OTC-19653-PP

Methodology to Establish the Fitness for Continued Service of a Hurricane Damaged Export Pipeline in 1000 m of Water

D. Raghu (Shell Global Solutions US, Houston, TX), Richard Swanson (RCS Engineering, Houston, TX), Chris Alexander (Stress Engineering, Houston, TX)

This paper was prepared for presentation at the 2008 Offshore Technology Conference held in Houston, Texas, U.S.A., 5–8 May 2008.

Abstract

Deepwater pipelines are critical arteries that transport gas and oil production from the Gulf of Mexico to onshore transportation hubs. The yearly hurricane season in the GoM has a serious impact on the reliability of this infrastructure, as evidenced by the severe damage experienced, and subsequent difficulty and delay returning to full service. The difficulty arises from the various challenges in damage inspection and evaluation as well as the delay in analysis and procuring the repair hardware needed for infrastructure in deepwater. Many of the damaged pipelines needed extensive and time-consuming repairs depending on the severity and criticality. However, if sufficiently conservative and prudent analytical methodologies are used, many of the damaged lines can be inspected, analyzed and established to be fit for continued finite service. Employing a combination of repair and fitness for service can effectively manage the risk of damaged deepwater lines.

In this paper, a approach is suggested that can be used to analyze and establish the integrity of damaged lines. It reviews the various analysis methods available and integrates one or more of the analysis methods to arrive at a unified approach. The inspection and data collection required to adopt the approach are detailed. The approach is illustrated through an example from a 20" dented pipeline in 1000 m of water, where the fatigue life was estimated using FEA and simple dent fatigue equations and further validated using full scale testing. A decision tree that provides guidelines for deepwater pipeline damage evaluation and fitness for service is provided

Introduction

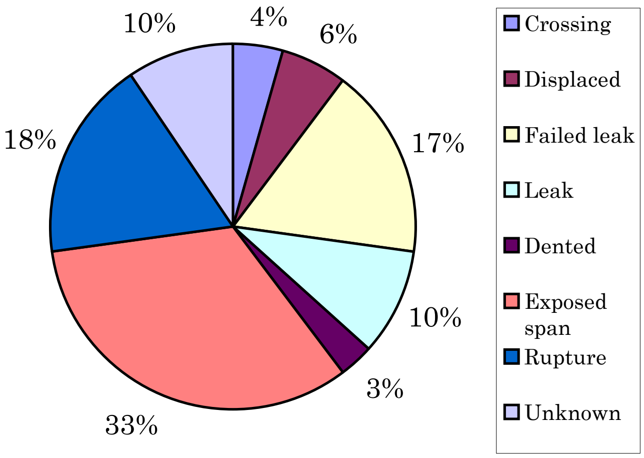
The ability to reliably transport hydrocarbon products from the Gulf of Mexico outer continental shelf to refineries in the continental US is very critical to the continued supply of energy to the nation. The total hydrocarbon production, over 300 million STB of oil end 1100 million SCF gas constitute 30% of the US oil consumption and over 25% of the gas consumption[1]. This hydrocarbon is primarily transported using pipelines that run from deep-water production sites to onshore facilities. In the Gulf of Mexico currently there are over 44,000 km of pipelines that transport oil and gas.

The importance of the pipeline infrastructure to this continued energy supply cannot be overemphasized. Therefore when natural hazards like hurricanes impact the Gulf of Mexico and damage platforms and sub sea pipelines infrastructures, it is imperative that it be a returned to full service as soon as possible. Over the last several years hurricanes like Rita and Katrina have had devastating effects on this pipeline infrastructure. In many cases the damage has been significantly severe requiring extensive replacements. Operators of the pipelines are faced with the increased challenge of inspecting the damage and quickly analyzing it to establish appropriate repair methods or in extreme cases replacement. Owing to the complexity that goes with deep-water pipeline infrastructure, viz. difficulty to access and inspect and the complex designs required to carry out repairs, operators have to develop specific protocols for inspection analysis and repair.

Types of Sub-Sea Pipeline Damage

A devastating hurricane like Kathrina or Rita can cause significant damage to pipeline infrastructure as was evident in its aftermath. Typically post-hurricane damage on pipelines can be broadly classified into two categories (a) direct damage due to hurricane or natural hazard (b) damage inflicted by secondary effects of the hurricane. The first category under direct damage 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. The second category includes damage from anchor drags, primarily from drilling vessels which 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[2]. Refer to Figure 1.

Figure 1



Challenges

Returning damaged pipelines back to service poses significant challenges owing to the depth at which the damage occurred, the complexities involved with inspections and analysis. The following section elaborates some of these challenges with the intent of highlighting the ones that need to be addressed. This will help effect an efficient and robust post-damage analysis and fitness for service assessment.

Potential challenges to returning damaged deepwater pipelines to service can be categorized under five main themes;

1. Inspecting the extent and specifics of the damage
2. Evaluating and quantifying the damage
3. Analyzing and modeling the damage with the intent of performing a fitness for service
4. Design for repairs
5. Practical difficulties like design and mobilization delays, hardware lead-time.

Once the type of damage is established, appropriate analytical techniques will have to be defined in order to carry out a fitness for service analysis. Fitness for service (FFS) algorithms exist for most commonly observed damage types: with good inspection data, mechanical damage like dents, kinks or different levels of cracking can be addressed and evaluated using published algorithms from API 579, PRCI (Pipeline Research Council) and EPRG (European pipeline research group). The key challenge here is to obtain inspection data that can be reliably applied in the fitness for service models. In its absence, a significant level of conservatism will have to be built into the crack and dent dimensions to account for any uncertainty that might arise in the inspection

Data Collection

Inspection of sub sea pipelines, especially the ones in deeper waters, are relatively expensive. It is therefore very important that clear inspection and data collection procedures be established before any kind of inspection is attempted. This will enable the remotely operating vehicle crew to seek and measure appropriate parameters and at the same time prevent or minimize the number of repetitions that need to be carried out in order to obtain all the data needed. Since no established guidelines exist for such an exercise, an example of the type of data collection is shown in Table 2 below.

Table 1
Required Data To Assess Damaged Sub Sea Lines (Example for dents on pipelines)

Type of suspected damage	Sub-sea data to be colleceted
Plain dents	• Dent location (girth weld, seam weld, base metal) • Dent orientation • Dent profile (x-y-z coordinates) • Dent depth • Global displacement of pipe (x-y-z) • Local wall thickness

Fitness For Service Analytical Methods

The fitness for service analysis enables an operator to estimate the reliability of the pipeline segment by predicting the safe limits for static and dynamic service-either for pressure containment or collapse and determines the remaining fatigue life. Fitness for service estimates therefore will have to be as accurate as possible in order to provide guidelines for continued service in such contingent situations.

Depending on the amount of material property and inspection data that are available, various levels of damage analysis can be performed. API 579 fitness for service defines three levels of damage analysis[3].

Level 1 analysis is considered the most conservative and evaluates damage using the allowable limits of the design code. As it implies, this analysis level requires only cursory knowledge of the damage. In this case, ASME-B-31.8[4] and 31.8 S[5]., which are the design and integrity codes for gas pipelines, are used to perform the Level 1 analysis. The assessment procedures included in this level are intended to provide conservative screening criteria that can be utilized with a minimum amount of inspection or component information. A Level 1 assessment may be performed either by plant inspection or engineering personnel

Level 2 analyses are intended to provide a more detailed evaluation that produces results that are more precise than those from a Level 1 assessment. In a Level 2 assessment, inspection information similar to that required for a Level 1 assessment is needed; however, more detailed calculations are used in the evaluation. Level 2 assessments are typically conducted by plant engineers. Typical Level 2 analysis would involve damage analysis using algorithms developed by PRCI (Pipeline Research Council Inc), EPRG (European Pipeline Research Group) and specific Joint Industry Projects like PDAM[6] (Pipeline Defect Assessment Manual). Specific algorithms in these publications address the evaluation and computation of residual life of pipeline components with defects like cracks, dents, gouges, corrosion etc.

In a Level 3 Assessment the most detailed inspection and component information is typically required, and the recommended analysis is based on numerical techniques such as the finite element method or experimental techniques when appropriate. A Level 3 assessment is primarily intended for use by engineering specialists experienced and knowledgeable in performing *FFS* assessments.

In the present paper, an additional level, viz. Level 4 is included. This part involves full scale testing of the components to conditions seen in the field, whereby the resistance to static and fatigue loads is evaluated.

A Level 5 is also added, which involves analysis and design for fit for purpose repairs. In most deepwater repairs, the nature of the damage warrants the use of sophisticated metrological and analytical tools to design the right remediation and mitigation.

Case Study:

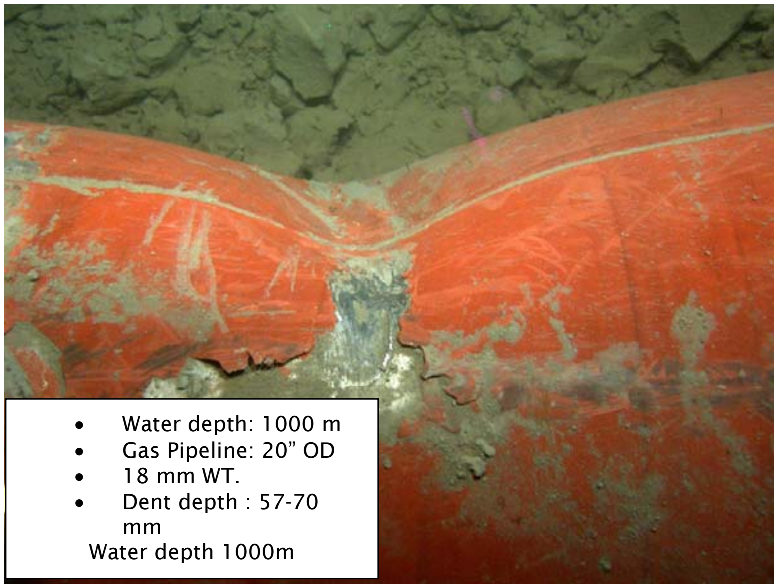
The Ursa TLP is located approximately 188 km (130 miles) south-east of New Orleans. It encompasses Mississippi Canyon blocks 808, 809, 810, 852, 853 and 854. The water depth averages approximately 1200 m (4,000ft). It is designed to process 150,000 bbl of oil and condensate , 400 MMcf of gas and 50,000 bbl of produced water per day. Production from the platform is transported approximately 70 km (47 miles) via an 18”-diameter oil pipeline and a 20”-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 ~ 1000m. 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”) OD x 18 mm (0.75”) 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, thus produced, was in the range of 57mm to 70 mm. (about 2 ¼ - 2 ¾ inches) deep.

Considering the business impact of having this asset out of service, there was an urgent need for remediation of the line. The damage indicated that the line could be reliably repaired using engineered sub-sea clamps. However, the lead-time to fabricate the clamp was estimated at 1-2 2 years, and hence there arose a need to establish the integrity of the line for continued operation until such time it was repaired.

Figure 2
Ursa Gas Pipeline Damage

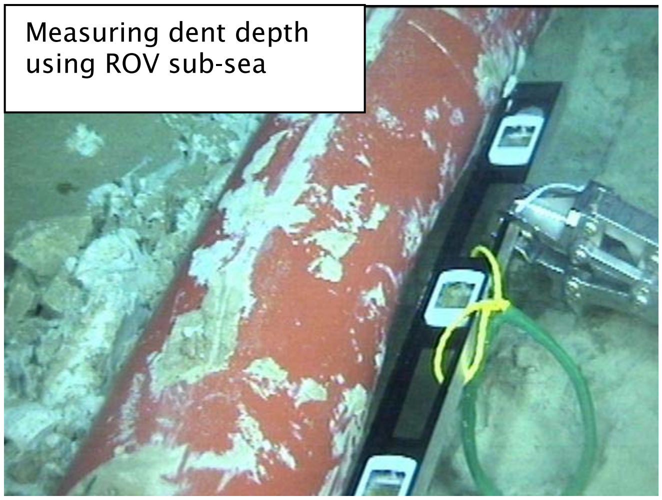


- Water depth: 1000 m
- Gas Pipeline: 20” OD
- 18 mm WT.
- Dent depth : 57-70 mm

Water depth 1000m

Figure 3

Specialized fixture for measuring dent profile (ROV deployed)



Measuring dent depth using ROV sub-sea

Inspection:

A ROV equipped with a specialized profile-measuring device was employed to measure the entire dent (x-y-z coordinates), and to measure the extent of gross deformation of the line. Refer to Figure 3. The measurements were intended to serve as an input to (a) the Level 2 fatigue and crack growth modeling (b) developing the FEA model was subsequent Level 3 analysis.

Level 1 analysis:

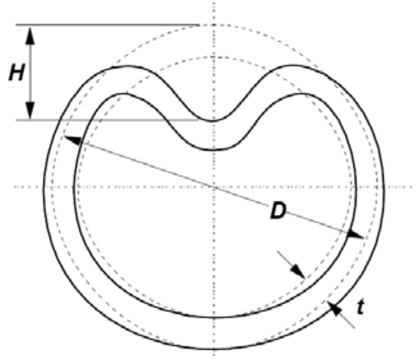
Level 1 utilized the guidelines provided in a ASME 31.8 and 31.8S. A dent threshold of 6% is stipulated here, provided it does not have stress raisers like gouges, cracks and kinks. Using the criteria, the dents in the Ursa gas line did not pass the Level 1 assessment-the dent was over 10% of the diameter. ASME B31.8 also provides the guideline for the maximum allowable strain in deformed sections; this criterion was not used in this case since the dent itself did not satisfy the depth criteria.

Level 2 analysis and assessments

Since the dent in did not pass the Level 1 assessment for fitness for service, the Level 2 analysis was performed. This assessment focused on (a) Residual life of the dent in the presence of a representative cyclic pressure spectrum. (b) Residual fatigue life of any potential crack in the dented section.

The residual fatigue life of the dent was estimated using equations developed by EPRG and a subsequent joint industry project document, PDAM (Pipeline defect in assessment manual). The primary inputs for the analysis are the tensile strength, the cyclic pressure and the dent depth. Figure 4 shows the typical dent with its critical dimensions. Representative equations for the dented life estimation are shown in equations 1, 2 and 3. The calculated fatigue life of the dent is reduced by a factor of 13 to represent the -95% confidence band. The method also requires the reduction of life by a factor of 10 if the defect is on a weld. Using a representative pressure spectrum of the Ursa gas line, the fatigue life was then computed and gave a life of in seven years. Subsequently the theoretical residual crack size based on the apex stresses from FEA was used in to compute a theoretical fatigue crack growth and residual life. The calculated residual life of a crack was estimated at 6.8 years.

Figure 4
Typical dimensions of the dent used for fatigue life estimation in Level 2



$$N = 1000\left[\frac{(\sigma_U - 50)}{2\sigma_A K_S}\right]^{4.292} \tag{1}$$

$$N = \left(\frac{1}{10}\right)1000\left[\frac{(\sigma_U - 50)}{2\sigma_A K_s}\right]^{4.292} \tag{2}$$

$$N = \left(\frac{1}{13}\right)\left(\frac{1}{10}\right)1000\left[\frac{(\sigma_U - 50)}{2\sigma_A K_s}\right]^{4.292} \tag{3}$$

- σ_u = Ultimate tensile strength
- σ_a = Alternating stress
- K_s = Parameter incorporating dent depth and mechanical properties

Level 3 FEA Analysis

The next level of analysis would typically involve application of the finite element method to determine the stresses and strains in the dent as precisely as possible and also compute stress ranges due to cyclic loading. Cyclic loading results from responses to pressure and temperature. Cyclic loading must be examined to estimate the remaining fatigue life at the dent location. Further, for deep-water, estimates can be made of collapse pressure to determine the existing factor of safety. This allows a decision to be made about whether remedial steps, such as, the installation of a clamp, must be taken to provide sufficient margin against collapse failure.

As an example the finite element analysis conducted for the damaged Ursa gas pipeline was comprised of the following:

1. Assembly and definition of the constitutive behavior of the pipe material. This of necessity included knowledge of the true stress as a function of true strain, since large plastic strains are involved.
2. Configuring the mesh with sufficient density in a three dimensional model, selecting an element that properly represents large strains.
3. Conducting analyses with the correct operating and boundary conditions, including:
    - Denting the pipe with a simulated rigid indenter over the range of dents, consistent with field observations,
    - Exposing the dent to various service loads expected during the remaining life of the pipeline and computing resulting stresses and strains,
    - Estimating collapse pressure over the likely range of dent sizes and geometries,
    - Estimating the stress ranges due to service at cyclic loads (temperature and pressure) expected during the remaining life.
4. Performing analyses to support testing, which was required to verify pipe response to various dents and examine fatigue performance.
5. Conducting analyses to support remedial efforts, which were also required.

The value of comparing finite element results with test results is extremely valuable. Favorable comparisons allow more confident decisions to be made regarding the pipe fitness for service.

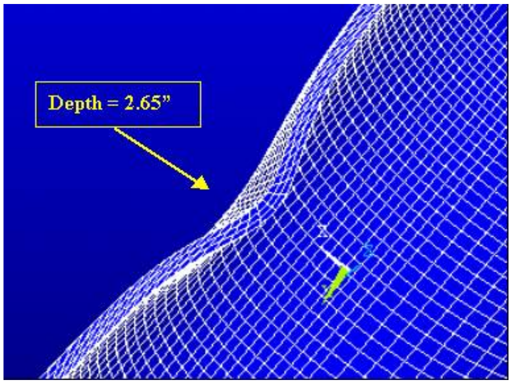
Typical results of the analyses done for the Ursa gas pipeline are shown in Figures 5 and 6.

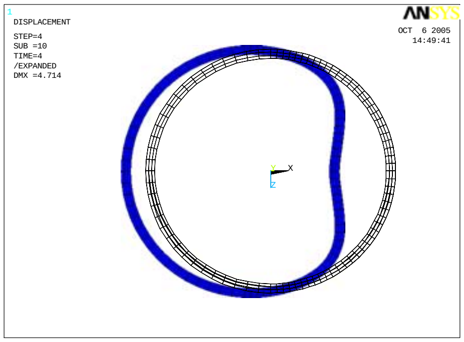
Figure 5 shows the overall mesh for the dented pipe and that of the section, compared to the undented original section. The results shown here are for a dent at the lower bound of that thought to exist in the field. (Profiling the dented pipe proved to be difficult, thus some sensitivity to the dent size must be taken into account in both analysis and testing.)

Figure 6 depicts the performance of the dent deformation as a function of the difference between internal and external pressure. Curves for three sizes of initial dent are shown, resulting in different collapse pressures. Note there is substantial reduction in collapse pressure as the dent size increases. The design collapse pressure for the un-dented pipe (with nominal ovality) is on the order of 15.16 to 17.23 Mpa (2200 to 2500 psi), giving a safety margin of about 75% in 900 m (3000 feet) of water. A 106.7 mm (4.2-inch) dent reduces this to 20%, which is not acceptable. Since the pipeline was damaged, the difference between internal and external pressures has been carefully controlled to avoid insufficient safety margin on collapse pressure.

The fatigue residual life of the dent (assuming no cracks) was estimated for API X’ using the stress obtained from the FEA for a representative pressure histogram. The estimated fatigue life was 722 years.

Figure 5 Overall Mesh For The Dented Pipe





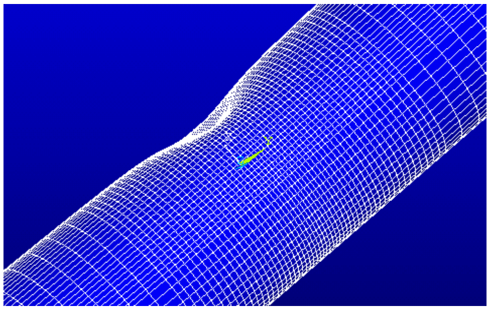
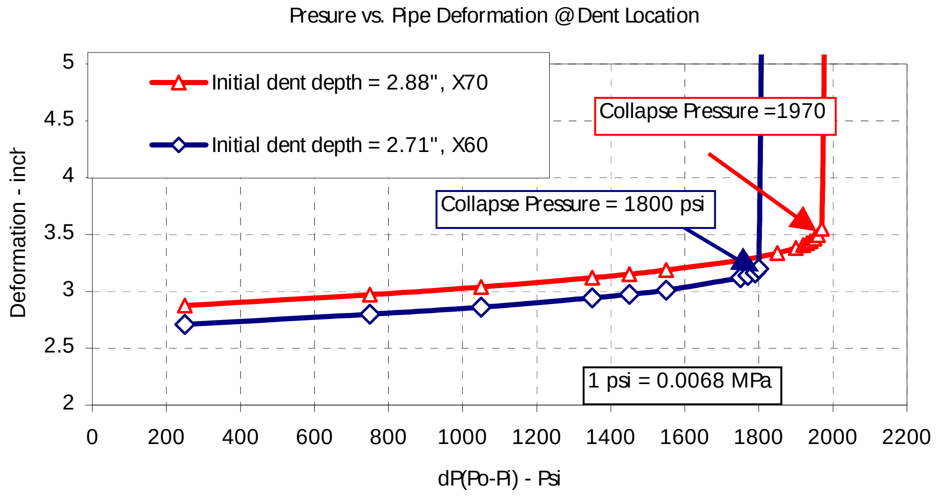


Figure 6. Collapse Pressure Sensitivity to Parameters



Level 4 – Full Scale testing

Full scale testing (Level 4) in the present case was carried out with the primary intend of achieving a higher degree of confidence in the fatigue results obtained from Level 2 and Level 3 analysis. All full scale testing was carried out at the structural labs of Stress Engineering Services.

Test Methods

The test program involved several specific phases of testing that included the following:

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

The sections that follow provide details on the above tasks.

Initial Work and Installation of Dents

The profile of the test dents was based on the dent profile of the actual dent in the subsea URSA pipeline. Using this profile, a carbon steel indenter was fabricated to achieve the intended dent shape. A hydraulic ram was used to force the indenter into the pipe sample. During the denting process, force as a function of displacement was recorded.

The following bullet list contains the specific steps that were used by SES in creating the dents. For continuity details are also provided on steps completed during fatigue testing and post-failure examination.

- Samples of the 20-inch x 0.75-inch pipe were fabricated by cutting 3.0 m (10-ft) lengths and welding elliptical end caps. Strain gages were installed on selected samples prior to denting. Dents were installed dent using a specific indenter to the specified depth in the seam weld (except Sample #8 where the dent was installed 180 degrees relative to weld seam). Data were recorded that included dent force as a function of indentation depth. Strain was also recorded on samples where gages had been installed.

- Once the dents had been installed, each sample was subjected to pressure cycles using an automated pressure cycle unit. Prior to pressure cycling, each of the dent samples was subjected to a brief hydrotest hold to a specified pressure. Pressure cycling was stopped once a leak developed in the test sample using an automated shut-down feature on the pumping unit.

- After the pressure cycling was completed, a post-failure examination was conducted that included taking photographs and measuring the dent profile using a dial caliper. Some samples were selected for further examination that included breaking open the crack using liquid nitrogen and inspecting the fatigue fracture surfaces.

Figure 7 is a photograph taken during the dent installation process. The average dent depth was 2.8 inches and the average force was approximately 1779 kN (400 kips). The observation from these results is that it takes a significant force to create the indented dent depths. Figure 8 is a plot that provides dent force as a function of dent depth for Samples #2 through #5. If one is to calculate energy, Sample #2 has the greatest area under the curve corresponding to an energy level of 123.2 kJ (90.8 kip-ft).

In reviewing the data provided in Figure 8 there are several important observations. First, there is good repeatability among the different test results indicating consistency in the test program. Secondly, the load-deflection response was similar to results from the finite element work, confirming the validity of the plasticity model used in the FEA.

Pressure Cycle Fatigue Testing

After denting the samples were hydrostatically tested and then pressure cycled to failure. The hydrostatic pressures were applied prior to fatigue testing to determine if the hydrostatic pressures would have any effects on increasing fatigue life. Prior research has shown that hydrostatic testing can be used to increase fatigue life as it tends to reduce the depth of the dent, which in turn reduces the level of alternating strain during pressure cycling.

A total of nine test samples were pressure cycled as part of the overall program. The following steps were involved in terms of the pressure cycle phase of testing.

- Hydrotesting (before pressure cycle testing)
- Cycle testing to failure to specified pressure range
- Recording strain gage data at specific cycle intervals
- Post-failure examination

In addition to the fatigue tests, a burst test was performed on a sample. The intent was to determine the static pressure capacity of a dent. The pipe burst at a pressure of 6,419 psi and occurred 180 degrees from the dent as shown in **Figure 9**.

Figure 7 – Indenter installing dent in the test sample

Figure 8 – Dent force as a function of dent depth for Samples #2 - #5

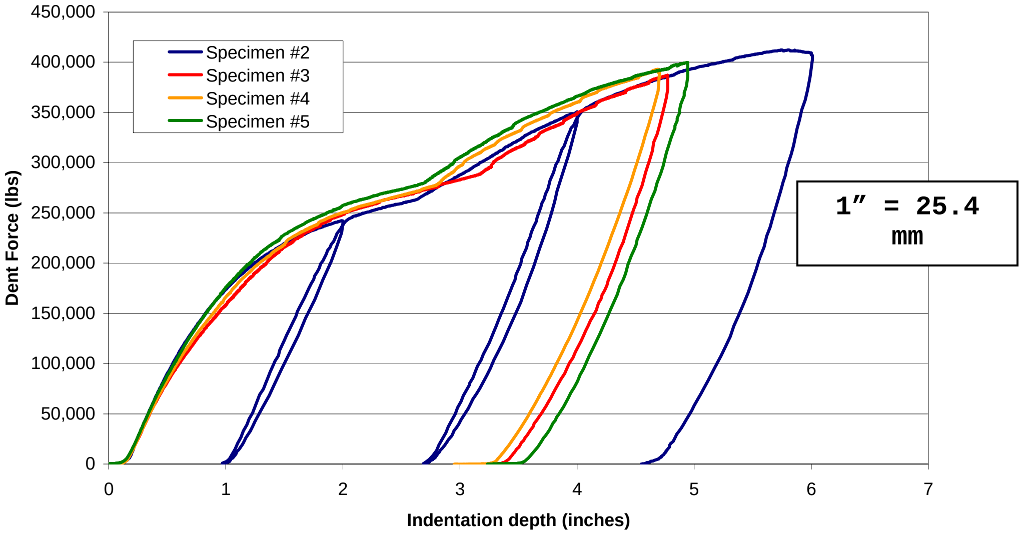


Figure 9 **- Failure of Dented Sample**

Fatigue Analysis

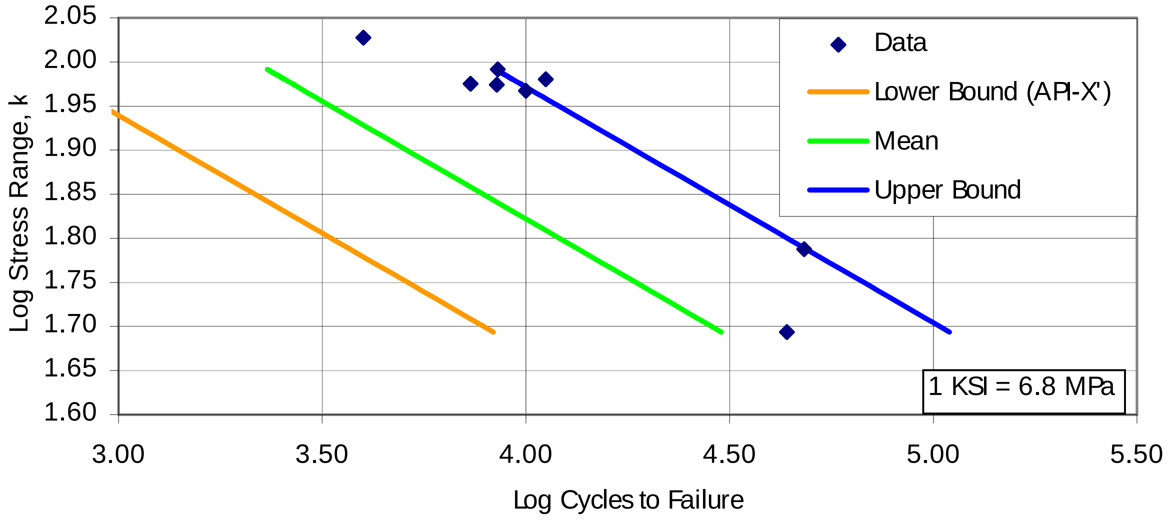
Using the fatigue results from the pressure testing, estimates have been made of the fatigue life of the dented pipe under various conditions of service and configurations of remediation. The entirety of this work is beyond the scope of this paper. However, it is useful to discuss the procedure for computing fatigue based on the pressure test data.

Figure 10 compares fatigue test data to three curves: API-X′[7] and the estimated mean and upper bounds for API-X′, using the standard deviations from DOE/DNV curves[8] . The upper bound was used for test planning, since it was expected that the seam weld in the dent and the dent itself would perform in fatigue in a manner consistent with the API-X′ curve (the lower bound curve in Figure 10). This has been borne out by the test data, also shown, so that the API-X′ curve has been used in estimating the fatigue life of the dented pipe. Stress ranges associated with the pressure cycles used in the testing were computed by finite element analysis, to allow mapping of the pressure fatigue data into the stress range used in Figure 10.

Based on the histogram derived from line operating parameters, the cyclic pressures, and hence stress ranges, at the dent have been estimated. This results in an estimated fatigue life at the dent of 183 years. This should be viewed with caution, however, since change in service, operating conditions or line position may result in higher cyclic stresses.

Due to these uncertainties and the concern about collapse margin, a clamp will be installed on the dented section of the Ursa gas pipeline. This clamp has the potential of being filled with water or some other material, such as epoxy. These will increase the fatigue life at the dent to 984 years and 0.5 million years, respectively. These are certainly satisfactory. However, since the water filled case depends on reliable seal integrity, filling the annulus with epoxy is still being considered.

Figure 10. Fatigue Failure Cycles as a Function of Stress Range



Discussion & Conclusion

The success of this proposed methodology relies on data, analysis and inputs from a variety of sources connected to the operating flow-line or pipeline.

Access to accurate material property data, from test certificates or construction data books is a pre-requisite. Mechanical properties like yield and, tensile, fracture toughness and material specifications should be collected for the various pipe sections and welds. The operator should also obtain accurate historical operating parameters like mean pressures, pressure cycles and pressure amplitudes over the period of interest. Typically operating parameters are scanned for several years and the representative histogram from a month is extracted and approximated over the whole lifespan. It is also very important that proper inspection data collection and acceptance criteria protocols are set up a front, so that all the stakeholders’ are in alignment about the outcome.

Since the damage assessment can become significantly resource intensive, depending on the amount of work done, it is of utmost importance that the stakeholders understand its benefits and limitations from the begining. Thus a Level 1 analysis can be termed” quick and dirty” and will give an idea of the present integrity of the system. However it doesn't give much indication of future integrity especially in the presence of transients like pressure fluctuations. Level 2 on the other hand is relatively quick and gives an idea of the present and future integrity, albeit with a high level of conservatism. Typically the level of conservatism is at least an order of magnitude, although in this case, Level 2 indicated a conservatism of two orders (X 200). Therefore, in many cases a Level 3 analysis for a realistic determination of remaining life may be required. Level 3 analyses is a very sophisticated and resource intensive process. Remaining life assessments are very realistic and typically significant reduction in the inspection frequency is realized compared to a Level 2 analysis. This aspect is very important when the life cycle cost analysis is considered-in most cases life cycle cost analysis would justify employing Level 3 analysis to determine inspection frequency. Level 4 analyses or full-scale testing is employed for two reasons (a) to establish the remaining life if Level 3 assessments do not make the acceptance criteria (b) to increase the level of confidence obtained in the level 2 and level 3 analyses. This testing is relatively expensive and time-consuming, and can be performed only at a limited number of specialized laboratories.

General methodology for assessing damage in sub-sea pipelines

Based on the experience with the Ursa gas pipeline, a general approach for assessing damage in offshore pipelines is proposed here. The methodology is schematically shown in the flowchart in Figure 11 a and b. Although this case study deals with dents on pipelines, the method can be used for most damage types encountered in sub-sea lines.

The process is broadly divided into six steps.

1. Step one consists of preliminary inspection to assess the extent and type of damage. This is generally done by flying the affected section of the line with a ROV. At this stage, extensive photographic evidence is collected. The operator is now able to assess the damage.
2. Step two is when a decision is made if the pipeline or flow line needs a replacement, repair or if the line can be put back in service. At this stage, the user determines if fitness for service can be reliably carried out.
3. Step three consists of establishing clearer inspection and evaluation protocols for every type of damage that can be expected in this pipeline.
4. Step four consists of carrying out level 1, level 2 or level 3 type of assessments as detailed in this paper.
5. Step five is carried out if analytical techniques in level 1, 2 and 3 failed to demonstrate adequate line integrity. At this stage, Level 4, full-scale testing is resorted to, in order to demonstrate continued integrity.
6. Step six consists of coming up with a conservative residual life, followed by the determination of the inspection interval.

The analysis on the Ursa gas pipeline enabled the operator to continue operating until such time the repair options were defined, designed and implemented. The proposed approach can potentially be employed for fitness for service determination of most sub-sea pipelines, irrespective of the damage mechanism.

Figure 11 (a)
Generalized flow diagram depicting the damage evaluation methodology on sub-sea lines

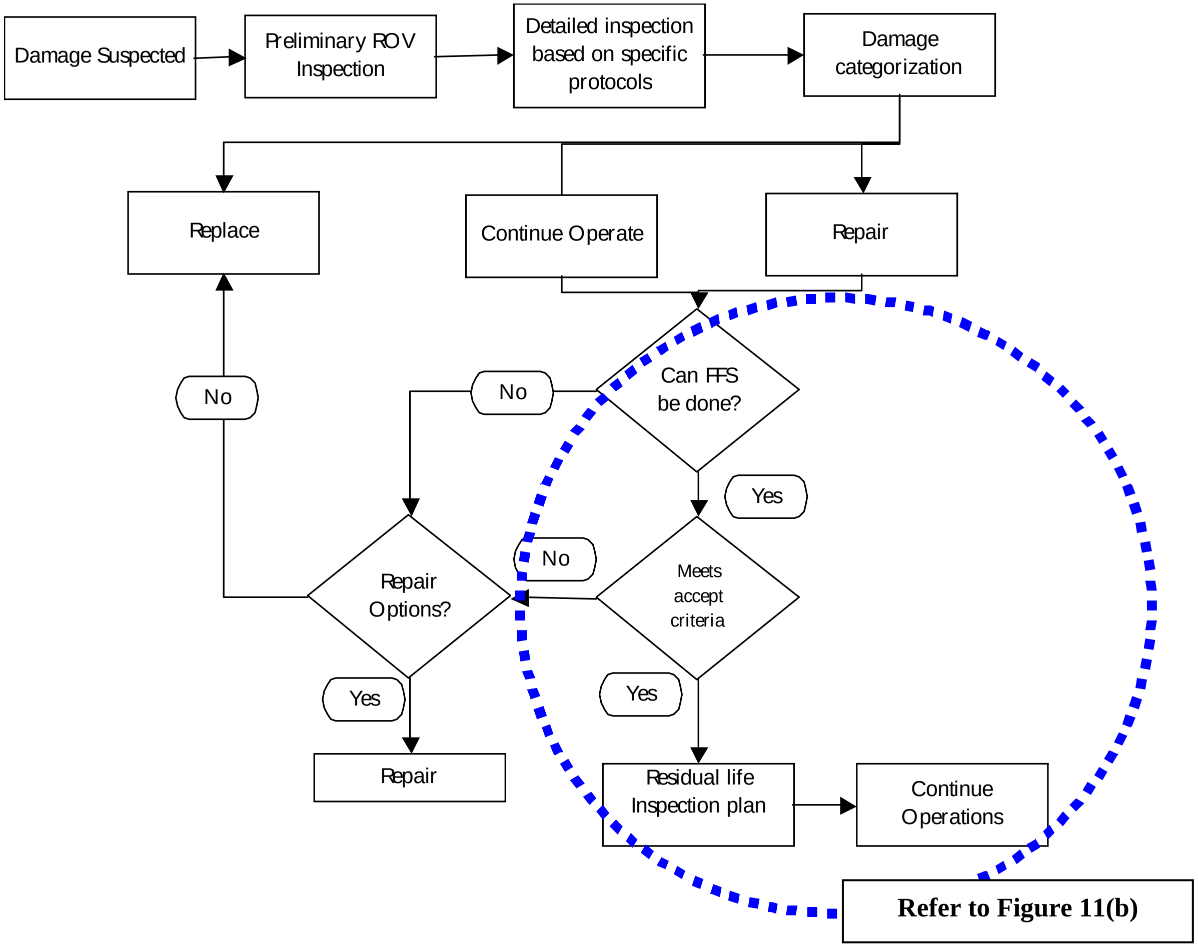
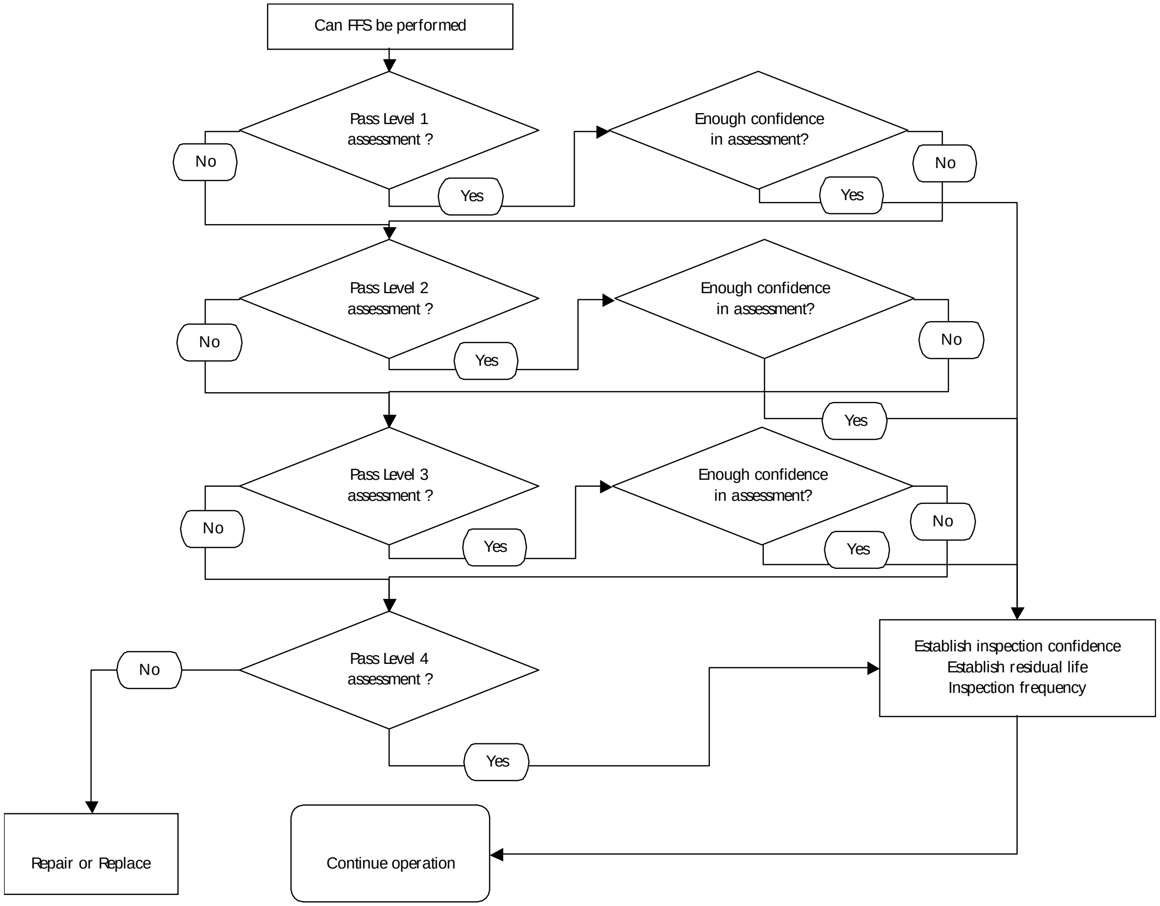


Figure 11 (b)
Decision tree for type / level of analysis needed on sub-sea lines


Can FFS be performed
Pass Level 1 assessment ?
No
Yes
Enough confidence in assessment?
No
Yes
Pass Level 2 assessment ?
No
Yes
Enough confidence in assessment?
No
Yes
Pass Level 3 assessment ?
No
Yes
Enough confidence in assessment?
No
Yes
Pass Level 4 assessment ?
No
Yes
Establish inspection confidence
Establish residual life
Inspection frequency
Repair or Replace
Continue operation

References:

---

[1] OCS Report- MMS Report 2001-067, New Orleans, August 2001

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

[3] API 579, Fitness for Service – API 579 / ASME FFS-1, June 5th, 2007.

[4] ASME B31.8-Gas Transmission and distribution piping systems (2007)

[5] ASME B31.8S-Managing system integrity of gas pipelines (2004); Supplement to ASME B31.8.

[6] Pipeline Defect Assessment Manual (PDAM-Version 2). Joint Industry Project Report: NR 00018/4238.1.10/R0.10-Andrew Palmer Associates

[7] API RP 2A (1986) Recommended practice for planning, designing and constructing fixed offshore platforms (American Petroleum Institute, Washington DC)

[8] Department of Energy (United Kingdom) – 1990 – Offshore installations; Guidance on design, construction, certification (4th Edition).

Acknowledgement:

The authors wish to acknowledge and thank the support from Shell Pipeline Co and Shell International E&P for the preparation of the paper. In particular, we acknowledge the financial support and coordination from Mike Coyne and Ken Zimmerman (SPLC), Frans Kopp and Mike Dupree for initiating this work and defining and advising on the scope and Mei Zhang and Heping Zhang for FEA analytical support.