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Corresponding Author: Prof Kenneth Macdonald,

Corresponding Author's Institution: University of Stavanger

First Author: Kenneth A Macdonald

Order of Authors: Kenneth A Macdonald; Andrew Cosham; Chris R Alexander; Phil Hopkins

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Dear Dai,

Assessing Mechanical Damage in Pipelines – Two Case Studies

Just a short note to accompany our manuscript for the above paper. It is asssociated with our oral presentation at ICEFA II.

Best wishes, Ken

ASSESSING MECHANICAL DAMAGE IN OFFSHORE PIPELINES – TWO CASE STUDIES

K A Macdonald
kenneth.macdonald@uis.no
University of Stavanger
4036 Stavanger, Norway
(formerly with Det Norske Veritas)

A Cosham
a.cosham@boreasconsultants.com
Boreas Consultants, Churchill House,
12 Mosley Street, Newcastle upon
Tyne, NE1 1DE, UK (formerly with
Penspen APA)

C R Alexander
chris.alexander@stress.com
Stress Engineering Services
13800 Westfair East Dr.,
Houston, TX 77041, USA

P Hopkins
p.hopkins@penspen.com
Penspen APA, Units 7&8 St Peter's
Wharf, Newcastle upon Tyne, NE6
1TZ, UK

ABSTRACT

Mechanical damage in the form of dents and gouges is recognised as a severe and common form of mechanical damage to pipelines. In general terms, dents and gouges reduce both the static and cyclic strength of a pipeline. The severity of a dent depends on a number of factors, including: the size and shape of the dent; whether it affects the curvature of a girth or seam weld; and whether it contains other defects, such as a gouge or a crack. An understanding of the issues that influence the severity of mechanical damage is required to ensure that the appropriate action is taken on finding such damage, and that all of the necessary information is gathered for conducting an assessment. For example, what inspection method(s) are appropriate, and when is it better to repair such damage, rather than assess it? This paper discusses some of the issues that may arise during the assessment of mechanical damage, such as: when is a feature really a dent; when does a superficial scrape become classified as a gouge; and the limitations of existing assessment methods. These issues are illustrated with two recent case studies of damage to offshore gas transmissions pipelines.

INTRODUCTION

The most common causes of damage and failures in onshore and offshore, oil and gas transmission pipelines in Western Europe and North America are external interference (mechanical damage) and corrosion. Assessment methods are needed to determine the severity of such defects when they are detected in pipelines. Some of these methods have been incorporated into industry guidance; others are to be found in the published literature.

Mechanical damage includes abrasion, spalling, gouges and dents. The most severe form of mechanical damage is a dent that contains defects.

Issues that arise during the assessment of mechanical damage in pipelines are illustrated with two case studies:

1. a 20 in. diameter, concrete coated offshore gas pipeline in the North Sea that was struck by an anchor in 2003; and

2. a 30 in. diameter, concrete coated offshore gas pipeline that was struck by an anchor in 2005.

THE SIGNIFICANCE OF DENTS

A dent in a pipeline is a permanent plastic deformation of the circular cross section of the pipe. Dent depth is defined as the maximum reduction in the diameter of the pipe compared to the original diameter (i.e. the nominal diameter less the minimum diameter), Figure 1. This definition of dent depth includes both the local indentation and any divergence from the nominal circular cross-section (e.g. out-of-roundness or ovality).

A dent causes a local stress and strain concentration, and a local reduction in the pipe diameter. The significance of dents in pipelines can be summarised as follows [1-5]:

- plain dents (i.e. a smooth dent that contains no wall thickness reductions, such as a gouge or a crack, or other defects, or imperfections, such as a girth or seam weld) do not significantly reduce the burst strength of the pipe;
- the fatigue life of pipe containing a plain dent is less than the fatigue life of plain circular pipe;
- constrained plain dents do not significantly reduce the burst strength of the pipe;
- the fatigue life of a constrained plain dent is longer than that of a plain unconstrained dent of the same depth[1];
- kinked dents have very low burst pressures and short fatigue lives; and
- the burst and fatigue strength of a dented weld, or of a dent containing a defect such as a gouge, can be significantly lower than that of an equivalent plain dent.

A dent should be considered to be on a weld if the dent changes the curvature of an adjacent girth weld or seam weld with respect to the original curvature of the pipe. A kinked dent is one in which there are abrupt changes in the curvature of the pipe wall; an empirical definition of a kinked dent is a dent where the radius of curvature (in any direction) of the sharpest part of the dent is less than five times the wall thickness [2].

Dents in a pipeline can also present operational problems even though they may not be significant in a structural sense. Consequently, any dent remaining in a pipeline should be checked to ensure that it does not significantly reduce flow rates or obstruct the passage of standard tools for cleaning or inspection, or intelligent pigs.

ASSESSING DENTS IN PIPELINES

An assessment of a dent in a pipeline must consider both static and cyclic (fatigue) loading. There are three simple questions that need to be answered by the detailed inspection of a dent, so that the dent can then be assessed:

- is the dent smooth or kinked?
- is the dent on a weld or not on a weld?

- does the dent contain defects or does it not contain defects?

The 'best' currently available methods for the assessment of pipeline defects, including dents, have been identified as part of the Pipeline Defect Assessment Manual (PDAM) joint industry project [4-6]. A summary of the methods recommended for predicting the burst and fatigue strength of a dent subject to internal pressure is given in **Error! Reference source not found.** [4].

CASE STUDY 1

Summary of Study

In May 2003, the general visual inspection of the 20 in. diameter East of Shetland (EOS20) pipeline (owned by the Magnus Field Group (comprising BP and its partners) and operated by BP) identified damage to the concrete weight coating. A large anchor was found lying adjacent to the pipeline. On discovery of the damage, the pressure in the pipeline was reduced. In September 2003, over the course of several days, the damage to the pipeline was inspected in detail by divers. The detailed inspections reported shallow denting (less than 6 mm deep) with some shallow abrasion in the dent (less than 1 mm deep). A detailed assessment of the damage concluded that it was acceptable under the expected static and cyclic loads over the design life of the pipeline. The excavated area was filled with grout bags and a concrete mattress was installed over the damaged section of the pipeline. The pipeline was then returned to normal service. In February 2005, the damage location was rock dumped to provide better protection. Monitoring will continue throughout the lifetime of the pipeline.

Background

The 508 mm (20 in.) diameter, 17.5 mm wall thickness, grade X65, East of Shetland (EOS20) pipeline is part of a pipeline system in the North Sea owned and operated by BP. The pipeline is 210.1 km long and transports natural gas from the Sullom Voe Terminal, on the Shetland Islands, to the Magnus platform. It was commissioned in 2002. In the area of interest, the pipeline was laid on the sea bed and had a 50 mm thick reinforced concrete weight-coat. The water depth was 128 m.

A general visual inspection (GVI) of the EOS20 pipeline, using a remotely operated vehicle (ROV), was conducted for BP by Stolt Offshore in May 2003. The GVI was part of BP's planned inspection and maintenance programme for this pipeline, and it was the first GVI since commissioning the pipeline. Damage to the concrete weight coating, extending over approximately 1.5 m, was discovered by ROV, Figure 2. No damage had been reported during the as-laid survey in 2001. Visual inspection of the area of damage, by ROV, located an area of scrape marks in the bare metal, over a total length of approximately 400 mm within the area of damaged concrete, Figure 3. The nearest field joint to the damaged area was approximately 4 m away.

A large anchor (measuring about 1.5 m between the flukes, 2 m along the stalk) was found lying 2 m from the pipeline, Figure 4. Attached to the anchor was approximately 150 m of anchor chain. The pipeline was found to have been displaced by up

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[1] An unconstrained dent is free to rebound elastically (spring back) when the indenter is removed, and is free to reround as the internal pressure changes. A constrained dent is a dent that is not free to rebound or reround, because the indenter is not removed (a rock dent is an example of a constrained dent).

to 14.5 m from the as-laid position over a length of about 370 m, with the apex of the displacement located at the site of concrete damage, Figure 5. The evidence is consistent with an anchor snagging the pipeline and subsequently being abandoned by the vessel.

In response to the report of the damage, the pressure in the pipeline was reduced.

Detailed Inspection of the Damage

In September 2003, the damage to the EOS20 pipeline was subject to a detailed visual inspection by divers. Then, the seabed below the pipeline was excavated to allow unrestricted access to the damaged area. Approximately 1 m of the concrete coating was removed around the full circumference, the asphalt enamel coating was removed, and the surface was blast cleaned to a bare metal finish, Figure 6.

The damaged area was then inspected in detail, using various methods:

- visual inspection of the full circumference of the cleaned area to locate the damage to the pipe;
- straight edge measurements to locate and size the dent;
- outside callipers to measure the pipe diameter, at grid positions around the circumference and along the axis of the pipe;
- compression wave ultrasonic wall thickness measurements, using Veritec Sonomatic Nautilus equipment;
- time of flight diffraction (TOFD) ultrasonic measurements in the circumferential and longitudinal directions, using Veritec Sonomatic Nautilus equipment;
- magnetic particle inspection (MPI) in and around the dented area; and
- a microset moulding of the abraded areas.

The detailed visual inspection identified a shallow dent and two areas of abrasion, between 6 o'clock and 9 o'clock (where 12 o'clock is the top of the pipe). No other areas of damage were identified. No crack-like indications were identified by the MPI or the ultrasonic inspections. A small number of inclusions were identified near the inside surface of the pipe wall. The abraded areas were lightly dressed with a hand file to remove some of the surface roughness.

The two areas of abrasion were described as parent metal surface abrasion with minor tramlines. Both were approximately 55 mm wide; one was 102 mm long and the other was 180 mm. Subsequent measurements taken from the microset of the damage area indicated that the maximum depth of metal loss was less than 1 mm.

Figure 7 is a radial representation of the dented area, based on the outside calliper measurements. The dent is coincident with a longitudinally flattened area of the pipe. It was concluded that this flattened area was a manufacturing feature, not related to the anchor impact; flattening of this sort, and in this location, is a credible manufacturing defect in UOE line pipe (and the size of the feature was within API 5L tolerances), and the extent and location of the flattening was not consistent with the concrete damage. The maximum depth of the dent was measured as 6 mm (1.2 percent of the pipe diameter). The dent depth is based on the maximum reduction in the diameter of the pipe, and therefore includes the flattened area. It was determined that the dent was smooth (the minimum radius of curvature of the dent was greater than five times the wall thickness). The dent did not affect the curvature of any welds.

Assessment and Sentencing of the Damage

The detailed inspection of the damage to the EOS20 pipeline indicated the following:

- the maximum depth of the dent was approximately 6 mm;
- the dent was smooth;
- the dent was not on or near a weld;
- there was no cracking in the dent;
- there were no laminar defects in the dent;
- there were two shallow areas of abrasion in the dent; and
- the maximum depth of the abrasion was approximately 1 mm, the maximum length (start to end) was approximately 340 mm and the maximum width was approximately 60 mm.

In addition to the damage to the pipe body, the pipeline had also been displaced. An analysis of the movement of the pipeline indicated that the stresses and strains were elastic, and within the limits of BS 8010 : Part 3 [7] and DNV-OS-F101 [8].

The assessment of the damage to the pipeline considered failure under static and cyclic internal pressure loading. The published methods for assessing a dent and gouge are only applicable to internal pressure loading. Although the damage was located at the apex of a gradual bend, because the bend was small (the minimum radius of curvature was approximately 430 m), it was assumed that the additional external loads due to the bend were small, and could be neglected.

The damage was assessed as a dent and gouge. The burst strength of the damage was estimated using the dent-gouge fracture model, as included in the European Pipeline Research Group (EPRG) recommendations for the assessment of mechanical damage [2,9]. The fatigue life of the damage was estimated using a plain dent fatigue model, developed by the EPRG [10], and then reducing the estimated fatigue life by a factor of one hundred [4]. The Pipeline Defect Assessment Manual (PDAM) joint industry project concluded that these were the 'best' methods for assessing a dent and gouge. The factor of one hundred on fatigue life is an empirical factor based on a review of full scale test data [4]. In both the static and fatigue assessments, lower bound estimates of the static and fatigue strength, respectively, were calculated, i.e. the scatter inherent in the assessment methods was considered. In most of the full scale tests, the dents were introduced at zero pressure. Therefore, in the assessment, a spring back correction factor was applied to account for the fact that the dent depth measured at pressure is less than that measured at zero pressure [2,4].

The published methods for assessing a dent and gouge assume that the dent is smooth, and that it contains a single, longitudinally orientated gouge. The methods were validated in burst and fatigue tests of dents containing machined notches or gouges. The abrasion in the dent in the EOS20 pipeline is shallow and wide, compared to the defects in the full scale tests.

The results of the assessment showed that the damage in the EOS20 pipeline was acceptable at the maximum allowable operating pressure of the pipeline, and that the remaining fatigue life was several times greater than the design life of the pipeline, i.e. the damage did not significantly reduce the burst or fatigue strength of the pipe.

Repair

On completion of the inspection activities, the excavated area was filled with grout bags to reinstate the original seabed level and a concrete mattress was installed over the damaged section of the pipeline. A detailed assessment of the damage indicated that no further repair was required. The restriction on the operating pressure of the pipeline was removed.

A GVI of the damage location by ROV in June 2004 discovered that one of the mattresses had been displaced. The ROV was able to place the mattress back in its correct position immediately. The damage location was subsequently rock dumped in February 2005 to provide better protection. Monitoring of the damage location and the cyclic internal pressure loading will continue throughout the lifetime of the pipeline.

CASE STUDY 2

Summary of Study

A 30 in. diameter offshore gas pipeline under construction in approximately 50 m water depth was believed damaged most probably by an anchor drag from a large ship. From preliminary damage assessment work based on defect dimensions gleaned from a calliper pig survey, it appeared that a reasonable opportunity might exist to accept the damage should it prove to be a plain dent. However, subsequent excavation and diver survey revealed the damage to be a complex collection of severe kinked dents, deeper than originally indicated by the calliper survey. More detailed calculations revealed high strains in the worst dent (approximately 15 %), well beyond the 6 % strain limit quoted in ASME B31.8 [3,11]. The damage was therefore sentenced for repair on the basis of the expected low burst strength and very short fatigue life typical of such a defect. On recovery to the surface, the true extent and severity of the damage became evident where, in addition to the local dent deformations, the pipeline had also been globally deformed.

Background

The installation of the 762 mm (30 in.) diameter, 17.5 mm wall thickness, grade X65, offshore gas transmission pipeline in question was completed earlier in 2005. The pipeline was trenched to a depth of 3 m below natural seabed. During commissioning activities, the presence of mechanical damage was initially detected by indications on the gauge plate of a gauge pig. The damage was subsequently localised using a calliper pig. This latter tool also indicated that the diameter was reduced at this location by some 109 mm (4.3 in.), Figure 8, equivalent to 14% of the outside diameter of the pipe. Anecdotal accounts suggested that an anchor drag from a large vessel during a storm early in 2005 might have been the cause of the damage. At this point in time the pipeline had been trenched, but natural backfill had not yet taken place, so the pipeline was therefore partially exposed.

Assessment and Sentencing of the Damage

The pipeline defect assessment activity was progressed in two parts: a preliminary study based on a finite element analysis of an idealised dent profile based on calliper pig survey data; and a subsequent in-situ study based on a dent radius inferred from visual inspection of the damaged area by divers.

The preliminary study made use of elastic-plastic, non-linear geometry FEA using a rigid indenter (Figure 9) to produce an equivalent residual dent depth (after re-rounding) to that recorded by the calliper pig, e.g. Figure 10. From this analysis a strain level on the order of 3% was calculated. This was initially not of particular concern as recently introduced ASME guidance allows strain in dents up to 6%. In addition, calculations using the design *S-N* curve with an appropriate stress concentration factor (SCF) for the dent (accounting for the increased strain) indicated very long fatigue lives under the expected fluctuations in internal pressure, giving further confidence. The cyclic hoop stress range was approximately 174 $N.mm^{-2}$ for a pressure range of 80 bar. Using this stress range, the fatigue life was found to be 188,980 cycles. This fatigue life corresponded to conditions that exceeded the service requirements many times over. Further supporting test data from the literature and confidential project data confirmed the conclusion that fatigue was not a limiting factor should the dent be as assumed, i.e. a plain dent, not on a weld.

It was thus apparent that an appropriate course of action was to inspect the dent to confirm a plain and smooth geometry, determine dent dimensions, and to ensure that it did not contain welds, or associated gouges or cracking. In other words, there was a clear opportunity to allow the dent to remain in the pipeline should it satisfy these conditions.

Although nominally trenched to a depth of 3 m, the damaged section of pipeline was found in a position 1 m below the seabed (measured from the top of pipeline to the natural seabed). Excavation of the pipeline followed by removal of the concrete weight coating revealed a cluster of at least three closely-spaced dents located away from both longitudinal seam and girth welds. The dents, however, were deeper than recorded by the calliper tool and were very sharp in nature, the most severe of which appeared by inspection to have radii on the order of 12 mm. In reality the minimum radii are likely to be more acute. Additionally, the pipeline had evidently been displaced vertically by the snagging event, although significant lateral displacement was not apparent from the diver survey.

The most severe of the three dents involved a 90 mm deep (3.5 in) by 160 mm long (6.3 in) feature. By ascribing a relatively smooth profile to this region, bending strains based on curvature were calculated that ranged from 2.9 % to 15.4 %, Figure 11. The estimated fatigue lives considering these strain values as elastic stress ranges were calculated to be only 792 cycles and 5 cycles, respectively. This is supported by unpublished test data for wrinkles (a similar defect) where a short fatigue life of 1,086 cycles was obtained. In conclusion, the simple strain calculations supported by test data demonstrated that the dents posed a significant threat to the integrity and future operation of the pipeline system. The defect(s) were therefore unable to be accepted to remain in the pipeline and were sentenced for repair. No further investigation for the presence of metal loss or gouges was necessary given the severity of the dents.

In any case, by simple inspection it would be impossible to categorise this collection of closely spaced, kinked dents as being plain dents, invalidating the analyses.

Recovery of Damaged Pipeline Section

On recovery of the pipe section to the surface, Figure 12, the true extent of the damage became readily apparent. The pipeline had been permanently deformed by the impact and the combination of this global deformation and the local dent damage, Figure 13, was even more severe than apparent from the diver survey.

Repair

The repair was made subsea using a replacement spoolpiece and mechanical pipeline connectors – a procedure where justification was made based on type approval and industry recommended practices [12,13].

LESSONS TO BE LEARNT FROM THE CASE STUDIES

Knowledge of the cause, or the likely cause, of damage to a pipeline is an important part of a fitness-for-purpose assessment. In both case studies, the probable cause of the denting clearly indicated the need to remove the concrete coating and inspect the damage (first excavating the pipeline if necessary), and to look for global deformation of the pipeline.

To be able to assess mechanical damage such as a dent in a pipeline, it is necessary to know the shape of the dent (e.g. smooth or kinked), the size of the dent, whether the dent is on or near a weld, and whether the dent contains any other defects (e.g. a gouge or a crack). This implies that a number of different inspection techniques are required to gather all of the necessary information. In an offshore pipeline, this can be a significant undertaking.

An in-line inspection tool may provide some, but not all of the necessary information. A calliper tool will detect deformation in a pipeline, such as dent, and provide an estimate of its size, but may not be able to give detailed information about the shape of the dent. The additional information can be obtained from a visual inspection (as in the second case study), or by running a geometry tool.

The shape of a dent can have a significant effect on the severity of the dent. In the second case study, a detailed inspection of the damage was not required once a visual inspection had identified that there were multiple, kinked dents in the pipeline.

The presence of defects in a dent can have a significant effect on the severity of the dent. In the first case study, a detailed inspection of the dent was required to determine the nature and extent of any damage in and around the dented area.

The assessment of dents containing shallow gouges is difficult, as the published models are prone to scatter, and based on idealised damage. In the first case study, areas of abrasion were found in the dent. This abrasion is unlike the machined notches or gouges used to develop the published models. It is likely that these methods are conservative when applied to such defects, but the level of conservatism is difficult to quantify.

CONCLUSIONS

1. Mechanical damage is one of the most severe forms of damage that is found in pipelines. In many cases it is necessary to repair such damage. However, in some cases, a combination of detailed inspection and assessment can demonstrate that the damage is acceptable.
2. An understanding of the failure behaviour of dents can allow inspection activities to be planned in a focused and methodical manner, allowing an informed decision on whether it is better to repair rather than inspect and assess.
3. Acceptance levels for dents containing other defects are small: it is important that a pipeline owner/operator's expectations are aligned with this fact at the outset of the inspection and assessment activities.
4. Additional research is required to better understand the significance of dents containing gouges or other surface damage: particularly for combinations of shallow dents and shallow gouges or minor surface damage.

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Figure 1 The dimensions of a dent

Figure 2 Damage to the concrete weight-coat

Figure 3 Area of bare metal within the damaged area

Figure 4 The anchor

Figure 5 Displacement of the pipeline

Figure 6 The damaged area after the removal of the coating

Figure 7 Radial representation of the dent in the pipeline

Figure 8 Calliper pig data in vicinity of feature

Figure 9 Finite element model

Figure 10 Comparison of dent profile based on calliper data and finite element results

Figure 11 Calculation of bending strain from curvature

Figure 12 Damaged section showing dents and global deformation of the pipe

Figure 13 Clustered and kinked dents

Table 1

	internal pressure (static) longitudinally orientated	**internal pressure (fatigue)**
plain dents	dent depth less than 7 percent of pipe diameter (empirical limit)[1]	EPRG [10]
kinked dents	no method[2]	
smooth dents on welds	no method	no method (empirical limits)[3]
smooth dents and gouges	dent-gouge fracture model [2,9]	no method (empirical limits)[3]
smooth dents and other types of defect	dent-gouge fracture model	no method

Note:

1. The acceptable dent depth depends on whether the dent is constrained or unconstrained, and, for an unconstrained dent, whether the dent is measured at zero pressure or at pressure [4]. The acceptable dent depth may be significantly smaller if the dent is subject to cyclic loading.
2. ‘No method’ represents both limitations in existing knowledge and circumstances where the available methods are too complex for inclusion in a document such as PDAM.
3. An estimate of the reduction in the fatigue life of a smooth dent on a weld, or a smooth dent and gouge, compared to the fatigue life of an equivalent plain dent on the same depth, can be made by reference to the test data [4].

Figure 1

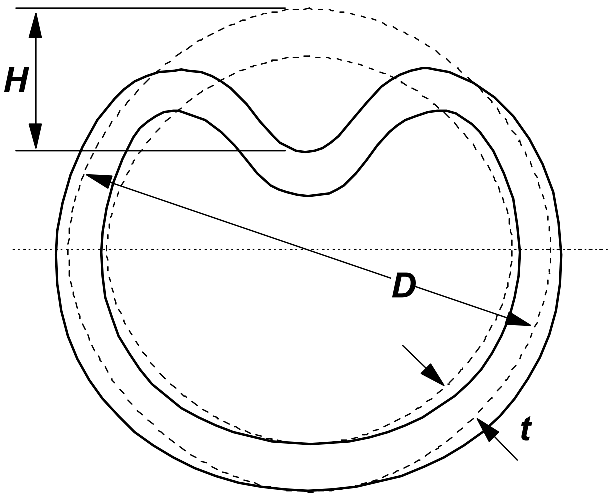


Figure 2

Figure 3

Figure 4

Figure 5

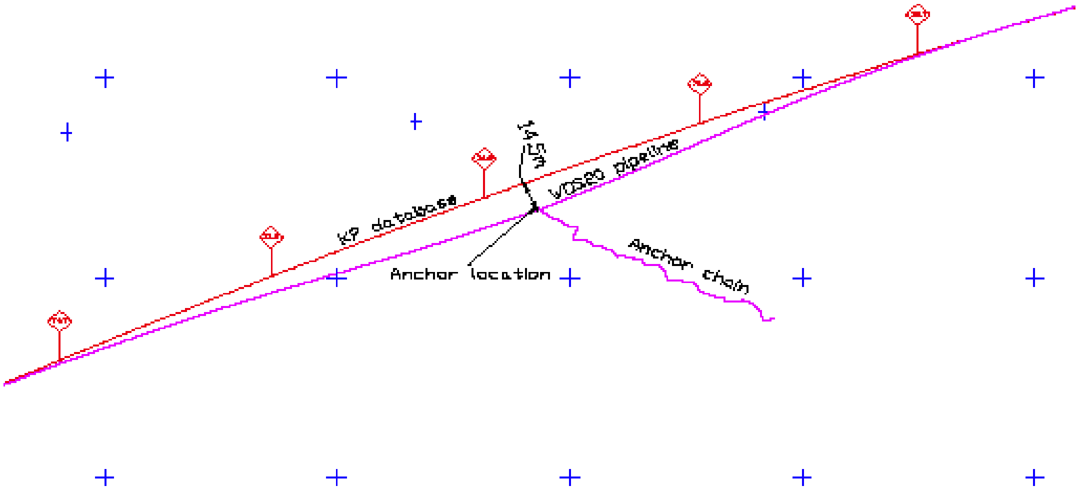

KP database
14.5m
VDS20 pipeline
Anchor location
Anchor chain

Figure 6

Figure 7

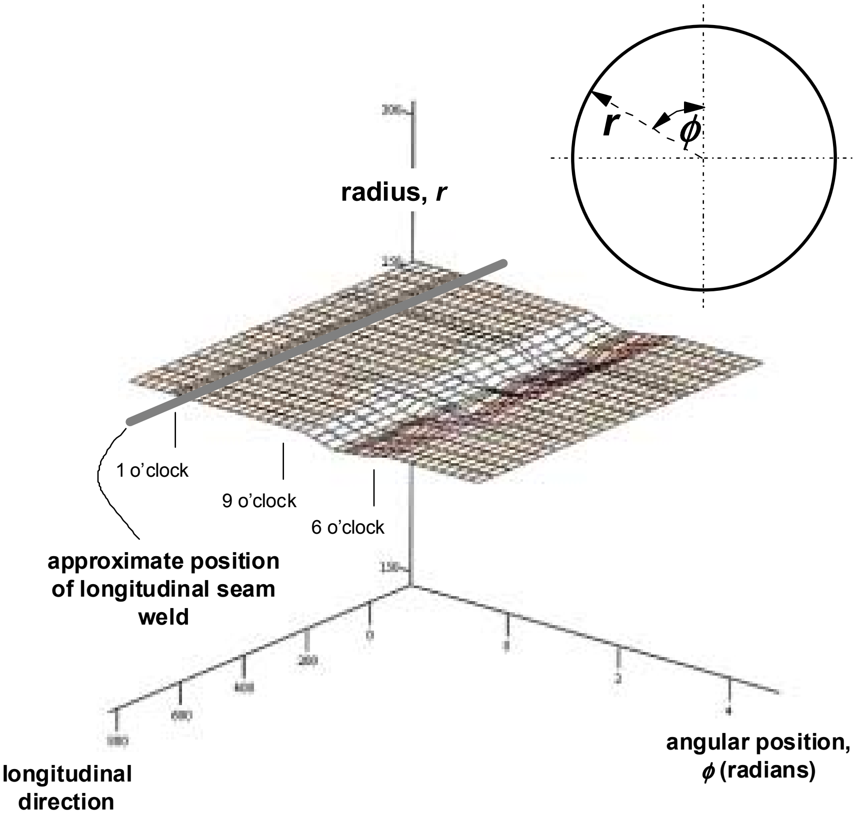
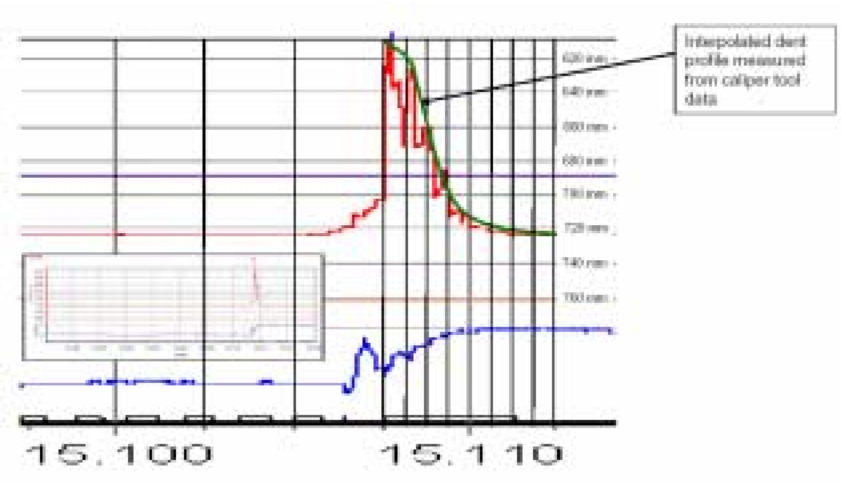

r
ϕ
radius, r
200
175
150
1 o'clock
9 o'clock
6 o'clock
approximate position of longitudinal seam weld
0
200
400
600
800
longitudinal direction
0
2
4
angular position, ϕ (radians)

Figure 8



Interpolated dent profile measured from caliper tool data

Figure 9

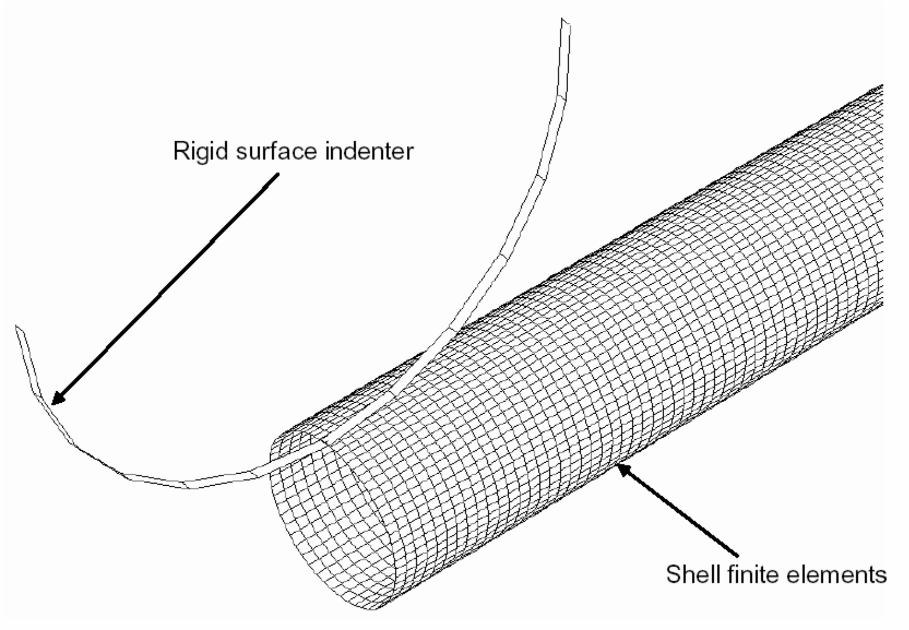
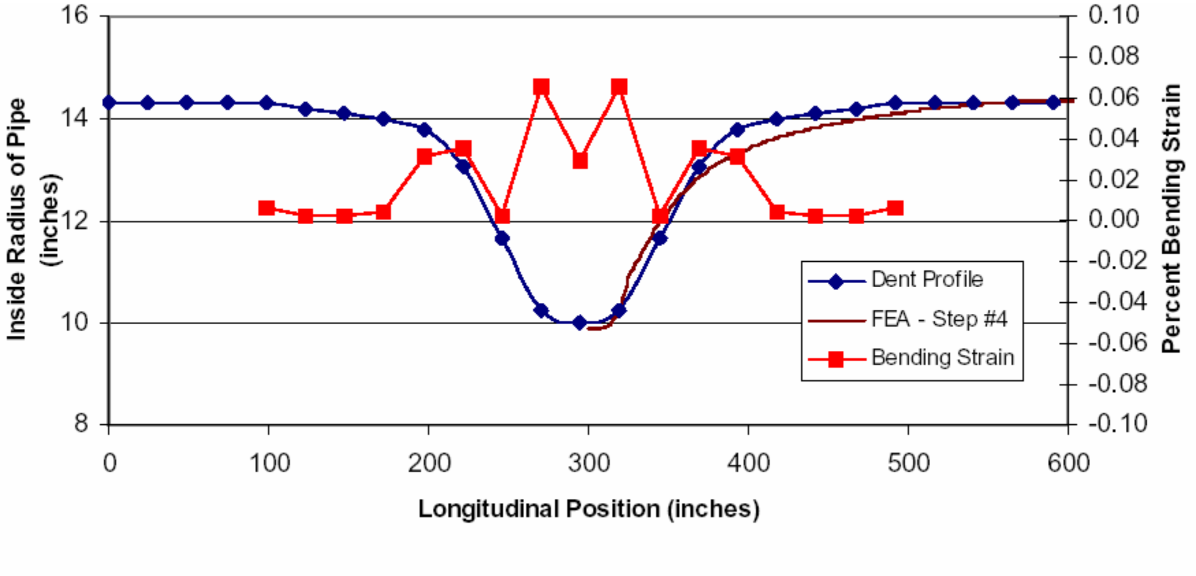
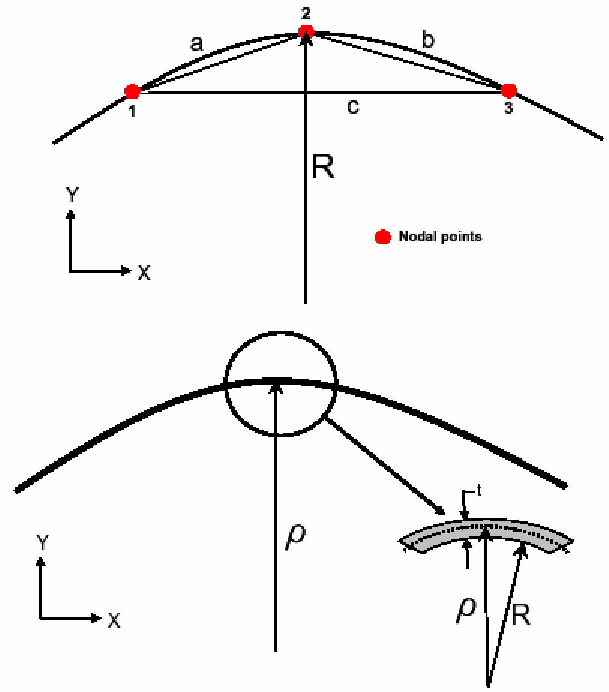


Figure 10



Inside Radius of Pipe (inches)
16
14
12
10
8
Percent Bending Strain
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
0
100
200
300
400
500
600
Longitudinal Position (inches)
Dent Profile
FEA - Step #4
Bending Strain

Figure 11



$$a = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$b = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$$

$$c = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$$

$$q = \frac{a^2 + b^2 - c^2}{2ab}$$

$$R = \frac{c}{2\sqrt{1 - q^2}}$$

$$\varepsilon = \frac{t}{2R} \qquad \rho = R + \frac{t}{2}$$

Nomenclature

ε – Bending strain
t – Thickness of beam
ρ – Radius of curvature (centerline)
R – Radius of **mandrel**

Figure 12

Figure 13