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INSPECTION & ASSESSMENT OF DAMAGED SUBSEA PIPELINES: A CASE STUDY

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ABSTRACT

The Central Area Transmission System (CATS) in the UK sector of the North Sea delivers natural gas through a 404 km pipeline from the CATS riser platform to the North East coast of England. During the summer of 2007 this 36 inch diameter natural gas pipeline was damaged by a vessel anchor. The anchor lifted the pipeline from under the seabed, dragged it across the seabed, bending the pipe and locally deforming it. This event resulted in a significant inspection, assessment and repair programme before the pipeline could safely return to operation.

This paper describes the detailed structural assessment of the damaged pipeline and the inspection and repair operations.

Following inspection of the pipeline by divers, the damage was assessed using the “Pipeline Defect Assessment Manual” (PDAM). The manual was prepared from research primarily for onshore pipelines: this paper discusses the strengths and weaknesses of PDAM and key differences in defect assessment for onshore and offshore pipelines.

The paper highlights several very important lessons learnt from this incident, including:

- the complex stresses developed in a pipeline that is pulled and moved by an anchor;
- the need for damage assessment methods for pipe containing high compressive stresses and 'locked-in' stresses;
- the safety aspects and complexity of inspecting a pressurised and damaged subsea pipeline.

These lessons learnt are then translated into recommendations for the industry, and advice to other subsea pipeline operators.

INTRODUCTION

The Central Area Transmission System (CATS) is a large diameter subsea natural gas pipeline in the UK sector of the North Sea, Figure 1.

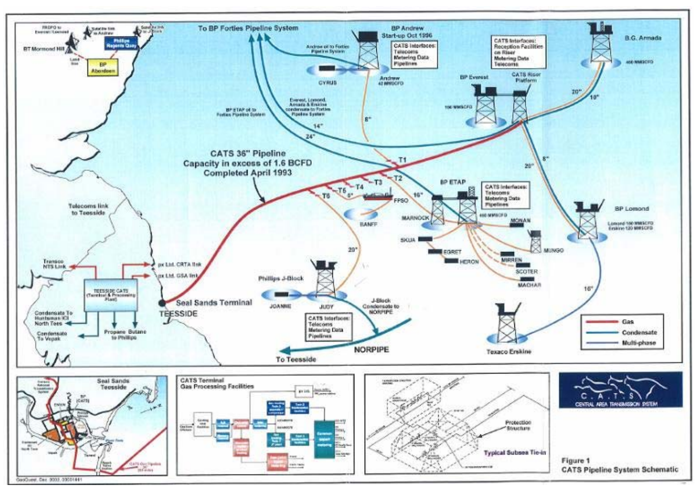


Figure 1 - CATS Pipeline Route

The pipeline is operated by BP on behalf of the CATS partners. It transports gas approximately 400 km from the central North Sea to a shore terminal at Teesside. The pipeline was installed in 1991-2.

The pipeline operates in dense phase with a maximum allowable operating pressure (MAOP) of 179 barg. The pipeline is API 5L X65 steel grade, 36” outside diameter, wall thickness of 28.4 mm, and coated with 51 mm of high density concrete. In the near shore area, the pipeline is trenched (with natural backfill) for stability and protection.

CATS PIPELINE INCIDENT

During the night of 25/26 June 2007, BP was notified that a large tanker moored off the Tees estuary in the North Sea had dragged her anchor across the CATS pipeline during a storm [1]. The incident occurred approximately 6 km from the pipeline landfall by the Tees estuary, in a water depth of approximately 32 m.

INITIAL RESPONSE

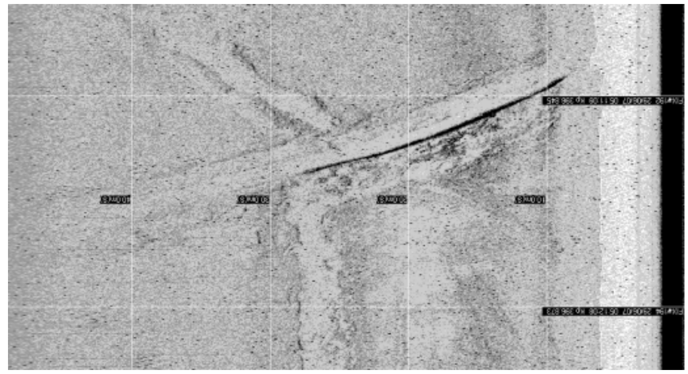
Following the report of possible contact between the anchor and the pipeline, the pipeline emergency response plan was put into action, in accordance with BP's internal standards. Monitoring of the flow and pressure in the pipeline confirmed that there was no loss of containment as a result of the incident. A guard vessel was positioned near the pipeline and a 1000 m radius exclusion zone designated around the damaged section.

BP's engineering technical practices refer to the Pipeline Defect Assessment Manual (PDAM) [2] for guidance following pipeline incidents and potential damage. PDAM recommends that the pipeline pressure is reduced immediately following an incident in order to stabilise the pipeline. Ductile materials can exhibit time dependent behaviour and it is possible that a damaged pipeline can fail some time after the incident, even though there may be no subsequent increase in the applied loading.

PDAM and other references recommend pressure reductions between 5% and 20% before inspecting or working on damaged pipelines. The dense phase CATS pipeline operates above a minimum cricondenbar pressure of 105 bar g and was operating at 112 barg at the time and location of the incident. The pressure was therefore reduced by 5% and monitored for 48 hours before inspecting the pipeline.

An Acergy survey vessel on contract to BP, the MV Polarbjorn, was diverted from its planned work to perform a survey of the pipeline using side scan sonar and a remotely operated vehicle (ROV). This survey revealed that the pipeline and its coating had been damaged by the anchor. The side scan survey identified that the pipeline had moved by a distance of approximately 4 to 5 m to the south-east. The movement had pulled the pipe through the backfill soil and caused pipeline exposure over a 94 m length. Based on disturbed seabed soil, lateral movement had occurred over a longer length of approximately 140 m. Anchor scars were clearly visible on the side scan sonar survey. The ROV video survey showed widespread damage to the concrete coating of the pipeline, see Figure 2. The pipeline concrete and underlying coal tar enamel coatings suffered extensive damage over approximately 4 m of the pipe and the pipeline steel was exposed in a number of areas.

The available video and still photography showed features that appeared to be gouges in the pipe wall, orientated in the longitudinal direction, and a possible dent in the pipeline, see Figure 2. The pipeline was shut in and the internal pressure was reduced to 105 bar g while further inspection works were planned.



Side Scan Sonar Image

Coating Damage

Coating and Rebar Damage (Detail)

Figure 2 - Damage to Pipeline

SAFETY ASSESSMENT

The extent of the damage required further detailed inspection by divers in order to assess the integrity of the pipeline. An engineering assessment was carried out to determine the actions required to ensure safety during the inspection works.

Pressure Reduction

The initial inspection demonstrated that the pipeline had suffered potentially severe damage. PDAM states that in some circumstances, particularly when the damage is very severe or there is the possibility that the pipeline may fail as a rupture, additional consideration should be given to reducing the pressure to a level corresponding to a hoop stress of 30% SMYS. This 30% limit is based on experimental evidence which shows that a pipeline is more likely to leak, rather than rupture, if the hoop stress is below 30% of the SMYS. In this context a rupture is a failure where the opening of the pipe wall extends beyond the extent of the original defect. Pressure reduction to this level reduces both the probability and consequences of any failure.

The limit of hoop stress equal to 30% SMYS is based on onshore pipeline practice where pipe loading is primarily due to internal pressure. Offshore pipelines may be subjected to other loads, such as bending moments or axial forces. For the CATS pipeline, diving works were necessary to expose the damaged section for inspection. This included excavation of the trench underneath the pipeline and concrete coating removal using a mechanized concrete removal tool mounted on the pipeline itself. These operations would induce further bending of the pipeline. The 30% stress limit was therefore applied to the nominal equivalent stress (excluding local stresses at the deformed pipeline) rather than hoop stress.

The initial inspection indicated that approximately 20 m of pipeline would have to be excavated to allow adequate access to the damaged section. Making allowance for the tolerances of excavation by jetting, calculations based on a possible 30 m span gave an allowable pressure of 54 bar g. The pressure in the pipeline was reduced to this value by exporting gas to the UK transmission system as far as possible, followed by flaring of the residual gas offshore. Depressurisation of the pipeline took place over more than a week.

Structural Analysis

The initial inspection indicated that the pipeline had seen significant deformations during the incident. The displacement of the deformed pipeline was modelled using finite element analysis (FEA) to understand the loads applied to the pipeline and the stress state within the pipe, both during and after the incident.

The FEA required a number of unknown parameters, including the loads applied to the pipeline by the anchor and the soil restraint acting on the pipeline. The unknowns were estimated by comparing the FEA predictions of pipe position and shape following the event against the results of the initial survey. The results of the FEA (Figure 3) showed that the pipeline had been plastically deformed in the region of lateral displacement and revealed areas of high longitudinal stresses, both tensile and compressive, in some areas of the pipe. These stresses were partially "locked-in" due to the residual stress distributions arising from the permanent deformation of the pipeline. The predicted peak stresses were tensile and close to the yield strength of the pipe material.

The analysis was extended to predict how the stresses varied during the depressurisation and proposed excavation and inspection works. The FEA considered the additional loading induced by the span, the concrete removal tool, and potential lateral movement of the pipeline during this work. The FEA produced a detailed mapping of the actual and predicted time history of stresses within the pipeline. The results from this FEA were used in a preliminary defect assessment to confirm the safety of the proposed inspection works.

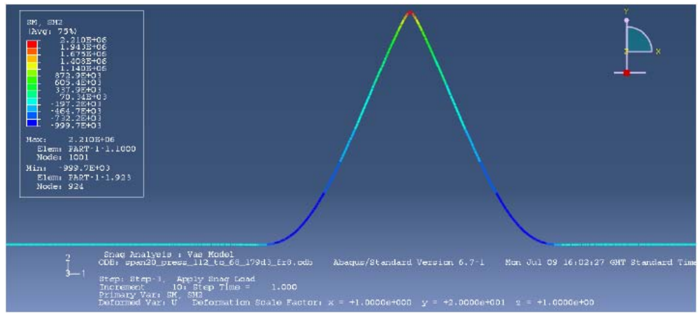


Figure 3 - Example FEA Pipe Profile

Preliminary Defect Assessment

A preliminary defect assessment was carried out to enable a decision to be made on the need to repair the pipeline once detailed inspection data were available.

In accordance with BP's engineering technical practices, the defect assessment was performed using the Pipeline Defect Assessment Manual (PDAM). PDAM is a compendium of the "best" available methods for assessment of pipeline defects based on a review of published assessment methods and test data.

The preliminary defect assessment was performed for the pipeline MAOP of 179 bar g. As the state of longitudinal stress varied significantly around the circumference of the pipeline in the area of coating damage, separate assessments were carried out for axial gouges subject to internal pressure loading and axial gouges subject to internal pressure and compressive axial stress.

The assessment of tolerable sizes for gouges in the areas of the pipe with no significant axial stresses was straightforward using the methods recommended in PDAM, and showed that a gouge 275 mm in length and 4 mm in depth could be tolerated at the MAOP of the pipeline.

PDAM does not contain a method for the assessment of longitudinally-oriented gouges subject to internal pressure and axial compressive loading, as there are no published methods addressing this defect and load combination. PDAM advises the user to seek specialist advice. The specialist advice provided by Penspen for the CATS assessment was to use the method recommended in PDAM for the assessment of a part wall corrosion defect subject to the same loading condition, and use the axial stress dependent term of this method to modify the standard method for longitudinal gouges under internal pressure loading. Using this modified method, Penspen produced defect acceptance charts which demonstrated that for the areas of the pipeline that were in axial compression, the tolerable defect size was so small that in practical terms any gouges in these areas of the pipe must be repaired before the pipeline could operate at MAOP, Figure 4. A similar result was obtained for circumferential gouges in the areas of highest tensile stress. These assessments conservatively considered the locked-in stresses to be primary (externally applied) stresses; no allowance was made for any relaxation of stress due to deformation.

Any defect assessment method will produce very small defect acceptance levels at these high stresses, as the methods used are 'flow stress' dependent, i.e. they cannot accommodate stresses much beyond yield, and at stresses approaching and beyond yield they produce vanishingly small acceptable defect sizes. This does not present a significant problem for onshore pipelines because such large axial stresses are rarely present; however, for subsea pipelines there is the potential for high locked-in compressive stresses to be generated as a result of pipeline displacement. The experience of the CATS incident shows that there is a need for further research to develop defect assessment methods that take account of these loads.

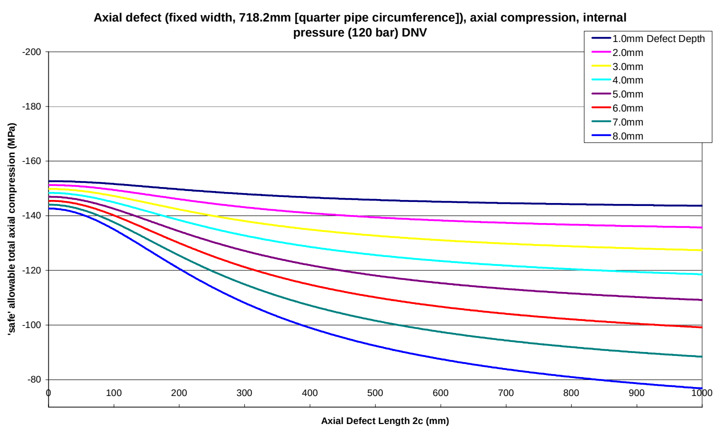


Figure 4 - Defect Assessment under Axial Compressive Loadings

Safety of Inspection Works

The high local stresses demonstrated that depressurisation to a nominal equivalent stress of 30% SMYS, although good practice, did not necessarily ensure integrity of the pipeline during excavation and inspection. For example, an increase in axial stress during excavation could still cause failure of circumferentially orientated defects at the reduced pressure. A further defect assessment was made to confirm that the excavation and inspection works could proceed safely with no risk of pipeline failure.

The initial survey indicated a number of possible gouges and other defects in the pipe wall. It was also possible that other gouges or defects could have been present elsewhere on the pipeline but were not visible in the initial survey. Given that the pipe defects were unknown at this stage, the safety assessment made use of the principle of proof loading, i.e. that any unknown defect in the pipeline would be safe ("proven") during the excavation and inspection works if it had already experienced a more onerous stress state since the incident.

The principle is illustrated in Figure 5 which shows the hoop and longitudinal stress path on depressurisation superimposed on the failure locus for two part wall corrosion defects. The stress paths correspond to two worst-case defects which would have been on the point of failure prior to depressurisation. The failure locus follows a "Tresca" condition, i.e. tensile hoop and axial stresses can be considered independently, while tensile hoop and compressive stresses are combined using a linear interaction model. Depressurisation reduces both hoop and axial tensile stress, and generally moves the stress state away from the failure locus. However excavation and inspection works introduce further axial stresses which may bring the stress state closer to the failure locus and may cause failure of a previously stable defect.

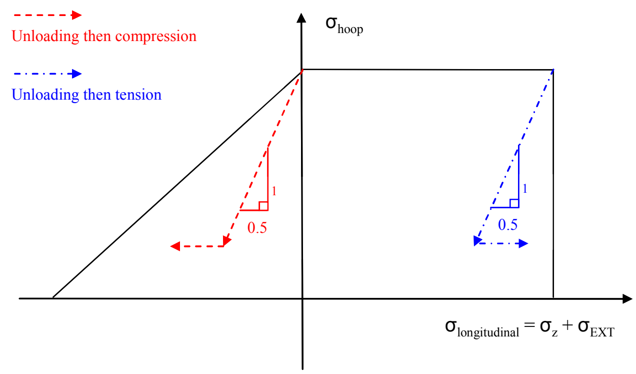


Figure 5 - Failure Diagram

The FEA results were used to demonstrate that the predicted loading history during excavation and inspection was acceptable for all areas of axial tensile stress following the incident, with an adequate margin of safety. However proof loading could not be demonstrated in all areas of compressive stress following the incident. After detailed review, these compressive stresses were concluded to be acceptable because (i) these stresses occurred on the opposite side of the pipe from the anchor, and therefore no gouging was expected at this location, or (ii) any defects of a plausible size could safely withstand compressive stresses of the predicted magnitude at the reduced pressure of 54 barg. This preliminary defect assessment therefore validated the earlier conclusions that excavation and inspection was safe at the reduced pressure.

INSPECTION OF THE DAMAGE

Following the reduction in pipeline pressure, remote jetting operations commenced from the MV Polarbjorn to excavate the damaged section of the pipeline. A more detailed visual survey was performed by ROV to assess the pipeline condition in more detail. The detailed ROV survey did not show any further damage to the pipeline or coating other than that already reported. Diving operations subsequently commenced from the Technip DSV Orelia. The operations consisted of a visual inspection of the pipe, removal of the concrete weight coating and coal tar corrosion coating from the pipeline, and a comprehensive inspection of the suspected damage, see Figures 6 & 7.

A mechanical coating removal tool was used to remove the concrete coating and rebar, followed by low pressure water jetting to remove the coal tar enamel. The work was performed carefully over a period of several days and completed successfully.

The scope of the subsequent inspection included close visual inspection of the pipeline, detailed geometrical mapping using out of straightness and ovality measurements with specially manufactured taut-wire and ovality jigs, MPI and UT inspection of all welds (including the longitudinal seam weld and circumferential welds on either side of the damaged section), full UT wall thickness survey, and measurement of any defects discovered.

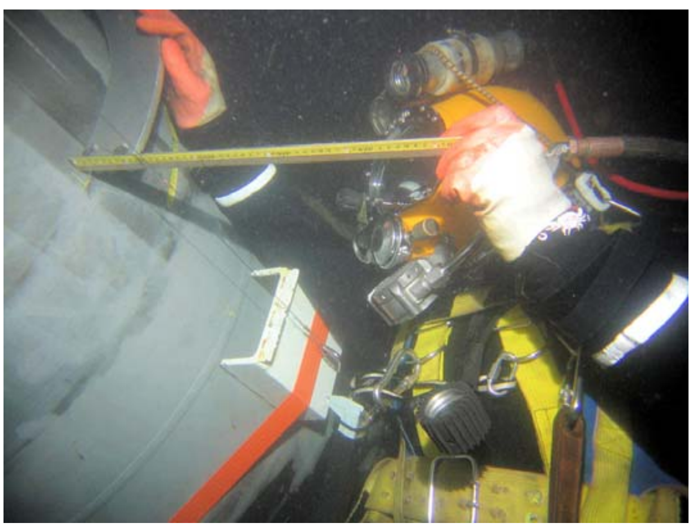


Figure 6 - Diver Inspection (Taut-Wire)

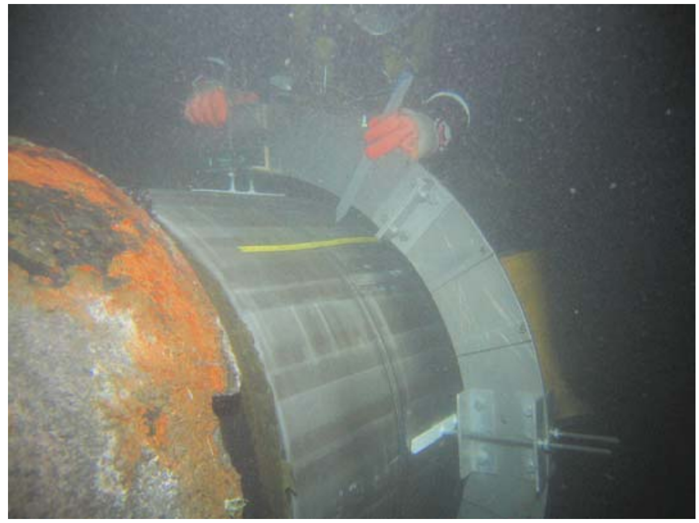


Figure 7 - Diver Inspection (Ovality)

Diver access and detailed inspection on the pipe gave unexpected results. The suspected gouges in the pipe turned out to be gouges in the coal tar enamel coating only which had subsequently filled with debris from the concrete weight coating. The detailed inspection determined that there were no gouges in the pipe wall, all welds were sound and free from defects, and there were no defects or other indications of cracks in the parent pipe. The suspected dents were not confirmed and the divers initially reported no dents in the pipe. However, following removal of the concrete coating from the entire pipe joint, further diver inspection revealed a complex dented feature which was confirmed by detailed geometric mapping. The dented area was centred at about 8 o'clock (looking along the pipe away from Teesside) and extended up to the pipe seam weld at around 10 o'clock. Detailed geometric mapping of the area determined that the overall axial extent of the deformed area was approximately 4 m, Figure 8. The feature consisted of an ovalised section due to the high bending curvature at the peak of the pull over, superimposed on which were two pronounced "dents". The greatest depth of the two dents was 31 mm at the deepest point.

The geometry closely matched the dimensions of the vessel anchor. The spacing of the two dents was approximately equal to the spacing of the anchor flukes while the mid-point between the two dents matched the point of maximum pipe curvature and ovality. Drawings showing the anchor and pipe supported the conclusion that the feature had been caused by the anchor hooking on the pipe and pulling it sideways, Figure 9.

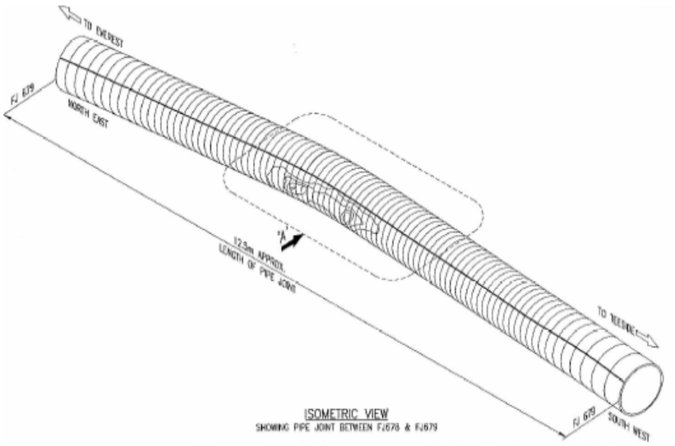


Figure 8 - Local Deformation

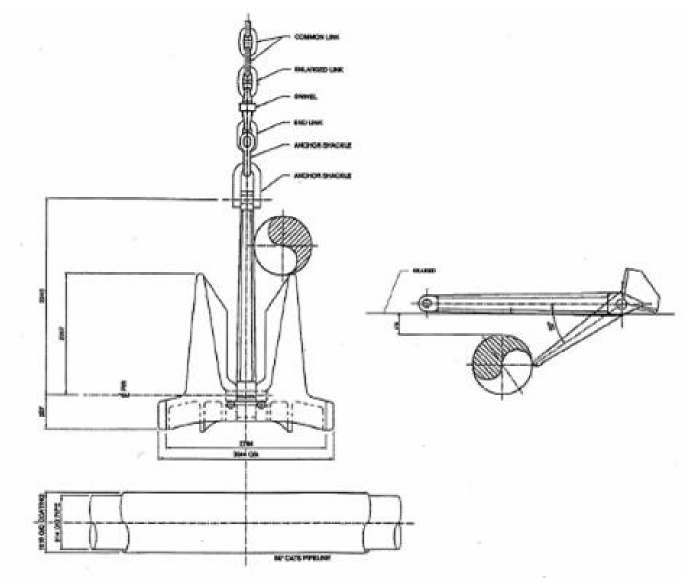


Figure 9 - Anchor and Pipeline (to scale)

Maritime data [1] indicate that the vessel crossed the CATS pipeline while drifting at a speed of around 2 knots. The kinetic energy of the anchor can be estimated from the effective mass of the anchor and was of the order of 10 kJ. In pipeline terms, the impact energy is relatively low, primarily because of the low anchor velocity. This impact energy can be absorbed by typical concrete coatings without affecting the pipe steel [3]. It is likely that the “impact” damage (i.e. at the moment of impact between anchor and pipeline) was limited to the concrete coating only. The locations of the two dents, equidistant from the point of maximum pipeline curvature, suggest that the two dents probably formed later due to the same anchor chain tension which induced the lateral movement of the pipeline. The other coating damage along approximately 4 m of pipe may have occurred as the anchor freed itself from the pipe.

ASSESSMENT OF THE DAMAGE

Dents in pipelines must be assessed as they may result in a reduction in the static strength of the pipeline, and also a reduction in the fatigue life if the pipeline is subject to pressure cycling.

Static Strength

There is no applicable method in PDAM for the assessment of the static strength of a dent containing a weld. PDAM states that dented welds are usually repaired and other industry guidance (e.g. ASME B31.8S) requires repair. PDAM notes that the reason for this is that “*the burst and fatigue strength of a dented weld is difficult to predict and can be significantly lower than that of a plain dent of the same depth, due to the possibility of the weld being damaged (cracked) during the denting process*”. However PDAM does state that “*If it could be established, with confidence, that the dent and the weld did not contain any defects, and that the welds were over-matched and had a high toughness, then it may be reasonable to assess the static strength of a dented weld as though it was a plain dent*”.

The UT and MPI inspection of the seam weld showed that the weld contained no defects and pipe material records were available which gave the required confidence that the weld was overmatched and had sufficient toughness. Therefore a judgement was made that the reported dents could be assessed using the method recommended in PDAM for the assessment of plain dents.

PDAM states that plain dents with depth less than 7% of the pipe diameter do not affect the static strength of the pipeline. The measured depth of the deepest dent in the CATS pipeline was 3.4% of diameter. Possible interaction between the two dents and the residual curvature of the pipe was assumed to have no effect on burst pressure. The assessment therefore concluded that the dent was tolerable at MAOP.

Fatigue Strength

PDAM recommends that the fatigue life of a dent containing a weld can be assessed using the method for a plain dent with the application of an additional factor to account for the presence of the weld. The recommended method determines a stress concentration factor due to the geometry of the dent and determines the resulting fatigue life using an S-N curve specific to steel pipelines.

Internal pressure data were obtained from the CATS shore terminal showing the variation in pressure at the damage location over the previous year. These data were used to determine the pressure cycling as an input to the fatigue calculation.

It was noted that the S-N curve used in the method recommended in PDAM is specific to pipes tested in air. Given that the pipe coating had been removed for inspection, the fatigue assessment of the dent was carried out assuming a seawater & CP environment. A correction factor of 2.5 was applied to the calculated fatigue life to account for this difference, in accordance with published guidance [4].

Using the PDAM recommended method, the remaining fatigue life of a 31 mm deep dent on the seam weld was calculated to be 17 years. This was considered an upper bound to the fatigue life of the reported damage, as the assessment did not take account of the complex shape of the feature, including the pipe curvature, the two dents, or the presence of a compressive axial stress. The estimated fatigue life was lower than the remaining design life of the pipeline, and therefore some form of pipeline repair or reinforcement would be required, although not necessarily immediately. A further fatigue check was then performed to assess the fatigue due to the single cycle of depressurisation from normal operating pressure down to 54 barg and back to normal operating pressure. This check was performed using the same PDAM method and indicated that a substantial proportion of the pipeline fatigue life would be consumed during this single depressurisation cycle. It was therefore decided to repair the damage prior to repressurising the pipeline.

<u>Discussion</u>

The PDAM assessment predicted significant fatigue damage due to only one pressure cycle over only half the operating pressure of the pipeline. This conservative result raised a number of questions regarding the application of the PDAM methodology to dented pipelines with welds. The methodology includes an empirical factor to take into account the detrimental effect of the weld, based on results of fatigue tests on pipes without welds and tests on pipe with welds. The location of the weld seam is not defined; the PDAM data set simply interprets the weld seam as present within the dented shape of the pipe. Consequently, the assessment considers the dent to be the same as a dent with a seam or circumferential weld running through its centre.

In the CATS case, the seam weld crossed the periphery of one of the dents. According to PDAM, the dent must therefore be considered as a dent with a weld. Some finite element analyses were performed later to assess the effect of the weld location and any interaction between the two dents and the overall shape of the pipe. Two analyses were attempted. The first FEA used the as-measured geometry of the pipeline and determined the linear elastic stress concentration factors which were applicable for subsequent elastic pressure cycling. The second FEA attempted to model the local elastic-plastic loading history of the dented pipe and the subsequent stress cycles during pressure cycling. The more complex second analysis was ultimately inconclusive, but the simpler first analysis gave realistic stress concentration factors at (i) the location of the weld and (ii) the most onerous location within the parent pipe. A conventional fatigue calculation was then performed using these stress concentration factors and S-N curves for parent pipe and welded pipe. The results gave a greater fatigue life than predicted from the PDAM model.

The two different approaches give different conclusions. The PDAM approach implicitly considers any side-effects of the denting process, such as changes in material toughness and micro-cracking of the parent pipe. PDAM also implicitly considers the observed statistical uncertainty in the fatigue performance of pipelines with dents. However these statistics are based on a relatively limited data set which may be inapplicable and overly conservative for the actual pipeline, dent and weld location. In contrast, the FEA approach uses more appropriate stresses at the critical weld, but relies on material data which may not necessarily represent the actual fatigue resistance of the pipe and weld after the denting incident, and may be non-conservative. Ultimately, the comparison between the two methods is inconclusive. However the comparison illustrates the potential benefits which could be obtained from more refined fatigue assessment methods for dented pipelines.

REPAIR & RESTART

It was decided to place a permanent repair over the damage. A grouted sleeve design was selected, see Figure 10.

The grouted steel sleeve repair consisted of a very rigid steel sleeve, fabricated in half-shells, with cementatious grout in the annulus between the pipe and sleeve. The grout provides rigid reinforcement to the dented pipeline and prevents further outwards radial movement of the dents under pressure cycling. The sleeve provides structural support only; it is not pressure-retaining but can withstand the structural loads exerted by the outside of the pipeline during pressurisation.

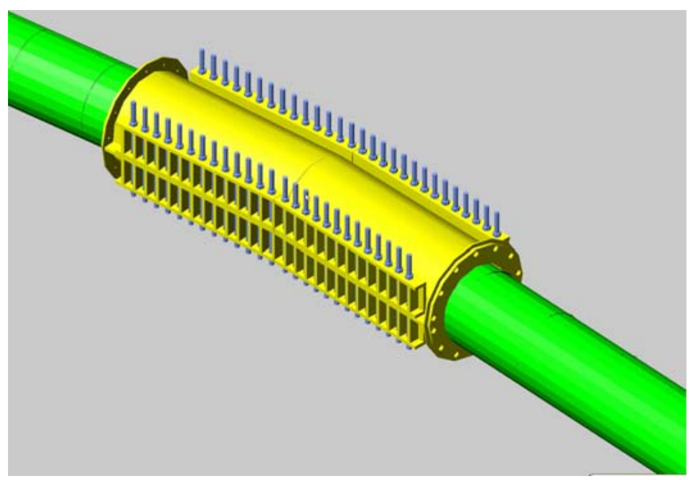


Figure 10 - Repair Sleeve

A complex mitred sleeve was required in order to accommodate the permanent bend at the peak of the deformed pipe section while limiting the thickness of the annulus and effective flexibility of the grout reinforcement. The sleeve was approximately 4.2 m length with a 6.5 degree mitred elbow at the centre. The clamp included seals at each end to hold the grout during curing. The clamp design was backed up with FEA and structural design calculations to confirm that the clamp and grout provided adequate restraint to prevent stress cycling of the pipeline dents.

The clamp was fitted by divers from the DSV Orelia. The lower half of the clamp was located under the pipeline using air bags, and the upper half then lowered down over the pipeline. Once the bolts were made up, grout was then injected into the annulus. Grout samples were retained to measure curing rates and confirm that the grout had reached adequate strength.

The pipeline was then put back into operation. The restart was a complex operation which required careful management of the liquids which had collected in the pipeline following the depressurisation below the cricondenbar. The timing of the restart and repressurisation was carefully managed to ensure that the increase in pipeline pressure did not exceed the allowable pressure determined by the curing of the grout within the repair clamp.

The pipeline returned into normal operation on 1 September. The damaged section was initially protected by guard vessel and later rock-dumped for permanent protection.

CONCLUSIONS

This paper has presented a summary of the inspection, assessment and repair of the CATS pipeline after damage due to an anchor snagging incident. The whole exercise was completed in 9 weeks.

Anchor damage to offshore pipelines can be both severe and complex, and it is necessary to conduct safety assessments at all stages of the inspection, excavation, assessment and repair process.

A number of important technical lessons were learned from the incident:

- Observations from initial visual surveys may be misleading. Detailed inspection data are essential for the accurate identification and assessment of defects in the pipeline;
- The process of snagging and pull over induces a complex stress state in the pipeline. Significant locked-in stresses can be induced;
- The high locked-in stresses could potentially lead to failure after the incident. The size and shape of defects are not known until the inspection is complete. Preliminary safety assessments are essential to demonstrate that inspection work can proceed safely;
- Methods are required to assess gouges in pipelines with significant locked-in stresses. Existing methods can lead to very onerous defect assessments;
- Current methods to assess fatigue in dented pipelines may be very conservative. There is scope for further refinement of fatigue assessment methods.

Existing pipeline defect assessment methods are largely based on onshore pipeline practice. The CATS pipeline incident has demonstrated that care is required when applying these methods to damaged offshore pipelines.

ACKNOWLEDGMENTS

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