The Impact of Double Dents on Pipeline Integrity

By

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DECLARATION

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ABSTRACT

Pipelines are used for the transportation of various products across the world. Most of these pipelines are installed underground, which makes it harder to detect a failure or to repair the pipeline when it is damaged. A dent is defined as a plastic deformation in a pipeline which can turn into a threat by causing stress concentration, and as a result the pipeline may fail, which can result in safety, economic and environmental disasters. Guidance is therefore needed for operators to identify which dents could potentially be damaging to pipeline safety and to consider which dents require further action such as excavation or repairing.

Experimental research on dents on a pipeline has been made for decades. To understand the severity of such defects on pipelines, various methodologies related to dent assessment have been developed based on the results of experimental studies as well as Finite Element Analysis (FEA).

Although many studies have been conducted on a single dent defects, there is no published guidance or assessment methods to determine the severity of multiple dent defects when they are detected in pipelines because current assessment methods or published guidelines treat dents as isolated defect which does not consider interactions with each other. Understanding and predicting the behaviour of pipelines that are subjected to a multiple dents will require an assessment to determine how severe the effect could be.

Analysis was carried with three standard parameters; dent depth, effects of distance between the dents and effects of indenter diameters. The objective for this study is to create a Finite Element Model (FEM) to develop a parametric study to determine interaction effect of each dents considering the dent shape, distance between the dents and the effect of internal pressure.

DEDICATION

I would dedicate my work to my lovely wife for constant supporting in South Korea. It must have been hard for her to take care of our son by herself. It was not an easy decision for our family to be away from each other for a year. Also, I many thanks and love to my beloved son. His presence itself was an kiss of life to me.

Also appreciation to my parents, who have supported me with their full material and emotional support. Discussion with my dad, who is also a Naval Architecture and Marine engineer, have been very helpful when I was stuck in some problems.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Overview

The most widely used structures for long distance transportation of resources such as oil and gas are pipelines due to their efficiency and safety. They are sometimes referred to as "lifelines" because of their importance (Liu and Zhang, 2016(a)). Due to its importance, when failure occurs in a pipeline, it can lead to environmental damage and economic loss. Since a large percentage of pipelines are installed underground, defects caused by rocks under the pipe or mechanical damage such as external damage caused by excavator's teeth. This kind of damage is directly related to the pipeline's structural integrity. However, being underground prevents detection of damages in the pipeline immediately or when damages occur. In this regard, in cases when damage does not lead to failure immediately, it is possible that these undetected defects can grow under operation which can affect the structural integrity of the pipelines and eventually cause failure sometime after the initial impact (Cosham and Hopkins 2004).

UKOPA, United Kingdom Onshore Pipeline Operator's Association, published a report about pipeline incidents to provide specific data for pipeline incidents in 2018 (Goodfellow, 2018). In this report, UKOPA stated that excluding 'other' category, external interference and corrosion are the two most common causes of product loss incidents of pipeline in UK from 1962 to 2016 (Figure 1.1). External interferences refer to damages that come from outside forces or third-party impact, such as excavation damage, previously damaged pipe, damage by vehicles, etc. Failure classified as 'Other' are generally failure due to causes other than 'External interference', 'Corrosion', 'Material and construction' and 'Ground movement (due to earthquake or for other reasons)'. However 84% of incidents recorded as 'Other' relate to pipelines that are constructed before 1970 which are not designed and constructed based on current pipeline standards.

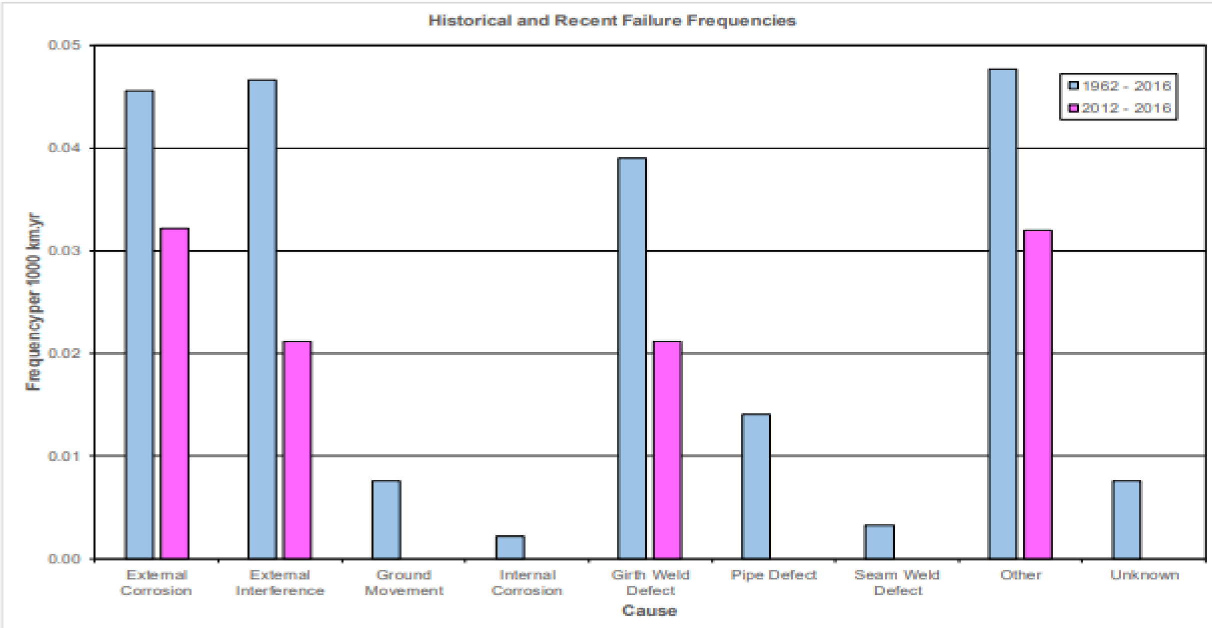


Figure 1.1 - Cause of incidents happened in transmission pipelines from 1962 to 2016 in UK (Goodfellow, 2018)

Although external interference and external corrosion causes less incidents year after year after 1970's, still they are the main causes of pipeline product loss incidents in last 5 years. Figure 1.2 shows the number of incidents in percentage that occurred in pipelines in this time period.

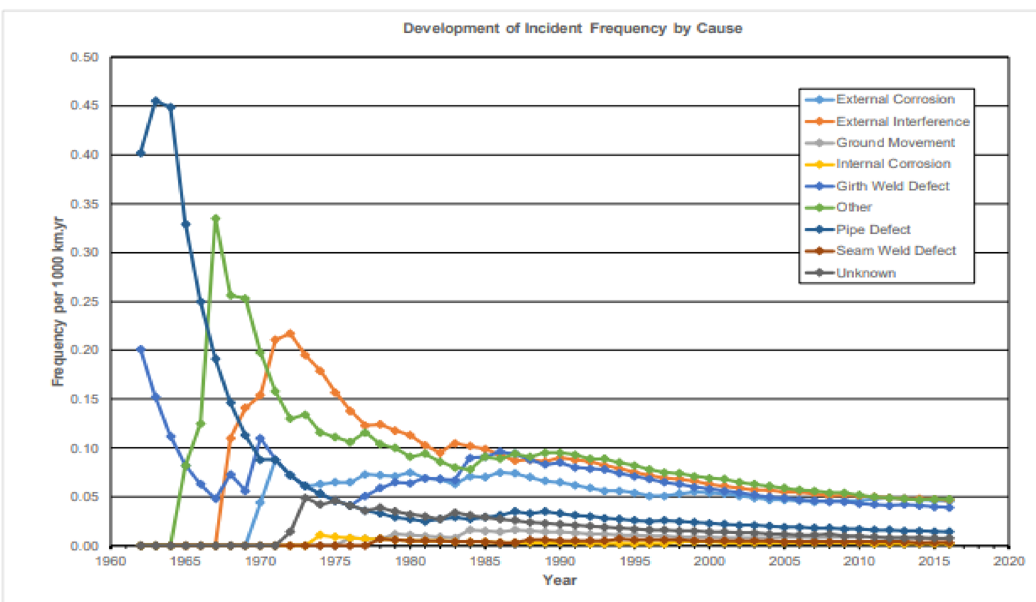


Figure 1.2- Product loss incident frequency by cause (Goodfellow, 2018)

Product Loss Cause	No. of Incidents	%age of Total
External Corrosion	42	21.3
External Interference	43	21.8
Ground Movement	7	3.6
Internal Corrosion	2	1.0
Girth Weld Defect	36	18.3
Pipe Defect	13	6.6
Seam Weld Defect	3	1.5
Other	44	22.3
Unknown	7	3.6
Total	197	100

Table 1.1- Product loss incident frequency by cause
Source: (Goodfellow, 2018)

Mechanical damage directly affects the integrity of pipeline by importing extra stresses and strains. Therefore, it is necessary to evaluate the state of stress of pipeline when it is exposed to mechanical damage to ensure it will be safe to operate.

1.2 Mechanical damage on the pipeline and definitions

Mechanical damage is terminology that refers to the damaged caused by third-party activities, which in pipeline industry mainly happens in excavation work, for example during pipeline lifting, stacking or laying. Al-Muslim (2010), classified mechanical damage in to four categories.

1) Dent with shape change in the pipeline cross section
2) Gouge with wall metal loss
3) Combination of Dent and gouge
4) Plain dent which does not have stress concentration but only shape change.

Furthermore, dents can be categorised on a basis of ability to move under pressure. Unconstrained dents are defined as able to re-round when pressurized whereas constrained dents are not free to re-round under pressure. Damages made during pipeline laying are usually classified as constrained as the indenter causing the dent is not removed. These kind of damage, such as dents on the bottom of the pipeline, however, are not considered fatal in general since the dent has survived the pre-service test and also is unable to move or change due to operating pressure. External interference, which is the highest cause of pipeline failures, mostly occurs on the upper part of the pipe (between the 8 o'clock and 4 o'clock positions). Dents caused by external interference are usually unconstrained, which allows them to flex or re-round due to changes of operating pressure. This type of dent is determined to be significant as they could also contain other defects like gouges or cracking. Generally, these kind of defects have to be dealt with immediate investigation and possible repair. In this regard, dent can be elaborated on a basis of ability to move under pressure.

Race (2008) summarized in the report to UKOPA the definition of dent as "a permanent plastic deformation of the cross section of the pipe caused by external forces". The terminology used below are quoted from the report.

- Smooth dent: A dent causing smooth in curvature of the pipe wall
- Kinked dent: A dent causing abrupt change in curvature of the pipe wall
- Plain dent: A smooth dent which does not contain other defect in the dent like gouges or cracks. Depending on dents curvature pattern, plain dent can be either smooth dent or kinked dent
- Shallow dent: A dent with depth less than 2% of pipeline outer diameter

Also, there are terms related to mechanical damage that needs to be defined.

- Spring-back: Refers to the reduction in the pipeline after elastic rebound when the indenter is removed
- Re-round: Change of dent depth due to internal pressure

Although plain dents were considered much less dangerous than other defects on the pipe, because plain dents may not cause immediate failure, but in the long-term they may result problems from fatigue cycling due to the change of operating pressure or development of corrosion (Baker 2004).

1.3 Research Background

United States Department of Transportation (DOT) have noted that mechanical damage are the largest reason of pipeline failure. According to DOT, up to 40% of transportation pipeline failure are caused by mechanical damage (Kiefner, 2000). Also study conducted by a major oil company in Saudi Arabia has reported that about 20% of pipeline failure incidents were due to mechanical damage (Advantica, 2004). In reality, numerous shallow dents are found in operating pipeline. However majority of them are considered not to impair integrity nor affect operation according to current assessments. However, all dents potentially have a capability to cause a stress increase in the dented area, and eventually affect the pipeline's integrity. Overlooking such defects can potentially cause economical and operational problems. The motivation of this study come from shortcomings of the existing criteria of dents. The existing assessment model was first proposed in 1981 and had only little change since then. There had been a lot of improvements in inspection techniques and risk analysis but only little improvements on the assessment model (Seevam, 2008).

Current codes and standards for dent defect assessments of pipelines provide simplified acceptance criteria which are based on the depth of dent or strain occurred in dent. Dent depth based criteria led to unnecessary replacements when dents deeper than 6% of pipeline's outer diameter but with low strains and left dents with low depth, less than 3% of pipeline's outer diameter with high strains due to sharp shapes. To overcome these problems, strain based criteria were proposed, but new problems arose of measuring the strain rate in the field using mathematical formulation (Gao 2008). Furthermore, all current code assessments of dents assume does not consider interaction but assume as isolated defects. However group of dents created close to each other, which is not hard to find in the field, for example dents made by multiple teeth excavator, will interact with each other with structural discontinuity. It is possible that dents close enough to interact with each other can result in producing more damage to pipeline. Operators should evaluate the pipeline which contains mechanical defects in order to determine the integrity of pipeline to avoid pipeline failure problems. Therefore, guidance is needed to identify dents for which excavation and inspection is necessary and could potentially be a threat to pipeline safety and dents that require further action.

1.4 Aim of the study

Although many studies have been conducted on a single dent defects, there is no published guidance or assessment methods to determine the severity of multiple dent defects when they are detected in pipelines. Considering that multiple dents interact with each other, it is important to carry out a study to develop practice guidance and support empirical guidelines for better understanding of multiple dent behaviour.

The aim of this work is to better understand and predict the behaviour of pipelines that are subjected to a double plain dent by determining the stress and strains and their locations in and around dent. A specific objective of this work is to create a Finite Element Model (FEM) based on experimental verification and validation. Second, to determine the value of the maximum stress and strains in and around specific dented region of a pipe for different dent diameters and distances. Third, to identify the significant parameters contributing to the interaction of dents close to each other. For dents interacting with each other, the distance between the dents or orientation angle between them should be primitive parameters. Hence, this study will determine the effect that the dent diameter, the dent depth, and the distance between the dents have on the maximum stress and strain value. Finally, recommendations will be made on additional work that may be required to develop more practical and effective dent assessments. The study should be practical for pipeline operators to revise more realistic assessment models.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Finite Element Analysis in Dent Defected Pipelines

Full scale experiments are convenient and intuitive to see behaviours but it is expensive and impossible to cover various cases with different parameters, such as pipe materials, geometries, dent profile, and so on. For these kind of reasons, FEA, finite element analysis, is widely used in study of pipeline defects.

Oliveira (2010) evaluated the stress concentration of dents in pipeline by varying parameter D/t, which is pipeline diameter (D) over pipeline wall thickness (t), using FEA and comparing it with an analytical equation. The state of stress was used to determine the failure of the pipeline. The results showed that analytical method determined was more conservative than FEA and increase in D/t ratio triggers higher stress concentration.

Ghaednia (2015) used full-scale tests and FEA to study burst strength of NPS30 steel pipes with dent-crack defects by varying internal pressures, dent depths, and dent configurations. It assumed failure when J-integral in any location reached $1.15J_{1c}$ (J_{1c} is critical integral).

Tian (2017) conducted a study about failure criterion of buried pipelines with dent defects. Although there are many suggested assessments of dents to determine failure of dent defected pipeline, some assessments showed highly conservative view on dent defects. Tian compared FEA and experiment results and verified that strength criterion used in FEA could be a good measurement for determining failure of pipeline.

There are only few works conducted on multiple dents. Published experimental data of interacting dents were fatigue experiment under cycling pressure conducted by API (1999). 10 cases were carried out under same indenter and same dent depth but only with different spacing of the dents. Spacing was defined as centre-to-centre distance, varying with 1/2, 1, 2 or 3 times of the indenter diameter. They determined the existence of interaction when the curvature of the two dents changed. They concluded that dents interacted with each other when they were only 1/2 diameter spaced.

Al-Muslim (2010) conducted study on impact of double dent on pipeline with FEA using deterministic analysis and probabilistic analysis. Al-Muslim considered spacing and orientation angle under cyclic pressure. Al-Muslim concluded that double dents in perpendicular direction, strains increased in double dent cases compared to single dent case but stress values did not show clear trend.

2.2 Review of Dent Assessment Codes

Most of guidelines on the assessment of dent severity take dent depth as the most important parameter. ASME B31.8 defines the depth of the dent as “the gap between the lowest point of the dent and the prolongation of the original contour of the pipe in any direction. The dent depth (d) is usually expressed as a percentage of the initial nominal outside diameter of pipeline (D).

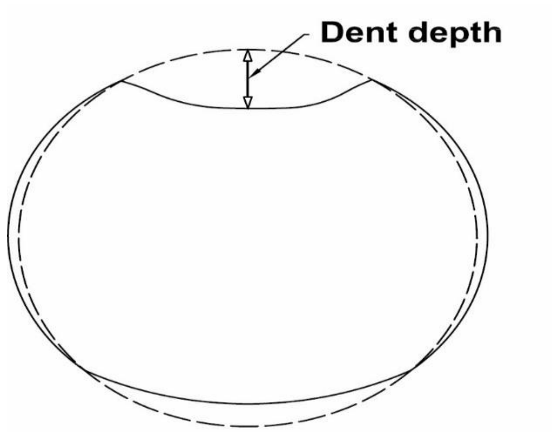


Figure 2.1 Dent depth according to the definition of ASME
Source: Ghaednia (2015)

Although it is considered that plain dent alone does not affect the integrity of the pipeline (Baker 2004), criteria have been made regarding acceptable limits for plain dents on the basis of the test data. British Gas concluded that plain dents up to 24%OD are unlikely to compromise the integrity of the pipeline, 8%OD have been set up as a measure which pipeline could safely operate (Hopkins 1989). EPRG state when dent depth measured under pressure is greater than 7%OD, the pipeline is required for a repair (Rinehart 2002). ASME B31.8 and B31.4 code set a criteria of 6%OD on plain dents under static loading.

Although historically the critical parameters in assessments of dent have been based on the dent depth, recent research support that the strain in the dent may indicate a better behaviour for the criteria. Recent code revisions and guidance documents also have strain based assessments for the pipeline.

Strain level of the dent can be a measure for determining the integrity of the pipeline. To obtain strains in the dented region of the pipe by using finite element method, it requires the solution of large plastic deformation with large number of nodes (Lukasiewicz 2006). Although there were many studies on calculation of strains in dented pipelines, different methods were used in each studies (Rosenfeld et al. 1998).

For example, Rosenfeld concentrated on determining the measurements of dents by inspection tools on pipeline to obtain the residual strain due to the denting process. In the study, he defined three different strain components that was necessary to assess the effect of the dent. Two of the strain components act in the pipe wall, in the circumferential and in longitudinal directions. The strain can be further categorized into membrane and bending components in each direction as shown in Fig. 2.2. The membrane strain act uniformly constant through the wall. On the other hand, the circumferential strain changes linearly though the wall about the neutral axis at t/2.

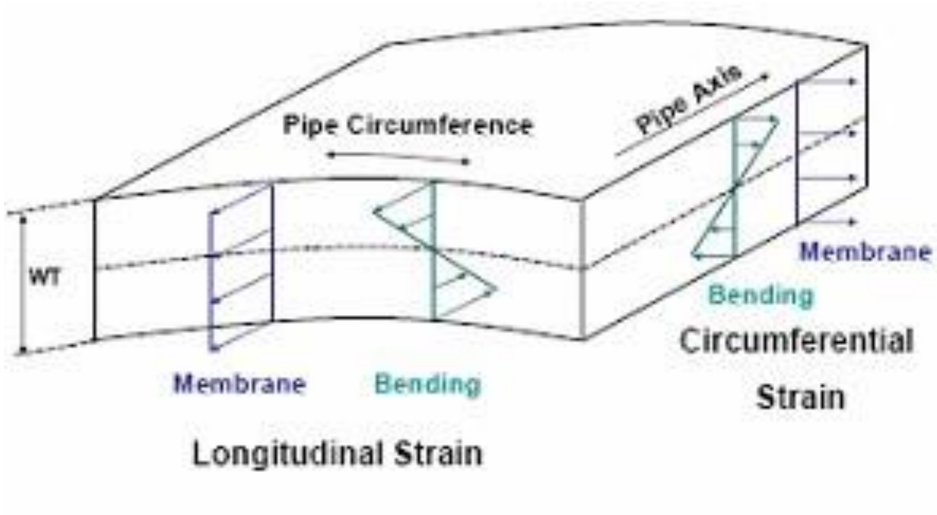
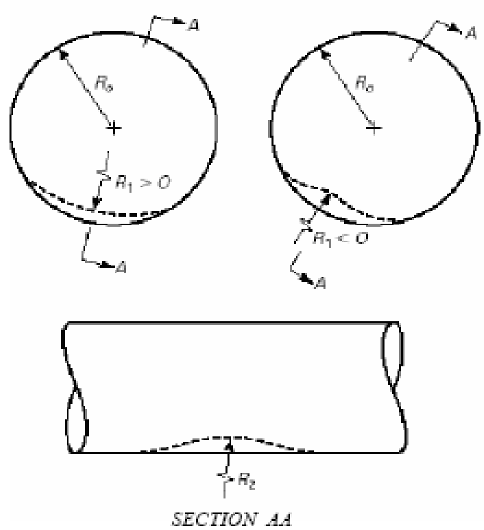


Figure 2.2 Strain Components in the Pipe Wall
Source: Lukasiewicz (2006)



Circumferential Bending Strain

R_o = Radius of curvature of undeformed pipe surface
R_1 = External surface radius of curvature in circumferential direction
R_1 is positive when the dent partially flattens the pipe and R_1 is negative for a re-entrant dent

Longitudinal Bending Strain

R_2 = External radius of curvature in the longitudinal direction
R_2 is generally always negative

Figure 2.3 Dent Geometry as Defined in ASME B31.8
Source: Noronha (2005)

Strain based criteria is introduced in ASME B31.8. However ASME allows other formulations of calculating strain of dents due to complication in dent profile measurement. ASME B31.8 (2016) provides strain calculation formulas as table below.

	ASME B31.8
Circumferential Bending Strain, ε_1	$\varepsilon_1 = \frac{t}{2}(\frac{1}{\mathrm{R}_0} - \frac{1}{R_1})$
Circumferential Membrane Strain, ε_4	Assumed to be zero
Longitudinal Bending Strain, ε_2	$\varepsilon_2 = \frac{-t}{2R_2}$
Longitudinal Membrane Strain, ε_3	$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2$
Shear Strain, γ_{xy}	Assumed to be zero
Effective Strain, ε_{eff}	$\varepsilon_i = \sqrt{\varepsilon_1^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2}$ $\varepsilon_o = \sqrt{\varepsilon_1^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2}$ $\varepsilon_{\mathrm{eff}} = Max[\varepsilon_i, \varepsilon_o]$

$t: wall\ thickness, \quad d: Dent\ depth, \quad L: Dent\ Length$

Table 2.1 Current strain calculation formula in ASME B31.8

Rules should be applied to determine whether dent is critical to the pipeline integrity and consider to take further assessment or repairmen is needed. A summary of the codes(rules) for the dent assessment are provided in Table 2.2.

	Plain Dents		
	Constrained		Unconstrained
ASME B31.8 (2016)	Up to 6%OD or strain level up to 6%		
ASME B31.4 (2016)	Up to 6% OD in pipe diameters > NPS 4 Up to 6mm in pipe diameters < NPS 4		
API 1156 (1997)	Up to 6%OD, >2% OD requires a fatigue assessment		
EPRG (1999)	≤7%OD at a hoop stress of 72%SMYS		
	Dents at welds	**Dents with cracks or gouges**	**Dents with corrosion**
ASME B31.8	Up to 2%OD or 4% strain on ductile welds Not allowed on brittle welds	Not allowed	Assess individually
ASME B31.4	Not allowed	Not allowed	Not allowed
API 1156	Up to 2%OD on ductile welds Not allowed on brittle welds	Not allowed	Not considered
EPRG	Not allowed	Not allowed	Not allowed

Table 2.2 Summary of Static Dent Assessment Methods

API 1156 presented limits for constrained dents in liquid pipelines considering effects of re-rounding. It is highly unlikely that in liquid pipelines, unconstrained plain dents greater than 5%OD depth or greater depth can be found in areas which have been pressurised up to 72% SMYS or more. API 1156 determined that the current criteria of 6%OD in B31.4 is reasonable for a static assessment and that that dents over 2%OD depth should be subject to a dynamic assessment.

Dents generated close to welds are vulnerable to extra damage such as cracks at the internal weld toe, particularly in low toughness material. In this regard, dents on welds were not accepted to the pipeline codes. However, Rosenfeld (2001) and API 1156 concluded that dents up to 2%OD on moderate to high toughness materials (ductile) welds do not affect the integrity in the gas and liquid pipelines and this has been updated in the latest codes.

2.3 Burst Pressure for Pipeline

Burst pressure is a pressure limitation of a pipe that can withstand before failure (without bursting). Equation for burst pressure is based on Barlow's Formula.

$$\mathrm{P} = \frac{2\,\sigma_{\mathrm{y}}\,t}{D_0 SF}$$

Equation assumes an ideal condition of pipeline such as room temperature, no defect on the pipe outer surface. SF, stands out for the safety factor of the material (σ_y, for the material yield strength (MPa), t, for wall thickness of pipe and D_0, for the outer diameter of the steel pipe. However, there are currently no other methods of determining burst pressure of dented pipeline, so it is essential to set up failure criteria to determination burst pressure.

Experiment is the best method to find out pipeline's failure criteria because it is based on actual behaviour of a structure and best to estimate, but expensive and time consuming. On the other hand, finite element method is low cost and can carry out all kinds of loading or load combinations in relatively short time. Bilinear or multilinear kinematic hardening rule which is available in ANSYS, is used to determine limit load as described in the following sections. Load-strain curve obtained by nonlinear finite element analysis and limit load determination criteria described in following sections are used.

2.3.1 Criteria for limit load estimation

Criteria are used to determine limit load estimation which represents an actual behaviour of a component. (strain hardening, large deformation, etc.). After the loading versus strain or displacement curve is measured, the limit load can be determined by the following criteria based on the achieved curve.

(l) Tangent intersection criterion

Tangent intersection criterion defines limit load P to a corresponding value where the drawing of tangent of elastic and plastic parts of loading-deformation meet.

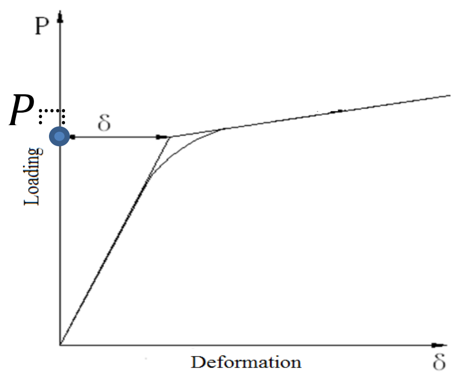


Fig. 2.4 Tangent intersection criterion

Source: Chen, Gao and Wang (2016)

(2) 0.2% offset strain criterion (ASME 1971)

Defined by ASME in 1971, as in Fig.2.5, this criteria was referenced by the concept of yield stress $\sigma_{0.2}$. The corresponding point which results from 0.2% offset strain is defined as limit pressure P.

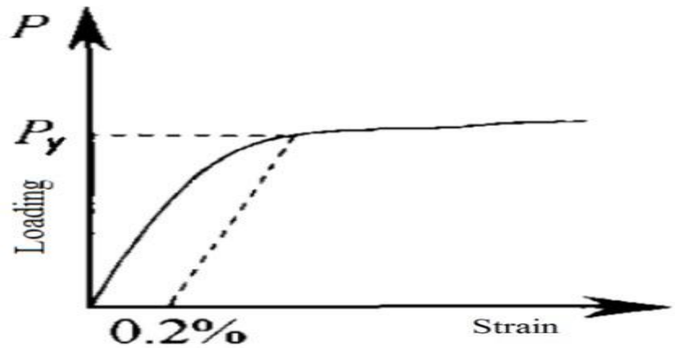


Fig. 2.5: 0.2% residual strain criterion

Source: Chen, Gao and Wang (2016)

(3) Plastic work criterion

Plastic work criterion was proposed by Gerdeen in 1979. It defines the limit load as a corresponding point of vertical axis value of suitable ratio of elastic work W_e and plastic work W_P (defined as shaded area respectively in Fig. 2.6a.) However, it defining the separation point of elastic work W_e and plastic work W_p was difficult. A concept of loading coefficient λ $(0 \leq \lambda \leq 1)$ was introduced in 1979. Setting the loading coefficient λ as vertical axis and the plastic work as horizontal axis, the intersection of the tangent of plastic part of λ–W_p curve and the vertical axis was defined as limit load (Fig. 2.6b). Combining two methods, the limit load is expressed as $P_L = \lambda^p P$

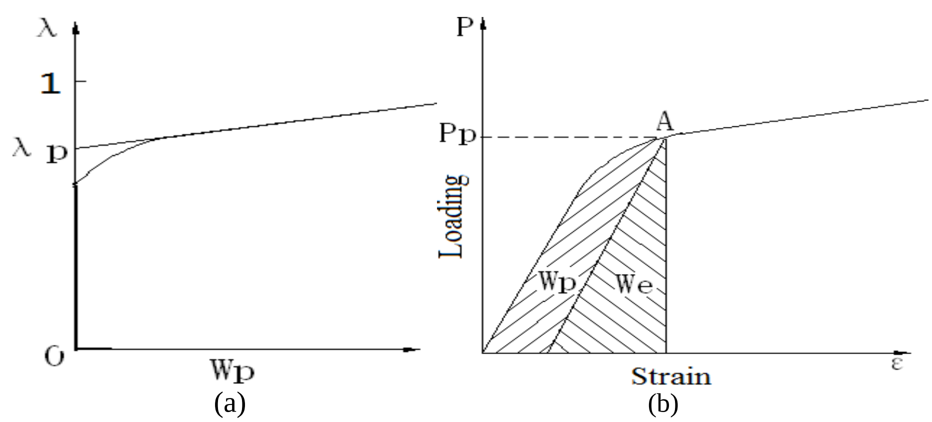


Fig. 2.6: Plastic work criterion

Source: Chen, Gao and Wang (2016)

(4) Ultimate strength criterion

The ultimate strength criterion defines the limit load as a corresponding point of vertical axis and asymptote position in load-displacement curve.

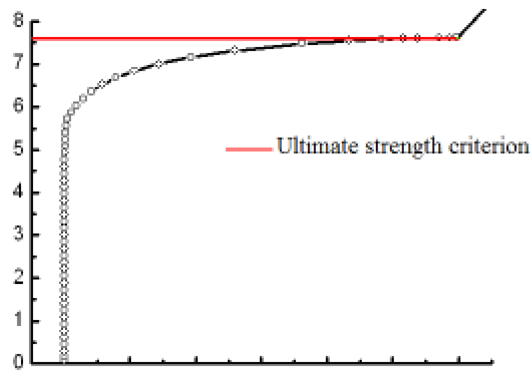


Fig. 2.7 Ultimate strength criterion

Source: Chen, Gao and Wang (2016)

CHAPTER 3

3.0 METHODOLOGY

3.1 Finite Element Analysis

Experimental testing is expensive and not viable to consider full-scale tests for a wide range of test parameters. Numerical tools like FEA an effective alternative method to study and predict the behavior of structures. In this study, considering both material and geometric nonlinearity, Finite Element (FE) method was employed to simulate the behaviour of the pipelines exposed to double dents for numerical analysis.

Commercially available FEM tool, ANSYS APDL version 18.0 was used to carry out the numerical modelling analysis of dented pipe behaviour.

ANSYS was chosen for its ability to model bilinear hardening material properties, and is one of the most effective and commonly used modeling tool to develop various load cases for a pipeline model. Furthermore, ANSYS is capable of simulating the experimental boundary conditions more precisely by selecting adequate contact interaction model. The objective of developing a FE pipeline model with ANSYS is to predict the behavior of a multiple dented pipeline when it the dent depth, dent diameter and dent distance is changed. Another objective is to observe the stress and strain around the dent region to determine if the pipe is within failure criteria. More importantly, if a parametric study is successfully conducted, it will greatly contribute to a new guideline for multiple dent defect assessments for pipeline. Such guideline will include different diameters of indenters, effect of internal (operating) pressures when the dent is made, depth of dent, and distance between dents.

3.2 Finite Element Analysis Model Setup

The procedure of ANSYS model setup is explained in the appendix in detail.

3.2.1 Pipeline

According to AER, the most commonly used diameters of crude oil pipeline in Alberta are 12 in and 30 in which is equal to 305 mm and 762 mm each (Ghaednia, 2015). In this regard, 762 mm of outer diameter pipeline were used in the FE model. Half section with full length of 2000 mm pipe and thickness of 17.5 mm was modelled to impose the symmetry condition in the pipe geometry, boundary conditions and indenters in order to reduce computational time. Pipe length was selected as same length with validation model to ensure that pipe length is long enough than indenter to not affect the results of the dented area.

3.2.2 Material Property

Ideal elastic-plastic model, which is considered as more conservative model than the actual material behaviour, were used in the FE analyses to simulate actual behaviour of pipe as possible during the denting and pressurizing process. The bilinear isotropic hardening model BISO, an elastic-plastic material model in ANSYS software was used for the pipe material. The stress vs. the strain curve is plotted and shown in Fig. 3.1. The BISO model in ANSYS requires a value of elastic slope, plastic slope and yield stress of the material each. The material properties used in the FE models are in Table 3.1. Elastic slope is equal to Young's modulus and yield stress of the pipe is provided in the table

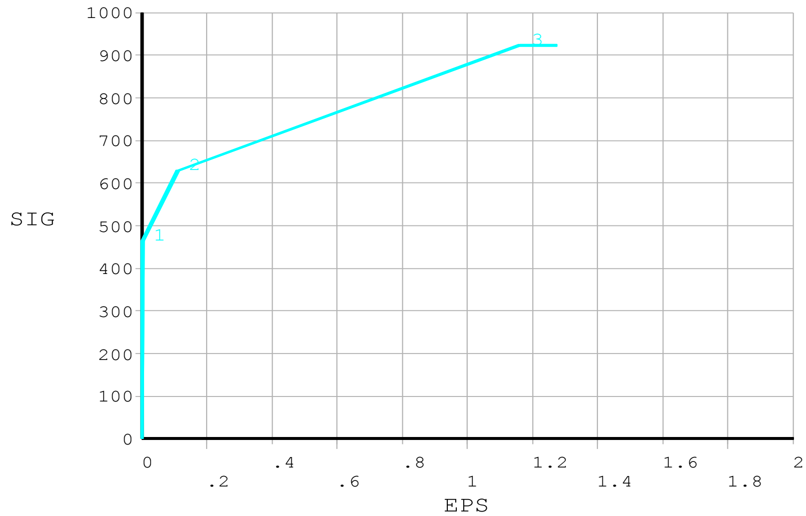


Fig. 3.1 The stress-strain curve of pipe used in FE analyse

3.2.3 Boundary Condition

Suitable boundaries were applied to simulate the conditions experienced in the field, as shown in Fig. 3.2.

(1) Surface A (only pipeline) and B were applied with symmetrical boundary conditions.
(2) Surface C was restrained only in the vertical direction to allow axial tensile stress.
(3) The bottom line of the pipe was fully fixed to prevent the rigid motion during the denting process.

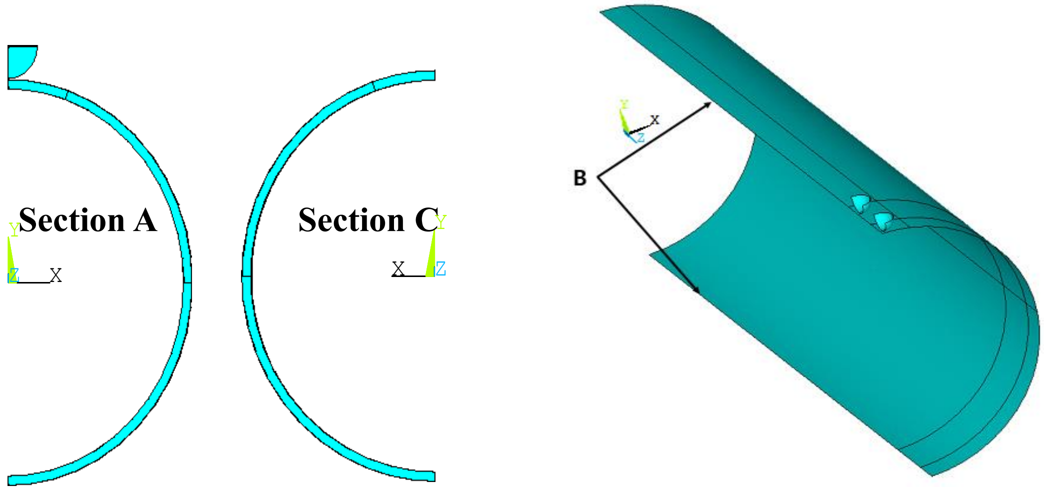


Fig. 3.2 Boundary condition of finite element model

3.2.4 Contact

In order to model denting process in ANSYS, when indenters come into contact with the pipe, a contact algorithm needs to be considered. The algorithm defines the behavior of actions between the indenter and the outer surface of the pipe. In ANSYS APDL, there are five different ways of modeling the contacts needs. They are rough, no separation, bonded, frictionless and frictional.

For the bonded method, no sliding or separation between the contact regions exists, which means that the contact region (length/area) will not change during the loading process. For the no separation method, which is similar to the bonded method, contact region will change only attributing to faces or edges of the regions. Separation is not allowed. However small amounts of frictionless sliding are allowed along contact regions. Frictionless method is widely used contact behavior, which assumes that normal pressure is zero when separation occurs, thus allowing free sliding. This method is a non-linear solution since the contact area may change when the loading is applied. The rough method is similar to the frictionless method. This method only applies to the faces or edges of the contact region, assuming infinite friction between the contact areas. Lastly the frictional method considers shear stresses during the contact, which means contact regions carry shear stresses before they start sliding to each other. Sliding begins once the shear stress exceeds a certain magnitude. In this study, frictionless method was applied to consider non-linearities of the analysis.

Additionally, there are different sets of contact elements that are suitable for specific conditions. A surface-to-surface element, CONTACT 174 and TARGET 170 were used for this FE model since this set of elements are able to support rigid-to-flexible and flexible-to-flexible surface contact cases. ANSYS APDL provides guidelines for selection of the surfaces. The indenters were meshed with CONTACT 174 elements as their surface is stiffer than that of the pipelines. The outer surface of the dented area of pipeline was meshed with

TARGET 170 elements.

3.2.5 Mesh

A mesh sensitivity analysis was performed to obtain the adequately refined finite element sizes. Fine mesh is applied within and around the dent defected area where the highest stress concentration is expected. Gradually coarse mesh was applied away from the indenter. The meshed model used in this study is shown in Figure 3.3.

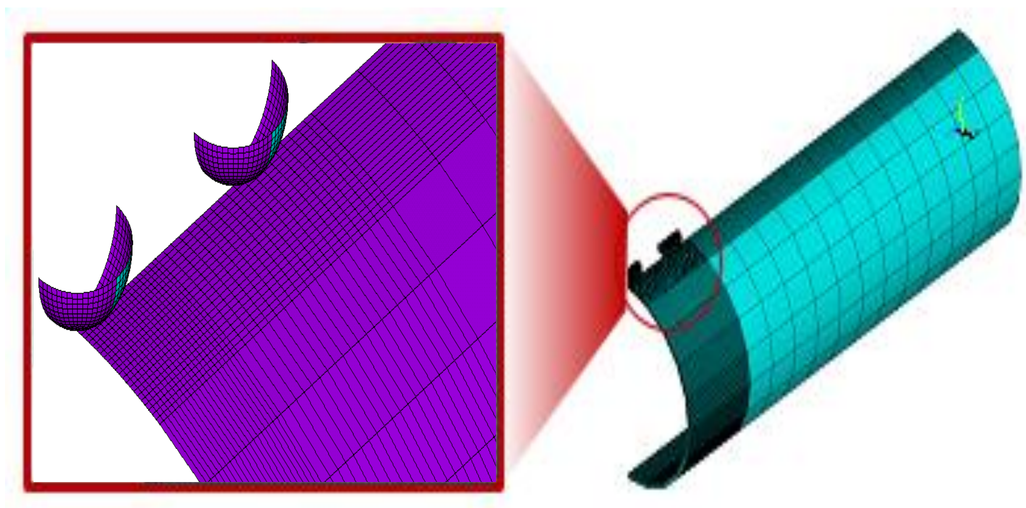


Fig.3.3: Meshed FE model zoomed in dent area

The number of element layers through the pipe wall thickness was compared to determine an optimal solution. The optimal size of mesh was selected through mesh sensitivity test by increasing the number of elements in the dented region until convergence in total strain are reached. Number of elements layers compared in the study was 1,2,3,4,5, and 6. It is observed that there is a small difference between the different mesh sizes after 4 layers as shown in Figure 3.4 which could be determined that total strain has reached convergence.

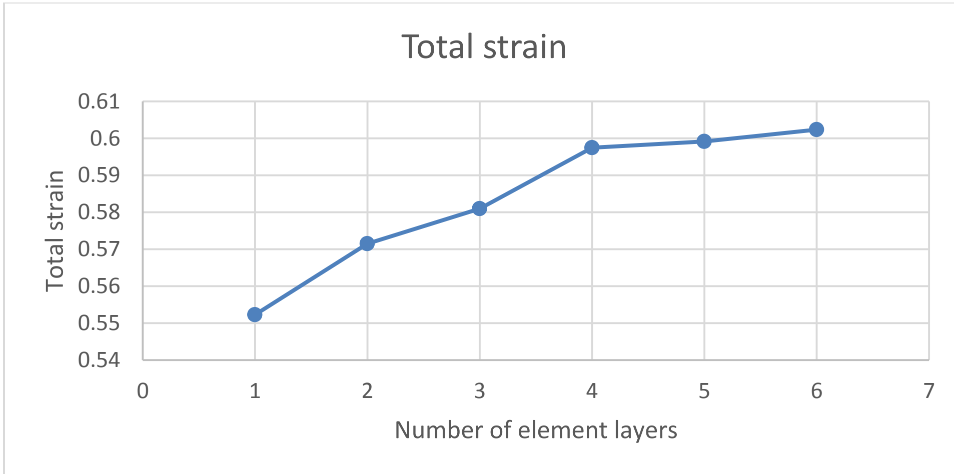


Fig. 3.4. Mesh convergence test result – Total strain

Theregore, considering both convergence and the computational time, an optimal solution was reached when using 4 element layers throughout the thickness.

Mesh sizes of indenters varied with indenter diameters. Generally, at least 10 to 15 elements are required for spherical shaped contact material not to simulate as polygonal shaped material. The optimal size used when meshing the 30 and 60 mm diameter indenter are 17.5 mm x 0.125. The optimal size used in 120 mm diameter indenter was 17.5 mm x 0.25 and 17.5 mm for 240 mm diameter indenter.

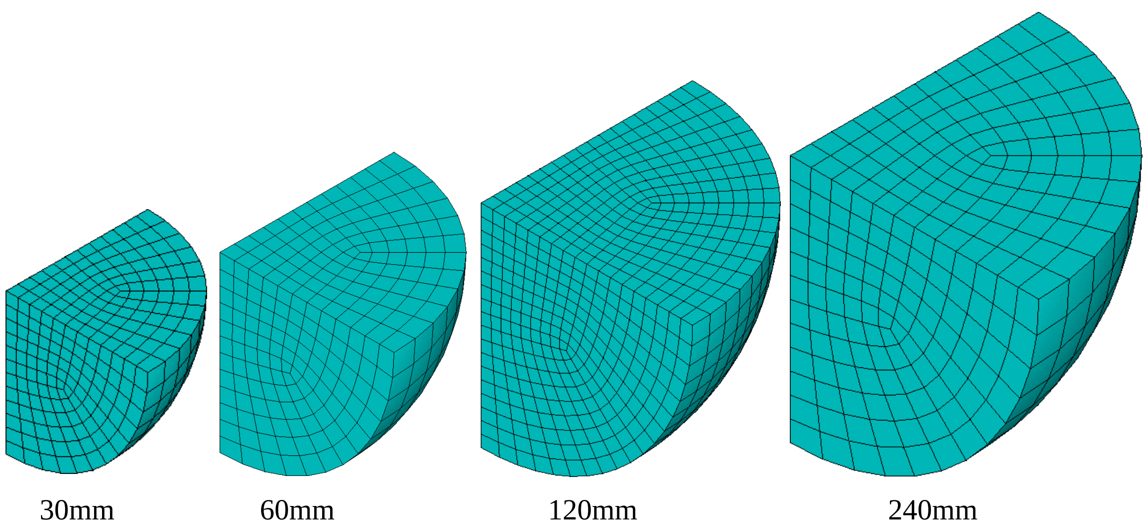


Fig. 3.5. Meshed indenter with different mesh sizes

3.3 Finite Element Analysis of Validation Model

It is accepted that experiment is the most practical and reliable way to achieve a better understanding of the behaviour of structural component which is subjected to various kinds of loads. However, experiments are usually expensive and time consuming. For this reason, adequate test results on the multiple dent defected pipeline behaviour is not available in the literature for validation of FE models for different indenter dimensions and distance between the dents. To this end, FE models for single dent defected pipes are first validated through comparison with the results from a thesis “Load bearing capacity of API X65 pipe with dent defect under internal pressure and in-plane bending” by Baek (2012). After validating single dent case, second indenter is going to be applied to the pipes to the validated model.

Baek (2012) worked on their study to obtain data on elastic-plastic material response to static pressure and bending behaviour of an API 5L X65 pipe with dent defect through experiment and FE analysis. An API 5L X65 grade pipe of outer diameter of 762 mm, wall thickness of 17.5mm and length of 2000mm was tested (Figure 3.6). Hemispherical shaped indenters with diameters of 40 and 80 mm were indented into the pipelines and generated 19, 38, 76 and 114 mm of dent depths. The dent manufacture process was carried out under displacement control, which mean that indenter was placed to a designated depth with a speed of 10mm/min. The pipeline was pressurized up to 25 MPa on the inside to obtain data of resistance on the internal pressure and compared with non-pressurized data.

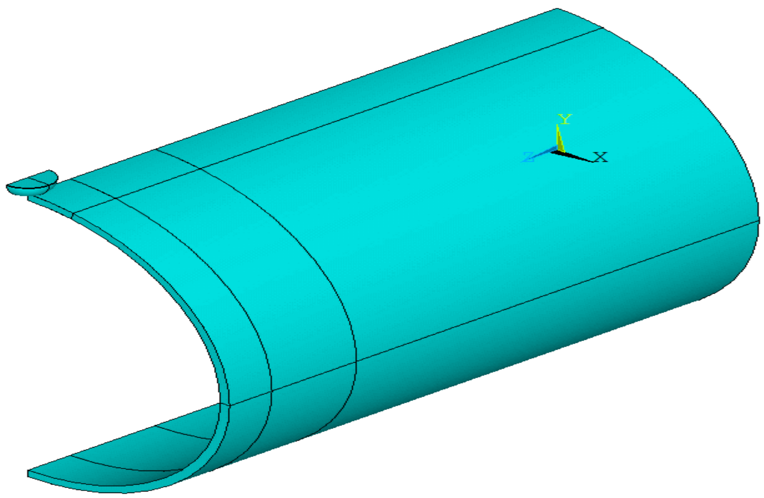


Figure 3.6. FE model of pipeline and Indenter (Single dent case)

The mechanical properties of pipeline used in experiment are given in Table 3.1.

Yield strength	464 MPa
Ultimate strength	563 MPa
True tensile strength	629 MPa
Poisson’s ratio	0.3
True fracture strength	923 MPa
True strain at necking	0.11
True fracture strain	1.16
Young’s modulus	210 GPa

Table 3.1 Mechanical properties of the API 5L X65 pipe
Source: (Baek, 2012)

The finite element (FE) models were validated comparing the spring-back behaviour and rerounding behaviour with the FE analysis result from Baek(2012) and data obtained from the FE analysis. Spring-back ratio is calculated as the following equation. Dent depth means dent depth before the indenter is removed.

$$Spring\ back(\%) = \frac{Initial\ dent\ depth - residual\ dent\ depth\ after\ removing\ indenter}{Inital\ dent\ depth} * 100$$

The comparison of the spring-back results between test and finite element analysis on 80 mm diameter indenter under different internal pressure with using different elements are shown in Figure 3.7(a) and Fig. 3.7(b). Graph is plotted by Spring-back, the Y axis, and inital dent depth, the X axis, which is the depth made by indenter during the denting process.

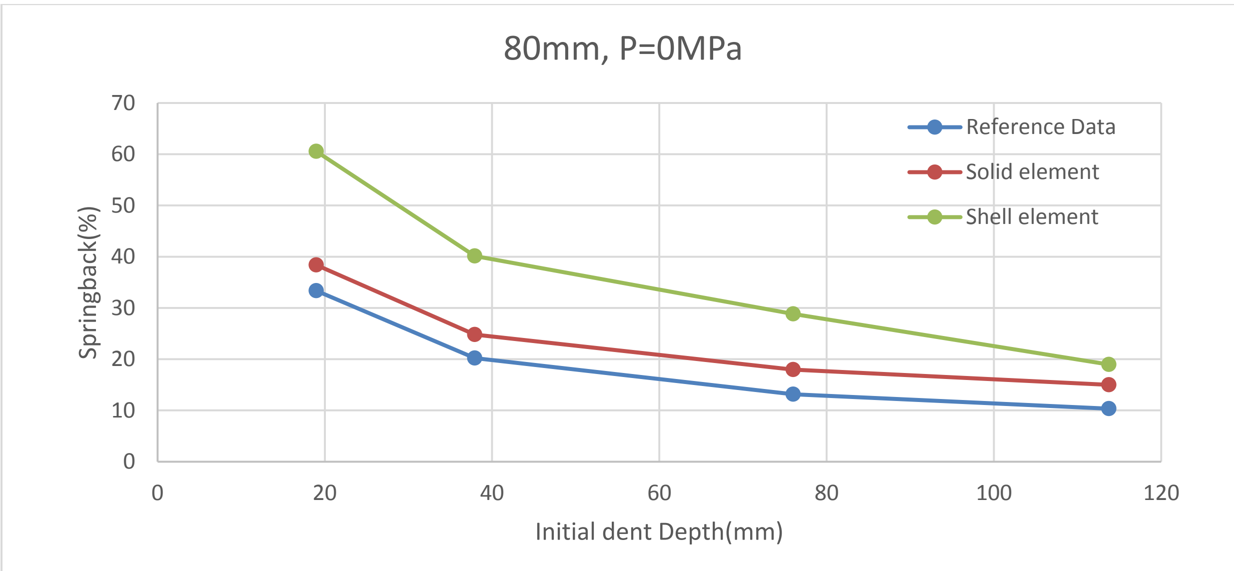


Fig. 3.7(a) Spring-back result using solid/shell element on 0 MPa internal pressure

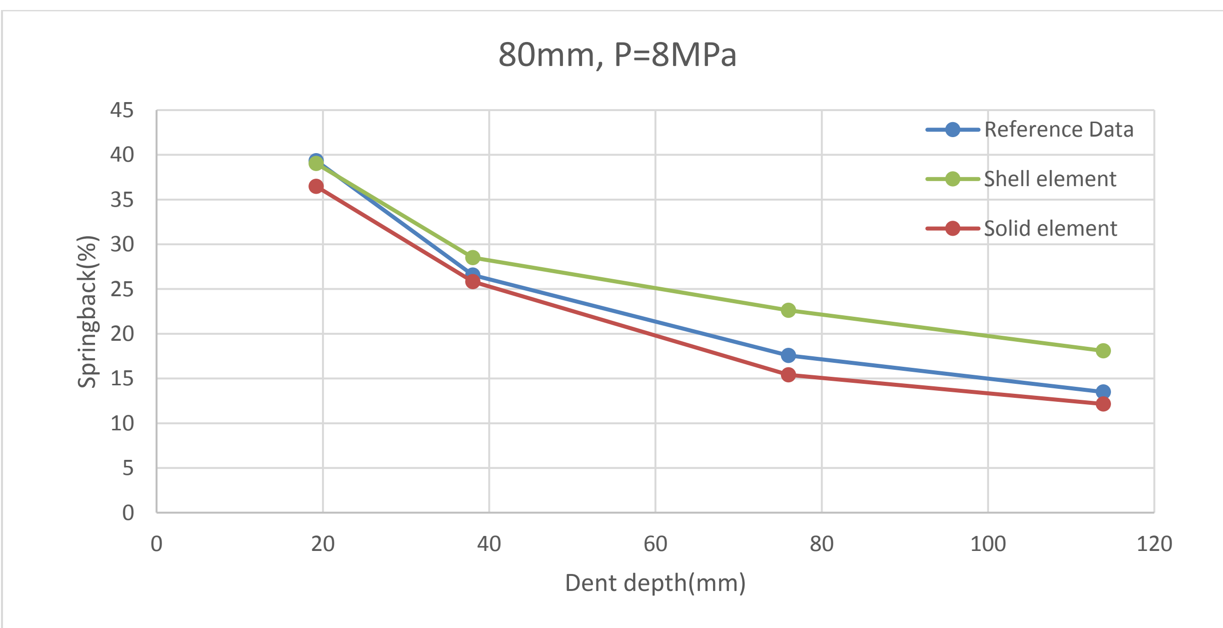


Fig. 3.7(b) Spring-back result using solid/shell element on 8 MPa internal pressure

Clearly solid element showed better agreement with the experiment data than shell element. In both cases, in 0 MPa internal pressure and 8 Mpa internal pressure, despite of some differences in values, results showed that the tendency of the spring back behaviour was almost same with experimental data. When internal pressure of 0 MPa, shell elements showed larger errors with the experimental data than 8 MPa case. Also, when dent depth got deeper in 8 MPa case, shell elements showed larger errors compared to solid elements. Shell elements are easier to mesh and allow huge computational time savings but they are only a mathematical simplication of solid elements of a special shape. Thin shell elements can not plot the stress in perpendicular direction of the element surface, which makes it hard to account for shear deformation which is necessary to determine failure later on. However, this is only general explaination of shell element, and it is not always true. In this case, solid element showed more accurate results than shell elements. Overall, FEA resulted with average of 4% (minimum 2% to maximum 9%) error with the experimental data. Zero internal pressure cases had larger differences than with the 8 MPa internal pressure cases. Moreover, the reason when dent depth got deeper errors get larger is that results of FEA rely heavily on the material and geometrical non-linearity. Considering that material property used in FEA is different from true stress-strain curve used in the experiment and that FE model can not exactly same as the experimental condition, error shows acceptable agreement with experimental data. In this regard, solid element were used in this study.

3.4 Finite Element Analysis Model Setup

As mentioned in section 3.3, second indenter was added to the validated Finite Element model. To investigate the interaction of double dents on pipeline, 128 FEA models were developed and analyzed using ANSYS APDL. The spacing between the dents is varied along the longitudinal directions. The depth of dent is also considered. The load cases considered in FE analysis are summarised in Table 3.2.

The actual geometry of dent defect is very complex, although existing literature mainly focuses on the maximum dented depth of the area and only pipe performance is concerned. Therefore, only spherical shaped dents were considered for generating the dent defects.

By applying simplified boundary condition, the efficiency of FEA is increased. In this regard, symmetric condition is applied to the model. Due to the symmetric condition, only half of the pipeline and indenter was modeled in the numerical model.

The parameters chosen in this study are: (1) d/D which is dent depth over outer pipe diameter that was varied from 0.025 to 0.2 to consider various sizes of dent that can be found in the field, (2) DD/ID which is distance between dents (from peak to peak) over indenter's diameter, and (3) internal pressure which was considered during the indentation. All combined cases are shown in Table 3.2.

Indenter diameter (mm)	Internal pressure during denting, P_i (MPa)	Target dent depth (% of outer diameter)
Plain pipe	0, 72% SMYS	–
30	0	2.5, 5, 10, 20
	72% SMYS	
60	0	
	72% SMYS	
120	0	
	72% SMYS	
240	0	
	72% SMYS	

Table 3.2 Cases for the FE analysis under a combined load

3.4.1 Element

As it is shown in figure 3.9 that solid element showed more accurate result than shell element, 20- node quadratic layered structural solid element, SOLID 186, was used for pipeline modelling. SOLID 186 has three degrees of freedom per node: translations in the x, y, and z directions. This element supports plasticity and large deflection options, which is the main issue for this model. The indenter was also modelled with SOLID 186, but were modelled with higher stiffness as they were almost rigid compared to the pipe wall. In order to perform more accurate deformation behavior of the pipe, pipe wall was layered with four equal sized solid elements (Fig 3.8).

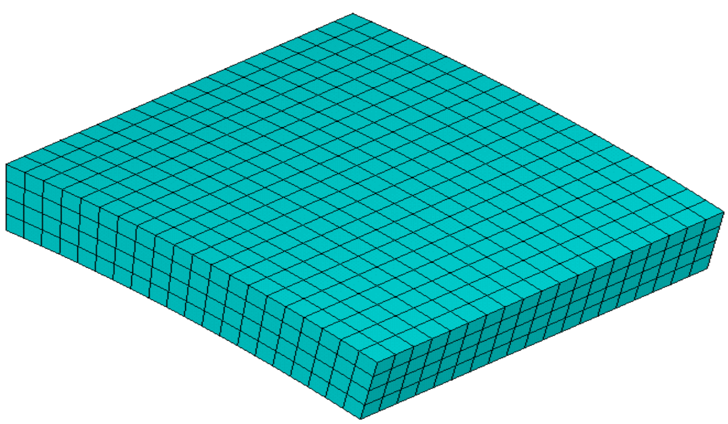


Fig. 3.8. Element layers throughout thickness (Fine mesh area)

3.4.2 Internal Pressure

Dents in pipelines can either occur whilst the pipeline is in operation under internal pressure, or while the pipeline is being installed. Therefore, for this study, two cases of internal pressure were considered. First case is when the denting of the pipeline is created under operation of pipeline. For the second case, dent was manufactured before the pressure was applied to the pipe. The internal pressure in FE analysis was applied as a constant pressure of 72% of SMYS and the pressure was kept unchanged during the entire process. The pressure was calculated as below.

$$0.72 * \sigma_y = \frac{P * D_o}{2t} \qquad \text{Eq 3.1}$$

$$\therefore \mathrm{P} = 15.34\ \mathrm{MPa}$$

$$\sigma_y: yield\ stress \qquad D_o: Pipe\ Diameter \qquad t: Pipe\ thickness$$

Internal Pressure while Denting

The internal pressure equivalent to a stress of 72% SMYS was applied during the indentation process to simulate the denting process which occurs in the field. The internal pressure of 72% SMYS was applied before the denting and kept unchanged for the entire load steps. The calculated value of P is 15.34 MPa as stated in Eq 3.1. The objective of this case is to obtain data of the effect of the internal pressure on the strain distribution and stress behavior around the dented region.

Internal Pressure after Denting

In this case, internal pressure equivalent to a stress of 72%SMYS was applied after the removing the indenter to determine the behavior of operating pre-dent defected pipeline. Also strain distribution and stress behavior were observed around the dented region.

3.4.3 Indenter

Four different indenters were used to produce different dents. The indenter was modelled with rigid model since the study is focusing on the behaviour of the pipeline. Four indenter diameters were used; 30 mm, 60 mm, 120 mm, and 240 mm diameters. The indenters were all hemisphere shaped. In indenter size was chosen to compare sharp dents and smooth dents effect. The distance between the dents varied with the indenter radius. The distance was measured by moving the second indenter from the point between the two center-bottom points of the dents. Distance were spaced with 3 cases, 0-radius away, 1-radius away, and 2-radius away (Figure 3.10). Also dent depth were varied with 2.5%, 5%, 10%, and 20% with each indenter cases. As a result, 48 cases of double dent cases and 16 cases of single dent cases were considered. Single dent cases were conducted as a reference case to compare whether interaction between the dents exists. Also to observe the effect of internal pressure while the denting process, each cases were compared by applying internal pressure of 72% SMYS and by applying no internal pressure. The total FEA cases were 128.

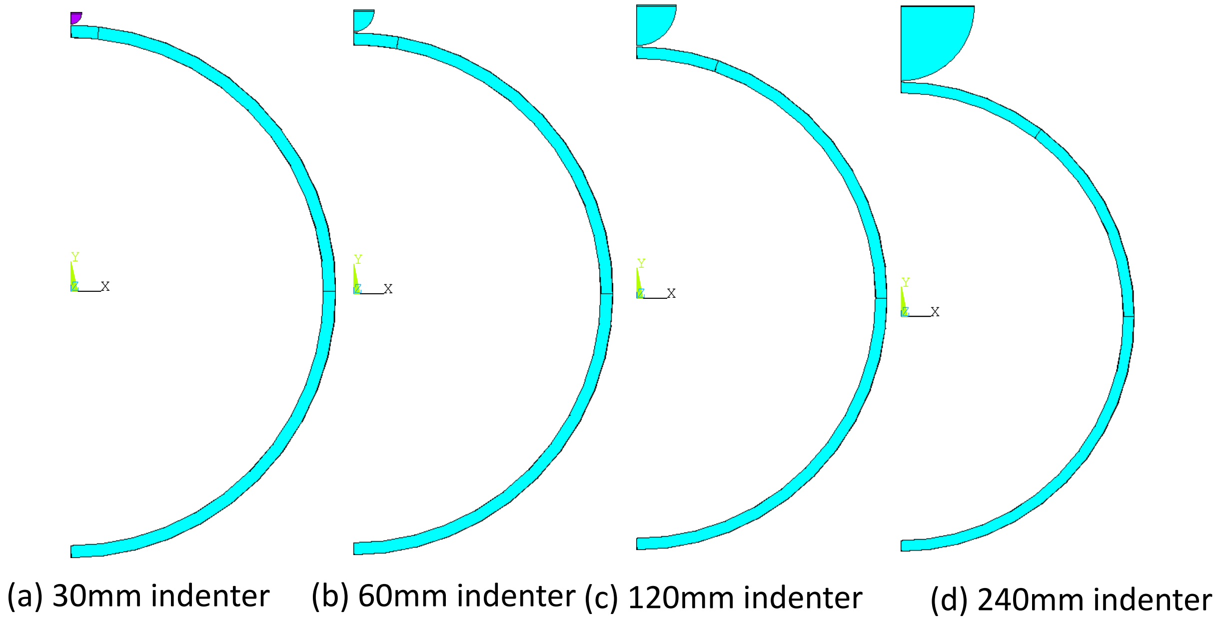


Fig. 3.9 Illustration of the four indenters

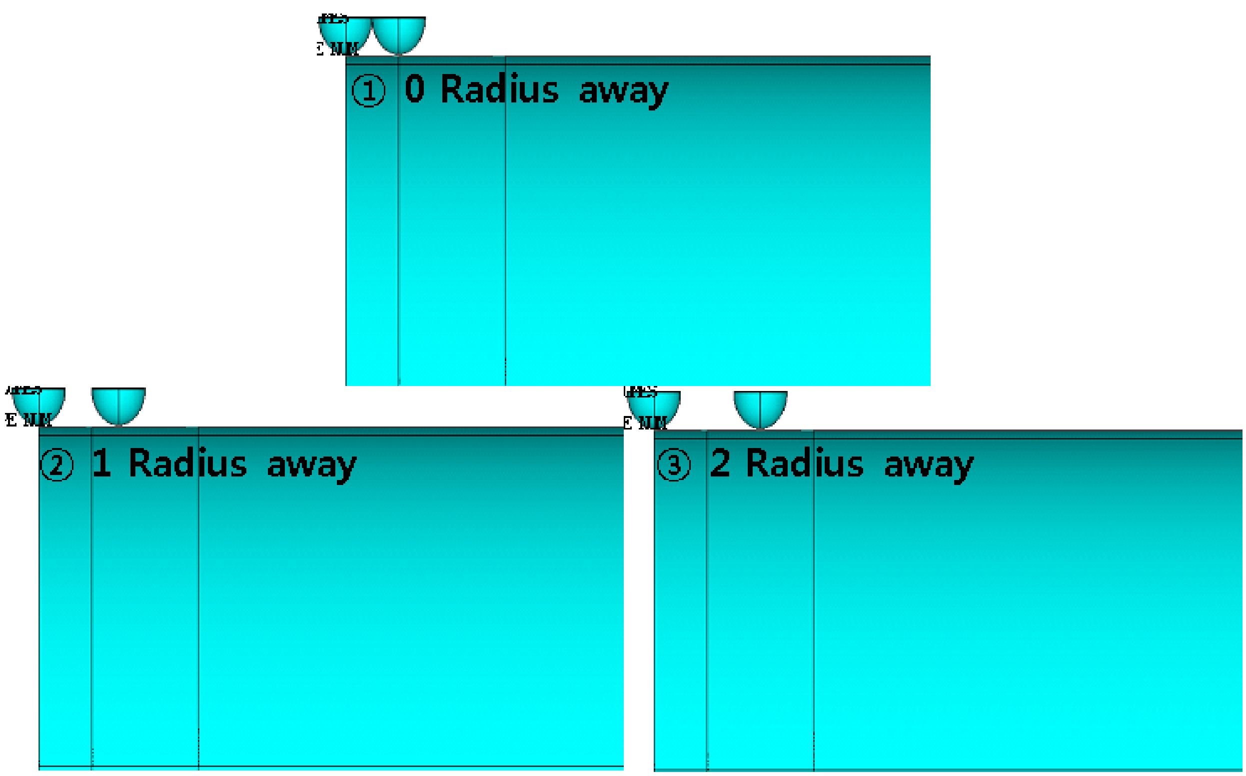


Fig. 3.10 Illustration of the dent distance

3.4.4 Simulation Procedure

(1) No pressure when indenting

Firstly, the indenters was placed above the pipeline. Next, the indenters was loaded onto the pipe surface to the specified depth. The indenter was released by imposing upward displacement to the indenter. Finally an internal pressure equal to pipeline‘s 72% SMYS, specified minimum yield stess, was applied to the inner surface of the pipeline to simulate the operating pipeline.

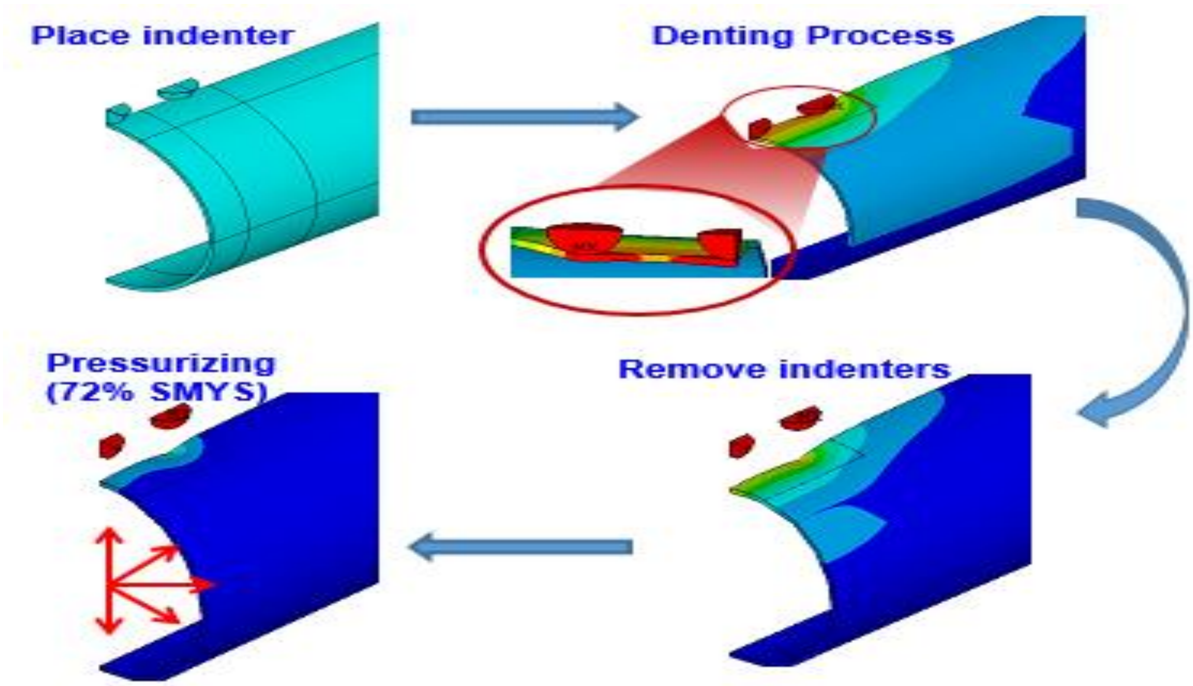


Fig. 3.11 Denting Procedure (no internal pressure in denting process)

(2) Internal pressure during denting process

An internal pressure of 72% SMYS was applied inside the pipe surface to simulate the service condition. Then, indenter was placed above the pipeline. Next, the indenter was displaced to the designated depth by displacement control, imposing downward displacement as a denting process. Finally, the indenter was removed by imposing upward displacement.

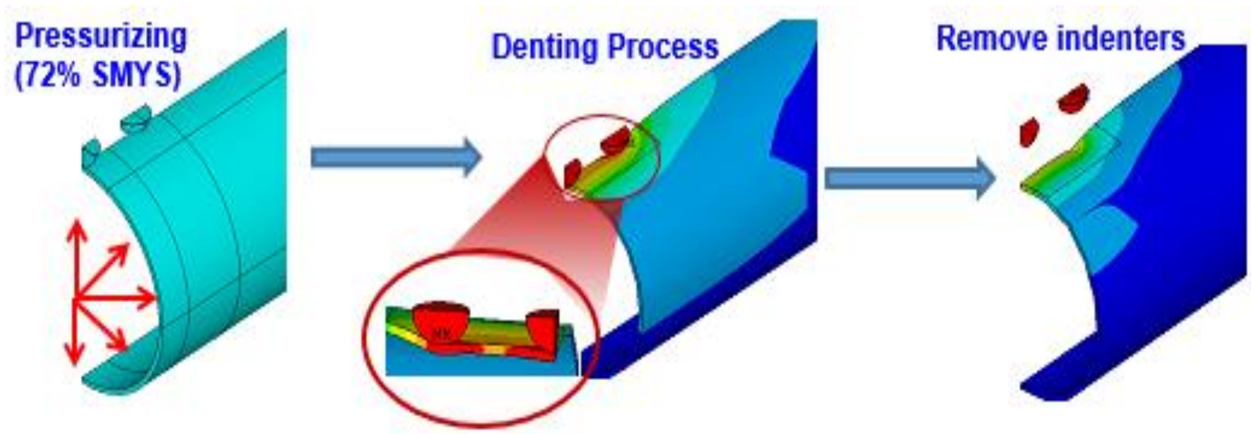


Fig. 3.12 Denting Procedure (pressurized pipe)

3.4.5 Criteria for failure in FEA

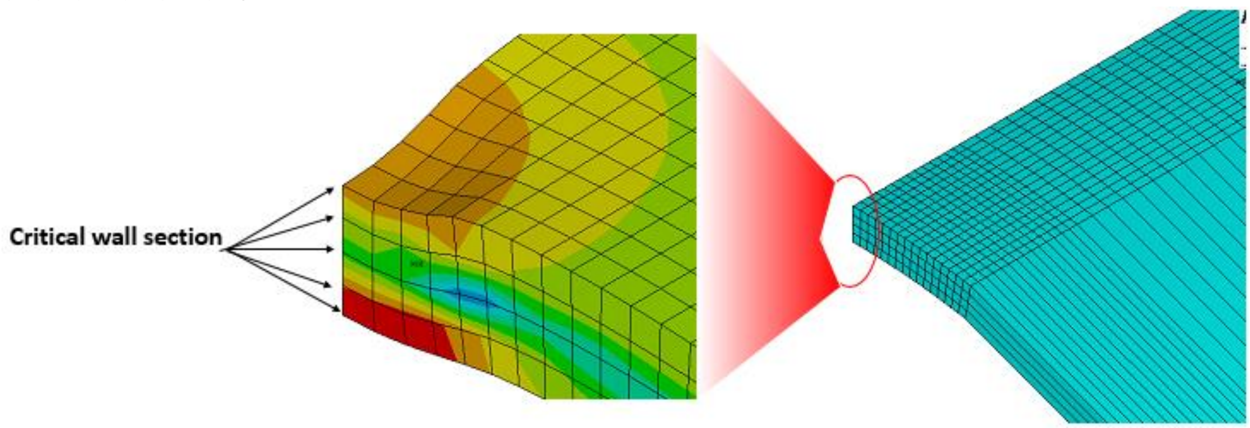


Fig. 3.13 Sketch of critical wall section

A commonly used criteria to evalutate failure of pipelines is net-section failure criteria (LIU 2017). The net-section criteria considers failure to occur when the minumum Von Mises stress value reaches the flow stress $\sigma_{f.}$ According to LIU (2017), flow stress is commonly assumed as:

$$\begin{cases} \sigma_f = \dfrac{\sigma_s + \sigma_b}{2} & (a) \\ \sigma_f = \sigma_b & (b) \end{cases}$$

$$\sigma_s: yield\ strength\ of\ pipe\ ,\ \ \sigma_b: ultimate\ strength\ of\ pipe$$

According to Table 3.1, flow stress is calculated as 513.5 MPa (a) and 563 MPa (b). Also, there are other ways of calculating flow stress, as mentioned in section 2.3.1. For Tangent section method, flow stress is calculated as 464 MPa and 465.85 MPa for 0.2% offset strain. From ANSYS burst pressure can be calculated with the flow stress given. It should be compared with experiemental results of burst pressure and decide which formula show closer result. However since there are no data to compare, (b), ultimate strength criteria, was taken as flow stress to present conservative view.

CHAPTER 4

4.0 Results and Discussion

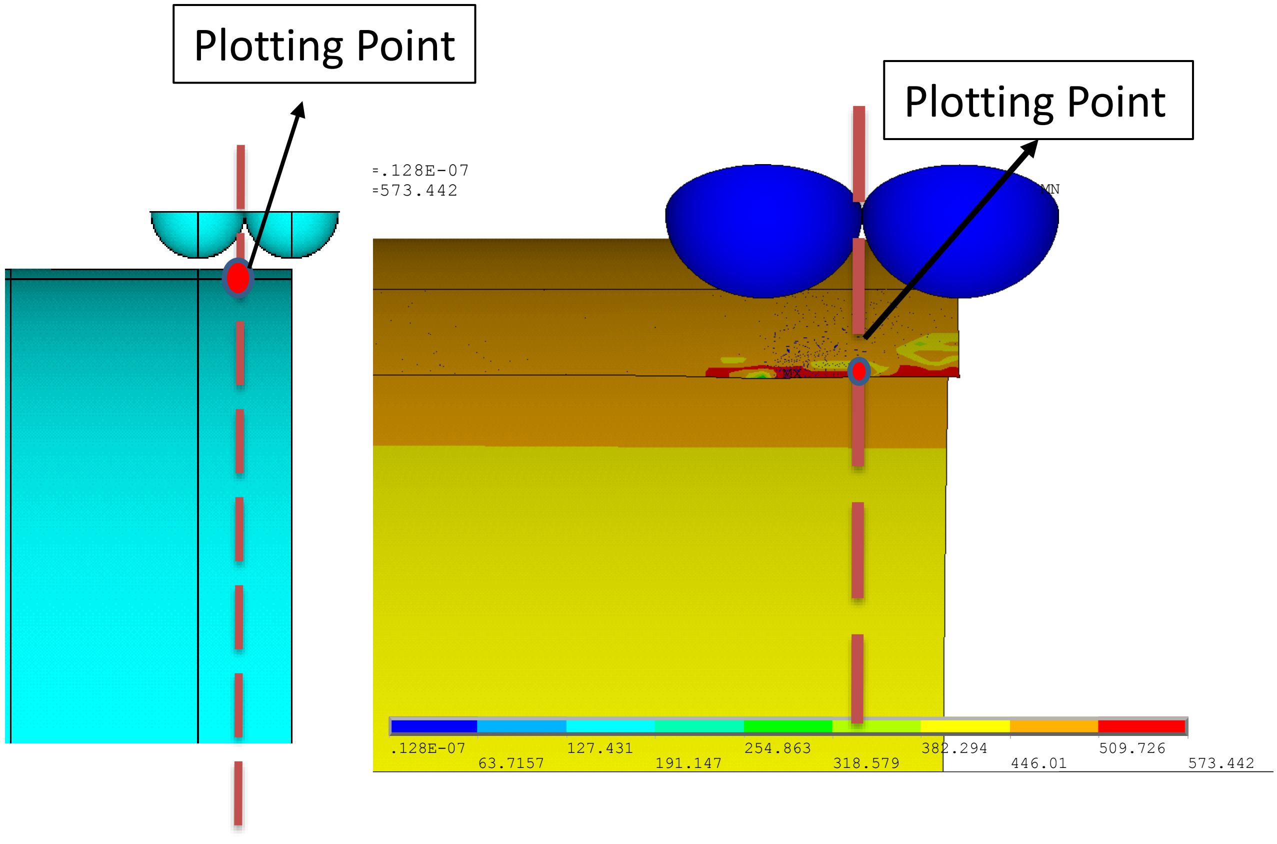


Fig. 4.1 Plotting point for comparing results

Plotting point was set to compare the results of various cases. A stationary point was set on the point on a pipeline where it is closest to the point where two indenters meet in '0-radius distance' double dent case. This point was set to determine interactions of dents clearly. If the plotting point is set as dent peak, where direct load is applied, stress is dramatic so it is hard to determine whether the stress contour is caused by interaction or direct loading.

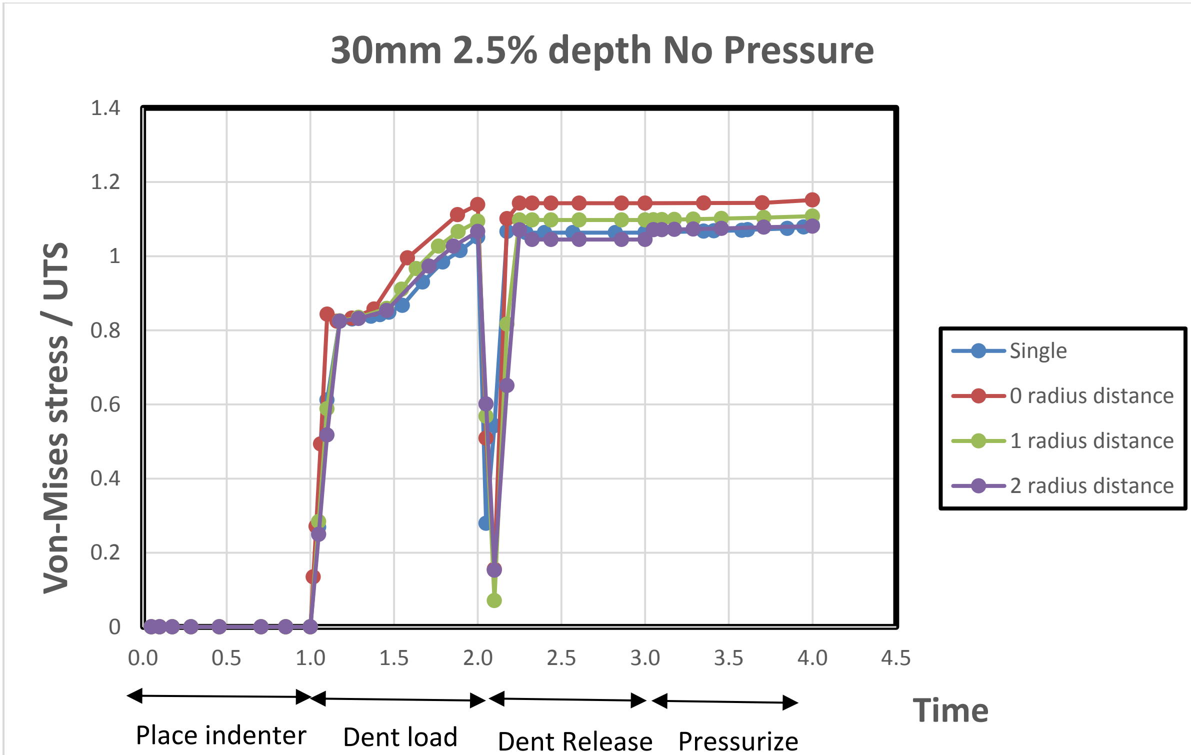


Fig 4.2 Time-Stress Graph of 30mm indenter 2.5% dent depth of pipeline, no initial pressure

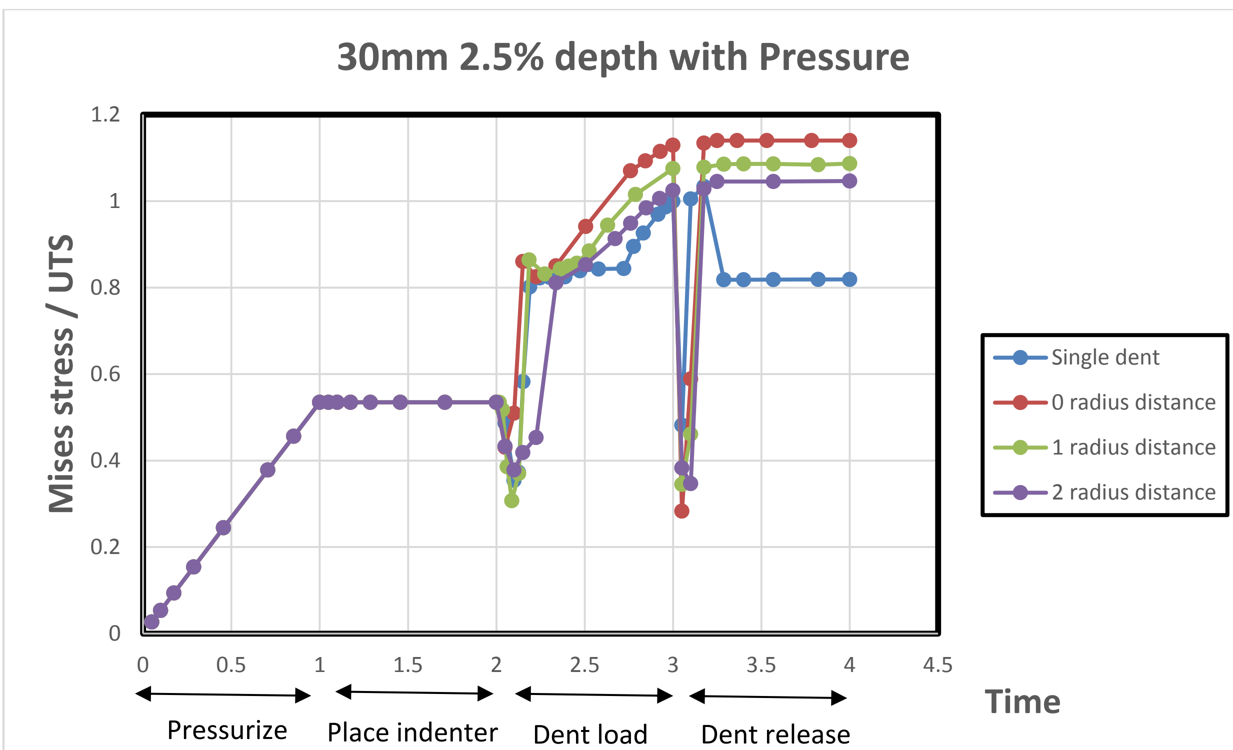


Fig 4.3 Time-Stress Graph of 30mm indenter 2.5% dent depth of pipeline, with initial pressure

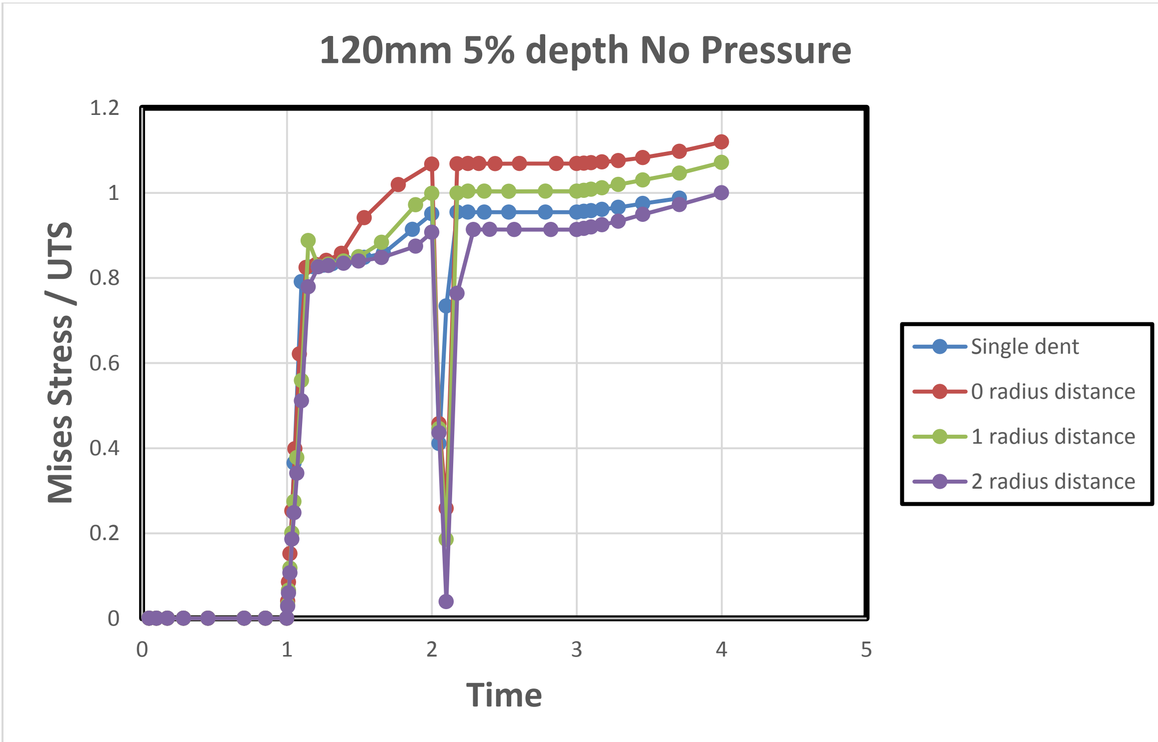


Fig 4.4 Time-Stress graph of 120mm indenter 5% dent depth of pipeline, no initial pressure

Figures above shows Von Mises stress trend in stationary point mentioned above. Y-axis is non-dimensional parameter which is Von Mises stress divided by Ultimate strength of pipeline. In the dent loading section, the stationary point becomes highly plastic as shown in the figures. It is hard to see residual stress when there is initial pressure before denting, however in figure 4.2 when indenter is released, residual stress remains in the point. As it is shown in the figures, when dent is made by single indenter, the Von Mises stress is the lower than the double dent cases. As dent distance is closer to each other, Von Mises stress increases and in this regard, as distance between the dents increases, Von Mises stress trend follows the single dent Von Mises stress graph.

4.1 Effects of Dent Distance and Indenter Diameter

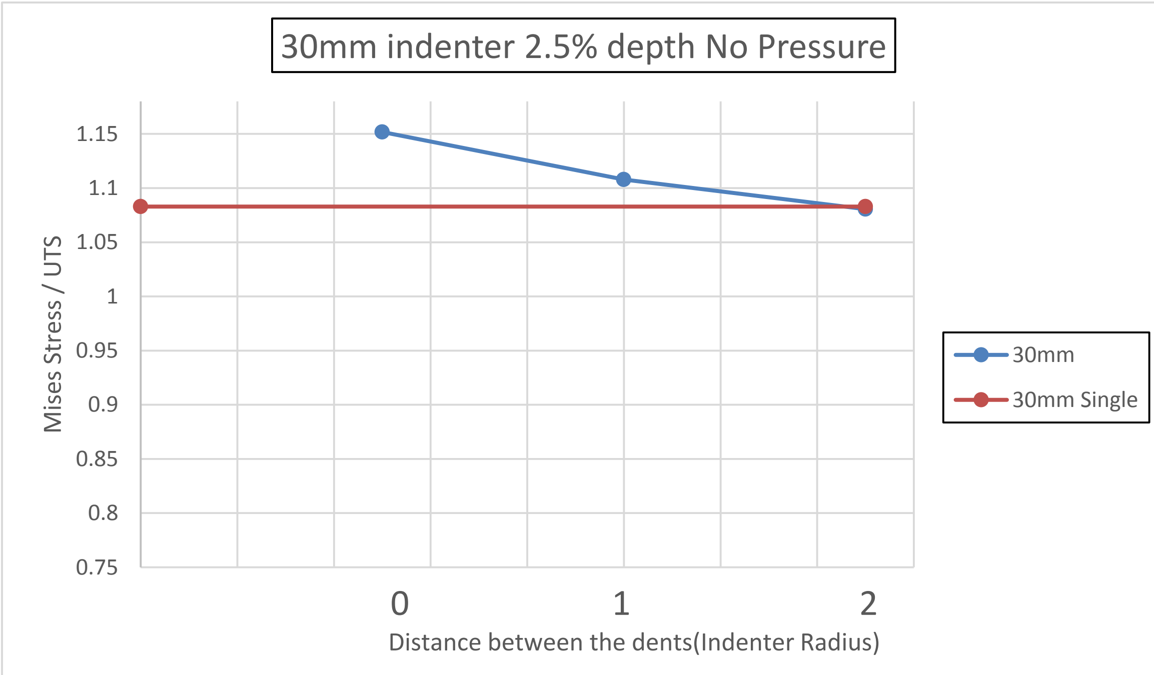


Fig 4.5 Von Mises Stress trend of 2.5% O.D. dent depth, no initial pressure – 30mm (a)

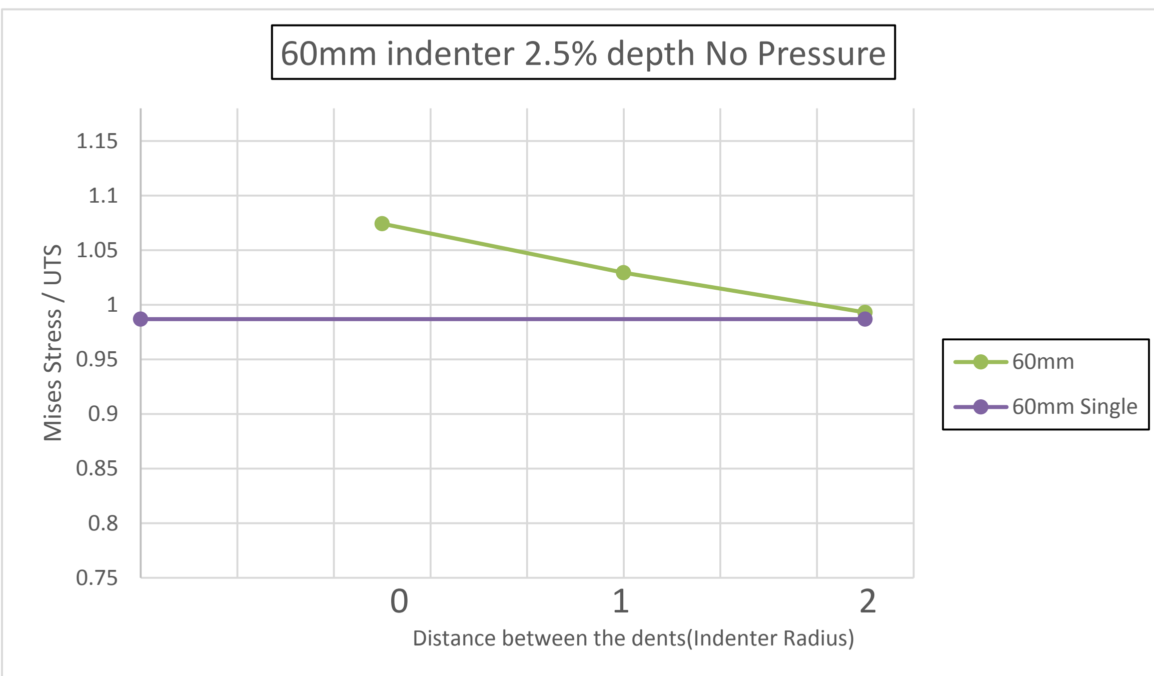


Fig 4.5 Von Mises Stress trend of 2.5% O.D. dent depth, no initial pressure – 60mm (b)

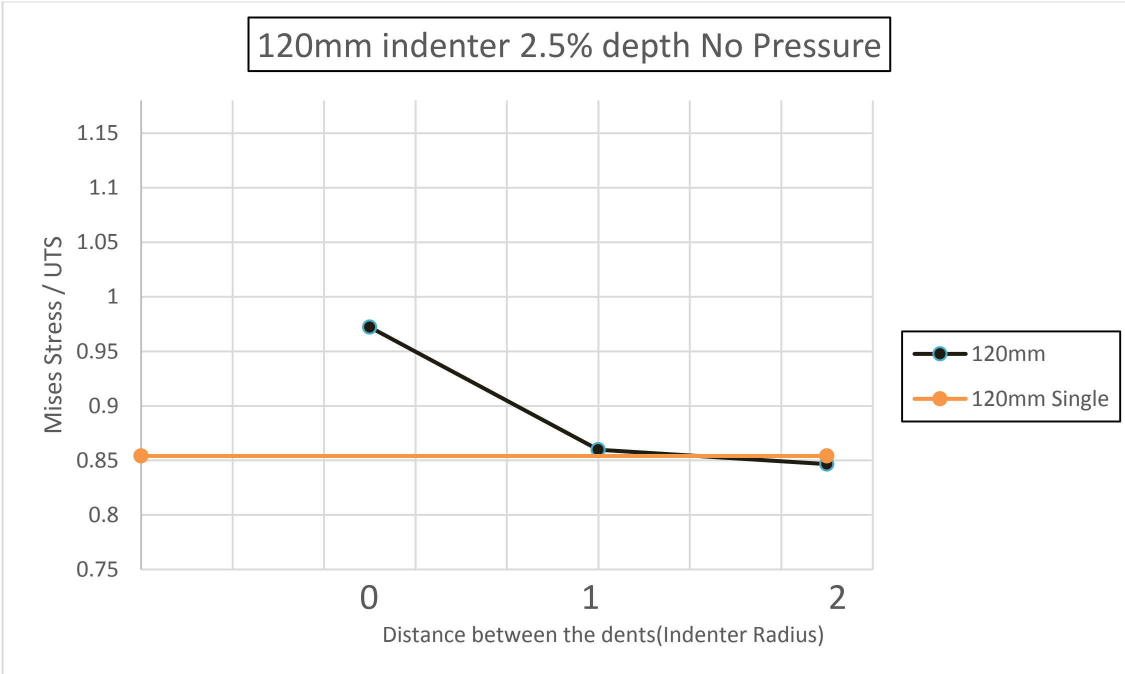


Fig 4.5 Von Mises Stress trend of 2.5% O.D. dent depth, no initial pressure – 120mm (c)

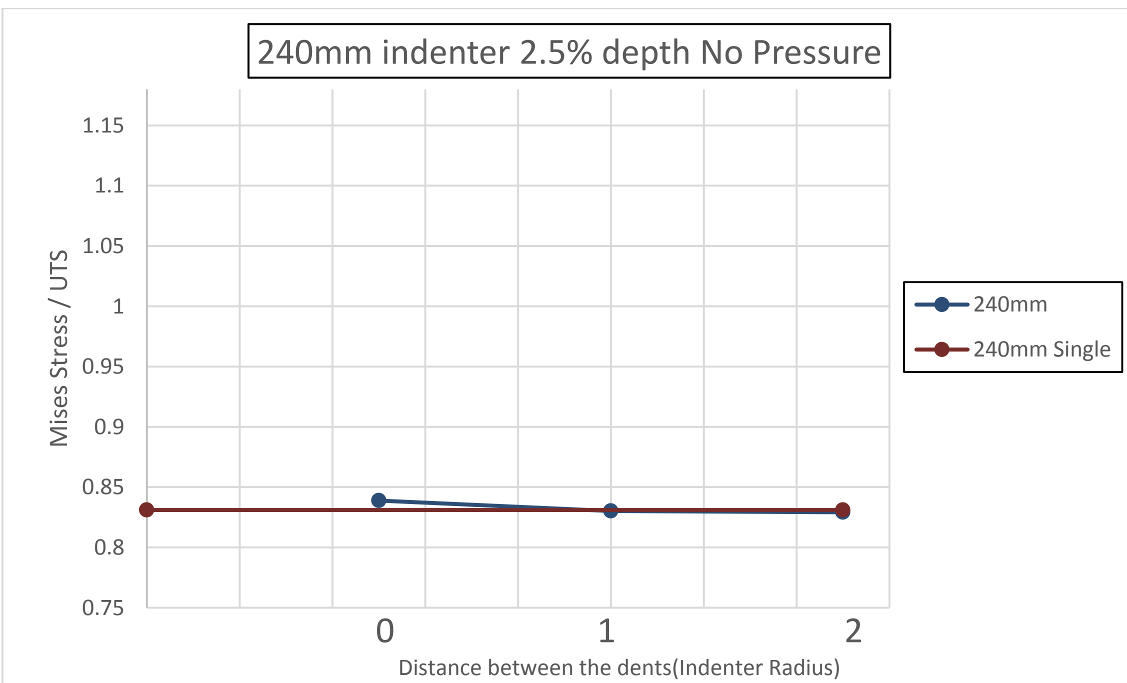


Fig 4.5 Von Mises Stress trend of 2.5% O.D. dent depth, no initial pressure – 240mm (d)

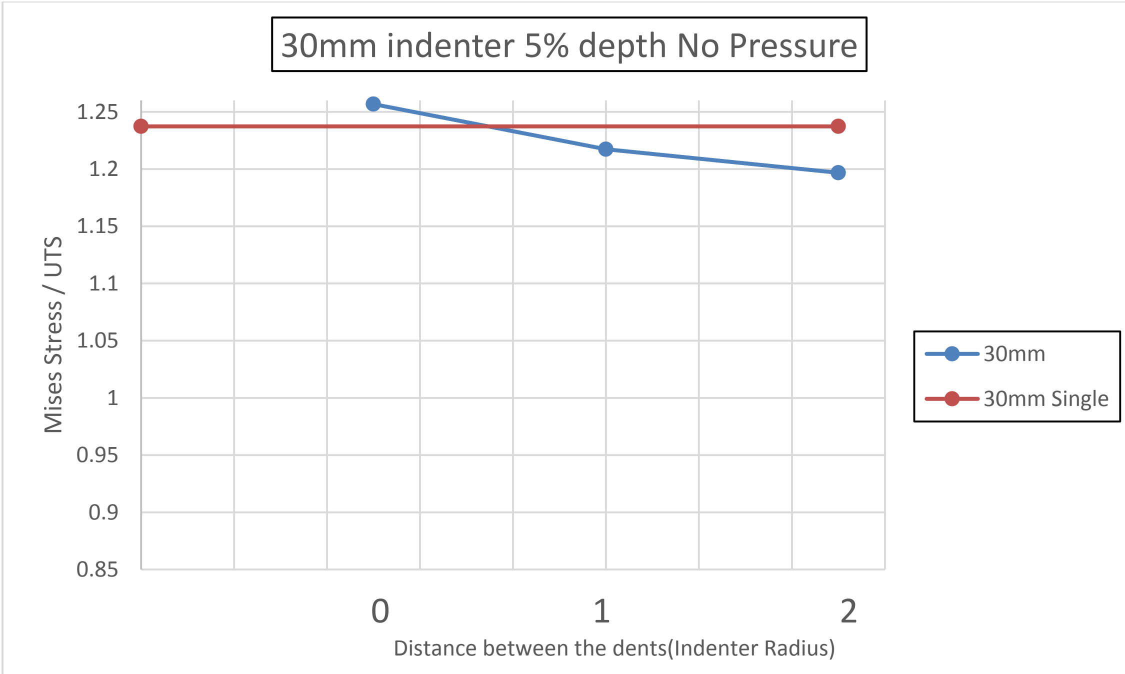


Fig 4.6 Von Mises Stress trend of 5% O.D. dent depth, no initial pressure – 30mm (a)

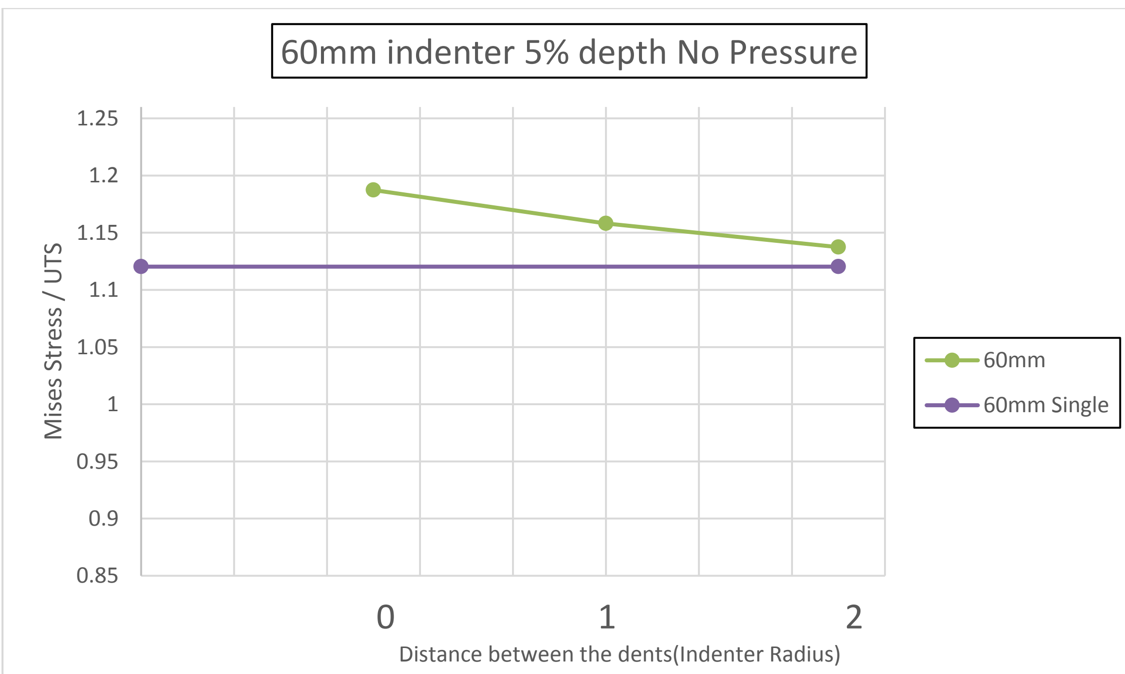


Fig 4.6 Von Mises Stress trend of 5% O.D. dent depth, no initial pressure – 60mm (b)

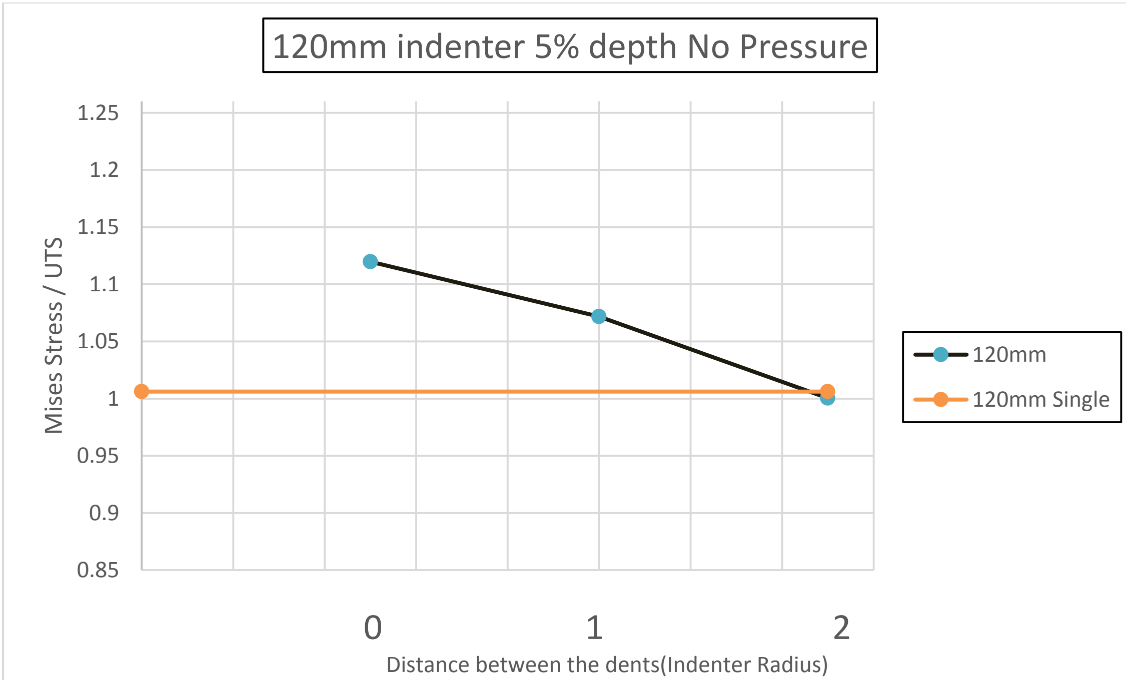


Fig 4.6 Von Mises Stress trend of 5% O.D. dent depth, no initial pressure – 120mm (c)

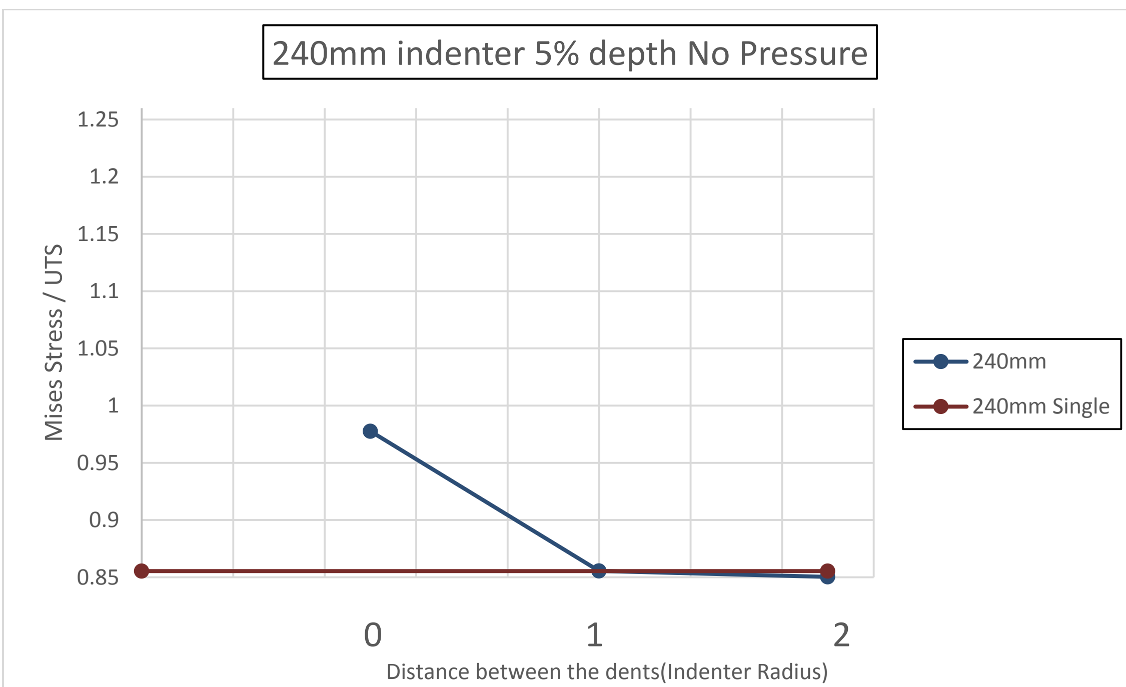


Fig 4.6 Von Mises Stress trend of 5% O.D. dent depth, no initial pressure – 240mm (d)

Four indenter diameter values were considered, i.e. 30, 60, 120, 240mm, throughout the work. Above figures lay out the relationship of normalized parameter, Von Mises Stress divided by ultimate strength of pipeline, and distance, presented as indenter's radius. The effect of distances between two dents in double dent cases are shown in figure 4.5 and 4.6. When dent depth is up to 5% of outer diameter of pipeline, it is determined that smaller indenter results higher Von Mises stress than larger indenters. This is because small diameter indenter causes radical change to the curvature of the pipeline compared to large diameter indenter. The Von Mises stress decreases as the indenter diameter increases for smaller bending strain will occur by a larger indenter and larger bending strain will be caused by a smaller indenter. Considering that pipeline's outer diameter is 762mm, 30mm diameter indenter's section area is only 0.16% of the pipeline's section area while 240mm diameter indenter's section area is nearly 10% of the pipeline's section area. In this regard, small size indenter can be represented as sharp dent and large size indenter can be represented as smooth dent. According to the analysis, this indicates that operators in the field should be more cautious about sharp dents. It can be also seen in these figures that as distance between the indenters are closer to each other, higher Von Mises stress is observed and as the distance increases, the Von Mises stress value follows the single dent case.

4.2 Effects of Initial Pressure

Single Dent	
30mm_2.5_P	Safe
30mm_2.5_NP	Safe
30mm_5_P	**Fail**
30mm_5_NP	**Fail**
30mm_10_P	**Fail**
30mm_10_NP	**Fail**
30mm_20_P	**Fail**
30mm_20_NP	**Fail**
60mm_2.5_P	Safe
60mm_2.5_NP	Safe
60mm_5_P	**Fail**
60mm_5_NP	Safe
60mm_10_P	**Fail**
60mm_10_NP	**Fail**
60mm_20_P	**Fail**
60mm_20_NP	**Fail**
120mm_2.5_P	Safe
120mm_2.5_NP	Safe
120mm_5_P	Safe
120mm_5_NP	Safe
120mm_10_P	**Fail**
120mm_10_NP	**Fail**
120mm_20_P	**Fail**
120mm_20_NP	**Fail**
240mm_2.5_P	Safe
240mm_2.5_NP	Safe
240mm_5_P	Safe
240mm_5_NP	Safe
240mm_10_P	Safe
240mm_10_NP	Safe
240mm_20_P	**Fail**
240mm_20_NP	Safe

Double Dent			
Distance (Radius)	0	1	2
30mm_2.5_P	Safe	Safe	Safe
30mm_2.5_NP	Safe	Safe	Safe
30mm_5_P	**Fail**	Safe	**Fail**
30mm_5_NP	Safe	Safe	Safe
30mm_10_P	**Fail**	**Fail**	**Fail**
30mm_10_NP	**Fail**	**Fail**	**Fail**
30mm_20_P	**Fail**	**Fail**	**Fail**
30mm_20_NP	**Fail**	**Fail**	**Fail**
60mm_2.5_P	Safe	Safe	Safe
60mm_2.5_NP	Safe	Safe	Safe
60mm_5_P	Safe	**Fail**	Safe
60mm_5_NP	Safe	Safe	Safe
60mm_10_P	**Fail**	**Fail**	Safe
60mm_10_NP	**Fail**	Safe	Safe
60mm_20_P	**Fail**	**Fail**	**Fail**
60mm_20_NP	**Fail**	**Fail**	**Fail**
120mm_2.5_P	Safe	Safe	Safe
120mm_2.5_NP	Safe	Safe	Safe
120mm_5_P	Safe	Safe	Safe
120mm_5_NP	Safe	Safe	Safe
120mm_10_P	**Fail**	Safe	**Fail**
120mm_10_NP	Safe	Safe	Safe
120mm_20_P	**Safe**	**Fail**	**Fail**
120mm_20_NP	**Fail**	**Fail**	Safe
240mm_2.5_P	Safe	Safe	Safe
240mm_2.5_NP	Safe	Safe	Safe
240mm_5_P	Safe	Safe	Safe
240mm_5_NP	Safe	Safe	Safe
240mm_10_P	Safe	Safe	Safe
240mm_10_NP	Safe	Safe	Safe
240mm_20_P	Safe	Safe	**Fail**
240mm_20_NP	Safe	Safe	Safe

Table 4.1: Summary of failure analysis results of pipeline

Above table is results of failure tests of the analysis. As the initial pressure will affect the stress state of the pipeline, two conditions mentioned in table 3.2 were considered. It should be regarded that failure may occur in the pipeline during the denting process. Since this work did not focus on the burst pressure of the pipeline, it only could be determined whether the failure occurred during the denting process, or if the pipeline failed in the pressurizing session or the pipeline remained safe. Among all 128 cases, 47 failure cases existed and about 96% of them occurred in the denting process. In addition, among the 47 failure cases, 10 cases showed the direct effects of initial pressure as pressurized pipe failed during the denting process while non pressurized pipe did not. It should be remarked that denting process is extremely large external loading process to pipeline and as a result, high plastic deformation occurs and in some cases failure may occur during the process, which this depth is defined as critical dent depth. ASME code defines critical dent depth as 6% of the pressurized pipe. Although ASME code is conservative view, regarding that increase in dent depth results in higher stress, 10% and 20% dent depth of the pipe diameter would be over or close to the critical dent depth so elements would not be plotting reasonable data if the pipeline has failure occurred.

In some cases, for example 30mm_5_P or 60mm_5_P, single dent case showed higher stress than double dent. This case can be explained by superposition of the loading. Single dent cases may cause more curvature to the pipeline at the loading point than the double dent case which causes higher stress, for example as shown in figure 4.7. Strain in single dent case, maximum strain 1.64994, is much higher than double dent case, maximum strain 0.647105. In other words, during the interaction of the dents stress can be overlapped each other but also can offset the stress as shown in figure 4.8.

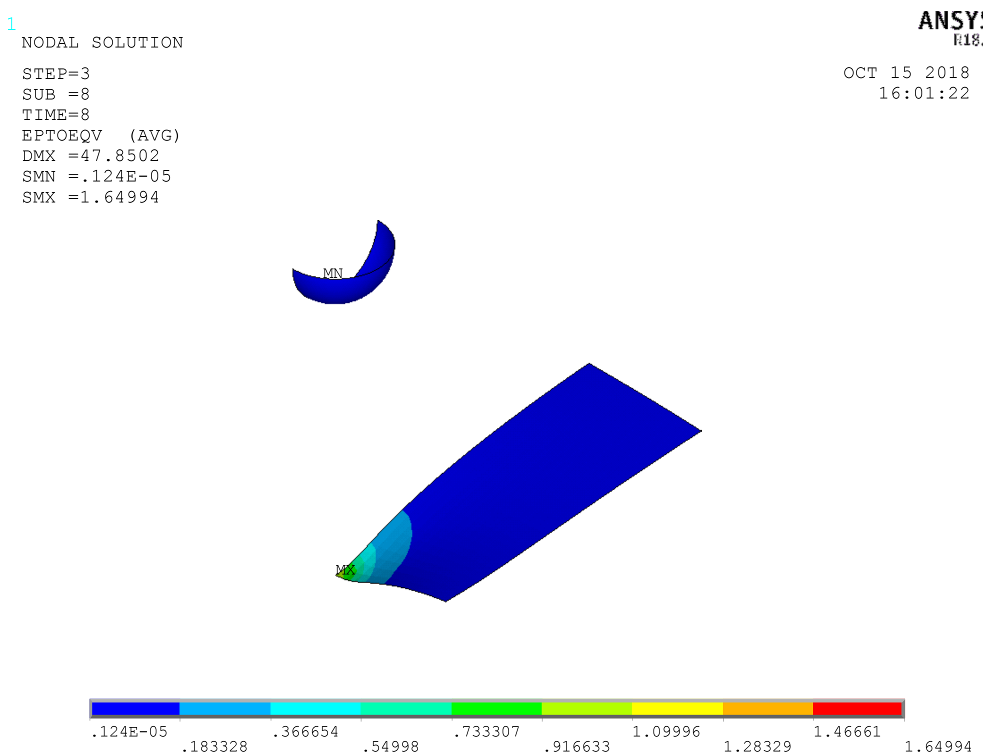


Fig 4.7 Strain distribution of 30mm_5_NP_Single (a)

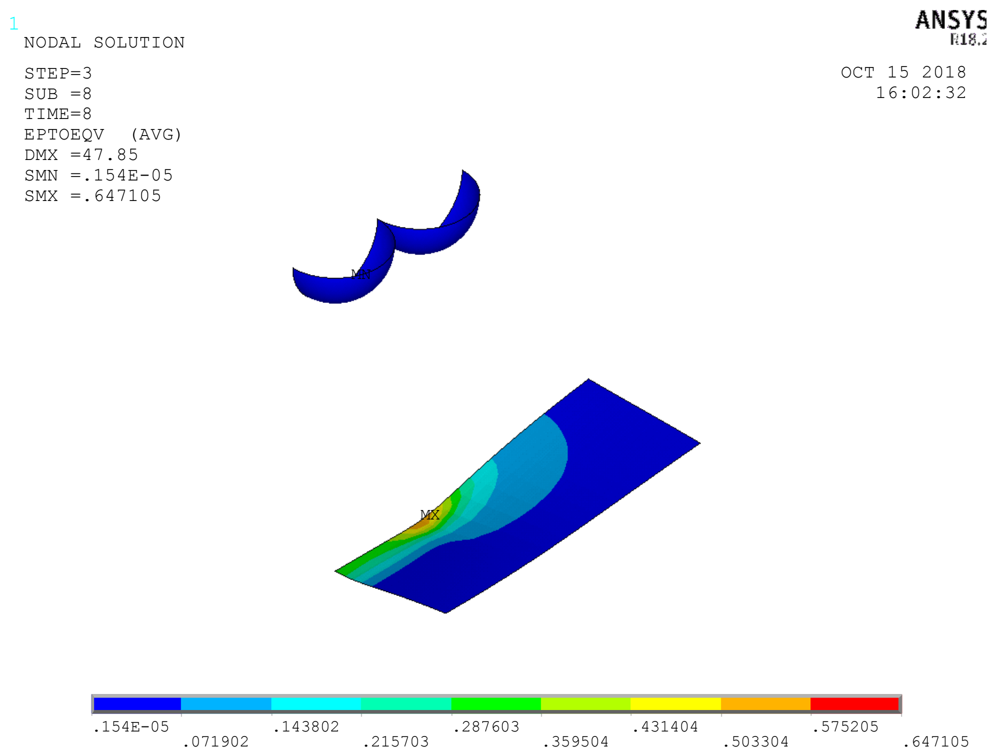


Fig 4.7 Strain distribution of 30mm_5_NP_0 (b)

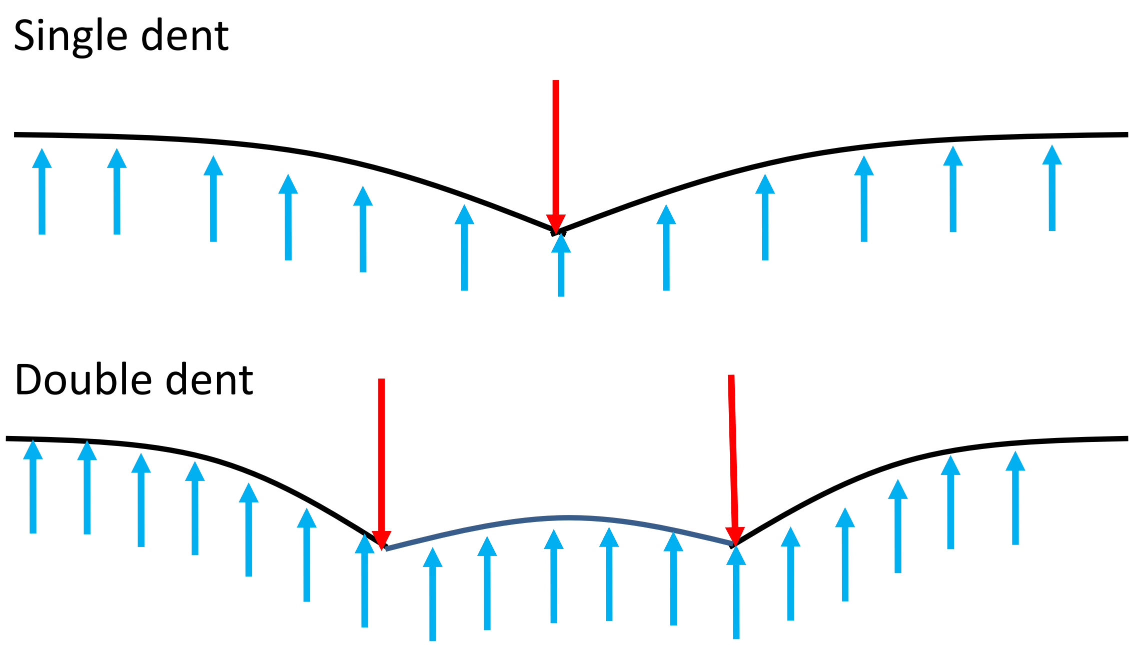


Fig 4.8 Schematization of the offset interaction of double dent

However it is hard to tell in which case the overlapping occurs or offset occurs. In this work only determination of failure is considered, which is hard to compare in quantifying results. To determine more definite interactions of initial pressure, it is better to compare burst pressure which was not considered in this work.

4.3 Conclusions

Von Mises stress trend on a dent defected pipeline was investigated in this study using FE analyses. 3D finite element model was established by software package of ANSYS 18.2 and validated by comparing data of a thesis by Baek (2012). FE analyses were performed to estimate effects of double dents varying the dent depth, presence of initial pressure and indenter diameter and distances between the indenters. Some conclusions could be drawn as below:

1. To a certain depth, as dent distance gets further from each other, the interaction becomes weaker and to some point, double dents should be considered as two single dents.
2. Initial pressure effects stress state of the pipeline, which makes it more vulnerable in denting process than non-pressurized pipeline.
3. As mentioned in section 4.1, according to the analysis, sharp dents are more dangerous than large dents.
4. In the interaction of double dents, not only overlapping of the stress exist but also offsetting of the stress exist.

CHAPTER 5

5.0 FURTHER WORK

For the future work of the study, the final goal would be to develop a guideline that could be used to evaluate the interactions of double dents and determine its damage if replacement is required. The following are some recommendations for future studies.

1. Compare burst pressures of the cases to better determine the behaviour of the initial pressure.
2. In some cases, single dents were more critical than double dent cases. Comparing large single dent and two adjacent double dents would be necessary to determine whether it should be seen as single dent case or double dent case.
3. Conduct analyses on different pipe model to know the effects of dent depths.
4. Perform more analyses on different size and shape of indenters in order to better understand the effects of double dents.

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APPENDIX

Finite Element Model Set Up

In this section, set up procedure for Finite element validation model in section 3.2 is provided. The software used for Finite Element Analysis of this work is ANSYS APDL 18.0. ANSYS APDL has advantage of using codes unlike other FE softwares. It is convienent when changing parameters because when using graphic interface, user have to set up the whole model for each cases but in APDL user can simply change the variable for different cases. The below is the whole code used in the validation model. The code will be explained in sections with ANSYS screen figures.

1. **Setting up parameters**

```
/PREP7
*AFUN,rad
ET,1,186,,,1      !Element Solid186 is used

!Indenter parameter
gap = 2           !the gap between the end of indenter and pipeline out dia.
ITR = 80/2        !indenter top radius
Depth = 2         !indenter depth without bottom radius
IBR = 80/2        !indenter bottom radius

!Pipe parameter

OD = 762          !Pipe outer diameter(Unit: mm)
OR  = OD/2        !out radius(UNIT: mm)
THK = 17.5        !wall thk.(UNIT: mm)
IR  = OR-THK      !inner radius(UNIT: mm)
ID  = 2*IR        !inner diamter(UNIT: mm)
L   = 1000        !length(UNIT: mm)
Mar = 2*ITR       !length margin for contact area
P   = 0           !applied inner pressure(UNIT:Mpa)
TS1  = P*ID*ID
TS2  = OD*OD-ID*ID
MSF1 = 1/4        !MESH SIZE FACTOR for dented area
MSF2 = 1          !MESH SIZE FACTOR for adjacent dented area
MSF3 = 8          !MESH SIZE FACTOR for other area
Dist = OR+gap+IBR+Depth
                  !distance between pipeline out dia. and top plane cent. of indenter
pi = acos(-1)
degree = nint(360*2*IBR/(2*pi*OR))+1
                  ! For fine meshing setting up the cutting angle

*AFUN,deg         !Using degree instead of radian
```

```
!Dent depth parameter
Ratio = 0.1        !dent depth vs. OD
DD = OD*Ratio             !dent depth
Idist = DD+gap !indenter moving distance
```

This part is setting up which element is going to be used and what the dimensions are for the pipeline and indenter. In the validation model, Solid186 element is used for the analysis. To use shell element, change the code from ET, 1, 186,,,1 to ET,1,181,,,1 which is Shell181 element. As it is mentioned in section 3.2, two types of indenter were used and the diameter is 40mm and 80mm each. In the code above, 80mm diameter indenter is set up. To model 40mm diameter indenter, change ITR and IBR value to 40/2. For pipe modelling, outer diameter was set as 762mm and thickness as 17.5mm. Length was modelled as 1000mm because symmetric boundary conditions are going to be applied later. Initial pressure was set as 0 MPa. To change the pressure, put different P value. Indenter are put in to the pipe to designated depth which is 19, 38, 76 and 114 mm, which is equal to 2.5%, 5%, 10% and 15% of pipe outer diameter of validation model. To change the dent depth, change ratio from 0.025, 0.05, 0.1 and 0.15.

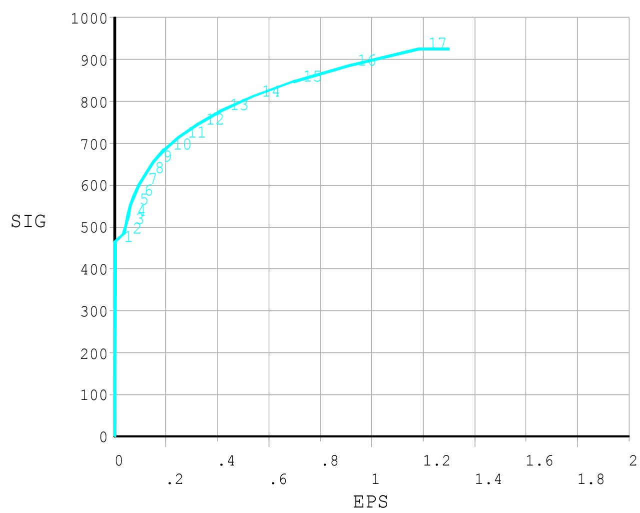
2. **Material Properties of Pipeline and indenter**

```
! MATERIAL PROPERTIES of PIPE
MP,EX,1,210000           !(UNIT: mm)
MP,PRXY,1,0.3
TB,MISO,1,1,17,
TBTEMP,0
TBPT,,0.0022095,4.64E+002
TBPT,,0.12021,6.2731E+002
TBPT,,1.1829,9.2471E+002
TBPLOT ,MISO,1
```

```
! MATERIAL PROPERTIES of Indenter
MP,EX,2,2070000         !(UNIT: mm)
MP,PRXY,2,0.3
TB,BISO,2,2               ! Activate a data table
TBTEMP,0.0                ! Temperature = 0.0
TBDATA,1,10000,1000          ! EPP model
TBPLOT
```

```
/VUP,1,Y
/VIEW,1,,,1
CSWPLA,11,1
```

For the pipeline, isotropic hardening was considered. Young's modulus were set up as 210GPa and Poisson's ratio as 0.3. Stress and strain values were put as provided. For the indenter, there weren't any material properties provided, only assumed as rigid material. Young's modulus for the indenter was set up as about 10 times higher to perform as rigid material compared to the pipeline. Indenter's hardening was set up as elastic-perfectly-plastic bilinear curve.



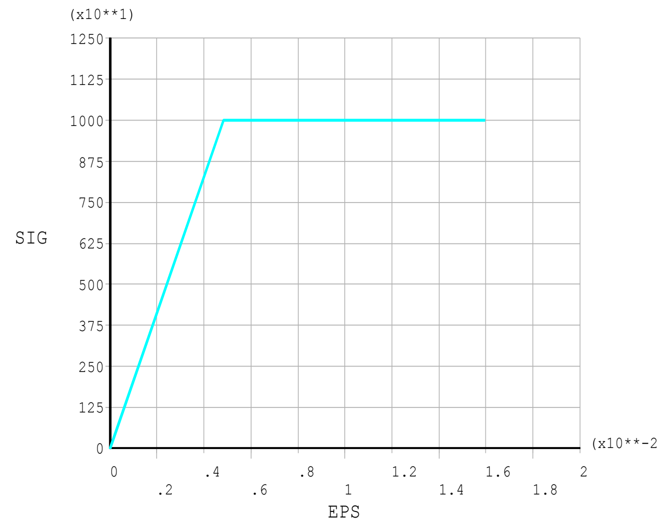


Figure A.1- Material Property of pipeline (left) and indenter (right) modelled in ANSYS

3. **Modelling pipeline and indenter.**

```
!MODELING
!KEYPOINT
k,1,
k,2,IR
k,3,OR
KGEN,2,2,3, , ,90, , ,0

!LINE
L,2,3
L,3,5
L,5,4
L,4,2

!AREA
AL,1,2,3,4
AGEN,2,1, , , ,-90, , ,0
NUMMRG,ALL
NUMCMP,ALL
/VIEW, 1 ,1,1,1
/REP
```

```
KGEN,2,1,,,,,L-3*Mar
*get,zero copy_kp,kp,,num,max
L,1,zero copy_kp
*get,zero copy_line,line,,num,max
VDRAG,ALL, , , , , ,zero copy_line
KGEN,2,zero copy_kp,,,,,2*Mar
*get,first copy_kp,kp,,num,max
L,zero copy_kp, first copy_kp
*get,first copy_line,line,,num,max
ASEL,S,LOC,Z,L-3*Mar
VDRAG,ALL, , , , , ,first copy_line
nummrg,all
numcmp,all
allsel,all
KGEN,2,first copy_kp,,,,,Mar
*get,second copy_kp,kp,,num,max
L,first copy_kp, second copy_kp
*get,second copy_line,line,,num,max
ASEL,S,LOC,Z,L-Mar
VDRAG,ALL, , , , , ,second copy_line
allsel,all
NUMMRG,ALL
NUMCMP,ALL

KGEN,2,1,,,,,L,,1
*get,CNC,kp,,num,max !Center of New Coordinate(CNC)
kwpave,CNC
cswpla,12,1

csys,11
k,,OD,90-degree
*get,KP1 for area,kp,,num,max

csys,12
k,,OD,90-degree
*get,KP2 for area,kp,,num,max

a,1,CNC,KP2 for area, KP1 for area
VSEL,S,LOC,Y,0,90
CM,volume_div.,VOLU
ASEL,S,LOC,Y,89-degree,91-degree
CM,area_div.,area
VSBA,     volume_div.,     area_div.
allsel,all
nummrg,all
numcmp,all
```

This code is for modelling the pipeline. To fine mesh the denting area later on, areas have to be divided in this modelling part. Below figure is the outcome of the code.

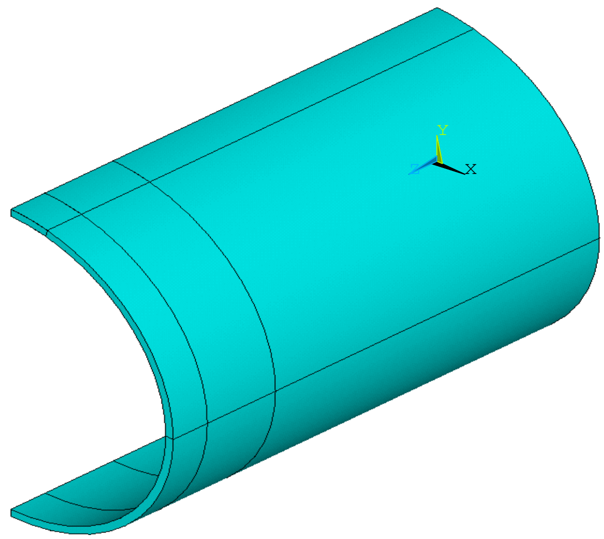


Figure A.2- Pipeline modelled in ANSYS

4. **Mesh attribution for pipeline**

```
!Mesh attributes & mesh for pipeline
CSYS,11
VATT,1,,1,11
VSEL,S,LOC,Z,L-Mar,L
VSEL,R,LOC,Y,90-degree,90+degree
ESIZE,MSF1*THK
VMESH,ALL
allsel,all
VSEL,S,LOC,Z,L-Mar,L-2*mar
VSEL,R,LOC,Y,90-degree,90+degree
ESIZE,MSF2*THK
VATT,1,,1,11
VMESH,ALL
allsel,all
VSEL,S,LOC,Z,L-2*Mar,L
VSEL,R,LOC,Y,90-degree,90+degree
CM,VOLUME_UNSELECT,VOLU
allsel,all
VSEL,U,,,VOLUME_UNSELECT
ESIZE,MSF3*THK
VMESH,ALL
allsel,all
```

To fine mesh dented area and achieve efficient computation time, mesh size varied from area to area. Areas were divided into 3 parts. First part is the fine meshed area, which is area where the contact of the indenter is directly made. As mentioned in chapter 3, 4 layers of solid elements were used throughout the pipe thickness direction.

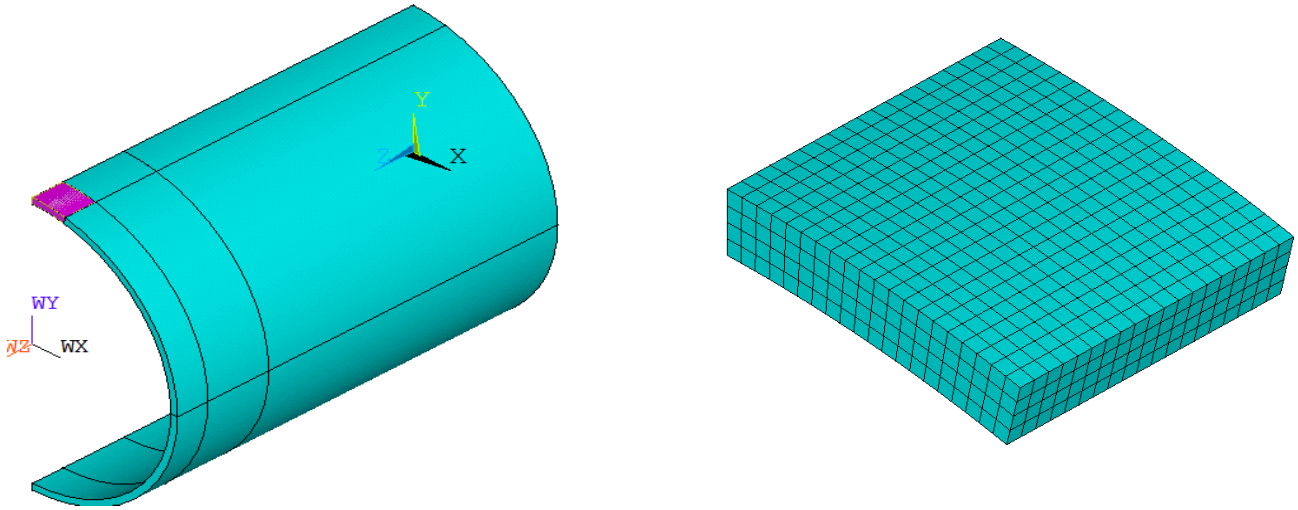


Figure A.3- Fine meshed area

Second part of the meshed area is where dent does not make contact directly but close to the dented area. This part was meshed with medium sized mesh, about 4 times bigger than fine meshed area.

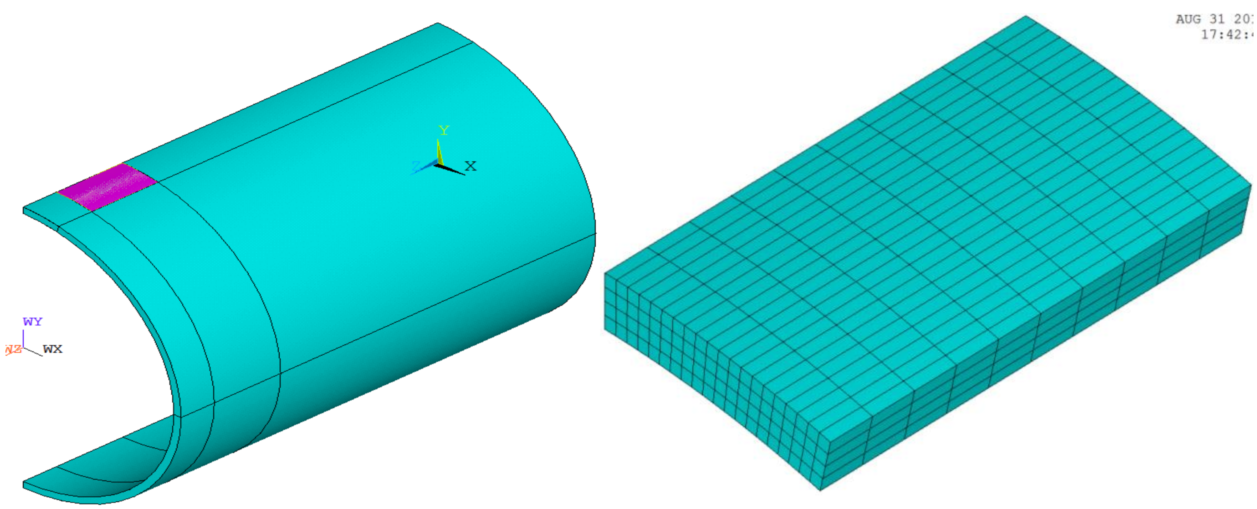


Figure A.4- Second part of meshed area

Lastly, rest of the part is meshed with large meshes, about 16 times larger than the fine meshed area. This is because pipe is much bigger than the indenter so denting does not affect the whole pipeline. It is true that using small meshes show better results, however considering that I this work about 130 cases have to be run so computational time is also important. The mesh size were decided after convergence test. The study is explained in section 3.3.7.

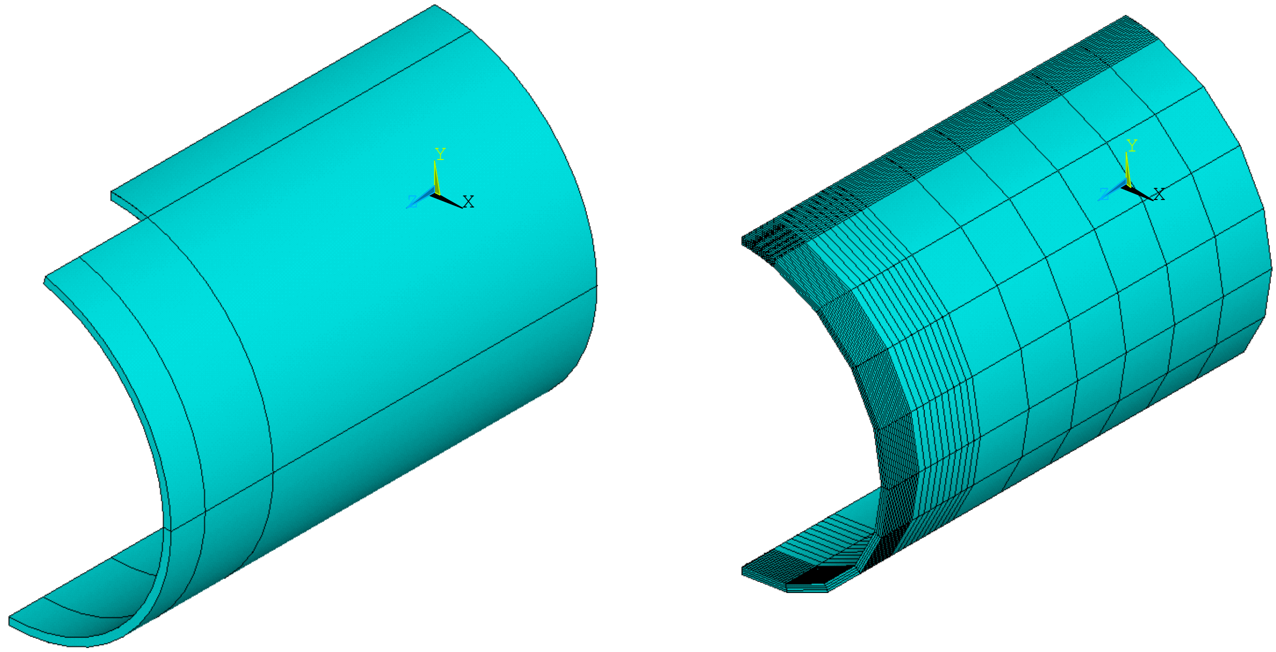


Figure A.5- Third part of meshed area (left) and meshed pipeline (right)

5. Indenter modelling and meshing

```
!Indenter modeling
CSYS,0
KGEN,2,1,,,,dist,,,1
*get,copy_kp,kp,,num,max
KGEN,2,copy_kp,,,,,L,1
*get,first_kp,kp,,num,max

kwpave,first_kp
KGEN,2,first_kp,,,ITR, , , ,0
*get,second_kp,kp,,num,max
KGEN,2,first_kp,,,ITR,-Depth, , ,0
*get,third_kp,kp,,num,max
KGEN,2,first_kp,,,,-depth-IBR, , ,0
*get,forth_kp,kp,,num,max
KGEN,2,first_kp,,,,-depth, , ,0
*get,fifth_kp,kp,,num,max
l,second_kp, third_kp
CSYS,11
kwpave,fifth_kp
PCIRC,ibr, ,270,360,
*get,first_area,area,,num,max
CSYS,0
```

```
A,first_kp,second_kp,third_kp,fifth_kp
*get,second_area,area,,num,max

VROTAT,first_area, , , , , ,first_kp,forth_kp360, ,
VROTAT,second_area, , , , , ,first_kp,forth_kp,360, ,
NUMMRG,ALL
NUMCMP,ALL

kwpave,1
VSEL,S,LOC,Y,OR+gap,dist
VATT,       2, ,   1,       0
ESIZE,MSF1*THK
!ESIZE,THK*1/4
VMESH,ALL
allsel,all
```

In the validation model, indenter was modelled as half-sphere with 80mm diameter. Indenter size can be changed by varying ITR and IBR parameter in section 1. Generally, it is considered that at least 10 to 15 elements along the radius are needed to perform a curvature. If there are few elements along the curvature, the shape gets uneven.

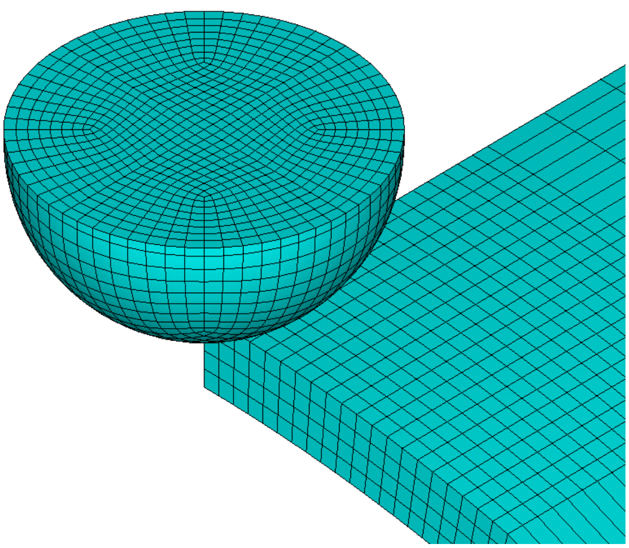


Figure A.6(a) - Meshed Indenter

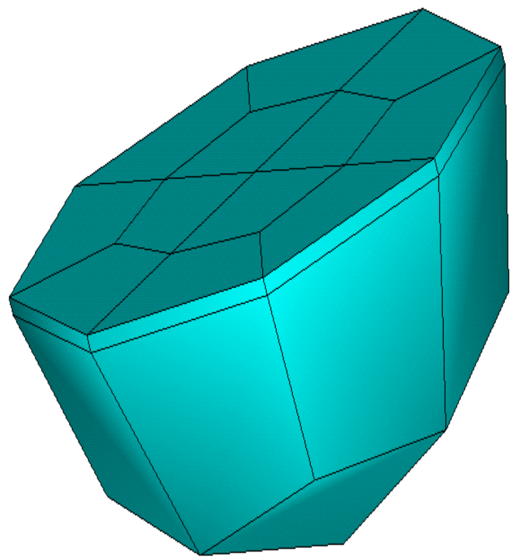


Figure A.6(b) - When elements are not enough to perform a curvature

6. **Contact between indenter and pipeline**

```
!!!!!!!!!! START OF CONTACT !!!!!!!!!!
/COM, CONTACT PAIR CREATION - START
CM,_NODECM,NODE
CM,_ELEMCM,ELEM
CM,_KPCM,KP
CM,_LINECM,LINE
CM,_AREACM,AREA
CM,_VOLUCM,VOLU
/GSAV,cwz,gsav,,temp
MP,MU,1,
MAT,1
R,3
REAL,3
ET,2,170
ET,3,174
KEYOPT,3,9,0
KEYOPT,3,10,2
R,3,
RMORE,
RMORE,,0
RMORE,0
! Generate the target surface
ASEL,S,,,40
CM,_TARGET,AREA
TYPE,2
NSLA,S,1
ESLN,S,0
ESLL,U
ESEL,U,ENAME,,188,189
NSLE,A,CT2
ESURF
CMSEL,S,_ELEMCM
! Generate the contact surface
ASEL,S,,,45
CM,_CONTACT,AREA
TYPE,3
NSLA,S,1
ESLN,S,0
NSLE,A,CT2 ! CZMESH patch (fsk qt-40109 8/2008)
ESURF
ALLSEL
ESEL,ALL
ESEL,S,TYPE,,2
ESEL,A,TYPE,,3
ESEL,R,REAL,,3
/PSYMB,ESYS,1
```

```
/PNUM,TYPE,1
/NUM,1
EPLOT
ESEL,ALL
ESEL,S,TYPE,,2
ESEL,A,TYPE,,3
ESEL,R,REAL,,3
CMSEL,A,_NODECM
CMDEL,_NODECM
CMSEL,A,_ELEMCM
CMDEL,_ELEMCM
CMSEL,S,_KPCM
CMDEL,_KPCM
CMSEL,S,_LINECM
CMDEL,_LINECM
CMSEL,S,_AREACM
CMDEL,_AREACM
CMSEL,S,_VOLUCM
CMDEL,_VOLUCM
/GRES,cwz,gsav
CMDEL,_TARGET
CMDEL,_CONTACT
/COM, CONTACT PAIR CREATION - END
!!!!!!!!!! END OF CONTACT !!!!!!!!!!
```

This part is making contact pairs with the pipeline and the indenter. This section is easier to explain in figures.

1.  Click this icon, Pair based contact management.
2.  Click this icon, Contact wizard
3. By clicking contact wizard, user have to choose the contact surface and target surface because to make a contact pair, target surface and contact surface has to be defined. Contact surface can penetrate target surface but target surface can't penetrate contact surface. Generally, contact surfaces are selected that has more rigid material properties between the two surfaces or when the material properties are the same, target surfaces are selected where the user wants to see more closely. In this study, fine meshed area was selected as target surface and indenter was selected as contact surface because of the reasons explained above.

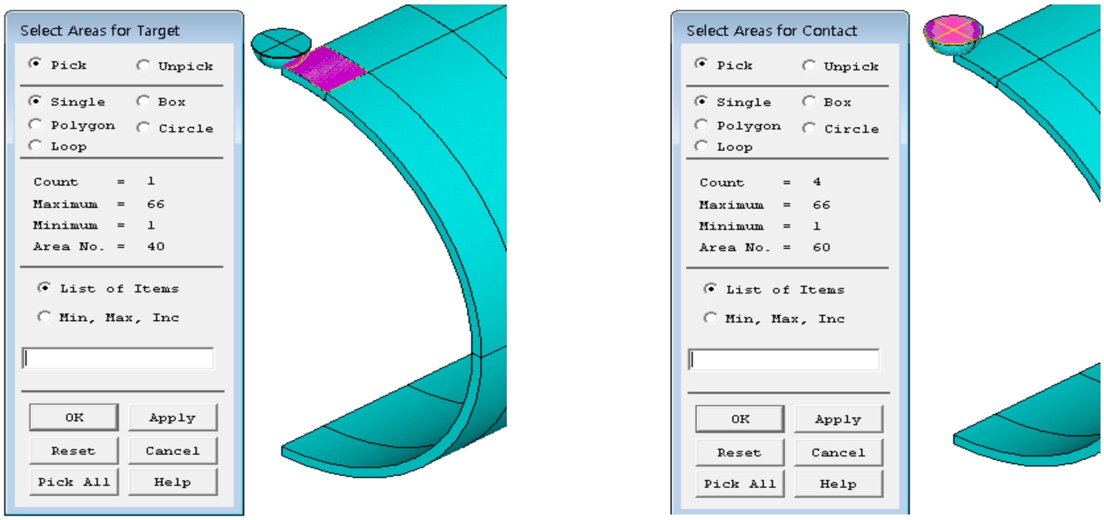


Figure A.7 – Selecting Target surface and Contact surface by contact wizard

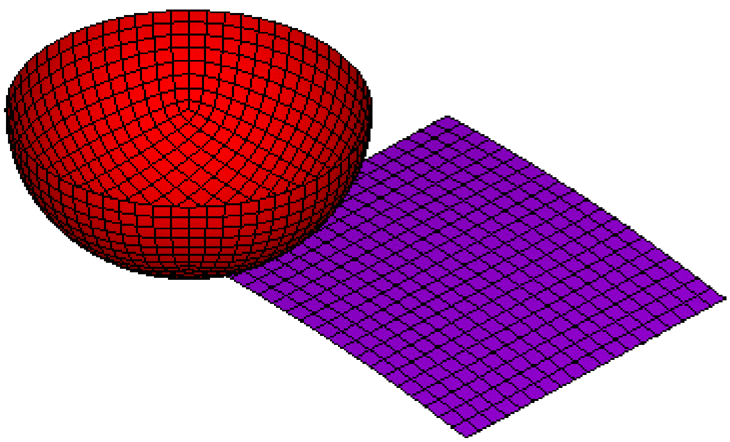


Figure A.8 – Contact pair made by contact wizard

7. **Boundary conditions**

```
NSEL,S,LOC,Y,OR+gap,dist
CM,indenter,NODE
allsel,all

FINISH
/SOL
LSEL,S,LOC,Y,-OR,,,0
DL,ALL,,ALL                              ! Bottom line fixed
allsel,ALL
```

```
ASEL,S,LOC,Z,0,,,0
DA,ALL,UY
Allsel,ALL                              ! Section C constrain


KSEL,S, , , forth_kp
NSLK,S
*get,BD_node,node,,num,max

ASEL,S,LOC,Z,L-1,L+1
DA,ALL,SYMM
allSEL,ALL                              ! Section B symmetric condition (side)

ASEL,S,LOC,X,-1,1
DA,ALL,SYMM
allSEL,ALL                              ! Section B symmetric condition (front)
```

As mentioned in chapter 3, pipe bottom was fully fixed to avoid rigid body motion. For the side and front of the pipe, symmetric boundary condition was applied. For the pipe end, boundary conditions were applied in only in Y direction to allow axial forces act on pipeline due to internal pressure.

8. **Load steps**

```
!Load step

D,BD_node, ,0, , , ,UX,UZ, , , ,               ! To avoid rigid body motion of indenter
D,indenter, ,-gap, , , ,UY, , , , ,
time,1
LSWRITE,1,

DDELE,indenter,UY
D,indenter, ,-dd-gap, , , ,UY, , , , ,
time,2
LSWRITE,2,

DDELE,indenter,UY
D,indenter, ,dd+gap, , , ,UY, , , , ,
time,8
LSWRITE,3,

FLST,5,9,5,ORDE,9
FITEM,5,6
FITEM,5,12
FITEM,5,18
FITEM,5,22
FITEM,5,28
FITEM,5,30
```

```
FITEM,5,35
FITEM,5,37
FITEM,5,42
ASEL,S, , ,P51X
SFA,all,1,PRES,P
allsel,all
time,38
LSWRITE,4,
```

There are four loading steps. Firstly, indenter is placed right above the pipe. One of the indenter node must be constrained in X and Z direction to avoid rigid body motion during the indentation. Second step is making the dent to the designated depth. Third step is removing the indenter to allow elastic rebound. Finally, internal pressure is applied. For the cases when internal pressure exist before denting, the finally step is carried out before the first step.

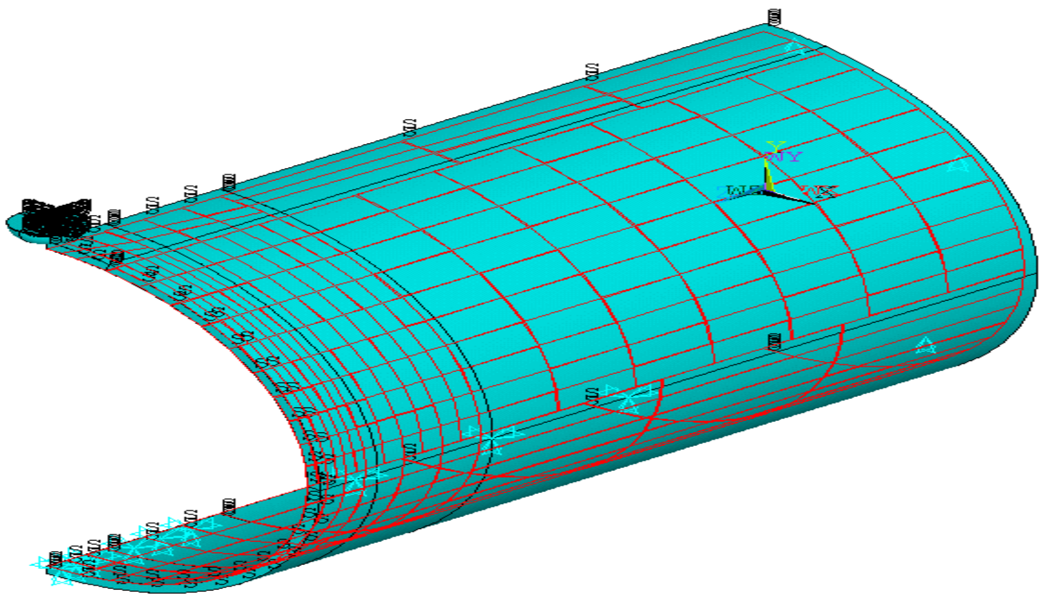


Figure A.9 – Boundary conditions and load steps applied to the model

9. **Non-linear options for analysis**

```
LNSRCH,ON              ! Line search on
NLGEOM,ON              ! Large deformation on
AUTO,ON
OUTRES,ALL,1
RESCONTROL,NORESTART,NONE
LSSOLVE,1,4,1,         ! Run steps from 1  to 4
```

Finally, options are adjusted for efficient and accurate analysis. Most importantly, large deformation option must be turned on to run non-linear analysis.