessel is connected to a fixed object on the sea floor. To mitigate this risk, the grout sleeve was deployed with a buoyancy module and a suppressor weight (Figure 12). The buoyancy module was sufficient to suspend the grout sleeve above the sea floor. This method allowed the assembly to be landed on the sea floor next to the pipeline and then quickly disconnected from the vessel. Once this package was on the sea floor the ROV was in complete control of the installation. A pair of ROV-operated winches, mounted on the spreader bar, was then used to pull the grout sleeve down onto the pipeline. This step is illustrated in Figure 13. Later these winches were used to provide a controlled ascent for the spreader bar and buoyancy module after the grout sleeve was disconnected.

## Metrology Tool

A special metrology tool was built to measure the pipeline curvature in the area where the grout sleeve would be installed. This ROV-operated tool was deployed on a skid that was disconnected from the lowering line after it landed on the sea floor. The ROV then docked with the tool and positioned it on the pipeline by centering it on the dent. The ROV powered two pair of hydraulic arms on the tool to clamp the tool on the pipeline. The ROV could then disconnect from the tool and make a video record of the readings on twenty equally spaced mechanical gages that rested against the pipeline at five selected positions along the length of the tool. After the tool was recovered to the workshop, short sections of pipe were fitted into the tool and positioned to duplicate the gage readings from the sea floor. These short sections were then welded together, removed from the tool, and laid into the open grout sleeve to confirm clearance around the pipe and the exit angle of the pipe from the sleeve.

## Offshore Installation

Installation of the grout sleeve required that an access hole be dredged under the pipeline. This hole needed to be approximately 20 feet long and 4 feet deep to provide clearance for the bottom half of the sleeve to swing closed under the pipeline (cf. Figure 13). It was recognized that the weight of the sleeve plus the cement grout would be approximately 12,000 lbs, when the buoyancy module was released. Therefore, to prevent the pipe from sagging into the hole ROV-operated pipe support frames were installed approximately 30 feet back from either side of the hole. Each frame consisted of two mudmats and a single, motor-operated grab. These frames did not lift the pipeline but simply added mudmat support. The support frames were used during installation so that the pipe functioned as a simple beam. The support frames did not lift the pipeline; rather they supported it so that it could not deflect into the mud. A simple beam calculation was made that showed that the pipeline could support itself between the pipe support frames. The weight of the sleeve was supported by the buoyancy until after the grout bag was installed in the hole. The pipeline did not see any significant loading during the repair. While the sleeve, spreader bar, and buoyancy module were connected to the pipeline, there was a net upward force of approximately 1,000 lbs on the pipeline. After the sleeve was filled with grout, there was a net downward force of approximately 1,000 pounds. After the grout bag was filled, we believe the pipeline was fully supported and there was no force acting on the pipeline.

After the grout sleeve was installed, the ROV pulled a fabric grout bag into the hole under the sleeve. This bag was then filled with cement grout to fill the vacant space below the grout sleeve. After the grout was allowed to cure for a few hours, the ROV disconnected the

spreader bar from the sleeve and it, along with the buoyancy module and suppressor weight, was recovered to the surface. The pipeline support frames were also released and recovered. The only components that remained on the sea floor were the grout sleeve and the grout bag supporting it. The final configuration is shown in Figure 14 in a photograph taken by an ROV. This remediation action cleared the pipeline for full operating pressure operation.

## CLOSING COMMENTS

The information presented in this paper detailed an effort involving four organizations to restore full service capacity to a deep water subsea pipeline damaged by an anchor. The work involved a combination and analysis and testing techniques to support the design, fabrication and deployment of a grouted subsea repair sleeve. In reviewing the associated body of work presented in this paper, the following observations are made:

- A horizontally split sleeve can be safely installed by an ROV on a live pipeline by use of a buoyancy module and pull-down winches.
- Cement grout can be prepared on a surface vessel and then pumped down a long hose to fill a grout sleeve on the seafloor.
- A purpose built metrology tool with mechanical gauges and simple fabrication techniques can produce an accurate model of the shape of a damaged pipeline on the seafloor.
- Using of analysis and full-scale testing techniques prior to deployment of repair methods improves confidence in the design and ensures that stresses in the damaged region of the pipeline are reduced to acceptable levels.

## REFERENCES

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Alexander, C.R., *Evaluating Damaged Subsea Pipelines Using an Engineering-Based Integrity Management Program*, Proceedings of IOPF 2009 (Paper No. IOPF2009-6002), ASME International Offshore Pipeline Forum, October 28-29, 2009, Houston, Texas.

**Table 1 – Summary of Burst Test Results**

Sample #	Sample Description	Burst Pressure	Failure Description
1	Dent with 11% deep axial groove	9,485 psi	Failed in seam weld (away from dent)
2	Dent with 21% deep axial gouge	9,739 psi	Failed in dent/gouge area <sup>(see note)</sup>
3	Dent with 11% deep axial gouge	9,986 psi	Failed in seam weld (away from dent)
4	Dent with 11% deep circumferential groove	9,530 psi	Failed in seam weld (away from dent)
Repaired	Dent with 21% deep axial gouge	9,486 psi	Failed in base pipe outside of repair

Note: This was the only failure to occur in the defect region of the pipe.



Figure 1 – ROV-assisted measurement of dent using a straightedge

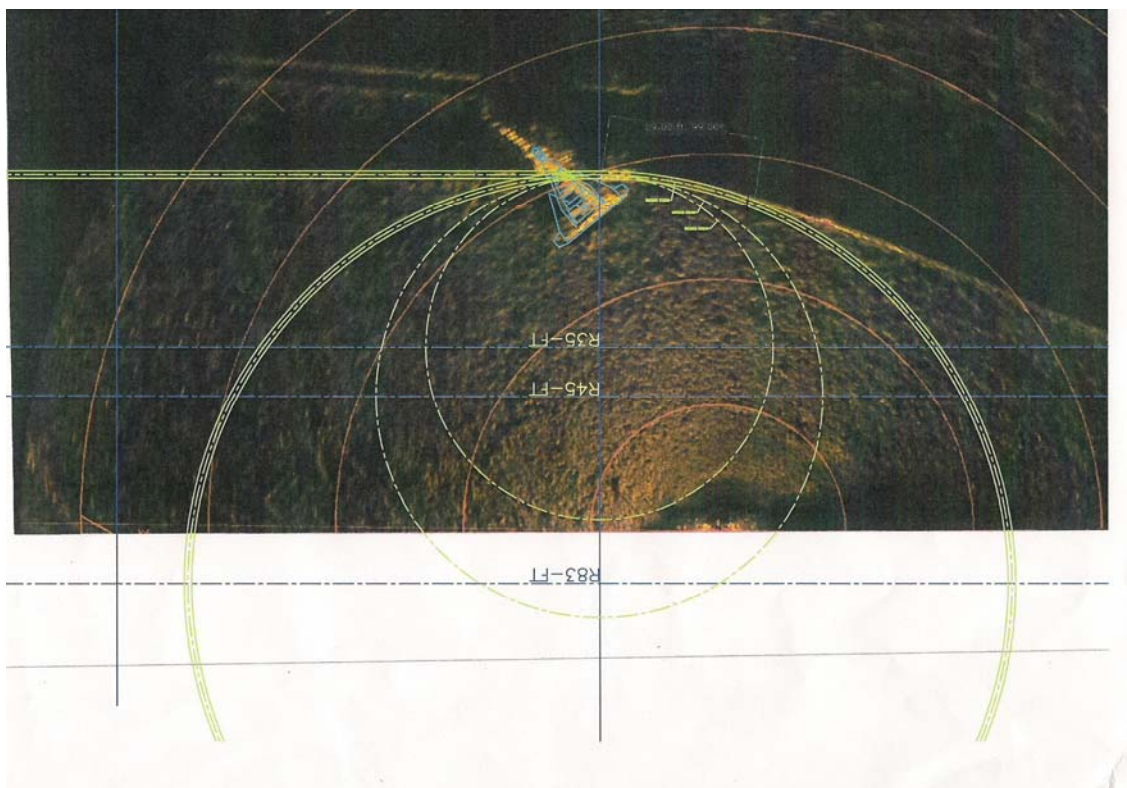
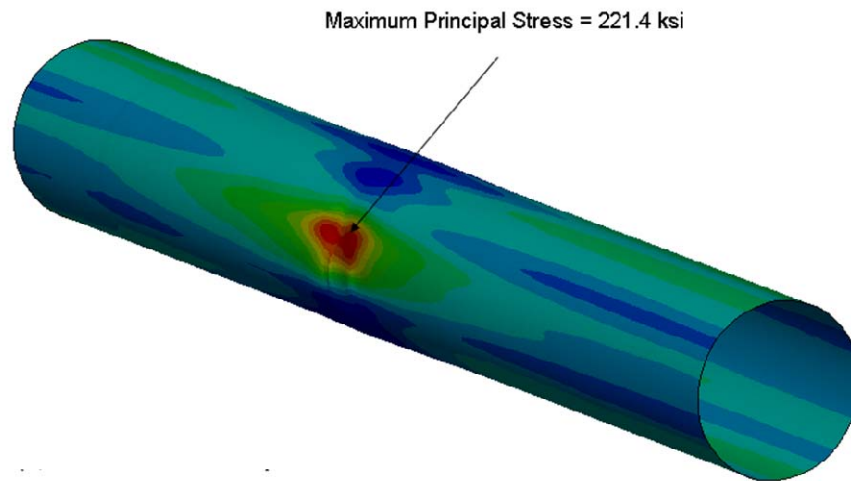
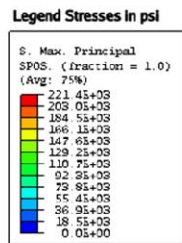


Figure 2 - Sonar image with radius of curvature estimation of the pipeline



Maximum principal stresses in Dent ID 339968

Figure 3 - Stress contour plot for dented region 100% SMYS (hoop stress of 60,000 psi)

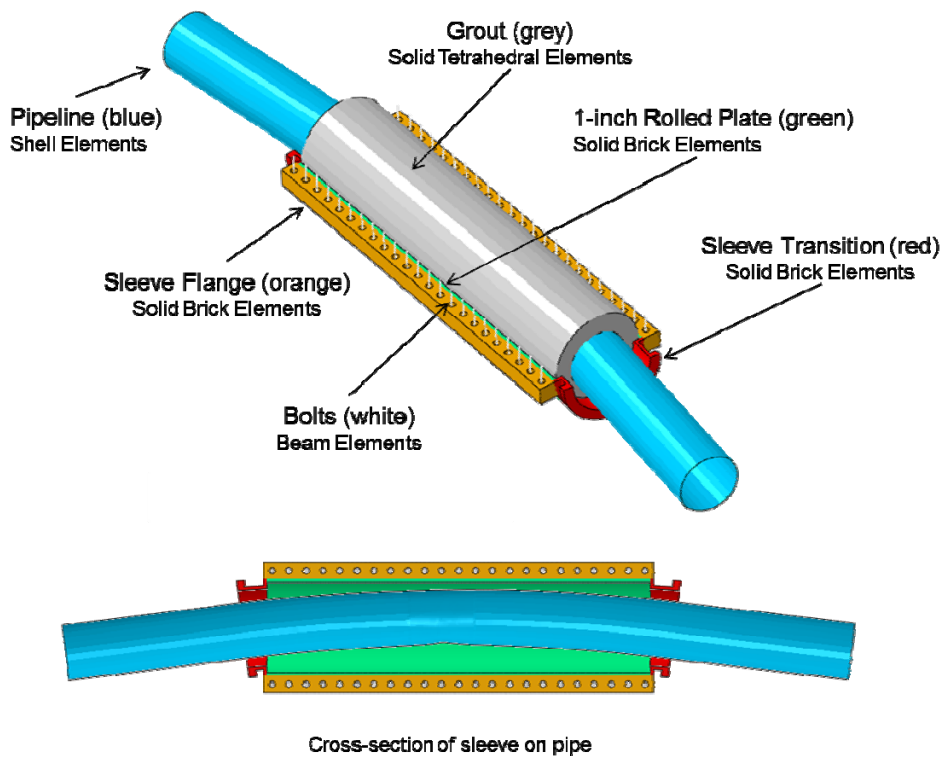


Figure 4 – Finite element model geometry of repair sleeve

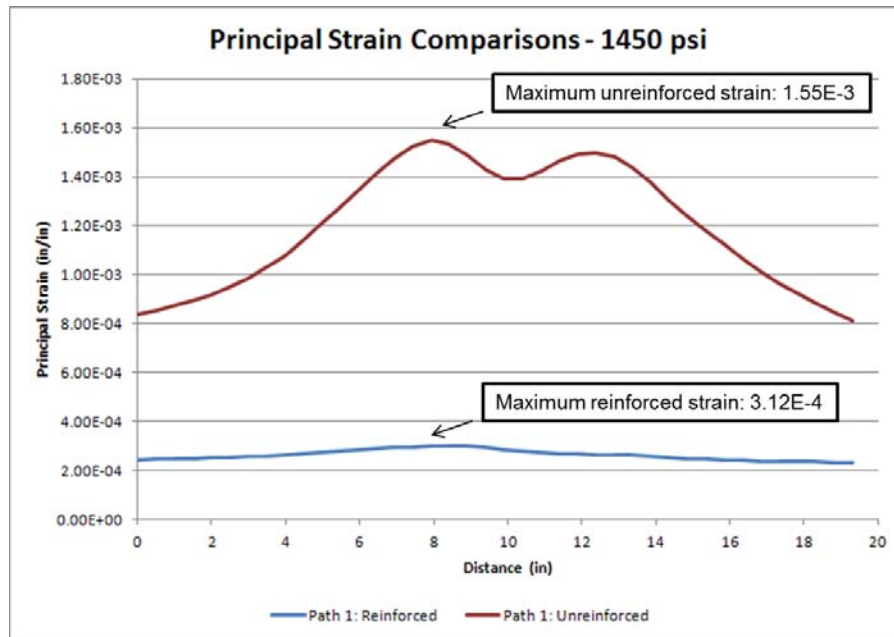


Figure 5 – FEA-calculated strains in dented region with and without sleeve reinforcement

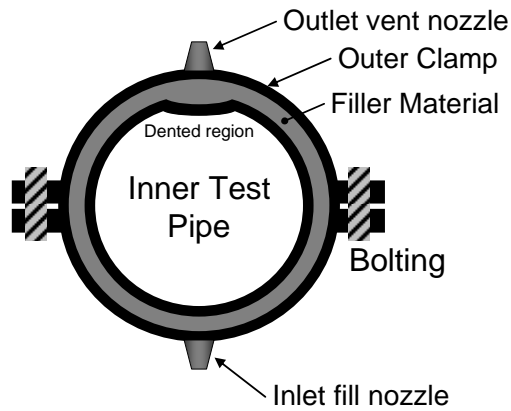


Figure 6 - Cross-section of bolt-on sleeve for sub-scale testing

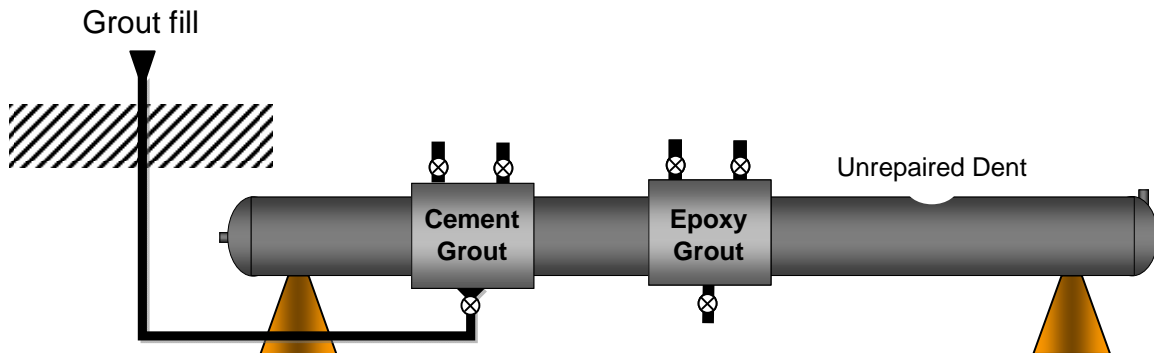
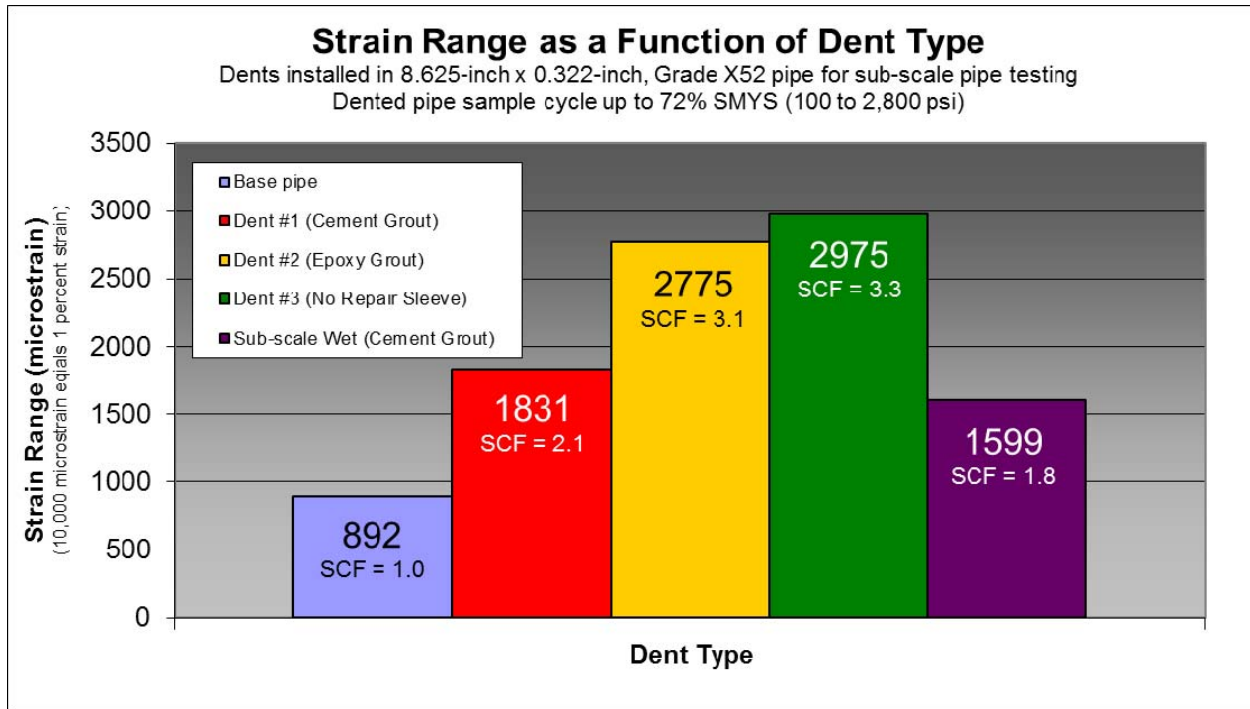
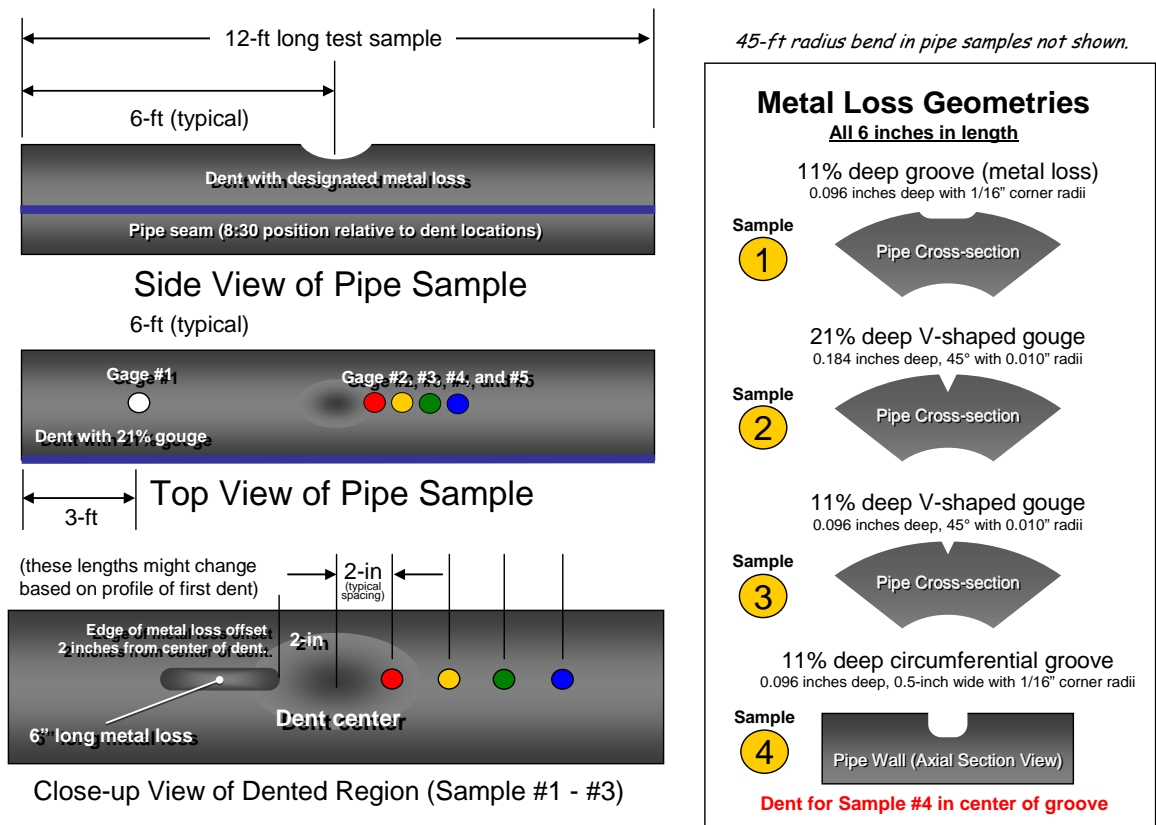


Figure 7 - Schematic diagram showing set-up for sub-scale dry test with repair sleeves





**Figure 8 - Strain range measurements from the sub-scale tests**



**Figure 9 - Schematic diagram showing layout for the two test samples**



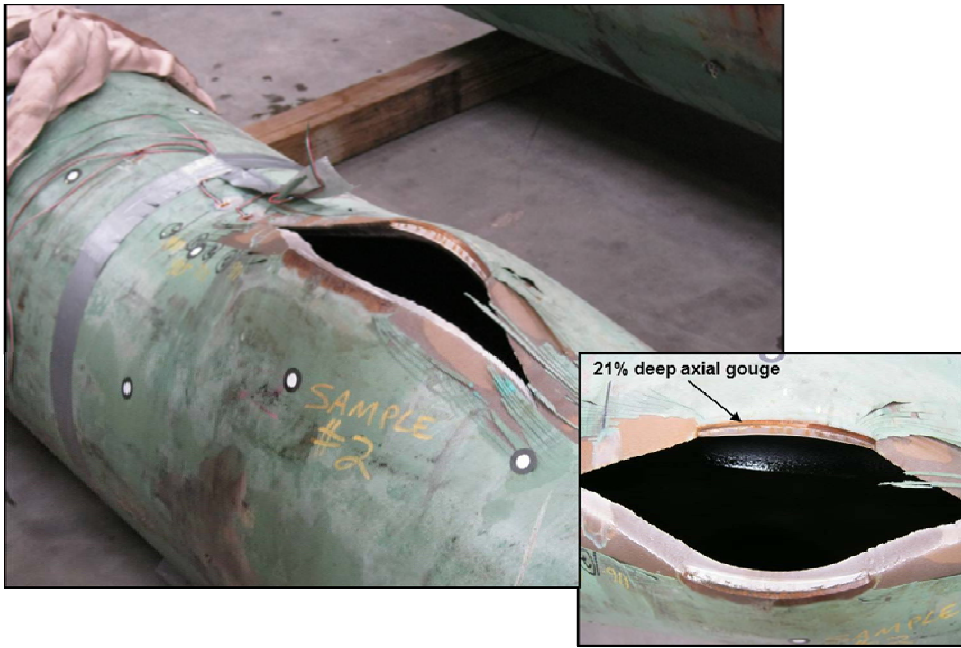


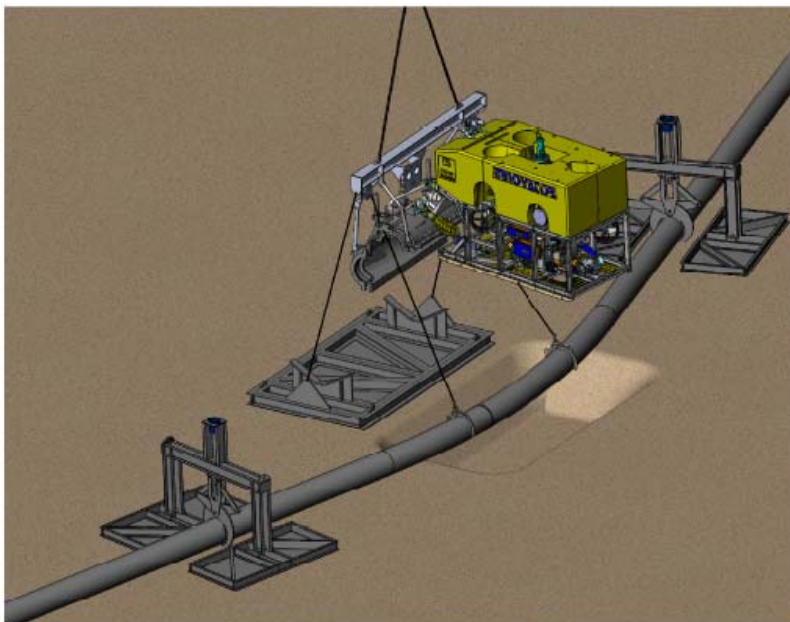
Figure 10 - Photograph showing burst test for Sample #2 (21% deep axial gouge)



Figure 11 - Photograph showing burst test for repaired sample with failure outside of sleeve



**Figure 12 – Grouted sleeve with suppressor skid and buoyancy module rigged for deployment**



**Figure 13 - ROV powers Spreader Bar Winches to pull Grout Sleeve down to pipeline**



Figure 14 – Grout sleeve and Grout Bag installed on pipeline