A STUDY OF PIPELINE RESPONSE DURING REEL-LAY INSTALLATION

by

© Ali Ahmed Dawood

A Thesis submitted to the

School of Graduate Studies

in partial fulfillment of the requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

August, 2014

St. John's Newfoundland

ABSTRACT

Pipeline installation by reel-lay is among the most cost effective methods currently being utilized in the offshore industry. It is advantageous over other conventional methods both in terms of cost and the rate at which the pipeline can be laid on the seabed. Reel-laying however, subjects a pipe to large bending which induce plastic strain reversals as the pipe is reeled on and off followed by aligning and straightening before exiting the installation vessel. Bending of a pipe beyond its elastic limit can change its initial mechanical properties. The realm of analyzing pipe response subjected to plastic bending holds a significant research potential for accurate assessment of the mechanical behavior of the pipeline. The current research effort aims at addressing some of the scenarios that may arise during reeling with the help of finite element methods (FEM). Pipe reeling was simulated using two different calibrated models for a perfect pipe. The study of material variation and weld offset were examined initially. The study was then extended to incorporate the pipe geometric imperfections and bifurcations, ovality, material combination, weld offset and joint to joint variations. The FEM were used to examine pipe behavior and led to conclusions regarding the stress and strain distributions that the pipeline experiences during the reeling process. Moreover, it was concluded that the girth-weld area hold critical importance during pipe bending during various stages of the reeling process. Incorporation of anisotropic properties i.e., the sensitivity of a material against the direction of applied load, in the material model was suggested to provide a more realistic response of the pipeline.

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor, Dr. Shawn Kenny, who provided me with his continuous guidance and support throughout the research program. His commitment and dedication towards mentoring his research group has been exceptional. I would like to express my utmost respect and gratitude to him as his assistance and strong hold on the research content which helped me throughout the research tenure. His supervision and constant encouragement helped me to perform efficiently and produce this work.

I am very thankful to my entire research group, the WoodGroup Research Lab, for the technical discussions, help and support over the last two years.

I would like to thank the School of Graduate Studies (SGS) for providing me with the SGS Baseline Fellowship for most part of my program. I would like to acknowledge the Wood Group Chair in Arctic and Harsh Environments Engineering at Memorial University of Newfoundland for sponsoring the research project. I would also like to thank Research and Development Corporation of Newfoundland and Labrador (RDC) for providing supporting funds.

Last but not the least, I owe my deepest gratitude to my loving parents, for their unconditional support in every challenge and step that I took. They have always been an inspiration and I owe all my successes and achievements to them.

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1 INTRODUCTION

1.1 Overview

With the global energy demands increasing, the need for exploration of new oil and gas reserves is inevitable. Huge investments are being made to explore new reserves in order to balance the supply and demand energy equation. The realm of offshore oil and gas exploration in this regard is critical. Significant technological advancements are being made to discover and extract oil from places that present huge design challenges. This encompasses but is not limited to offshore pipeline installation techniques that are currently being used. Offshore pipelines are responsible for the transportation of great quantities of oil and gas. Possessing pivotal importance, the need to study the mechanical response of these pipelines to avoid any catastrophic failure; leading to production loss, casualties, significant environmental damage is of extreme prominence. The knowledge of pipe behavior during installation of these pipelines is a key to ensure smooth and effective installation that eventually will result in a longer service life of the pipeline.

Pipelines undergo different types of loading conditions depending upon the installation technique. The most common installation types include S-Lay, J-Lay and Reel-Lay. Each method has certain advantages and disadvantages over each other and are related to various factors such as strength, durability, length, depth, capacity and installation time. For relatively shorter distances, the reel-lay method is technically and economically advantageous over other methods (Huguchi and Shitamoto; Meissner et al., 2009). Also, for relatively moderate sizes of upto around 16 inch, the reel-may method is also considered to be the most effective installation method for infield subsea flowlines and risers (Smith and Clough, 2010).

However, reel-lay method includes the pipe being exposed to repeated bending that induces plastic strain reversals. Although being widely used, the induction of cyclic plastic strains on the pipeline generates a thought that the reeled pipe might have lost its structural integrity and strength and must be down-rated in comparison to other installation techniques (Denniel, 2009). Thus, an accurate assessment and study of the pipe behavior during bending in case of a reel-lay installation is important. The current research effort is focused on studying the pipe mechanical response during bending with an intent that it will help update the industry in the design and installation of pipelines using reel-lay method.

1.2 Scope and Objectives

During offshore pipeline installation by reel-lay method, the pipe undergoes cyclic bending that subject the pipe to plastic strain reversals. A number of variables need to be accounted for to effectively perform the pipe behavior study. In order to examine the mechanical response of the pipe; including weld joints, wrinkle formation, stress and strain distributions etc, the need for having an adequate amount of information available that can define the reaction when underdoing such type of installation is important. Several public domain studies (Kyriakides and Ju, 1992, Martinez and Brown, 2005, Castello and Estefen, 2005, Focke, 2007, Meissner et al., 2009, 2012, Arjomandi and Taheri, 2009 and Pasquallino and Neves, 2010 have studied the pipe response in relation to reeling.

The public domain database was used to generate calibrated finite element models that replicated reel laying of a pipeline. Once confidence in the models was achieved, a range of variables were examined which included the effect of weld off-set and material variations across the pipe weld joint.

The study was then extended to incorporate the effect of geometric and bifurcation imperfections, pipe ovalization, weld and material variation of the pipeline. A parametric study was performed over a range of D/t ratios and then examined the the effect of weld off-set and material variations across the pipe weld joint with respect to pipe thickness.

Conclusions were drawn that shed more light onto pipe mechanical response under reeling. The research effort can be used in better understanding of pipe reeling and for the development of future more realistic models.

1.3 Thesis Layout

The thesis is divided into five chapters in which the first two of chapters concentrate on the scope of work of the current research effort and the literature review respectively. The literature review summarizes the study of domain data that was carried out to assess the efforts that have been put in terms of experimental investigations, finite element modeling. numerical simulation, current research efforts that are being carried out to study pipe installation techniques, technological advancements in studying pipe bending behavior and areas with further research potential. A variety of different research efforts were examined which helped in focusing at different potential scenarios that can occur which need to be addressed. These were used as a platform for the development of numerical modeling procedures presented in detail later in this report.

Chapter 3 and 4 are peer review publications that discuss in detail, the research effort that encompasses development of calibrated numerical modeling procedures, subsequent studies that address the parametric influence on the pipeline and relevant conclusions related to pipeline response.

The calibration study has been presented in chapter 3. The numerical modeling carried out was based on earlier studies that were performed to understand the pipe behavior during reel-lay installation. A variety of baseline parameters have been studied in this chapter. Two different calibration models were initially formed to gain more confidence in the research effort that was put in later.

Chapter 4 extends the study performed in the earlier chapter and includes a variety of other parameters pertinent to pipe mechanical response. The calibration study carried out in chapter 3 was used as a baseline reference. The effect of linear perturbations and imperfection wavelength was incorporated and a comprehensive parametric study was carried out. The parametric study is focused on the effect of D/t ratio, weld offset, imperfection wavelength, material variation,

The last chapter focusses on summarizing the results and the subsequent conclusions that were drawn as part of the research program. Results generated were compiled and the mechanical response of the pipeline under different scenarios presented in the earlier chapters was reviewed. Recommendations were formulated that can be incorporated to extend the study further. It was stated that the incorporation of anisotropy and physical experimentation will add more confidence into the numerical study carried out and will help improve the numerical modelling procedures for predicting the pipeline mechanical response with greater confidence and more predictable outcomes. It was also stated that the current research effort can act as a starting point to develop complex and enhanced finite element methods (FEM) that incorporate the effect on intricate pipeline systems such as Tight-Fit-Pipe (TFP) and Pipe-in-Pipe (PIP) systems.

2 LITERATURE REVIEW

2.1 General

The ever increasing global oil & gas demands, especially in the 20th century led to the broadening of development horizons that can overcome the challenges related to pipeline installation. Pipelines are considered to be the most economical and cost effective way to transport hydrocarbons in significant quantities over relatively large distances. The offshore industry in this regard has been continuously facing the challenge to develop solutions for pipeline installations needed to extract hydrocarbons from deeper and more complex reservoirs in different parts of the world. Several installation methods are currently being utilized with certain pros and cons associated with each method. A number of factors govern the selection of the optimum pipeline installation technique.

Pipeline installation through reel-lay method goes back to the early 1940s. The first reel-lay pipeline was in 1944 named the PLUTO (Pipeline under the Ocean) project which was executed during the World War 2 (Denniel 2009). One of the pipelines that were laid as part of the PLUTO project later on collapsed due to propagation buckling which is evident of more research effort that was essential to be put into understanding and overcoming the challenges pertinent to this technique. Commercial use of this technology, however gained importance only in the nineteen seventies with the Reel Ship named Apache, commissioned in 1979 being one of the first to be used for pipeline installation with this technique (Smith & Clough, 2010). Since then, pipeline installation by reel-lay has been of pivotal importance due to certain economic advantages over other conventional installation methods. However, it has to be noted that in order to ensure smooth and reliable operation of pipelines, there are certain parameters that are needed to be addressed. This encompasses but is not limited to the study of pipe fabrication defects, structural integrity, weld joints, plastic stress and strain reversals etc. Over the years, a number of international codes and standards have been published providing a guideline for designers when studying the structural response of a pipeline. ASME B31 was released in the 1930s addressing these issues. Enhancements and improvements in the structural integrity led to the upgrade of ASME B31 which was then divided into ASME B31.4 which covered transportation of liquid hydrocarbons and ASME B31.8 governing the transport of natural gas. Extensive work was put in over the years to publish a number of standards that expanded the horizons and provided guidelines relevant to pipeline design and manufacture, in service behavior, installation techniques, inspection, preventive maintenance and repair. Some of these standards include ASME B31.4, ASME B31.8, API 5L, DNV-OS- F101, API-RP 1111 etc.

2.2 Reel-Lay Installation

Since its inception, the reel-lay method has become one of the most advantageous offshore installation methods. Reel-lay allows rapid deployment of the pipe onto the seabed in addition to less dependency on weather conditions. Significant research effort has been put in to increase the reliability of this process and to provide sufficient conclusive research evidence supporting the gains of this method. Currently, pipe installation through reel-lay method has been successfully carried out for pipe diameter of up to 16” outer diameter (OD) and wall thickness of 30 mm (Anelli et. al, 2006).

In a reel-lay installation technique, as opposed to other conventional methods such as J-Lay and S-lay, long spools of pipelines as welded onshore at a production facility which is also referred to as a spool-base. The spool-base comprises of a number of pipe manufacture essentials including welding and beveling stations, non-destructive testing areas (NDTs) and field joint coating stations. Figure 2-1 shows the Subsea7’s spool-base at Port Isabel in Texas, USA. Once the pipe lengths have been welded and tested for installations, they are wound on a reel-drum on the installation vessel from the Tie-in point. The vessel then sails to the designated installation site for pipe laying.

Figure 2-1: Seven Oceans docked at Port Isabel Spool-base (Subsea 7)

Although it seems to be a simple concept, the process of reeling a pipe onto the reel-drum and lying it onto the seabed involves complex mechanics and plastic stress and strain reversals that the pipe undergoes. These plastic deformations can induce the idea of reduced reliability of a reeled pipe as compared to a pipe being installed by any other conventional method. Moreover, this may reduce the confidence in using this technique on commercial basis and lead to reduced economic efficiency by using a thicker pipe (Denniel, 2009). Therefore, a thorough study in understanding the contact mechanics and the stress and strain distributions that the pipe undergoes is essential. Figure 2-2 presents a schematic representation of the reeling vessel.

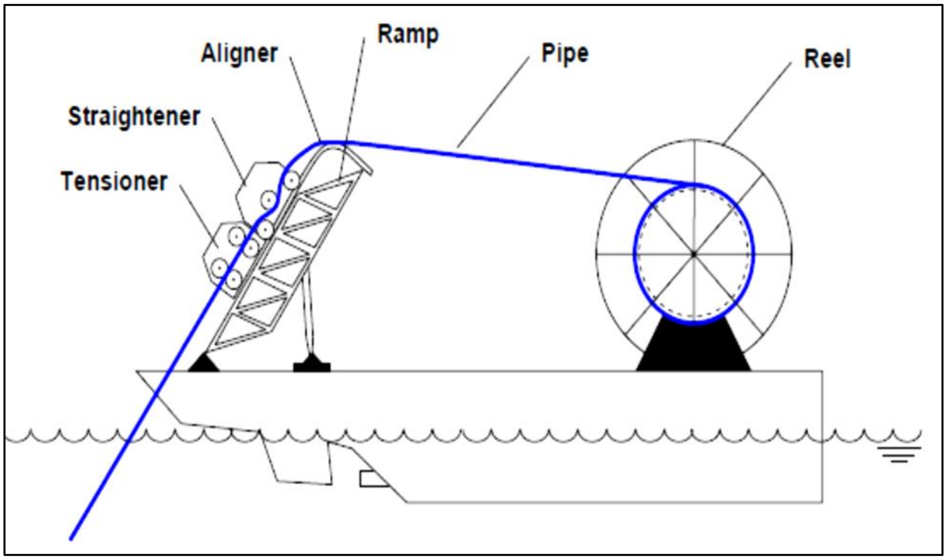

Figure 2-2: Schematic representation of a reeling vessel (Jukes et al., 2008)

A typical reel-lay installation vessel will comprise of a) a reel drum, b) the aligner reel, c) straightener and d) tensioners. Each unit has a specific purpose and is better understood in relation to the deformation that the pipe undergoes in a reeling process as explained below. A generic reel-lay process can be summarized in four basic steps which explained by the help of a characteristic moment-curvature plot.

After manufacturing, the pipe is wound around the reel-hub where it is bent beyond its yield point (A). The first wrap is equal to the radius of the reel with every successive wrap having a higher radius of curvature. On a moment-curvature plot as shown in Figure 2-3, this has been represented by point B.

The pipeline is then unwound and passed through the aligner. It should be noted that as the pipe is unwound from the reel, the pipeline exhibits a straight span owing to pipeline self-weight and the back tension. The back tension is needed to prevent the pipeline from buckling. The pipeline undergoes reverse plastic deformation represented by point C. Point D in the figure represents the straight span of the pipeline.

The pipeline is then plastically deformed by passing it through the aligner reel. This is done in order to bend the pipe to a uniform curvature (the radius of the aligner wheel) before being fed into the straightener as mentioned in the figure as point E.

The plastic deformation induced into the pipeline has to be removed before it is being laid on to the seabed. This is crucial to ensure the structural integrity of the pipeline. The pipeline is passed through a set of straighteners which ensure that the pipe is straight before being it exits the vessel and onto the seabed. This has been represented by point F in the figure.

The straighteners are normally designed to have a three point arrangement with radii ensuring that the pipe is straightened. Note that there is still residual stress and strains left on to the pipe which however, are within the defined limits of the codes and standards developed for such installation technique (Denniel, 2009).

In addition to inducing change in the mechanical properties of the pipeline after undergoing through cyclic loading, the pipe may also undergo geometrical changes that are caused by the elongation and induced ovalization in the pipeline. These can affect the mechanical response of the pipeline which has been discussed in later sections of this research effort.

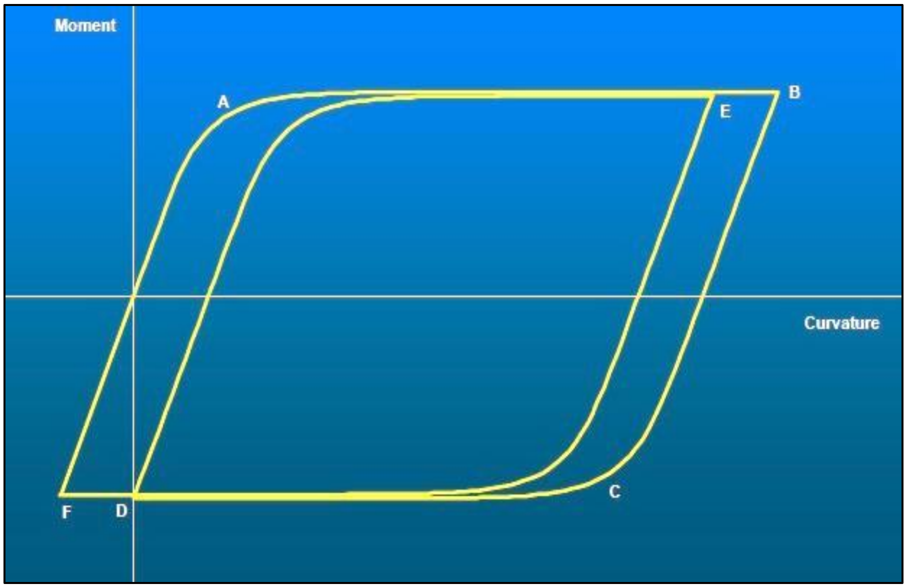

Figure 2-3: Moment Curvature Plot During Reel Lay (Denniel, 2009)

2.3 Bauschinger Effect

As mentioned before, a pipeline undergoes plastic strain reversals as the pipe passes through different sections of a reeling vessel. This plastic deformation may affect the pipe mechanical properties such as structural integrity, pipe strength, ductility and toughness. Therefore a thorough understanding of the same is crucial. The change in pipe properties is dependent upon the direction of pre-strain of the pipe. This is most significant during the last step of deformation, which in this case is the straightening. This means that the plastic deformation which the pipe undergoes while being bent onto one direction will increase the elastic limit and the yield strength of the pipeline in the direction at which the pipe is being bent while simultaneously causing a reduction of pipe strength in the opposite direction. This phenomenon is termed as the Bauschinger Effect (Meissner et al., 2009), and has been named after the German engineer Johann Bauschinger who first studies this effect in 1881.

This means that a material that has been plasticized in compression will therefore yield at a relatively lower value when put into tensile loading scenarios provided that the loading conditions are somewhat similar (Manouchehri et. al, 2008). However, if the stress and strain distributions in other directions are considered, then the Bauschinger effect is less prominent (Martinez & Brown, 2005). Although, the Bauschinger Effect is a critical parameter in understanding pipe reeling mechanics, studies have shown a reduced trend in the significance of this effect with increased cycles (Castello & Estefen, 2005).

The Bauschinger effect is not exclusive to pipe reeling and is also observed in pipe manufacturing process such as during the cold expansion of the UOE pipes. In general, it is of extreme practical importance in any scenario that involves strain path reversals or where tension and compression of a metal co-exist. There are a number of factors that can give rise to Bauschinger Effect. Some of the examples are asymmetric plasticity, residual stresses, non-uniform plasticity induction in the metal etc (Sinclair, 2009).

2.4 Factors Aiding the Reeling Process

As mentioned earlier, reeling induces plastic deformation in the pipe which questions the structural integrity of the pipeline. However, if one digs into the actual mechanics that are involved, there are certain parameters which strongly justify and support the reliability and suitability of the reeling process. Some of the factors have been summarized below:

Displacement is the key element governing the pipe reeling. This is explained by the fact that the pipe that is being plastically bent on to the reel is geometrically limited by the radius of curvature of the reel which also limits the bending strain experienced by the pipeline.

Steel by nature is a ductile substance. Moreover, during the reeling process, the ductility ensures that the strain levels that the pipe is exposed to is below limit so that there is no wall thinning, necking or buckling of the pipeline. Strain hardening is defined as the strengthening of a metal due to plastic deformation and the level of induced strain is deficient to cause work hardening in the pipeline thus not affecting the pipe structural integrity during reeling.

Since long lengths of pipe are welded together in the spool-base before they are reeled onto the vessel, the quality and the structural capacity of the weld itself poses a question about the reliability of the reeling process. However, to overcome this issue, the weld material used has more strength than the pipe material. This ensures that the welds don't act as limitations when it comes to reeling and also to prevent potentially higher than limit strain levels that might lead to failure or localized buckling.

Reeling of the pipeline gives rise to the tendency of localized buckling of the pipe. Since the pipe that are being wound around the reel-hub are empty, an increased chance of collapse is prominent that should be taken care of. Therefore, a back tension is applied onto the pipe whenever a pipe has to undergo bending in different stages of the reeling process in order to ensure structural stability and prevent buckling of the pipeline. Generally the necessary tension is provided by the one or a combination of tensioners that tend to grip the pipe during the process. The shape, material, frictional behavior and the supporting structure of the tensioners may vary and is dependent upon a number of factors including contact pressure and the type and quality of the pipe coating. (Smith & Clough, 2010).

2.5 Effect of Reeling on Weld Joints

As mentioned earlier, the reeling process has significant technical and economic advantages in comparison to other installation techniques. This is because of the fabrication of the pipe lengths onshore before they are reeled on to the hub. Although the fabrication process includes high-quality welds and a series of inspection tests, one has to consider that reeling involves bending of the pipeline beyond the elastic region. Therefore, special considerations are to be taken to study the effect on pipe welds during the reeling process. Although, the weld material is overmatched to ensure structural reliability, any dimensional changes across the weld seam (in case of a girth weld) resulting from strain concentrations developing across the weld have to be taken into account to prevent any unfavourable scenarios including crack growth and propagation (Soriede et. al, 2010).

It has been observed that fatigue loading is more prominent in case of a reeled pipelines and thus to ensure confidence in the installation methodology, the detrimental effects of reeling are to be considered in reference to fatigue failure. The high level of strains developed during the reeling process as a whole (reeling on, aligning, straightening etc.) can lead to detrimental effects by the development of ductile tearing and LCF (low cycle fatigue) crack growth which can post adverse effects on any pre-existing welding flaws (Hudak et. al., 2006). These pre-existing flaws are because of the fact that welding induces residual stresses in the pipe due to weld travel and also having a localized heat source. Moreover, in case of a girth weld, these stresses are developed in the hoop direction of the pipe cross-section (Noecker et. al., 2009). Moreover, during the manufacturing processes of pipelines, special consideration is given to fabricate pipes with constant material and geometric properties. However, in reality there are slight variations in pipe lengths. Welding of two pipes together that have different strength and moment capacities may result in localized buckling close to the weld area due to an increased amount of strain concentration (Focke, 2007). These strain levels can not only be caused due to deviation in material strength but also flaws in the welding procedure such as mis-alignment etc. Design considerations based on crack propagation becomes a subject of increased attention due to these local strain concentrations across the girth weld.

A lot of work has been put in to study these effects with the help of numerical modeling as well as experimental calculations over the years. These experiments have been conducted to study various aspects that can influence pipe weld. These include the variation in pipe wall-thickness and material strength variations. Experimental setups have enabled to carry out SSR (Small Scale Reeling) tests as well as FSR (Full Scale Reeling) tests. Both have their own advantages depending upon the research focus and the range of parameters under study.

2.6 Small and Full Scale Reeling Tests

In order to study the effect of different parameters of a pipe when it undergoes plastic strain reversals in the reeling process, certain physical test procedures have been developed. These can be categorized into Small Scale Reeling tests and Full Scale Reeling tests.

A SSR Test is normally carried out on a smaller scale to study minute details or behavioral changes that the pipe might undergo. These are preferred due to their economic reasons as actual pipe specimens are not used to examine the mechanical response of the pipeline. Normally, the conclusions drawn from a SSR are then taken to carry out a FSR for verification and to attain more confidence in the experimental effort.

A typical SSR setup includes a pipe specimen that will undergo reeling. One end of the pipe is fixed and is attached to a fixation point. The other end is connected to a hydraulic actuator which pulls the pipe down and bends in onto the reel. A schematic representation of SSR setups is given below:

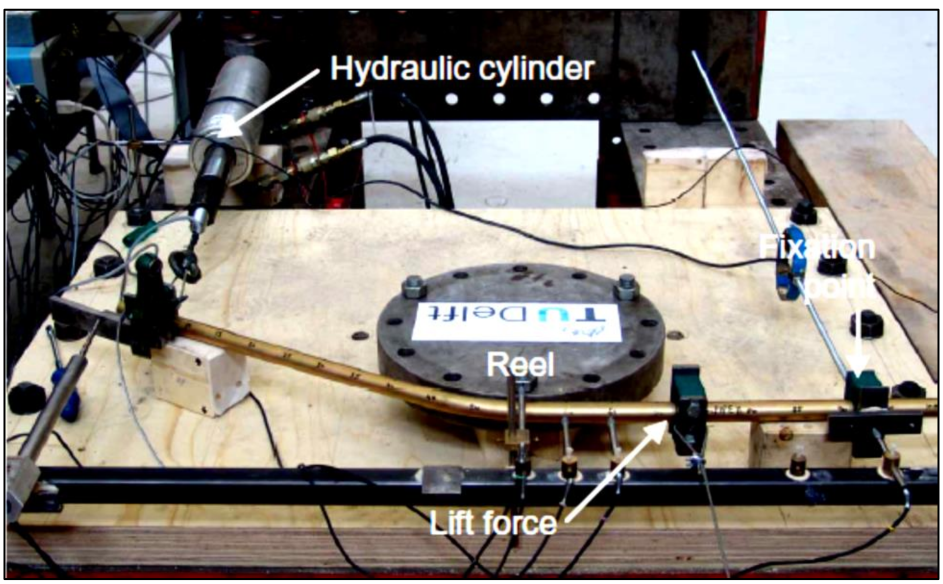

Figure 2-4: Bending of pipe in a small scale reeling test (Focke, 2007)

A force is applied towards the fixation end of the pipe as it is being bent. This force is necessary to slightly lift the pipe from its original position to reduce the initial contact reaction force between the pipe and the reel. This helps is reducing the chances of any unwanted results including pipe buckling near the fixation point and unintended induced ovality.

The pipe is bent onto the reel where it takes the shape equal to the radius of the reel-hub used in the experiment. There are however a number of differences between an actual reeling process and an experimental reeling process that are necessary to take into account. The scaling down of the actual reeling process for SSR means a reduced distance between the reel and the tension applied to the pipe. Therefore, this may result in difference in the contact reaction force between the specimen and the reel-hub. This reaction force is constantly maintained during the actual reeling process as a large length of onshore fabricated pipeline is being wound. In an SSR, the reaction force will increase as the pipe is being bent onto the reel and the distance between the pipe and the hydraulic actuator decreases. Similarly, the tension force that is necessary to be applied on to the pipe in case of reeling onto a vessel is constant and is calculated in order to prevent the buckling of the pipeline during the reeling-on phase. In the case of a SSR, the tension force changes due to an increase in the reaction force and a continuous change in the hydraulic cylinder direction. The difference in the generation and values of the contact loads, which are concentrated at the point of contact, are not negligible and play a pivotal role in the prediction of the final pipe ovality. Most importantly, small scale reeling simulations generally do not account of the weld joints in the pipe length as opposed to actual reeling (Focke et. al., 2006).

In order to comprehensively study the effect of pipe reeling, including any exclusive behavioral changes across the weld joints, full scale reeling (FSR) tests are conducted. A full scale reeling tests comprises of a reeling former and a straightening former, whose radii have been carefully selected and normally vary depending upon the type of analysis being carried out. A general arrangement of a FSR test setup can be understood by looking at the FSR facility at Heriot-Watt University in Edinburgh. The arrangement consists of two spine beams that hold the reeling and the straightening formers and are interchangeable.

Once in their respective position, both the formers are permanently attached to the spines. The pipe however, is fixed at one end but allowed to rotate freely. The free end is attached to cables that drive the pipe towards the two formers. Reeling is achieved by bending the pipe on to the reeling former, relaxed and then bent on to the straightening former and finally brought back to the initial position to finish one complete cycle. A complete reeling analysis might consist of several of these cycles. Sophisticated laser profiling tools are used that measure the inner section of the pipe whereas an ultrasonic device measures the thickness of the pipeline. A schematic representation of the FSR test setup is given below. SSR and FSR are used as a reference to develop calibrated finite element models for further scenarios based analysis.

Figure 2-5: HWU Full Scale Reeling Test Setup (Chouhan, 2010)

2.7 Pipe Ovality, Imperfections and Bifurcation

Pipelines are subjected to several loads during installation and in service irrespective of the installation technique used. The structural integrity of the pipeline is dependent upon its resistance to buckle and collapse during installation and throughout the service tenure. Certain parameters influence the calculation of pipe integrity. Since pipe reeling involves bending of the pipeline into the plastic region, a change in pipe cross-section and uniformity can occur. This can be understood by the fact that as the pipe starts to bend on a specified curvature, the outer side of the pipe experience a pull with a small component directed towards the centerline of the pipe. Similarly, the inner side of the pipe will undergo the same experience but in the opposite direction. This eventually leads to the flattening of the pipe resulting in pipe ovality. Predicting the extent of ovality is a key parameter in the calculation of pipe structural integrity and failure resistance particularly with a higher D/t ratio.

Ovality in terms of reeling is defined as the flattening of the pipe on the two extremes. These are also referred to as “intrados” and “extrados” with the first defined as the section of the pipe that comes in contact with the reeling former.

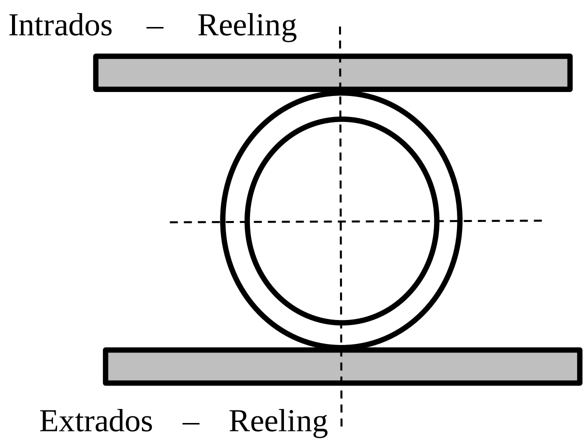

Figure 2-6: Pipe cross-section representing Intrados & Extrados, Chouhan – 2010)

Ovalization of a pipeline is a well-known phenomenon; a pipe that is being subjected to bending will tend to ovalize with the degree of ovalization being directly proportional to the extent of the bending and the initial pre-bending ovalization present in the pipeline.

A number of industrial codes covering different aspects such as design, installation, maintenance and operation of offshore pipelines have are present that act as a guideline for offshore pipeline installation such as DNV-OS-F101, ISO 13623, API RP 1111, ASME B31.8, CSA Z662 and BSI 8010. All have specific design criteria and tolerances that are acceptable for the safe and reliable operation of offshore pipelines (Baek, 2011). The ovality guidelines as per DNV-OS-F 101, state that the ovality should not exceed a maximum of 3%. API standards however, are stringent with the maximum allowable ovality being at 1.5% unless conclusive evidence can be provided about the pipe integrity with an increased percentage of ovality (Denniel, 2009). The DET NORSKE VERITAS (DNV) standard DNV-OS-F101 (Submarine Pipeline Systems) by also specifies a minimum range wall thickness fabrication tolerance at 0.15 t – 0.125 t with reference to the wall thickness of the pipeline. Ovality in general can be calculated using the following equation presented in DNV-OS-F101:

$$f = (D_{max} - D_{min})/D$$

where D is the nominal outside diameter, D_{max} is the greatest measured outside diameter and D_{min} is the smallest measured outside diameter.

In API 5L "Specifications of Line Pipe", the ovality is calculated using the following equation:

$$Ov = (D_{max} - D_{min}) / (D_{max} + D_{min})$$

where D_{max} and D_{min} represents the maximum and minimum measured pipe diameter respectively.

Optimum selection of the pipe wall thickness in parallel consideration to ovality is a key parameter that must be used by the designers. The approved values of wall thickness must not only cater for the nominal ovality for pipe reeling but should also incorporate localised peaks or variations in the ovality resulting during pipe reeling and during the manufacturing phase; also referred to as geometric imperfections.

Complex finite element codes have been developed that study the mechanical response of a pipeline under different scenarios both in the linear and the non-linear regimes. However, in order to have a more realistic approach on the actual behavioral changes that the pipe will undergo, the effect of imperfections must be added to the numerical models. This is so because no real system in the world is perfect. Although modern day technology has dramatically improved the manufacturing processes, a pipe cross-section is not constant in the longitudinal direction. There is always a small amount of variation, namely imperfections that exist. Therefore, inclusion of these imperfections is necessary to not only improve the numerical modeling but also to predict the response of the pipeline as close to an actual scenario to achieve a far reaching confidence in the structural integrity of a pipeline. These geometric imperfections are added onto the pipeline using complex numerical techniques as waveforms having a specific wavelength and amplitude as gathered over the years and through manufacturing database. During the study of pipe bending analysis, such as reeling, the geometric imperfections and the imperfections caused by bending itself are studied in co-relation to obtain a realistic conclusion about pipe behavior. Over the years, several techniques have been developed to define and incorporate the initial geometric imperfections including the database, model analysis and idealized Fourier characterisation of nodes both in the longitudinal and circumferential for numerical modeling (Fatemi & Kenny, 2012).

In case of bending, a pipe will generally undergo two modes of deformation. Both modes are dependent upon pipe wall thickness and diameter with the first one being more prominent in pipelines of smaller diameter and wall thickness. This mode is governed by the Brazier's effect which means that the pipeline will undergo ovalization across the cross-section during bending. Similarly, the second mode of deformation has been studied in pipelines with a relatively larger pipe diameter and wall thickness. It is different to the Brazier's effect because in this case the pipelines will continue to exhibit a linear moment-curvature relationship till it reaches the bifurcation point. Bifurcation is termed as the mathematical concept that is used to generate a solution to a system of equations that are characteristic to the system where a dominant parameter passes through a critical or peak value (Fatemi & Kenny, 2012). At the bifurcation limit, deformation of the pipeline in terms of short axial waves will occur. Bifurcation analysis in particular has been extensively studied and is used to generate Eigenvectors that can be used to incorporate initial perturbations to the pipe geometry (Kyriakides & Ju, 1992). These generated Eigenvectors are a governing factor in defining the initial pipe imperfection profiles in relation to a specific mode shape as well as the imperfection amplitude. This type of behavior has been studied to be present in pipelines of all diameter and wall thicknesses with reference to the linear perturbation analysis. Kyriakides states the nonlinear plastic perturbation should be conducted with deformation plasticity. The local buckling FEA can be conducted using J2 plasticity. Studies by Fatemi have shown that pipe with larger diameter has a smaller error when using linear perturbations or eigen value analysis.

In actual scenarios, however, a pipeline will deform in a way that is affected by both modes of deformation. The domination of one of the modes over the other is dependent upon mechanical properties of the pipeline, the type of imperfections present and the amplitude of the imperfection wavelength on the pipeline. Moreover, the bifurcation and buckling response of the pipeline shells is influenced by a number of factors that include diameter, wall thickness, the initial geometric imperfections added, loading scenarios and material behavior.

2.8 Existing Work

As mentioned earlier, installation of pipeline using reel-lay method has many technical and economic advantages over other installation techniques. However, the study of the actual pipe reeling mechanics is critical in order to gain confidence in the method and to further test the limits of pipe installation by reel-lay. This involves extensive research exclusively related to plastic strain reversals as well as the mechanical response of the pipeline undergoing bending. Comprehensive study of pipe mechanics through reel-lay is a therefore a broad, interconnected subject covering a vast realm of concepts.

Design codes such as API RP-1111 "Recommended Practice for the Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), DNV-OS-F101 "Submarine Pipeline System", API 5L "Specification of Line Pipe" and ASME Code B31.8 "Gas Transportation and Distribution Piping Systems" are the current recommended guidelines for offshore pipeline systems.

The generation of axial wavelengths; imperfections in relation to bifurcation and localized instabilities plays an important role in determining the realistic pipe behavior. Kyriakides & Ju in 1991-92 carried out an array of experiments on aluminum shell pipes consisting of different diameters to study the behavior of cylindrical shells that are subjected to pure bending. They concluded that for shells with a lower D/t ratio, short periodic wavelengths are generated on the compression side of the pipeline. Contrary to this, thinner pipelines (D/t > 100) tend to ovalize and generate a limit load instability after which the pipe would eventually go to a collapse state. For intermediate diameter pipelines, a combination of axial waveforms and ovalization was observed. However, these responses were examined to have a strong dependency on the plastic characteristics of the material under study. Similarly, considering finite strain, calculation to predict the D/t ratio that will result in the buckling of the pipeline on a characteristic stress-strain curve can be carried out. This can then be used in generation of a range of strain levels that will cause wrinkling as function of D/t (Peek, 2000).

Coflexip Stena Offshore Norge AS was awarded a contract by Statoil to install the majority of infield flowlines for the Asgard field in the Norwegian Sea. The project involved the installation of a pipeline with thick insulation coating. A number of local buckling instances were recorded during the installation phase which led to the rapid study of factors governing pipe behavior in such conditions. Reeling effects on the pipeline were studied and it was concluded that the possibility of local buckling of the pipeline is possible if proper combination of pipeline design, reeling parameters and coating thickness or stiffness are not taken care of (Crome, 1999). This signifies the importance of a thorough study of pipe mechanics during reeling.

Several researchers have studied the effect of reeling on pipelines under different loading scenarios in the past. To name a few Martinez and Brown (2005), Castello and Estefen (2005), Focke (2007), Meissner et al., (2009, 2012), Denniel (2009), Arjomandi & Taheri (2009), Smith and Clough (2010), Chouhan (2010), and Pasquallino and Neves (2010) have looked into various parameters that are related to pipe reeling.

Full scale reeling tests were carried out on an 18” outer pipe diameter to study the changes in pipe properties and ovalization during reeling. The reeling analysis was carried out considering the dimensions of Technip’s Deep Blue vessel. It was observed that the nominal bending strain reached a peak value of 2.29% which is under the DNV-OS-F101 limit. A specific code was developed in Abaqus to incorporate the anisotopic properties for a further realistic approach towards reeling. It was observed that the maximum load or contact reaction is at the touch-down point between the pipe and the former as mentioned earlier for SSRs. It was concluded that the incorporation of pipe anisotropy significantly improves the correspondence between numerical models for pipe reeling and physical experiments (Martinez & Brown, 2005). Castello & Estefen (2005) studied the effect of reeling on Sandwich Pipes. They developed finite element models that accounted for the calculation of ultimate strength under external pressure and bending considering the pipe material to be API-X60. They determined that the collapse pressure of the sandwich pipe after it has underdone reeling did not reduce to a significant amount. A reduction of 1.4% was observed even with an increase of ovalization from 0.2% to 0.56%, which meant that reeling can be extended to the installation of complex piping systems such as sandwich pipes.

The study of complex piping systems such as Tight Fit Pipe (TFP) was extensively studied by Focke (2007). His work focussed on the degree of wrinkling of the liner pipe and also the amount of ovalization occurring during the reeling on phase of the pipeline both using numerical finite element models and experimental efforts. He also concluded that welded joints in the circumferential orientation having a relatively higher bonding strength will result in the development of wrinkles at a lower curvature.

Denniel (2009) put in a research effort to summarize the mechanics that are involved in pipe reeling. He stated the additional parameters apart from the industrial codes present such as API 5L that are to be included when considering pipelines that will undergo reeling. He also studied the minimum reeling wall thickness of a pipeline in accordance with DNV-OS-F101 and API-RP-1111 that is necessary to prevent buckling and collapse of the pipeline. It was concluded that ovality has a detrimental effect on a pipe's resistance to hydrostatic collapse. Moreover, the importance of Engineering Criticality Assessment (ECA) was highlighted when considering fatigue sensitive pipe lengths.

Later on Meissner et al., in 2009 and 2012 studied the stress and strain distributions on the pipeline under actual reeling and in case of FSR by utilizing finite element analyses (FEA). The intrados of the pipe were observed to show a compressive stress whereas the extrados were observed to undergo tensile stress. Specimens were extracted from the reeled pipelines in order to further study the changes in the mechanical properties. They observed that reeling and ageing has an effect on the pipe's toughness and strength after plastic deformation and is dependent upon the direction of the last load step.

Arjomandi and Taheri (2009) put in their research efforts that looked into the pre-buckling, buckling and post buckling response of the pipelines under pure bending that had different types of imperfections. They studied a range of pipe diameters and wall thicknesses and developed numerical models in correspondence with the physical test data obtained. They observed that the finite element Eigenvalue analysis was sensitive to the properties of the pipeline within the elastic region. The effect of plastic strains due to pipe reeling with initial imperfections and its subsequent impact on the collapse pressure of pipelines was also studied by Pasqualino and Neves (2010). A number of pipe samples were studied and coupons cut from the original pipes were then examined under tension to measure the stress-strain material response. The ovalization of the bent samples was seen to increase by a significant amount. Ovalization values which initially were in the range of 0.194% - 0.295% increased to 0.558% - 0.729%. The research effort concluded that the reeling of a pipeline will not affect the collapse pressure of the pipeline to a considerable amount.

Smith and Clough (2010) presented an overview of the pipe reeling in relation to Seven Oceans, which is one of the largest and most advanced reeled pipeline installation vessels. He also summarized the technological advancements that have enabled to reel complex piping systems including high frequency induction (HFI) pipe, polymer (PE) lined pipe, mechanically lined pipe, clad flow lines and steel catenary risers (SCR). The scope of reeling was supported by outlining various reeling projects that have been successfully executed.

3 PIPELINE MECHANICAL DAMAGE ASSESSMENT USING FINITE ELEMENT METHODS

This paper has been published in the proceedings of 32nd ASME International Conference on Ocean, Offshore and Arctic Engineering – OMAE (an Offshore Technology Conference event) in Nantes, France, 2013. As the principal investigator and first author, I was responsible for conducting the numerical investigation, analyzing the data, and reporting it in this paper. The second author, Dr. Shawn Kenny, was responsible for supervising the investigation and data analysis.

Authors: Ali Ahmed Dawood and Shawn Kenny

3.1 Abstract

Finite element modelling procedures to simulate the pipeline mechanical response during reel lay installation are calibrated from the available literature. A three-dimensional continuum model was developed to simulate the bending and straightening processes during reel lay installation and was compared with physical tests conducted within a bending rig and four-point bending test frame. A range of pipeline diameters, wall thicknesses, material grades and weld offsets are examined.

3.2 Introduction

The origins of modern pipeline fabrication methods, for both seamless and flexible pipe technologies, and reel-lay installation techniques can be traced back to the 1940’s during World War II (Pipelines International, 2010; Palmer and King, 2007). The reel-lay installation method was further refined in the 1960’s and 1970’s and provides technical and economic advantages in comparison with other installation techniques such as S-lay and J-lay installation methods (Higuci and Shitamoto, 2010; Meissner et al., 2009). The pipe make-up can be conducted onshore at the spool base with the pipe spools inspected, qualified, ready for load-out and installation, which improves the pipe-lay rate and reduces cost. For umbilicals, pipelines and risers, less than 406.4 mm (16") outer diameter, reel-lay installation is the preferred and cost effective installation method (Smith and Clough, 2010).

There are a number of limitations for reel-lay technology including upper limits on pipeline diameter, and difficulties in the use of concrete coatings and bundle installation. The pipe diameter and spool size will restrict the total length of pipe layout from approximately 2 km to 15 km length.

The pipe also experiences complex contact mechanics and plastic deformations as the initially straight pipe string is wound onto the reel drum. As the pipe string is wound onto the drum, the effective drum radius is continuously increasing as the pipe is spooled onto an underlying pipe layer whereby the radius of curvature is decreasing (Focke et al., 2003). Thus the pipe adjacent to the spool hub experiences compression and the pipe on the outer circumference of the spool experiences tension. To install the pipeline onto the seabed from the spool, the pipe must be un-reeled and straightened, which induces a cyclic plastic response with stress (strain) reversal and potential Bauschinger effects (Denniel, 2009; Focke, 2007; Higuchi and Shitamoto, 2010; Meissneret et al., 2009; Toguyeni and Banse, 2012). This may result in pipe ovalization and local wrinkling that may affect local buckling and system collapse. Thus during the complete reel-lay process, the pipe experiences a non-uniform strain history and may require supplemental requirements in the materials specification to achieve mechanical performance targets.

In this study, numerical modelling procedures are calibrated using physical data available in the public domain. The numerical predictions are compared with this dataset and a sensitivity analysis is conducted that examines a range of pipeline diameter, wall thickness, material grades and weld offsets.

3.3 Numerical Modeling Procedures

3.3.1 Overview

Two physical modelling techniques used to simulate the reeling process are the Small Scale Reeling - (SSR) and the Full Scale Reeling (FSR). Studies have shown the suitability of both techniques (Meissner et al., 2009). The FSR simulates the pipe reeling process with respect to plastic bending for placement onto the spool and straightening to simulate the aligner on a reeling vessel.

The finite element (FE) models developed in this paper are based on the earlier efforts by Technip as part of their experimental program at HWU (Chouhan, 2010). The modeling techniques discussed by Pasqualino and Neves (2010), on the collapse pressure of reeled pipelines have also been incorporated.

3.3.2 FE Model of Bending Rig

A schematic illustration of the bending rig is shown in Fig. 3-1. The pipe is held in a fixed position at one end and bent about the reel and straightener forms with different curvature radii.

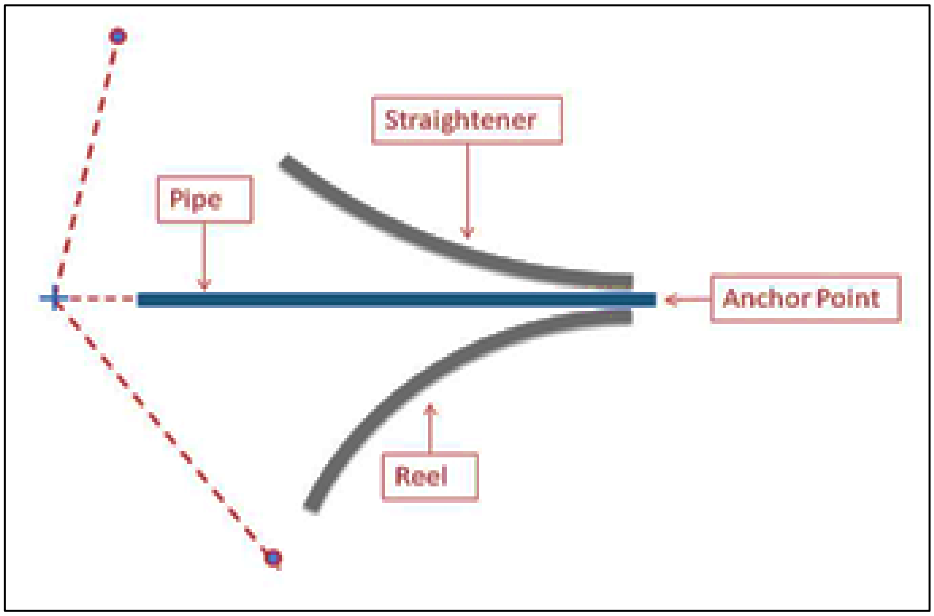

Figure 3-1: Typical Representation of a Bending Rig

For the FE model, a line of symmetry was adopted to reduce computational cost. The pipe was discretized using shell (S4R) elements with meshing governed by the circumferential edge (Fig. 3-2). The reel and straightener formers were modeled by rigid elements. A combination of beam and axial connectors was used to simulate the "pulling" of pipes to either of the two formers. Surface-surface contact governs the interaction between the pipe outer surface and the formers.

Comprehensive calculations were carried to determine the position of the connector ends for each bending. The pipe was pinned at the anchor end and the bending cycle was carried out by the respective adjustments of axial connector lengths in subsequent steps.

The reeling process was performed in the following steps:

- Reeling: Bending of the pipe onto the reeling former by reducing the axial connector length.
- Unreeling: The connector length was adjusted to its position for unreeling.
- Straightening: Similarly, the straightening connector was shortened to bend the pipe onto the straightener.
- Initial Position: The unloading was performed by increasing the connector length back to its initial position.

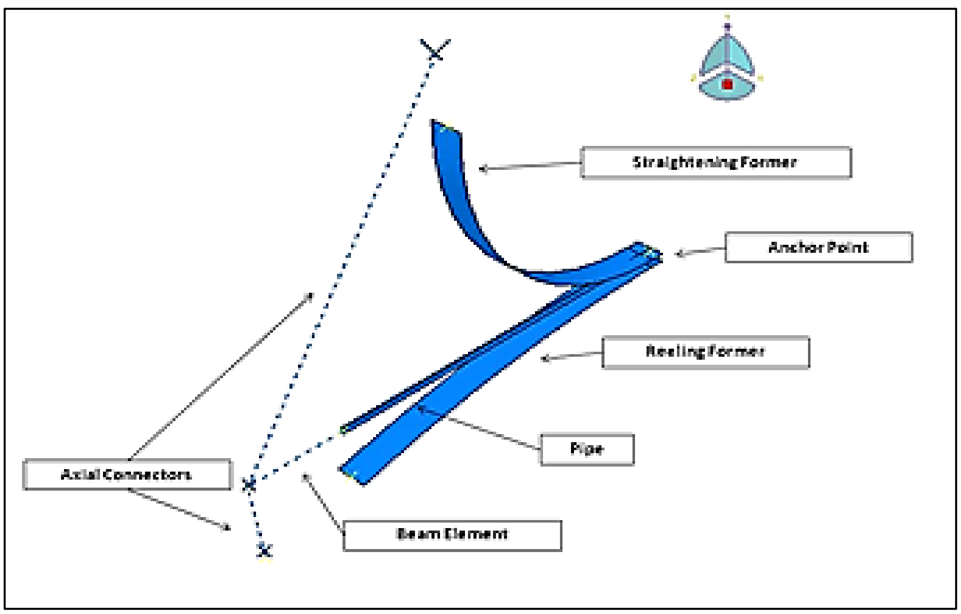

Figure 3-2: Load-displacement relationship during lateral buckling with OOS

3.3.3 FE Model 4-Point Bend Rig

Studies have been carried out using a four point bending simulator (Fig. 3-3) to understand the longitudinal plastic deformations that a pipe experiences when it is bent onto a reel surface. The approach is slightly different as compared to a bending rig (Fig. 3-2).

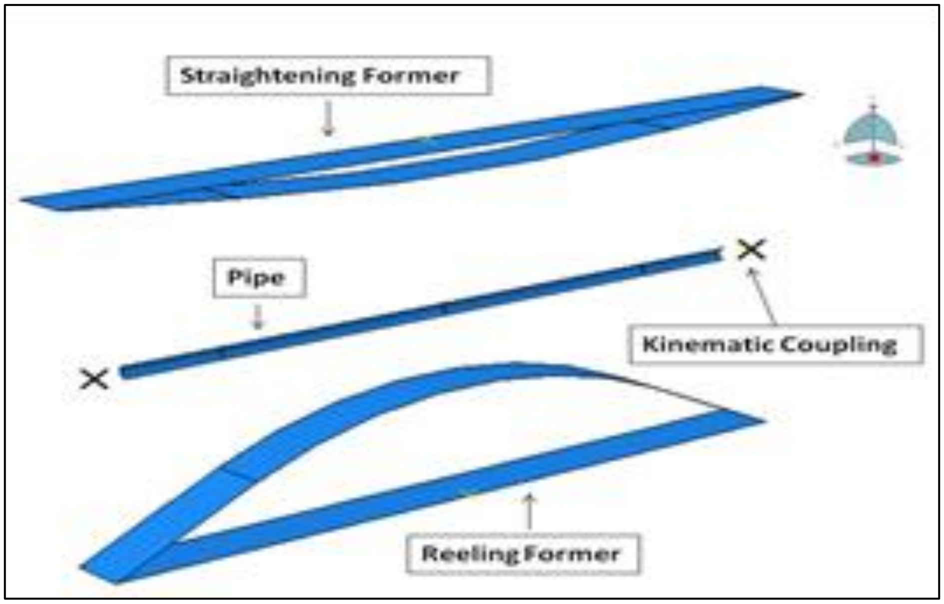

Figure 3-3: Four point bending simulation

The pipe is placed between the subject formers and the desired phenomenon is achieved with the help of hydraulic forces that bend the pipe to perform the reeling and straightening processes. The longitudinal and transverse movement of the pipe as it bends is controlled though roller assemblies (Castello and Estefen, 2005).

The FE modeling for the bending simulator is similar to that of a bending rig with the pipe being modeled as shell (S4R) elements. The reeling and straightening formers are composed of rigid surfaces. The pipe was placed in between the two formers with its motion controlled at each end with the help of kinematic coupling constraints. The longitudinal and traverse motion of the pipe was controlled using adequate boundary conditions at the coupling control points. The reeling process was simulated by the movement of the formers towards the pipe for the necessary bending in contrast to a bending rig approach.

3.4 Calibration Study

3.4.1 Overview

The numerical modelling procedures were calibrated with a grade 450 (X65), 273.1 mm (10") OD pipeline with a 12.7 (0.5") wall thickness that corresponds to a pipe diameter to wall thickness (D/t) ratio of 22. The pipe length was 12 m with a length to diameter ratio of 44. An elastic modulus of 207 GPa was used with the Ramberg-Osgood expression defining the stress-strain relationship with piecewise continuous representation.

3.4.2 Results

The axial and hoop stress distribution generated from the two simulations were compared after pipe reeling. The comparison between the two models (i.e. bending rig and 4-point bending frame) is presented in Fig.3-4 and Fig. 3-5. Note that the angular position at zero (0) degrees conforms to the surface of the pipe in contact with the reeling form.

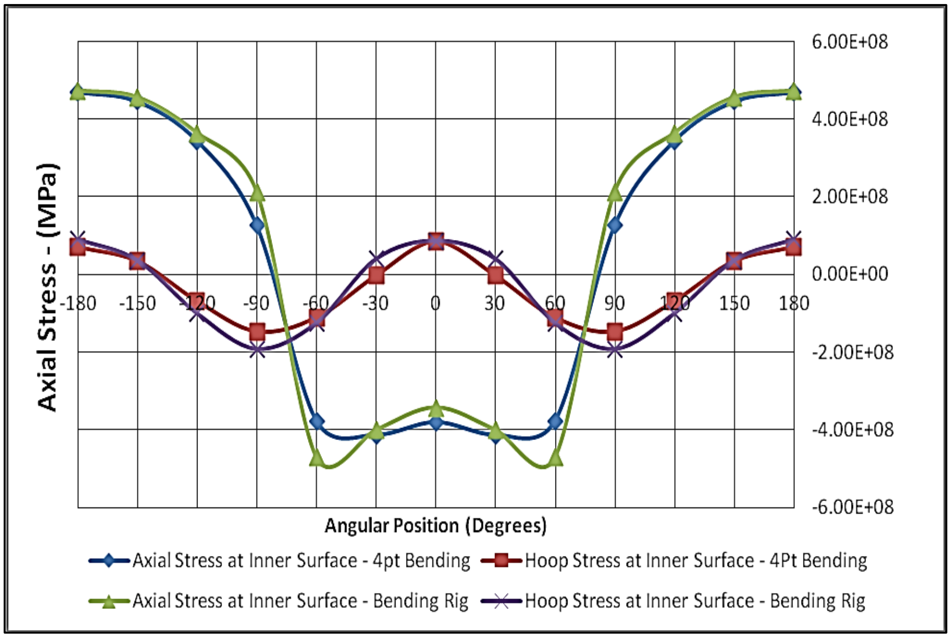

Figure 3-4: Axial and hoop stress distribution along the pipe circumference after reeling – Inner Surface

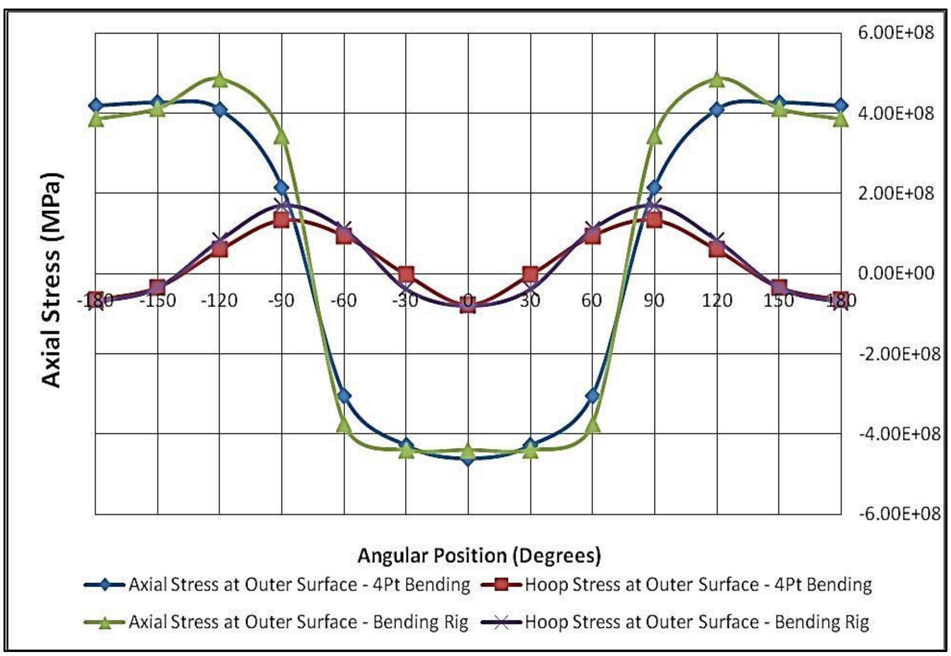

Figure 3-5: Axial and hoop stress distribution along the pipe circumference after reeling – Outer Surface

As observed, the bottom surface of the pipe (zero degrees) shows a compressive stress value and the top surface (180 degrees) in tension, which is indicative of the pipe being bent onto the reel. Earlier studies have reported that a variation in the deformation patterns generated by bending rig in comparison to a 4-point bending setup due to differences in the loading scheme (Meissner et al., 2009).

The four-point bending simulator was then used for extended calibration purposes considering a grade 415 (X60), 457.2 mm (18”) diameter pipeline with a 23.8 (0.5”) wall thickness that corresponds to a pipe diameter to wall thickness (D/t) ratio of 19. The pipe length was 12 m with a length to diameter ratio of 26. These parameters were selected based on the study by Martinez and Brown (2005).

The axial and hoop stress distribution predicted using the current modelling procedures with the study by Martinez and Brown (2005) are presented in Fig. 3-6 and Fig. 3-7, for the inner and outer surface, respectively. The stress contours at the touch down point have been presented in Fig. 3-8. The 4-point bending frame FE modelling procedures were used. The FE predictions are in excellent agreement with the study by Martinez and Brown (2005). The discrepancies may be attributed to differences in the stress-strain relationships, contact mechanics, and lack of defined initial pipe geometric imperfections (e.g. variation in section ovality) and kinematic hardening model used in the current study. Potential local instability may be observed in Fig. with the longitudinal variation in hoop stress.

Although some uncertainty exists, the results provided confidence in the numerical modelling procedures to be used in a limited sensitivity analysis. Future studies will look to further advance these numerical modelling procedures. Key refinements to the numerical modelling procedures will include geometric imperfections (e.g. section ovality), pipe configurations (e.g. pipe-in-pipe systems), stress-strain relationships (e.g. yield plateau elongation) and constitutive models (e.g. nonlinear kinematic hardening).

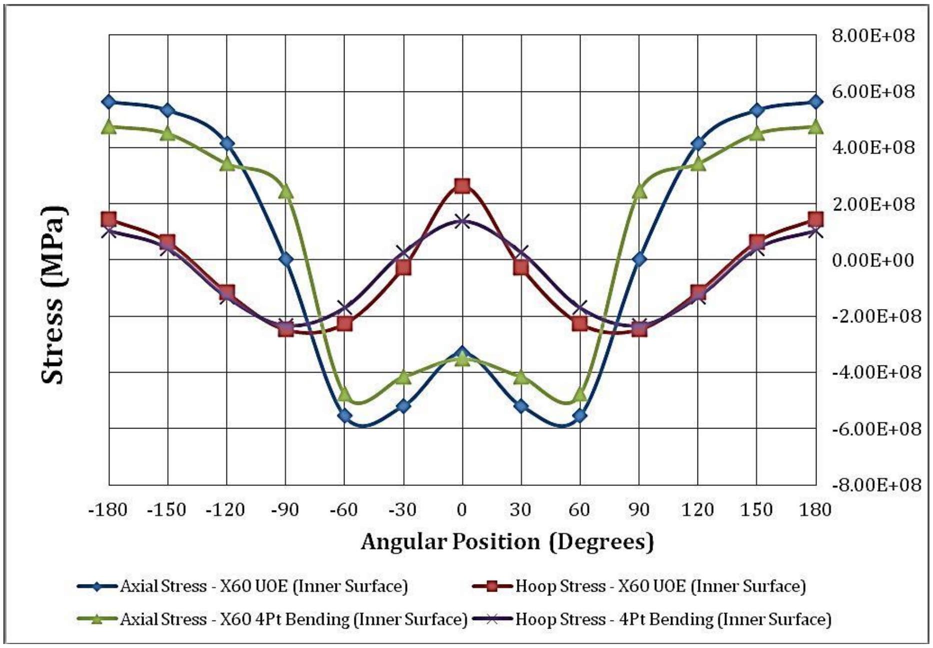

Figure 3-6: Axial and hoop stress distribution along the pipe circumference after reeling – Inner Surface

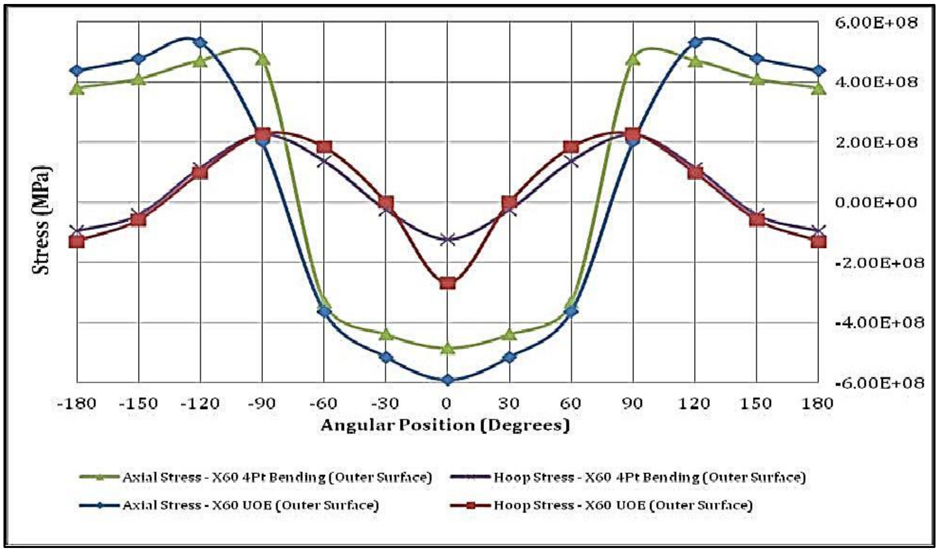

Figure 3-7: Axial and hoop stress distribution along pipe circumference after reeling – Outer Surface

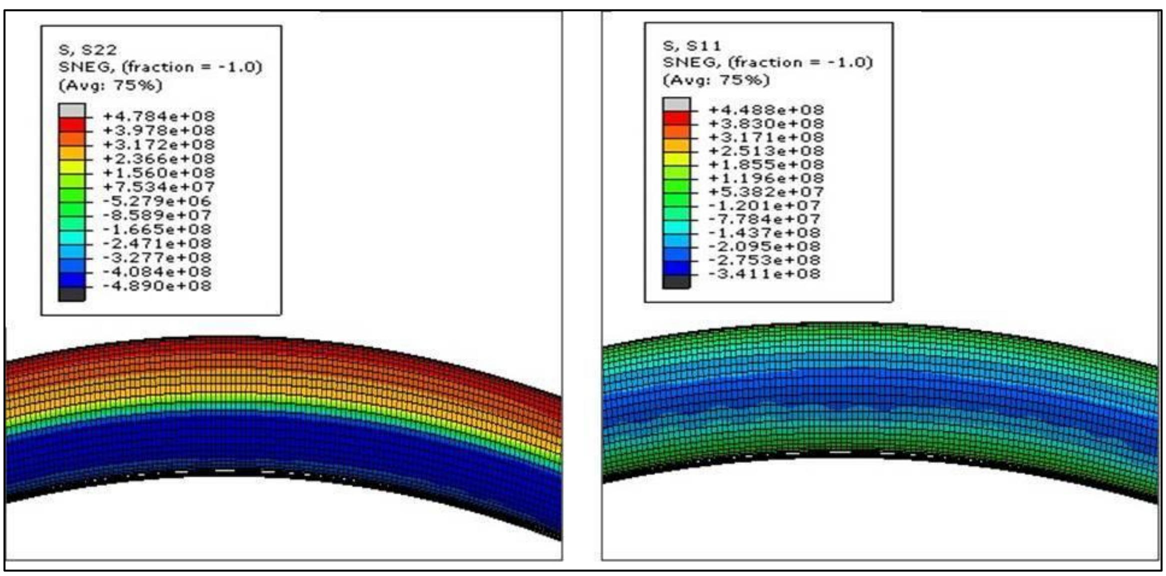

Figure 3-8: Axial and hoop stress distribution at the pipe-reel contact zone

3.5 Parameter Study

3.5.1 Overview

Having established confidence in the numerical modelling procedures, a limited sensitivity analysis was conducted. The baseline analysis was a grade 450 (X65), 273.1 mm (10”) diameter pipe with a 12.7 mm (0.5”) wall thickness. This baseline pipe configuration comprised the modelling of two pipe joints with the same material properties having a circumferential weld connection with weld offset (Fig. 3-9). The weld stress-strian relationship was defiend by the grade 450 material behaviour with a 10% overmatch.

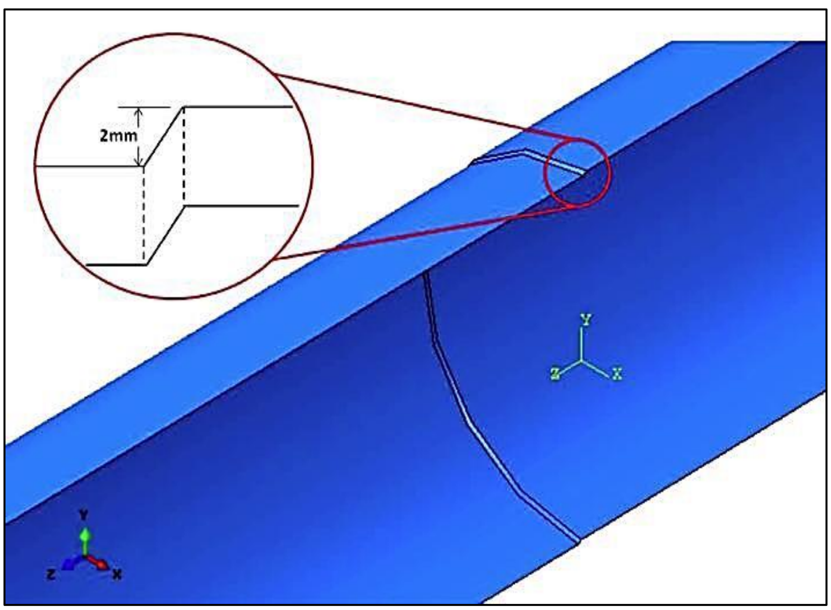

Figure 3-9: Weld offset for reeling simulation

Three additional analysis cases were defined to examine the effects of material grade and weld offset. For the two pipe joints welded together (joint A–joint B) the parameters included (1) grade 450 –450 pipe joints with 2 mm weld offset, (2) grade 450 –415 pipe joints with no weld offset, and (3) grade 450 –415 pipe joints with 2 mm weld offset. Using the 4-point bending rig simulator, a complete reeling and straightening cycle was perfromed. The axial stress, axial strain, hoop strain, residual stress and hysteretic response was examined.

3.5.2 Influence of Material Grade

The bending response of unequal joints strengths exhibited an asymmetric response (Fig. 3-9) with the maximum stress observed at the initial contact between the pipe and reel at the joint connection, which was positioned at the pipe mid-length and center of the bending frame. Due to differences in the moment capacity and pipe curvature, the axial strain behaviour also exhibited an asymmetric response (Fig. 3-10). A discontinuity on the axial stress and strain response across the girth weld was observed.

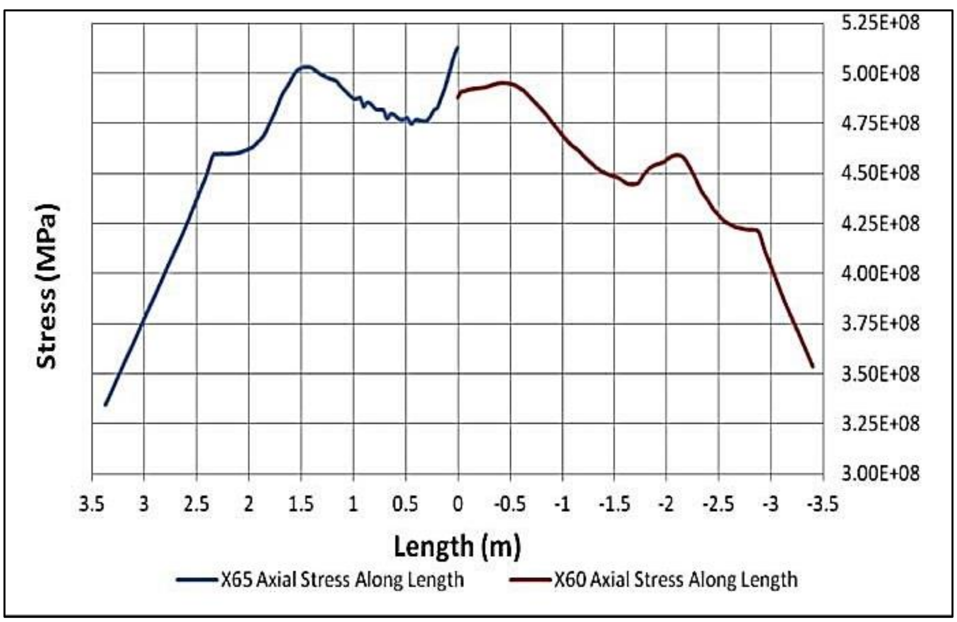

Figure 3-10: Axial stress distribution for grade 450 – grade 415 pipe segment

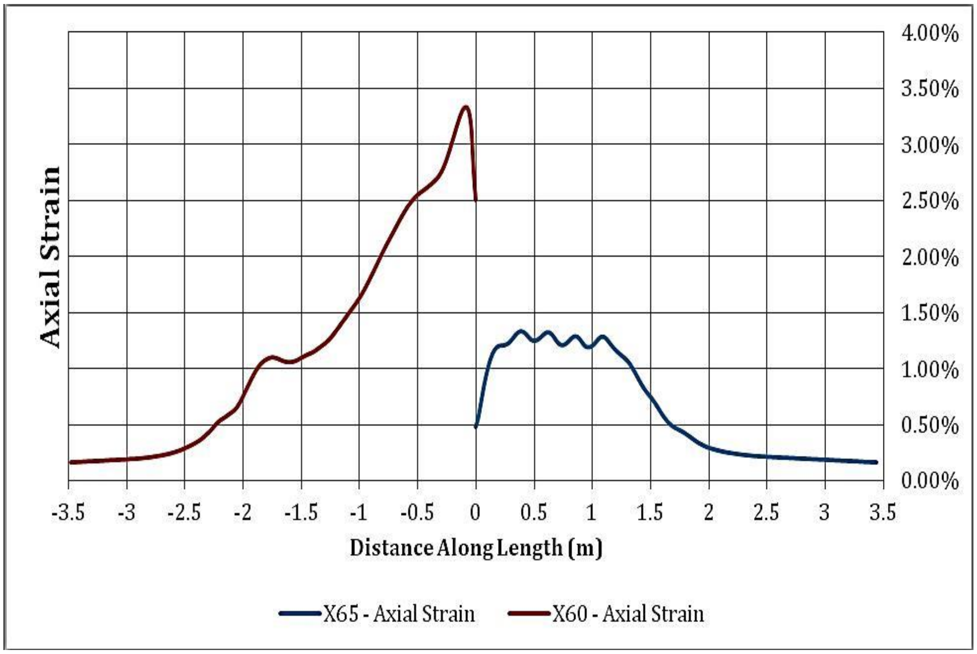

Figure 3-11: Axial strain distribution for grade 450 – grade 415 pipe segment

The circumferential distribution of hoop strain on the outer pipe surface at the girth weld is shown in Fig. 3-11. Based on experience with the local buckling of conventional and high strength grade pipelines (Al-Showaiter et al., 2011; Fatemi and Kenny, 2012a,b, 2011; Fatemi et al., 2010), the analysis suggests the existing modelling procedures must be refined and account for geometric imperfections (i.e. plastic bifurcation modes, pipe body imperfections, and girth weld offset) and material behaviour (i.e. yield point elongation, nonlinear kinematic hardening).

The cyclic load response (Fig. 3-12) and residual stress state during the reeling process was evaluated. The hysteretic behaviour and redistribution of the residual stress state requires further investigation after the numerical modelling procedures are refined.

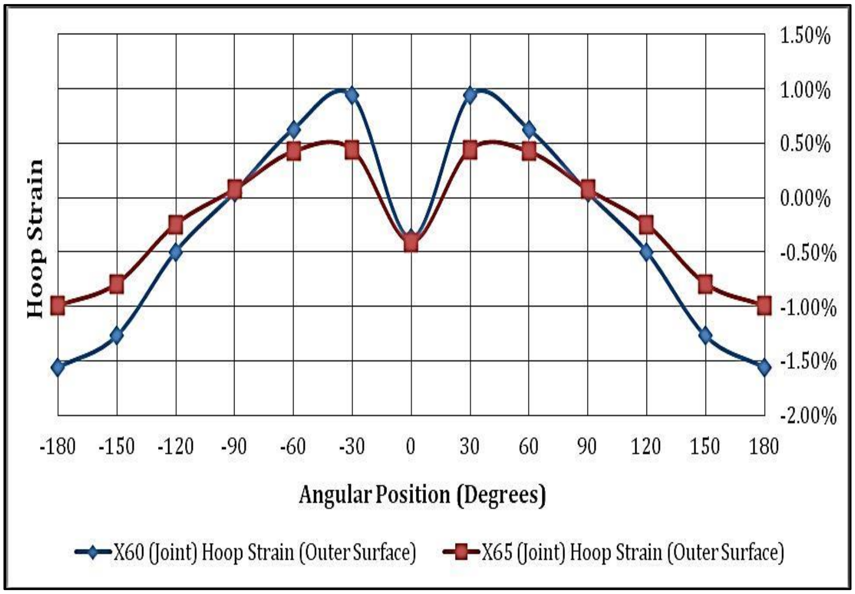

Figure 3-12: Hoop stress distribution for grade 450 – grade 415 pipe segment

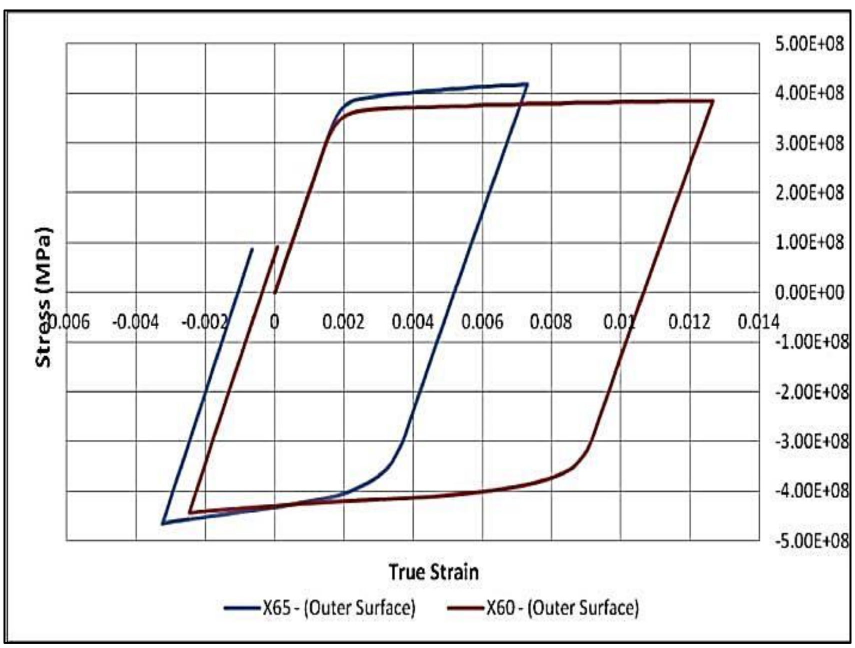

Figure 3-13: Hysteresis loop for grade 450 – grade 415 pipe segment

3.5.2 Influence of Weld Offset

The weld offset had a significant influence on the pipe mechanical response, across the girth weld, due to the changes in the contact mechanics for each pipe joint through the reeling simulation. This is shown in Fig. 3-13 through Fig. 3-15 for the axial stress and hoop stress distributions for the analysis case 2 (i.e. pipe segment with grade 450 – 450 pipe joints having 2 mm weld offset). A discontinuity across the circumferential weld seam was observed with generally symmetric response propagated along the pipe segment length away from the mid-length.

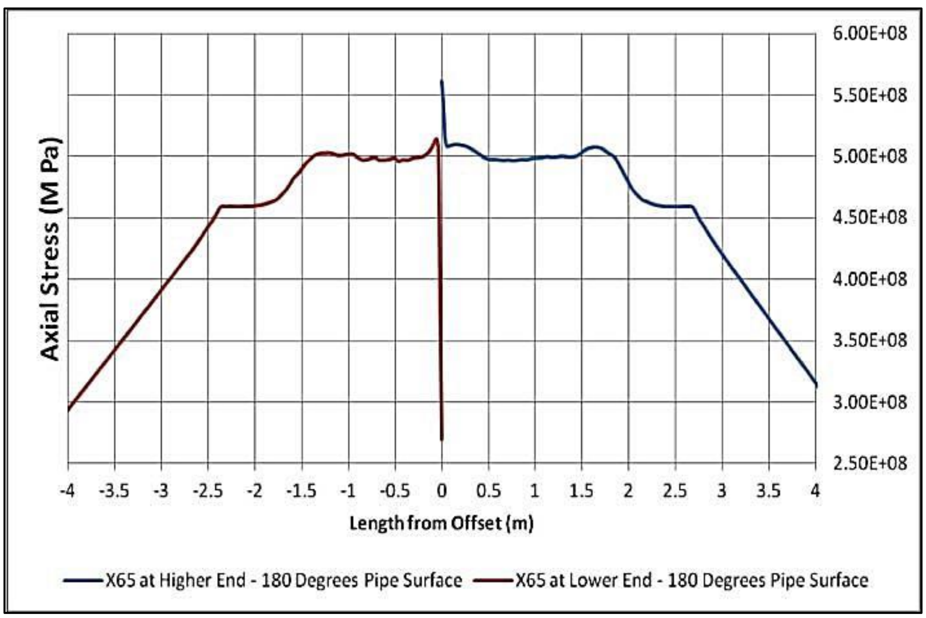

Figure 3-14: Axial stress distribution for grade 450 – grade 415 pipe segment with 2 mm girth weld offset

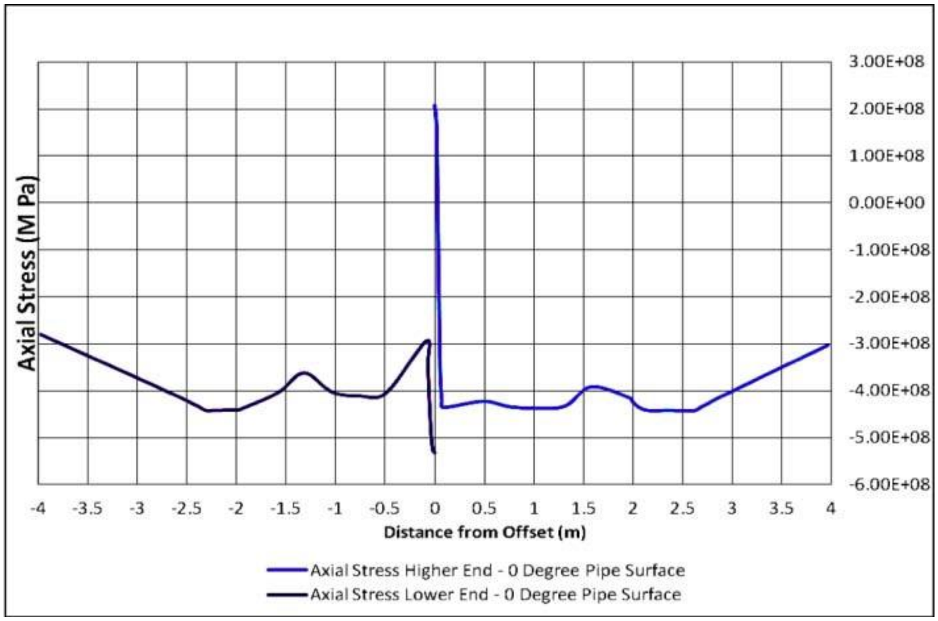

Figure 3-15: Axial stress distribution for grade 450 – grade 450 pipe segment with 2 mm girth weld offset

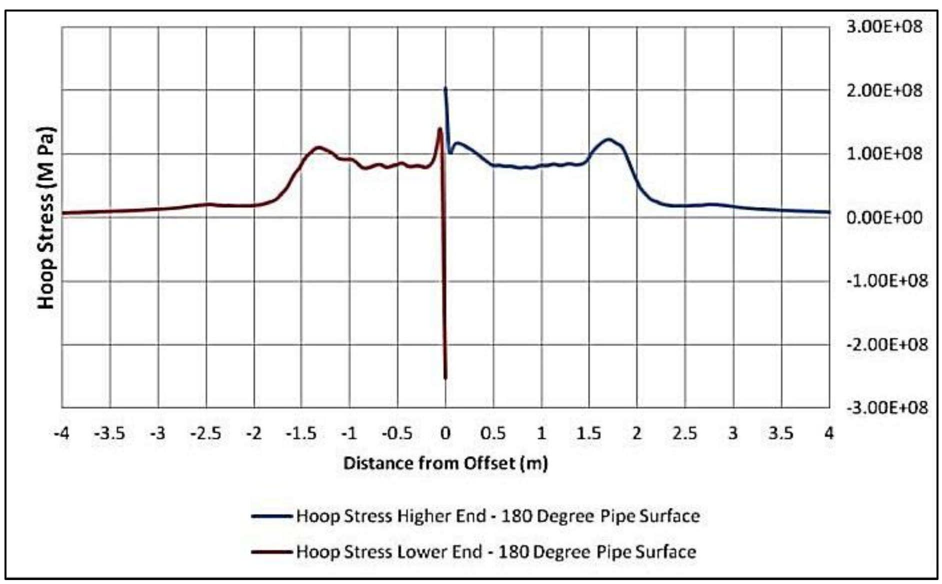

Figure 3-16: Hoop stress distribution for grade 450 – grade 450 segment with 2 mm girth weld offset

For case 3 with the dissimilar pipe materials (i.e. grade 450 –415 pipe joints) having a 2 mm girth weld offset, however, the discontinuity at the girth weld was observed, and consistent with case 2 (Figs. 3-13- 3-15), but was also propagated with distance along the pipe length as an asymmetric response (Fig. 3-16 and 3-17).

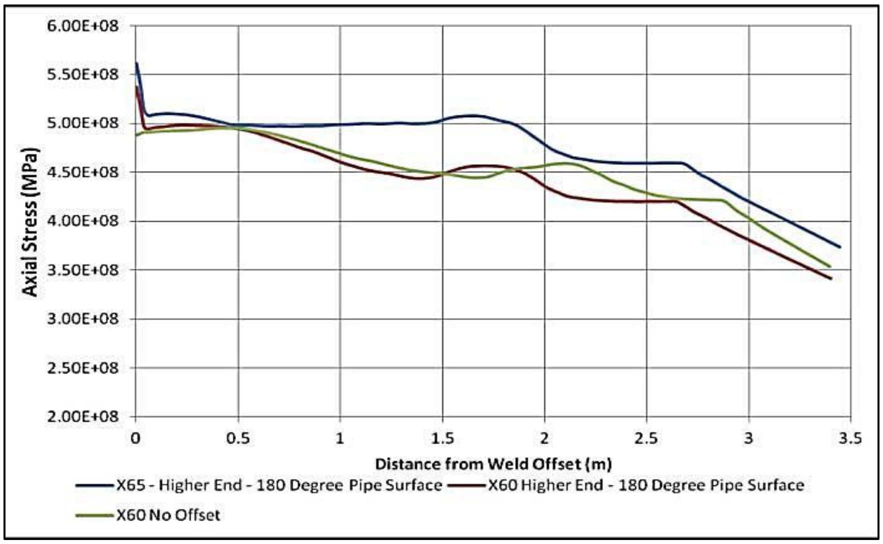

Figure 3-17: Axial stress distribution for grade 450 – grade 415 pipe segments with 2 mm girth weld offset

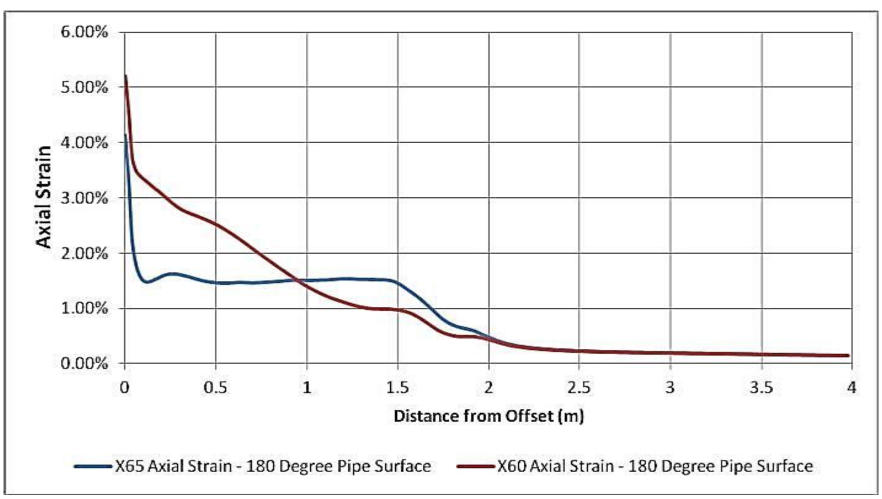

Figure 3-18: Axial strain distribution for grade 450 – grade 415 pipe segment with 2 mm girth weld offset

3.4 Conclusion

Three-dimensional FE modelling procedures simulating the pipe mechanical response during reel-lay installation were developed and calibrated from public domain literature. A range of pipeline diameter, wall thickness, material grades was examined. Numerical modelling procedures simulating the bending test rig and four-point bending test frame for full-scale reeling physical modelling studies were developed. Excellent correspondence between the FE models developed in this study with third-party investigations was observed.

The four-point bending model was used to conduct a limited sensitivity study examining the effects of a joint-to-joint variation in material properties and girth weld offset amplitude for a single pipe diameter and wall thickness. The weld material properties was defined as a 10% overmatch. Differences in pipe material and geometric properties across the girth weld results in a discontinuous stress and strain field distribution across the girth weld connecting two joints. The combination of dissimilar material grades and girth weld offset further resulted in an asymmetric distribution of the stress and strain fields.

The current study will provide a framework to extend the analysis addressing other design factors and provide further insight into the pipe mechanical behavior during reel-lay installation. Future studies will examine the importance of geometric imperfections (e.g. section ovality), pipe configurations (e.g. pipe-in-pipe systems), stress-strain relationships (e.g. yield plateau elongation) and constittuive models (e.g. nonlinear kinematic hardening) on the pipe mechanical response during reeling.

3.5 Acknowledgements

The authors would like to acknowledge the Wood Group Chair in Arctic and Harsh Environments Engineering at Memorial University of Newfoundland for sponsoring the research project. The opportunity to conduct the research and publish the findings of the project is greatly appreciated.

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4 A PARAMETRIC STUDY ON THE INFLUENCE OF IMPERFECTIONS ON PIPE MECHANICAL RESPONSE DURING BENDING IN REEL-LAY INSTALLATION USING FINITE ELEMENT METHOD

This paper has been accepted for publication in the proceedings of 33rd International Conference on Ocean, Offshore and Arctic Engineering – OMAE (an Offshore Technology event), San Francisco, California, USA, 2014. As the principal investigator and first author, the author of the thesis was responsible for conducting the numerical investigation, analyzing the data, and reporting it inside this paper. The second author, Dr. Shawn Kenny, was responsible for supervision of the investigation and guidance on data analysis.

Authors: Ali Ahmed Dawood and Shawn Kenny

4.1 Abstract

Finite element modelling procedures were developed to examine the effect of pipe diameter, ovality, wall thickness, imperfection formulations, joint-to-joint material strength variation and radial weld offset on the pipe mechanical response through numerical simulation of the reeling process. This study examines the pipe deformation, stress concentration, and strain discontinuity developed during simulation of the pipe reelingprocess. The key parameters influencing the pipe mechanical response are identified and recommendations on future work provided.

4.2 Introduction

Manufacturing of seamless and flexible pipe for oil and gas service dates back to the middle of the 20thcentury (Pipeline International, 2010; Palmer and King, 2007). Advancements in the offshore exploration and extraction, and pipe installation processes are considered to be one of the most critical aspects of modern day research. Various factors have to be taken into account to conclude the advantages, disadvantages and suitability of one technique over the other. Various parameters such as strength, durability, depth, capacity and installation time play key roles in the selection of pipeline installation technique. Over short distances; such as infield flowlines, reel-lay installation provides technical and economic advantages in comparison with other methods such as S-lay and J-lay installation (Higuchi and Shitamoto, 2010; Meissner et al., 2009). During reel-lay installation, the pipeline experiences plastic deformation through reverse bending cycles. The load magnitude and corresponding stress response is a property of the type of installation technique that is being used (Arjomandi and Taheri, 2009). The study of the response of the pipe under bending during installation as mentioned above is critical in order to make efficient and effective design improvements.

Earlier work discussing the stress and strain distribution obtained from bending of a perfect pipe during reel-lay installation over a range of parameters has been performed. (Dawood and Kenny, 2013). The current study extends this research effort through examination of other parameters to assess the pipe mechanical response during reeling simulations.

A parameter study examined a range of pipe diameter to wall thickness ratios (D/t of 20, 25, 30), material grade, bend radius and weld offset. The reel lay installation method is limited by the size of the reel or spool holding the pipe, which limits the maximum diameter of rigid pipe to approximately 508 mm (20”) and D/t ratio of 25. From this perspective, the D/t parameter matrix was selected toprovidean insight on the pipe mechanical responsefor different load case scenarioswithin the framework of numerical simulation. With emerging challenges providing an incentive for advanced research into pipeline design, the importance of effective installation methods is inevitable. The paper helpedin adding more confidence to the utilization of reeled pipe systems in the industry. Different imperfection wavelengths have been studied and discussed. Stress and strain distribution along the longitudinal and the hoop direction has been studied in relation to changes in the pipe behavior due to the inclusion of pipe imperfections.

4.3 Numerical Modeling Procedures

4.3.1 Overview

Finite element modelling procedures simulating the placement of a pipe onto a reel, using a bending rig and four point bend test frame have been developed and calibrated in a previous investigation (Dawood and Kenny, 2013). The current study utilizes the four-point bend test to examine the effects of pipe diameter, ovality, wall thickness, imperfection formulations, joint-to-joint material strength variation and radial weld offset on the pipe mechanical response.

The finite element modeling was performed in the commercially available software ABAQUS. The pipe was modeled using the reduced integrated shell elements (S4R) with mesh governance using the circumferential edge. Circumferentially, the pipe mesh is composed of 36 elements around half pipe circumference. Line of symmetry was adopted for the FE model in order to reduce computational cost. A total pipe segment length of 3m was modeled, which represents a length of 10 times the pipe diameter. Previous studies on local buckling response of conventional and high strength pipe have established this pipe length to be effective in mitigating the effects of end boundary conditions on the pipe response (Fatemi and Kenny; 2011,2012; Fatemi et al. 2009a,b). A schematic representation of the model is presented in Fig 4-1.

The reel lay process was idealized through movement of the rigid reel former towards the pipe (Fig. 4-1). The pipe end boundary conditions were defined as a roller connection, at one end, and pin connection at the other pipe end. This approach was adopted in order to control the longitudinal and traverse motion of the pipeline during bending as part of the simulated reeling process, which was used in similar study by Castello and Estefen (2005).

The analysis was carried out using the Static General algorithm with a small time step and load increment, established through a sensitivity study in order to maintain a convergent solution and account for the mechanical response with respect to deformation and strain mechanisms. The contact condition was defined as frictionless between the pipe and the roller in the tangential direction. Moreover, the pressure-overclosure relationship for the normal contact behavior between the two bodies was considered to be as a “Hard” contact formulated in Abaqus.

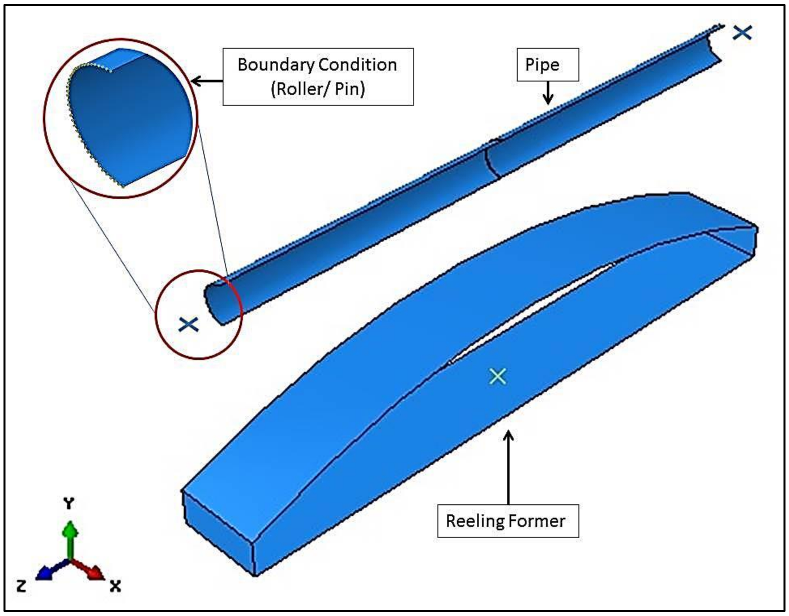

Figure 4-1: Bending simulation schematic

4.3.2 Model Geometry and Imperfections

The bending and local buckling response of shells is sensitive to initial perturbations in the initial pipe geometry and loading conditions. When modeling cylindrical shell elements, studies have shown that results obtained for perfect structure vary from the corresponding experimental results by a considerable amount. (Arjumandi and Taheri, 2009; Kougias, 2009; Kyriakides and Ju, 1992; Fatemi and Kenny, 2012). Consequently, imperfections were incorporated within the perfect model geometry to account for load path bifurcation in the numerical simulation of the pipe mechanical response and imperfections to account for physical variations in the pipe geometry due to manufacturing and welding processes.

Bifurcation analysis is a mathematical concept that characterizes the stability of a system where the governing parameter moves through a critical value(i.e. two or more equilibrium paths exist). The bifurcation point indicates the critical load for the initiation of axial wrinkling deformations independent of the imperfection magnitude triggering the local mechanisms. Studies have shown that a new deformation pattern, which varies from the principal pattern, begins to develop at the first bifurcation point. This resulting pattern is termed as the bifurcation mode. (Ju and Kyriakides, 1991,1992; Kyriakides and Ju, 1992; Peek, 2000; Bruschi et al., 2008, Fatemi and Kenny, 2012). In addition a number of studies have demonstrated the complex interaction between the coupling effects between section ovalization and axial bifurcation waveforms (Fatemi & Kenny, 2012; Kyriakides and Ju, 1992).

The importance of material properties (e.g. isotropic, anisotropic behaviour) and constitutive modeling approach for incorporating bifurcation wavelengths has been has been established (Corona et al., 2006; Kyriakides et al., 2005; Peek and de Jong, 1998).Although there are recognized constraints with this approach, an eigenvalue analysis, which is a linear perturbation procedure in Abaqus/Standard, was performed to generate small amplitude Eigen mode perturbations to the pipe diameter. These perturbations are required to promote numerical stability through the bifurcation response that is associated with the tightly spaced natural frequencies of shell elements. The bifurcation mode was included as small amplitude geometric perturbations within all numerical modeling procedures. Although this approach has been successful in other studies (e.g. Fatemi et al., 2012), the significance for adopting this idealization to generate the bifurcation perturbations, on the bifurcation and post-buckling response (e.g. Corona et al., 2006), requires further investigation.

The wavelength obtained by these analyses was extracted using the NODE FILE command in Abaqus scripting and then imparted on the pipe as imperfection to study the response in pipe bending. Figure 4-2 shows the wave pattern on the pipe segment near the weld obtained after the eigenvalue analysis for a grade 450-415 material transition across the girth weld. Linear perturbation was carried out for every material configuration presented in the parametric matrix.

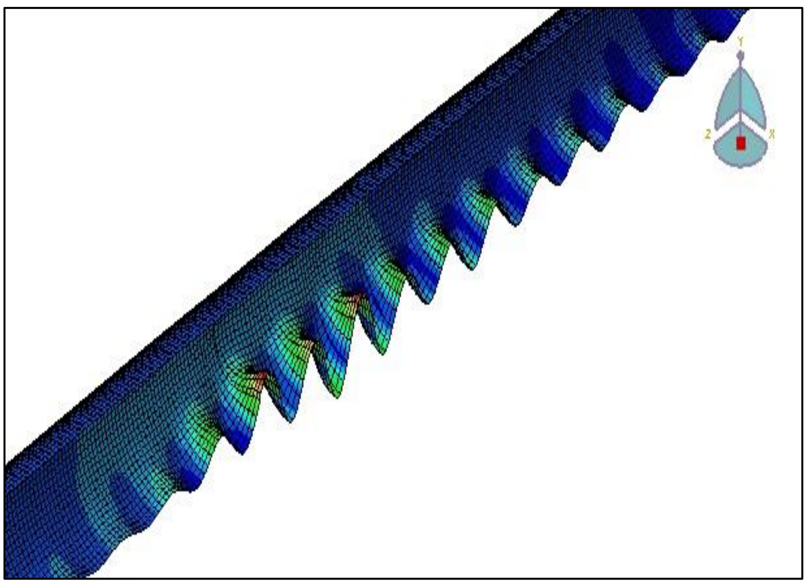

Figure 4-2: Eigenvalue wave pattern, X65-X60 – Exaggerated

Initial geometric imperfections were incorporated within the pipe geometry to account for variation in the pipe diameter (i.e. initial ovality) due to manufacturing processes. The ovality waveform was induced into the pipe segment using Python scripting. Figure 4-3 shows the ovality imperfection waveform on the pipe. The amplitude has been exaggerated for demonstration purposes. Radial offset imperfections at the girth weld between two pipe joints were also included in the pipe model accounting for misalignment during welding. Although the imperfection formulation defines an idealized configuration, the approach has proven to provide a rational and effective method to incorporate the effects of pipe body imperfections (e.g. pipe section ovality) on the local buckling response (Corona et al., 2006; Fatemi and Kenny, 2011,2012a,b; Kyriakides and Corona, 2007).

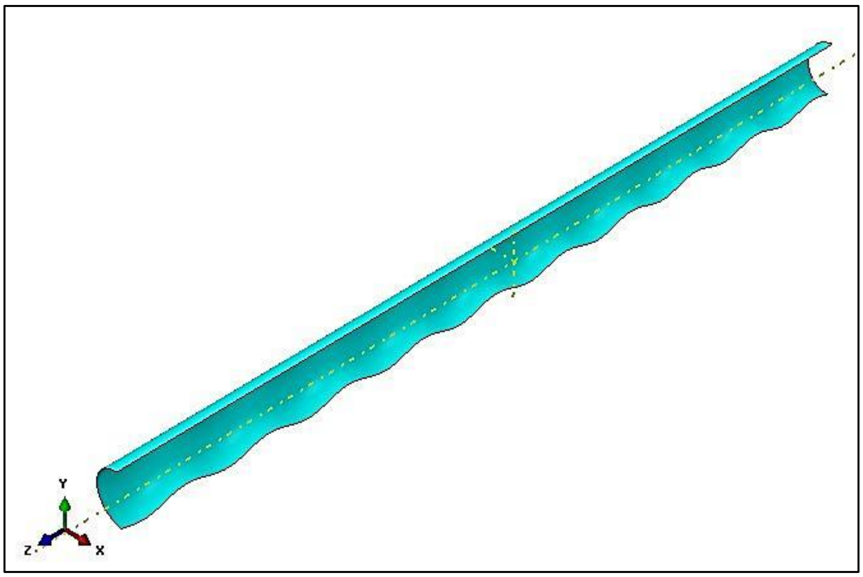

Figure 4-3: Pipe Ovality Waveform – Exaggerated

4.3.3 Material Properties

The stress-strain relationship for the base pipe metal was defined as a piecewise, non-linear elasto-plastic relationship assuming isotropic hardening rule with the von Mises yield criterion. The pipe material properties examined in this study are summarized in Table 4-1.The weldment was defined by the base metal parameters with a 10%

overmatch. The base metal and weldment were assumed to behave as isotropic material. The pipe joints were modeled with both uniform and discontinuous grade material across the girth weld.

S/No	Pipe Grade	Young Modulus	Poisson's Ratio
1	450 (X65)	207 GPa	0.3
2	415 (X60)	205 GPa	0.3

Table 4-1: Material Properties of Pipeline

4.3.4 Applied Loading Conditions

The wave pattern generated from the eigenvalue analysis (Fig.4-2) was then added onto the pipe surface, which had to come in contact with the reel. Imperfections with amplitude of 0.2 mm were generated on the pipe edge for the analyses. A reeling former having a radius (Fig.4-1 & Fig. 4-4) of 6.5 m was used and was defined as a rigid body.

Bending analysis was performed to study the longitudinal plastic deformations of the pipe as it is bent onto the reel. This approach marginally varies from a bending rig simulation as the reeling former is displaced towards the pipe to achieve bending as opposed to the movement of the pipe in the bending rig simulation (Dawood & Kenny, 2013). Figure 4-4 shows the bending of the pipe by the movement of the reeling former.

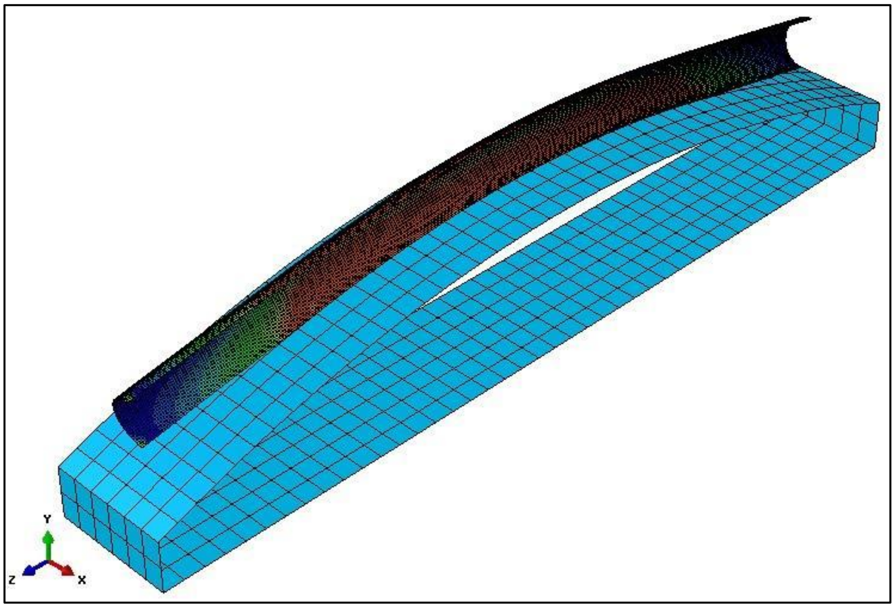

Figure 4-4: Pipe bending over the reeling former

4.4 Parametric Study

4.4.1 Overview

An analysis matrix was formed to incorporate different scenarios related to material grade, weld offset, D/t ratio etc. The baseline analysis was a grade 450, 305 mm (12”) diameter pipeline with 15.25 mm (0.6”) wall thickness. This configuration had two pipe joints of the same material properties with a girth weld width of 6 mm but no radial weld offset. Table 4-2 summarizes the parameter matrix used in the analysis for a 305 mm diameter pipe with a 1 mm ovality amplitude and 0,2 mm bifurcation perturbation amplitude.

<table>
<tr><th>D/t Ratio</th><th>Material Orientation</th><th>Weld Offset (mm)</th><th>Ovality Wavelength (mm)</th></tr>
<tr><td rowspan="4">20</td><td>X65-X65</td><td>0</td><td>500, 750</td></tr>
<tr><td>X65-X65</td><td>2</td><td>500, 750</td></tr>
<tr><td>X65-X60</td><td>0</td><td>500, 750</td></tr>
<tr><td>X65-X60</td><td>2</td><td>500, 750</td></tr>
<tr><td rowspan="2">25</td><td>X65-X65</td><td>0, 2</td><td>500</td></tr>
<tr><td>X65-X60</td><td>0, 2</td><td>500</td></tr>
<tr><td rowspan="2">30</td><td>X65-X65</td><td>0, 2</td><td>500</td></tr>
<tr><td>X65-X60</td><td>0, 2</td><td>500</td></tr>
</table>

Table 4-2: Analysis Matrix

4.4.2 Pipe Bending

Studies have shown that pipe subject to pure flexure or bending with combined loads will result in cross-section ovalization (i.e. Brazier effect), reduction in the slope of the moment-curvature (i.e. stress-strain) relationship and may lead to membrane action and local buckling (Bai, 2001; Fatemi & Kenny, 2012; Kyriakides and Ju, 1992; Kyriakides and Corona, 2007)

The axial and hoop stress response of a reeling simulation with pipe joints having uniform material properties across the girth weld (450-450) with no radial weld offset, which represents the baseline analysis case. The stress and strain patterns were observed to follow a symmetric distribution along the length of the pipe with the weld connection being the reference point for measurement as shown in Figure 4-5.

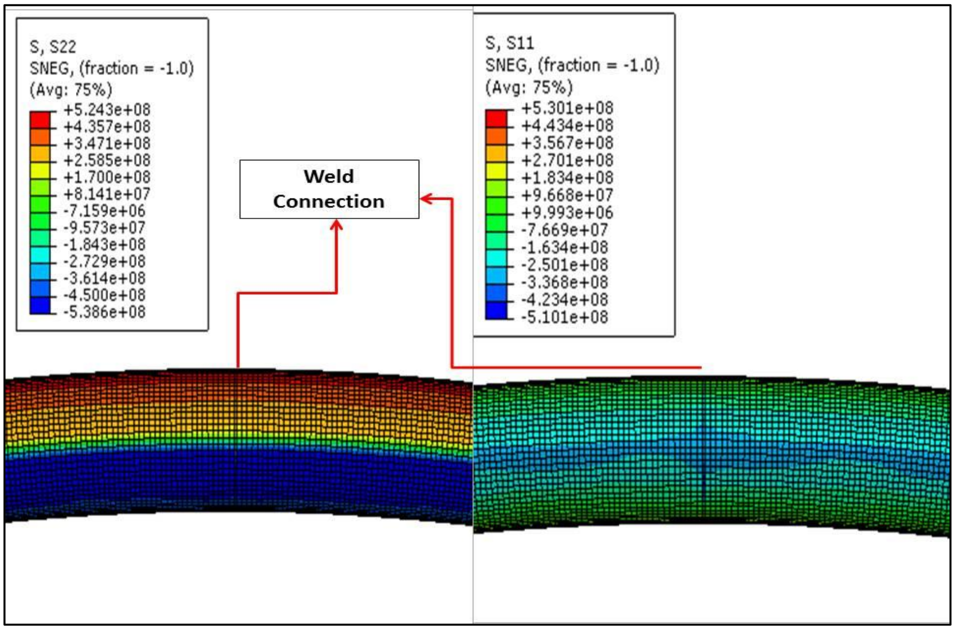

Figure 4-5: Axial and Hoop stress distribution at the pipe reel contact zone

Similar observations can be stated for the response illustrated in Fig. 4-6, which presents the axial stress at the top surface of the pipe. Note that the stress response is generally symmetric with the peak stress observed at the circumferential weld connection. The slight asymmetry can be attributed to the boundary conditions and post-buckling response (e.g. Fatemi et al., 2009b). There was a higher stress discontinuity across the girth weld with increasing D/t ratio. The stress increases by a factor of approximately 1.1 for D/t = 30. Also the overall stress values are observed to be higher for larger D/t ratio pipeline.

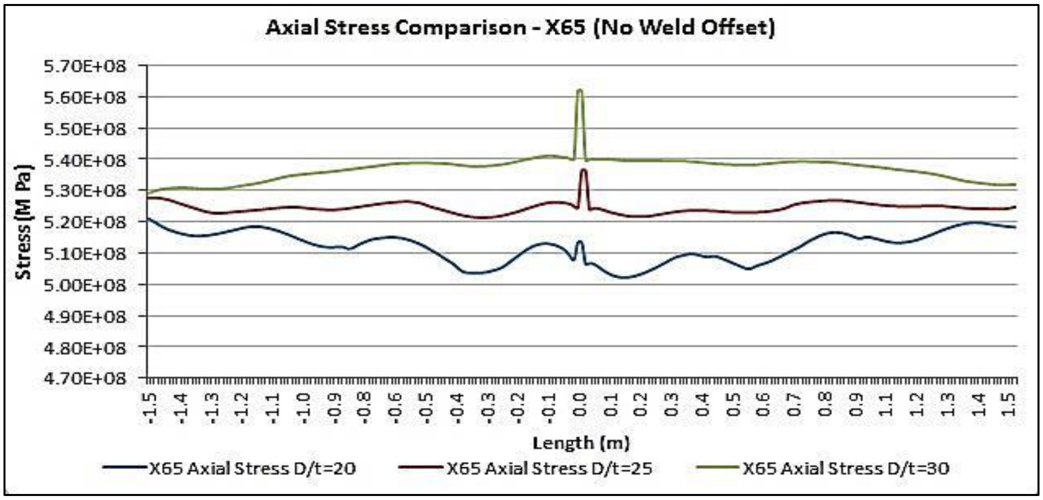

Figure 4-6: Axial stress distribution along the length – “450-450”

Asymmetric response was also observed for the axial strain distribution along the pipeline segment length (Fig. 4-7).The axial strain decreases by a factor of 0.5 for D/t=30 across the girth weld due to the local mismatch in the strength of the base metal in comparison with the weld material. The increase in pipe deformation was, however, proportional to D/t ratio.

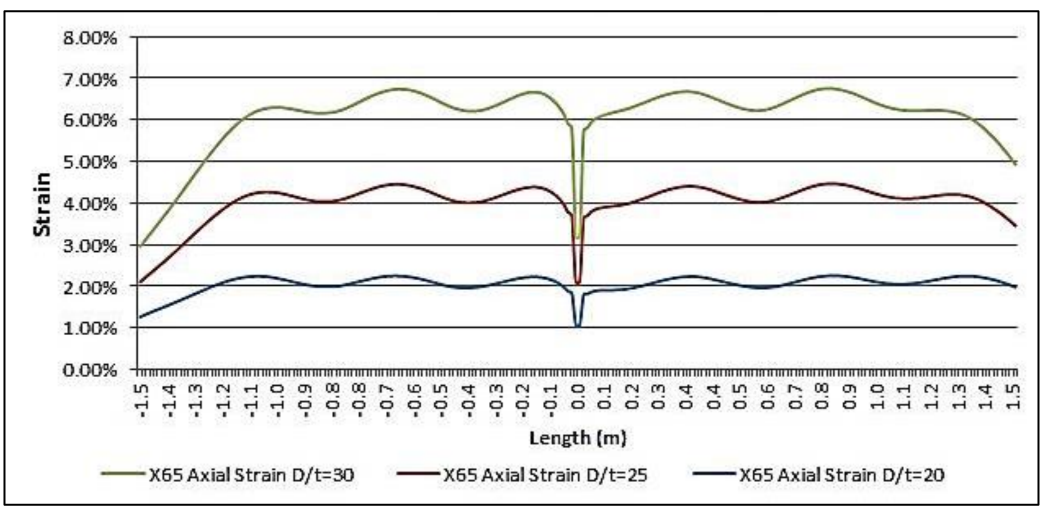

Figure 4-7: Axial strain distribution along the length – “450-450”

4.4.3 Influence of Pipe D/t Ratio

Pipe behavior with respect to change in the diameter to wall thickness ratio (D/t ratios = 20, 25 and 30) was examined. The pipe diameter was constant with a variation in the pipe wall thickness used to modify the D/t ratio. The induction of ovalization due to bending of relatively thin walled cylindrical pipes is well known. Earlier studies regarding the response governing the buckling behavior of pipelines have been carried out. Indication of characteristic localized deformation has previously been observed in many shells. This ovalization has been considered to be a critical aspect for pipe stability. (Kyriakides and Ju, 1992).

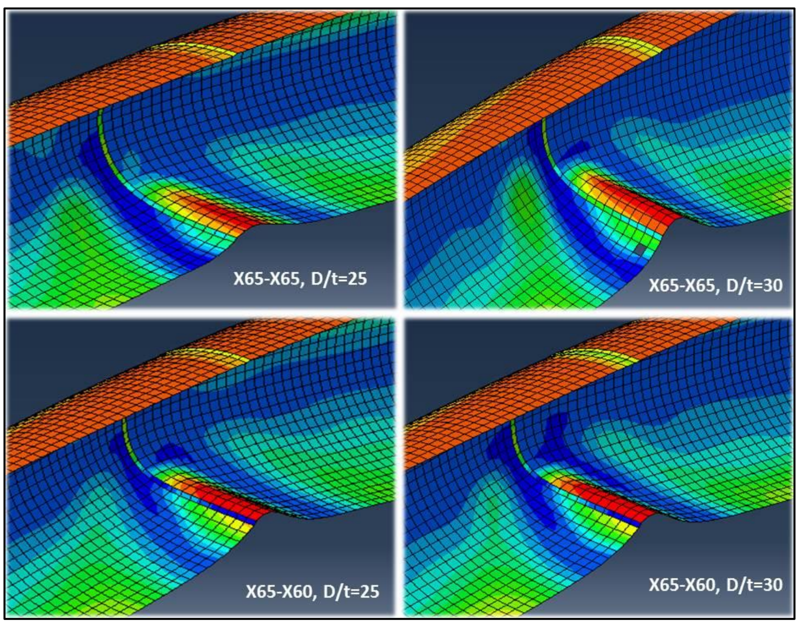

Figure 4-8: Localized buckling at higher D/t ratios

It was observed that as the ratio changes to have a thinner pipe, localized ovalization leading to buckling triggered near the weld connection. The result is an increased stress concentration at the local buckling region and a gradual reduction in the stress-strain patterns along the rest of the pipe. This confirms to the studies by Kyriakides and Ju, 1992 stating that for shells that fall within the approximate range of 26 < D/t < 40, long wavelength ripples amplify and result in a localized growth of ovalization. The resultant pattern is observed to be a localized kink. This is shown in figure8for the cases of grade 450-450 and 450-415 configuration for D/t values of 25 and 30.

The same can be seen when looking at the axial stress comparison for a grade450-415 pipe configuration with weld offset in figure 9. It can also be seen that the effect of localized kink is more prominent in higher D/t ratio (i.e., 30) as compared to other lower D/t values.

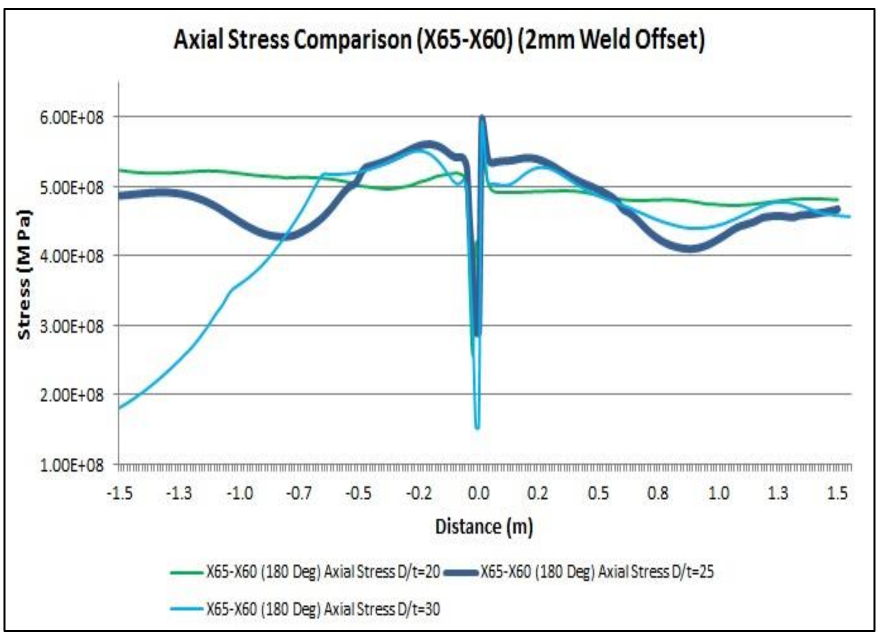

Figure 4-9: Axial stress comparison against D/t ratio

This illustrates the complexity of the interaction between the competing modes of deformation (i.e. ovalization versus axial waveform) and the influence of other factors;

such as geometric imperfections and material properties, on the simulated pipe mechanical response(Fatemi et al., 2009b,2010; Fatemi and Kenny, 2011; Marzinez and Brown, 2005). The maximum concentration is along the weld area where the localized buckling has initiated. The resulting behavior is a reduction in effect of bending of the pipe along the length as the localized buckling dominates in pipe deformation. Figure 4-9 shows that this effect is more prominent in a higher D/t ratio pipeline.

Increased strain values were also seen at the weld itself. This was observed to be consistent throughout the pipe circumference. A comparison between the circumferential values of axial strain for D/t ratios is shown in figure 4-10.

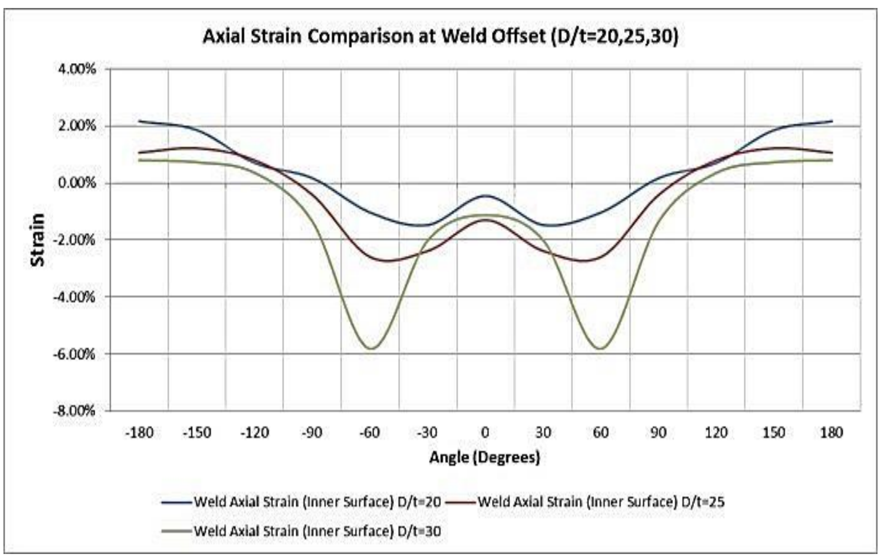

Figure 4-10: Axial strain along circumference at weld offset for different D/t ratio

4.4.4 Effect of Imperfection Wavelength

The imperfection wavelength (λ = 500 mm & 750 mm) did not have any significant influence on the pipe mechanical response with respect to the deformation modes and mechanical response in the axial and circumferential directions. A characteristic response, illustrating the influence of imperfection waveform on pipe mechanical response, is presented in Fig. 4-11 for the longitudinal distribution of axial stress. The distributions follow similar patterns with variations partly attributed to differences in the contact mechanics associated with the imposed imperfection wavelength. A similar response was observed for the distribution of hoop stress and axial strain.

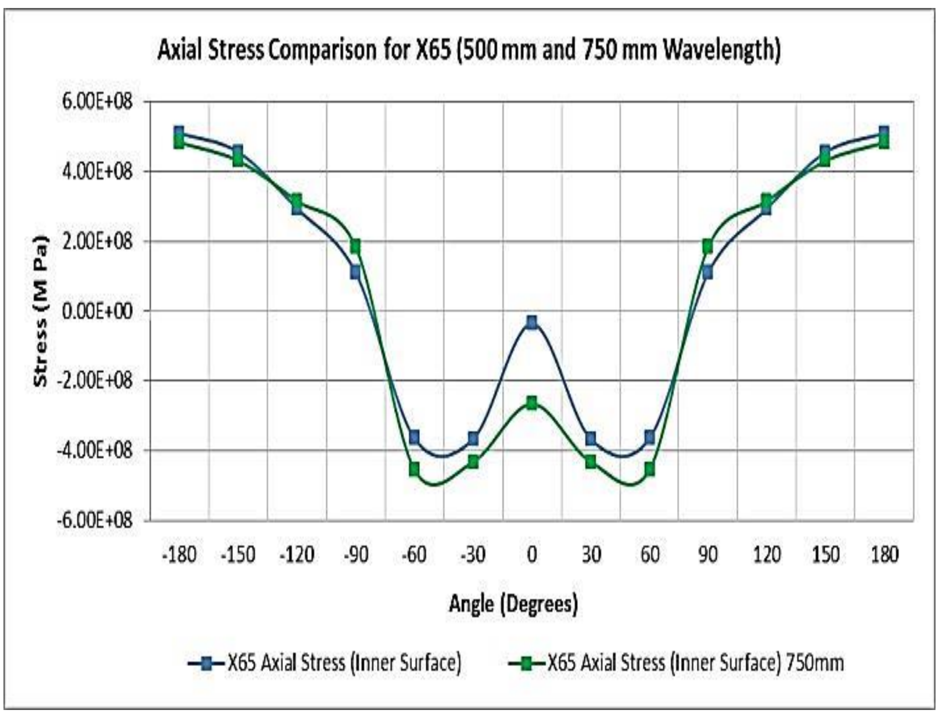

Figure 4-11: Axial stress comparison – 500 & 750 mm wavelength

4.4.5 Influence of Material Grade

The influence of non-uniform material grades across the girth weld was to trigger an asymmetric response in the longitudinal distribution of axial stress and strain. This is due to the different moment capacity and pipe curvature for each material grade, which is consistent with previous studies (Dawood & Kenny, 2013;Fatemi et al., 2009b). Increased stress and strain values were observed for the grade 415 pipe segment as shown in figure 4-12 and figure 4-13.

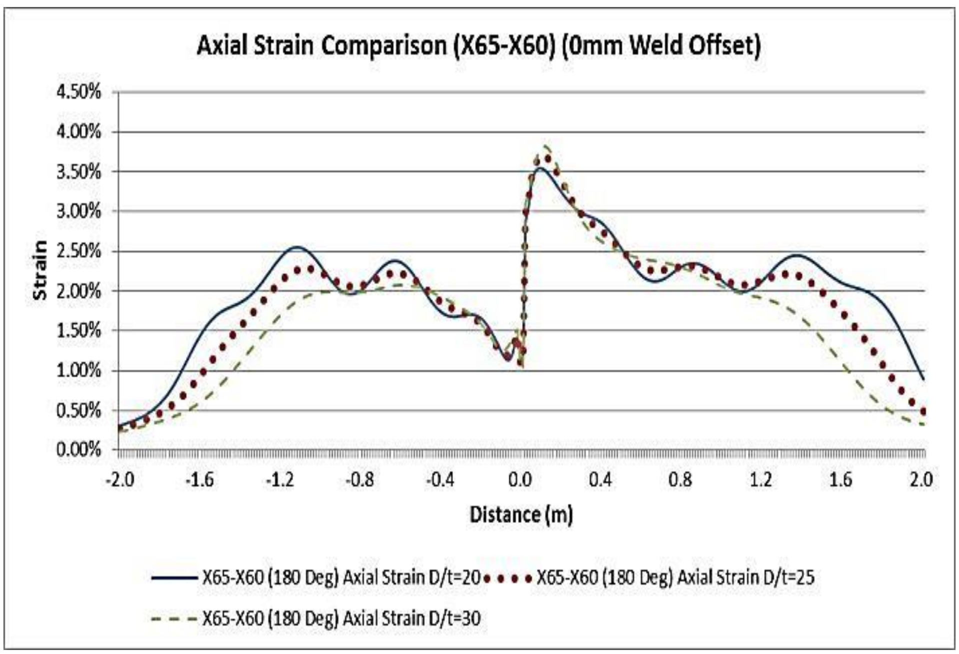

Figure 4-12: Axial strain comparison – 450 – 415 without weld offset

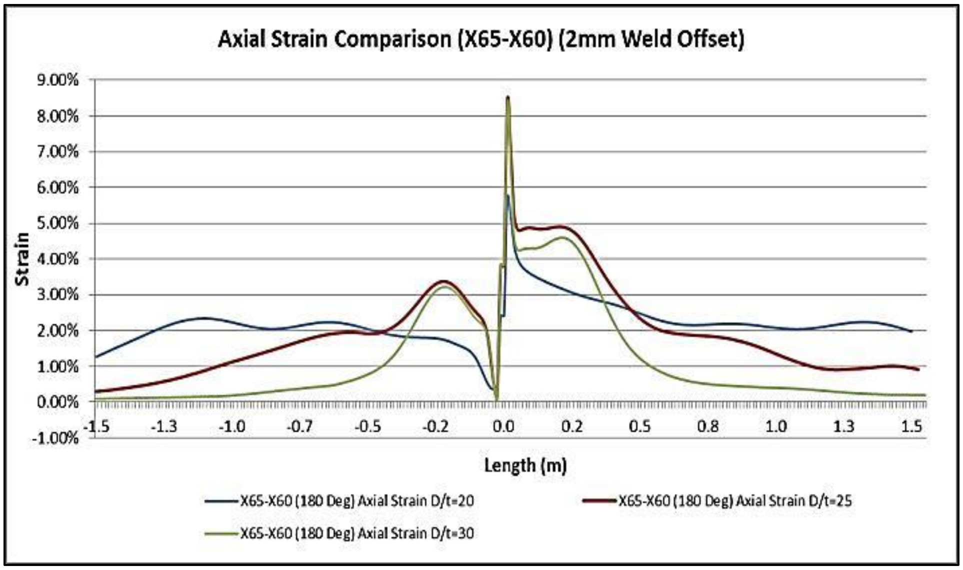

Figure 4-13: Axial strain comparison – 450 – 415

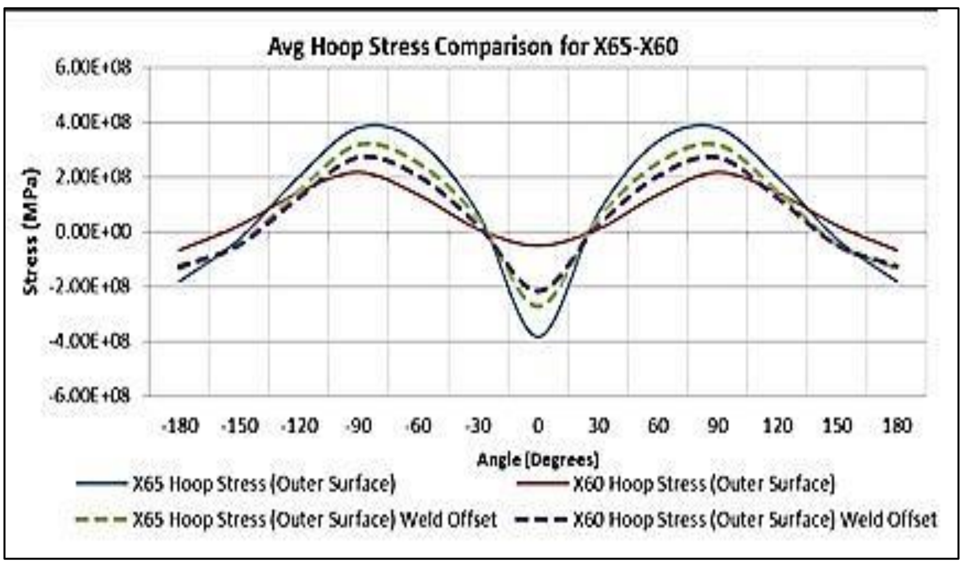

Figure 4-14: Average hoop stress comparison – X65 – X60

The difference in material grade had an impact on the hoop stress and strain distribution of the pipeline as well. Moreover, the weld offset in such a configuration resulted in significant difference from a perfect geometry. The hoop stress distribution for a grade 450-415 configuration is shown in figure 4-14. The hoop stress value has been observed to be maximum at 0 and 90 degrees where the maximum effect of pipe bending was observed and consistent with the study by Martinez and Brown (2005).

4.4.6 Effect of Weld Offset

Earlier studies have shown that the weld offset plays a significant role on the pipe mechanical response (Al-Showaiter et al., 2008,2011; Fatemi et al., 2009b; Fatemi and Kenny, 2011). For the numerical simulations conducted in this study, the response is affected by variation in the contact mechanics when the pipe is bent onto the reel (Dawood & Kenny, 2013).

The base line study was extended to carry out a range of different analyses that incorporated pipe segments connected through a weld connection.

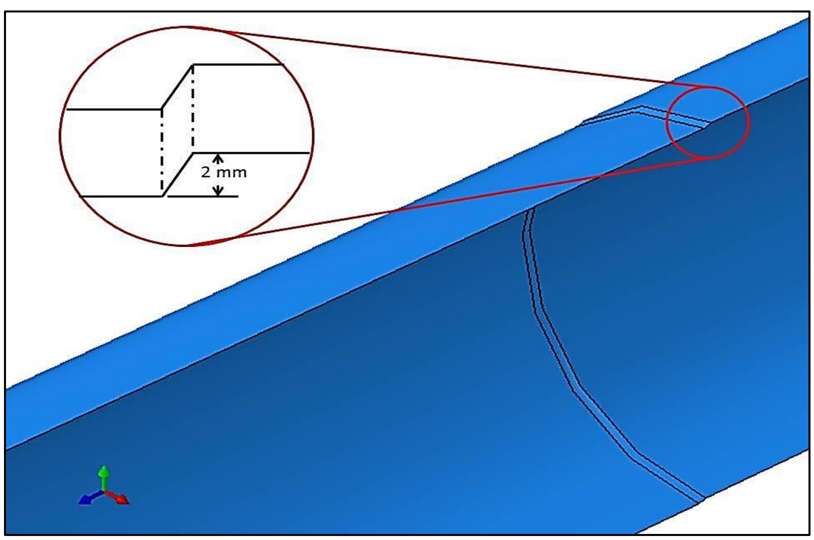

Figure 4-15: Weld offset for bending simulation

However, the weld was modeled with a 2 mm radial offset as shown in figure 4-15. The weld offset was modeled using the “Loft” feature in Abaqus CAE. Grade 450 material characteristics with a 10% overmatch were used to define the weld stress-strain relationship.

The analyses were carried out for different material configurations using material grade 450 and 415 pipes. These were then examined for the axial stress, axial strain, hoop stress, and hoop strain distributions of the pipeline under study.

For the case of a weld offset with similar material properties at both ends, peculiar stress peaks were observed near the weld area. This is represented by figure 4-16, which shows a comparison between the stress distribution along the length for a similar pipe configuration with and without weld offset. It was observed that the remaining background stress distribution was generally symmetric along the pipe length and was not influenced by the weld offset.

Similarly, a comparison between the axial stain distribution along the length for no offset and a 2 mm offset is shown in figure 4-17. It can be observed that significant changes in strain values occur in case of a weld offset.

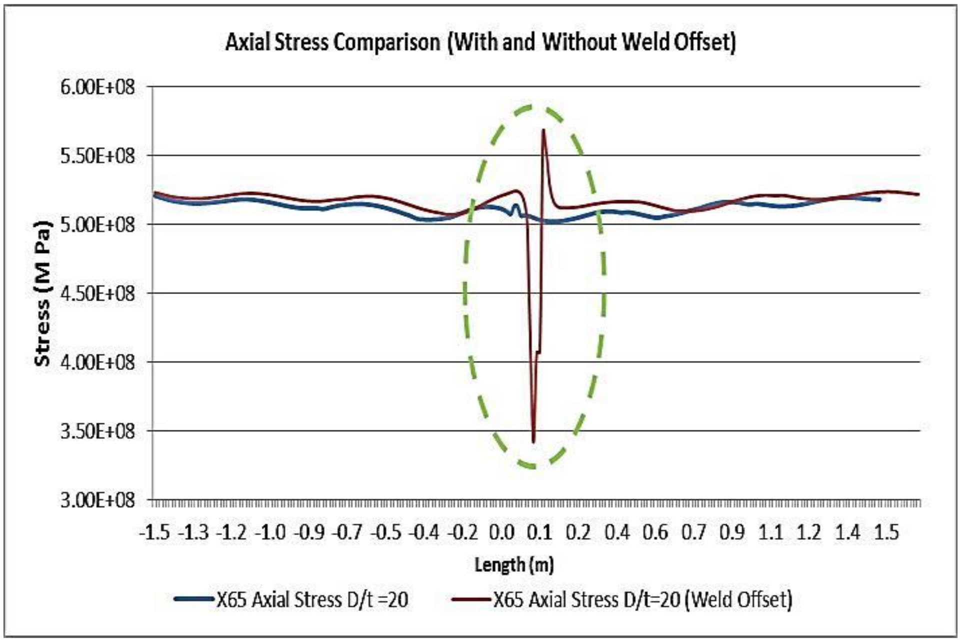

Figure 4-16: Axial stress comparison for grade 450 pipeline with and without weld offset

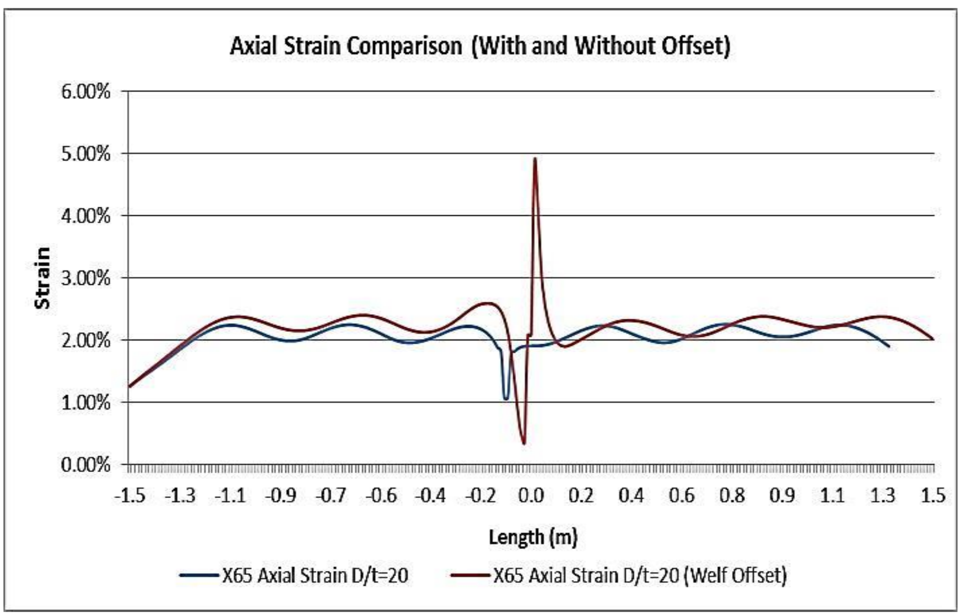

Figure 4-17: Axial strain comparison along length – with and without weld offset

The variation due to weld offset can is primarily due to the fact that having a geometrical configuration like this will make the weld itself the first point of contact with the reel. Therefore, much of the stress and strain concentration is borne by the weld area.

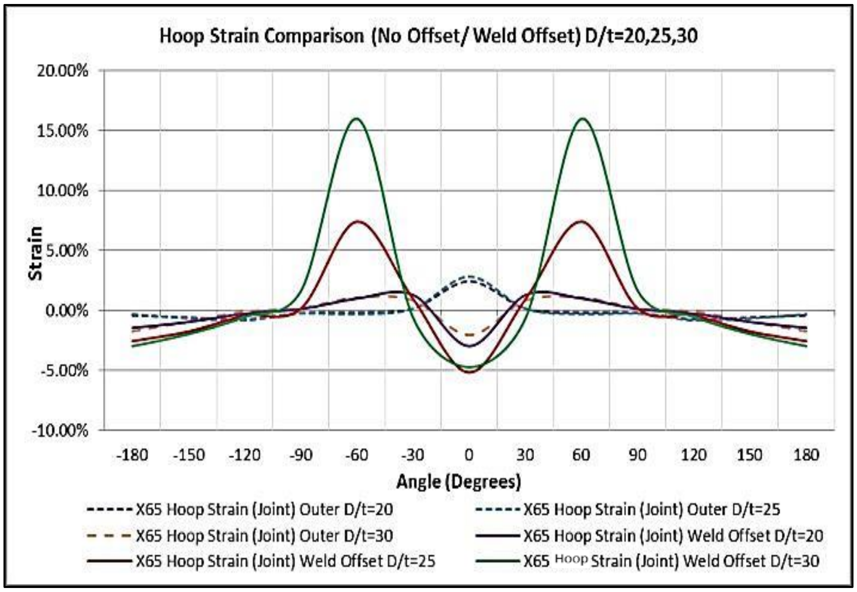

Figure 4-18: Hoop strain comparison along circumference – with and without weld offset

This effect can also be seen in the hoop strain distribution along the circumference of the pipeline as shown in figure 4-18. The graph shows the strain values at every 30 degree increment along the pipe circumference. The presence of physical radial offset significantly influences the amplitude and distribution of axial stress and strain across the girth weld. The strain values increase from 2% for no offset at D/t=30 to 5% for the presence of a weld offset.

4.5 Conclusion

A parametric study using continuum finite element modelling procedures was performed to study the effect of pipe mechanical response under bending during the reeling process. The effect of pipe geometric orientation, material grade, D/t ratio and imperfection wavelength was studied. The weld joint in between two pipe segments was modelled as a 10% overmatch with respect to the pipe base metal.

Maximum concentration of stress was observed at the pipe reel touch down point in a weld-offset configuration. The region around the weld was observed to be the most critical region that defined the stress distribution along the length of the pipe. A symmetric response was observed for a similar grade pipe configuration whereas an asymmetric distribution was observed for an unequal material grade configuration.

Generation of local buckling was observed for higher D/t pipe ratio with the buckle then governing the stress and strain response of the pipe. The pipe behavior was examined to be sensitive to changes in the pipe ovality wavelength both for the eigenvalue analysis as well as pipe bending. An increase in the values of stress and strain was observed for both the cases.

The girth weld offset in combination with material grades influences the stress and strain response of the pipeline. It was observed that physical radial offset resulted in a significant increase in the pipe stress and strain response especially in the weld vicinity.

Imperfection amplitude and wavelength have secondary effects but accurate measurement through physical experiments is needed to confirm the values presented in the paper.Moreover, the inclusion of anisotropic properties into the pipe in order to have a more realistic assessment of the bifurcation calculation and the wrinkle wavelength is recommended as it has been observed to significantly influence the pipe behavior in pipe bending analyses (Corona et al., 2006).

The current research will be extended to further study the mechanical response of complex piping system such as a Tight-Fit-Pipe (TFP)

4.6 Acknowledgement

The authors would like to acknowledge the Wood Group Chair in Arctic and Harsh Environments Engineering at Memorial University of Newfoundland for sponsoring the research project. The opportunity to conduct the research and publish the findings of the project is greatly appreciated.

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5 SUMMARY AND CONCLUSIONS

Reel-lay process is one of the most efficient methods to install offshore pipelines. The pipe lengths to be installed are fabricated and inspected at an onshore assembly site known as the “spool-base” before they are reeled onto the vessel. The pipeline then undergoes unreeling, straightening and it finally exits the vessel. However, during the reeling process, the pipeline is subjected to repeated plastic bending cycles, which may result in modification of pipe properties, which can be geometric such as ovalization, mechanical such as the changes in the stress and strain properties of the pipeline and in service fatigue (Martinez & Brown, 2005). Such concerns need to be addressed in order to gain significant confidence in strength and reliability of the pipeline in terms of designing as well as during service. The present research effort aims at studying the mechanical response of the pipeline when subjected to reeling with the help of various scenarios that address variable sensitive to the structural integrity of the pipeline.

A literature review was carried out to analyze and assess the existing database of physical and numerical modeling simulations, industrial design codes and standards that are currently available as guidelines for the designing, installation, maintenance and inspection of offshore pipelines. The public domain data was evaluated to set up a baseline platform to correlate the existing work done on the subject topic. This helped in identifying the available knowledge base, technological advancements and potential constraints that are to be addressed in order to add more confidence in the installation of pipelines using the reel-lay method.

Once the foundation for the study and framework for the numerical modeling procedures was developed, ABAQUS/ Standard, the commercially available FEM software was utilized to generate algorithms that simulate the reeling of the pipeline using different techniques. The numerical modeling procedures developed were calibrated using input from already available physical and numerical database (Pasqualino & Neves, 2010, Martinez & Brown, 2005 and Chouhan, 2010) in order to gain confidence in the response exhibited by the pipeline under different scenarios. The developed finite element models were then compared against each other in order to obtain consistency and reduce computational cost by selecting the more efficient numerical procedure.

Based on the calibrated models, a sensitivity study was performed. The baseline analysis was carried out on a grade 450 (X65) pipeline with an outer diameter of 273.1 mm (10”) and a wall thickness of 12.7 mm (0.5”). The sensitivity study examined the study of pipe reeling across a weld joint with a 10% overmatch for the same pipe material. It was then extended to different material combination and with weld offset. Axisymmetric response was observed in case of different material combinations due to difference in the moment capacities. Moreover, a discontinuity was observed across the girth weld in terms of stress and strain distributions primarily due to the difference in the material strength between the pipe and the weld.

The studies were then extended further to incorporate the effect of geometric and bifurcation imperfections on the pipeline. A parametric study comprising of different variables such as diameter to wall thickness ratio (D/t), imperfection wavelength and weld offset for improved result. Earlier studies carried out on local buckling response high strength pipelines (Fatemi and Kenny, 2012 a,b; Fatemi et al., 2010) have highlighted the importance of imperfections in analyzing pipe buckling due to bending. Eigen value analysis was carried out to generate the bifurcation imperfection on the pipe. The combination of geometric imperfection and bifurcation imperfections were then super imposed on to the pipe and a comprehensive bending analysis was performed. The analysis included the study of weld offset and imperfection wavelength onto the pipe. Axial and hoop stress and strain responses were examined along the longitudinal and the hoop direction as well as near the weld joint.

Stress peaks were observed near the weld area for pipes with similar material grade in case of a weld offset. Moreover, for higher D/t ratio, a formation of localized buckling near the weld area was observed. The stress and strain distribution across the length of the pipe was examined to significantly reduce following the development of a localized kink.

The research effort studied the effects of different parameters and helped in understanding the pipe behavior during reel-lay installation. The existing work can be extended to provide more detailed approach towards pipe response by adding factors such as kinematic hardening, anisotropic material properties etc. Experimental efforts replicating the developed numerical models are suggested to add more confidence to the research and to draw more detailed conclusion on pipe performance. The current research effort can provide a platform to carry out further research on pipe reeling of complex pipe systems that include Pipe-in-Pipe (PIP) systems and Tight Fit Pipe (TFP) systems.

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