The mechanics of pipeline reeling

An Insight Into The Mechanics Of Pipeline Reeling

Abstract :

Written here is a paper devoted to the mechanics of pipeline reeling. It contains an initial background into the various techniques used for rigid pipe lay, as well as a brief insight into the vessels used. The mechanics of pipeline reeling is discussed in detail, with the effect of pipeline ovalisation as well as a detailed understanding of the moment/curvature response and D/t ratios being defined. An insight into the material selection stage is given, before introducing one to the Recommend Practice for flaw control, involving Engineering Critical Assessment (ECA) as well as specimen testing. Finally the paper will be rounded off with an insight into future concepts and studies being carried out by the industry.

1. Introduction

The aim of this paper is to address the mechanics of the ridged pipe reeling process, as used frequently in the offshore oil and gas industry. The use of pipelines to transfer goods or product is highly proven, having been utilised since the late 20th century where the potential for oil was first realised. The relentless demand for oil meant that the need to look past existing onshore reserves was realised, with experimentation into the offshore environment inevitable. Today, pipelines are considered to be one of the most economical ways to transfer petroleum products such as oil, gas and water, in large quantities and over vast distances both reliably and safely.

The steady growth of the oil and gas industry ensures that boundaries are constantly widening regarding pipeline installation, with ever-greater challenges of water depth and location becoming apparent. Pipelines are highly versatile in this respect, aided greatly by the many devised pipe lay methods. The J-lay, S-lay, and reel barge allow installation of rigid pipelines in a vast array of different water depths, at different lengths and speeds. The reeling method of installation differs from the others in that it puts the pipe under reverse plastic strain deformation, resulting in increased potential for enhancing induced defects. This lay technique will receive the majority of report analysis.

Reel lay of rigid pipelines is now a well-proven method of installation in the offshore environment. The issue of fracture control due to plastic strain under installation is generally very well understood, indeed to such an extent that it is already well standardised for both actual pipeline design and the treatment of fracture control during plastic deformation. These standards take the form of the DNV RP-F108 and DNV OS-F101 respectively. Whilst fracture itself in todays offshore pipeline installations is now unheard of, ductile tearing does indeed occur, especially in laboratory and finite element testing. There also appears to be no recent published accounts of in-service leaks as a result of fabrication flaws to date. An attempt will be made to analyse and understand these relevant topics through the mechanics of pipe reeling.

As a final aspect to the report, an insight into future aspects regarding rigid pipe reeling will be given. As an example, flaw tolerances due to the introduction of new pipeline materials and the ever-increasing exposure to H2S (sour service) environments are known to cause material stress cracking.

2. Pipeline Installation And Field Overview

Offshore pipelines come in many different forms, dependant on their location in the field. The further downstream they are located, the larger their potential diameter as more flow streams connect. Pipeline design is dependant on the findings of 3 main stages of design, namely conceptual, preliminary and detail engineering. Within the first stage the concept is evaluated for feasibility and all restraints are identified. Preliminary engineering focuses on the defining of the project parameters and goes into enough detail to order the pipeline. The final detail engineering breaks everything down to the finest detail for submitting as work tender to the client.

Improved welding techniques, survey capabilities, anchor handling techniques and procedures have all helped contribute towards more fast and efficient installations. The main loading considerations during pipeline installation are hydrostatic pressure, tension and bending. Three main lay methods exist for the installation of offshore pipelines. These are the J-lay and S-lay methods, as well as the technique of reeling.

S-lay/Steep S-Lay

The S-lay pipelay configuration offers the ability to install pipeline in typically shallow to intermediate water depths. It gets its name from the ‘ S’ shape, formed from the overbend at the vessel stinger to the sagbend before contact with the ocean floor. This can be seen in the following Figure 1.

S-lay of pipeline involves a normal or semi submersible vessel with an attached stinger. The stinger, used to minimise curvature and thus bending stress, supports the pipe as it is being offloaded, housing rollers to allow smooth movement of the pipe as it moves off. Tension is typically provided in the form of track loop deck tensioners, and varies depending on waterdepth, submerged pipeline weight, departure angle and sagbend and overbend curvatures respectively. A ‘ firing line’ is installed on the vessel, containing the welding stations and relevant inspection stages for pipeline assembly.

S-Lay is ultimately limited in deeper waters due to tension capacity and thus high overbend strains. As water depth increases the stinger length required becomes unfeasible, with more buoyancy being required to support the longer pipe length for the steeper lift off angle.

J-lay

The J-lay configuration allows for the installation of rigid pipeline in water depths of over 500ft. The term ‘ J’ comes from the shape the pipeline takes up during the lay, as seen in Figure 2, below. The J-lay method works via the use of a barge with an installed tower, used to provide the required vertical drop and lower the product. Due to its configuration, the J-lay method requires no stinger and thus overbend stresses are eliminated and lay tension is reduced.

The setup typically suffers from slower productivity than a comparable S-lay due to the vertical setup on the vessel. This can often result in the method being more cost prohibitive. It is however easier to utilise smaller vessels such as smaller barges and support vessels due to the relatively compact tower arrangement. Improved motion characteristics of the majority of J-lay vessels also results in lower dynamic pipe stresses.

Reeling

Reeling of pipeline is a configuration often utilised for offshore pipelines as well as catenary risers. It differs from the previous two installation methods in that the pipeline itself is first welded together and insulated as required, before being spooled onto a large drum on a reel lay vessel, all onshore.

Upon loading the pipeline onto the reel, plastic strain deformation occurs. Once the lay vessel is in location, the pipe is then unreeled and straightened using a straight ramp, before being layed via either of the above J-lay and S-lay methods, typically dependant on conditions such as water depth and vessel configuration, namely horizontal or vertical reel. Throughout the lay, the pipe is tensioned and anchored to prevent sagging. Once complete a pullhead is attached to the tail end, before an abandonment cable guides it to the seabed, with an attached buoy used as a location marker. Reeling can typically be used for pipe diameters of up to 16”, as well as for pipe-in-pipe installations.

As the pipeline is not being created during the lay, reeling offers the advantages of short installation times which can be particularly advantageous in short weather windows. Reeling of pipelines also tends to be more cost effective for this reason, offering the potential for better safety as well as a better quality product as a whole, that can be fabricated from exotic steels, coatings and internal liners as required. Weld joints can suffer from fewer flaws due to enhanced onshore inspection, often from Non Destructive Testing (NDT) via X-ray methods before the pipeline is reeled.

A possible downside to the reel lay method is that the pipe radius tends to restrict the length of pipe layed, typically around 3 to 15km. Because of this, if the pipeline is made up of multiple segment lengths, connecting the set can prove challenging after their initial lay, and multiple segments being layed many miles offshore can result in undesired transit time. The pipeline also comes under plastic strain deformation, potentially resulting in ovalisation of the pipeline as well as affecting maintenance and monitoring of the product. Buckling can also occur, being time consuming to correct and due to the occurring deformation throughout the reel lay process, traditional coatings such as concrete cannot be used.

Reeling Ships/Barges

Typically, reel lay vessels often take the form of barges, as well as modified drillships and bulk carriers. Purpose built vessels also exist, examples being the 1978 CSO Apache pipelay vessel, seen below in Figure 3. Depending on the vessel configuration, reeling can be horizontal or vertical. Horizontal reeling is typically used with the S-lay configuration, with the vertical setup used mostly with J-lay. The CSO Apache vessel however, is an exception to this rule, being a vertical setup for use with S-lay.

3. Mechanics Of Pipe Reeling

The pipe reeling method produces high levels of bending strain on the product, often just slightly below pipe shell buckling strain values. The primary concern is that because of this reverse plastic strain from reeling on and off, the pipeline is being ‘ degraded’, being downgraded below that of conventional J-lay and S-lay an so producing a greater failure risk. This, along with the aligning and straightening processes required, modifies the pipe material properties resulting in uncertainty to its performance. Pipe reeling also produces uncertainty with regards to burst, collapse, and fracture of the pipeline. Collapse in particular is directly linked with pipeline ovality, a result of the installation process.

Despite all this it is fairly obvious that if plastic reeling strains were such a concern then we wouldn't be installing flowlines with them! The reality is that there is no reduction in performance provided that certain items are carefully considered during the design, procurement and fabrication processes. As an example, poor understanding can result in a greater pipe wall thicknesses, but with the reeling method now extremely well understood, to such an extent that there are detailed standards for it, there are nearly always relevant procedures to follow.

Pipeline Ovalisation

The method of rigid pipe reeling is such that the inducing of ovalisation to the pipe is inevitable. Ovalisation is the deformation of the pipe from a near perfect circle to an elliptical cross section due to plastic strain deformation. The challenge with such an installation method is maintaining an ovality that is within acceptable limits during the pipe lay. Ovalisation can be increased with bending and external overpressure and also decreased with bending and internal overpressure. It is a non-linear effect that greatly increases as the material reaches its elastic range.

Ovality is strongly influenced by material properties such as rate of strain hardening, as well as the pipe diameter over thickness ratio, D/t and the reeling geometry configuration. Also of particular concern, is the relationship that a variation in material properties between pipes can bring, mostly over the required welded connections. The concept of ovalisation is not concerned with the materials yield stress itself but depends on the material yield anisotropy, that is the ratio of yield stress in the hoop to the axial direction.

In order to ensure that the pipe does not collapse during installation, it is important to ensure ovality is kept within set parameters, as defined in the DNV-OS-F101 Offshore Standards. This is based around the characteristic resistance for external pressure collapse, pc and can be seen below in Equation 3. 1.

afab is the pipe material fabrication factor and is used for manufacturing processes that introduce cold deformations, giving different strength in compression and tension. The maximum value this can represent is a value of 1 for a seamless manufacturing process. This reduces to as low as 0. 85 depending on the fabrication method used, for example the UOE bending, forming and welding process.

The ovality value, fo is outputted as a percentage and from the DNV standards is not to exceed 3% in a reeling application. It is critical in the selection of wall thickness during design stages and must be of large enough value to take into account not only the expected ovality but localised peaks. Too large a fo value will result in a pipeline being of thicker wall thickness than required.

When a pipe is bent plastically to a positive curvature (i. e. when spooling) and back again (coming off the reel), most ovalisation is recovered when the pipe is straightened. If too high an amount of ovalisation is still present however, then external forces in the form of rollers can encourage straightening, though this itself can be disadvantageous due to the potential to damage any linepipe coating. Ovalisation is disadvantageous for certain tasks that will be carried out throughout the pipelines lifespan, such as pigging and through flow line (TFL) tools. Pigging, a form of linepipe maintenance for cleaning and inspection, can be carried out without halting product flow by using the pressure of the flow to carry the pig from its launcher to its receiver. However as they are designed to fit snugly in a round pipe, excessive ovalisation would cause potential blockage or incompatibility.

Moment – Curvature

Another aspect for consideration in order to gain a further in-depth understanding of the reel lay process is the relationship between moment and curvature during pipeline installation. The moment/curvature relationship is based round that of the pipes physical geometry, as well as the relationship of stress and strain in the material. An example of a moment/curvature diagram can be seen below in Figure 4.

The pipeline is initially spooled onto the reel resulting in plastic deformation, and thus is taken past the material yield point (A) to the extent that the maximum installation curvature (B) is experienced by the pipe. This curvature will be dependant on the radius of the reel being utilised, with the radius increasing as pipe is overlapped. From its reeled state, the pipeline is transported to the lay destination for unspooling. It is unreeled to the pipeline aligner, a stage that due to the pipeline weight and applied back tension from the reel, results in reverse plastic deformation (C). With the pipe now resting between these two points, it sits visually straight in its span.

Passing the pipe through the aligner of radius (E) and towards the straightener, bends it in the same direction to that is was initially spooled. The 3-point straightener itself exerts a further reverse plastic bend (F) on the pipe. Taking it slightly past its initial curvature results in it sitting physically straight on the seabed when all tension upon it is relaxed. The delivery state to the seabed location will correspond to the relevant standards as denoted in DNV-OS-F101.

It is generally considered that the maximum moment to be sustained by the pipe during reeling will be around that of (B), with this moment being less than the plastic moment. This is due to the fact that at this point the bending behaviour of the pipe is stable and so buckle is unlikely to occur, with moment still increasing with curvature. The plastic moment at any point of the pipeline is a function of the pipes diameter, wall thickness and yield strength respectively, with the post yield strain hardening as well as the section ovalisation also playing a less extreme factor.

One issue that tends to arise with pipeline reeling regarding moment and curvature occurs with the use of different pipe grades during production. When pipe is requested by a supplier, it is done so by grade. The supplier will create batches of pipe to the specified specification, but due to manufacture no two batches will be exactly alike i. e. some pipe will be weaker than others and vice versa. Despite all batches of pipe adhering to a minimum specification, the mismatched material specifications each react slightly differently during reeling, potentially resulting in high local curvatures and in extreme cases, local buckling. In the case of a pipeline being reeled, the moment required to spool a pipe onto the provided reel is provided by that of the following 12m section in line. Should this pipe be of weaker grade than the initial one, the potential that the moment will not be sufficiently supported arises, resulting in a localised increase in curvature, producing the greater potential for local buckling.

D/t Ratio

The pipe diameter over thickness ratio (D/t) is of high importance in pipe selection, being directly related to that of buckling. Typically, as the D/t ratio decreases the pipe can withstand a higher strain before buckling. However this comes at the expense of a large increase in ovality to the extent that it may go over desired limits, affecting such procedures as pigging of the pipeline. This can be seen below in Figure 5.

Figure 5: Plot of Allowable Strain and Ovalisation at Allowable Strain

As a further example to the relation to the D/t ratio to ovalisation, research carried out on pipe of API steel grade X65 gave the following results, as found in the following Table 1.

Material Selection

Material selection for pipelines is highly important for several different factors, and can determine the standards to follow and installation procedure. For a carbon steel for example, the requirements for a reeled pipeline are not that far removed from the requirements of national standards, but for other materials such as high strength pipe grades, careful review may be required. All materials require a certain level of constraints to be effective, with control typically needed on factors such as tensile ranges, maximum diameter to thickness ratio (D/t) and inner diameter (ID) tolerances. By working with suppliers who understand the installation process, a the chance of a suitable product is greatly increased.

DNV standards dictate several basic requirements for pipe reeling. A maximum yield strength value of no greater than +100MPa of the Specified Minimum Yield Strength (SMYS) is to be used, with a yield spread no greater than 100MPa. Wall thickness tolerance is considered to be dependant on the pipes actual wall thickness and a yield to tensile ratio of no greater than 0. 90 is to be used. Strain aged testing of parent pipe material must also be carried out to the expected levels experienced during the reeling process.

For the reeling of rigid pipeline, the choice of pipe material is strongly influenced by the manufacture method, both in terms of properties and geometry. Two main manufacturing methods exist, being submerged arc welded (SAW) and seamless (SMLS). SAW pipe is created by rolling a plate and welding the seam. It is a closely controlled method of fabrication offering tighter dimensional tolerances and better availability than seamless pipe. Seamless pipe involves the driving of a billet over a piercing rod, creating a hollow shell. This method typically offers better availability than welded pipe, at the expense of poorer tolerances in properties, in particular geometrically.

Technip made an attempt to explore the variation of wall thickness in four 10km length pipelines of 6”, 10” and two 12” diameters, with stated wall thickness from 12. 7 to 21. 3mm. Measurements were taken at various points of each pipeline through their circumference, building up a broad cumulative distribution function for the thickness of each pipe. It was found that there was large variation in the wall thickness values throughout each pipe.

Despite initial concerns, it was said to be almost impossible for a large to thin extreme of wall thickness to occur at a weld connection, due to the large variation of possible thicknesses in each pipe. It was concluded that the plastic moment capacity of seamless pipe was dominated primarily by the variation in average wall thickness through a pipes cross section. A highly exaggerated illustration of the deviance of each outside diameter (OD) for each type of pipe manufacture can be seen in the following Figure 6. The variation in OD of any pipe is closely related to ovality of the linepipe and can be obtained from additional analysis.

An additional issue that tends to arise with pipeline reeling, regarding material selection, occurs with the use of different pipe grades during production. When pipe is requested by a supplier, it is done so by grade. When a grade is selected as being suitable for use, a supplier will ensure that the material supplied exceeds the grade, often level with the next grade up, in order to prevent rejection of the pipe due to it being under specification, which could cost them vast amounts of money. This results in welding issues as higher grade materials are more difficult to weld to standard, requiring overmatching (where the weld is stronger than the pipe itself) with the surrounding material. In order to prevent this, companies have been known for requesting material in the form of a YS/UTS ratio, yield strength over ultimate tensile strength, described in more detail below, keeping tighter control on what is produced. This comes at a disadvantage to suppliers due to the finer tolerances involved.

Reeling can also cause unacceptable strain hardening in certain materials, as well as large work hardening in higher grade steels. Strain hardening can be described as the increase in material resistance after previously exceeding its yield point from plastic strain. In ratio form it is YS/UTS, with lower ratio values indicating a greater material resistance after yield, and thus greater material stability under plastic deformation. A typical graph of strain hardening in a material can be seen below in Figure 7. The increase in material resistance can be seen from the positive slope produced. Work hardening, the increase in yield from repetitive straining is also of concern, but happens in fewer materials.

Corrosion is an issue for pipelines in such areas as sour service. In areas such as hydrocarbon production pipelines, an inner liner, often of high-density polyethurene, is inserted as a form of corrosion prevention. This greatly enhances the life of the pipeline but issues have arisen with such a setup, including liner collapse. Liner collapse can occur when gas that is travelling through the liner becomes trapped between it and the outer pipe. During service this has little effect due to the pipeline operating pressure, but when the pipeline is depressurised, it can expand and collapse the liner.

It has been shown that certain materials can experience increased resistance to fracture due to a growth in micro cavities and other such defects that can initiate ductile crack propagation. Due to the nature of the reeling method for pipeline installation this effect is given less attention however, instead aiming to reduce the chance of fracture via carefully selected material grade. This is due to the fact that reeling produces much smaller plastic strain levels than is ideal for the theory to work to great effect.

Plastic Strain Effects On Materials And Welding

The majority of load carrying structures in an engineering environment have cracks present in their construction, through either the linepipe material itself or the welding that was carried out through construction. It is more or less unheard of to have a pipeline with no defects at all, and it would be highly uneconomic to repair every flaw found. As such it is important to develop an acceptance criteria in order to establish defects that are acceptable and those that are not and have the potential to cause failure – one that states a guaranteed fitness for purpose and integrity of the pipeline. Considering the two possible lay methods in terms of strain, that is plastic strain and elastic strain installation respectively, each has different assessment criteria to carry out. The standard procedures for elastic loading are not equal to plastic loading, being modified to suit.

The severity of a flaw is dependant mostly on its size, location, loading and the material properties. As an example, installation methods involving significant plastic strain normally require high toughness materials in order to allow acceptance of realistic flaw sizes in the girth welds. An acceptance criteria must be carefully considered to ensure that it is not over cautious. It must be ensured that no unnecessary work is carried out with regards to weld repair, inspection and pre-weld treatments, and that no weld methods, materials or design are wrongly disqualified throughout the process. The industry as a whole accepts that flaws in structures are acceptable as long as they are accounted for and cannot cause failure.

Modern pipeline design is based on a limit state design, with each failure mode designed for independently. One of the main failure modes in rigid pipelines for reeling is the fracture of girth welds. For girth welds, it is important to ensure that the strength and fracture toughness are well optimised, as this will help to prevent any present flaws from extending and thus affecting the overall pipeline integrity. It needs to be demonstrated that the pipeline has adequate resistance against crack extension by tearing and unstable fracture during its installation, as well as operation. This is done via an Engineering Critical Assessment (ECA), which was devised in order to help determine acceptable flaw sizes in girth welds.

Recommended Practice For Flaw Control

The standards by the DNV give a Recommended Practice to be used for cyclic plastic deformation as found in rigid pipe reeling. The Practice is made up of 3 key elements, namely a procedure for fracture resistance testing, an Engineering Critical Assessment (ECA) procedure and finally a validation testing procedure. Each of the three stages is expanded on below.

The purpose of the initial element of the procedure is to characterise the pipe materials fracture resistance as well as the fracture resistance of the girth welds. This is done to help determine acceptable flaw sizes in the pipeline. There are two ways of carrying out such analysis according to the utilised BSI BS 7448, namely via the use of either a SENT (Single Edged Notched Tension) or a SENB (Single Edged Notched Bend) specimens. Due to the loading characteristics of reeling, the SENT specimen is the most frequently utilised, as it is considered to be the more representative of the two with regards to the crack tip constraint of girth weld flaws. Use of the SENB specimen results in conservative results.

With regards to cyclic loading effects regarding fracture resistance, research carried out by both TWI and DNV has shown, through both small and large scale testing, that cyclic loading does little to affect the fracture resistance of both the pipe material and its welds. Due to this, the DNV standards recommend that the fracture resistance values are determined for later ECA analysis through the use of one-directional monotonic testing of the SENT specimens, before later being verified by small scale testing of Segment specimens, used to resemble conditions of a girth weld during linepipe installation.

Characterise The Pipe Materials Fracture Resistance

To begin with, monotonic testing of the SENT specimens was carried out, in order to characterise the materials fracture resistance values by J-R (or CTOD-R) curves. For this application the BS 7448 standard is followed, with exception to the use of the SENT specimen in order to account for obtaining a loading mode and thus crack tip constraint similar to that of a pipe circumferential surface or embedded flaw. No set standard is currently available for this configuration of SENT testing.

The typical SENT specimen, as seen above in Figure 8, is of recommended dimensions B = 2W and contains a surface notch that is used to represent the relevant orientation for defects in girth welds. The aim of this testing stage is to evaluate results for all possible defect locations on a reeled rigid pipeline. The sample is to be either clamped in position or pin loaded for testing, with both methods being deemed acceptable for comparison of flaws in pipe girth welds. A minimum of 6 specimens will be tested, with each loaded to a tearing length of anything from 0. 2mm to 3mm, in order to obtain an accurate J-R or CTOD-R curve. It must be ensured that no brittle fracture occurs before attainment of the expected maximum load value, or that of a stable crack extension of at least 1. 5 mm, for the results to be effective. Testing is done at the lowest predicted install temperature the pipeline will foresee, with consideration also made for install temperatures of over 50°c due to the possibility of a reduced stable crack tearing resistance.

The J-integral is obtained from the relationship

where Je represents the elastic area of the J-integral and Jp the plastic respectively.

Perform An Engineering Criticality Assessment (ECA)

The second stage of the procedure is based around an ECA assessment. An ECA assessment is used in order to help determine acceptable flaw sizes that will not cause failure during linepipe installation and later operation. It can be broken down into 3 basic stages, those being material properties, flaw data and material stresses. Having any two of the three available allows the third to be found, but the most common method utilised is establishing the maximum tolerable flaw size from material properties and applied stress information. In 2007, the DNV-OS-F101 standards had an Appendix A added, based on the BSI BS 7910 standards, in an attempt to clarify all existing information relating to ECA calculations.

The previously found fracture properties, established from testing of SENT specimens, are used to ensure that no weld flaws will cause failure during installation. Failure itself is defined as a preset crack extension and final crack size being exceeded, as well as the occurrence of plastic collapse and unstable fracture. The crack size definitions are mostly recommended for study in the installation phase, giving desirable information on flaw size after installation, that itself being during the pipeline operation.

The ECA assessment itself is described in the BSI BS 7910 level 3 tearing instability analysis, but for the purpose of pipe reeling is modified to suit. The method is fairly in-depth, but a summery will be given to illustrate what is involved. The initial requirement is to adjust the found stress/strain and curve data from the SENT in order to help create a Failure Assessment Diagram (FAD), used to help distinguish between acceptable results and those that would cause possible failure. This is done by plotting both brittle fracture Kr against plastic collapse Lr. A cutoff value for plastic deformation must be found, as the FAD cannot account for arbitrary large plastic deformations. An example FAD diagram can be seen below in Figure 9.

Figure 9: Failure Assessment Diagram (FAD)

It is also required to calculate the actual stress and strain concentration of the pipeline. The act