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IBP1032_11 RAPID DECISION-MAKING IN EMERGENCY SUBSEA PIPELINE REPAIR

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Abstract

Large diameter oil and gas pipelines are major assets. Damage to these pipelines may result in a failure or an unsafe defect. Shutting down a pipeline will result in huge costs for deferred production, and may result in punitive consequential damages; for example, gas supplies are not delivered. Consequently, the ability to rapidly evaluate any damage and make decisions regarding the requirement for repair and the type of repair is critical.

This paper presents a study of a set of large diameter subsea high pressure gas pipelines supplying an LNG terminal. The damage that might result from an anchor interaction incident with each of the pipelines was modelled, and broad limits for different levels of response were defined. Particular attention was paid to possible damage that could be quickly and efficiently repaired with a grouted clamp system, rather than requiring a complex and expensive cut-out repair.

The result of this study is a document that allows damage to be categorised rapidly and the most appropriate repair system to be mobilised. In addition, models and acceptance criteria have been developed that would allow detailed case-specific damage analyses to be completed quickly and reliably. Finally, some limitations in the available damage assessment methods have been identified that, if addressed, could reduce conservatism in the assessments, and prevent unnecessary production loss and repair.

1 Introduction

Qatargas Operating Company (Qatargas) operates a system of large (16inch to 42inch) diameter subsea gas and condensate pipelines in the Arabian Gulf, Figure 1. They are establishing an Emergency Pipeline Repair System (EPRS) for these pipelines.

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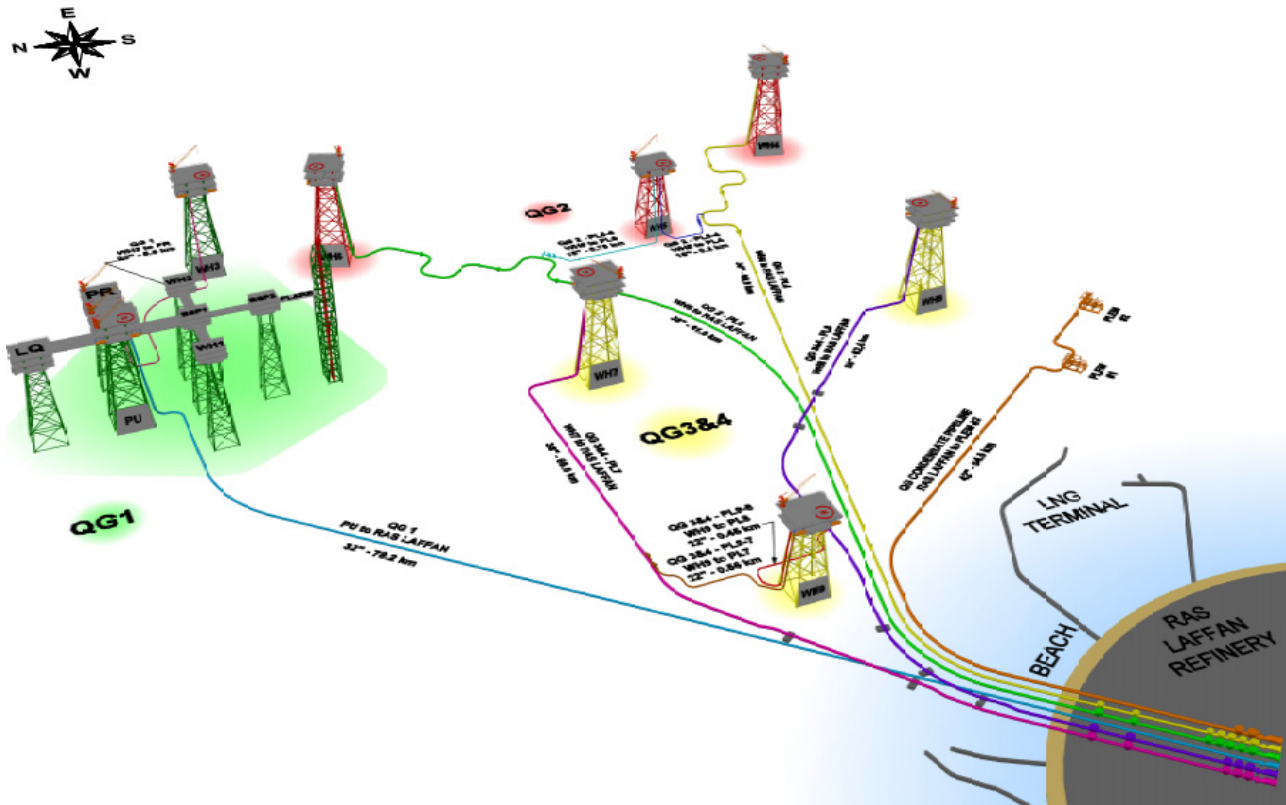


Figure 1 General Layout of Key Qatargas Pipelines in the Arabian Gulf

As prudent operators, Qatargas are aware of the need to identify and assess pipeline defects, and to take any remedial action required. Ship traffic presents a hazard to pipelines, as shown by the BP CATS incident reported by the MAIB and Espiner et. al.. Anchor interaction has been identified as a credible hazard for these pipelines. Qatargas therefore asked Penspen Ltd. UK to develop damage assessment criteria which address the potential consequences of anchor interaction incidents, in terms of the damage caused to the pipelines. The goal of these criteria is to allow rapid decisions to be made on the need for pipeline repair, the choice of repair, and the timing of repair.

When an anchor hits a pipeline it can cause damage. There are four possible outcomes:

1. A rupture (a large release of oil or gas and a large fracture in the pipeline);
2. A leak (a small release of oil or gas from a small hole);
3. Damage that could fail in service (for example, a large dent); or
4. Superficial damage (for example coating damage).

If a pipeline is ruptured the required course of action is relatively clear: the pipeline must be isolated. This means the valves at each end must be closed, efforts must be made to contain lost product, and a new section of pipe must be inserted.

In the case of a leak the appropriate course of action is less clear. Shutting down is an obvious first step, but if it is a gas pipeline then shutting down will allow water into the pipeline that can result in hydrate formation and a blockage. This can lead to a requirement to replace a section.

Where the pipeline has not failed, but has been damaged, assessment and possible repair is required.

Qatargas intend to have two repair options available:

1. Grouted steel sleeve; and,
2. Cut-out and replacement.

In the event of a pipeline damage incident, Qatargas plan to implement the process outlined in Figure 2.

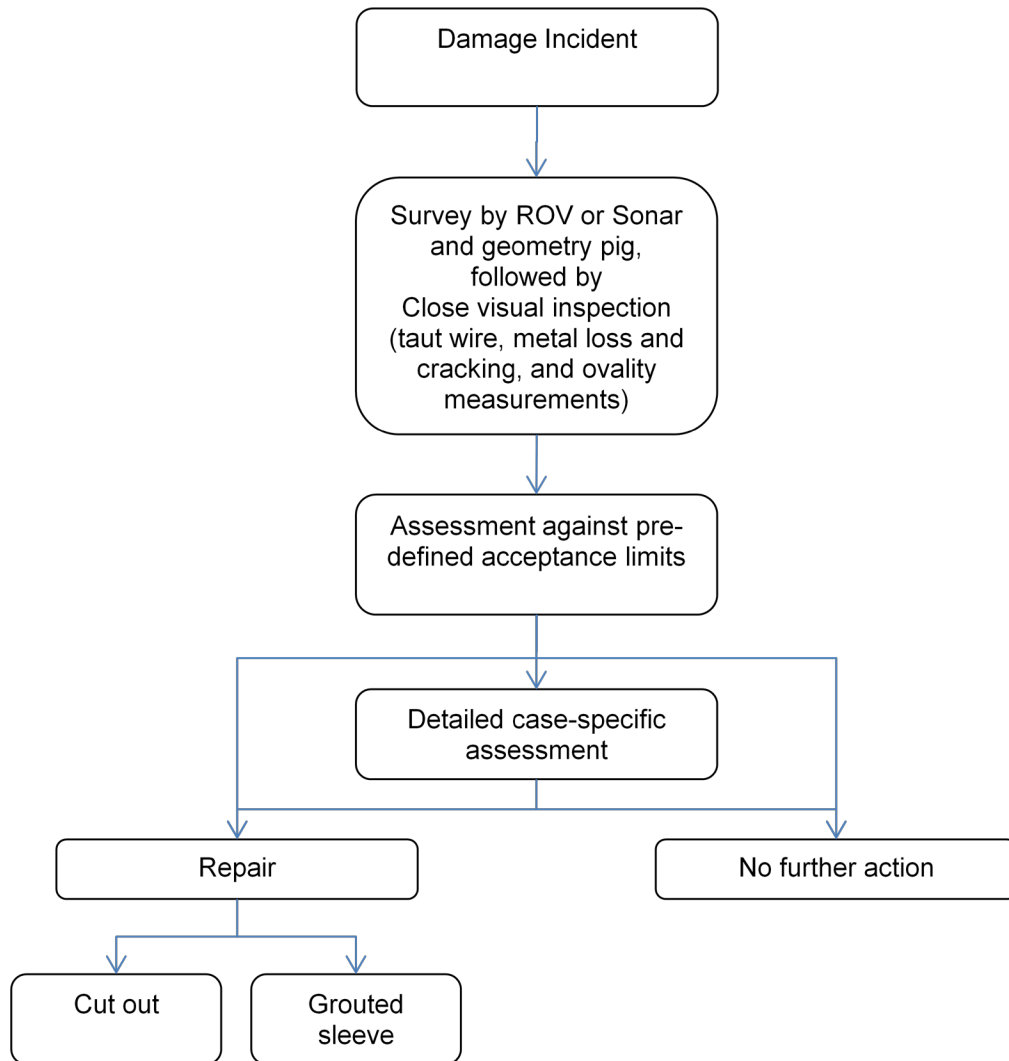


Figure 2 Repair Decision Process

The following anchor damage types were identified as credible, and potentially requiring an emergency repair:

- Displacement
- Gouge
- Dent
- Dent with gouge, or on a weld
- Dent and displacement

2 Overview of Pipeline Anchor Interaction Damage

There are a number of scenarios which could result in interaction between a ship's anchor and a subsea pipeline. These are outlined below, together with definitions of types of pipeline damage.

2.1 Dropped Anchor

Anchors are normally deployed when the ship has been brought to a stop by the ship's engines. When the anchor is dropped from a ship it will probably penetrate vertically into the seabed. The depth of penetration depends on the weight and shape of the anchor, and the characteristics of the seabed soils.

When a vessel requires to anchor routinely, the ship's captain will normally inspect sea charts to avoid obstacles, and preferably choose an area assigned for anchoring. But in the event of an emergency situation this may not be the case. There is therefore the potential for the anchor to be dropped directly on to the pipeline and to damage it, resulting in loss of product, or a dent and/or a gouge.

2.2 Dragged Anchor Impact

Once the anchor is on the seabed, more anchor chain would normally be paid out so to that the chain will rest on the seabed. This should cause the anchor flukes to dig into the seabed when the anchor chain tightens as it begins to hold the vessel against the tide. The flukes gradually work down into the soil until the body of the anchor is either partly or wholly embedded in the seabed and the anchor attains its maximum holding power. If the anchor were to drag across the pipeline during this process it could hit it, applying an impact load. This could result in loss of product, a dent and/or a gouge.

2.3 Anchor Snag and Pull-Over

If interaction occurs, a secondary load may be applied to the pipeline after the anchor impact in the form of a snagging load or a pullover load as outlined in DNV RP-F107. If the anchor should snag the pipeline there is the potential for kinetic energy of the vessel to be transferred to the pipeline, unless the anchor chain breaks. Alternatively, the anchor may initially catch on the pipeline but may then come free again as the anchor chain tightens and the anchor rotates over the pipe. This is known as a 'pull-over', and results in a smaller load being applied to the pipeline for a shorter time.

During a pull-over interaction, some of the kinetic energy of the vessel and anchor may be transferred to cause denting or gouging of the pipeline, and some of the energy may be used in pulling the pipeline along the seabed, until the anchor chain breaks or the anchor pulls over the line. Depending on the loads and restraint applied to the pipeline, the interaction will cause bending of the pipeline which could lead to local buckling at the point at which the anchor pulls the line. This event could therefore result in a combination of denting, gouging, global pipeline displacement, and local buckling.

3 Damage Assessment Approach

Damage limits based on quick and simple measurements are required to allow rapid decision-making on the need for repair or replacement. These limits can be generated by carrying out appropriate generic analyses and comparing the results with existing assessment limits. Any real case will of course be different to the generic examples, but it is expected that simple limits will give an indication of the best course of action, which will allow the mobilization of appropriate equipment. A case-specific assessment can then start, drawing on the methodology and limits set in completing the generic assessments.

Consideration of potential anchor interaction incidents identified that there are three principal types of damage of concern for planning emergency repairs for the Qatargas pipelines:

- Dents;
- Gouges; and,
- Local buckling.

There are various published acceptability limits, and recommendations for actions following identification of these features. This study refers to the following relevant documents:

- The Gas Transportation and Distribution Piping code ASME B31.8; note that this gives guidance for acceptability both at the design/installation/testing stage and also during operation and maintenance;
- The industry-standard Pipeline Defect Assessment Manual (PDAM). This gives guidance on the assessment of most feature in pipelines; and,
- DNV-OS-F101; this code does not give direct methods to assess gouges or dents but does give the latest strain criteria for the onset of local buckling.

In addition to the limits given in these documents, it is important to be aware of practical limits during operation; for example, for pigging operations.

3.1 Dent Repair Criteria

A dent is defined as a depression which produces a gross disturbance in the curvature of the pipe wall, caused by contact with a foreign body, resulting in plastic deformation of the pipe wall. Dents require assessment against three criteria:

- Operability – A dent may reduce the internal diameter and restrict the reliable passage of cleaning or inspection pigs. They may also restrict flow.
- Strain Limits – Plain dents¹ generally do not have a significant effect on the burst strength of a pipeline. Traditionally, empirical approaches based on the depth of the dent have been used. In recent years strain-based approaches have been developed, for example, in ASME B31.8.
- Fatigue Strength – A dent may limit the fatigue life of a pipeline. The stress concentrations and cyclic bending associated with a dent subject to cyclic pressures can result in the development of fatigue cracks that can lead to failure.

When a pipeline is dented, the pipe surface may also be gouged, this combined defect is considered separately.

Operability

Diameter restrictions of up to 10% of diameter are generally acceptable for the cleaning and inspection of large diameter pipelines. However, the Qatargas pipelines require regular cleaning and intelligent pig inspection. To ensure that internal inspections can be conducted safely and reliably Qatargas have adopted a deformation limit of 5% of diameter. Consequently any dents deeper than 5% of diameter will need to be cut-out, although this requirement may not be urgent. The current 5% deformation limit may be increased in view of envisioned next generation inspection tool capabilities.

Strain Limits

The acceptability of a dent can be evaluated by considering the membrane and bending strains generated in the pipe wall by the formation of the dent. Modern line pipe is ductile; however, at high strains cracks can be formed. These cracks may then cause failure or grow to a critical size due to cyclic loading. ASME B31.8-2007 suggests a strain limit of 6% for plain pipe, or 4% for a weld. These limits give some margin for errors in measurements, calculations of strain, and material properties. Cracking is not expected to develop until strains of 12% are reached.

For the preliminary assessment of a dent in a coated subsea pipeline it may be difficult to identify the location of the seam weld. Consequently, for a ‘first pass’ assessment, the 4% strain limit is considered appropriate.

The strain level in a dent depends on the shape of the dent. A deep dent with a smooth profile may have low strains whereas, a shallow dent with a sharp profile may have a high strain. The thickness of the pipe also has an influence as the through-thickness bending strain increases with thickness, so a dent shape that would have low strain in a thin walled pipe, would have a higher strain in a thicker pipe. It should be noted that more energy is needed to dent a thick walled pipe than a thin walled pipe.

The detailed measurements required to accurately estimate dent strain take time to collect. To provide simple limits for an initial assessment based on a quick measurement of dent depth it is necessary to consider the likely dent shapes and then calculate the strains. This can be done using non-linear finite element analysis (FEA).

For the Qatargas pipelines a number of non-linear FEA models were run to cover the full range of pipeline geometries. The finite element code ABAQUS was used. The Qatargas pipelines are surface-laid. Hence, it was assumed that any anchor dragging on the seabed would strike the pipeline with the flat part of the stock or flukes rather than the points of the flukes. It should be noted that for a buried pipeline it is more likely that the points would strike, making a different shape of dent. In practice, anchor-pipeline impact dynamics may affect the dent shape and strain localisation, but the quasi-static approach adopted here is considered adequate for the purposes of a screening assessment.

The results from one of the models are shown in Figure 3.

¹ Dents that do not have any associated gouging, or affect a seam or girth weld.

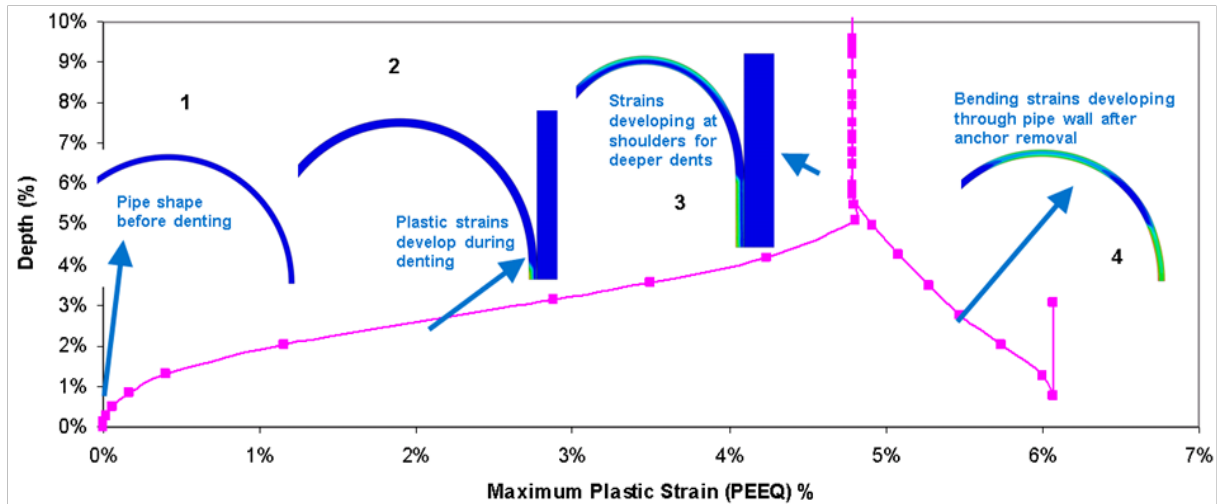


Figure 3 Strain History During Dent Formation Process

The following sequence was observed during each analysis, as illustrated in Figure 3² for the formation of a dent. The red line is the strain at the impact location showing increase in strain with dent depth. Pictures 1, 2, 3 and 4 are snapshots of the strain distribution in the FEA model:

- Initial gradual increase in strain as the pipe is dented (increasing % dent depth as the centre of the dent yields), pictures 1 and 2;
- A sharp increase in depth (at constant strain at the contact position) once the strains at the contact position reach 4%, plastic hinges form at the 12 and 6 o'clock positions, and the strains increase here instead of at the contact position, picture 3;
- A further increase in strain at the contact position when the indenter is removed (reducing % dent depth), picture 4;
- A small increase in depth (at constant strain) if the pipeline is then depressurised.

The point at which the 6% strain limit for plain dents is reached is not indicated by the models due to the formation of the plastic hinge, but the 4% strain limit for dents on welds can be determined. The flat indenter results for the 4% strain limit give limiting dent depths measured after indentation or when depressurised, which are 0.5-0.6% and 1.3-1.5% of diameter respectively. These limiting depths are small, and are not supported by industry experience summarised in PDAM which indicates that dents of up to 7% of diameter should not be a problem under static internal pressure conditions. However, the test data presented in PDAM is for pipe with wall thicknesses of 4.8 mm to 12.7 mm, which is a typical of onshore pipelines. The Qatargas pipelines considered here have wall thicknesses between 23 mm and 26 mm. The through-thickness bending strain due to denting in a 23 mm thick pipe will be higher than in a 12 mm thick pipe.

Where strain limits have been exceeded, but the pipeline has not failed, a repair that strengthens to pipe and reduces the stresses in the damaged area is required to limit any further deformation and prevent the bulging that precedes failure. A loose-fitting full encirclement steel sleeve, with a grout fill between the pipe and sleeve, will provide the required restraint, as shown in a stress analysis shown in Figure 4.

² PEEQ is the ABAQUS term for equivalent plastic strains, i.e the maximum total plastic strain.

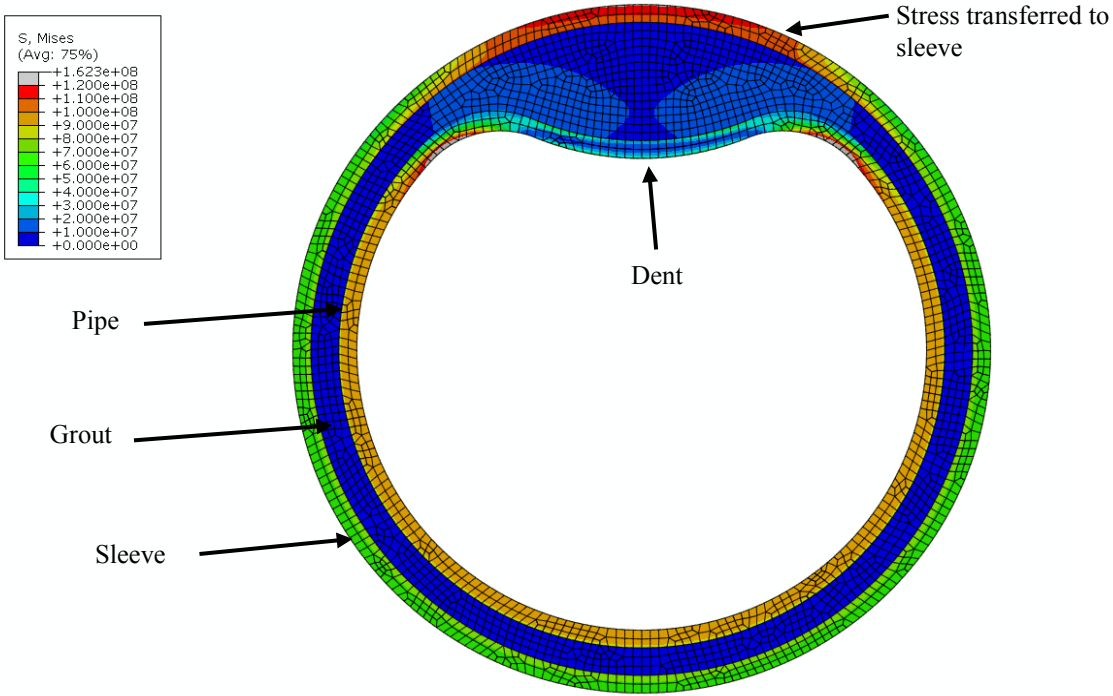


Figure 4 Example of Stress Transfer to Sleeve from Dented Pipe

Fatigue Limits

The stress concentrations associated with a dent in a pipeline will reduce the fatigue life. PDAM recommends a dent fatigue life assessment method published by the European Pipeline Research Group (EPRG). The Qatargas pipelines run at steady pressure with occasional shutdowns. It was concluded that only the shutdowns were significant in fatigue terms. The EPRG method was used to define an acceptable number of shutdowns for a range of dent depths on plain pipe, and affecting a weld. Typical results are shown in Figure 5.

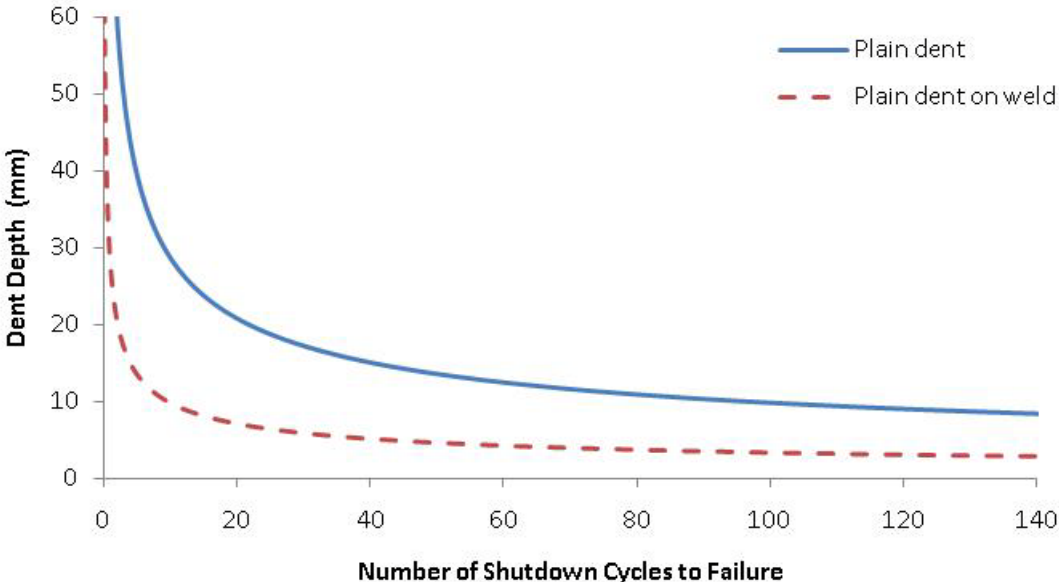


Figure 5 Example of Dent Fatigue Life

Where fatigue is the limiting criterion an immediate repair may not be required. A repair that restrains the pipe, and reduces the stresses in the damaged area is required to repair a dent subjected to fatigue. This restraint will limit any further deformation, and prevent the bulging that precedes failure. A loose-fitting full encirclement steel sleeve, with a grout fill between the pipe and sleeve will provide the required restraint.

Dent and Gouge

When a pipeline is dented the surface may also be gouged. Dents with associated gouging must be repaired due to the potential for a short fatigue life and low burst pressure. There are methods available to assess combined dents and gouges, but due to the number of uncertainties related to dent shape, gouge shape, and the potential for cracking associated with the gouge they are conservative and will generally result in a recommendation for repair for any measureable combination of dent and gouge in a high pressure pipelines. The repair of a dent and gouge will require the dressing³ of the gouge, followed by the strengthening of the dented area with a loose fitting full encirclement steel sleeve, with a grout fill between the pipe and sleeve.

Summary of Dent Repair Criteria

The dent repair criteria developed for the Qatargas pipelines to allow rapid preliminary assessment, identification of the likely need for repair and the repair selection is presented in Table 1.

Table 1. Qatargas Dent Repair Criteria

Dent Depth (% diameter)	Gouge in Dent?	Dent on Weld?	Repair Requirement	Schedule
<5%	Yes	Not applicable	Depressurisation, dressing and grouted sleeve	As soon as possible
<1.2%	No	No	No repair	Not applicable
≥1.2% and <3%	No	No	Grouted sleeve (note that case-specific analysis may shown that repair is not required)	6 months
	No	Yes	Grouted Sleeve	6 months
≥3% and <5%	No	No	Grouted sleeve	6 months
	No	Yes	Depressurisation and grouted sleeve	As soon as possible
≥5%	No	No	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	6 months
≥5%	Yes	Not applicable	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	As soon as possible
≥5%	No	Yes	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	As soon as possible

³ Dressing is the controlled removal of metal from the surface of the pipeline to remove areas of stress concentration, or material with altered properties. Dressing is a skilled operation requiring detailed procedures.

3.2 Gouge Repair Criteria

A gouge is defined as a surface damage to a pipeline caused by contact with a foreign object that has displaced or removed material from the pipe wall, resulting in a metal loss defect.

The material at the base of a gouge will have been severely cold worked as a consequence of the gouging process. This work hardened layer will have a reduced ductility and may contain cracking caused during the gouging process. The hard layer at the base of a gouge may also be a site for future initiation of cracking. The maximum depth of the hardened layer is typically 0.5 mm to 0.7 mm.

The interaction incident may have resulted in multiple types of damage, and gouges may also be associated with denting, cracking⁴ or displacement. Note that a dent introduced together with a gouge may have completely re-rounded, and so may not be apparent.

Gouges are a severe form of pipeline defect due to the potential for cracking at the base of the gouge. As a result, no gouge should be left in a pipeline without repair or dressing.

The acceptability of a gouge under the action of internal pressure is assessed considering its length and depth, using the flow stress dependent part-wall NG-18 equation (Kiefner et al.). This is a failure criterion for a single, longitudinal part-wall defect subject to internal pressure. The method was originally validated against a total of 48 full scale tests on pipe containing artificial, longitudinally orientated, machined V-shaped notches carried out by Battelle in the 1960s and 70s, for the American Gas Association (AGA). Although the method was not developed specifically for the assessment of gouges, it is recommended for their assessment by PDAM.

The repair of a gouge will involve dressing to remove any cracking and the hardened layer from the base of the gouge, and may also require the strengthening of the pipe using a grout filled sleeve or similar.

For rapid assessment pipeline specific charts were developed allowing an initial assessment to be carried out prior to any dressing to remove cracking in the base of the gouge. Final assessment can then be completed using measurements taken after the removal of the gouge by dressing. An example of the assessment plots is given in Figure 6. Separate assessments for burst and fatigue are not required. Once the gouge has been dressed, and then strengthened as necessary, fatigue is not expected to be a problem.

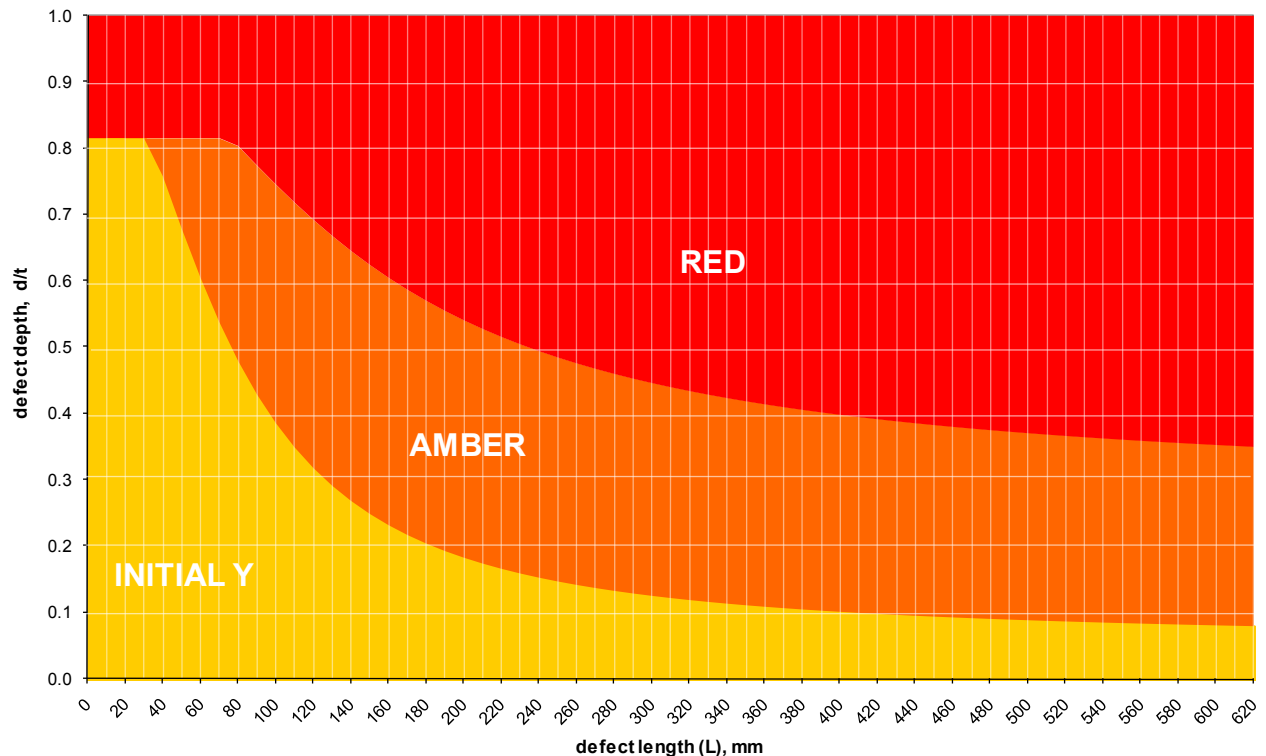


Figure 6 Illustration of Gouge Initial Assessment Plot

When an anchor strikes a pipeline creating a gouge, and then drags the pipeline across the seabed there will be a combined internal pressure load and compressive axial load due to the bending. This compressive axial load may result in a reduction of the burst pressure. Operating a pipeline at an elevated temperature can also result in a compressive

⁴ A force is applied to the pipe during the gouging process and this may also introduce a dent. Once the interaction is over, and the force is removed, any dent formed will tend to re-round. The hardened layer in the base of the gouge may then crack as the indenter is removed and the pipe attempts to regain its original shape.

axial stress. To account for this possible compressive axial stress, additional assessment charts were developed based on assumptions about the gouge size and the stress level.

Once the initial assessment has been completed and the gouge has been dressed, a final assessment may be carried out based on updated defect dimensions, and suitable repairs selected as defined by Table 2.

Table 2. Qatargas Gouge Repair Criteria

Result from Figures	Classification and Recommended Action
Red	Red – repair required (grouted sleeve)
Amber	Amber – repair required (grouted sleeve)
Yellow	Yellow – reinstate the pipeline

3.3 Displacement (Local Buckling) Repair Criteria

If a pipeline is displaced, stresses and strains may exceed acceptable limits. A number of lateral displacement cases have been assessed using finite element analysis (FEA) to provide a look-up table linking lateral displacement, length of pipe affected, visible local buckling (e.g. wrinkling at the intrados), and curvature, to strain levels and the onset of local buckling.

The limiting criteria for lateral displacement are:

- Yielding of the pipeline material;
- The general strain limit in DNV-OS-F101 (2% strain); and,
- The strain limit to cause local buckling as given in DNV-OS-F101.

The local buckling strain limit was calculated for each pipeline using the method in DNV-OS-F101. The strain limit for the pipelines calculated using this formula is approximately 4% for all of the lines under consideration. Therefore, 4% was chosen as the maximum allowable strain limit as strains above this limit could lead to localised buckling and therefore a significant reduction in effective diameter, and very high local through thickness bending strains which could result in cracking.

The local buckling equations are derived from a lower bound fit to the experimental results used to derive these equations. These equations should therefore be conservative and under-predict the failure point in most cases. As a result there may be capacity after this point, but this cannot be reliably predicted or quantified. Buckling in general is an unstable mechanism and once the buckling point is reached significant deformation can happen very quickly. The maximum displacement criterion has therefore been selected such that local buckling does not occur.

Models were developed using ABAQUS for each pipeline to simulate the pipeline shape after a pull-over event. Due to the high stresses induced by bending, which will lead to material plasticity, and the relatively large deformations which take place, a non-linear analysis is required to accurately model the behaviour of the pipeline. To achieve the best estimation of the effect of strain at the crown of the imperfection, it is important to model the pipeline geometry, soils interaction, and the material characteristics as accurately as possible.

The models assume that the pipelines remain pressurised following the pull-over, and that the pull-over load has been removed: i.e., that the anchor is not attached when the line is inspected.

The steps in the analysis are:

- Initialise model – apply the appropriate pressure and temperature;
- Pull pipeline; and,
- Release pull load.

The results should therefore be appropriate to be reviewed against a remotely operated vehicle (ROV) or sonar inspection and/or internal geometry inspection of the pipeline where the pipeline is still operating.

A number of sensitivity assessments were carried out to give an understanding of the parameters having the most significant effect on the behaviour of the pipeline during a pull-over event. The most notable parameter controlling the response of the pipeline is the concrete thickness. Each pipeline has a number of changes of concrete coating along its length. Figure 7 shows the effect of two concrete thicknesses: the red line corresponds to a thickness of 60 mm and blue

gives the results for 110 mm thick concrete. The resulting difference in displacement until the strains at the snag location reach the local buckling limit is approximately a factor of 2.

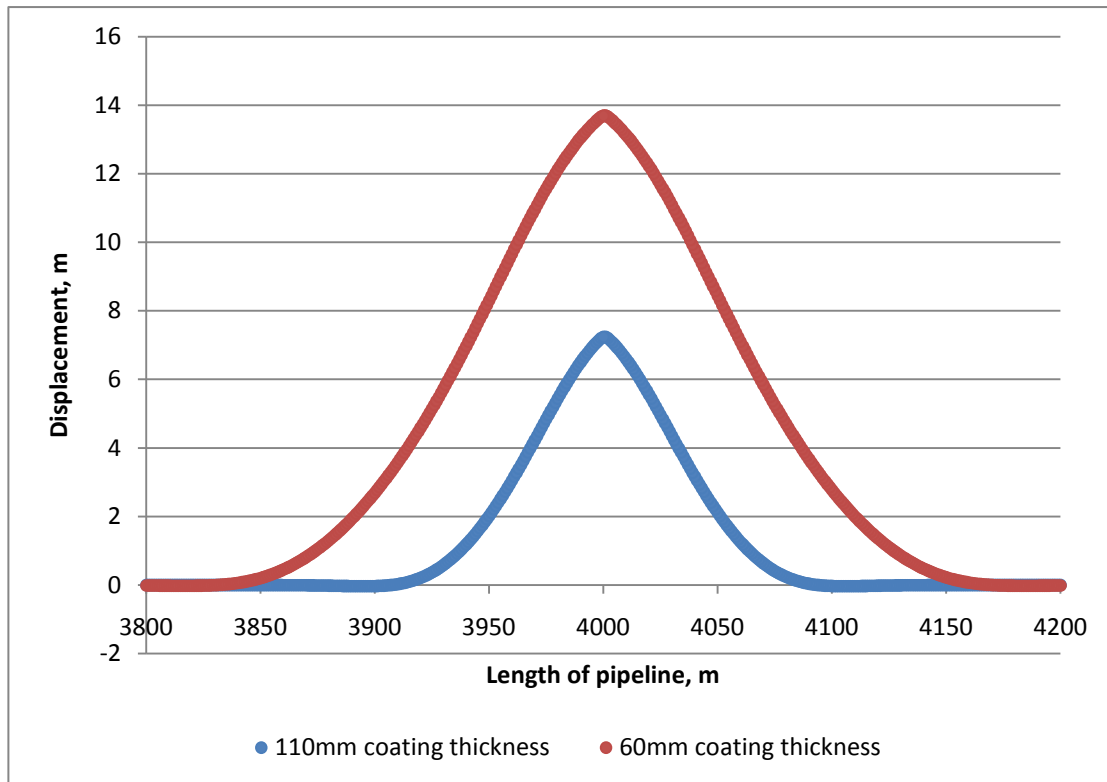


Figure 7 Effect of Concrete Thickness on Displacement

The reason for this difference is the effect of the change in concrete thickness on the submerged weight of the pipeline, and hence the frictional restraint provided by the seabed. The aim of the assessment is to give inspection and repair criteria, based on the maximum strain caused during a pull-over event. Therefore, since it has such a large effect on the results, the concrete thickness chosen for the assessment is important. Thicknesses up to 130 mm are present on the pipelines, but these are predominately located in the inshore areas where a pull-over event with large vessels is unlikely. Therefore, a value of concrete thickness was selected that represents the majority of the length of the pipelines. The selected concrete thicknesses were in the region 100 mm. The results derived from the assessments are therefore expected to be conservative. However, the results here indicate that, should an event happen, it would be beneficial to model the actual local pipeline design and operational parameters before a repair decision is made.

To allow rapid assessment based on a Sonar or ROV survey, limits were extracted for:

- Lateral displacement;
- Length of pipeline affected; and,
- Global angle of displaced section.

These parameters are illustrated in Figure 8.

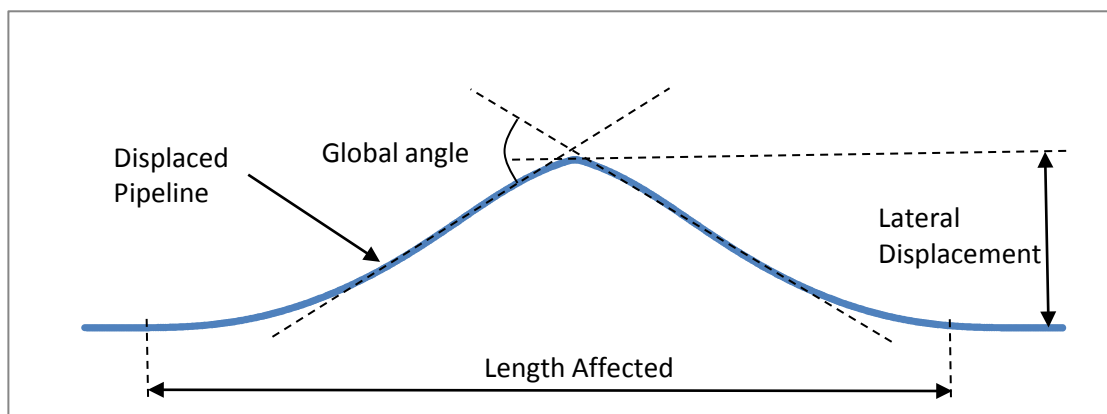


Figure 8 Displaced Section Measurements

Repair recommendations for displacement are given in Table 3. These recommendations are only valid if there is no denting, gouging, or other damage of the pipe surface. It should be noted that once strains exceed 4% local buckling of the pipe wall may occur and collapse of the pipe cross section will occur shortly afterwards. Due to the unstable nature of the structure, predicting the reduction in local diameter against displacement cannot be done reliably. However, should some local buckling of the pipe wall develop without collapse of the cross section then a grouted sleeve repair will be acceptable. If the diameter is severely restricted then the grouted sleeve will only be a temporary measure until the damaged pipe can be cut out.

Table 3. Qatargas Displacement Repair Criteria

Strain	Repair	Schedule
<2%	No repair (confirm by case-specific assessment)	Analysis within 6 months
Between 2% and 4%	Grouted steel sleeve (Note that case-specific assessment may show that a repair is not required)	Repair or further analysis within 6 months
>4%	Grouted steel sleeve is acceptable if any associated ovality or denting results in less than a 5% diameter reduction (a grouted sleeve would also be acceptable for a diameter reduction greater than 5% provided pigging operations are not restricted, or as a temporary measure until the damaged pipe is cut out). Cut-out is required otherwise to meet ILI limit.	Repair or further analysis within 6 months

4 Conclusions and Recommendations

Shipping presents a significant hazard to offshore pipelines. Anchors that impact or snag a pipeline can cause extensive damage. To ensure safety, and minimise disruption of service, an understanding of the potential severity of any damage and the ability to mobilise suitable repair systems is required. The following conclusions are drawn from the study completed:

1. Screening Criteria - Modelling and evaluating credible damage scenarios has allowed the creation of a set of damage screening criteria that can be used for the rapid preliminary assessment of any damage, and to select likely repair options.
2. Case Specific Analysis Required - The number of variables and uncertainties is such that in the event of any actual damage case specific assessment will be required before final choices are made
3. The Advantages of Model Development - The development of pipeline-specific denting and displacement models in advance, has allowed the development of modelling protocols, and is expected to allow rapid efficient, case-specific analyses, provided appropriate skills and experience are maintained.
4. Limitations in the Assessment Methods - In evaluating the potential damage scenarios it is evident that the assessment of some damage types is limited by the historical focus on empirical models. For example, criteria are available for the fatigue assessment of dents. These criteria were developed based on testing, the test data is based on dents in typical onshore pipelines with wall thickness ranging from 5 mm to 17 mm. Large diameter offshore pipelines commonly have wall thicknesses of 20 mm or more. Testing of thick-walled pipe would increase confidence in the assessment methods, and provide improved support for decision making.

The following general recommendations are made:

1. The offshore pipeline industry should invest in the testing of the resistance of large diameter thick walled pipelines to anchor damage. This will allow the development of analysis methods that can be supported with test data and will improve confidence in decision-making in the event of pipeline damage.
2. The operators of large diameter offshore pipelines should consider the development of screening assessments to augment the decision-making process in the event of a damage incident.

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