PREDICTION OF LOCAL BUCKLING BEHAVIOR OF REELED PIPELINE WITH PROBABILISTIC APPROACH USING FINITE ELEMENT ANALYSIS

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PREDICTION OF LOCAL BUCKLING BEHAVIOUR OF REELED PIPELINE WITH PROBABILISTIC APPROACH USING FINITE ELEMENT ANALYSIS

ABSTRACT

Reel-lay is a fast and cost-effective method for the installation of infield flowlines and smaller export lines up to 20”. Pipelines installed by this method undergo large plastic deformation during reeling. The natural variation of yield strength and wall thickness in the steel pipe dictates the potential for bending strength mismatches between adjacent pipes. These mismatches can cause a localized peak in strain and drive gross deformation of the pipe, which may result in a buckle if not addressed at the engineering stage.

DNVGL-ST-F101, the industrial standard widely used in the oil and gas industry for subsea pipelines, provides a formula to analyze local buckling using the displacement controlled condition. However, equations derived in the code are fixed with safety factors, limiting the minimum acceptable wall thickness. The standard also considered the presented requirements using results from pure bending. Based on successful track records that use wall thickness less than the standard has specified, Technip has published a paper addressing the discrepancy. The standard and the refined assessment procedure by Technip are both studied in this research, and then used to establish the probabilistic method.

This research outlines the probabilistic method which firstly defines the probability of failure in calculating the mismatch. Finite element model is then developed and analyzed to verify that the level of safety associated with the method is met. The reeling studies carried out in this research has shown that the probabilistic method requires far less analyses to be done, while still meeting DNVGL’s requirement.

Keywords: Local Buckling, Reeled Pipelines, Probabilistic Approach, Finite Element Analysis

RAMALAN PERLAKUAN GESERAN TEMPATAN SALURAN PAIP BERGULUNG MENERUSI PENDEKATAN PROBABILISTIK MENGGUNAKAN ANALISIS UNSUR TERHINGGA

ABSTRAK

“Reel-lay” adalah kaedah yang cepat dan kos efektif untuk pemasangan saluran paip di lapangan dan talian eksport yang lebih kecil sehingga 20”. Saluran paip yang dipasang menggunakan kaedah ini menjalani perubahan bentuk plastik yang besar semasa lingkaran. Perubahan semulajadi kekuatan dan ketebalan dinding dalam paip keluli menetapkan potensi untuk kekuatan lenturan yang sepadan antara paip berdekatan. Ketak-padanan ini boleh menyebabkan saluran paip memuncak setempat apabila dalam ketegangan dan mengubah bentuk paip, yang boleh menyebabkan lengkokan jika tidak ditangani di peringkat awal kejuruteraan.

DNVGL-ST-F101, kod standard perindustrian yang digunakan secara meluas didalam industri minyak dan gas untuk saluran paip sublaut, menyediakan formula yang menganalisis lengkokan tempatan dengan menggunakan anjakan keadaan terkawal. Walaubagaimanapun, persamaan yang diperolehi dari dalam kod telah ditetapkan dengan faktor keselamatan, membataskan ketebalan dinding minimum yang boleh diterima. Standard ini juga dianggap sebagai syarat-syarat yang ditetapkan menggunakan keputusan dari lenturan tulen. Berdasarkan rekod prestasi yang berjaya yang menggunakan ketebalan dinding kurang daripada standard yang ditetapkan, Technip telah menerbitkan kertas penyelidikan menangani percanggahan ini. Standard dan prosedur penilaian yang ditapis oleh Technip dikaji dalam kajian ini dan kemudian digunakan untuk mewujudkan kaedah kebarangkalian.

Kajian ini menetapkan kaedah kebarangkalian yang mentakrifkan kebarangkalian kegagalan dalam mengira ketak padanan. Model elemen terhad kemudian dibangunkan dan dianalisis untuk mengesahkan bahawa tahap keselamatan yang berkaitan dengan kaedah dipenuhi. Kajian semula yang dijalankan dalam kajian ini telah menunjukkan bahawa kaedah kebarangkalian memerlukan analisis yang jauh lebih rendah untuk dilakukan, dalam masa yang sama masih memenuhi syarat-syarat keperluan DNVGL.

Keywords: Lengkokan Tempatan, Lingkaran Saluran Paip, Kaedah Kebarangkalian, Analisis Unsur Terhingga

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LIST OF SYMBOLS AND ABBREVIATIONS

FORM	:	First Order Reliability Method
LV NO105	:	Lay Vessel North Ocean 105
3D	:	3-Dimensional
FEA	:	Finite Element Analysis
DNV GL	:	Det Norske Veritas Germanischer Lloyd
JIP	:	Joint Industry Project
SMYS	:	Specified Minimum Yield Stress
SMLS	:	Seamless
ULS	:	Ultimate Limit State
SLS	:	Serviceability Limit State
SWS	:	Strong-Weak-Strong Case
SSW	:	Strong-Strong-Weak Case
D	:	Outer Diameter
t , wt	:	Wall Thickness
M	:	Plastic Moment Capacity
ΔM	:	Difference in Plastic Moment Capacities (Mismatch)
σ_y	:	Yield Strength
D_{nom}	:	Nominal Outer Diameter
t_{min}	:	Minimum Wall Thickness
t_{tol}	:	Wall Thickness Negative Tolerance
$\varepsilon_{b\text{-}nom}$, ε_F	:	Nominal Bending Strain
R	:	Radius of Reel Drum
$t_{coating}$	:	Pipeline Coating Thickness

γ_{ε} : Strain Resistance Factor

γ_{F} : Functional Load Factor

γ_{C} : Condition Load Factor

α_{h} : Strain Hardening Factor

α_{gw} : Girth Weld Factor

P_{F} : Probability of Failure

Φ : Standard normal distribution cumulative distribution function

β : Reliability Index

k_t & k_f : Beneficial effect of reduced variability for an averaged cross section compared to the variability of individual measurements

σ_{t} : Standard deviation for individual wall thickness measurements

σ_{f} : Standard deviation for individual, point-wise, yield strength measurements

α_{ft} : 0-90 degrees. The mismatch distribution between the wall thickness and yield strength defined as an angular variation of these parameters

CHAPTER 1: INTRODUCTION

1.1 Research Background

Reel-lay method is a fast, cost effective method of pipelaying for pipelines up to 20” in diameter. Reel-lay pipelines are plastically deformed to conform to the radius of the reel drum that is fixed on the vessel. The reeling operation requires a high level of engineering to ensure the pipe does not buckle nor have a high lift off during reeling. This comes at the design level where the selection of wall thickness is driven by the requirements to avoid local buckling. The requirements imposed are taken from DNVGL-ST-F101, the submarine pipeline systems’ standard that is widely used in the oil and gas industry in designing pipeline. However, the requirements in the design standard have been developed under the assumption of pure bending, accounting for the presence of mismatches in bending moment between pipeline joints within fixed safety factors.

A refined assessment procedure for pipeline reeling based on the in-house assessment procedure from Technip has been published due to the discrepancy in the minimum reelable wall thickness. This procedure firstly determines the mismatch combination that is most likely to occur. Finite element models are then developed and analyzed to create a failure boundary using different combinations of mismatches. The reliability index is then determined using the failure boundary, which is then used to calculate the probability of failure. (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2009)

Finite Element Analysis (FEA) for this research will be using Abaqus FEA software suite, a tool used for modelling and analysis of components. 3D simplified reeling finite element model will be developed using this software, enabling the end user to visualize finite element analysis result in detail.

1.2 Problem Statement

The requirements set by DNVGL-ST-F101 considered geometrical and yield strength mismatches between pipe joints with safety factors, basing this off a pure bending pipe test. A refined assessment procedure published has addressed this, with multiple finite element analyses carried out to include yield strength difference between pipe joints, to obtain the probability of failure by means of a first order reliability method (FORM).

This research intends to predict local buckling behavior of reeled pipeline with a probabilistic approach using finite element analysis. The probabilistic approach will be based on the refined assessment procedure mentioned above. Additionally, this research intends to utilize the probabilistic approach in designing a transition joint, a specially made pipe that connects together pipes of different geometrical dimensions and yield strength. This approach will produce the most likely combination of mismatches given a targeted acceptable probability of failure, hence still maintaining the structural integrity of the pipelines.

1.3 Objectives

The objectives of this research are as follow:

1. To propose a probabilistic local buckling analysis method of reeling a pipe with a transition joint.
2. To analyze the local buckling of a subsea pipeline using FEA based on the above probability method.
3. To validate the FEA results of the proposed probabilistic approach against the DNVGL standard.

1.4 Structure of the Report

The structure of this report contains five chapters that are structured in a way to provide general information about the research, before delving deeper into the content and study, with the last chapter dedicated to summarizing the whole research.

Chapter One provides a brief explanation of the research. It contains the background of the research, problem statements, objectives, and an explanation of the structure of the report. This chapter would provide an understanding of the content of the research in general.

Chapter Two features the literature review where the background of reeling and local buckling is explained. The current requirement of reeling based on DNVGL-ST-F101 is outlined within the displacement control check method. Additionally, a paper published that developed a refined assessment for reeling is also discussed here. The method of basic reliability assessment is included in this chapter and will be used as a base in creating the probabilistic approach.

Chapter Three describes the methodology of this research. The calculations from the probabilistic method are explained in this section. The boundary condition, loading, and other inputs associated with the model in Abaqus are also detailed in this chapter.

Chapter Four presents the results from Abaqus analysis and compares it to the outcome from the DNVGL standard. The results would also be discussed extensively in this chapter.

Chapter Five concludes the research with a summarized discussion on the results and analysis. Possible area of interest that should be looked into will also be recommended in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Pipe Installation Methods

Pipeline installation is the process of laying the pipes on the seabed from a vessel. It is a challenging offshore operation that requires a high level of engineering design and analysis. Typically used pipeline installation methods are

- J-lay
- S-lay
- Reel-lay.

J-lay and S-lay installation methods are characterized by the "J" and "S" curve of the pipes during installation. Both methods require pipes to be welded on the vessel, resulting in high installation costs. Reel-lay offers a cost-effective alternative as welding of the pipes are done onshore at the spoolbase. The welds are also of higher quality as the weld flaw sizes are smaller due to better control. The pipes are reeled onto the reel drum on the vessel before taken offshore for installation. This method reduces installation period as the pipes are simply rolled out. This research will only focus on reel-lay installation method with rigid pipelines.

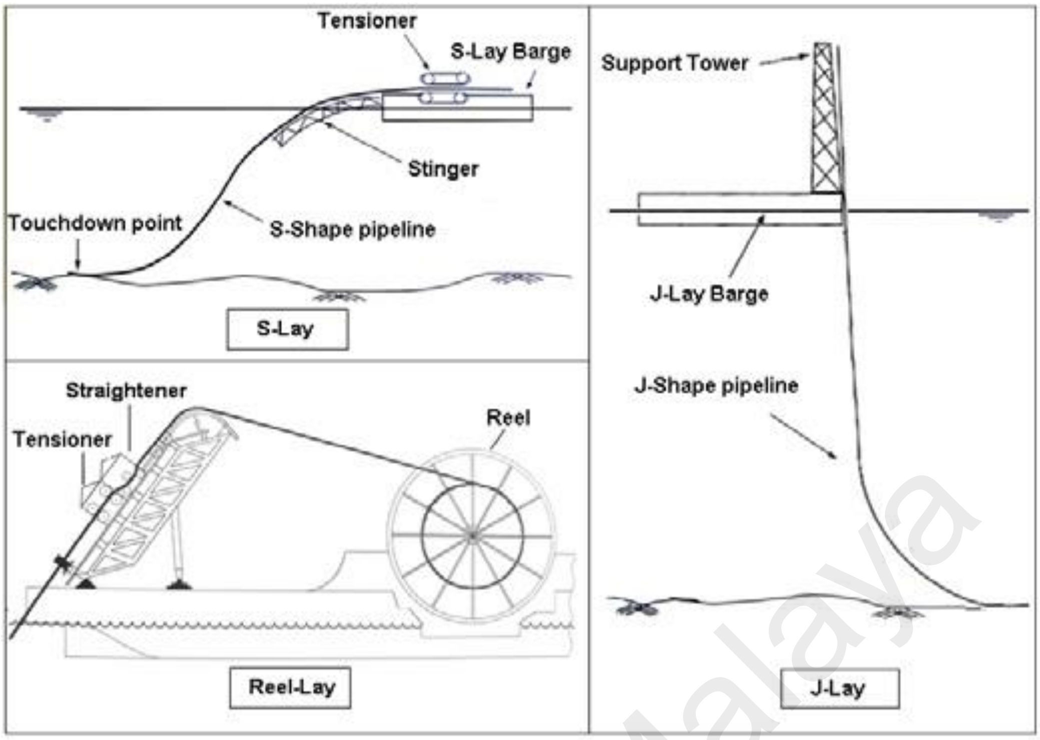


Figure 2.1: S-Lay, J-Lay, and Reel-Lay Methods (da Silva, et al., 2008)

Figure 2.2 below shows one of McDermott's marine construction vessel, Lay Vessel North Ocean 105 (LV NO105). The vessel is capable of reel-lay of both rigid and flexible pipelines (McDermott, 2019).

Figure 2.2: McDermott's Lay Vessel North Ocean 105 (McDermott, 2019)

Vessels such as LV NO105 have the reel drum permanently attached to the vessel. Hence, after all the pipeline has been reeled off and laid on the seabed, the vessel must be docked again to repeat the reeling process. This research focuses on reel-lay installation method with rigid pipelines.

2.2 Mechanics of Pipe Reeling

Typically, pipes are bought and sent to the spoolbase, an onshore facility designed to facilitate the handling of pipes on the fabrication line. The length of pipes bought and transported are limited by the size of the trucks transporting them, with the typical size of each joint being 12m. At the spoolbase, the pipes are welded under protected and controlled conditions to form a stalk of pipe, typically of lengths 1km to 2km. Once the vessel is in place and ready, the pipe stalks are then welded together to form a continuous pipeline. The pipeline would be reeled onto the reel drum which is mounted on the deck of the vessel. The reeling of rigid pipelines onto the reel drum is the area of interest for this research.

Figure 2.3: LV NO105 Docked in Spoolbase at Batam Island, Indonesia (McDermott Legacy, 2014)

Figure 2.4: Pipeline Reeling Operation on LV NO105 (McDermott Legacy, 2014)

2.3 Local Buckling During Reeling

Buckling is a structural instability that leads to the structure failing. Typically, two types of buckling are discussed and analyzed. Firstly, global, or lateral buckling, are known to happen during operation where the high pressure and temperature from the product induces high axial force. This could lead to localized buckling collapse or cyclic fatigue failure (Qiang Bai; Yong Bai, 2014). Global buckling occurs over a long section of the pipe. Secondly, local buckling, which is prone to occur during reeling if the pipeline is not designed correctly. Local buckling occurs over a short section of the pipe, damaging the pipe. Local buckling can be predicted using Finite Element Analysis (FEA) as shown below, and proper mitigation can be planned.

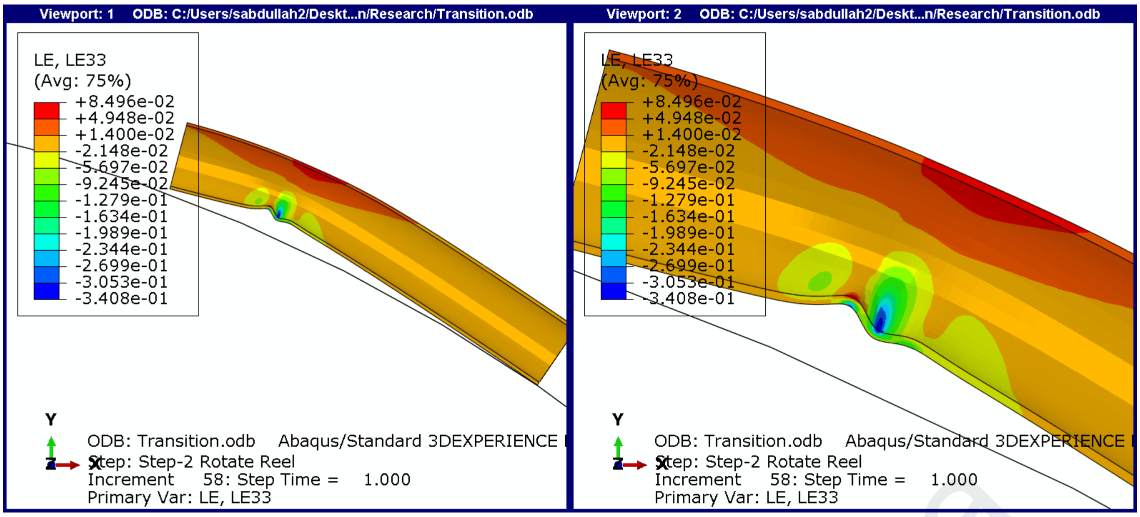


Figure 2.5: Finite Element Model of Local Buckling

Pipelines during reeling can experience local buckling if the wall thickness is too thin, resulting in a high slenderness ratio. Selection of wall thickness is commonly known as the governing factor for local buckling. Slenderness ratio (outer diameter to wall thickness) of above 45 according to the standard is more likely to wrinkle, an onset of local buckling (DNV GL, 2017).

$$Slenderness\ ratio = \frac{D}{t} \tag{2.1}$$

D = Outer diameter

t = wall thickness

Other than the slenderness of the pipeline, other factors such as radius of reel drum, back tension that is applied to the pipeline during reeling, geometrical and yield strength mismatch, and arrangement of spooling equipment also affects the probability of local buckling. The radius of reel drum, also known as the bending radius, is the maximum curvature (minimum radius of curvature) the pipe would be plastically deformed. Smaller reel drum radius would mean the pipe would need to be deformed more during reel packing, resulting in higher probability of buckling.

2.3.1 Geometrical and Yield Strength Mismatches

In an ideal world, the geometrical dimensions and yield strength of each pipe joint are the same. Unfortunately, that is not the case. In fact, these mismatches can be the deciding factor in whether a pipe is reelable. The magnitude of mismatch is confined to be within the manufacturing tolerance either based on the standard, or an in-house requirement. A high mismatch magnitude can result in a highly localized compressive strain, subsequently inducing local buckling. This happens during reeling when the bending moment for the stronger pipe (pipe with bigger geometry and higher yield strength) is provided by the weaker pipe trailing it. As the stronger pipe reaches the reel first, the trailing pipe needs to provide a higher bending moment to match the stiffness of the stronger pipe. Lift off, a condition where the weaker trailing pipe is unable to provide the equivalent bending moment resistance to the stronger pipe, would take place until the weaker pipe touches the reel. High lift-off can complicate reel packing operation and should be avoided (Manouchehri, 2012).

The difference in geometrical and yield strength between pipe joints occurs across girth welds. Girth welds are circumferential welds used to connect to two pipe joints together, typically using material of higher grade than the parent pipe. The plastic moment capacity of a pipe is a function of the yield strength, outer diameter, and the wall thickness as outlined in the equation below.

$$M = \sigma_y \frac{D^3 - (D - 2t)^3}{6} \tag{2.2}$$

M = plastic moment capacity

σ_y = yield strength

D = outer diameter

t = wall thickness

The difference in plastic moment capacities can be calculated based on the equation below.

$$\Delta\mathrm{M} = 2\frac{M_1 - M_2}{M_1 + M_2} \tag{2.3}$$

ΔM = difference in plastic moment capacities (also known as mismatch)

M_1 = plastic moment capacity of stronger pipe

M_2 = plastic moment capacity of weaker pipe

2.4 Reelability Assessment

DNV GL, an internationally accredited registrar and classification society has produced a submarine pipeline system standard, that is widely used in the oil and gas industry. The standard provides guidance to estimate the minimum reelable wall thickness for a given pipeline and reel drum radius. However, this standard assumes pipelines with uniform properties instead of the real case scenario where each pipe joint is of varying geometry and yield strength. This has led engineers in TechnipFMC (previously known as Technip) to develop a refined assessment procedure that can demonstrate the reelability of a given pipeline design in accordance to a given safety level (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2009).

This subsection will elaborate on two things

1. DNV GL Requirements – Reelability requirements set by the standard that is widely used in the industry.
2. Refined Assessment Procedure – Incorporate mismatches in the assessment procedure, reliability index, and probability of failure.

2.4.1 DNVGL Requirements

There are four typical design conditions that are checked during installation, depending on the installation method (JIP Participants, 2015):

- On-reeling (reeling installation only)
- Over bend (as applicable)
- Stinger tip (as applicable)
- Sag bend (all installation methods)

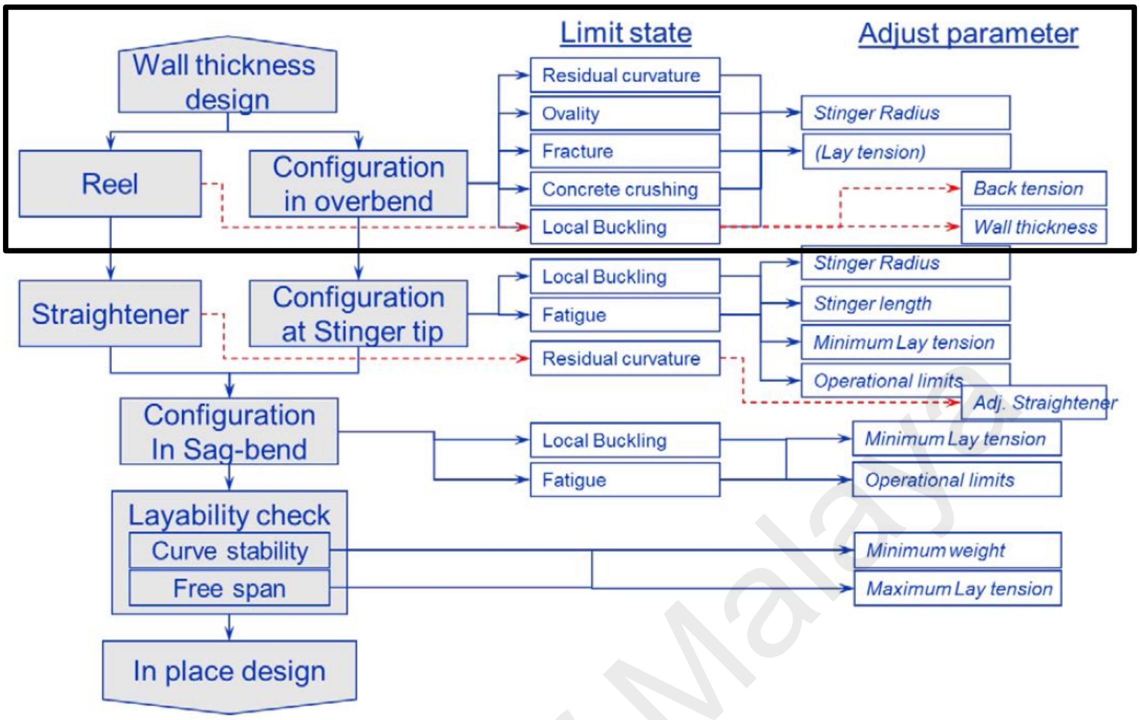
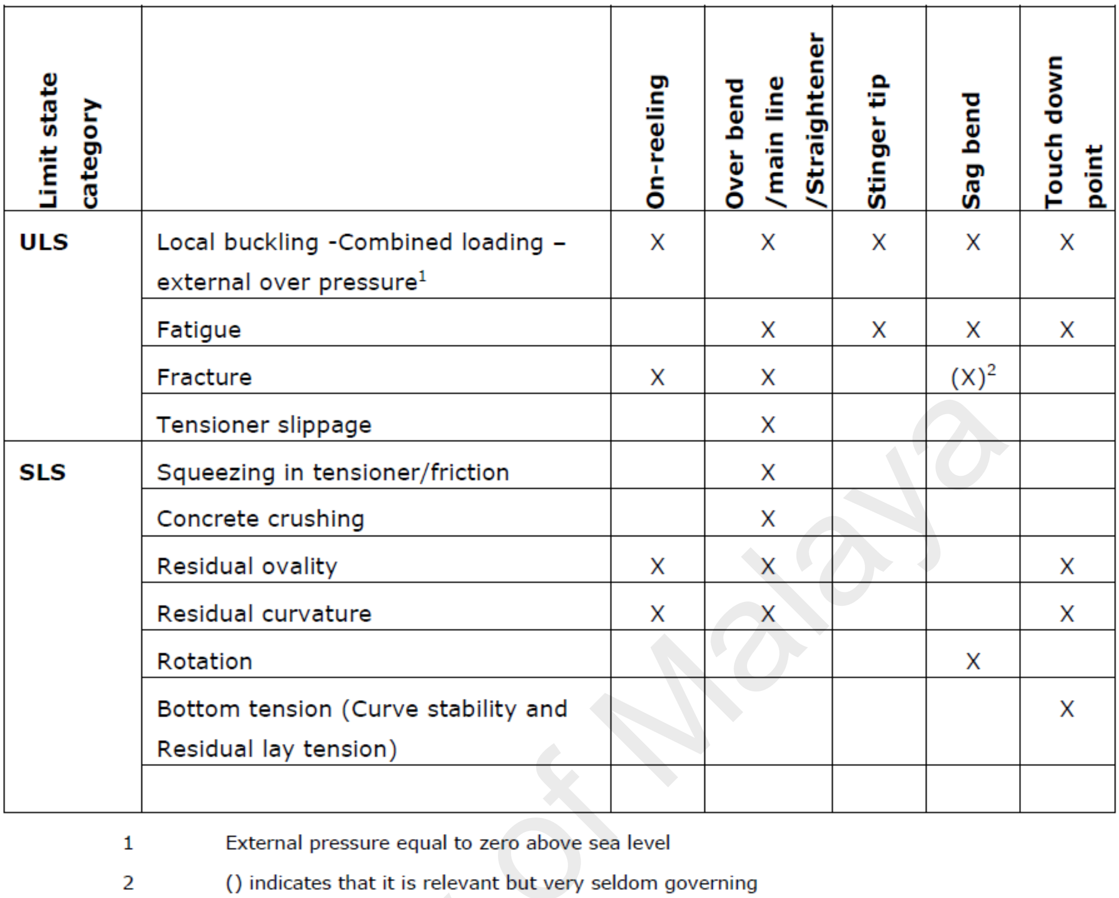


Figure 2.6: Design Flow for Installation Design

This research will only look into wall thickness design for reeling to avoid local buckling as shown in the box section in Figure 2.6. The underlying reasoning here is because this research intends to focus on the design of a temporary transition joint that will only be used during reeling. This transition joint will not be laid on the seabed. There are certain limit state criteria that needs to be fulfilled based on the standard. A summarized and modified limit state criterion for installation that removed the excessive conservatism imposed in DNVGL-ST-F101 are as in Table 2.1.

Table 2.1: Specific Limit States for Installation



Limit state category		On-reeling	Over bend /main line /Straightener	Stinger tip	Sag bend	Touch down point
ULS	Local buckling -Combined loading – external over pressure[1]	X	X	X	X	X
	Fatigue		X	X	X	X
	Fracture	X	X		(X)[2]	
	Tensioner slippage		X			
SLS	Squeezing in tensioner/friction		X			
	Concrete crushing		X			
	Residual ovality	X	X			X
	Residual curvature	X	X			X
	Rotation				X	
	Bottom tension (Curve stability and Residual lay tension)					X

1 External pressure equal to zero above sea level

2 () indicates that it is relevant but very seldom governing

Ultimate Limit State (ULS) in the offshore industry corresponds to the maximum load carrying resistance of a structure. Serviceability Limit State (SLS) corresponds to the ability of the structure to resist accidental load, maintaining integrity and performance due to local damage or flooding. (NORSOK Standard N-003, 1999)

The definition of maximum allowable bending strain that a pipeline can sustain given the outer diameter and wall thickness by the DNV GL standard was formed based on the assumption of pure bending moment and uniform pipe geometry and yield strength. Despite the simple form of the equation, it is only valid when certain manufacturing tolerances are met. The acceptable manufacturing tolerances will be included later in this section.

$$t_{nom} = \frac{t_{min}}{1 + t_{tol}} \tag{2.4}$$

$$t_{min} = 2 \cdot D_{nom} \cdot \varepsilon_{b-nom} \tag{2.5}$$

$$\varepsilon_{b-nom} = \frac{D_{nom}}{2 \cdot R + D_{nom} + 2t_{coating}} \tag{2.6}$$

t_{nom} = nominal wall thickness

t_{min} = minimum wall thickness

t_{tol} = wall thickness negative tolerance

D_{nom} = nominal outer diameter

R = Reel drum radius

$t_{coating}$ = pipeline coating thickness

ε_{b-nom} = nominal bending strain (bending strain induced during reeling)

Based on the above equations in the standard, pipelines are considered to be reelable when ε_{b-nom}, the nominal bending strain does not exceed the maximum allowable bending strain. The nominal wall thickness takes into account negative fabrication tolerance for safety measure. A positive fabrication tolerance would increase the thickness of the pipe, reducing probability of local buckling. The equations can be arranged so that the minimum wall thickness is a function of nominal outer diameter and nominal bending strain.

The design formula given in DNVGL-ST-F101 to calculate functional strain (equivalent to nominal strain for reeling) incorporates multiple safety factors as listed below.

$$\varepsilon_F \leq \frac{1}{\gamma_\varepsilon \cdot \gamma_F \cdot \gamma_c} \cdot \frac{0.78}{\alpha_h^{1.5}} \cdot \left(\frac{t}{D} - 0.01\right) \cdot \alpha_{gw} \tag{2.7}$$

ε_F = functional strain (equivalent to nominal strain for reeling)

γ_ε = strain resistance factor (2.0 for safety class low during reeling)

γ_F = functional loads factor (1.2 for system effects)

γ_c = condition load effect factor (0.77 for reeling using seamless pipe)

α_h = strain hardening factor, $\left(\frac{R_{t0,5}}{R_m}\right)_{max}$ or yield stress to ultimate tensile stress ratio

α_{gw} = girth weld factor (1.0 for D/t ≤ 20, linearly decreasing to 0.6 for D/t = 60)

Another simplified acceptance criterion, as a guidance for bending strain, can be referenced to in the Installation JIP Guideline. The criterion is a function of wall thickness and outer diameter. This can be assumed as the maximum allowable bending strain from the standard. The bending strain is averaged over one diameter pipe length from the weld towards the weaker pipe joint. Higher wall thickness and smaller outer diameter results in higher allowable bending strain (JIP Participants, 2015).

$$\epsilon \leq 1.2 \cdot \frac{t}{D} - 0.01 \tag{2.8}$$

ϵ = bending strain

t = wall thickness

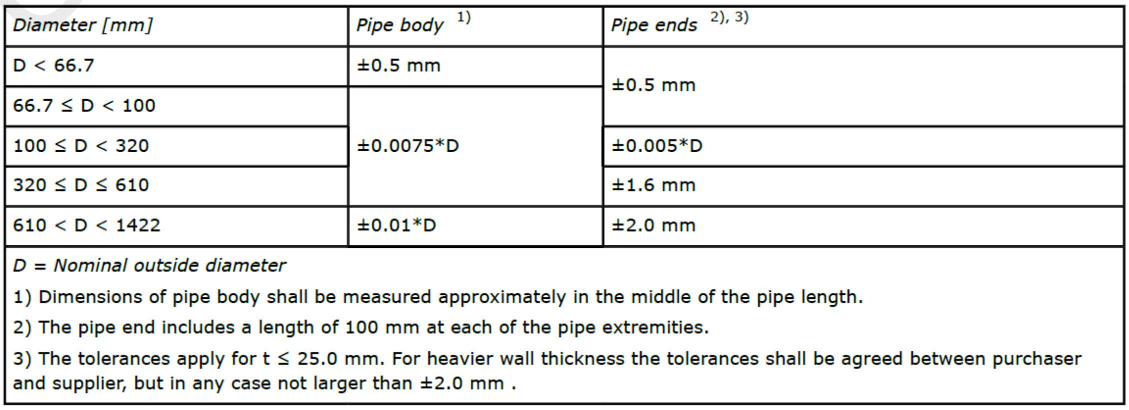
D = outer diameter

As reel-lay method requires the pipe to undergo plastic deformation, supplementary requirements are imposed to ensure the validity of the equations. Supplementary Requirement P requires additional testing are to be performed on the line pipes to ensure that there are lesser geometrical and mechanical properties variation across the girth weld between two adjacent line pipes. This supplementary requirement also requires that Supplementary Requirement D be imposed as well. The acceptance criteria from Supplementary Requirement P are as follows:

- Maximum variation of yield strength between two line pipes should not exceed 100MPa, with minimum yield strength higher than the Specified Minimum Yield Stress (SMYS)
- Yield strength to tensile strength ratio should not exceed 0.90
- Uniform elongation length of more than 5%

Supplementary Requirement D is an additional dimensional requirement for pipeline and should be done by the purchaser considering the influence of dimensions and tolerances on reeling activities. This requirement is beneficial to avoid local buckling and to have a more accurate local buckling FEA prediction. Requirements from Supplementary Requirement D are as listed in the tables below (DNV GL, 2017).

Table 2.2 SMLS Pipe Diameter Tolerances



Diameter [mm]	*Pipe body* [1)]	*Pipe ends* [2), 3)]
D < 66.7	±0.5 mm	±0.5 mm
66.7 ≤ D < 100	±0.0075*D	
100 ≤ D < 320		±0.005*D
320 ≤ D ≤ 610		±1.6 mm
610 < D < 1422	±0.01*D	±2.0 mm

D = Nominal outside diameter

1) Dimensions of pipe body shall be measured approximately in the middle of the pipe length.

2) The pipe end includes a length of 100 mm at each of the pipe extremities.

3) The tolerances apply for t ≤ 25.0 mm. For heavier wall thickness the tolerances shall be agreed between purchaser and supplier, but in any case not larger than ±2.0 mm .

Table 2.3 SMLS Pipe Wall Thickness Tolerances

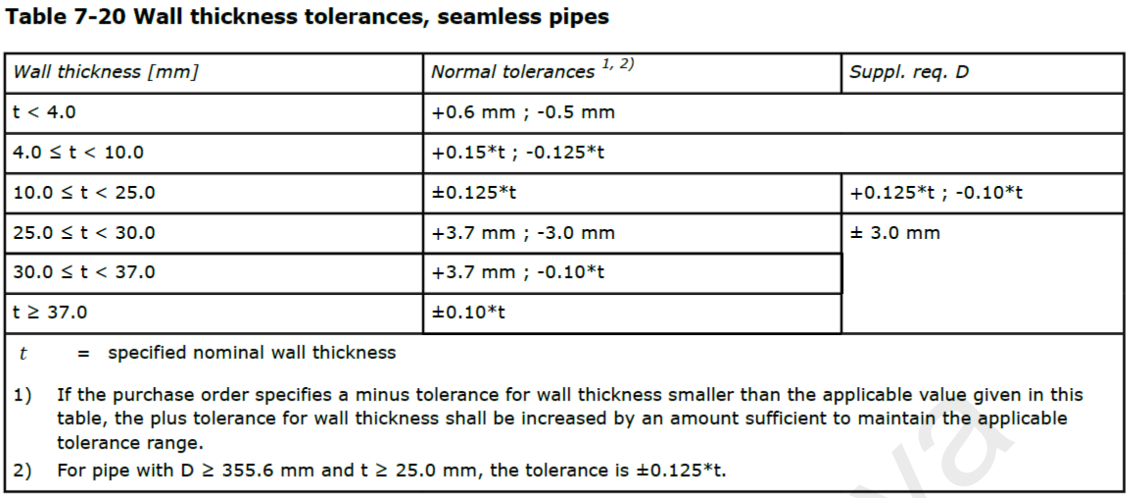


Table 7-20 Wall thickness tolerances, seamless pipes

Wall thickness [mm]	*Normal tolerances* [1, 2)]	*Suppl. req. D*
t < 4.0	+0.6 mm ; -0.5 mm	
4.0 ≤ t < 10.0	+0.15*t ; -0.125*t	
10.0 ≤ t < 25.0	±0.125*t	+0.125*t ; -0.10*t
25.0 ≤ t < 30.0	+3.7 mm ; -3.0 mm	± 3.0 mm
30.0 ≤ t < 37.0	+3.7 mm ; -0.10*t	
t ≥ 37.0	±0.10*t	

t = specified nominal wall thickness

1) If the purchase order specifies a minus tolerance for wall thickness smaller than the applicable value given in this table, the plus tolerance for wall thickness shall be increased by an amount sufficient to maintain the applicable tolerance range.

2) For pipe with D ≥ 355.6 mm and t ≥ 25.0 mm, the tolerance is ±0.125*t.

The requirements imposed are vital in ensuring the safety of the project. Typically, each company have their own procurement specification in terms of mechanical and geometrical properties, with the specification being slightly stringent than the requirement imposed.

2.4.2 Refined Assessment Procedure

A more refined assessment procedure has been developed using reliability and finite element techniques to establish the minimum reelable wall thickness and the associated probability of failure. As geometrical dimensions and yield strength plays a significant role in the success of reeling, Technip's in-house defined assessment formulae was used to determine the variation of the mismatches. This is done by firstly defining the probability of occurrence of high mismatch at a weld corresponding to a probability of occurrence of 10^{-2} for the whole project. What this implies is that for all the line pipes in the project, the probability of two line pipes being welded having this high mismatch is 10^{-2} or 1 in 100. The most likely output for the combination of yield strength and geometrical mismatch based on first order reliability method (FORM) is then used as inputs in the finite element reeling analysis. The objective of the finite element analysis is to ensure that this extreme combination of mismatches would not trigger local buckling in the pipeline during reeling operations. If the analysis does trigger a local buckle, possible solutions would be to increase back tension applied to the pipeline during reeling, and in some cases, using pipeline with a thicker wall thickness.

Probability of failure of the refined assessment procedure was obtained by carrying out parametric analyses for different combinations of wall thickness and yield strength. Solid symbols in Figure 2.7 indicate a successful combination, where there are no signs of local buckling. The open symbols indicate a failed combination, where local buckling occurred during reeling analyses. A linear line is drawn over the failed combination to demonstrate the failure boundary in physical space.

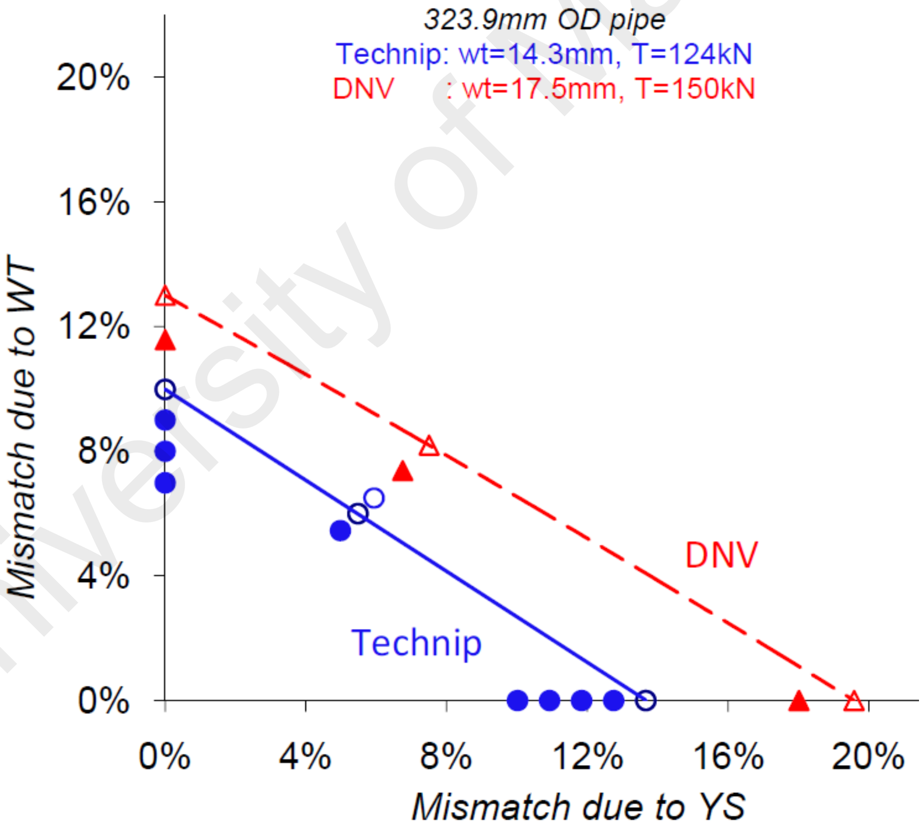


Figure 2.7: Failure Boundary in Physical Space

The points in physical space are converted from multi-dimensional physical space (one dimension per random variable) to Z-values, in multi-dimensional unit-normal space (Z-space). Four random variables are involved, namely the wall thickness and yield strength modelled in the stronger and weaker pipe. This transformation enables the problem to be reduced from a 4D problem to a 2D problem using equations below. (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2011)

$$Z_{weak/strong} = \frac{\Delta}{f \cdot \sigma} \tag{2.9}$$

$$Z_{mismatch} = \sqrt{2} \cdot Z_{weak/strong} \tag{2.10}$$

<u>Note:</u> f is a reduction factor, adjusting the standard deviation associated with a tolerance or range

The failure boundary in physical space is then converted into unit space as shown in Figure 2.8. This step is crucial to obtain the reliability index, β, which is defined as the shortest distance from the origin to the failure boundary. The probability of failure is a function of the reliability index, as shown in equation (2.11) (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2009).

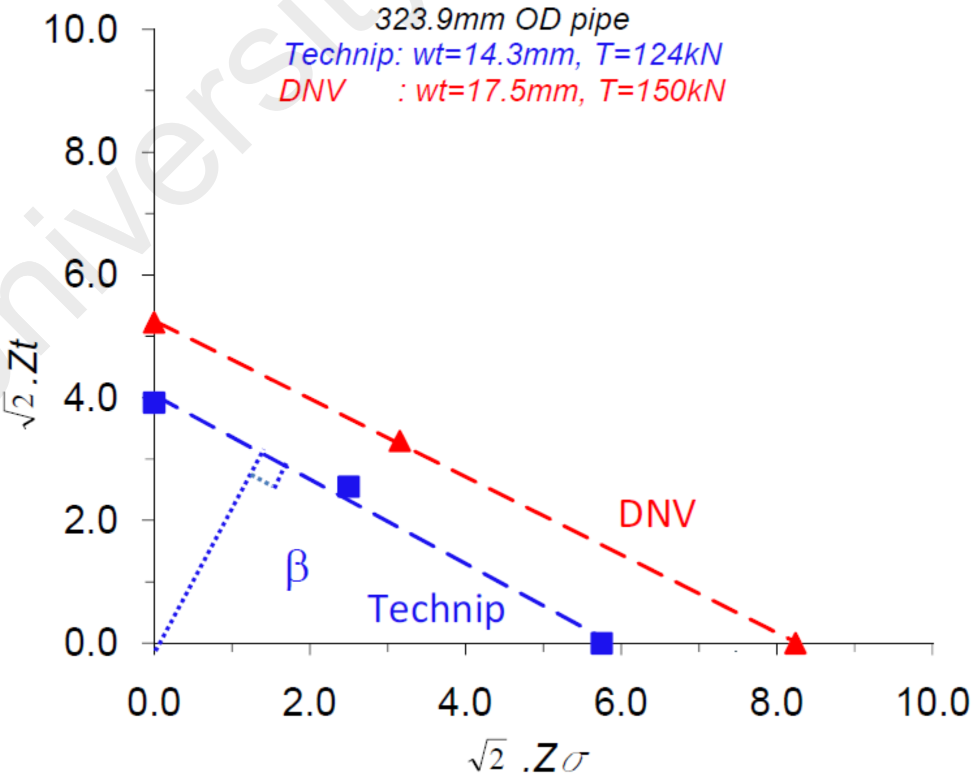


Figure 2.8: Failure Boundary in Unit Normal Space

$$P_F = \Phi(-\beta) \tag{2.11}$$

P_F = Probability of Failure

Φ = Standard normal distribution cumulative distribution function

β = Reliability index

Based on an extensive study done by Technip, it was concluded that the failure boundary is a linear function. This significant finding allows for a more simplified probability of failure calculation by eliminating the requirements for an analytical method such as FORM as only two points are necessary to outline the failure boundary.

2.5 Transition Joint

During reeling operation, there are occasions where line pipes of different geometries are required to be reeled together for installation purposes. To accommodate this situation, transition joints have been used to connect these line pipes, ensuring a smooth mismatch ‘transition’ between the line pipes. For pipelines that will be installed on the seabed together, the geometrical differences between pipes are minimal. For temporary transition joints that used to connect two pipes either of different outer diameter, or wall thickness, or both, the differences are much more perceptible. The main idea for transition joint is to aid the pipes to a more gradual change between two pipes. A lift off is to be expected at the end of the transition towards the weaker section but should be minimized whenever possible.

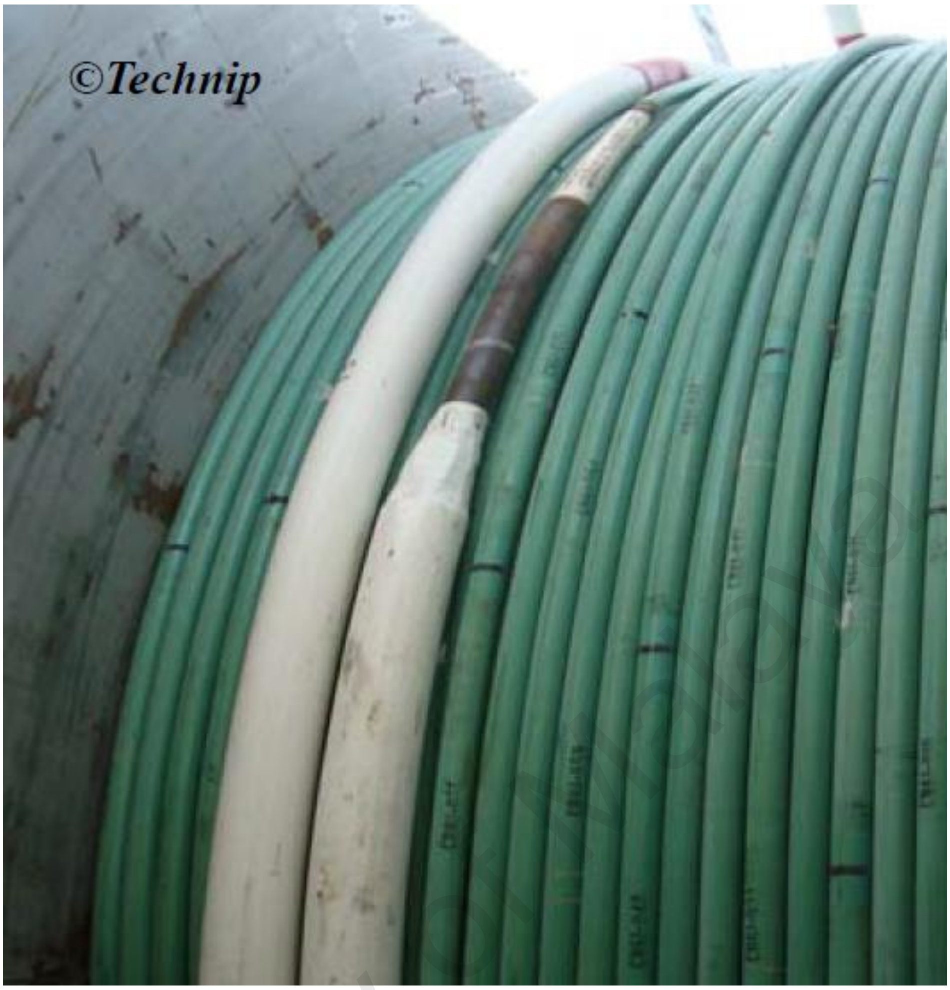


Figure 2.9: Transition Joint on Reel Drum Courtesy of Technip

2.6 Abaqus

The software used to develop the finite element model in this research is Abaqus/CAE, or “Complete Abaqus Environment”. Abaqus is the industry standard general purpose finite element analysis software. It is well known for its nonlinear solver and material models. Studies exploring novel ways to mitigate pipeline walking and buckling has used FE models time and again (Seyfipour, 2019). Non-linear is when the stress of the material is higher than the yield, hence creating a non-linear material curve. In other words, the material is analyzed when it is plastically deformed. A typical stress-strain curve of seamless pipe that exhibits Luder’s Plateau is shown in Figure 2.10.

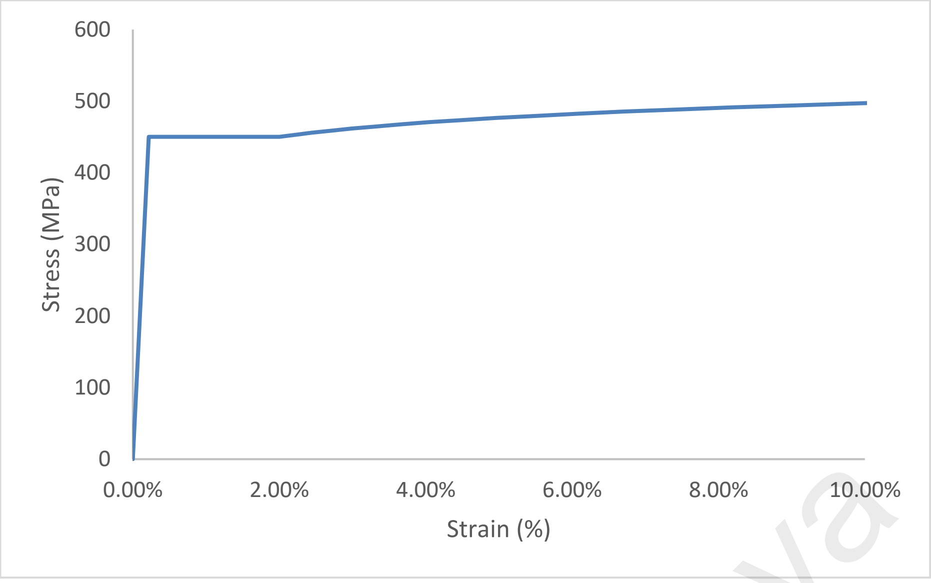


Figure 2.10: Stress-Strain Curve for Seamless Pipe

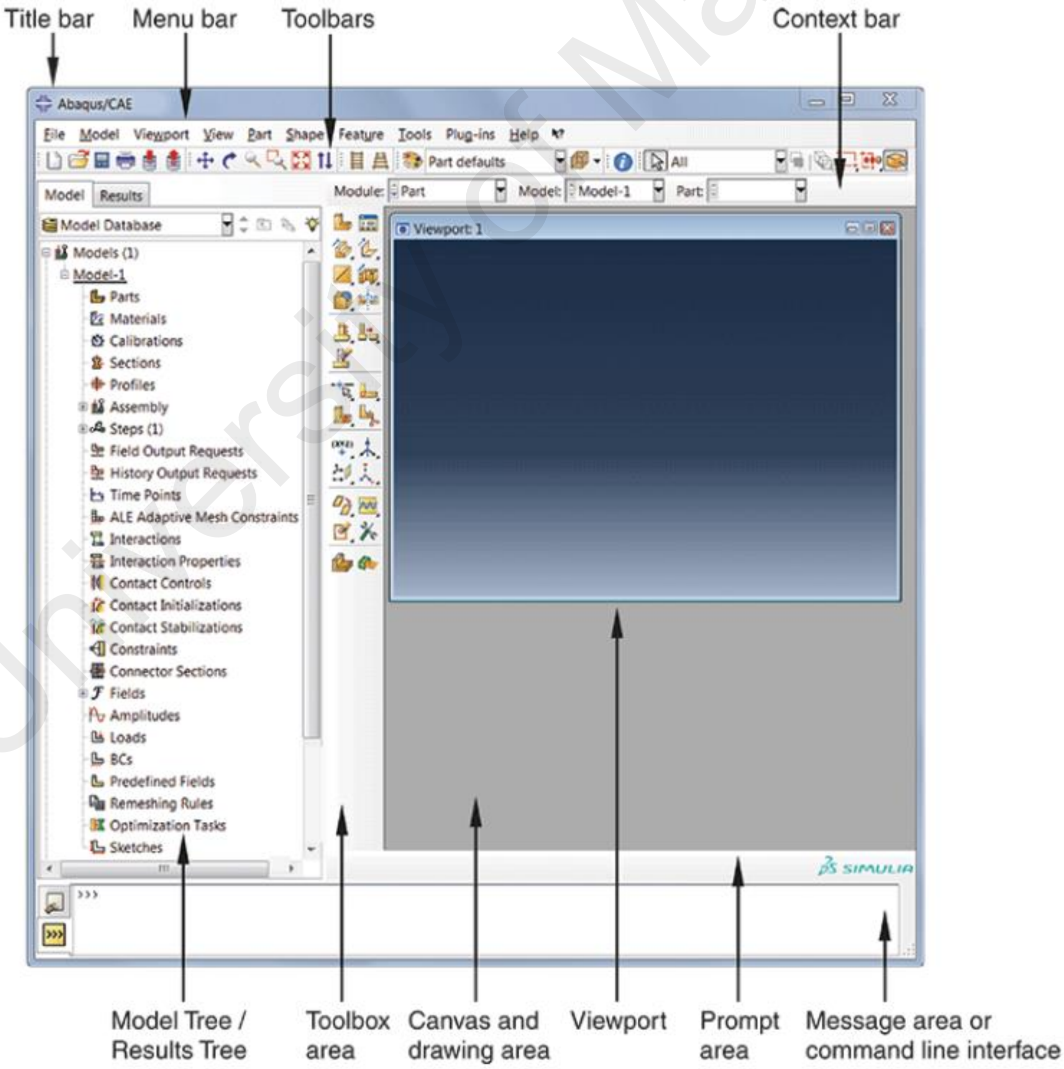


Figure 2.11: Components of Abaqus/CAE Main Window

2.7 Summary

Based on the equations in the DNV GL’s standard, the requirements for reeling a pipeline is fixed with safety factors. Mismatches can be the deciding factor for reelability of a pipeline, as seen from the development of a refined assessment procedure paper published to present Technip’s in-house assessment. Reeling has been proven to affect structural performance of pipelines, hence finite element to simulate the structural integrity is crucial in assessing the pipelines (Liu & Kyriakides, 2016). FEA analysis ensures that buckling can be detected and that the maximum strain does not exceed the allowable limit (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2009).

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter explains the calculations and analysis required to be simulated in completing this research. This research started with collecting information regarding proposed pipeline data. The data is used in the reliability based assessment against the standard. Mismatch calculation is then performed to be used as input for the finite element analysis in Abaqus. If no buckling is detected, then the analysis is considered a success. The result is then analyzed, discussed, and concluded. The flow of work can be seen in Figure 3.1.

This research will not disclose confidential information regarding the pipe. Any assumption presented here can be assumed as typically used information within the industry. The results presented would also exclude details of the analysis due to confidentiality agreement. As an example of the probabilistic method in this research, a transition joint to connect pipe of outer diameter 304.8mm to 254mm will be developed and analyzed.

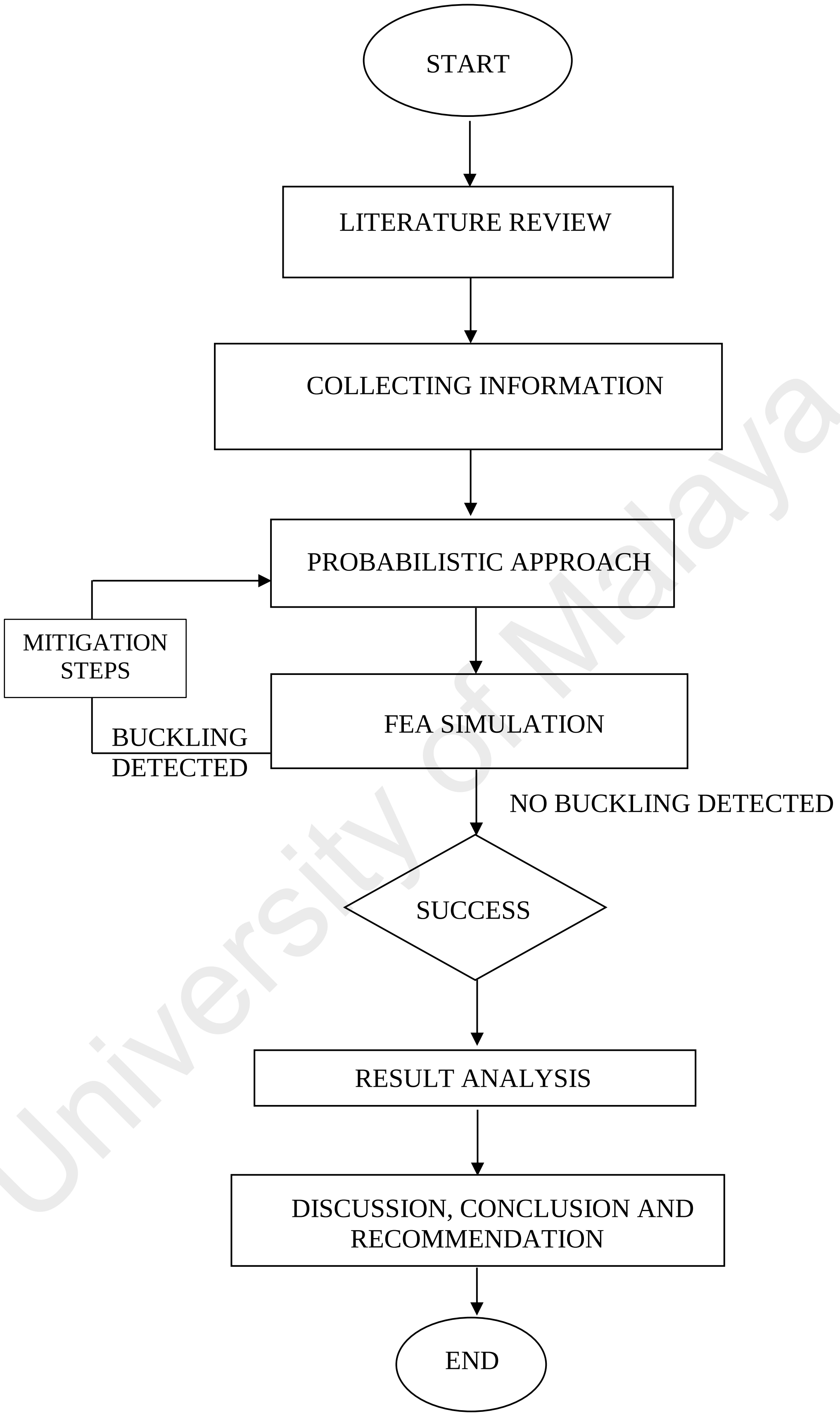


Figure 3.1: Flow Diagram of Research

3.2 Probabilistic Approach

3.2.1 Safety Class and Nominal Target Failure Probability

As described in the standard, if alternative methods and procedures to those specified in the code are used, it shall be demonstrated that the safety level obtained is equivalent to the ones specified in the standard. Additionally, the allowable target failure probability level shall be based on the failure type given in Table 3.1, as it is not feasible to calibrate nominal target failure probability against similar pipeline designs. (DNV GL, 2017)

Table 3.1: Safety Class for Pipeline During Reeling

Safety Class	**Limit States**	**Allowable System Failure Probabilities (P_F)**	**Remarks**
Low (for reeled pipelines)	SLS	10^{-2}	A higher probability of failure corresponding to a serviceability limit state may be allowed during the installation phase provided that: • Aids to detect buckle are provided • Repair of potential damage is feasible and may be performed during laying • Buckle arrestors are installed if the external pressure exceeds the initiation propagating pressure

3.2.2 Mismatch Calculation Method

There are multiple variables that can affect reliability assessment for pipe reeling that it would be computationally prohibitive to account for all of it. Extensive and numerous FE analysis would need to be simulated to assess all of them. A paper has been published suggesting that the key property variations that can affect the overall reliability of pipe buckling during reeling are the combinations of wall thickness and yield strength mismatches across the girth weld. Hence, only these two factors will be considered in predicting the probability of failure (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2011).

Allowable system failure probabilities for reeling of the entire pipeline as described in Table 3.1 is as in equation below.

$$P_f = 1 - \Phi(\beta)^n \tag{3.1}$$

Where n is the number of pipe joints to be reeled.

Table 3.2: Mismatches Across Girth Welds

Parameter	**Wall Thickness**	**Yield Stress**
Mismatch (1, 2)	$\Delta t = \frac{\sqrt{2}}{2} \cdot k_t \cdot \sigma_t \cdot \beta \cdot \sin \alpha_{ft}$	$\Delta f = \frac{\sqrt{2}}{2} \cdot k_f \cdot \sigma_f \cdot \beta \cdot \cos \alpha_{ft}$
Strong Pipe	$\mathrm{t}_{strong} = \mathrm{t}_{ave} + \Delta t$	$f_{strong} = f_{ave} + \Delta f$
Weak Pipe	$\mathrm{t}_{weak} = \mathrm{t}_{ave} - \Delta t$	$f_{weak} = f_{ave} - \Delta f$

Notes:

1. Total mismatch is assumed to be shared equally between the strong and weak pipe.
2. The wall thickness and yield stress are assumed to be normally distributed.

k_t & k_f = Represents the beneficial effect of reduced variability for an averaged cross section compared to the variability of individual measurements. If no other data is available, the following values are to be used:

- 2/3 for SAW pipe formed from plate
- 0.6 for seamless pipe

σ_t = Standard deviation for individual wall thickness measurements. If no other data is available, the following value is used, where $t_{fab,max}$ and $t_{fab,min}$ are the maximum and minimum fabrication tolerance, respectively:

$$\sigma_t = (t_{fab,max} - t_{fab,min})/6$$

σ_f = Standard deviation for individual, point-wise, yield strength measurements. If no other data is available, the following value can be used

- Maximum yield mismatch between pipe joint / 6 = 100MPa/6

α_{ft} = 0-90 degrees. The mismatch distribution between the wall thickness and yield strength is defined as an angular variation of these parameters.

From the above equation, α_{ft} which results in the highest ΔM using equations in Section 2.3.1 is determined as the most onerous case. Δt and Δf are then calculated to obtain the geometrical and yield strength value to be used as input in the 3D FEA reeling analysis involving strong and weak pipe. (Denniel, Tkaczyk, Howard, Levold, & Aamlid, 2011).

The advantage of this method is that the wall thickness and dimension for the strong and weak sections are calculated individually. For example, in designing transition joints, two pipe joints that are to be connected may have different mean yield strength and wall thickness tolerance. The mismatch calculation based on the probabilistic method would be able to calculate the strong and weak value of each one, hence a more realistic finite element result given a targeted probability of failure can be obtained.

3.3 Finite Element Analysis

3.3.1 General

A 3D simplified reeling model has been developed to analyze the output from the mismatch calculation. The model is labelled as simplified as the bending radius of the reel is modelled without considering their specific location on the vessel. Hence, the pipe is assumed to be reeled at the center of the drum. The material properties of the parent pipe are based on the Luder’s Plateau material model of SMLS X65, whereas the transition part is based on the Ramberg-Osgood material model of Forged F65. The non-linear material curve has been developed using McDermott’s in-house calculation. Figure 3.2 below shows the different material within the pipe section of a proposed transition joint.

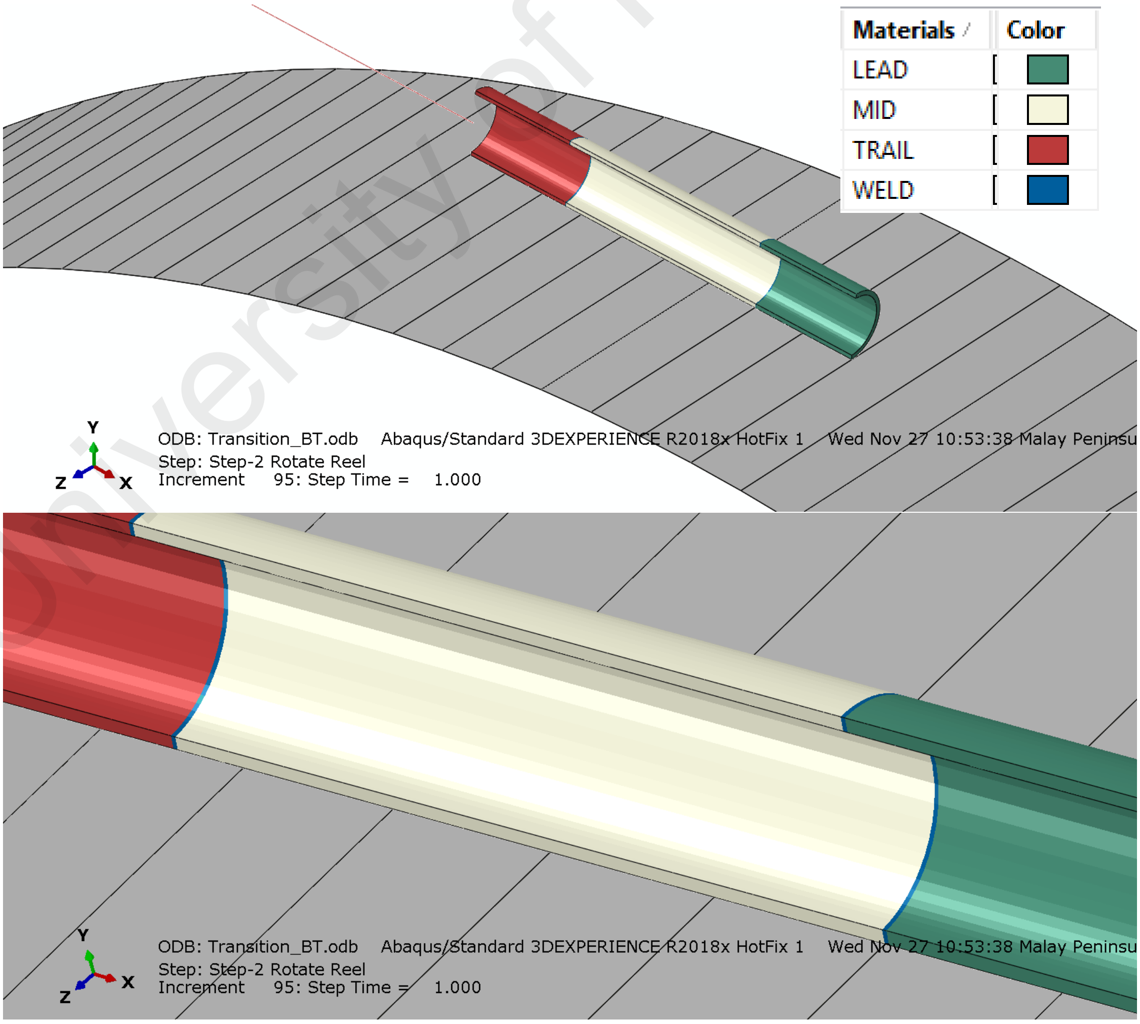


Figure 3.2: Material Sections

Two cases have been analyzed as listed in Table 3.3 below. Lead is the pipe being reeled and touches the reel drum first, followed by mid-section, which is the transition joint, and finally the trail. The transition joint connects the lead and trail pipes of different geometries by having a tapered geometry. This enables the changes between different pipe sizes to occur gradually throughout the reeling operation. Initial configuration of the FE model is shown in Figure 3.3 below.

Table 3.3: FE Model Analyses

Section	**Lead**	**Mid**	**Trail**
Case 1 (SWS)	Strong	Weak	Strong
Case 2 (SSW)	Strong	Strong	Weak

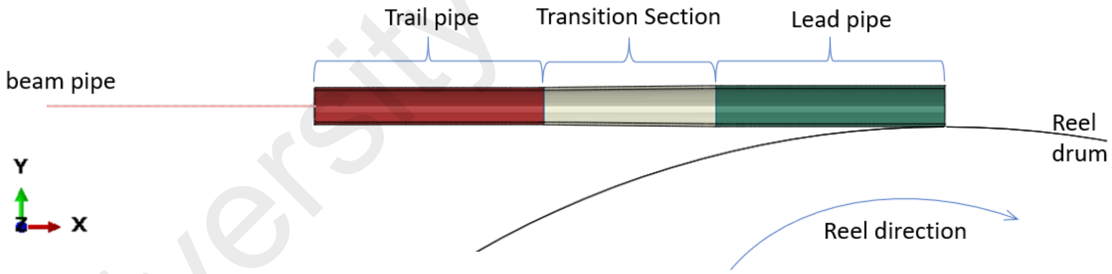


Figure 3.3: Initial Configuration of FE Model

3.3.2 Element Type and Mesh Density

The 3D simplified reeling FE model is made up of three parts;

1. Pipe (Lead, mid and trail sections)
2. Pipe beam (attached to the trail to assist on the back tension)
3. Reel drum

The pipe is created using SC8R, quadrilateral continuum shell element with reduced number of integration points. Continuum shell elements have only displacement degrees of freedom. From an analysis point of view, the continuum shell elements behave like three-dimensional continuum solids, while their kinematic and constitutive behavior is similar to conventional shell elements. The overall length of the solid element pipeline model designed in Abaqus/CAE must be sufficient to capture all the details required, and the design must ensure that there is no potential end effect influence from the coupling to the beam elements. The reel drum has been developed using an analytical rigid surface to decrease computational source required by the contact algorithm.

Three elements are modeled through the pipeline thickness. Three elements were also modeled through the girth weld thickness and length. The solid element's mesh varies along the pipeline with the area closer to the weld having more refined mesh compared to the coarse mesh away from the weld. Since buckling occurs close to the girth weld, having a fine mesh at the area of interest would be able to capture the results better. Figure 3.4 below illustrates the mesh in the 3D FEA model.

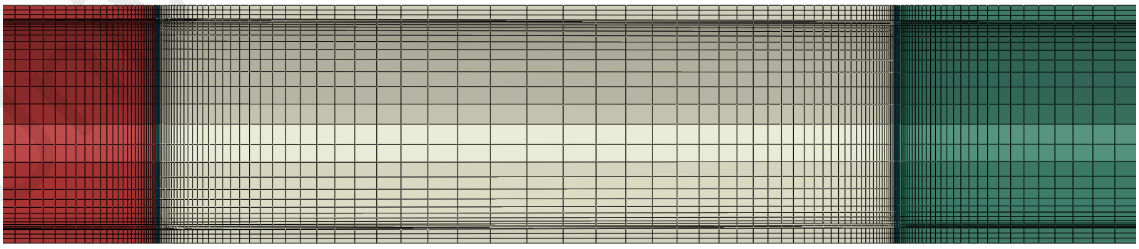


Figure 3.4: Mesh Across Pipeline Girth Weld

3.3.3 Boundary Conditions and Analysis Steps

To optimize computational time, a half symmetrical model was used. Symmetry boundary conditions are applied to the surface in the X-Y plane of the pipeline. The reel drum is restrained in all degrees of freedom except the rotation about the Z-axis to simulate the reeling operation. The leading end of the pipe is connected to the reel via a connector element. The trailing end of the solid element of the pipe is attached to the beam element section through couplings. The required back tension is calculated and applied at the end of the beam element section. The property of the beam element section has been adjusted for equivalent bending stiffness as the half symmetry solid element section. The material orientation is set to be based on a cylindrical coordinate system to have a better visualization on the longitudinal strain when the pipe is reeled on the drum.

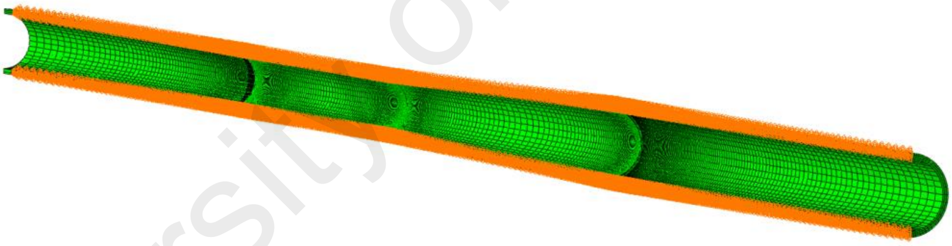


Figure 3.5: Boundary Conditions

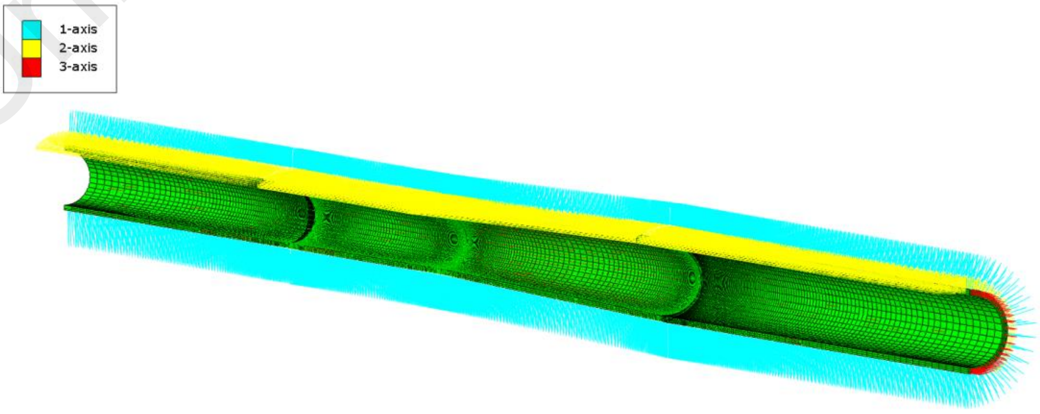


Figure 3.6: Material Orientation

The analyses are carried out with the following sequential steps:

1. Half of the calculated back tension is applied at the end of the beam that has been coupled to the end of the pipe. The back tension is halved to take into account the symmetry boundary with half model.
2. The reel is rotated until the pipeline ends touches the reel to simulate the reeling operation.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Probabilistic Method

Based on the Serviceability Limit States (SLS), probability of system failure, P_f is set to 10^{-2} in equation $P_f = 1 - \Phi(\beta)^n$. ‘n’ is the number of pipe joints to be reeled, which could be obtained from project data. Assuming ‘n’ to be 1 and P_f to be 10^{-2}, β is calculated to be 2.326. Next, wall thickness and yield strength mismatches is calculated using equations $\Delta t = \frac{\sqrt{2}}{2} \cdot k_t \cdot \sigma_t \cdot \beta \cdot \sin \alpha_{ft}$ and $\Delta f = \frac{\sqrt{2}}{2} \cdot k_f \cdot \sigma_f \cdot \beta \cdot \cos \alpha_{ft}$. All the variables are known at this point as outlined in Section 3.2.2, and the output data from the probabilistic method, Δt and Δf are used to calculate ΔM using equation (2.2) and (2.3). The value of α_{ft} that gives the highest ΔM is used as inputs in developing the finite element model. Figure 4.2 shows ΔM against α_{ft} for case 1; SWS.

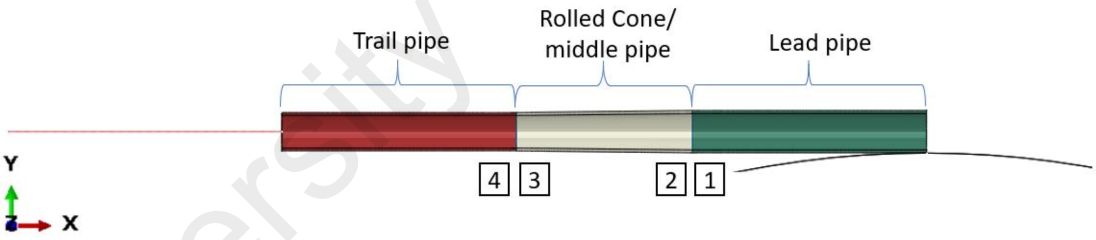


Figure 4.1: Calculated Mismatch Sections

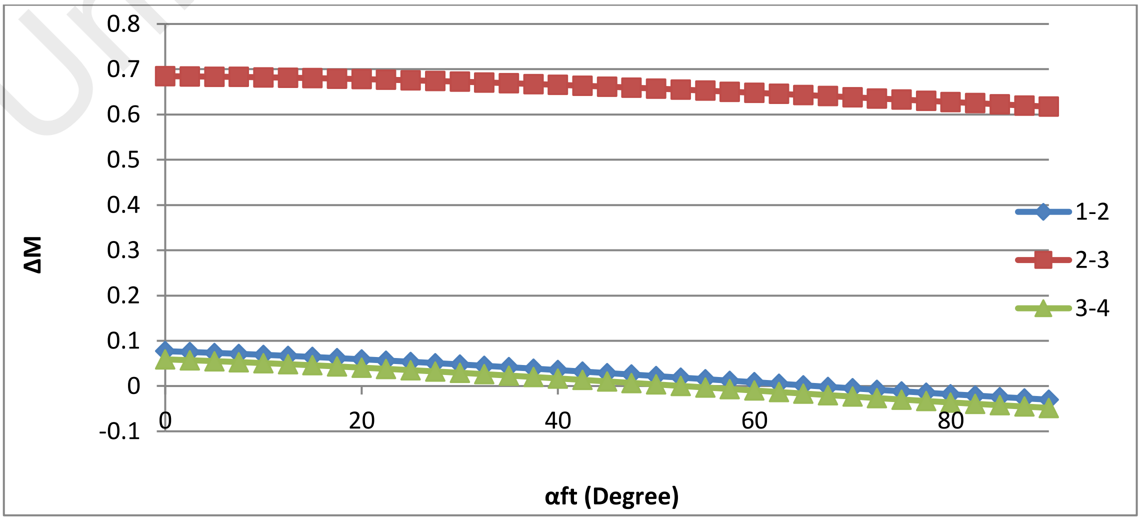


Figure 4.2: Graph of Mismatch against α_{ft} Values

From the graph, $\alpha_{ft} = 0$ shows the highest ΔM of 0.412N.mm, and hence is used to calculate t_{strong}, t_{weak}, f_{strong}, and f_{weak}, given t_{ave} and f_{ave} below. The calculated geometrical and yield strength mismatch based on the probabilistic method are also tabulated in Table 4.1 and Table 4.2.

Table 4.1: Geometrical and Yield Strength Mismatch for Case 1: SWS

	Strong (1)	Weak (2)	Weak (3)	Strong (4)
D (mm)	304.80	304.80	254.00	254.00
t_{nom} (mm)	13.53	13.53	10.10	10.10
t_{strong} , t_{weak} (mm)	13.70	13.53	10.10	10.23
f_{ave} (MPa)	500.00	500.00	500.00	500.00
f_{strong} , f_{weak} (MPa)	516.45	483.55	483.55	516.45

Table 4.2: Geometrical and Yield Strength Mismatch for Case 2: SSW

	Strong (1)	Strong (2)	Strong (3)	Weak (4)
D (mm)	304.80	304.80	254.00	254.00
t_{nom} (mm)	13.53	13.53	10.10	10.10
t_{strong} , t_{weak} (mm)	13.70	13.53	10.10	10.23
f_{ave} (MPa)	500.00	500.00	500.00	500.00
f_{strong} , f_{weak} (MPa)	516.45	516.45	516.45	483.55

It should be noted that this method assumes the mismatch to be shared equally between the strong and weak pipe. For example, if the mean yield strength is 480MPa, and calculated Δf is 20MPa, then a strong section would have a yield strength of 500MPa whereas a weak section would have a yield strength of 460MPa. Total yield strength mismatch would be 40MPa. The mean yield strength value is based on statistical data obtained either from the manufacturer or based on in-house data. The same concept applies to wall thickness tolerance. However, wall thickness tolerance has a set upper and lower limit hence it is a controlled variable.

Unfortunately, this does not apply to yield strength. For example, X65 Specified Minimum Yield Strength (SMYS) is 448MPa. That means 448MPa is the lowest acceptable value of yield strength for steel of grade X65. In the rare occasion that the pipe bought from a manufacturer is tested to have a yield strength way outside the range of $f \pm \Delta f$, then there is a chance the design would not work due to the large mismatch value. Although the pipe is stronger, the bending moment required to bend the pipe to conform to the reel drum radius would be higher, and this would take a toll on the weak pipe. When the compressive strain is higher than the pipe capacity, local buckling may be expected. Fortunately, local buckling can be predicted using FEA once test data of pipe bought are attained, and mitigation plan can be executed before operation.

4.2 Finite Element Analysis

The length of the lead and trail pipe modelled in FEA is 1 meter each, to ensure the end effect does not influence the result in the area of interest; the transition joint. The length of transition joint is also modelled to be 1 meter. Finite element analysis begins with analysis of the parts, boundary conditions, contacts, loads and other settings that has been incorporated during the development of the model, and whether it can be setup properly before proceeding. In this research, the model initial setup is as pictured in Figure 4.3.

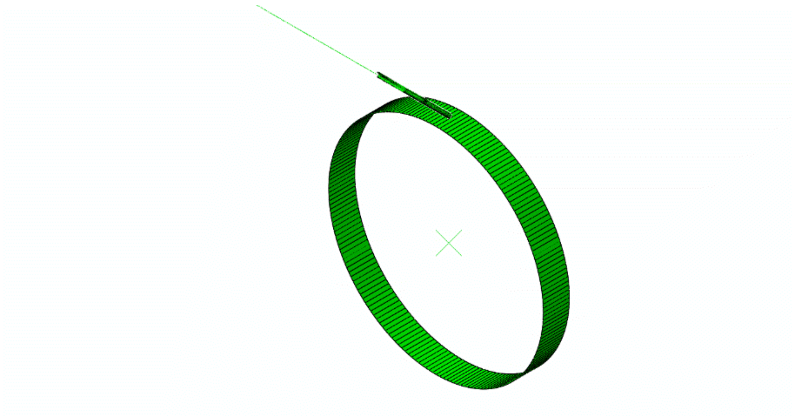


Figure 4.3: Initial Configuration of FEA

The model is then reeled until the whole transition joint is on the reel drum as shown in Figure 4.4.

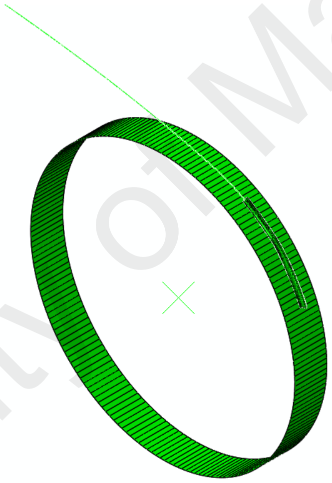


Figure 4.4: Pipe with Transition Joint during Reeling

Aside from the peak longitudinal strain, the pipeline is also visually analyzed for any sign of onset of buckling, such as wrinkling. The first case analyzed is of a strong lead pipe, followed by a weak transition joint, and finally a strong trail pipe (SWS). The maximum allowable compressive strain by DNV GL using equation (2.8) for 254mm outer diameter and 10.1mm wall thickness is -3.772%.The pipe starts to visibly wrinkle as the peak compression strain reaches -10% in Figure 4.5, and then buckled in Figure 4.6.

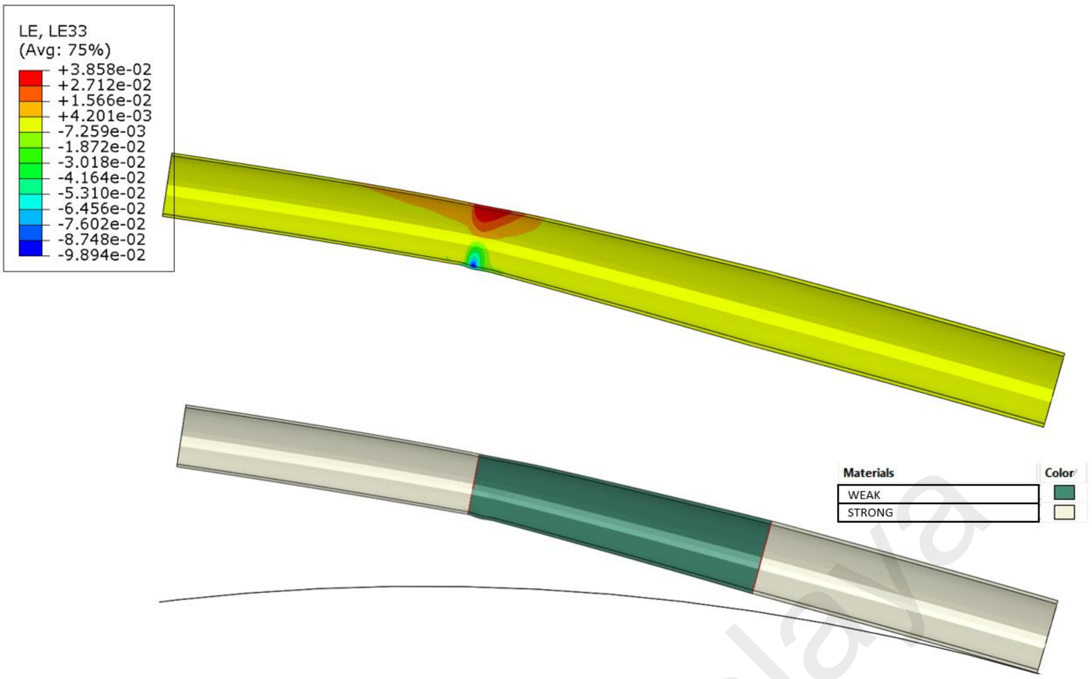


Figure 4.5: SWS Pipe Onset of Buckling

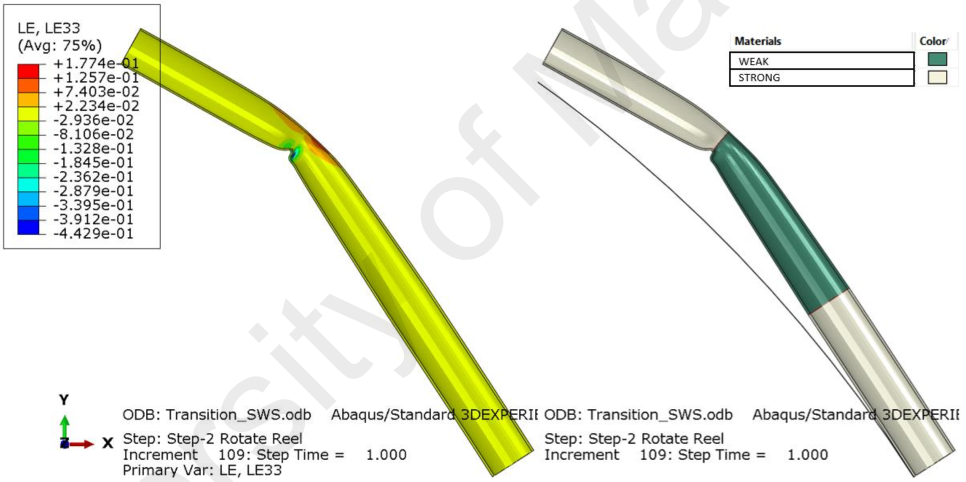


Figure 4.6: Buckled SWS Pipe

The local buckling occurred at the smaller geometry of the weak transition joint with a peak compression strain of -44% post buckling. The yield strength of the smaller pipe is higher than the transition joint, inducing a high bending moment that exceeded the capacity of the transition joint. Case 2: SSW for the same wall thickness are not analyzed as the same probability of failure has shown that the pipe buckled in one of the two cases, exhibiting high risk. To mitigate the high compression strain, the wall thickness for the smaller pipe is increased from t = 10.1mm to 14mm, and is analyzed in the next section.

4.3 Sensitive Analysis

The same procedure using the probabilistic method is used to calculate geometrical and yield strength mismatch for increased wall thickness. The calculated values are as in Table 4.3 and Table 4.4. FEA results are captured in Figure 4.7 and Figure 4.8.

Table 4.3: Updated Geometrical and Yield Strength Mismatch for Case 1: SWS

	Strong (1)	Weak (2)	Weak (3)	Strong (4)
D (mm)	304.80	304.80	254.00	254.00
t_{nom} (mm)	13.53	13.53	14.00	14.00
t_{strong} , t_{weak} (mm)	13.70	13.53	14.00	14.18
f_{ave} (MPa)	500.00	500.00	500.00	500.00
f_{strong} , f_{weak} (MPa)	516.45	483.55	483.55	516.45

Table 4.4: Updated Geometrical and Yield Strength Mismatch for Case 2: SSW

	Strong (1)	Strong (2)	Strong (3)	Weak (4)
D (mm)	304.80	304.80	254.00	254.00
tnom (mm)	13.53	13.53	14.00	14.00
tstrong , tweak (mm)	13.70	13.53	14.00	14.18
fave (MPa)	500.00	500.00	500.00	500.00
fstrong , fweak (MPa)	516.45	516.45	516.45	483.55

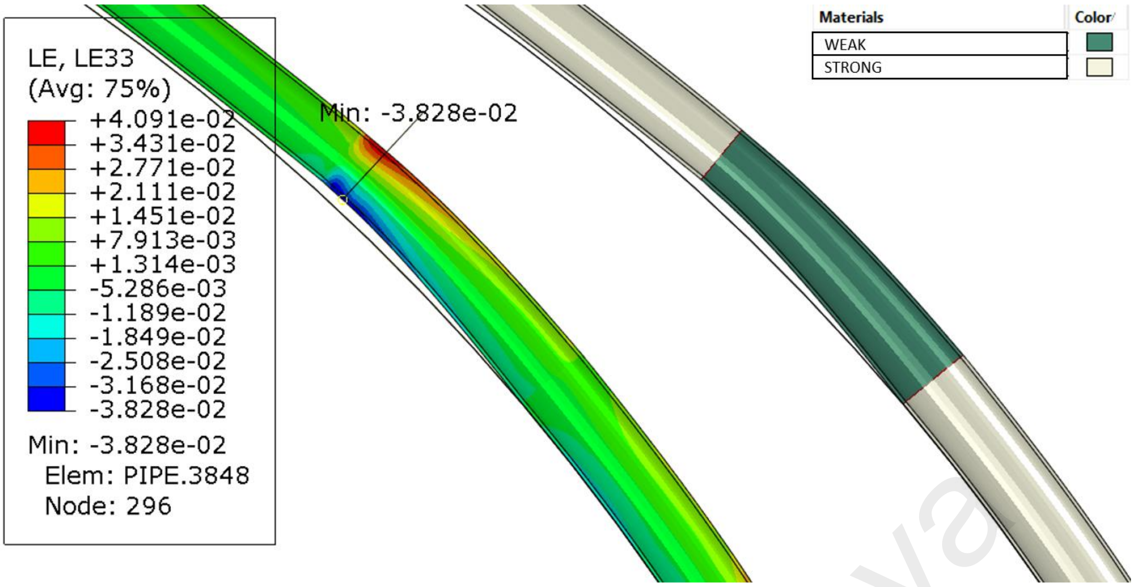


Figure 4.7: Strain in Case 1: SWS

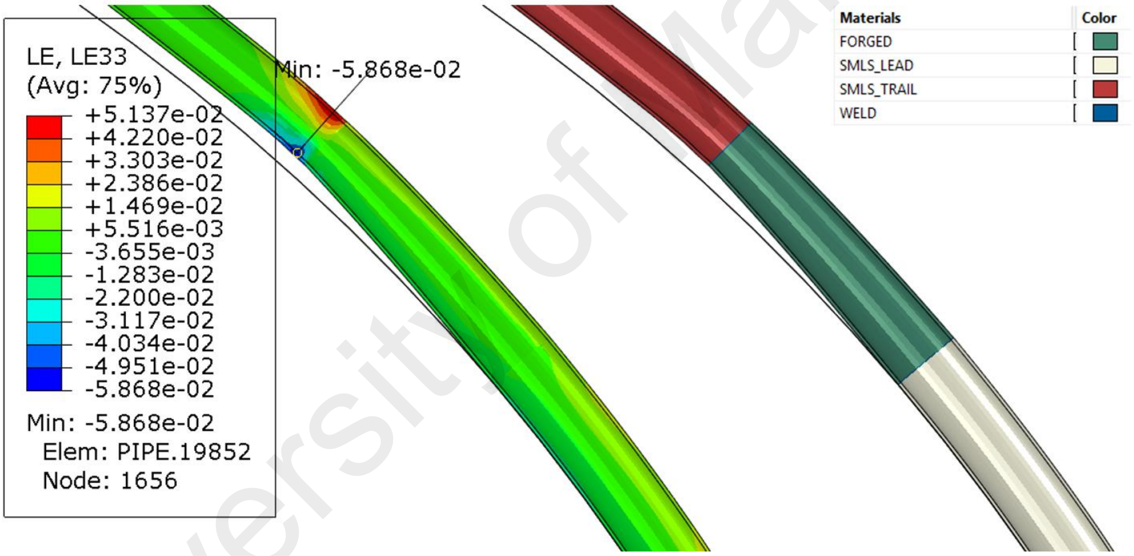


Figure 4.8: Strain in Case 2: SSW

The average compressive strain within one outer diameter from the girth weld after the trail pipe touches the reel is recorded and compared to maximum allowable bending strain equation, $\epsilon \leq 1.2 \cdot \frac{t}{D} - 0.01$ by DNV GL to ensure that it fulfils the requirement. The peak, average, and allowable compressive strains on the weak section for each case are tabulated in Table 4.5.

Table 4.5: Peak, Average, and Allowable Strains

Case	Peak Strain (%)	Average Strain (%)	DNVGL Allowable Strain (%)
SWS	-3.828	N/A	-5.614
SSW	-5.868	-3.616	-5.699

Note: Average strain is not calculated if peak strain is less than allowable strain.

For case 1, the peak compressive strain occurred at the weak section; the transition joint. The bending moment required to bend the lead pipe and the geometrically superior end of the transition joint induced a high strain at the smaller section of the transition joint. The peak compressive strain for case 2 also occurred at the weak section, the trail pipe. The average compressive strain one diameter from the girth weld is calculated and compared to DNV GL requirement. The averaged compressive strain is found to be less than the maximum allowable bending strain, which means that it has passed the requirement.

The analysis has shown that the probabilistic method is capable of reducing the number of iterations required to form a failure boundary by defining the probability of failure in the first place. This ensures that the calculated mismatches adhere to DNVGL's level of safety. To further establish the safety of the design, possible cases of finite element models are analyzed to verify the risk of local buckling. Additionally, the compressive strains from the analyses are also compared to DNVGL's requirement.

CHAPTER 5: CONCLUSION

5.1 Conclusion

The minimum reelable wall thickness by DNVGL are fixed with safety factors which are proven to be too conservative. The refined assessment procedure by Technip has addressed this, presenting their track record and in-house method. However, this method requires multiple finite element analyses to be simulated to obtain the probability of failure. The probability of failure ensures that the Serviceability Limit State imposed by the standard to ensure a safe design is adhered.

The probabilistic method developed in this research has eliminated the computational time required to form the failure boundary by defining the probability of failure first. This method makes it easier to calculate the mismatch despite geometrical and yield strength difference. Finite element model developed using Abaqus has used the calculated mismatch as input. The model has been optimized to reduce computational time by using the symmetrical boundary and having a fine mesh at the area of interest and a coarse mesh away from it.

The first model analyzed experienced local buckling, displaying the weakness of the probabilistic method. The method does not define the minimum reelable wall thickness, rather it gives an estimation of the possible mismatches given a wall thickness and mean yield stress. The local buckling shows that despite the defined probability of failure, the mismatch can still be too high and FEA implied that it is risky to proceed with the same wall thickness. This is also the strength of the method as the industry typically has specified the details of the pipe during bid stage. Hence, this method is more applicable in real life application.

A second model with a thicker wall thickness is developed and analyzed. The result of the analysis has been compared to the requirement by DNV GL and has passed. Additionally, there was no sign of buckling within the updated model which confirms the success of the design.

5.2 Recommendation

Some studies have stated the reeling configuration such as the reel drum and tensioner, plays a role in influencing on-reel local buckling. Current standard provided a standardized equation that considered the configurations with fixed safety factor. It could be beneficial to look into the effect of these configurations by running a series of parametric finite element analyses while also applying statistical information on the mechanical and geometrical properties variation. Additionally, reeling of pipeline with bulkheads would be an interesting topic to be studied. Bulkheads would have different geometry compared to transition joint and pipeline, and hence the requirements might differ.

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