

# **MECHANICAL INTEGRITY OF OFFSHORE PIPELINES**

by

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## **ABSTRACT**

Pipelines experience mechanical damage (e.g. dent, gouge, local wrinkling) due to external interference (e.g. anchor dragging, third-party) and ground deformation (e.g. slope movement, ice gouging). The type and severity of pipe damage may influence the development of integrity management programs. Assessment of mechanical damage may be of greater significance for pipeline systems located in remote harsh environments that may influence operational, repair and intervention strategies due to remote location and logistical constraints. There is limited engineering guidance and uncertainty for predicting mechanical response of defects and interacting defects; such as dent feature interaction with an adjacent girth weld or dent with gouge feature; and their corresponding effects on pipe integrity and fatigue life. This study addresses this technology gap through the development of calibrated numerical tools, conducting parametric studies and providing empirical equations that can characterize the effects of local damage and applied loads on pipe mechanical response.

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## List of Symbols and Abbreviations

$\alpha$	Ramberg-Osgood yield offset coefficient
$\epsilon_{\text{eqv}}$	Equivalent plastic strain (mm/mm)
$\sigma_{\text{h}}$	hoop stress due to internal pressure (MPa)
$\sigma_{\text{y}}$	specified minimum yield strength (MPa)
$\omega$	ovality level (%)
API	American Petroleum Institute
$d$	indentation depth (mm)
$D_{\text{max}}$	maximum pipe diameter (mm)
$D_{\text{min}}$	minimum pipe diameter (mm)
$D_{\text{nom}}$	nominal pipe diameter (mm)
$D$	pipe outer diameter (mm)
EPRG	European Pipeline Research Group
FEA	Finite element analysis
HAZ	Heat affected zone
$H_0$	dent depth measured at zero pressure (mm)
$H_r$	dent depth measured under pressure (mm)
$I_{\text{axial}}$	interaction distance between dent and girth weld (mm)
$ID$	indenter diameter (mm)
$l$	distance between dent peak and half peak height (mm)
$L$	indenter length (mm)
$L_a$	axial shoulder length upto inflection point (mm)

$L_r$	radial shoulder length upto inflection point (mm)
$L_s$	shoulder length (mm)
$n$	Ramberg-Osgood strain hardening exponent
$OD$	pipe outer diameter (mm)
$P_{int}$	internal pressure (MPa)
PDAM	Pipeline Defect Assessment Manual
PRCI	Pipeline Research Council International
$R$	pipe radius (mm)
$SR$	strength ratio
SMYS	specified minimum yield strength (MPa)
$t$	pipe wall thickness (mm)

# 1 INTRODUCTION

## 1.1 Overview

Offshore and onshore pipelines are responsible for transporting large quantities of oil and gas that forms an integral component of global economy. Failure in such pipelines is catastrophic, as it may lead to injuries, fatalities, loss of production and environmental damage. Therefore, structural integrity plays a key role to ensure safe and sound operation of pipelines. However, such integrity can be affected by different type of defects that may be introduced in the pipeline during manufacturing, installation or its service life. Historically, pipe defects found and assessed were grouped into three categories; namely corrosion, weld and mechanical defects (MSL 2000). Corrosion and weld defects have been extensively studied in literature with solutions provided for the assessment of such defects (API 1104, ASME B31G, BS7910, DNV OS-F101). Mechanical damage has also been assessed in the past and effective literature was published in Pipeline Defect Assessment Manual for isolated dents. Interaction of defects (e.g. dents with welds) and resulting pipe mechanical response, however, still remains an area of uncertainty with only limited engineering guidance available in literature (Cosham and Hopkins 2002, 2003, 2004, MSL 2000). Considering the limitations of the data available in public domain, this study focuses on mechanical defects that occur as a result of external force or load events. The main focus of this study rests in assessing pipe defects in the form of dents, as isolated feature, their interaction with girth weld and corresponding effect on pipe mechanical response.

## 1.2 Scope and Objectives

In order to develop a mechanistic based model to characterize pipe mechanical response when subjected to indentations, there must be sufficient information available that can describe deformed pipe behavior when subjected to varying load scenarios. There are several public domain studies (Alexander and Kiefner 1997, 1999; Fowler *et al.*, 1995; Keating and Hoffmann, 1997) that have provided insight on dent severity assessment. However, these investigations did not provide sufficient details on pipe material properties and boundary conditions for the calibration of numerical modelling procedures that could be used to conduct parameter studies on a wider range of practical design conditions.

Recent work conducted by British Maritime Technology (BMT) fleet, supported by Pipeline Research Council International (PRCI), was able to generate detailed experimental data for cyclic pressure failures using a variety of indenter diameters, material properties, material geometries (e.g. D/t) and pressure ranges. Several recent studies (Alexander and Kiefner 1997, 1999; BMT 2007; Bolton *et al.*, 2008, 2010; Tiku *et al.*, 2012) were used to develop the calibrated finite element modelling procedures, using ABAQUS v 6.10, was presented in this report.

Once confidence in model was achieved for varying indenter restraint conditions (constrained and unconstrained), an analysis model matrix was established to account for a range of influential parameters including indenter shape, diameter to wall thickness ratio, indenter diameter to pipe diameter ratio, indenter travel to pipe diameter ratio, hoop

stress due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ), and kinematic boundary conditions.

Using the results from the numerical parameter study, nonlinear multivariate regression analysis was conducted to establish functional relationships that characterize the effects of local damage and applied loads on the pipeline response to relate output variables with practical measured variables. A MATLAB regression code was generated to develop closed form expressions separately for zero pressure and 80% Specified Minimum Yield Strength (SMYS) pressure indentations that efficiently predicted response variable. The influence of geometric imperfections (pipe ovality), due to manufacturing processes, on the pipe mechanical response was also examined.

The regression analysis was focused on the development of a simple and practical design tool that could assess the effects of isolated and interacting mechanical defects on the pipe stress and strain response. Based on code requirements and regulatory guidelines, the design tool could assist the end-user in decision making by establishing a quantitative framework to assess the pipe mechanical response with respect to defect tolerance, and pipe maintenance, repair and intervention strategies.

### **1.3 Thesis Layout**

The thesis is divided into six chapters with chapter one and two focusing on scope of work and literature review respectively. The literature review assessed the existing database of physical modelling and numerical simulation, engineering practice and design

codes/standards for the effects of mechanical damage on pipeline performance and fatigue life. A range of mechanical damage features including external interference (e.g. grooves, gouges, dents), operational conditions and physical loads were examined. This task helped in identifying the existing knowledge base, technology gaps and potential constraints that were used as foundation for the study and framework to develop the numerical modelling procedures.

Chapters 3 through 5 are based on peer reviewed publications that discuss in detail, the different studies that were conducted to develop calibrated numerical modelling procedures and empirical tools for pipeline integrity assessment.

The primary calibration exercise is discussed in the first study (Chapter 3), that focused on developing calibrated unconstrained pipe-dent model and analyzed dent interaction with girth weld. A sensitivity analysis was conducted and highlighted the significance of essential boundary conditions and presence of circumferential girth welds on the mechanical response of the dent features.

The second part of the study (Chapter 4) focused on developing calibrated numerical tools that can simulate constrained dent conditions. Effect of boundary conditions on pipe mechanical response was also studied and was found coherent with initial study (Chapter 3). Once confidence in numerical procedures was achieved, an analysis matrix was established to account for a range of influential geometric and operational parameters. Results from this study provided a base to support a broader initiative for developing an engineering tool that could predict pipe mechanical response under varying dent

conditions and restraints, material and geometric properties and kinematic boundary conditions.

The last part of the study (Chapter 5) is based on extending the model matrix by taking into account different indenter shapes and manufacturing defects (e.g. pipe ovality). A MATLAB regression code was generated that used model matrix results as input parameters. The code was used to develop closed form expressions for varying operational parameters (internal pressure) that can efficiently predict pipe mechanical response in case of a damage event.

Chapter 6 focuses on summarizing and concluding the research study. Results generated throughout the study were compiled and the use of developed numerical and empirical tools is explained in this chapter. Recommendations were formulated and it was stated that validation of the numerical tool through physical testing will assist in predicting more efficient and reliable pipe mechanical response and useful fatigue life.



## **2 LITERATURE REVIEW**

### **2.1 General**

Pipelines are considered to be one of the most practical and low priced method for transporting Oil and Gas since 1950's. In the last 3 decades, the installation of transmission pipelines has increased drastically. As a result of this, failure problems due to different mechanisms have also increased, thus compromising the structural integrity of pipelines. The safe operation and high reliability of pipelines depend on various factors including material defects, mechanical damage, fatigue caused by cyclic loading, welded joints etc. Due to increase in structural integrity concerns, different codes and standards have been introduced over a period of years. Pipeline standards started in the US in 1930's when the first code B31 was released that was further upgraded to B31.4 (for transportation of hydrocarbon liquids) and B31.8 (for transportation of natural gas). Over the years, much work has been done to introduce a number of national standards to cover issues that include pipeline design, manufacture, installation, construction, inspection and repair (e.g. ASME B31.4, ASME B31.8, CAS-Z662-99, DNV1996, API 5L).

### **2.2 Pipeline Defects**

With a good safety record, pipelines are considered to be an efficient mode of oil and gas transportation for both on and offshore environments. However, just like any other engineering structure, there is always risk involved and there have been reported cases in which pipelines have failed (MMI, 2008). According to literature (Cosham and Hopkins,

2003), one of the most common mode of onshore and offshore pipeline failure in Western Europe and North America has been attributed to external interference and corrosion defects.

Defects can be introduced in the pipe during manufacturing, installation or operational phase. A defect is a material or geometric discontinuity or irregularity that is detectable by inspection in accordance with the requirements of the applicable codes and standards (MSL, 2000). Different codes have different criteria of accepting or rejecting a defect. Onshore and offshore pipelines are subjected to mainly 3 types of defects:

- 1) Weld
- 2) Corrosion
- 3) Mechanical

Figure 2-1 illustrates the different type of defects that a pipeline may experience during its service life.

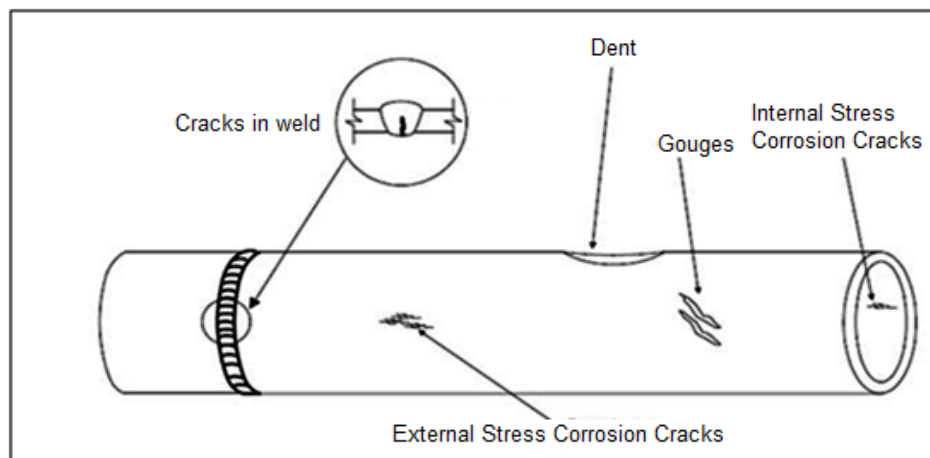


Figure 2-1 - Pipeline Defects (MSL, 2000)

Various studies have been conducted and codes/standards published that emphasized on assessment techniques for weld and corrosion defects (API 1104, ASME B31G, BS7910, DNV OS-F101). With the introduction of new materials and high temperature high pressure pipelines, the effects of manufacturing, welding and corrosion defects were further reduced. However, mechanical damage during service life of the pipe due to a rock dent, the teeth of a backhoe excavator bucket, large deformation ground movement, anchor dragging etc, can result in unexpected defect formation that if found severe can raise integrity issues.

With mechanical defects categorized to be as the prime reason for recent pipeline failures, the scope of the study was limited to this type of defect. Different types of mechanical defects include:

- 1.) Dent – local variation in pipe section diameter, characterized by curvature of the pipe surface, due to mechanical damage that does not result in significant wall thickness reduction (Cosham and Hopkins, 2003). This defect may impart local stress concentration and residual strain in the pipe wall.
- 2.) Gouge – surface imperfection due to mechanical damage that results in the loss of pipe wall thickness (MSL, 2000)
- 3.) Groove and Surface cracks –stress concentration resulting in pipe wall reduction

### 2.3 Pipeline Codes

Based on their usage, pipeline systems can be grouped into 2 different categories 1) Oil Pipelines and 2) Gas Pipelines. A number of national codes have been developed over the last few years for design, installation, inspection, repair and maintenance of pipelines. These codes are aimed at providing guidance for contractors and clients who are involved in the designing and certification process. The widely used codes and standards are listed below:

- 1) Pipeline Transportation System for Liquid Hydrocarbons and other Liquids, ASME B31.4, 1998, US
- 2) Gas Transmission and Distribution Piping Systems, ASME B31.8, 1995, US
- 3) Oil and Gas Pipeline systems, CAS-Z662-11, 2011, Canada
- 4) Rules for Submarine Pipeline Systems, DNV 1996, 1996, Norway
- 5) Rules for Subsea Pipelines and Risers, GL 1995, Germany

However, recent developments of significant hydrocarbon reserves around the world led to diversity of pipeline standards, with many countries implementing those standards that best suit their own requirements and reflects personal interests of the regulatory authorities. This practice resulted in development of a whole lot of standards and recommended practices worldwide, with varying flaw acceptance and integrity requirements, thus resulting in the lack of a unified criterion to assess pipe mechanical damage.

## 2.4 Dent Definition

Dents have been categorized and defined in literature (Cosham and Hopkins, 2003) as follows:

Table 2-1: Dent Definition

<b>Dent type</b>	<b>Definition</b>
Smooth	Dent leading to smooth curvature in pipe wall
Kinked	Dent leading to abrupt change in pipe wall curvature
Plain	Type of smooth dent containing no pipe wall thickness reduction
Constrained	Dent that cannot rebound or re-round due to constant interaction with indenter
Unconstrained	Dent that tends to rebound(elastically) and re-round(in-elastically) when indenter is removed

## 2.5 Dent Significance

Dented pipe segments may develop high level of local stress and strain concentration points. Substantial reduction in pipeline's tolerance to static and cyclic load may be observed if the developed dent lies in close proximity of another discontinuity (e.g. girth weld). Such a behavior may again be attributed to high stress values in dented region and heat affected zone (HAZ). Dents in pipelines may result in operational worries as it may reduce flow rates or may obstruct the passage of data monitoring intelligent pigs.

Material and geometric parameters are responsible for defining dent profiles and pipe mechanical response. Amongst different other parameters, dent depth is considered to

affect pipe burst strength and useful fatigue life to the most (Cosham and Hopkins, 2003). The length and width of the dent defines the strain and stress distribution on a dented segment (Cosham and Hopkins, 2003). According to literature, the maximum stress and strain for long dents occurs at dent base, while for short dent it occurs on the flanks (Ong *et al.*, 1989, Ong, 1991, Ong *et al.*, 1992, Beller *et al.*, 1991, Eiber *et al.*, 1981. Lancaster and Palmer, 1996). It has also been reported that for same dent depths, long dents tend to exhibit greater stress values than short dents (Ong *et al.*, 1989, Ong, 1991, Eiber *et al.*, 1981).

A lot of research has been carried out by different independent bodies to provide insight and guidelines on mechanical damage. European Pipeline Research Group (EPRG) and American Petroleum Institute (API) have conducted extensive research to develop guidelines and codes aimed at damage assessment. With no definitive guidance and unified recommended practices available in literature, Pipeline Defect Assessment Manual (PDAM) assessed and distilled all pertinent damage assessment literature. PDAM recommended best available methods for pipeline defect assessment by analyzing each technique against published data. Guidelines as recommended by PDAM are given below (Cosham and Hopkins, 2002, 2003):

- 1) Burst strength of the pipe is not significantly affected by plain dents or constrained plain dents
- 2) Useful fatigue life of a plain dented pipe segment is lesser than a pipe with no dents.
- 3) Comparing fatigue lives, pipe segment with a constrained plain dent possesses a longer fatigue life than an unconstrained plain dent.

- 4) Kinked dents, on the other hand, possess low burst pressures and useful fatigue lives
- 5) A coupled defect (e.g. dented weld or a dent containing another defect) can possess significantly low burst and fatigue strength values than an equivalent plain dent.

## **2.6 Constrained and Unconstrained dents**

Constrained and unconstrained dents are identified by indenter application and removal. Constrained dents mostly occur at the bottom of the pipe due to presence of rocks during pipe lay process. The rock stays in contact with the bottom half of the pipe during pipeline service life, thus giving a condition of constrained dent. Such pipes will only fail if the indenter is sharp enough to cause a puncture (Alexander and Kiefner, 1997, 1999). Unconstrained dents on the other hand, are mostly caused by external interference e.g. anchor dragging, and are typically present at the pipe top half (Alexander and Kiefner, 1997, 1999). Once the indenter is removed, such pipelines may fail due to thermal and pressure fluctuations that occur over a large number of cycles. Number of such cycles, however, is dependent on the pressure range; higher the range, lesser will be the number of cycles to failure (Fowler *et al.*, 1995, Kiefner *et al.*, 2004)

## **2.7 Dent Depth Definitions**

As part of the project, different dent depths at different load steps were studied. The following definitions are provided to assist the reader with dent terminologies that will be used later in the thesis:

- 1) Indentation/Initial Depth: This depth refers to the user-specified maximum depth achieved by the indenter when it is translated into the pipe segment. The dent depth has been defined as percent of pipe diameter throughout the report.
- 2) Rebounded/Spring back Dent Depth: This dent depth refers to indentations placed at zero pressure pipe condition. This is the residual dent depth measured once the indenter is removed and the pipe is allowed to rebound back elastically.
- 3) Re-rounded Dent Depth: This is the residual dent depth that is measured after the pipe has been indented and then pressurized to a given level of internal pressure. This term applies to the pipe when it was pressurized during or after indentation. Pressurization level has been defined as percent SMYS throughout the report.
- 4) Final Dent Depth: The residual dent depth that is measured at zero internal pressure after the testing is completed.

## **2.8 Elastic Rebound and Re-rounding**

Unconstrained dents are mostly related to the phenomenon of elastic rebound once the indenter is removed, and plastic re-rounding under the influence of pressure fluctuation. Dent depth in this case, is directly related to the amount of re-rounding at the end of pressure cycling, which ultimately affects the number of cycles to failure. Dents act as stress and strain concentrators, and this stress concentration is a function of dent depth (Cosham and Hopkins, 2003). The stress and strain distribution is also dependent on other dent dimensions including length and width of dent; keeping dent depths same, maximum



stress in a long dent would be greater than in a short dent (Eiber et al., 1981, Ong *et al.*, 1989).

Under the influence of the elastic rebound/springback effect of pipe wall (due to indenter removal) and re-rounding (due to internal pressure), the residual dent depth changes, thus reducing the stress and strain concentrations. Most of the dents will be introduced in pressurized conditions during pipeline service during which a pipe may come in contact with an underlying rock, while some of the dents may be introduced at zero pressure conditions during construction and handling processes. Considerable work was carried out by EPRG and Battelle Institute (Maxey 1986, Hopkins *et al.*, 1992) to provide a spring back correction factor to relate dent depths that were introduced at zero pressure conditions with the one that were introduced under internal pressure conditions. Keeping in concern the limitations of different correction factors provided by different sources, Pipeline Defect Assessment Manual (PDAM) recommends the use of EPRG correction factor due to its ease of use. Equation 2.1 describes the effect:

$$\frac{H_o}{D} = 1.43 \frac{H_r}{D} \quad \text{Eqn 2.1}$$

Where,  $H_o$  = dent depth measured at zero pressure (mm)

$H_r$  = dent depth measured under pressure (mm)

$D$  = pipe outer diameter (mm)

## 2.9 Existing Work

Dent integrity is of prime concern for pipeline operators. The practical issue for this exercise is to identify which dents would actually threaten pipeline integrity and what should be done to troubleshoot the issue. Currently, codified approaches have been used to deal with integrity issues; however, the approaches have been identified as conservative for some cases (Cosham and Hopkins, 2003).

As discussed previously, liquid pipelines in the United States are typically governed by the ASME B31.4 code, while the gas pipelines are governed by ASME B31.8. Both the codes follow the accept/reject criterion for dent management, prescribing removal of unacceptable damage that may alter pipe curvature at seam or girth weld. In addition to this, both codes categorize sharp flaws such as gouges, grooves, scratches etc. as unacceptable. For plain dents (without gouges) on liquid / gas pipelines, dent depth to pipe diameter percentage ratio,  $d/D$ , is considered to be as the prime variable for assessing dent severity. As per ASME codes B31.4 and B 31.8, for liquid pipelines and gas pipelines,  $d/D$  ratios greater than 6% and 2% respectively, are considered to be unsafe and demand the need for repair. Fluctuating pressure and temperature conditions that may lead to fatigue cracks have been identified as the prime reason for repairing such damages.

Several researchers have studied dent behavior and performed fatigue life estimations. To name a few Fowler *et al.*, (1995), Keating and Hoffmann (1997), Hagiwara *et al.*, (1999), Cosham and Hopkins (2003), Alexander and Kiefner (1997, 1999) and recently Bolton *et*

*al.*, (2008, 2010) and Tiku *et al.*, (2012) have been involved in developing approaches and body of pipeline dent literature. Fowler *et al.*, (1995) concentrated on physical lab testing and studied a wide range of pipe diameter to thickness ratio ( $D/t$ ) combinations, coupled with varying  $d/D$  ratios and dent-weld interaction. The dent geometry, however, was fixed for this study. The main outcome of the study was dent failure through fatigue due to varying pressure conditions. Re-rounded dent depth under fluctuating pressures also indicated the dent severity. It highlighted that the stress and strain concentration that resulted due to damage was the prime reason for fatigue failure. Furthermore, it was observed that these stress concentration factors varied with varying  $D/t$  ratios, the reason for which could be attributed to shell thickness and pipe wall stiffness.

Keating and Hoffmann (1997) conducted a second experimental study, that studied the effects of varying  $d/D$  and  $D/t$  ratios along with varying dent geometry and dent restraint conditions (constrained or unconstrained). Pipe grade were also varied that included API 5L Gr. B (nominal yield of 30 ksi), Gr. X42 (nominal yield of 42 ksi) and Gr. X60 (nominal yield of 60 ksi). Indenter shapes were also varied to study varying dent geometries and their effects. Long dome shaped indenters with round edges (referred to as Type A), actual teeth from a backhoe excavator bucket (referred to as Type BH) and relatively round piece of rock (referred to as Type R) were used to conduct the study. Multiple dents with varying  $d/D$  ratios were formed which were then subjected to variable pressure conditions (between 60% - 70% SMYS). Pressure was cycled until a dent failed or until the cycles reached a number of 100,000 cycles. All the un-failed dents were further pressurized to 77% SMYS for high pressure proof testing. Results from the study

complimented the findings from Fowler *et al.*, (1995) about the significance of  $d/D$  ratios for determining dent severity. It was observed that crack location was also influenced by dent geometry. For long dome (Type A) indenters, the fatigue cracks appeared in dent center, while for short dents (Type BH) the cracks developed at dent periphery. However, the most important finding was the importance of dent length in determining fatigue life for unconstrained dents. The experimental study compared the fatigue lives of Type A and Type BH indenters for the same  $d/D$  ratios. It was reported that long dents had much shorter fatigue lives than short dents. To further this finding, it was reported that many short dents didn't fail within the benchmark 100,000 cycles, while most long dents developed cracks prior to the 100,000 cycle mark. This important finding raised serious questions about dent acceptance criterion based solely based on dent depth in ASME codes B31.4 and B31.8.

The phenomenon of in-elastic dent re-rounding further raises concerns for depth based code criterion. During early pressure cycles, the pipe wall flexes to a significant amount under the influence of pressure cycles, thus making the dent to be shallower (Fowler *et al.*, 1995; Bolton *et al.*, 2008, 2010). It has been reported in Keating and Hoffmann (1997) that for equal dent depth, long dents tend to re-round more than short dents. This re-rounding effect had almost negligible effect on short dents, however it causes long dents to be forced out, thus resulting in less residual dent depths for long dents. This re-rounding behavior resulting in varying residual dent depths for different indenter shapes puts serious questions for the single depth based dent acceptance criterion for all dent geometries. According to this criterion, long dents that possess short fatigue lives, may not

be considered dangerous due to their efficient re-rounding capabilities. However, short dents that normally possess high cycle fatigue lives, may still be rejected due to their lesser re-rounding capabilities. This alteration in the dent geometry due to re-rounding can also affect the stress field across the dent, which may further affect the useful fatigue life.

American Petroleum Institute sponsored a project in order to determine the effects of smooth and rock dents on integrity of liquid petroleum pipelines (Alexander and Kiefner 1997, 1999). In practice, there may be dents present that do not constitute any threat to pipeline serviceability. Therefore, the main intent of this present work is to define a criterion that can help pipeline operators to assess pipeline integrity and to help them in categorizing which dents or defects are significant and need to be repaired and which are not. The study involved 12.75, 24 and 32 inch diameter pipes of typically Gr. X-52, indented with dome, pyramid or bar like indenters. Varying  $D/t$  ratios (68, 96, 102) and  $d/D$  ratios (6%, 12%, 18%, 24%) were used with different indenter restraint condition (constrained or unconstrained). Most of the cases discussed in this study focused on unconstrained indentations made at zero internal pressure condition. The specimen was later pressurized to failure to determine the effect of dent on ultimate pressure capacity, or cyclically pressurized to determine useful fatigue life. The main outcome of the study was that unconstrained dents deeper than 5% of pipe diameter will not exist due to significant levels of re-rounding. However, any dent that has a depth greater than 5% pipe diameter in a high pressure pipeline, could be considered as a constrained rock dent that will normally exist at the 6 o'clock pipe position. Due to significant effects of inelastic re-rounding on dent profile for high pressure pipes, the study also considers the depth based

dent acceptance criterion laid down by ASME codes B31.4 and B31.8 to be not an appropriate measure. However, the significance of dent re-rounding was still not captured accurately by the study and it was concluded that smooth stress free dents less than 2% of pipe diameter may need not to be repaired. This statement was contradictory to the work done by Keating and Hoffmann (1997) as stated previously, which highlighted that dents in high pressure pipelines may undergo significant re-rounding and thus a depth acceptance criterion may not be applicable without analyzing indenter shapes and dent restraints.

Over the last one decade, BMT Fleet with support of PRCI, has been engaged in extending the dent fatigue life database. BMT has been involved in developing finite element based dent-weld interaction criteria (BMT 2007) and a validated dented pipe finite element model (Bolton *et al*, 2008, 2010, Tiku *et al*. 2012), the main aim of which is to provide solutions to integrity management issues. In order to develop FE based dent-weld interaction criterion, constrained dent conditions under zero internal pressure condition were used in order to replicate rock dents. The modelling parameters were based upon the full scale test data as used by API for UD12A-3 test (Alexander and Kiefner, 1997, 1999), with evaluation made for both constrained and unconstrained dents. A model matrix was generated to account for a range of pipe material and indenter geometry parameters that included:

- 1) Pipe geometry (12.75", 24" pipe diameter)
- 2) Material properties (Gr. X-52, X-65)
- 3) Dent depth ( 3%, 6% pipe diameter)

- 4) Indenter Diameter (1", 2", 4")
- 5) Dent restraint (constrained, unconstrained)
- 6) Weld type and location (seam weld, girth weld)

Limitations on reported data were observed while replicating testing conditions used by API to run UD12A-3 test. The following assumptions were thus made for FE analysis.

- 1) Length of specimen was not reported and it was assumed to be ten times outer diameter of the pipe as observed from the photographs.
- 2) The material stress- strain curve was not provided in the report. 0.5% offset yield strength and ultimate tensile strength were the only parameters provided. This limited material data reported was found to be insufficient to accurately characterize the highly non linear cyclic stress-strain response of pipe material.
- 3) The dimensions of the saddle that was used to restrain the pipe vertically were not reported. Therefore a sensitivity analysis was done that concluded 450mm of vertical restraint on pipe at 6 o' clock position was able to replicate desired results.

### ***2.9.1 Interaction of Dents with Long Seam Welds***

The criterion involved studying symmetrical dent profile and their interaction with long seam welds. As quoted in BMT 2007, the criterion stated:

“For a symmetrical dent profile, a long seam weld does not interact with a dent to reduce the fatigue life of the pipe segment if the long seam is located beyond outside the zero deflection position of the circumferential profile through the dent”

The criterion is illustrated below in Fig 2-2.

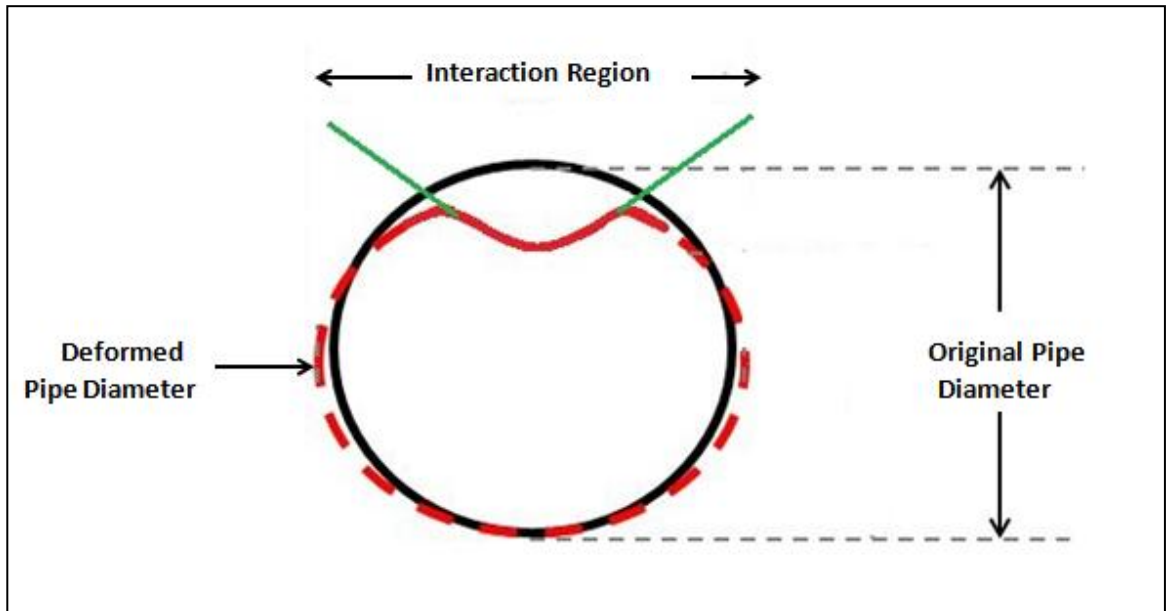


Figure 2-2 : Dent Interaction Criterion

### 2.9.2 Interaction of Dents with Girth Welds

For girth weld interaction criterion, the following parameters were observed to have the highest impact on the regression analysis performed.

- 1) Strength Ratio: ratio of pipe material ultimate tensile strength to 552 MPa (maximum value applicable for materials evaluated using ASME design curve)
- 2)  $D/t$  ratio: diameter to wall thickness ratio
- 3)  $d/D$  ratio: dent depth to pipe diameter percent ratio
- 4)  $d/\sqrt{L_s}$  ratio: dent depth to square root of shoulder length ratio
- 5)  $l/\sqrt{L_s}$  ratio: distance from dent peak to half peak height to square root of shoulder length ratio



Dent geometry parameters used for the study are illustrated in Fig 2-3.

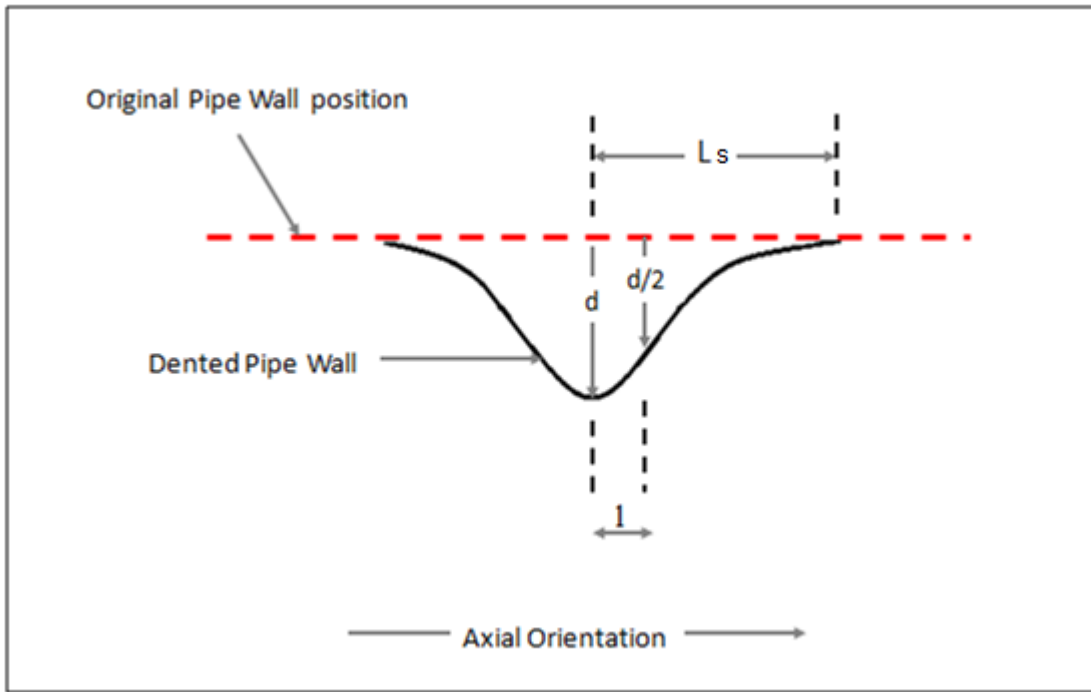


Figure 2-3 : Dent Geometry Parameters as used in BMT 2007

Regression analysis was performed in order to evaluate the acceptable interaction distance between the dent and the girth weld. However the generated equation involved cumbersome calculations that further involved analyzing a number of dent parameters for the end user to get the permissible distance. Equation 2.2 highlights the developed criterion through multi-variate regression analysis, with  $A_{sr}$ ,  $B_{sr}$  etc acting as regression coefficients.

$$I_{axial} = 1.2 [A_{SR}(SR)^2 + B_{SR}(SR) + C_{SR}] + \left[ A_D \left( \frac{D}{t} \right)^2 + B_D \left( \frac{D}{t} \right) + C_D \right] + [A_d(d)^2 + B_d(d) + C_d] + \left[ A_{\frac{d}{\sqrt{L_s}}} \left( \frac{d}{\sqrt{L_s}} \right)^2 + B_{\frac{d}{\sqrt{L_s}}} \left( \frac{d}{\sqrt{L_s}} \right) + C_{\frac{d}{\sqrt{L_s}}} \right] + \left[ A_{\frac{l}{\sqrt{L_s}}} (l/\sqrt{L_s})^2 + B_{\frac{l}{\sqrt{L_s}}} \left( \frac{l}{\sqrt{L_s}} \right) + B_{\frac{l}{\sqrt{L_s}}} \right] \quad \text{Eqn 2.2}$$

In parallel to working on dent-weld interaction criteria, BMT has also been involved in developing a validated dent fatigue model. Both full scale tests backed up with finite element analysis have been performed in order to develop a validated dented pipe finite element model (Bolton *et al.*, 2008, 2010; Tiku *et al.*, 2012). The program generated experimental data for cyclic pressure failures of pipe segments subjected to dents for varying pipe material and dent geometric parameters. 57 full scale tests have been carried out to date that cover different pipe grades (X52, X70), pipe diameters (18", 24"), indentation depths (5, 7.5, 10, 15 and 20 % pipe diameter) and indenter restraint (constrained and unconstrained). The indenter shapes were kept simple by using either hemispherical or 2:1 ellipsoidal indenters having nominal diameters of 2.375", 4.5", 8.6" and 12.75". The dent fatigue life database took into account plain dents, dents interacting with welds and dents interacting with simulated metal loss under cyclic pressure loading. Finite element model validation was performed, where the validation effort involved comparing indentation loads during dent formation, dent shapes and strain values during cyclic pressure loading. Reasonable coherency was observed between model predictions and full scale test data (Tiku *et al.* 2012). However, a validated model is yet to be developed which should take into account varying material and geometry parameters, indenter shapes, pressure histories, imperfections etc.

As discussed previously, depth based standards may not provide the right solution to the dent acceptance issues, in fact it has been reported in literature that leaks were developed when  $d/D$  was less than 3% (Dinovitzer *et al.*, 2002), which again contradicts code requirements (ASME B31.4, B31.8). With difference in fatigue lives observed for dents

with different length characteristics (Keating and Hoffmann, 1997), the consideration of a depth based dent acceptance criterion is not considered safe and an improved accept/reject dent assessment approach is required. In particular, pipe and indenter geometry characteristics and pipe imperfections must be considered while developing an acceptance approach. As discussed, a fair amount of work has been done on dent fatigue problem, both experimentally and through finite element analysis (Al-Muslim and Arif, 2010; Beller *et al.*, 1991; Dinovitzer *et al.*, 1999, 2000; Fowler *et al.*, 1995; Hart *et al.*, 1998; Keating and Hoffmann, 1997; Pal and Salpekar, 1999; Rinehart and Keating, 2002). Previously conducted research indicates that dent characteristics (depth and length) play a major role in determining dent profiles and useful fatigue life, however, a general and unified understanding of the phenomenon still does not exist. Therefore, it was felt that a study needs to be conducted that takes into account pipe and indenter geometry characteristics, pressure history and material imperfections in order to develop a model that compliments and adds value to the current dent literature, and also describes mechanical response of damaged pipeline in an efficient way. To understand mechanical relationships in a better way and to provide the end user with an easy to use dent assessment tool, a closed form expression was developed through rigorous finite element work was considered to be the best option in terms of time and available resources.

### **3 PIPELINE MECHANICAL DAMAGE ASSESSMENT USING FINITE ELEMENT METHODS**

This paper has been published in the proceedings of Arctic Technology Conference (an Offshore Technology Conference event) in Houston, Texas, 2012. As the principal investigator and first author, I was responsible for conducting the numerical investigation, analyzing the data, and reporting it in this paper. The second author, Dr. Shawn Kenny, was responsible for supervising the investigation and data analysis.

Authors: Waqas Hanif and Shawn Kenny

#### **3.1 Abstract**

Onshore and offshore pipelines may be subjected to mechanical damage during installation and operation due to environmental loads, external forces and third party interference (e.g. anchor dragging). The type and severity of pipe damage may influence operational, repair and intervention strategies. For conventional pipelines, the assessment of mechanical damage plays a role in the development of integrity management programs that can be of greater significance for pipeline systems located in remote, harsh environments. The current study highlights the effect of plain dents and interaction of plain dents with girth weld on pipe mechanical response using continuum finite element methods. The modelling procedures are calibrated with available physical datasets and also demonstrate excellent correlation with third party simulations. Confidence in the numerical simulation tool provides a basis to evaluate the effects of mechanical damage through a broader parameter study and assess effects on fatigue life performance.

### 3.2 Introduction

Onshore and offshore pipelines may contain defects (e.g. corrosion features, weld anomalies) and, in arctic regions with more frequent anthropogenic and commercial activity, may be subjected to damage (e.g. dent, gouge) during handling, installation or operations due to external interference. The significance of defects resulting from fabrication and girth welding processes, which may affect mechanical integrity, are generally assessed using accepted practices with predictable outcomes (e.g. Cosham and Hopkins, 2003). In addition, operational factors and engineering models to predict and evaluate the effects of internal and external corrosion mechanisms are not being evaluated in this study.

Mechanical damage can be characterized as local physical features; such as a dent, gouge, groove or surface crack, resulting in a stress concentration or strain localization that may affect pipeline integrity. The outcome may be immediate loss of product containment (e.g. leak, rupture), which is generally associated with thinner wall pipe, delayed effects resulting in pipe failure due to burst limits (e.g. coating damage with corrosion mechanisms) and fatigue life degradation (e.g. local defect subjected to cyclic loads). Current engineering guidelines and practices (e.g. ASME B31.8, ASME B31.4, CSA Z662 and DNV OS-F101) recognize mechanical damage as a design issue but do not provide explicit methods for assessment. The key engineering parameters influencing the dent formation and pipe integrity response include pipe diameter and wall thickness, pipe internal pressure, pipe elastic and plastic strength properties, loading path (i.e. indenter

force, internal pressure), dent depth (i.e. amplitude) width (i.e. lateral extent, indenter shape), local radius of curvature (i.e. dent type), and kinematic boundary constraints (i.e. constrained, unconstrained). The engineering significance of dent features on pipe integrity are reduced strength capacity (i.e. utilization) and fatigue life (i.e. useful life).

Over the past four decades, the effects of mechanical damage on pipeline integrity have been examined through a number of studies (e.g. Cosham and Hopkins, 2003; Fowler, 1993; Hagiwara and Oguchi, 1999; Hart *et al.*, 1998; Hope *et al.*, 1995; Hyde *et al.*, 2011; Ironside and Carroll, 2002; Leis and Hopkins, 2003; MSL, 2000; Rosenfeld, M.J., 1998; Roovers *et al.*, 2000; Stevick *et al.*, 1998). The main outcome has been engineering guidance; based on general characterization of the damage severity (e.g. dent depth) with governing semi-empirical acceptance criteria, to assess the effects of plain dents and gouges, as separate independent features, on pipe mechanical integrity. For kinked dents (i.e. abrupt changes in the pipe wall curvature) and interacting defects (i.e. plain dent and gouge) resulting in a local wall thickness reduction, the pipe burst strength and fatigue life are reduced (Macdonald *et al.*, 2007). For plain dents up to 4% of the pipe diameter, the fatigue life was reduced by a factor of 10; however, there exists poor correlation between predictions and observations (e.g. Cosham and Hopkins, 2004).

There is limited engineering guidance and greater uncertainty for predicting the mechanical response of interacting defects; such as dent feature interaction with an adjacent girth weld or dent with gouge feature, and corresponding effects on pipe integrity (e.g. Cosham and Hopkins, 2002,2003,2004; MSL, 2000), and low-cycle fatigue

response of pipe with localized damage; such as local compressive buckling (e.g. Das, 2003). The later issue may be of significance for pipelines subjected to large deformation geohazards (e.g. ice gouging, frost heave, thaw settlement) where localized pipe wall deformations (e.g. severe local damage) may develop and potentially affect pipe integrity. Reliable engineering tools with predictable outcomes are needed to assess the need, scope and requirements for any potential mitigation and intervention activities that may have bounding constraints associated with schedule (e.g. limited seasonal access) and logistics (e.g. pipeline excavation, repair and re-burial).

As part of the Wood Group Chair, a program of research has been engaged to advance numerical modelling procedures and engineering design tools for the evaluation of interacting defects on pipeline mechanical integrity with respect to strength utilization assessment and high-cycle fatigue life. In this paper, the development and calibration of numerical modelling procedures simulating the effects of mechanical damage for plain dents is presented. Comparison of the displacement field and mechanical stress response for the dent and pipe with available physical data is presented and assessed. A sensitivity analysis was conducted to examine the effects of dent interaction with a circumferential girth weld. Results from this study are evaluated with recommendations on future enhancements and research needs provided.

During the course of this study, capabilities of the \*Direct Cyclic method (ABAQUS v6.10-2) to evaluate the fatigue life response were investigated. It was established that technical issues exist with internal software algorithms, where initial boundary conditions

(i.e. plastic stress and strain state) were not adequately propagated with successive load steps. Numerical modelling procedures addressing both high-cycle and low-cycle fatigue will be presented in a future publication.

### **3.3 Calibration Study on Unconstrained Plain Dents**

#### ***3.3.1 Overview***

The calibration study is based on investigations conducted for the American Petroleum Institute (API) that examined the effects of dents on the mechanical integrity of liquid petroleum pipelines (Alexander and Kiefner, 1997,1999). The API study was conducted to provide guidance for pipeline operators by establishing methodology and criteria for categorizing dents or defects that need repair and to assess pipeline integrity. The test program involved a range of pipe diameters (12", 24", 32"), material grade (X-52) and indenter shape (round-dome shaped, round-bar shaped, pyramid shaped).

In this paper, numerical modelling procedures were developed to simulate the formation of a surface dent in a pipe by a rigid indenter. The numerical procedures were calibrated with the full scale test UD12A-3, which was material grade X-52, 323.85 mm (12" nominal) diameter pipeline with a 4.85 mm wall thickness (D/t ratio of 67). The indenter used in the physical test was dome shaped (i.e. spherical) having a 219.1 mm diameter. The pipe dent was formed, as an unrestrained feature, by translating the spherical indenter 38.9mm (12% pipe diameter) at zero internal pressure and then releasing contact. An internal pressure was applied to the pipe after indentation, which was equivalent to hoop



stress equal to 65% of the pipe specified minimum yield strength. The pipeline was depressurized and the effects of dent elastic rebound and re-rounding were examined.

As shown through the analysis presented in this paper, although the dataset was useful for the calibration study, there were some limitations. The pipe segment length was not reported and in this study it was assumed to be 10 times the pipe diameter based on photographs presented in the report by Alexander and Kiefner (1997). The stress-strain relationship was not provided, with only the yield strength (371.5 MPa) at 0.5% strain and ultimate tensile strength reported. Dimensions of the saddle used to support the indented pipe and details of the essential boundary conditions were not reported. Furthermore, location deviations in the pipe wall thickness or section ovality were not reported. The studies by Alexander and Kiefner (1999) and BMT Fleet (2007) provide further discussion of the test series and limitations.

### ***3.3.2 Numerical Modelling Procedures for Plain Dents***

Numerical modelling procedures were developed to simulate the API test UD12A-3 (Alexander and Kiefner, 1997). The test condition was modelled as a one-quarter pipe segment with lines of symmetry along the longitudinal axis (6 and 12 clock positions) and at the midspan along the pipe length (Fig. 3-1). There was limited information provided in the literature on the essential boundary conditions used in the physical model. A sensitivity study was conducted to investigate the influence of the essential boundary conditions provided by the saddle support as defined in the numerical modelling

procedures. The saddle was modelled as a vertical line support at the 6 o'clock position with distributed lengths of 350mm, 450mm and 900mm (Fig. 3-1). The pipe indentation response and elastic rebound were examined where the 450 mm line support provided the best results in comparison with the numerical data as published in BMT Fleet (2007). The significance of adequately defining the actual essential boundary conditions on the elastic recovery of the dent feature is further examined within a sensitivity analysis presented later in this paper.

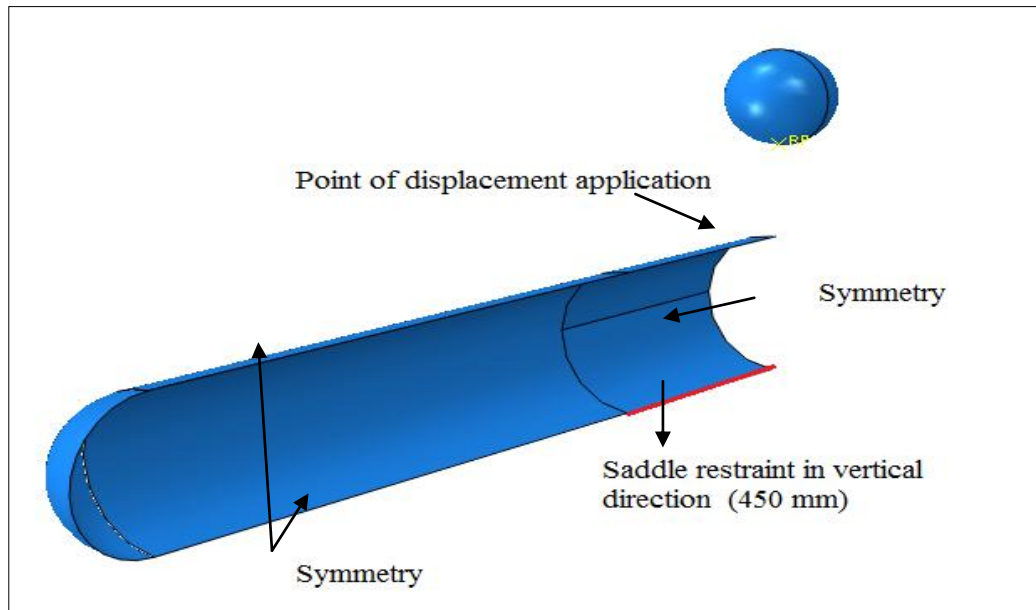


Figure 3-1 : Finite element model for plain dent calibration study

The pipe segment was modelled using the 4-node, doubly curved, reduced integration S4R shell element, which is a general purpose element suited for large strain and displacement analysis (ABAQUS 6.9 EF documentation). The element mesh size near the site of indentation was 10 mm square over a distance of 1.5 pipe diameters with

decreasing mesh density in the transition toward the pipe end. The indenter was modelled using rigid R3D4 elements.

The pipe material properties were defined as an elastic-plastic, piecewise continuous relationship. An elastic modulus of 200 GPa and Poisson's ratio of 0.3 was used. The von Mises yield criterion with isotropic hardening was sufficient for the monotonic loading condition during indentation for the low grade, ductile steel pipe. The studies by Alexander and Kiefner (1997,1999) did not report the stress-strain relationship where the true stress-stress relationship for the pipe was adopted from the studies of BMT (2007).

Translating the spherical indenter 38.9 mm onto the pipe surface, with no applied internal pipe pressure or other natural boundary conditions imposed, a dent was formed within the pipe. The indenter was removed, under zero internal pressure, and the pipe elastic rebound was monitored. An internal pressure of 7.0 MPa, equivalent to hoop stress of 65% SMYS, was applied and removed, through a ramping load function, to examine the effects of internal pressure on unconstrained dent response and re-rounding.

### ***3.3.3 Calibration Study Results on Plain Dent Features***

The pipe was indented by applying displacement, equal to 12% pipe diameter, to a reference node tied with the rigid spherical indenter. The dent profile was monitored and analyzed. As shown in Figure 3-2, the maximum radial inward displacement was observed at the initial point of contact between the pipe and rigid spherical indenter, which is the abscissa coordinate value at the origin. The inward radial displacement amplitude of the dent feature, measured at the pipe segment 12 clock position, decreased

with increasing distance from the point of indentation as a function of the axial position (i.e. pipe longitudinal axis coordinate). The comparison demonstrates excellent correlation between the numerical predictions from this study with the BMT (2007) model for both the peak amplitude and distribution of inward radial displacement of the dent feature.

The modelling procedures developed in this study, the numerical predictions on dent depth and elastic rebound also demonstrated consistency with other physical modelling studies (Alexander and Kiefner, 1997,1999; Fowler *et al.*, 1993). The FE simulations predicted an initial dent depth of 38.9 mm (12 % of pipe OD) and residual dent depth after elastic recovery of 24 mm (7.4%). The corresponding residual dent depth after elastic recovery was 22 mm (6.8%) based on the API studies (Alexander and Kiefner, 1997,1999). Discrepancies may be attributed to uncertainties related to the material properties (i.e. the physical test study did not report the stress-strain relationship), application of the applied loads during indentation (i.e. kinematics, orientation, and compliance of the indenter system) and prescribed essential boundary conditions (i.e. line support versus saddle support).

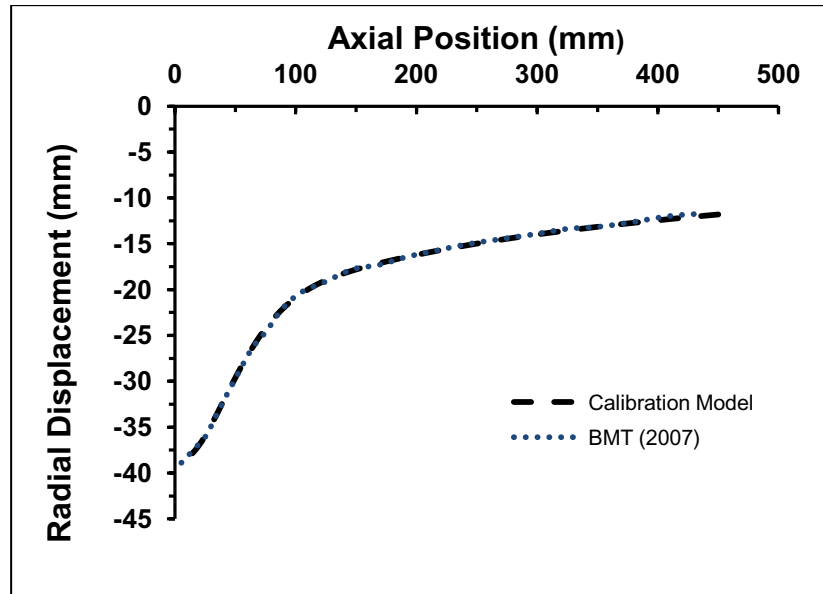


Figure 3-2 : Comparison of the predicted profiles of dent radial displacement between BMT (2007) and this study

The inelastic re-rounding due to the application of a single internal pressure cycle (i.e. pressurization to a specified design factor followed by de-pressurization to zero internal pressure) was examined. The dent depth and re-rounding measurements, for an application of one internal pressure cycle equivalent to 65% SMYS, as reported by the API studies were 3.8 % of pipe diameter and 68% of initial indentation depth. In this study, the corresponding FE predictions were 4.5 % of pipe diameter and 63% of initial indentation depth. For pipe with  $D/t$  ratio greater than 50, there is evidence the pipe mechanical response exhibits elastic-plastic behavior (Fowler *et al.*, 1993). The  $D/t$  ratio for this calibration study was 67. Given the limitations of the dataset, as discussed in the overview section on the calibration study, there exists excellent correlation between the physical data and numerical simulation. The primary sources of uncertainty for the

calibration include definition of the stress-strain relationship and essential boundary conditions. Additional data such as pipe initial ovality across the region of dent interaction, and pipe section ovalization response would be useful to further refine the numerical modelling calibration and validation process.

Nonetheless, the calibration study provided confidence in the numerical modelling procedures. Prior to the event causing mechanical damage, the pipeline may be surface laid with partial soil embedment or fully buried. In addition, the pipeline may have come into operation with the stiffening effects of internal pressure that influence pipe mechanical response. As discussed by Cosham and Hopkins (2003), the elastic springback and re-rounding response of dents are influenced by the pipe wall thickness, internal pressure amplitude and load path and degree of circumferential support. A sensitivity analysis was conducted to examine the effects of end boundary conditions (i.e. axial restraint) and vertical support boundary conditions (i.e. circumferential restraint) on the degree of elastic springback. A pipe with no internal pressure was indented with a rigid spherical indenter for the API study parameters (Alexander and Kiefner, 1997,1999). The essential boundary conditions for the vertical support included (1) line support at the pipe 6 clock position, and (2) distributed contact on one-half pipe circumference from the 3 clock to 9 clock position. For each vertical support boundary condition, the pipe segment end degree-of-freedom (DOF) was either fixed (i.e. fully restrained) or free (i.e. translation and rotation allowed).

The dent shape after elastic rebound for the defined essential boundary conditions is illustrated in Fig. 3-3. The pipe segment end DOF restraint had limited influence on the longitudinal distribution of the dent profile with the greatest effect for the line load vertical support condition. The predicted remaining dent depth for the saddle support boundary condition was 32.5 mm regardless of the imposed end DOF, whereas for the vertical line support boundary condition was 28.8 mm with axial DOF restraint and 26.6 mm with no axial restraint.

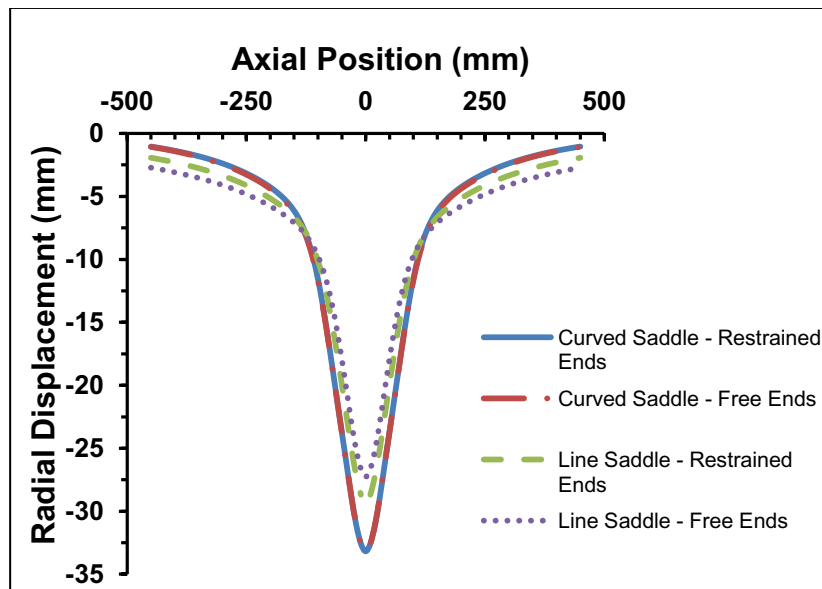


Figure 3-3 : Effect of essential boundary conditions on the residual dent profile

The effect of load path on the unconstrained dent elastic recovery and internal pressure re-rounding was examined for the case of UD12A-3 specimen (Alexander and Kiefner, 1997,1999) as shown in Fig. 3-4. For an unconstrained, smooth plain dent, the in-elastic

re-round after an internal pressure application with hoop stress equivalent to 65% SMYS was found to be 14.5 mm (63%), which corresponds to an equivalent correction factor of 1.65 based on the EPRG semi-empirical approach. A comparison of the hoop stress between the FE model for this study and the predictions by BMT (2007) demonstrated a difference of less than 3%. For unconstrained dents, these observations are consistent with previous studies (Alexander and Kiefner, 1997,1999; Bolton *et al.*, 2010; Cosham and Hopkins, 2003; Fowler *et al.*, 1994).

Based on the difficulties encountered to resolve the observed discrepancy and uncertainty among past datasets and investigations, the analysis conducted in this study suggests the mechanical integrity and fatigue assessment of pipeline dents must proceed on a rational basis in order to develop validated numerical procedures that can be used with confidence in engineering design. Thus, the boundary conditions (i.e. essential and natural), load path (i.e. indenter load, internal pressure), dent constraint conditions, constitutive relationships (i.e. stress-strain behavior, anisotropy) and construction related factors (e.g. girth weld, residual stress) must be systematically defined. In terms of modelling physical tests, the pipe deformational response (i.e. changes in section ovalization & local dent geometry) and mechanical behavior (i.e. distribution of stress and strain on longitudinal and circumferential axes) must be captured. This does not dismiss the value of utilizing the available data and recognize the insight gained and contributions provided from these studies.



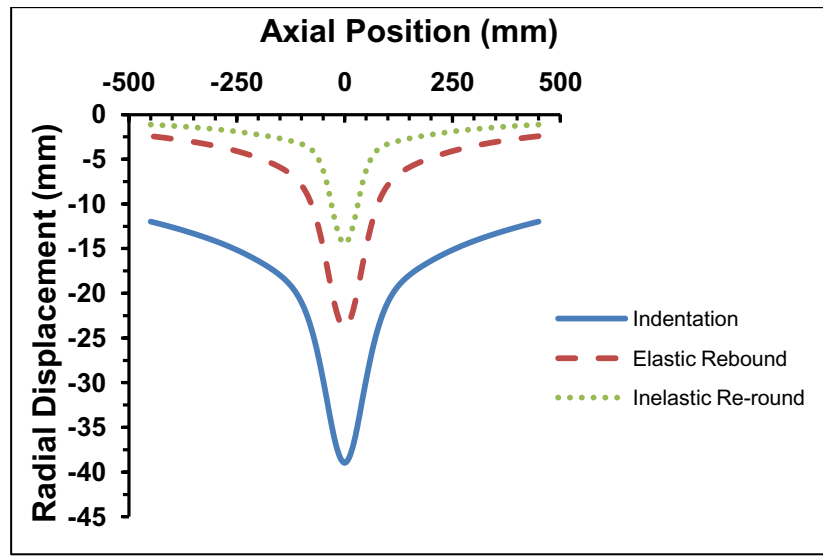


Figure 3-4 : Longitudinal profile of dent radial displacement with respect to load path

### 3.4 Dent Interaction with Girth Welds

Based on the calibrated modelling procedures, a sensitivity study was conducted to examine the coupling and stress concentration effects of a plain dent interacting with a circumferential girth weld. Due to stress concentrations, variations in pipe and weld material properties and presence of weld defects, the burst strength and fatigue life performance of interacting dents with welds is significantly reduced in comparison with plain dents (MacDonald *et al.*, 2007). The calibration study parameters (Alexander and Kiefner, 1997, 1999) were used as the baseline with additional parameters defining the girth weld summarized in Table 3-1. Three load cases were examined that included (1) plain, smooth dent within plain pipe body, (2) smooth dent with centerline on the girth weld centerline, and (3) smooth dent with centerline offset of 1D from the girth weld centerline. The general characteristics of the load case and boundary conditions are

illustrated in Fig. 3-5. The key features of the numerical modeling procedures for this analysis, which can be differentiated from the procedures used in the calibration study are as follows: lines of longitudinal symmetry were only considered, end caps were not included, and a girth weld with a constant offset shift was used to join two pipe segments together. Across the girth weld width, 5 S4R elements were used in the transition between joining pipe segments.

Table 3-1: Plain dent/girth weld interaction study

<b>Parameter</b>	<b>Value</b>
Pipe Diameter	323.85 mm (12")
Pipe Length	3238.5 mm (10 OD)
Pipe WT	4.85mm
Pipe Yield Strength @ 0.5% Strain	371.5 MPa
Indenter Type	Round Dome Shaped
Indenter Diameter	219.08 mm
Initial Indentation	38.9mm (12% OD with zero internal pressure)
Dent Condition	Unconstrained
Girth Weld Offset	$\frac{1}{4} \times$ wall thickness (1.2 mm)
Girth Weld Width	7 mm
Girth Weld Strength Properties	$1.15 \times$ Base Metal Properties

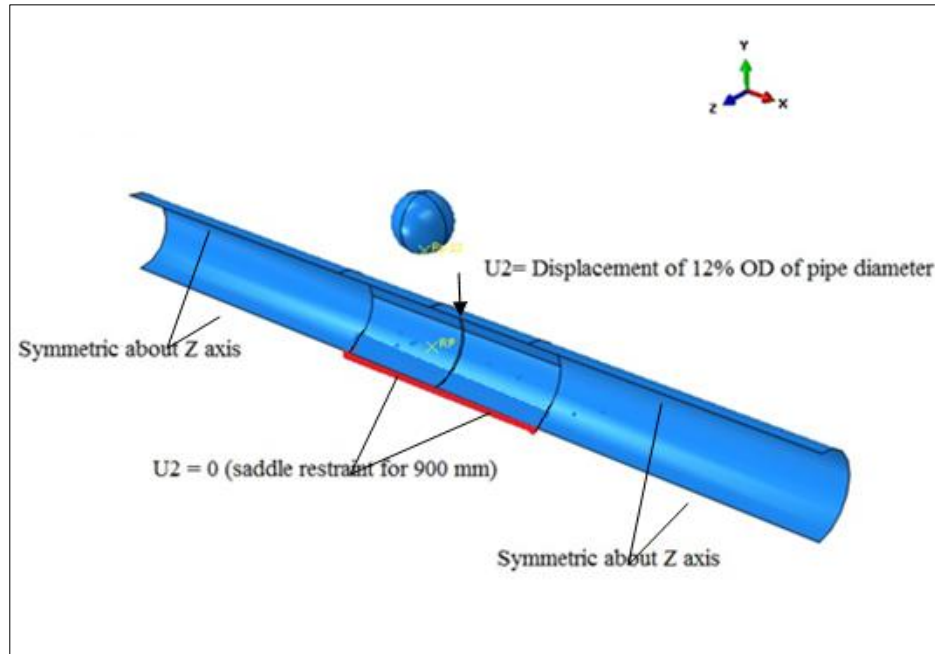
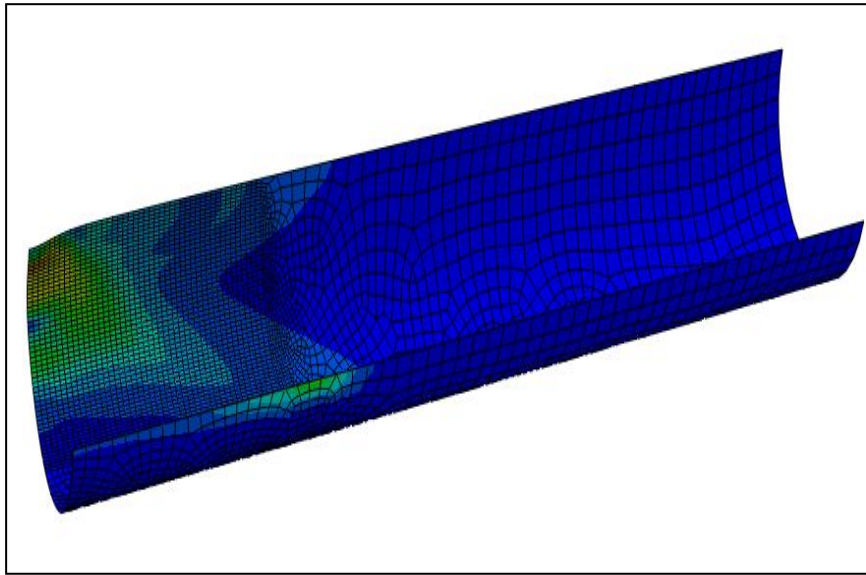
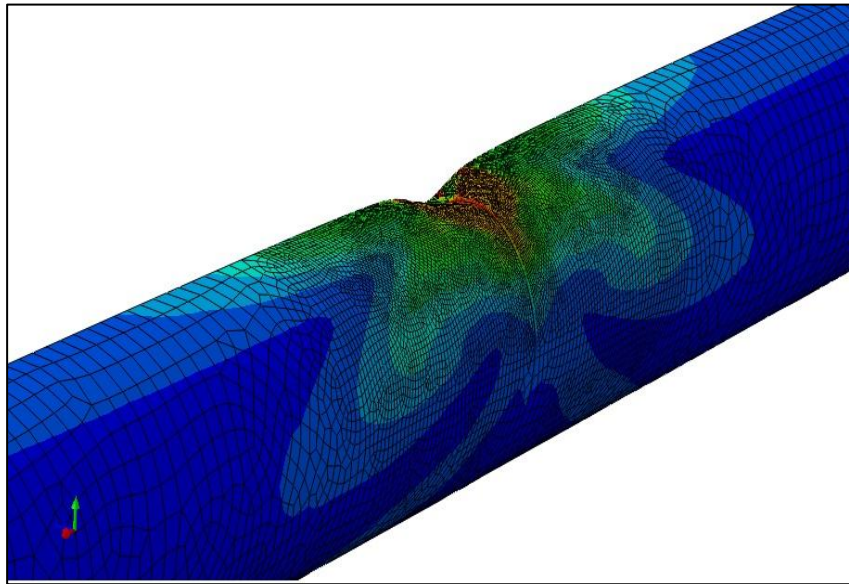


Figure 3-5 : Schematic illustration of the dent/weld interaction model

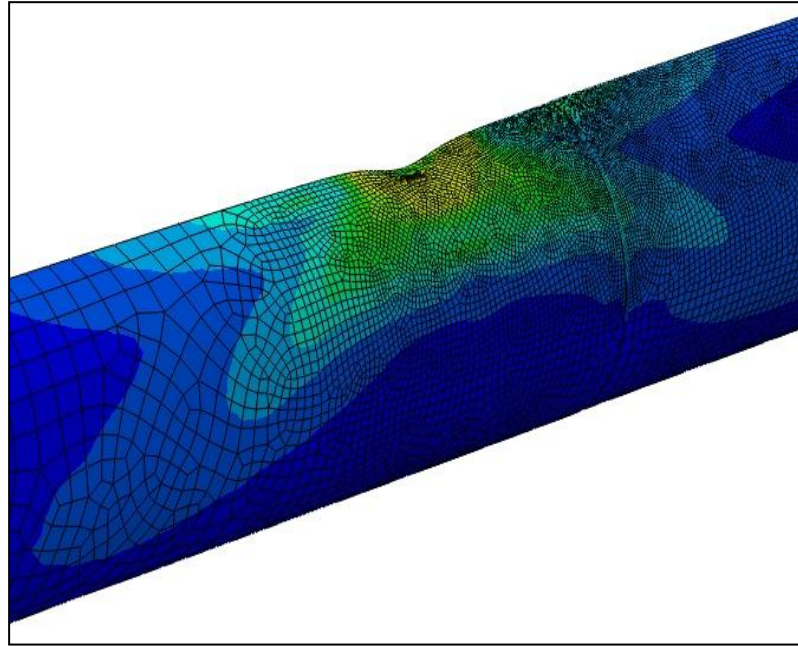
A typical distribution of the equivalent (von Mises) stress surrounding the smooth dent region interacting with the centerline of a girth weld is shown in Fig. 3-6. The deformation response and stress state distribution are presented for the residual dent condition (i.e. pipe indentation and removal of indenter) without any effects of internal pressure.



a)



b)



c)

Figure 3-6 : Generalized distribution of von Mises (equivalent) stress for smooth dent interacting with (a) plain pipe, (b) girth weld centerline and (c) girth weld centerline offset

A typical distribution of the equivalent plastic strain (PEEQ) contour for a smooth dent region interacting with the girth weld centerline is shown in Fig. 3-7. The deformation is presented for the residual dent condition (i.e. pipe indentation and removal of indenter) without any effects of internal pressure. A localized plastic zone (0.13%) was observed to develop within the girth weld at the point of contact with the indenter.

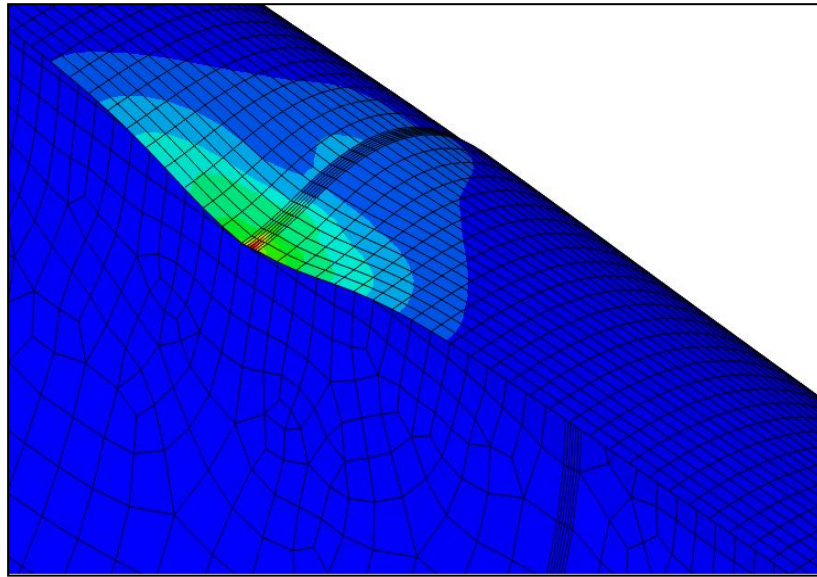


Figure 3-7 : Generalized distribution of PEEQ contour plot for smooth dent interacting with girth weld centerline

Analysis of the longitudinal and circumferential profile distribution of radial displacement of the dent feature did not indicate any sensitivity on the residual dent depth with each load case (i.e. smooth dent interaction with plain pipe, girth weld centerline and girth weld centerline offset). An equivalent correction factor of 1.6 was observed, which is reasonably consistent with existing experience (Cosham and Hopkins, 2003). Interaction of the dent feature with girth weld caused the axial stress to increase at the dent shoulder region, which may be related to the geometric offset and material strength discontinuity at the girth weld. The longitudinal and circumferential distribution of the principal stress was influenced by the girth weld presence with increased amplitude at the shoulder of the dent feature in comparison with the smooth plain dent load case. This may also be associated with the discontinuity at the girth weld. The von Mises stress response

exhibited greater sensitivity in the circumferential direction. The stress concentration factors for dent interaction with girth welds was 3 to 5, which is consistent with other studies (BMT, 2007; DNV, 2012). Other factors that may influence the pipe mechanical response that were not considered in this study include pipe diameter and wall thickness, pipe ovality, imperfections for numerical stability, material properties, dent amplitude, shape and local curvature, essential boundary conditions, internal operating pressure and load path. These issues will be addressed in a future parameter study.

### **3.5 Extension of FE Model Procedures on Plain Dents**

The calibrated model was extended to analyze recent investigations for different parameters including pipe diameter, pipe wall thickness, indenter diameter and indentation depth (Tiku *et al.*, 2012). Test 57 was selected and the parameters are summarized in Table 3-2; however, this reference study did not provide sufficient details on the physical testing and numerical modelling procedures. Consequently, in this paper there were several assumptions required to address uncertainty on test procedures (e.g. essential boundary conditions, indenter system compliance) and material properties (e.g. stress-strain relationship). Consequently, in this study several assumptions were required to develop the modelling procedures that included a continuous vertical line support at the 6 clock position, and representative material properties based on a previous study (Bolton *et al.*, 2010).

Table 2-2: Model Details

<b>Parameter</b>	<b>Value</b>
Pipe Grade	X-52
Pipe OD	457 mm
Pipe Length	4570 mm (10 OD) [assumed]
Pipe WT	7.9 mm
Indenter Type	Ellipsoidal [2:1 ratio]
Indenter Diameter	323.85 mm
Initial Indentation	91.4mm (20% OD with zero internal pressure)
Dent Condition	Unconstrained

Based on these assumptions, comparison of the indenter load-deflection response is presented in Fig. 3-8. The initial 10 mm indentation is primarily associated with section ovalization response with increased localized deformation being developed in the dent feature with increasing displacement. As discussed in the calibration sensitivity study (Fig. 3-3), the pipe support essential boundary conditions play a role in the dent formation and elastic rebound response. Another factor that may account for the observed discrepancy is the constitutive model used. In this study, plastic yielding was governed by the von Mises criterion with isotropic hardening. The study conducted by Bolton *et al.* (2010) employed a nonlinear kinematic hardening model.



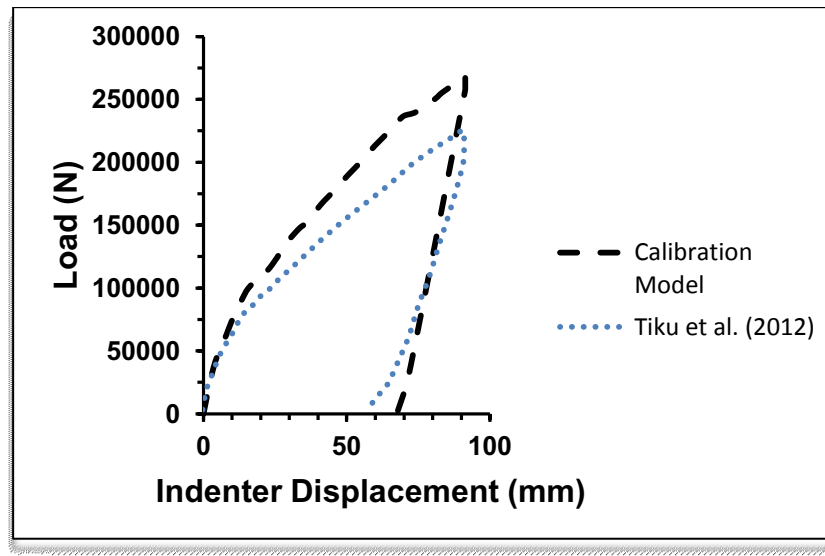


Figure 3-8 : Comparison of the load-deflection response between this study and Tiku *et al.* (2012)

As shown in Fig. 3-9, there also exists discrepancy in the predicted residual dent depth between the current study and the investigations conducted by Tiku *et al.* (2012). The residual dent depth; i.e. elastic rebound after removal of the indenter for an unconstrained dent with no internal pressure, was 70 mm in the present study and ~50 mm in the Tiku *et al.* (2012) investigation. For an initial indentation travel of 20% pipe diameter (91.4 mm) this would represent a relative elastic restitution of 23% and 45%, respectively. The present study suggests an equivalent correction factor of 1.3. The reasons for a much higher elastic rebound observed in the study by Tiku *et al.* (2012) are unclear but it is stated the FE model had scatter that lay outside the  $\pm 10\%$  range. For cyclic loading conditions, the need for a kinematic hardening model is recognized; however, for this monotonic loading condition the discrepancy between the two models, outside the region of significant dent plasticity, is uncertain. These issues warrant further investigation.

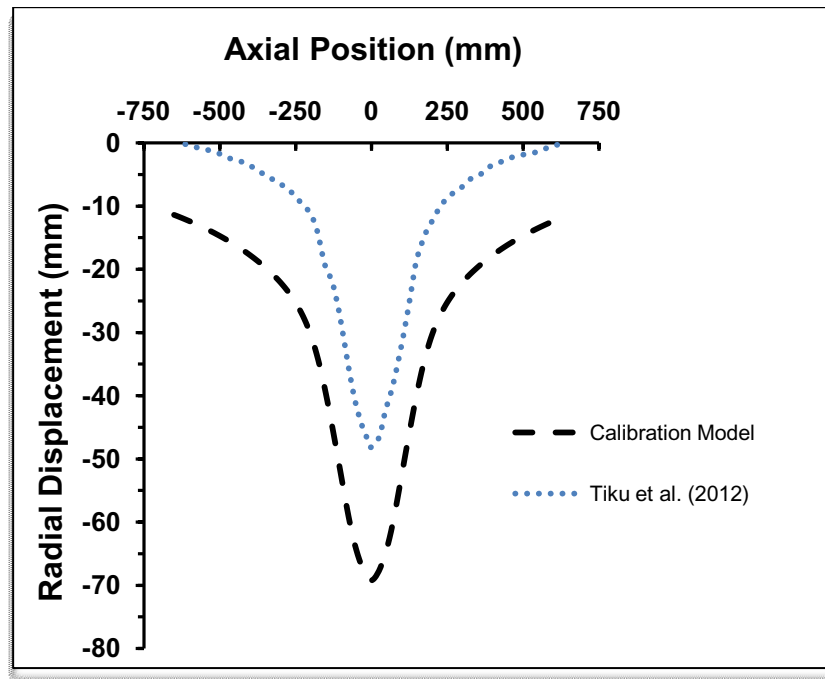


Figure 3-9 : Comparison of the load-deflection response between this study and Tiku *et al.* (2012)

### 3.6 Future Work

Future work will aim at initially addressing the discrepancies observed in comparison study with Tiku *et al.* (2012). Research efforts will be carried out to reduce the uncertainties associated with the model. Once achieved, parametric and sensitivity analysis will be performed for different variables ( $D/t$  ratio, indenter shape, imperfections, material model etc) that may affect the life-cycle response of the dent feature through formation, elastic recovery and re-rounding. The primary goal is to establish credible conditions for the pipe mechanical response at the initial state for subsequent fatigue life analysis and mechanical performance prediction.

The main objective and primary outcome from this study was the calibration of numerical modelling procedures for the simulation of plain, smooth dent formation and pipe mechanical response. The observations and conclusions from a sensitivity study, on the effects of boundary conditions and presence of girth weld, highlighted the direction for building a systematic and integrated research framework to leverage the existing knowledge and data. This would provide a technical basis to develop engineering guidance and criteria for the assessment of interacting defects (e.g. mechanical damage, girth weld, metal loss) and coupled mechanical behaviour over a range of practical design parameters, which is viewed as a current technology gap. This will allow for the development of technical framework to address pipe mechanical behaviour, defect assessment criteria and fatigue life performance.

Finally, although the results are not reported in this paper, the direct cyclic step in ABAQUS (ABAQUS 6.9 EF Documentation) was used to estimate the fatigue life of dented pipe segments. This cyclic step definition was used as it offers considerable computational efficiency (i.e. time and resources) where the effects of thermo-mechanical stress and cumulative damage can be extrapolated in the estimation of high cycle fatigue life performance. The initial stress boundary conditions and localized and plastic stress state, due to the formation of a dent feature, was not propagated correctly within the subsequent direct cyclic step analysis due to issues with internal software algorithms. This issue is currently being investigated through collaboration with ABAQUS and will be addressed in future studies. For the interim, the mechanical performance and fatigue

life assessment of pipe segments subject to mechanical damage will be examined using more computationally intensive methods.

### **3.7 Conclusion**

Numerical modelling procedures have been developed, within ABAQUS/Standard, to simulate the formation, elastic recovery and residual behaviour of plain, smooth dents on pipe segments that can be associated with mechanical damage events. Available physical data and third party numerical simulations (Alexander and Kiefner, 1997, 1999; BMT, 2007) were used to calibrate the numerical modelling procedures, which demonstrated excellent correlation with these studies. A sensitivity analysis was conducted and highlighted the significance of essential boundary conditions and presence of circumferential girth welds on the mechanical response of the dent features. Finally, the calibrated model was extended to simulate other mechanical damage scenarios based on recent investigations (Tiku *et al.*, 2012). The numerical model also highlighted areas where discrepancies exist. Further investigations are required to define with confidence the reasons for observed differences. Areas of uncertainty that have been identified include reporting (e.g. limited and selective information presented in the public domain on physical test data, mechanical response, pipe stress-strain relationships) and modelling procedures used in the current calibrated model (e.g. lack of initial pipe body geometric imperfections, idealized constitutive model).

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## **4 ASSESSMENT OF PARAMETERS INFLUENCING MECHANICAL RESPONSE OF CONSTRAINED AND UNCONSTRAINED DENTS USING FINITE ELEMENT MODELLING**

This paper has been published in the proceedings of 32<sup>nd</sup> International Conference on Ocean, Offshore and Arctic Engineering, Nantes, France, 2013. As the principal investor and first author, the author of the thesis was responsible for conducting the numerical investigation, analyzing the data, and reporting it inside this paper. The second author, Dr. Shawn Kenny, was responsible for supervision of the investigation and guidance on data analysis.

Authors: Waqas Hanif and Shawn Kenny

### **4.1 Abstract**

Pipelines may experience damage (e.g. dent, gouge) during handling, installation and normal operations due to external interference. Pipelines in offshore environment may be prone to mechanical damage from events such as ice gouging, frost heave, and seismic fault movement. Damage mechanisms can be associated with deformation or metallurgical/metal loss that may include pipe dent, pipe ovality, ice gouging, pipe buckling, corrosion etc. The type and severity of pipe damage may influence operational, repair and intervention strategies. For conventional pipelines, the assessment of mechanical damage plays an important role in the development of integrity management programs that may be of greater significance for pipeline systems located in remote harsh environments due to remote location and logistical constraints.



This study examines the effects of plain dents on pipe mechanical response using continuum finite element methods. Finite element software ABAQUS/Standard (v 6.10-1) was used to simulate damage events and pipe response. Modelling procedures were developed and calibrated against physical and numerical data sets available in public domain. Once confidence in numerical procedures was achieved, an analysis matrix was established to account for a range of influential parameters including Diameter to wall thickness ratio ( $D/t$ ), indenter diameter to pipe diameter ratio ( $ID/OD$ ), hoop stress due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ), and kinematic boundary conditions.

The results from this study provide a basis to support a broader initiative for developing an engineering tool for the assessment of damage interaction with pipeline girth welds and development of an engineering performance criterion.

## **4.2 Introduction**

Pipelines are considered to be one of the most practical and low price method for transporting Oil and Gas since 1950's. Due to a number of explorations in the offshore environment, last few decades have witnessed an increasing demand of transportation pipelines in subsea environment. With a good safety record, pipelines are considered to be an efficient mode of oil and gas transportation for both on and offshore environments. However, just like any other engineering structure, there is always risk involved and there have been reported cases in which pipelines have failed (MMI, 2008).

The most common mode of damage and failure for both on and offshore pipelines in North America and Western Europe has been due to external interference or corrosion

(Cosham and Hopkins, 2003). Pipelines may be subjected to more frequent damage in offshore environment during handling, installation or external interference (anchor dragging). Damage mechanisms can be associated with deformation or metallurgical/metal loss that may include pipe dent, pipe ovality, ice gouging, pipe buckling, corrosion etc. Mechanical damage caused by any of the above cases may result in stress concentration or strain localization that may affect pipeline integrity. This may result in an immediate loss of product containment (e.g. leak, rupture) which may generally be attributed to thin walled pipes, delayed effects resulting in pipe failure due to burst limits (e.g. coating damage due to corrosion) and fatigue life degradation (e.g. local defect subjected to cyclic loads).

Current engineering codes and guidelines have been widely used to specify minimum requirements for design, installation, operation and abandonment of offshore pipeline systems; however they do not provide explicit methods to assess such defects (ASME B31.8, ASME B31.4, CSA Z662 and DNV OS-F101). The key influential parameters for dent formation and pipe integrity response include pipe diameter, wall thickness, pipe elastic and plastic strength properties, pipe internal pressure, loading path (i.e. indenter force, internal pressure), dent depth (amplitude), dent width (i.e. lateral extent that is defined by indenter shape), local radius of curvature (i.e. dent type), kinematic boundary constraints (i.e. constrained or unconstrained) and true physical boundary conditions.

The effect of above mentioned parameters, if coupled with one another, may severely compromise pipe strength capacity and useful fatigue life. Extensive work has been

conducted over the last few decades to measure the effects of mechanical damage on pipeline integrity (Cosham and Hopkins, 2003; Fowler, 1993; Hagiwara and Oguchi, 1999; Hart *et al.*, 1998; Hope *et al.*, 1995; Hyde *et al.*, 2011; Ironside and Carroll, 2002; Leis and Hopkins, 2003; MSL, 2000; Rosenfeld, M.J., 1998; Roovers *et al.*, 2000; Stevick *et al.*, 1998), the main outcome of which has been engineering guidance to assess effects of plain dents and gouges as independent features, on pipe mechanical integrity. However, uncertainty on such engineering guidance and studies has been witnessed with poor correspondence between predictions and observations also reported (Cosham and Hopkins, 2004).

With limited engineering guidance and greater uncertainty for predicting mechanical response of interacting defects; such as dent feature interacting with girth weld or dent-gouge interaction and their corresponding effects on pipe integrity (Cosham and Hopkins, 2003, 2004; MSL, 2000), a program of research has been engaged to advance numerical modelling procedures and engineering design tools for evaluation of interacting defects on pipeline mechanical integrity with respect to strength utilization assessment and high cycle fatigue life. Dents interacting with girth welds, and the resulting stress and strain fields were discussed and analyzed in an earlier publication (Hanif and Kenny, 2012).

This paper forms the continuation of the series of publications aimed at providing engineering guidance on dents and imperfections (metal loss and pipe ovality) interaction with girth welds under cyclic pressure loading. In this paper, further model calibration for

plain dents on pipe segment was done based on physical testing and numerical modelling procedures developed by BMT Fleet (Bolton *et al.*, 2008). Comparison of displacement field, mechanical stress and strain response and EPRG correction factor calculations are presented and assessed. Finite element model matrix was generated to account for a range of influential parameters including dent type (unconstrained),  $D/t$  ratios,  $\sigma_h/\sigma_y$  ratios, indenter shape and depth and boundary conditions. Sensitivity analysis replicating testing boundary conditions and true field conditions was also carried out and was found consistent with earlier work done (Hanif and Kenny, 2012).

Results from this study are evaluated with recommendations placed on future enhancements and research needs. Numerical modelling procedures addressing both high and low cycle fatigue lives will be presented in a future publication.

### **4.3 Model Calibration Study**

#### ***4.3.1 Overview***

This paper is part of a current research program focused on the development of finite element modelling procedures that can be used to predict the fatigue life of a pipeline with a damage state (e.g. dent interaction with girth weld) for a range of practical design parameters (e.g. material properties, internal pressure, boundary conditions). Numerical modeling procedures have been calibrated for simulation of unconstrained dents (Hanif and Kenny, 2012). A major outcome from this study was model uncertainty that was attributed to the incomplete reporting on the test boundary conditions, constitutive stress-strain relationships, initial pipe imperfections and pipe mechanical response. In this study,

the approach is further extended to the simulation of constrained dents based on the work of Bolton *et al.* (2008).

#### 4.3.2 Numerical Model Calibration

The investigations conducted by American Petroleum Institute (API) on the mechanical integrity of liquid petroleum pipelines (Alexander and Kiefner 1997, 1999) were analyzed. As discussed by Hanif and Kenny (2012), numerical models for unconstrained dents were generated and calibrated against physical tests (Alexander and Kiefner 1997, 1999, Tiku *et al.*, 2012). The approach was used to simulate physical tests on constrained dents by the application of a rigid indenter on Specimen 1. Details of Specimen 1, as reported by Bolton *et al.* (2008) are summarized in Table 4-1.

Table 3-1: Details of Specimen 1

<b>Specimen</b>	<b>Pipe Grade</b>	<b>t (mm)</b>	<b>D/t</b>	<b>Indenter Diameter (mm)</b>	<b>Dent</b>
1	X-52	7.9	77	60.33	Constrained

The indenter was spherical and the pipe dent was formed as a constrained feature by applying a displacement controlled load under zero pressure conditions. The indenter displacement was increased gradually until it reached the target depth of 7.5% pipe diameter (45.72mm). The indenter was then kept at this depth level in order to generate constrained dent conditions. An internal pressure equivalent to 100% SMYS was then

applied in 10% increments. The pipeline was then depressurized and the effects of elastic rebounding and dent re-rounding on the pipe wall stress and strain fields were captured.

Although the calibration datasets were useful to provide confidence in the numerical procedures developed, there were limitations in the reported data, procedures and results that limit utility and influence model certainty. The general test procedures were highlighted (Bolton *et al.*, 2008), however, specific details were missing or incomplete. For example, the pipe segment length was not defined. Based on available information, the pipe length was assumed to be 5 times the pipe diameter. Data on the stress-strain relationship and details of kinematic boundary conditions were not reported. Furthermore, the pipe initial imperfections (e.g. variation in pipe diameter) or pipe section response during the test (e.g. section ovality) were not reported.

#### ***4.3.3 Model Details for Plain Dents***

The test specimen was modelled as one quarter of pipe segment due to symmetrical geometry, loading and boundary conditions. Lines of symmetry were applied along axial section plain (6 and 12 o'clock positions) and along transverse section plain. Saddle used to support the indented pipe was modelled as a vertical line support at 6 o'clock position for a length of 127mm. Due to limitation on reported essential boundary conditions used in physical model, pipe with and without jack end support were modelled that further provided a vertical restraint of 76.2mm at far end of the pipe. In addition, a single node that was created at the bottom where the 2 plains of symmetry intersected, was restricted

in all degrees of freedom (DOF) in order to impart numerical stability and avoid any rigid body motion. Figure 3-1 provides an insight on the boundary conditions used.

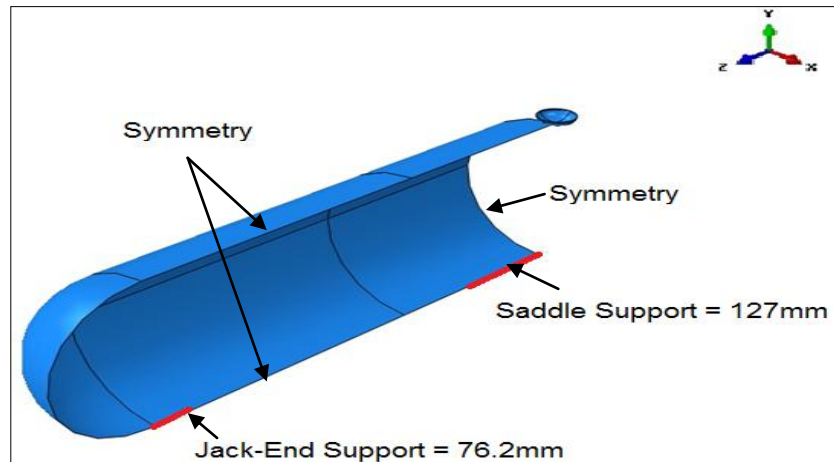


Figure 4-1 : Finite element model for plain dent calibration study

The segment was modelled using 4-node, doubly curved, reduced integration S4R shell element. S4R elements are general purpose elements that are well suited for large strain and displacement analysis (ABAQUS 6.9 EF documentation). The element size was kept to 5mm square in the indentation zone with decreasing mesh density up to 25mm square away from indentation site. The indenter was modelled using R3D4 elements with smooth edges in order to avoid any sharp stress risers.

#### **4.3.4 Material Model**

The pipe material was defined by grade 360 (X52) with an elastic modulus of 200GPa and Poisson's ratio of 0.3. The pipe stress-strain behavior was defined by an elastic-plastic piecewise continuous function using the Ramberg-Osgood relationship with  $\alpha$

taken as 1.86 and  $n$  set equal to 17.99 (Walker and Williams, 1995). The von Mises yield criterion with isotropic hardening was used to define plastic response.

#### ***4.3.5 Dent Creation***

The dent creation and pipe re-rounding response was a 3 step process in which initially the rigid indenter was translated to the target depth. The indenter was kept in place in order to give constrained dent condition and the indentation profile was monitored. Initial pressure cycle equivalent to 100% SMYS (9.3 MPa) was applied in 10 increments. The pressure was then ramped to zero. Three pressure cycles were applied that fluctuated between pressures equivalent to 10% - 80% SMYS. The residual dent depth, stress and strain fields were recorded.

#### ***4.3.6 Calibration Study Results***

In the physical testing procedures, strain gauges were used at various locations placed on the outer diameter surface of pipe. To measure dent re-rounding, bi-axial strain gauges were placed along the longitudinal centerline of pipe at distances of 152.4mm and 609.6mm (Bolton *et al.*, 2008). To keep consistent with the physical tests, average rebound and re-round values of 5 elements (5mm square each) were monitored at similar distances in the FE model.

As shown in Fig 4-2, the general trend of dent profile is consistent with physical models with inward radial displacement amplitude of dent feature decreasing with increasing



axial distance from the point of indentation. The discrepancy between the physical tests conducted by Bolton *et al.* (2008) and results from this numerical study can be attributed to lack of detailed information on the physical test program being reported that leads to uncertainty with the prescribed kinematic boundary conditions, initial pipe geometry, material properties, and relative compliance of the pipe and indenter system. As discussed by Hanif and Kenny (2012), the essential boundary conditions have a significant influence on the pipe mechanical response

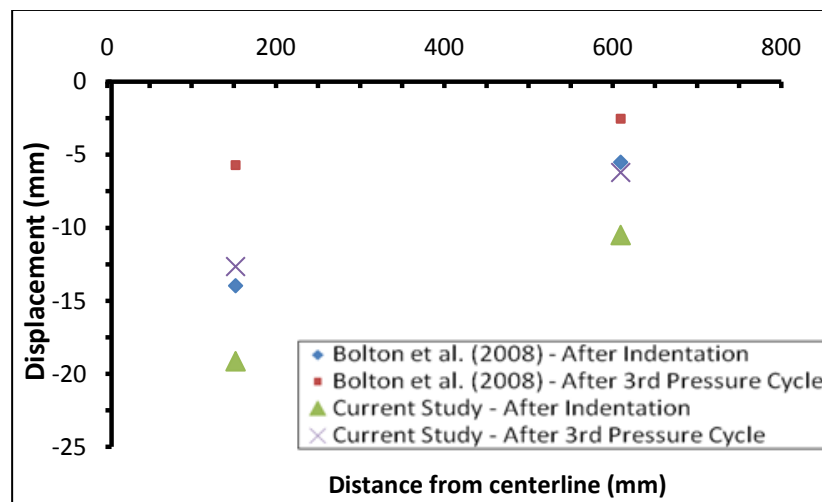


Figure 4-2 : Radial displacement of pipe wall for initial indentation and after 3<sup>rd</sup> pressure cycle

Comparison of rigid indenter load-deflection response is presented in Fig 4-3. Significance of the defined kinematic boundary conditions on the force-deflection response is demonstrated. Two cases were studied: 1) With Jack End Support and 2) Without Jack End Support. The Jack End support is referred to as “End Saddle” in the

current study. Results were then compared with physical tests and numerical models presented by Bolton *et al.* (2008).

The FE simulations conducted in this study, assuming no end saddle support boundary conditions, were consistent with the numerical simulations conducted by Bolton *et al.* (2008). However, assuming the kinematic boundary conditions included end saddle support, the numerical procedures developed in this study were more consistent with the physical test data presented by (Bolton *et al.*, 2008). Specimen specific stress-strain curves (e.g. stress-strain relationship for specimen 1) and imposed boundary constraints were not fully reported in literature that can be attributed to affect the calibration procedures.

The initial indentation response, less than 10 mm of indenter displacement, is primarily associated with the pipe section ovalization. Localized pipe wall deformation tends to dominate the pipe mechanical response with increasing indenter displacement. The lack of information on the spatial variation of initial pipe diameter and local pipe section ovalization, results in further uncertainty that is further explored in this paper through a sensitivity analysis.

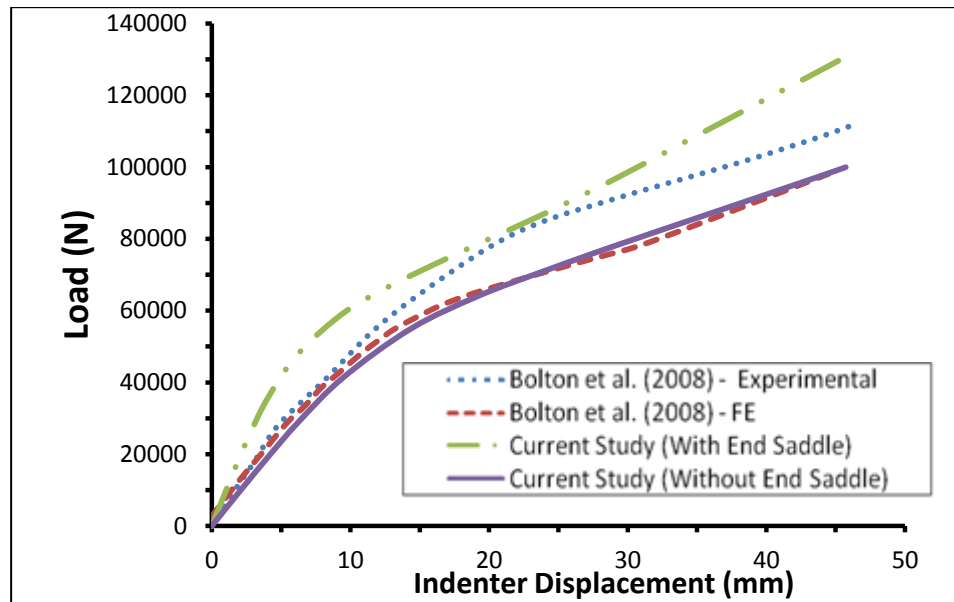


Figure 4-3 : Indenter load-deflection response for physical and numerical models

More detailed comparisons between FEA strain values against full scale test results for outer diameter hoop and axial strains is presented in Fig 4-4 and Fig 4-5. Hoop and axial strain values located axially from the point of indentation are presented at the end of indentation phase. Good agreement between results can be observed for experimental values and predicted strains for both with and without end saddle restraint which shows less dependence of pipe strain response with variations in the end boundary conditions.

Comparing dent rebound and re-round plot (Fig. 4-2) and microstrain plots (Fig 4-4 & 4-5) with the study of Bolton *et al.* (2008), the difference in coherency of results is observed. It is to be noted that the rebound and re-round values are more of a global response of pipe that are strongly dependent on pipe elastic (for rebound) and plastic (for re-round) strength properties along with the boundary conditions used. Boundary

conditions can further be related to the external kinematic constraints used (e.g. line versus distributed saddle support) as reported earlier (Hanif and Kenny, 2012). Ideal conditions were used to determine stress-strain curve (Ramberg-Osgood relation) with assumptions placed on boundary conditions, as a result of which rebound and re-round values were affected. Also the pipe local sectional response (e.g. ovality, denting) and measurement technique can further influence the magnitude of the displacement field. For microstrain values, the results showed more consistency as the indentation is a localized plastic phenomenon which is more dependent on compliance of indenter system and boundary conditions used, and have less dependency on pipe strength properties particularly for displacement controlled indentations. The combined effect of the parameters mentioned above can be attributed to generate more consistency towards microstrain plots and less towards pipe deflection response.

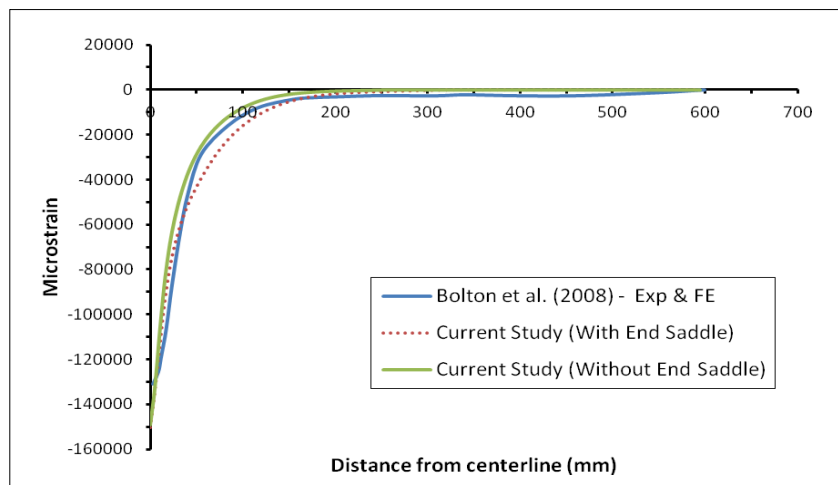


Figure 4-4 : Extreme fiber hoop strain along pipe longitudinal axis for physical and numerical models

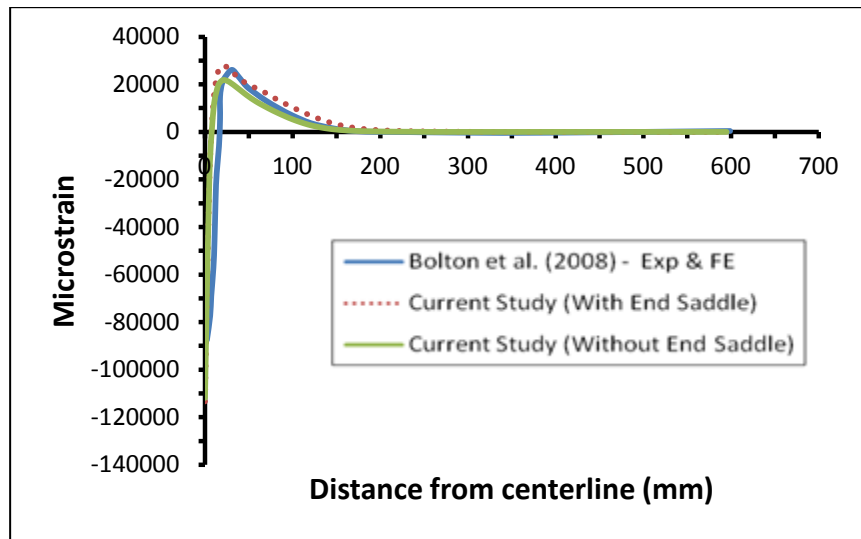


Figure 4-5 : Extreme fiber axial strain along pipe longitudinal axis for physical and numerical models

The pipe stress response is a product of a complex loading history that may include indentation, elastic unloading for unconstrained dents, and dent re-rounding for pipe with applied internal pressure. The localized plastic deformation is focused at the dent apex and crest of shoulder regions. The predicted stress distribution may be influenced by the boundary conditions and constitutive relationships being defined. The variation in hoop stress, based on numerical predictions, is illustrated in Fig 4-6. This raises questions on model uncertainty particularly with respect to fatigue life prediction. Further, these simulations do not account for other possible influences on the pipe stress state such as residual stress due to fabrication and heat affected zone due to girth welding. Fatigue cracks typically arise in the dent shoulder region, therefore if reliable dent data closer to peak indentation could be monitored then better fatigue life estimations could be established.

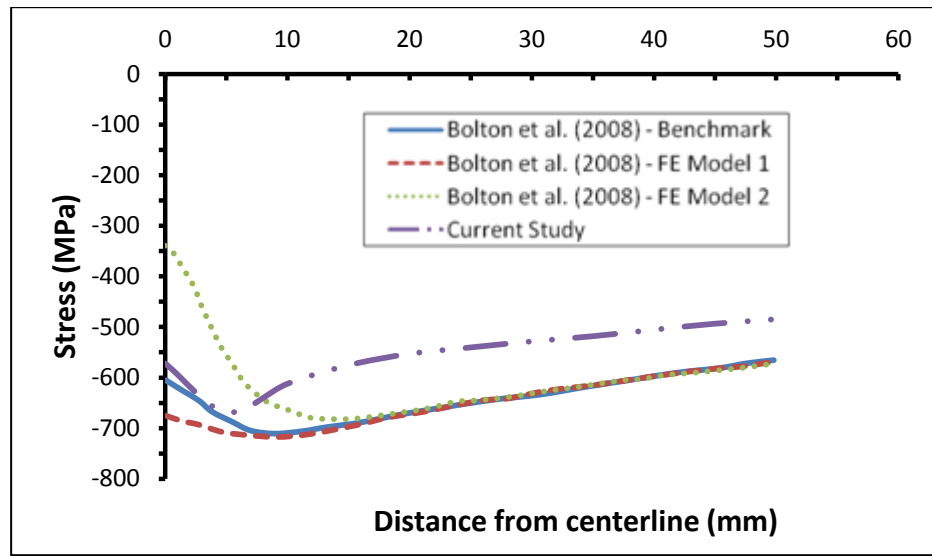


Figure 4-6 : Distribution of extreme fiber surface hoop stress along pipe longitudinal axis

The numerical modelling procedures developed in this study have been calibrated with available physical test data and simulation tools for the pipe mechanical response subject to localized indentation. Although there exist limitations in the third party calibration dataset, the insight and contributions provided are recognized. Areas of model uncertainty included the kinematic boundary conditions, initial pipe state (e.g. variation in pipe diameter, residual stress), pipe constitutive behavior (i.e. lack of coupon data) and pipe response (e.g. section ovalization) during indentation.

#### 4.4 Model Matrix

Based on the calibrated modelling procedures developed for constrained dents, the approach was carried forward to study the effects of varying pipe diameter to wall thickness ratios ( $D/t$ ), indenter diameter to pipe diameter ratios ( $ID/OD$ ), and hoop stress

due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ) for unconstrained dent conditions. A model matrix was generated (Table 4-2) to examine dent profiles and stress/strain fields in close proximity of the pipe dent.

Table 4-2: Model Matrix – Plain Unconstrained Dents

<b>Specimen</b>	<b>D/t</b>	<b>Indenter Diameter (% OD)</b>	<b>Indentation Pressure (%SMYS)</b>
1	40	10	0
		20	
		30	
2	60	10	0
		20	
		30	
3	80	10	0
		20	
		30	
4	40	10	80
		20	
		30	
5	60	10	80
		20	
		30	
6	80	10	80
		20	
		30	

#### 4.5 Numerical Model

Numerical modelling procedures were developed for pipe grade 450 MPa (X-65) having a nominal diameter of 609.6mm (24"). Length of the pipe was selected as 10 OD (modelled as 5 OD due to symmetrical conditions). The indenter shape was selected as

hemispherical with indentation depths kept constant at 10% OD (60.96mm) for all cases. The  $D/t$  and  $ID/OD$  ratios were varied from 40 – 80 and 10% – 30%, respectively. Unconstrained dents were created for 2 different loading scenarios. The first case involved dent creation by translating the rigid indenter to target depth at zero internal pressure conditions. Once the indenter was removed and contact released, an internal pressure equivalent to 80% SMYS was applied. The second loading scenario involved dent creation on a pressurized pipe. Pressure equivalent to 80% SMYS was applied before indentation phase. The pipe was then indented under pressurized conditions and contact released. Pipe residual stresses and initial geometric imperfections associated with the manufacturing processes were not modelled. Elastic modulus of 200 GPa with a Poisson's ratio of 0.3 was used. Von Mises yield criterion with isotropic hardening was used and material anisotropy was ignored. Pipe material properties were defined as an elastic-plastic piece wise continuous relationship which was developed using Ramberg-Osgood relationship.  $\alpha$  was taken as 1.29 while  $n$  was set equal to 25.58 (Walker and Williams, 1995).

Based on earlier done sensitivity analysis on boundary conditions (Hanif and Kenny, 2012), line saddle support at 6 clock position was used to restrict pipe motion in vertical direction. Such boundary condition was used to replicate field conditions for surface laid pipe with negligible soil embedment. Fixed pipe ends were modelled assuming the pipeline to be infinitely long, thus restricting the pipe in axial direction. Figure 4-7 illustrates boundary conditions used for the study.



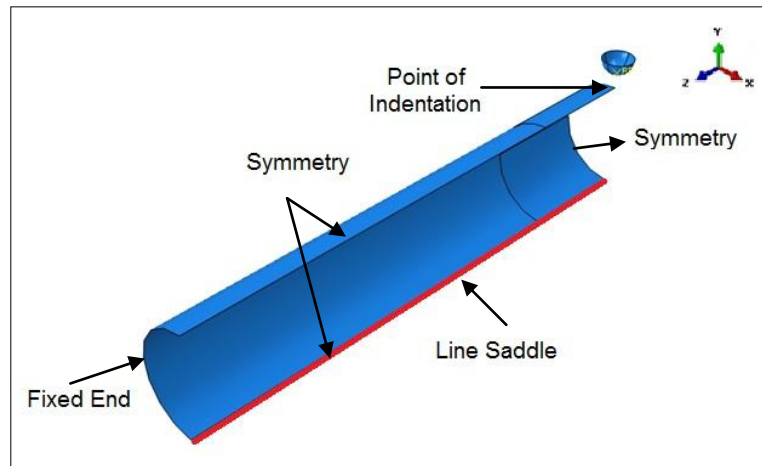


Figure 4-7 : Finite element model for plain dent calibration study

Element sets were generated at 12, 1:30 and 3 clock positions in longitudinal direction extending upto a distance of 2.25 OD. Results for model matrix were generated and examined for all load steps for both pressurized and unpressurized loading scenarios. Results are analyzed in detail in the section to follow.

## 4.6 Results and Discussion

Analysis of longitudinal profile distribution of radial displacement of dent feature was done for elements at 12 o' clock position. Results were further generated for element sets at 12, 1:30 and 3 clock o' position for residual stresses and strains for varying load sequences.

### 4.6.1 EPRG Correction Factor – Spring Back Effect

Spring back is the phenomenon associated with dented pipe segments, which tend to revert back to their original position upto some degree when the indenter is removed, thus

producing spring back effect. To study the effects of plain dents, most of the full scale tests in literature were conducted with pipe under zero pressure conditions. However, in-service dents are primarily formed when the pipe is in the operational, pressurized condition. The European Pipeline Research Group (EPRG) developed a correction factor that related residual dent depth for zero pressure conditions to the dent depth under pressurized conditions (Corder and Chatain, 1995). The Pipeline Defect Assessment Manual (PDAM) recommends the use of EPRG correction factor over other empirical methodologies due to its ease of use and ease of measuring its effect against published test data (Cosham and Hopkins, 2003). However, the EPRG factor is an empirical correction factor with variability and uncertainty (Cosham and Hopkins, 2003). The correlation between residual dent depth on an unpressurized pipe and a pressurized pipeline, as established by EPRG is given in Eq. (4.1).

$$\frac{H_o}{D} = 1.43 \frac{H_r}{D} \quad \text{Eq. (4.1)}$$

The springback effect is a complex function of pipe geometry, material properties, internal pressure and dent shape (Cosham and Hopkins, 2003). In this study, correction factors were calculated across the parameter range (table 4-2) where an average correction factor of 1.57 was established. This study specific factor is consistent with the EPRG factor of 1.43 as defined in Eqn (4.1), which is considered to be a conservative estimate (Corder and Chatain, 1995).

In this study, it was observed that the effect of  $ID/OD$  percent ratio on residual dent depths for unpressurized case were not significant. For pressurized case, the indenter  $ID/OD$  showed an inverse relation with residual dent depth where the dent depth reduced with increasing  $ID/OD$  ratio. As expected, an inverse relation between pipe  $D/t$  and dent depth was also observed. High  $D/t$  ratio pipelines have thinner wall thickness and lower bending stiffness, which is related to  $Dt^3$ , that results in greater amplitude of pipe rebound and re-round response in comparison with pipes having lower  $D/t$  ratios.

For unconstrained dents with internal pressure, the residual dent depth after release of the indenter constraint is illustrated in Fig 4-8. The residual dent depth increases with decreasing  $D/t$  and decreasing  $ID/OD$  ratios. The relationship with  $D/t$  appears to be nonlinear whereas a linear relationship with  $ID/OD$  was observed. For the dents formed in this study, the indenter is defined by prescribed displacement and not governed by load control. As the pipe  $D/t$  increases, the pipe wall bending stiffness decreases and this results in greater recovery of the pipe wall (i.e. lower magnitude of residual dent depth) on removal of the indenter. As the  $ID/OD$  ratio increases, the pipe section exhibits global section ovalization in response to the indenter loading, which will be discussed in more detail later in this paper.

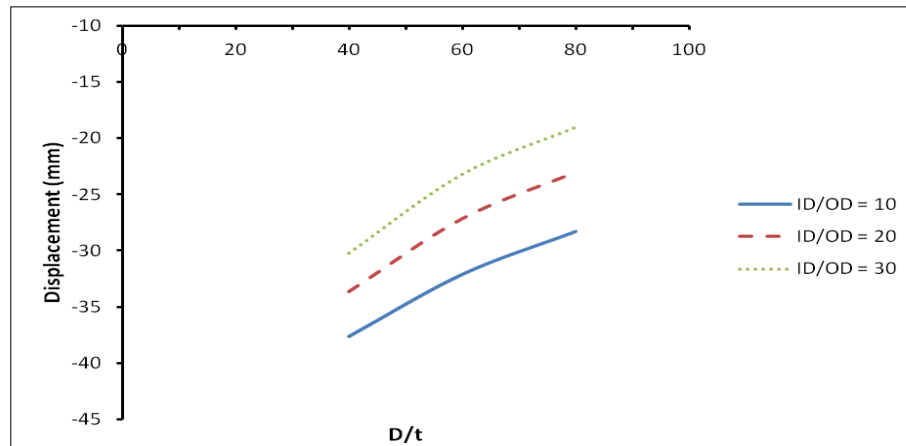


Figure 4-8 : Residual depth of an unconstrained dent after indenter release as a function of  $D/t$  and  $ID/OD$  (%)

#### 4.6.2 Dent Profile – Zero Pressure Indentation

Dent profiles were generated and the effect of load path on unconstrained dent elastic recovery and internal pressure re-rounding was observed for the loading scenario with no initial internal operating pressure. Axial dent profiles were generated at the end of three load step cases including: 1) indentation phase (i.e. loading), 2) indenter removal (i.e. unloading) and 3) 80% SMYS internal pressure application (i.e. pressurization). Consistent with the literature (BMT, 2007), pipe wall flexural response was observed when the internal pressure, equivalent to hoop stress of 80% SMYS, was applied after indentation phase. As shown in Fig 4-9, the dent elastic rebound, prior to pressure application, exhibited a linear relationship with  $D/t$  ratio. The elastic recovery increased from 20% to 30% across the  $D/t$  ratios examined but was not influenced by the  $ID/OD$  percent ratio. The dent re-rounding behavior due to internal pressure exhibited a nonlinear relationship with  $D/t$  and weak relationship with  $ID/OD$  ratio. (Fig 4-9).

Characteristics of the dent shoulder response were also examined (Fig 4-10, 4-11). The shoulder lengths tended to increase (factor of 1.22) with increasing  $D/t$  ratios and a decrease (factor of 0.70) with applied internal pressure, which was consistent with other studies (Bolton *et al.*, 2008, BMT, 2007). This mechanical behavior is in response to greater pipe wall flexural compliance with increasing  $D/t$  and dent re-rounding with stiffening effects due to internal pressure. Varying ID/OD ratios did not have any significant influence on the dent shoulder response during the pressurization stage. However during the indentation and unloading phase, ID/OD ratios dictated the profile shape where the dent shoulder length increased with increasing ID.

The peak amplitude and longitudinal extent of the dent profile was also analyzed. The effects of initial loading and subsequent application of internal pressure on the dent response was examined. After pressurizing the pipe, the maximum radial deflection, measured at the centerline of the indenter, was 30% of the initial indentation amplitude and the longitudinal extent of the dent shoulder region was reduced by 90% (Fig 4-11).

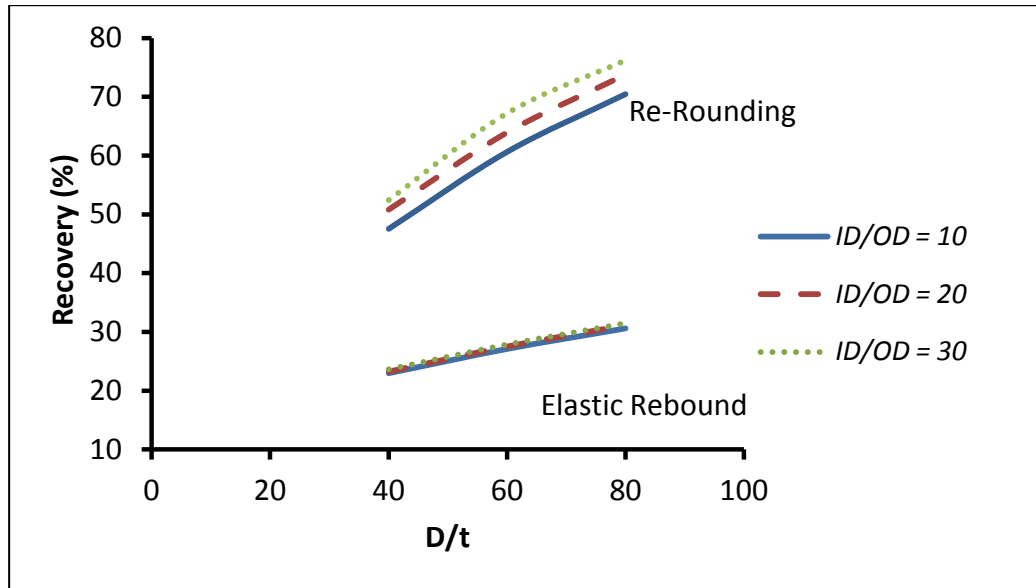


Figure 4-9 : Residual dent depth (elastic rebound and pressure re-rounding) as a function of D/t and ID/OD ratio for initial zero pressure indentations

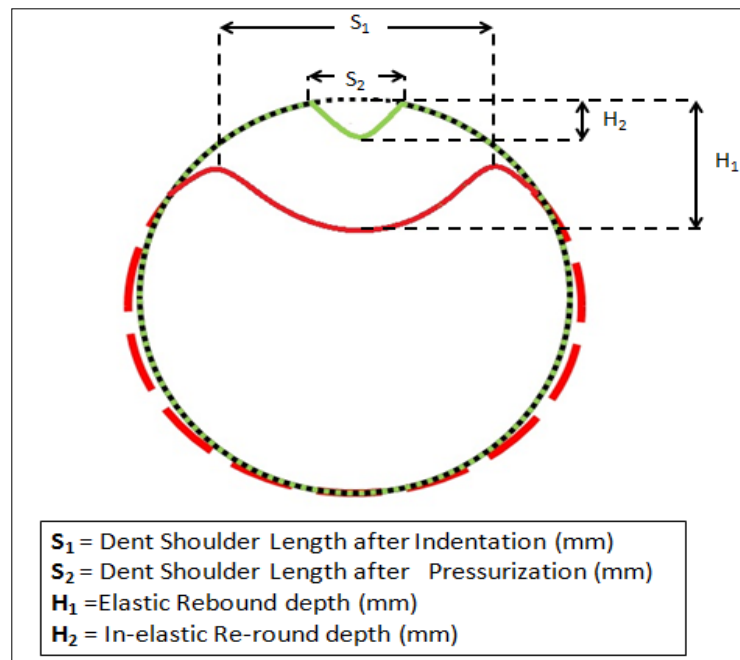


Figure 4-10 : Schematic illustration of dent shoulder region and measurement terms

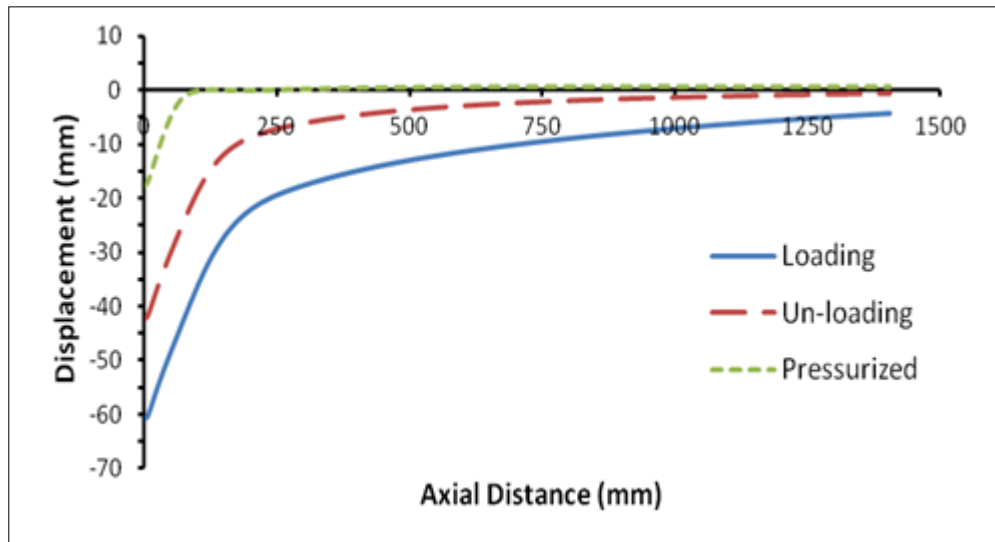


Figure 4-11 : Typical dent profile for zero pressure indentation load case

#### 4.6.3 Dent Profile – Pressurized Indentation

For pressurized indentations, dent shapes along axial centerline were recorded at 2 stages; 1) during indentation and 2) after the indenter were removed. A typical dent profile for Specimen 6 as summarized in Table 3 (ID/OD = 10%), is illustrated in Figure 4-12. The dent depth on unloading was typically 50% of the initial indentation depth and was influenced by  $D/t$  and ID/OD ratios. The average elastic recovery for pressurized indentations is approximately twice as high as elastic recovery for unpressurized indentation. This should not be confused with the EPRG correction factor as different response parameters are being examined. Comparing Fig 4-12 with Fig 4-11, the internal pressure develops a stiffer pipe response with higher curvature in the dent profile and greater unloading recovery (i.e. lower residual dent depth). However, the total dent

recovery is greater (i.e. lower residual dent depth) for the zero pressure indentation load case (Fig. 4-11).

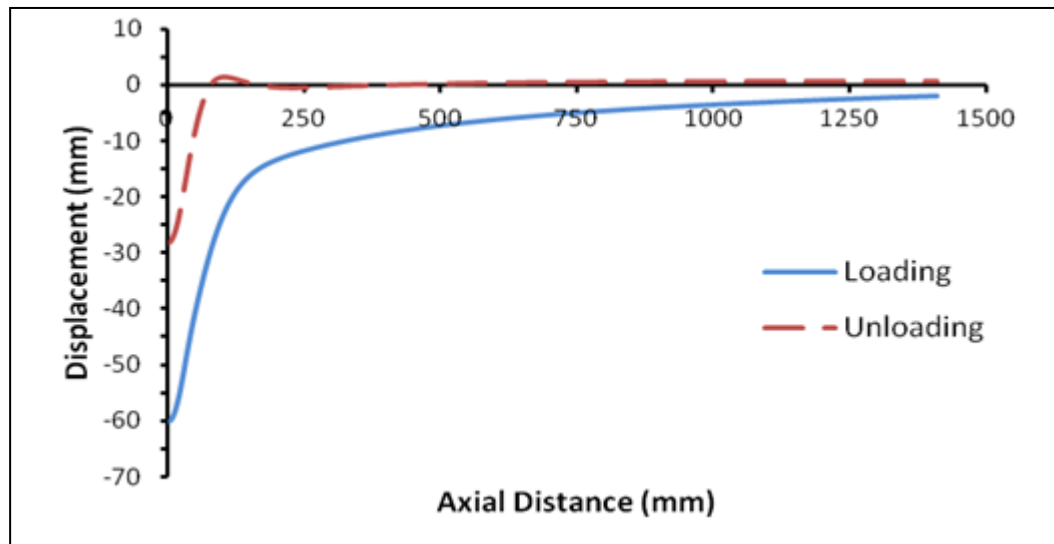


Figure 4-12 : Typical dent profile for pressurized indentation load case

#### 4.6.4 Load vs Displacement

The indenter load-displacement response for zero pressure and pressurized load cases were analyzed (Fig 4-13, 4-14). The stiffness decreased with increasing  $D/t$  and the load-displacement relationship exhibited an initial elastic and secondary plastic response. The elastic response was associated with global pipe section ovalization, whereas the plastic hardening response was associated with local deformation within the dent zone. The relative effects of internal pressure, through comparison of Fig 4-13 with Fig 4-14 was to increase the pipe stiffness. For the unpressurized load case, the load-deflection response



was not influenced by the effect of  $ID/OD$  ratio, unlike pressurized case where the load values to achieve same target depths, increased with increasing  $ID/OD$  ratios.

The plastic pipe stiffness response decreased with increasing  $D/t$  ratios (40 to 80) by a factor of  $2/5$  and  $1/2$  for unpressurized and pressurized load case, respectively. This effect can be related to thin walled pipes which may offer less bending stiffness (related to  $Dt^3$ ) and ultimately less indentation loads to achieve same target depths than thick walled pipes. For the pressurized load case, the load required to achieve the target indentation depth of 10%  $OD$  (60.96mm) was approximately double the magnitude for the corresponding unpressurized load case (comparison of Fig 4-13 with Fig 4-14). The pipe stiffness was significantly influenced by the effects of internal pressure where the stiffness increased by a factor of 2.6 at  $D/t$  ratio of 40 and factor of 3.4 at  $D/t$  ratio of 80 (Fig 4-15).

These observations are supported by Fig 4-16 and 4-17 that illustrate the elastic and plastic strain energy through the loading cycles. Figure 4-16 shows the pipe elastic strain energy which is extended up to an axial distance of approximately 500 mm from the centerline of the indenter, and fluctuates between each load step. This response reflects the significance of hoop stress response due to section ovalization and internal pressure. The plastic strain energy does not exhibit the same variation (Fig 4-17) between different load sequences with the peak magnitude near the point of indentation that is associated with the localized plastic deformation response.

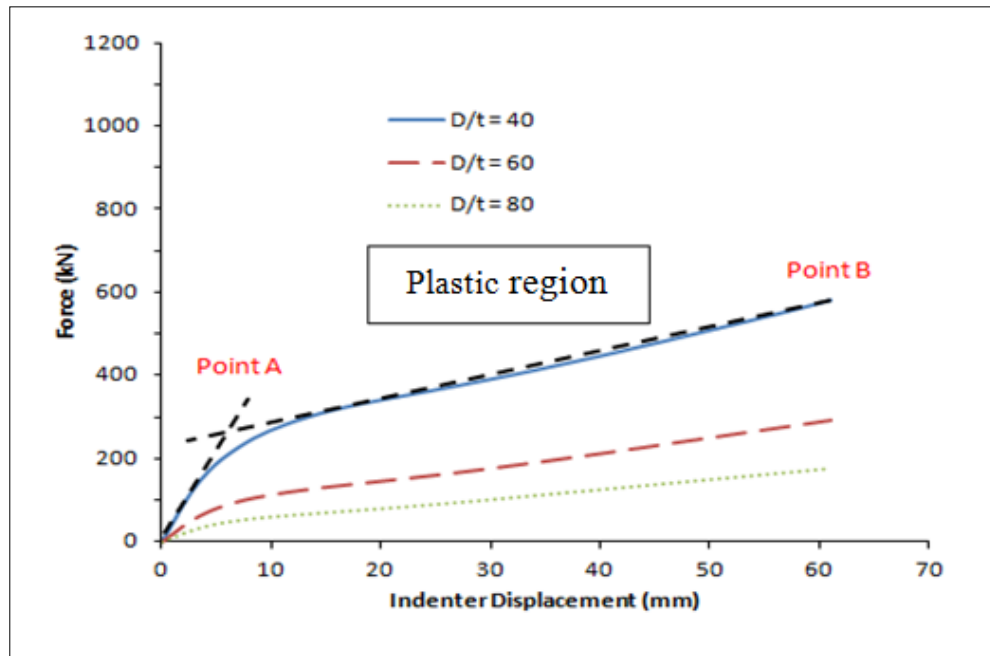


Figure 4-13 : Indenter force-deflection response for zero pressure indentation load case

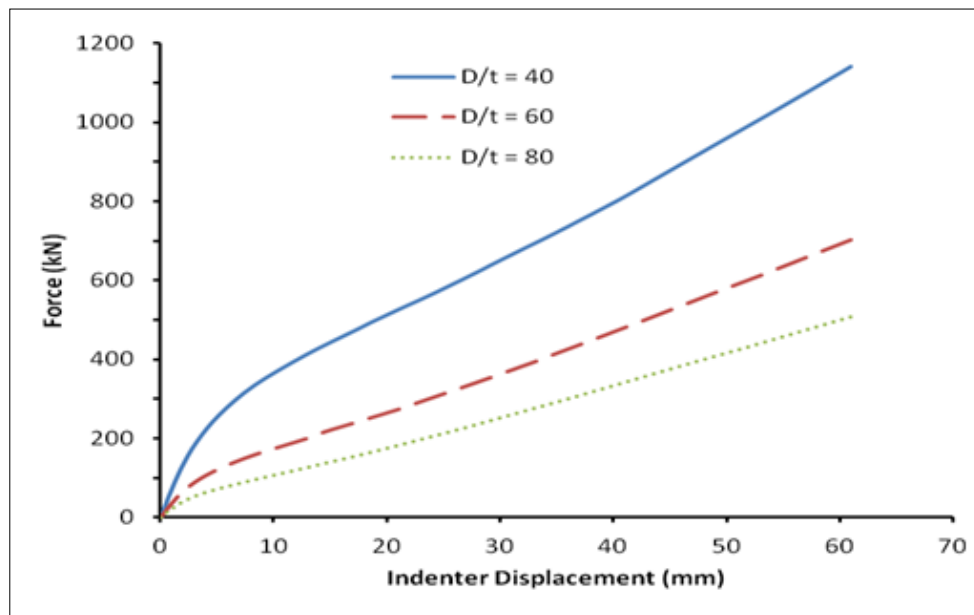


Figure 4-14 : Indenter force-deflection response for pressurized indentation load case

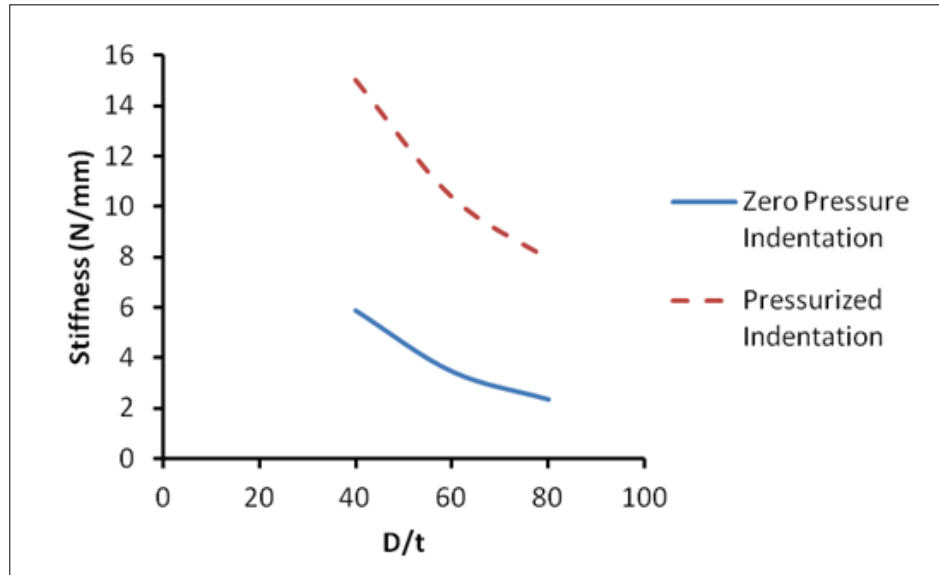


Figure 4-15 : Pipe plastic stiffness response for zero pressure and pressurized indentation load cases with ID/OD = 10 %

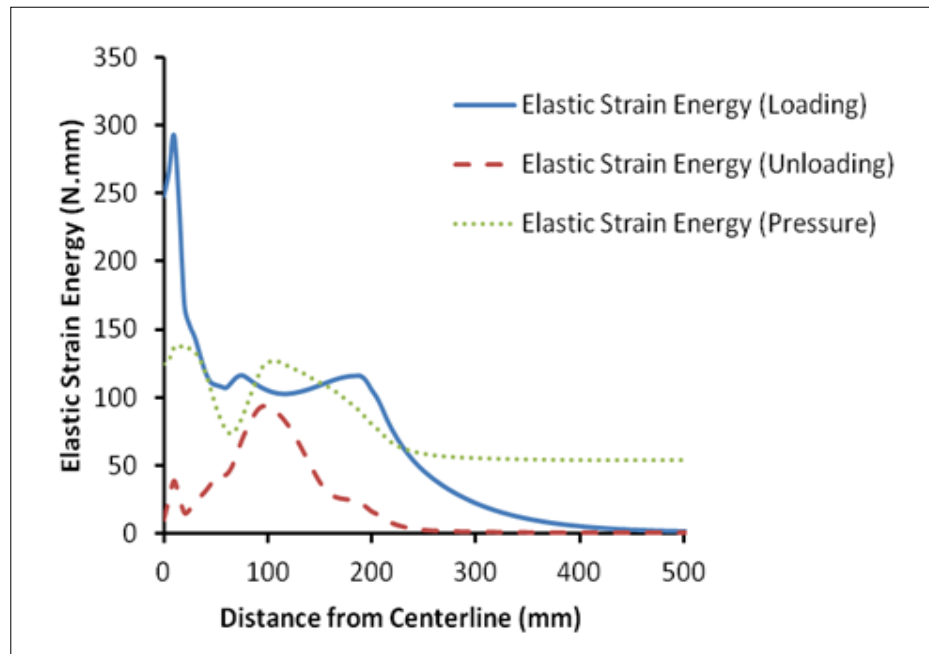


Figure 4-16 : Longitudinal distribution of elastic strain energy (D/t = 80, ID/OD = 10)

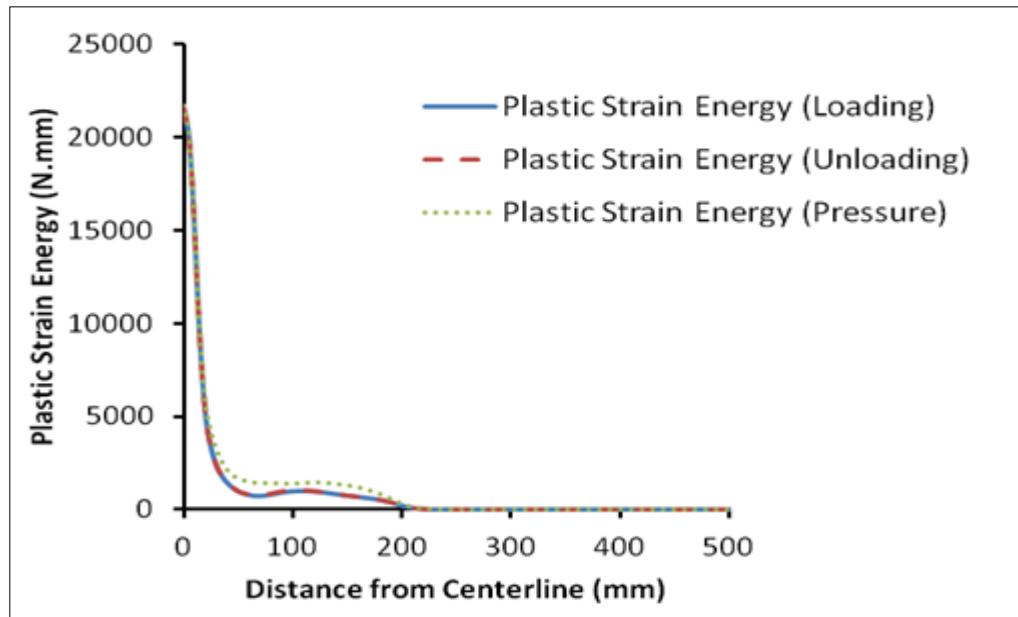


Figure 4-17 : Longitudinal distribution of plastic strain energy ( $D/t = 80$ ,  $ID/OD = 10$ )

#### 4.6.5 Pipe Ovality

Pipe section ovality was examined and defined as maximum difference between the smallest and largest diameter that exists at a given cross section. Equation (4.2) provides pipe ovality basic relationship followed by a graphical illustration in Fig. 4-18:

$$\omega = \frac{D_{max} - D_{min}}{D_{nom}} \times 100 \quad \text{Eq. (4.2)}$$

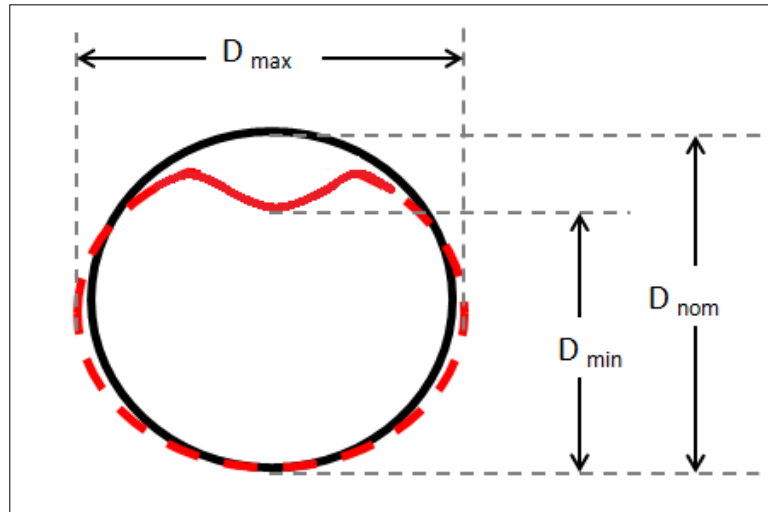


Figure 4-18 : Dimensional changes due to indenter application

For the purpose of analysis, pipe ovality is referred to as the degree of ovalization that was observed during different load steps, i.e. during and after indentation phase, followed by initial re-rounding for zero internal pressure indentations. During initial indentation, the ovality tends to increase with increasing  $D/t$  ratios as a function of  $ID/OD$  ratio. This is due to local pipe deformation and global pipe response where pipe diameter tends to decrease to a maximum extent in the indentation direction ( $D_{min}$ , Fig 4-18) and increase radially ( $D_{max}$ , Fig 4-18). The ovality tends to increase with increasing  $D/t$  ratios as lesser stiffness is offered by pipes with higher  $D/t$  and thus the pipe tends to expand more along horizontal axis and reduces more vertically (Fig 4-18). However, during unloading and pressurized phases, an inverse relation is observed between  $D/t$  and ovality. This is related to internal pressure effects where pipes with higher  $D/t$ , under pressure, tend to decrease their radial dimensions due to more re-rounding and wall flexing at indentation points, thus increasing  $D_{min}$  and decreasing  $D_{max}$ . It should be noted that for displacement

controlled loading,  $D_{min}$  stays the same for all  $D/t$  and  $ID/OD$  ratios during indenter application phase due to imposed displacement constraint (i.e. indenter travel distance). Therefore, care must be taken while interpreting results for the cases where boundary conditions are load controlled. Figure 4-19 reflects the ovality trend observed for initially zero pressured pipe after 80% SMYS pressure application phase.

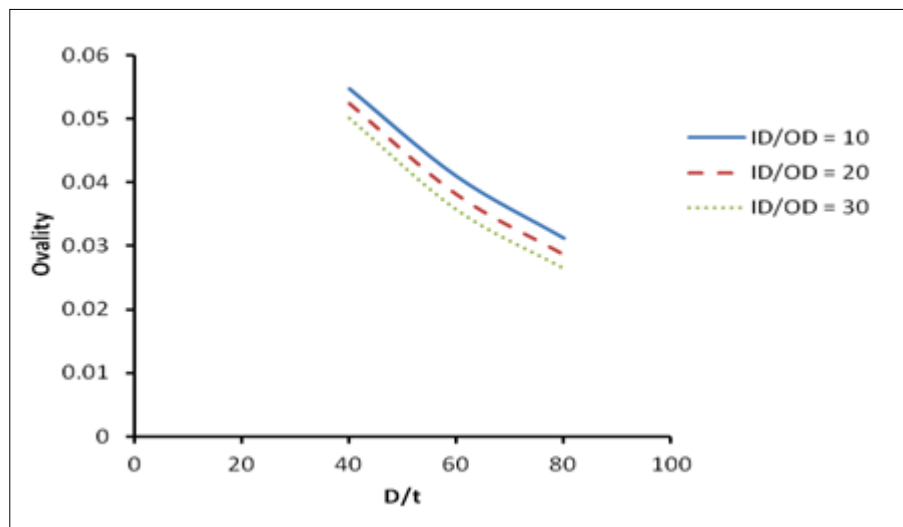


Figure 4-19 : Ovality Comparison for Zero Pressure Indentations as a function of ID/OD

#### 4.7 Concluding Remarks

Numerical modelling procedures have been developed and calibrated to simulate the pipe mechanical response for unconstrained and constrained plain smooth dents. A parametric study was conducted to examine the effect of pipe diameter to wall thickness, indenter to pipe diameter and hoop stress due to internal pressure to yield strength ratios.

The  $D/t$  and  $\sigma_h/\sigma_y$  ratios had significant effects on the dent elastic and inelastic re-round depths, with no significant influence from the  $ID/OD$  ratios. Indenter load-deflection response was studied and it was observed that pipes with lower  $D/t$  ratios, due to lower bending stiffness, offered less load values than thick walled pipes for same indentation depths. Study on pipe ovality helped in drawing the conclusion that pipe ovality is a strong function of  $D/t$  ratios and possesses a weak relation with  $ID/OD$  ratios. Ovality trends tend to change during varying load scenarios due to significant dimensional changes.

Effects of boundary conditions were also analyzed and it was observed that boundary conditions had significant effects on 1) dent rebound and re-round depths and 2) pipe load-deflection response. The effects of boundary conditions were found consistent with earlier work done (Hanif and Kenny, 2012).

Areas of uncertainties for developing modelling procedures were also highlighted and it was concluded that more refined numerical predictions could be made by 1) utilizing coupon data for constitutive stress-strain relationships, 2) incorporating integrated effects of pipe geometric imperfections due to manufacturing processes and residual stresses due to heat affected zones and 3) reporting and replicating true boundary conditions used for physical testing.

The results from this investigation and a recent calibration study (Hanif and Kenny, 2012) have demonstrated confidence in the numerical procedures developed. The sensitivity analysis presented in these studies has demonstrated the observed discrepancies between

the physical tests and numerical simulations, which can be attributed to the lack of reporting on key parameters, test conditions (e.g. kinematic boundary conditions, initial pipe ovality at the location of the dent and stress-strain relationship) and data uncertainty. Furthermore, the numerical simulation procedures used in these studies were found consistent with third-party numerical simulations. These observations suggest data uncertainty to be the key issue rather than model uncertainty and the numerical modelling procedures.

#### **4.8 Acknowledgements**

The authors would like to acknowledge the Wood Group Chair in Arctic and Harsh Environments Engineering at Memorial University of Newfoundland for sponsoring the research project. The authors would also like to thank Research and Development Corporation of Newfoundland and Labrador (RDC) for providing supporting funds, the opportunity to conduct research and publish the findings of the project is greatly appreciated.

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## **5 MECHANICAL INTEGRITY AND DEFECT ASSESSMENT OF OFFSHORE PIPELINE SYSTEMS USING FINITE ELEMENT MODELLING**

This paper has been published in the proceedings of 6<sup>th</sup> International Pipeline Technology Conference, Ostend, Belgium, 2013. As the principal investigator and first author, the author of this thesis was responsible for conducting the numerical investigation, analyzing the data, and reporting it inside this paper. The second author, Dr. Shawn Kenny, was responsible for supervision of the investigation and guidance on data analysis. It is to be noted that ID/D terminology is used in this paper instead of ID/OD, however both the terminologies reflect the same ratio, i.e. indenter diameter to pipe diameter ratio.

Authors: Waqas Hanif and Shawn Kenny

### **5.1 Abstract**

Onshore and offshore pipelines may be subjected to mechanical damage during installation and operation due to environmental loads, external forces and third party interference. Pipelines in offshore environment may be prone to mechanical damage from events such as ice gouging, frost heave, and seismic fault movement. Damage mechanisms can be associated with deformation or metallurgical/metal loss that may include pipe dent, pipe ovality, ice gouging, pipe buckling, corrosion etc. The type and severity of pipe damage may influence operational, repair and intervention strategies.

For conventional pipelines, the assessment of mechanical damage plays an important role in the development of integrity management programs that may be of greater significance for pipeline systems located in remote harsh environments. This study examines the effect

of dents on pipe mechanical response using continuum finite element methods. ABAQUS/Standard (v 6.10-1) software was used to simulate damage events and pipe response. Modelling procedures developed and calibrated against physical test results and numerical data sets available in public domain were reported previously in Hanif & Kenny 2012, 2013. Once confidence in numerical procedures was achieved, an analysis model matrix was established to account for a range of influential parameters including indenter shape, diameter to wall thickness ratio, indenter diameter to pipe diameter ratio, indenter travel to pipe diameter ratio, hoop stress due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ), and kinematic boundary conditions. A nonlinear multivariate regression analysis was conducted to establish parametric relationships that characterize the effects of local damage and applied loads on the pipeline mechanical response to relate output variables with practical measured variables

## **5.2 Introduction**

Pipeline systems are an integral component of the subsea infrastructure for transportation of oil and gas resources from the field development regions to market. Due to the remote location and harsh physical subsea environment, there are technical challenges and constraints on engineering design, operations and maintenance that influence decisions for maintaining pipeline integrity and safety. With a good safety record, pipelines are considered to be an efficient mode of oil and gas transportation for both on and offshore environments. However, just like any other engineering structure, there is always risk involved and there have been reported cases in which pipelines have failed (MMI, 2008).

Pipelines in offshore arctic environment may experience damage (e.g. dent, gouge) during handling, installation and normal operations due to external interference from natural (e.g. large deformation ground movement) or anthropogenic (e.g. anchor dragging, trawl gear interference) events. In ice environments, pipelines may be prone to mechanical damage from events such as ice gouging. The type and severity of offshore pipe damage may influence operational, repair and intervention strategies. Assessment of mechanical damage plays an important role in the development of integrity management programs that may be of greater significance for pipeline systems located in remote harsh environments due to remote location and logistical constraints.

Pipe mechanical damage can be characterized as local physical features; such as a dent, gouge, groove or surface crack, resulting in a stress concentration or strain localization that may affect pipeline integrity. The outcome may be immediate loss of product containment (e.g. leak, rupture), delayed effects resulting in pipe failure and burst (e.g. coating damage with corrosion mechanisms) and fatigue life degradation (e.g. local defect subjected to cyclic loads). Current engineering guidelines and practices (e.g. ASME B31.8, ASME B31.4, CSA Z662 and DNV OS-F101) recognize mechanical damage as a design issue but they do not provide explicit methods for assessment. The key engineering parameters influencing the dent formation and pipe integrity response include pipe diameter and wall thickness, pipe internal pressure, pipe elastic and plastic strength properties, loading path (e.g. indenter force, internal pressure), dent depth (i.e. amplitude), dent width (i.e. lateral extent, indenter shape), local radius of curvature (i.e.

dent type), and kinematic boundary constraints (i.e. constrained, unconstrained). This may result in reduced strength capacity (i.e. utilization) and fatigue life (i.e. useful life).

Over the past four decades, the effects of mechanical damage on pipeline integrity have been examined through a number of studies (e.g. Cosham and Hopkins, 2003; Fowler, 1993; Hagiwara and Oguchi, 1999; Hart *et al.*, 1998; Hope *et al.*, 1995; Hyde *et al.*, 2011; Ironside and Carroll, 2002; Leis and Hopkins, 2003; MSL, 2000; Rosenfeld, M.J., 1998; Roovers *et al.*, 2000; Stevick *et al.*, 1998). The main outcome has been general characterization of the damage severity (e.g. dent depth) with semi-empirical acceptance criteria used to assess the effects of dents and gouges on pipe mechanical integrity. However, uncertainty on such engineering guidance and studies has also been witnessed with poor correspondence between predictions and observations also reported (Cosham and Hopkins, 2004).

Reliable engineering tools with predictable outcomes are needed to assess the need, scope and requirements for any potential mitigation and intervention activities that may have bounding constraints associated with schedule (e.g. limited seasonal access) and logistics (e.g. pipeline excavation, repair and re-burial). With limited engineering guidance and greater uncertainty for predicting mechanical response of lone defects and interacting defects; such as dent feature interacting with girth weld or dent-gouge interaction and their corresponding effects on pipe integrity (Cosham and Hopkins, 2003, 2004; MSL, 2000), a program of research has been engaged to advance numerical modelling

procedures and engineering design tools for evaluation of defects on pipeline mechanical integrity with respect to strength utilization assessment and high cycle fatigue life.

The paper is the continuation of the series of papers (Hanif and Kenny, 2012, 2013) aimed at providing engineering guidance on dents and imperfections (metal loss and pipe ovality) and their interaction with girth weld under cyclic pressure loading. Dents interacting with girth welds, and the resulting stress and strain fields were discussed and analyzed in an earlier publication (Hanif and Kenny, 2012). Numerical modelling procedures developed in recent calibration studies (Hanif and Kenny, 2012, 2013), have demonstrated confidence in the developed tool. Generated models were calibrated against physical tests and numerical models available in public domain (Alexandar and Kiefner, 1997, 1999, BMT 2007, Bolton *et al.* 2008, Tiku *et al.* 2012). Once confidence in developed tool was established, a finite element model matrix was generated to account for a range of influential parameters including varying indenter shape (spherical, long dome, thin elongated), diameter to wall thickness ratio, indenter diameter to pipe diameter ratio, indenter travel to pipe diameter ratio and hoop stress due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ). Comparison of displacement field, load-deflection, ovality variation and strain response is presented and analyzed. A numerical parameter study was carried out across a range of non-dimensional parameters for practical design conditions. Results generated from model matrix were then used to perform nonlinear multi-variate regression analysis in Matlab and Design of Experiments software. Regression analysis was done to establish parametric relationships that characterize the effect of local damage and applied loads on the pipeline mechanical response to relate output variables; such as

displacement, strain and stress concentration, with practical measured variables. Closed form expressions relating output variable to different dent and pipe geometries were developed separately for indentations with zero internal pressure and indentations made at 80% SMYS internal pressure conditions. Results from this study would provide a basis to support a broader initiative for developing an engineering tool for the assessment of damage interaction with pipeline girth welds and development of an engineering performance criterion.

### **5.3 Numerical Model**

#### ***5.3.1 Overview***

The investigations conducted by American Petroleum Institute on the mechanical integrity of liquid petroleum pipelines (Alexander and Kiefner 1997, 1999) and BMT Fleet (BMT 2007, Bolton *et al.* 2008, Tiku *et al.* 2012) were used as bench marks to calibrate the developed model. Calibration procedures and research outcomes on constrained and unconstrained dents and their interaction with girth welds were published in Hanif & Kenny 2012, 2013. As discussed by Hanif and Kenny (2012), numerical models for unconstrained dents were generated and calibrated against physical tests (Alexander and Kiefner 1997, 1999, Tiku *et al.*, 2012). For constrained dent conditions, physical tests conducted by BMT Fleet (Bolton *et al.* 2008) were used for calibration purpose. Excellent correspondence was achieved between numerical procedures and physical tests. Once numerical calibration was achieved, the approach was then carried



forward to develop a finite element model matrix that accounts for a range of operational parameters coupled with varying dent shapes, indentation depths and pipe geometries in order to study their effects on mechanical integrity of pipelines.

### 5.3.2 Model Matrix

Based on the calibrated modelling procedures developed for constrained and unconstrained dents (Hanif and Kenny 2012, 2013), the approach was carried forward to study the effects of varying indenter shapes, indentation depths, pipe diameter to wall thickness ratios ( $D/t$ ), indenter diameter to pipe diameter ratios ( $ID/D$ ) and hoop stress due to internal pressure to yield strength ratio ( $\sigma_h/\sigma_y$ ). A model matrix was generated (Table 5-1) to examine dent profiles and stress/strain fields in close proximity of the pipe dent.

Table 5-1 : FEA Model Matrix

Indenter Shape	Indenter Diameter (ID - %D)	D/t	Indentation Pressure (% SMYS)	Indentation depths (d - %D)
Spherical	10%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10
	20%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10

Indenter Shape	Indenter Diameter (ID - %D)	D/t	Indentation Pressure (% SMYS)	Indentation depths (d - %D)
Spherical	30%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10
Long Dome	10%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10
	20%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10
	30%	40	0	5, 10
			80	5, 10
		60	0	5, 10
			80	5, 10
		80	0	5, 10
			80	5, 10
Thin Elongated	10%	40	0	5,7.5,10
		60	0	5,7.5,10
		80	0	5,7.5,10
	20%	40	0	5,7.5,10
		60	0	5,7.5,10
		80	0	5,7.5,10
	30%	40	0	5,7.5,10
		60	0	5,7.5,10
		80	0	5,7.5,10

Spherical and long dome indenters were penetrated upto 10%  $D$  indentation depths for both zero pressure and pressurized loading scenario. For spherical and long dome

indenter shapes, indentation depths upto 20%  $D$  under zero pressure conditions were also targeted, however due to localized excessive plastic strain, some of the simulations were terminated and therefore were not considered in the model matrix. Convergence issues due to excessive localized strain restricted the thin indenter upto 10%  $D$  indentation depths for zero pressure conditions. For pressurized conditions indentation depths upto 2.5%  $D$  were achieved and hence were not considered in regression analysis as described later in the paper.

### ***5.3.3 Indenter Types***

Indenters were modelled as rigid bodies using 4 node rigid elements R3D4. Three different type of indenter shapes were looked into that included 1) hemispherical shape 2) long dome shape and 3) thin elongated shape. Indenters were designed in such a way that the local radius of curvature at the point of contact with pipe was kept to be consistent for ease of comparison purpose. The indenters used are illustrated in Fig 5-1.

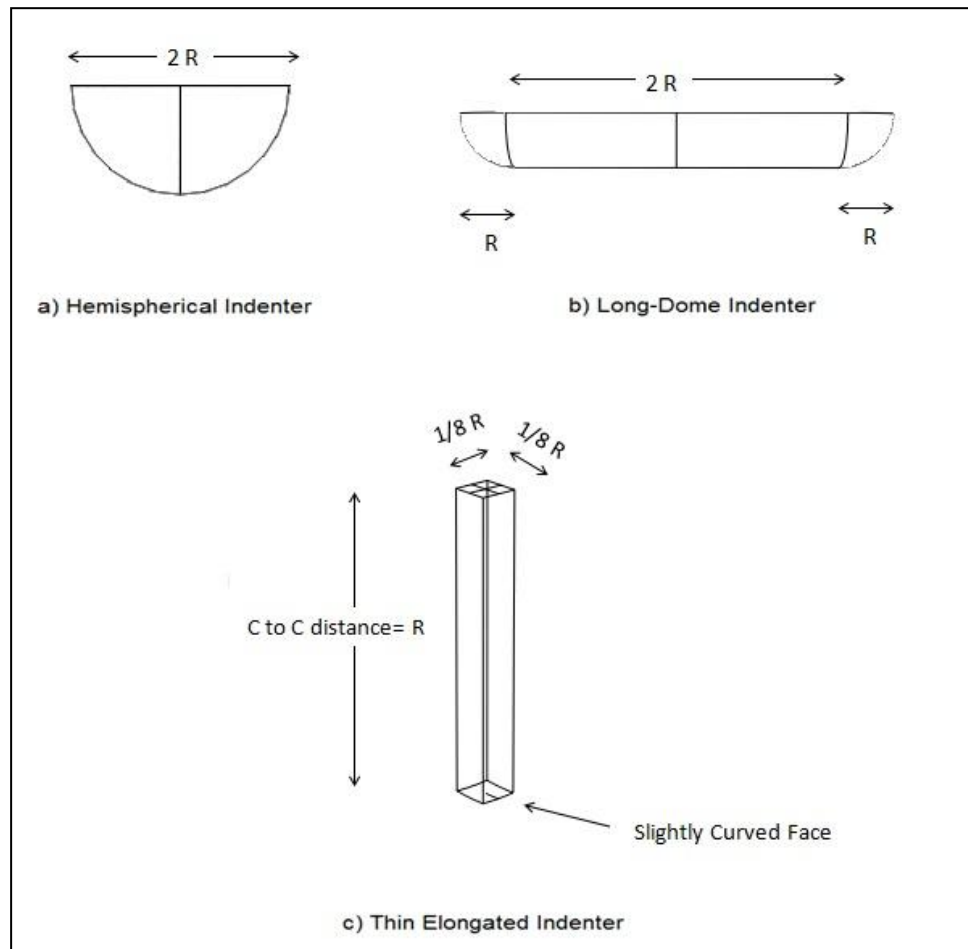


Figure 5-1 : Different indenter shapes used for FEA analysis

#### 5.3.4 Model Details and Boundary Conditions

In this study, numerical modelling procedures were developed to simulate formation of surface dents in a pipe by a rigid indenter on one quarter of pipe segment that utilized symmetrical geometry, loading and boundary conditions. Numerical modelling procedures were developed for pipe grade 450 MPa (X-65) having a nominal diameter of 609.6mm (24"). Length of the pipe was selected as 14 OD (modelled as 7 OD due to

symmetrical conditions). This particular length was selected after performing a sensitivity study to check for edge effects. The pipe dent was formed as an unrestrained feature and the indenter shape was selected as either hemispherical, long dome or thin elongated with indentation depths varying in between 5% -10% D (based on indenter shape). The D/t and ID/D ratios were varied from 40 – 80 and 10% – 30% D, respectively. Dents were created for 2 different loading scenarios. The first case involved dent creation by translating the rigid indenter to target depth at zero internal pressure conditions. The second loading scenario involved dent creation on a pressurized pipe. Pressure equivalent to 80% SMYS was applied before indentation phase. The pipe was then indented under pressurized conditions and contact released. Initial geometric imperfections associated with manufacturing processes in the form of ovality were modelled based on DNV-OS-F101 (2010). Maximum ovality of 0.015D was incorporated in the model with maximum pipe dimensions kept in horizontal pipe axis (3-9 o'clock) for hemispherical and long dome indenter and in vertical pipe axis (12-6 o'clock) for thin elongated indenter. Elastic modulus of 200 GPa with a Poisson's ratio of 0.3 was used. Von Mises yield criterion with isotropic hardening was used and material anisotropy was ignored. Pipe material properties were defined as an elastic-plastic piece wise continuous relationship which was developed using Ramberg-Osgood relationship.  $\alpha$  was taken as 1.29 while n was set equal to 25.58 (Walker and Williams, 1995).

Based on earlier done sensitivity analysis on boundary conditions (Hanif and Kenny, 2012), line saddle support at 6 clock position was used to restrict pipe motion in vertical direction. Such boundary condition was used to replicate field conditions for surface laid

pipe with negligible soil embedment. Assuming the pipeline to be infinitely long, fixed pipe ends were modelled that restricted the pipe in axial direction. The pipe segment was modelled using 4-node, doubly curved, reduced integration S4R shell element. S4R elements are general purpose elements that are well suited for large strain and displacement analysis (ABAQUS v 6.9 EF documentation). The element size was kept to 5mm square in the indentation zone with decreasing mesh density up to 25mm square away from indentation site. For thin elongated indenter, mesh size was further reduced in indentation zone in order to better capture stress and strain fields. The indenter was modelled using R3D4 elements with smooth edges in order to avoid any sharp stress risers. In addition, a single node that was created at the bottom where the 2 plains of symmetry intersected, was restricted in all degrees of freedom (DOF) in order to impart numerical stability and avoid any rigid body motion. Figure 5-2 illustrates boundary conditions used for the study.

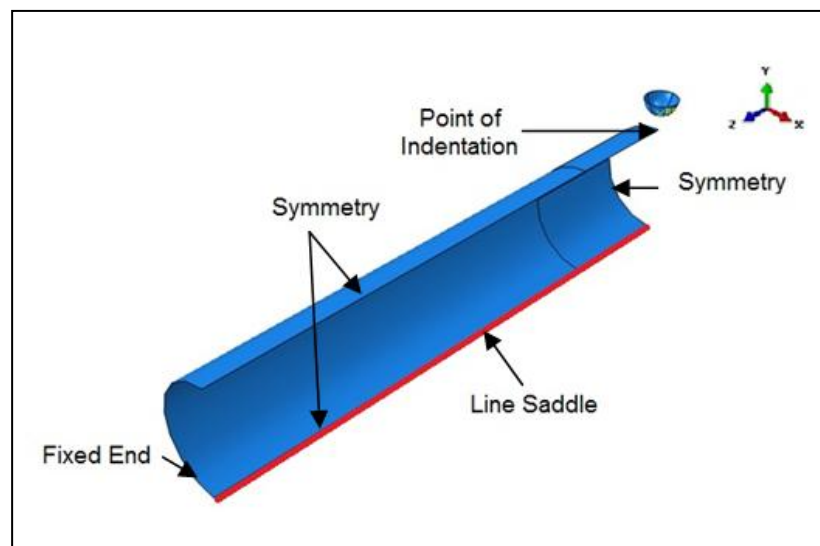


Figure 5-2 : Boundary conditions used for Finite element model

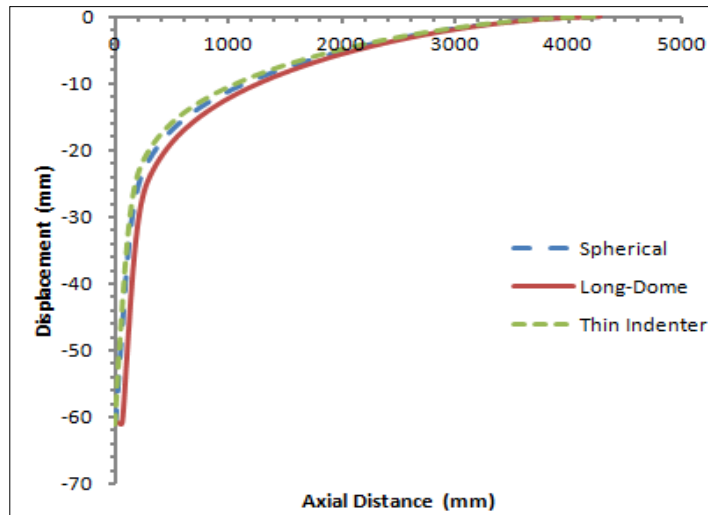
## 5.4 Results and Discussion

Results discussed in this section were used to develop regression equations as described in the section to follow. Axial and radial dent profiles were studied and their corresponding effect on displacement field is discussed. Pipe ovality and load-displacement plots for varying dent and pipe geometries were also looked into. For stress and strain measurements, elements in close proximity of indentation points were examined.

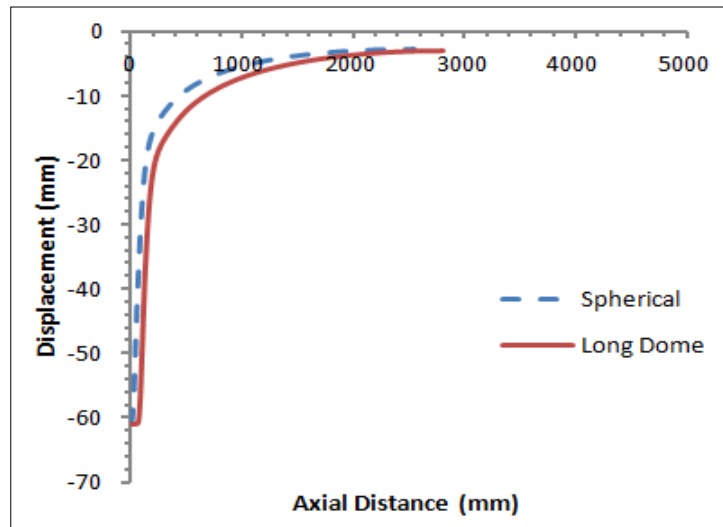
### 5.4.1 Displacement Field

Axial and radial dent profiles were studied for loading step for zero pressure and 80% SMYS pressure conditions. Consistent with Hanif and Kenny 2013, dent shoulder lengths for zero pressure indentations were found to reflect strong dependency on  $D/t$  ratio and a comparatively weak relation with  $ID/D$  ratios; dent shoulder lengths tended to increase with increasing  $D/t$  and  $ID/D$  ratios. This mechanical behavior is in response to greater pipe wall flexural compliance with increasing  $D/t$  ratios. Shoulder lengths also tend to change with changing indenter shapes (changing aspect ratios) with highest shoulder length occurring for long dome indenters and lowest reflecting to thin elongated indenter. For pressurized indentations, dent shapes along axial and radial centerline were also recorded during indentation phase. The shoulder lengths tend to slightly increase with increasing  $D/t$  and  $ID/D$  ratios, however the relation was not found to be as strong as for zero pressure indentations. This phenomenon could be attributed to stiffening effects

caused by internal pressure application. Figure 5-3 a) and b) illustrate typical axial dent profiles for varying indenter shapes for zero pressure and pressurized indentations respectively.



a)



b)

Figure 5-3 : Axial dent profiles for varying indenter shapes for a) Zero Pressure and b) 80% SMYS pressure conditions ( $ID/D = 20\%$ ,  $D/t = 80$ ,  $d/D = 10\%$ )



In order to better capture dent profiles with varying indenter shapes and depths, dent shoulder lengths were used in regression analysis in the form of axial and radial inflection points. These inflections points were calculated by applying tangents to axial and radial displacement plots separately. The point of intersection of the tangents and the corresponding axial distance was chosen to be as inflection point. Figure 5-4 illustrates the means of calculating inflection points.

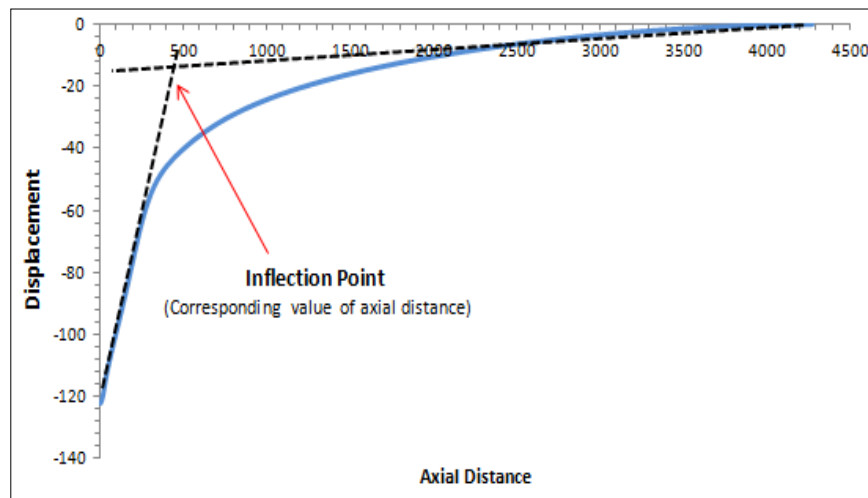


Figure 5-4 : Inflection point calculation for Spherical Indenter ( $ID/D = 20\%$ ,  $D/t = 80$ ,  $d/D = 20\%$ ) under zero pressure conditions

#### 5.4.2 Load - Displacement

The indenter load-displacement response for zero pressure and pressurized load cases were analyzed (Fig 5-5). It was observed that the stiffness decreased with increasing  $D/t$  ratio and the load-displacement relationship exhibited an initial elastic and secondary plastic response. The elastic response was associated with global pipe section ovalization,

whereas the plastic hardening response was associated with local deformation within the dent zone. In order to achieve same indentation depths for pressurized and unpressurized loading scenarios, the load values for pressurized cases triggered due to internal pressure stiffening effects, as illustrated in Fig 5-5. It was also observed that for zero pressure indentations, the load-deflection response was not influenced by the effect of  $ID/D$  ratio, unlike pressurized case where the load values to achieve same target depths, increased with increasing  $ID/D$  ratios. The results were found to be consistent with Hanif and Kenny (2013).

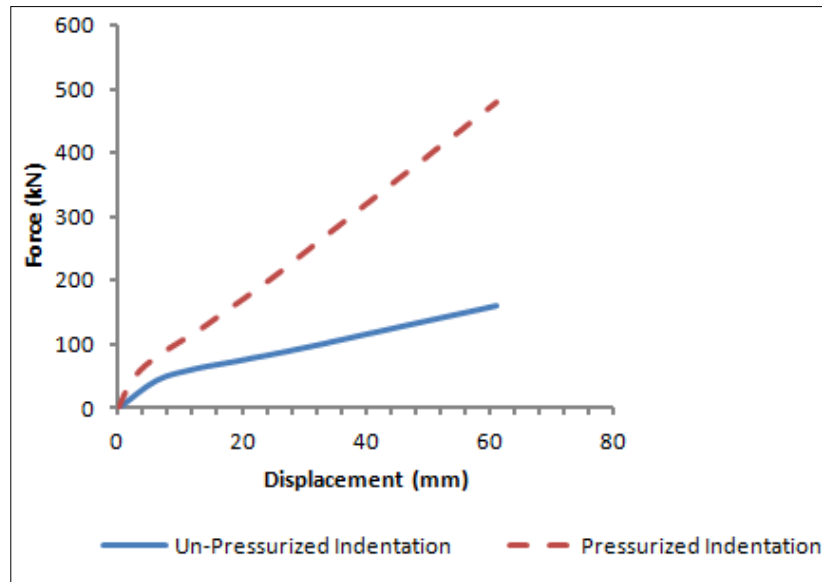


Figure 5-5 : Comparison of Load-Displacement plots for pressurized - unpressurized load case ( $ID/D = 10\%$ ,  $D/t = 80$ ,  $d/D = 10\%$  )

#### 5.4.3 Pipe Ovality

Pipe section ovality was examined at the end of loading phase and defined as maximum difference between the smallest and largest diameter that exists at a given cross section.

Equation (5.1) provides pipe ovality basic relationship followed by a graphical illustration in Fig 5-6:

$$\omega = \frac{D_{max} - D_{min}}{D_{nom}} * 100 \quad \text{Eq. (5.1)}$$

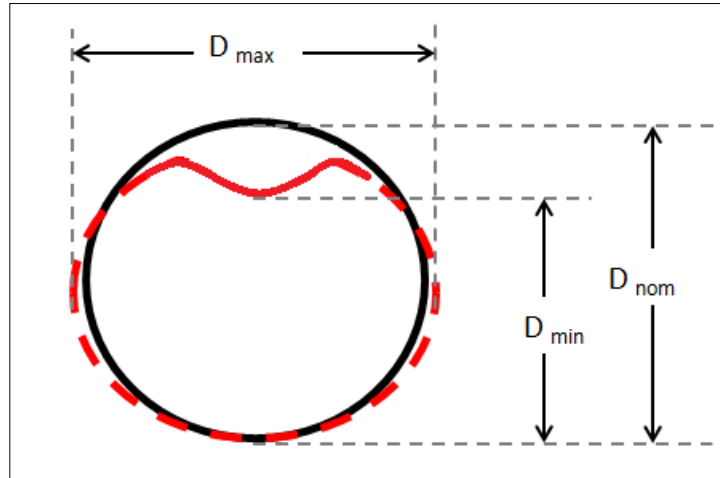


Figure 5-6 : Dimensional changes due to indenter application (Hanif & Kenny 2013)

For the purpose of analysis, pipe ovality is referred to as the degree of ovalization that was observed during indentation phase. During initial indentation, the ovality tends to increase with increasing  $D/t$  ratios as a weak function of  $ID/D$  ratio. This is due to local pipe deformation and global pipe response where pipe diameter tends to decrease to a maximum extent in the indentation direction ( $D_{min}$ , Fig 5-6) and increase radially ( $D_{max}$ , Fig 5-6). The ovality tends to increase with increasing  $D/t$  ratios as lesser stiffness is offered by pipes with high  $D/t$  values, thus causing the pipe to expand more along horizontal axis and reduces more vertically (Fig 5-6). As expected, increase in indentation depths ( $d/D$  ratios) caused more dimensional changes and resulted in enhanced ovality

values (Fig 5-7). It is to be noted that for pressurized loading case, stiffness effects due to internal pressure oppose pipe ovalization due to indenter application, which in turn results in less dimensional changes and ovality values. It should also be noted that for displacement controlled loading,  $D_{\min}$  stays the same for all  $D/t$  and  $ID/D$  ratios during indenter application phase due to imposed displacement constraint (i.e. indenter travel distance). Therefore, care must be taken while interpreting results for the cases where boundary conditions are load controlled. Figure 5-7 reflects the ovality trend observed for zero pressure and pressurized indentations.

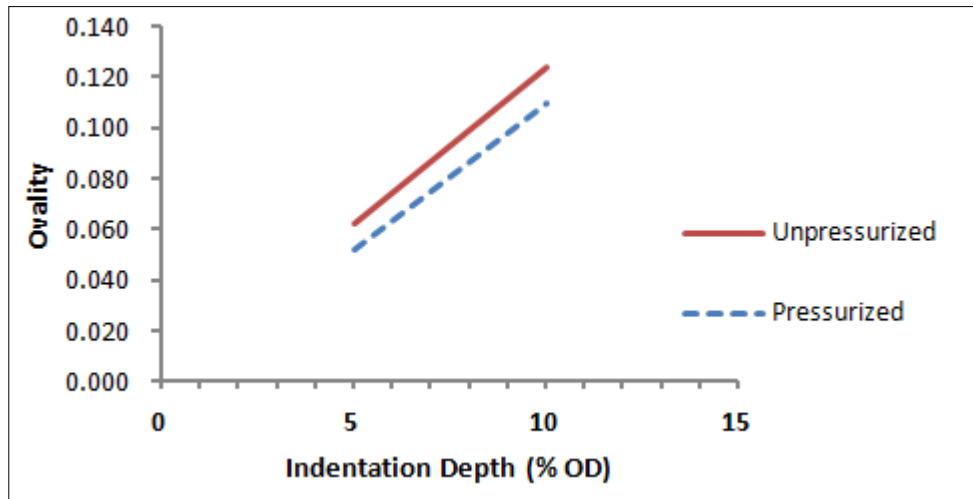


Figure 5-7 : Ovality variance for pressurized and unpressurized indentations with changing indentation depths

### 5.5 Regression Analysis

In order to make results from FEA analysis to be easily applied to practical dent problems, a multi-variate nonlinear regression analysis was conducted to derive mathematical formulae to output variables in terms of practically measured variables.

MATLAB was used to develop a code that took into account different parameters to perform regression analysis. Several possible parameters were investigated and were grouped in three categories; 1) material, 2) dent geometry and 3) loading. Parameters were selected and made non-dimensional in order to better analyze their effects. The analyzed parameters also took into account ring and shell bending stiffness due to indenter application; however parameters that affected the regression equations most are listed in table 5-2. Once set of non-dimensional parameters was generated, its significance was checked against the output variable. Non-dimensional parameters took into account pipe and dent geometry, dent axial and radial profiles and pressure loading conditions. Design – Expert 8 software was further used to check interactions between different non-dimensional parameters. 2 different set of equations were developed that accounted for varying indenter shapes and pressure conditions. For unpressurized indentation case, all 3 indenter shapes and indentations of 5% and 10% D were taken into consideration. For pressurized loading scenario, convergence issues restricted the thin indenter upto indentation depths of 2.5 % D. This resulted in exclusion of sharp dent profiles from the equation and limited it to hemispherical and long dome indenters with indentation depths of 5% D and 10% D.

Table 5-2: Non Dimensional Parameters

<b>Non Dimensional Parameter</b>	<b>Parameter Classification</b>
$D/t$ ratio	<b>Pipe geometry parameter</b> Pipe diameter to wall thickness ratio.
$d/D$ ratio	<b>Dent geometry parameter</b> Indenter travel as a percentage of pipe outside diameter to define peak dent value.
$L/d$ ratio	<b>Dent geometry parameter</b> Ratio of indenter length to penetrated depth
$La/D$ ratio	<b>Dent geometry parameter</b> Axial inflection point to pipe diameter ratio
$Lr/D$ ratio	<b>Dent geometry parameter</b> Radial inflection point to pipe diameter ratio
Pipe Ovality	<b>Pipe and Dent geometry parameter</b> Ratio of pipe dimensional changes to pipe nominal diameter
$\sigma_h/\sigma_y$	<b>Operational parameter</b> Ratio of hoop stress due to internal pressure to yield strength

### 5.5.1 Zero Pressure Indentations

Zero pressure indentations gave more flexibility and data points to perform regression analysis. For ease of calculation and to consider consistent depths for all 3 indenter shapes, results for indentations of 5% D and 10% D were used to perform regression analysis. The equation utilized non dimensional parameters for both predictor and response variables. Equation 5.2 provides a nonlinear relationship between equivalent plastic strain and the generated non dimensional parameters.

$$\epsilon_{eqv} = 0.9 - 0.06 \left(\frac{L}{d}\right) - 0.008 \left(\frac{D}{t}\right) + 1.9 \left(\frac{La}{D}\right) - 2.77 \left(\frac{Lr}{D}\right) + 1.12(\omega) - 11.56 \left(\frac{d}{D}\right) \left(\frac{La}{D}\right) + 1.61 e^{-4} \left(\frac{Lr}{D}\right) \left(\frac{D}{t}\right)^2$$

Eq.(5.2)

The equation was developed against a set of 54 simulations covering a range of pipe and dent geometries (Table 5-1). Histogram plot for residuals, that characterizes the difference between observed and predicted values, was generated and it was observed that the residuals (error terms) complied with normal distribution with on significant discrepancy. A useful statistic to measure the quality of the regression analysis is Cook's distance that characterizes data points with potential leverage and influence on the regression solution, and can be used to identify outliers in the observations. Cook's distance plot was evaluated which exhibited no outliers. It is to be noted that observations with a Cook's distance larger than three times the mean Cook's distance could be considered as an outlier. In this study the mean Cook's distance is indicated by a dashed line in the Cook's distance plot as illustrated in Fig 5-8.

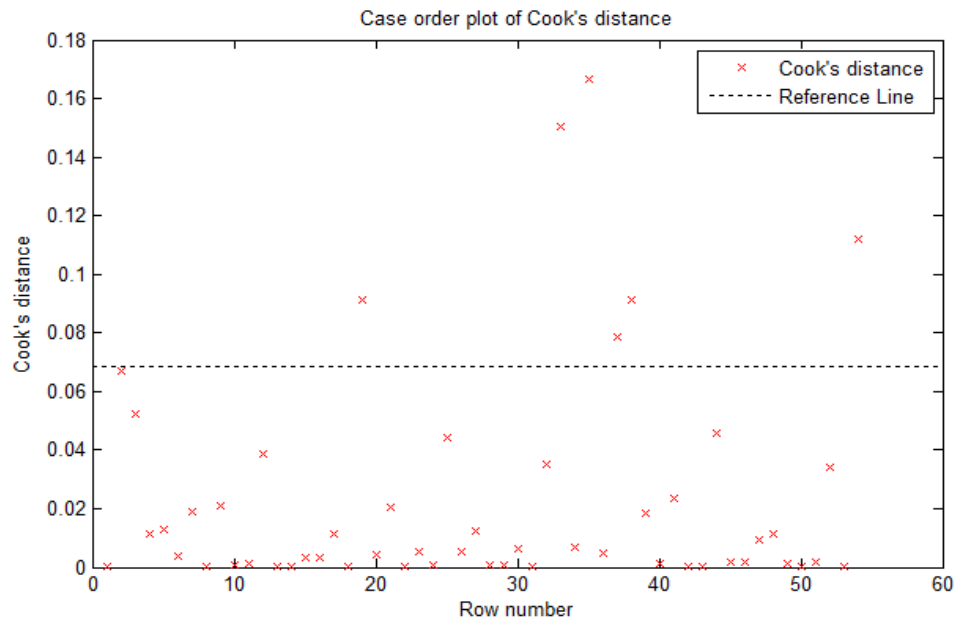


Figure 5-8 : Cook's distance plot for unpressurized loading scenario

Relationship between response-predictor engineering tool and the finite element analysis data is illustrated in Fig 5-9. Good correspondence between the engineering design tool and the source data based on the parameter study using finite element methods was observed.

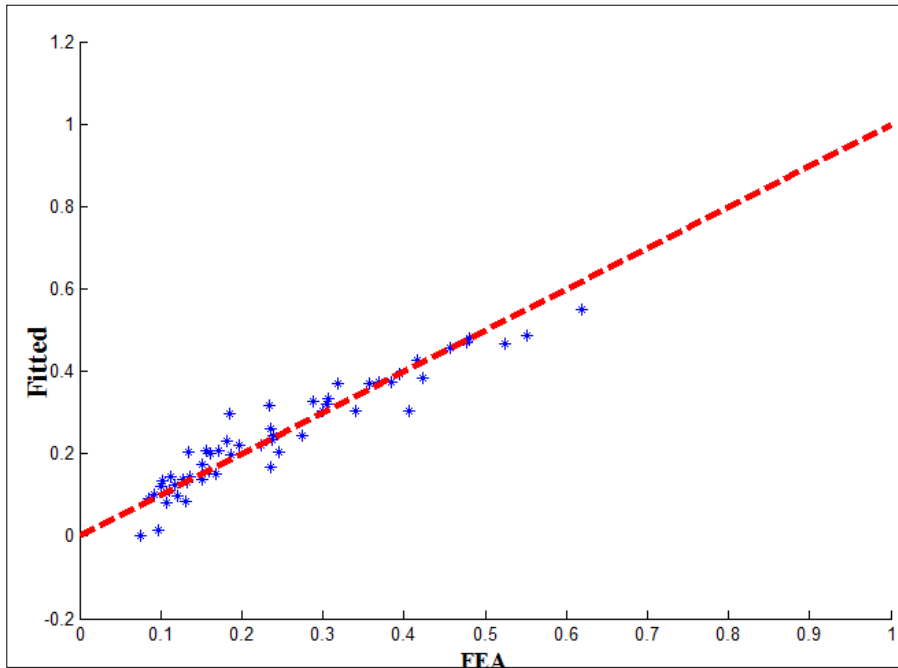


Figure 5-9 : Relationship between predicted and FEA values for unpressurized loading case

To check the quality of the engineering tool (Equation 5.2), 9 simulations for thin elongated indenter corresponding to indentation depths of 7.5%D for varying D/t (40 – 80) and ID/D (10%D – 30%D) ratios were selected. This extrapolation was done to see how well the equation extrapolates the results for varying indentation depths, D/t and ID/D ratios. Results from FEA were generated and plotted against the predicted values using Equation 5.2. As illustrated in Fig 5-10, good correspondence was achieved between observed and predicted values.



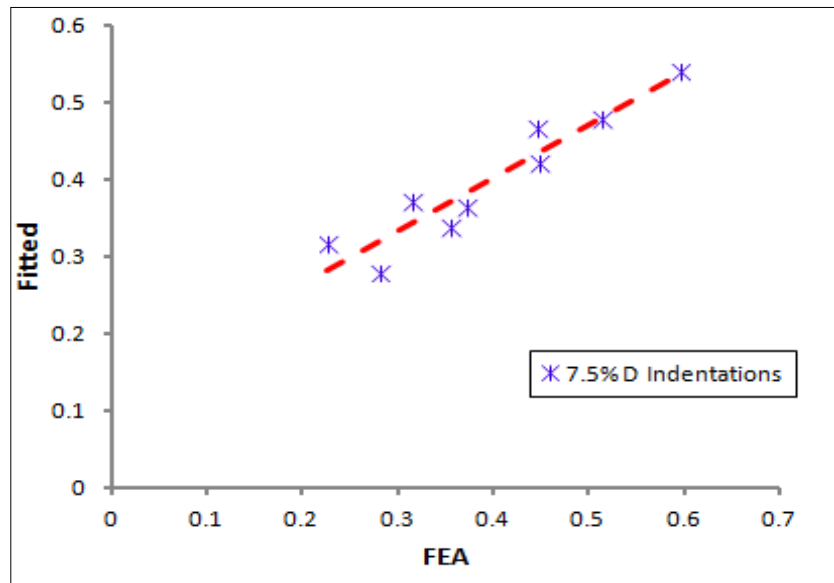


Figure 5-10: Relationship between predicted and FEA values for 7.5%D indentation depth

For the above stated reasons, backed up with decent R squared value of 0.91, confidence in the form of defined engineering tool for zero pressure indentations (Equation 5.2) was established.

### 5.5.2 Pressurized Indentations

For regression analysis of pressurized indentations (80% SMYS), 34 cases were studied for spherical and long dome indenters corresponding to indentation depths of 5% D and 10% D for varying  $D/t$  (40 – 80) and  $ID/D$  (10% D – 30% D) ratios. Thin elongated indenter was not taken into consideration for pressurized loading scenario due to convergence issues that rose due to stiffness effects by internal pressure application. The

developed equation utilizes non dimensional parameters for predictors and response variable. As given below, Equation 5.3 provides the relationship between equivalent plastic strain and the generated non dimensional parameters.

$$\epsilon_{eqv} = 0.77 - 0.12 \left( \frac{L}{d} \right) - 0.006 \left( \frac{D}{t} \right) - 0.69 \left( \frac{La}{D} \right) \left( \frac{\sigma h}{SMYS} \right)^2 + 9.2 e^{-5} \left( \frac{La}{D} \right) \left( \frac{D}{t} \right)^2 + 0.014 \left( \frac{L}{d} \right)^2$$

Eq. (5.3)

The equation was developed against a set of 34 simulations covering a range of pipe and dent geometries (Table 5-1). Histogram plot for residuals and Cooks distance were generated and analyzed. For histogram plots, no significant discrepancy was observed and the residuals complied with normal distribution. Cook's distance plot was also evaluated which exhibited one outlier (corresponding to spherical indenter, ID/D 10%, d/D 10%, D/t 40) for which the cook's distance was found to be larger than three times the mean Cook's distance. Figure 5-11 illustrates the Cook distance plot with the outlier identified.

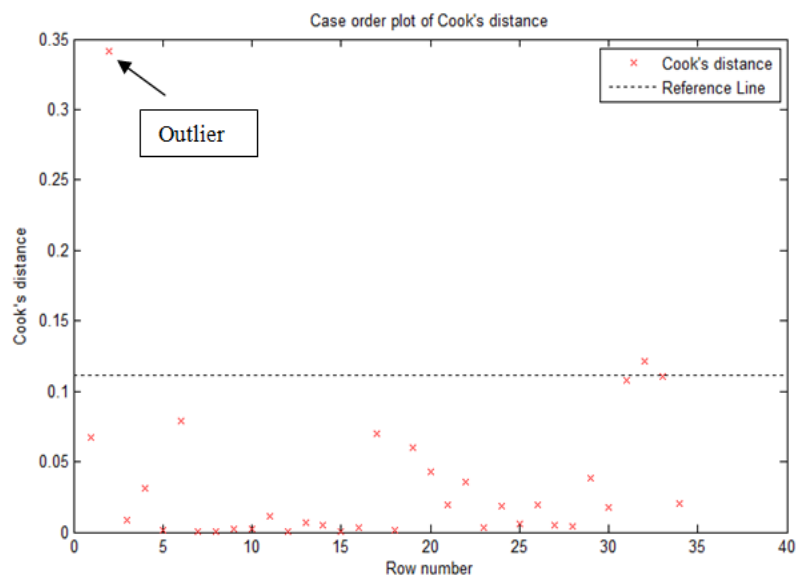


Figure 5-11 : Cook's distance plot for pressurized loading scenario

Relationship between response-predictor engineering tool and the finite element analysis data is illustrated in Fig 5-12. Like Equation 5-2, good correspondence was again achieved between the engineering design tool and the observed FEA values as illustrated in Fig 5-12.

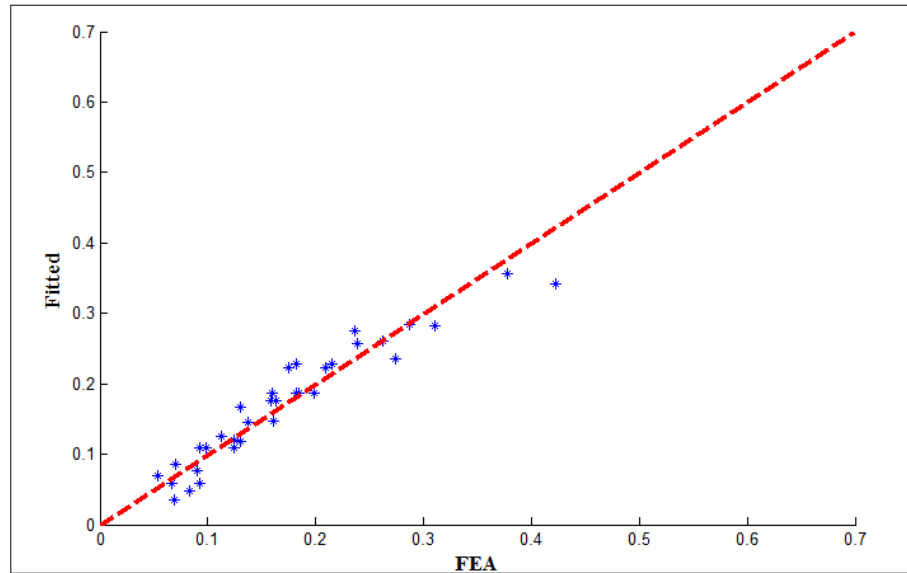


Figure 5-12 : Relationship between predicted and FEA values for pressurized loading case

For the above stated reasons, backed up with decent R squared value of 0.907, confidence in the form of defined engineering tool for pressurized indentations (Equation 5.3) was established. The developed equations can help in identifying any stress or strain concentration points that may have occurred due to dent application which can affect and reduce pipeline useful fatigue life under static and cyclic pressure loading.

## 5.6 Concluding Remarks

Numerical modelling procedures to simulate pipe mechanical response for unconstrained and constrained plain smooth dents were developed and calibrated previously against available literature (Alexander and Kiefner, 1997, 1999; BMT, 2007; Bolton *et al.*, 2008; Tiku *et al.* 2012) and reported in Hanif and Kenny (2012, 2013). The approach was taken forward and a numerical model matrix was established to account for a range of dent and pipe geometries for parametric study. The main intent was to develop closed form expressions through regression analysis that could efficiently predict response variable, taking into account geometric imperfections in the shape of pipe ovality that are inherited due to manufacturing processes. Separate engineering tools (in the form of equations) were developed for zero pressure and 80% SMYS pressure conditions. To measure the quality of regression analysis, various plots were analyzed and the equation was extrapolated to different indentation depths with varying dent and pipe geometry features, which reflected good correspondence between predicted and observed response variable values. The intent of developing such a tool was the ease of its practical application. Developed regression equations could be used by an end-user (e.g. pipeline operator) by feeding them into spread sheet. After pipe inspection is executed, the end-user would only need to input dent dimensions, pipe geometry and operating pressure conditions to get estimated values of plastic strain. Once the data is plugged in the spreadsheet, the dimensionless parameters would get multiplied to their corresponding regression coefficients to give estimated equivalent plastic strain values. Based on the code requirements issued by the local regulatory authority, the values generated through these

tools would then assist the end-user to make a decision of whether to tolerate the defect, to repair the pipe or to replace it.

## **5.7 Acknowledgements**

The authors would like to acknowledge the Wood Group Chair in Arctic and Harsh Environments Engineering at Memorial University of Newfoundland for sponsoring the research project. The authors would also like to thank Research and Development Corporation of Newfoundland and Labrador (RDC) for providing supporting funds. The opportunity to conduct research and publish the findings of the project is greatly appreciated.

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## 6 SUMMARY AND CONCLUSIONS

Pipelines installed in harsh arctic environment can get exposed to mechanical damage due to external interference from natural events (e.g. large deformation ground movement) or anthropogenic (e.g. anchor dragging, trawl gear interference) activities. These events and activities may result in large pipe deformations that result in localized pipe damage and the formation of regions with stress risers or strain concentrations. The presence of mechanical damage can significantly affect the pipe service life with respect to serviceability and ultimate limit state criteria. With limited engineering guidance and greater uncertainty for predicting the mechanical response of defects, a research effort was conducted to establish closed form expressions and numerical tools to predict pipe mechanical response (equivalent strain) subjected to damage events for varying load scenarios.

A literature review was conducted to assess the existing database of physical modelling and numerical simulations, engineering practices and design codes/standards for analyzing the effects of mechanical damage and defect interaction on pipeline mechanical performance and fatigue life. This task helped to identify the existing knowledge base, technology gaps and potential constraints that were used as foundation for the study and framework to develop the numerical modelling procedures.

Numerical modelling procedures were developed, within ABAQUS/Standard, to simulate the formation of dents on pipe segments that can be associated with mechanical damage events. Available physical data and third party numerical simulations (Alexander and



Kiefner 1997, 1999; BMT 2007; Bolton *et al.*, 2008, 2010; Tiku *et al.*, 2012) were used to calibrate the numerical modelling procedures, which demonstrated excellent correlation with these studies for different restraint conditions.

Based on the calibrated modelling procedures, a sensitivity analysis was conducted to indicate the significance of essential boundary conditions and presence of circumferential girth welds on the mechanical response of the dent features. The developed numerical model also highlighted areas where discrepancies exist. Once confidence in developed calibrated tool was achieved, a FE model matrix was generated that examined a range of pipe and indenter geometries, operating conditions, pipe imperfections, indenter shape configurations, and realistic boundary conditions. The significance of design parameters was assessed through a sensitivity study with developed numerical modelling procedures.

The key engineering parameters influencing the dent formation and pipe integrity response included pipe diameter and wall thickness, pipe internal pressure, pipe elastic and plastic strength properties, loading path (e.g. indenter force, internal pressure), dent depth (i.e. amplitude), dent length (shoulder length), dent width (i.e. lateral extent, indenter shape), local radius of curvature (i.e. dent type), pipe ovality and kinematic boundary constraints (i.e. constrained, unconstrained). Nonlinear, multivariate regression analysis techniques were performed to assess the results where rational engineering tools were developed that could be used to provide guidance on assessing the effects of localized damage on pipe mechanical response. In order to assess the efficiency of tools,

plots were generated for predicted strain values obtained through empirical tools against strain values extracted from FE analysis, results of which were found to be coherent.

The main outcome of the study was the contradiction with the depth based dent acceptance criteria as described in ASME B31.4 and B31.8. The research effort supported the studies conducted by Fowler *et al.* 1995 and Keating and Hoffmann 1997, that emphasized on considering rebounded dent depths and varying dent geometries if a depth based criterion was to be used. Based on the research outcomes, the current study also emphasized on the fact that depth based dent acceptance criterion is not considered safe and the need for a more improved accept/reject dent assessment approach is required. This proposition was used to develop empirical tools that took into account varying operational and geometric parameters in order to efficiently predict pipe mechanical response.

The developed empirical tools can provide design engineers, operators and regulatory authorities an efficient engineering framework to assess the effects of mechanical damage on pipe response. Based on the code requirements issued by the local regulatory authority, the equivalent strain values (in damaged zone) generated through these tools would then assist the end-user to make a decision of whether to tolerate the defect, to repair the pipe or to replace it. The tools could also provide a rational approach to assess damage events and assist in developing integrity management programs by identifying the potential maintenance activities and intervention and repair strategies. The conducted

study and the research outcomes, therefore, addressed a technology gap and fulfilled an existing industry need.

Future work can focus on validating the developed numerical model that could help to predict pipe mechanical response more efficiently. Laboratory tests could be conducted to establish the stress-strain relationships, including Bauschinger effects, nonlinear kinematic hardening and hysteretic behavior, that could be used to enhance the constitutive models used in the numerical simulation tool. Physical tests should be conducted on large-scale coupons with specified damage levels and full-scale pipe segments to examine the effects of mechanical damage, defect interaction on the structural response and fatigue life performance. The stated tasks can help in developing validated numerical model that can provide a technical basis to develop an engineering guidance document, addressing the characterization of mechanical damage, evaluation of the effects on pipeline mechanical behavior and estimation of the remaining fatigue life.

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