Novel Measurement Techniques for Assessment of Geometrical Variations in the Reeling Process

Brett Howard and George Brown
Technip Offshore UK Ltd.

Abstract

The reeling process introduces a degree of ovalisation to the pipeline in excess of the nominal geometry provided by the pipe mill. The extent of ovalisation is dependent not only on the basic properties of the pipe and the geometry of the reeling configuration, but the interaction of variations in properties between pipes, particularly across welded connections. Technip have initiated a programme to improve understanding of these mechanisms. This paper presents the structure of the development programme and introduces the tools and testing procedures adopted for the validation exercises.

Introduction

The integrity of a pipeline in deep water is often governed by collapse during installation. A key parameter in achieving adequate collapse resistance is maintaining the installed out-of-roundness, or ovality, of the pipe within acceptable limits.

The rigid reeled installation process is a fast and cost effective method for the installation of high quality pipelines since the welding and inspection process is conducted away from the vessel critical path at onshore fabrication facilities. The nature of the reeling process, however, induces a degree of ovalisation to the pipeline. The extent of ovalisation is dependent not only on the basic properties of the pipe and the geometry of the reeling configuration, but the interaction of variations in properties between pipes, particularly across welded connections.

This may lead to local fluctuations in the degree of ovalisation at points along the pipe, and also to variations in the level of plastic strains experienced by the pipeline material. Technip have initiated a programme to improve understanding of these mechanisms. To achieve this goal sophisticated engineering models have been developed and novel technology and testing procedures are used to validate the analytical processes.

This paper presents the structure of the development programme and introduces the tools and testing procedures adopted for the validation exercises. An example of a detailed survey of geometrical variations before, during and after the simulated reeling process is presented. Also shown is an assessment of the strain distribution across the welded connection seen during this trial. The accurate knowledge thus obtained is a vital input for deep water pipeline design to guarantee pipeline integrity.

Framework for Development

The as-installed ovality of a pipeline is a key input to the calculation that establishes the resistance of a section to collapse from external pressure. For illustration, the equation used by DNV [1] is shown below:

$$(p_c - p_{el})(p_c^2 - p_p^2) = p_c p_{el} p_p f_o \frac{D}{t_2} \tag{1}$$

where, f_o is the as installed ovality of the pipe defined in Equation 3 later in the paper. In deep water applications the value that the pipeline engineer uses in design code checks is critical to the resulting wall thickness selected for the pipeline. The value selected must however be big enough to reflect not just the nominal ovality of the reeled pipe but localised peaks which may occur periodically along the pipeline. It is important to consider these localised peaks in the pipeline design. Too large a value, however, and the pipeline will be unnecessarily thick, thus reducing the advantages offered by the reeled installation method in comparison to alternative techniques.

The work presented here-in forms a small part of an ongoing internal development programme. This programme has been undertaken to improve the understanding of the detailed mechanics of the reeling process in order to optimise the design process for reeled pipelines in deep water. The techniques employed are not limited to deterministic prediction of ovalisation for given input parameters, but include probabilistic techniques used to predict frequency and magnitude of peak ovality occurrences.

A selection of the topics addressed is listed below:

- *Development of an anisotropic metal plasticity material model for use in finite element simulations:* The multi-axial material behaviour seen under cyclic loading is highly complex and comparison of finite element simulation and test data demonstrated that existing models are not sufficiently refined to accurately predict geometric deformations through the full reeling cycle.

- *Development of fully representative finite element models of bending trials and the pipe lay process from the CSO Apache and CSO Deep Blue:* The mechanical loading seen by a pipe during the reeling process is heavily dependent on the exact configuration and geometry of the equipment used. Over simplifications made in finite element models can have a significant effect on results.

- *Review of available data and commissioning of further mechanical testing to establish the statistical variation in pipeline mechanical properties:* As explained later in this paper mismatches in mechanical properties between adjacent pipe joints are a cause of local increases in ovality. Probabilistic design techniques to predict the magnitude and frequency of mismatches along a pipeline require a significant data set of mechanical properties.

- *Survey of a large sample of project line pipe as-delivered to the spool base facility to obtain a representative indication of the mean and variation in initial pipe ovality:* The modelling techniques described above are used to predict the increase in ovality caused by the reeling process. This must be combined with the out-of-roundness of the as-delivered pipe. The information gained by this exercise is a key input to the selection of the design ovality used in the code checks.

- *Validation of finite element modelling:* Careful validation of the complex material and geometrical finite element models is required prior to use in pipeline design. One of the key parts of this validation has been the measurement and geometrical survey of a bending trial specifically arranged to contain a mismatch between pipe sections. It is this activity which is described in detail in this paper.

Mechanics of the Reeling Process

In order to explain fully the purpose of the analytical and practical engineering development programme contained in this paper, the following section presents a brief introduction of the mechanics of the reeling process.

Moment - Curvature Relationship

A pipe follows a number of bending processes during the full reeling cycle. These can best be described using a plot of pipe moment against curvature. Following the path of the pipe during the reeling cycle as described in Figure 1, the moment-curvature main steps are as follows:

0 – A	The pipe is bent around the reel, the curvature increases until first yield occurs in the outer fibres of the pipe. Bending continues until the pipe curvature is equal to that of the reel; this is point A.
A – B	During unreeling the pipe begins to straighten as it moves between the reel and the ramp and the moment unloads elastically. The pipe then undergoes plastic bending such that the pipe is almost fully straightened in the span between the reel and the aligner, point B. It is assumed in the FE model that the pipeline is perfectly straightened in the free span.
B – C	As the pipe begins to conform to the aligner, re-loading occurs, until the pipe is fully conformed to the aligner at point C.
C – E	As the pipe moves towards the straightener it unloads elastically and is then plastically deformed producing a negative curvature through the straightener to D. Once through the straightener elastic unloading occurs to return the pipe back to zero moment and zero curvature, point E.

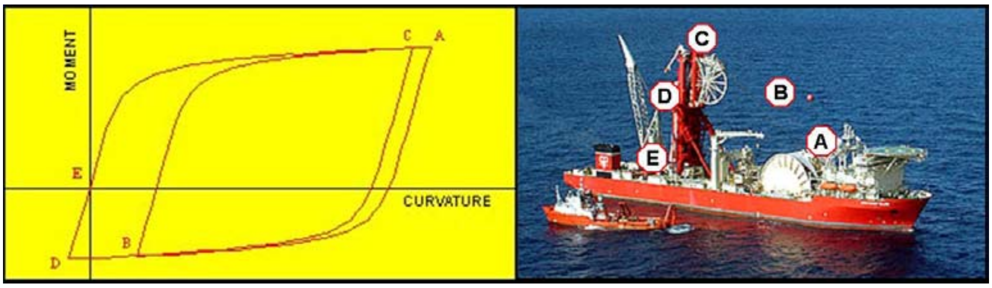


Figure 1 - Description of Reeling Process Using Moment-Curvature Plot

The plastic moment of a pipe, M_p is defined as the maximum moment that can be sustained by the section. This can be simplistically defined as being a function of the diameter, wall thickness and yield strength; however the post-yield strain hardening and ovalisation of the section also have an effect.

The calculation of the minimum reelable wall thickness has traditionally been based on ensuring that the curvature at which the peak plastic moment occurs is greater than the vessel reel curvature. That is, the maximum moment during the reeling cycle, generally at point A, is less than M_p. The theory is that the moment in the pipe is still increasing with increasing curvature and therefore the bending behaviour is stable and a buckle cannot occur. The current Technip minimum reelable wall thickness criterion is derived from the experimental results of pure moment bending tests presented in [2].

A series of finite element analyses were performed of reeling of homogenous pipe with specified minimum wall thickness. The results showed that, if the pipe is completely homogenous, it could be reeled to a radius one third of that of the reel hub. The ease and stability with which an ideal homogeneous pipe can be reeled to high curvatures illustrates that the empirical reelability criterion currently used is actually assessing the ability of the pipe to withstand an alternate more complex displacement controlled loading, not necessarily its ability to withstand being formed to a reel. This more complex loading arises from the inhomogeneous nature of actual line pipe.

The failure of the pipe during reeling on is not the subject of this paper; however, prior to the onset of a buckle, local increases in curvature cause an associated increase in ovalisation of the pipe cross section. Whilst it has been shown during bending trials that much of this increased ovality seen on the reel is recovered during straightening, there can be a residual local shape effect after installation.

It is known that mismatches between adjacent pipe ends are the limiting factor as this causes local high curvatures and in extreme cases local buckling. The effect of a weaker pipe following a stronger one onto the reel can be illustrated by reference to the simplified diagram presented as Figure 2, below.

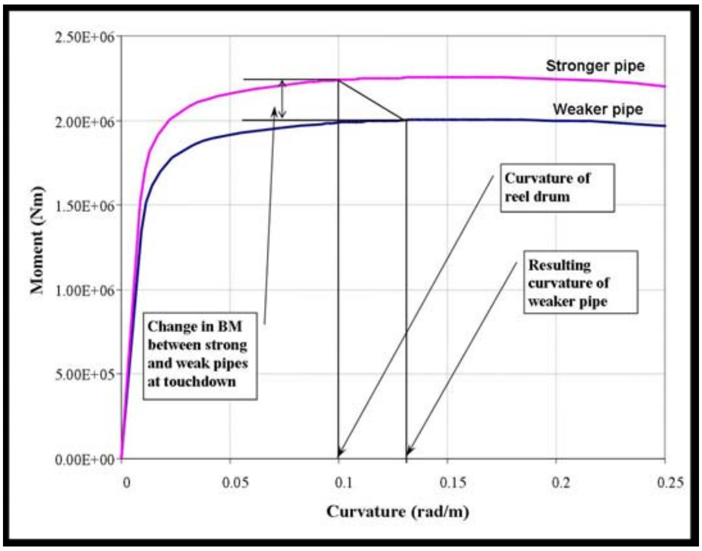


Figure 2 - Effect of Stiffer Pipe on Curvature of Weaker Trailing Pipe

The moment required to form a pipe section to a given curvature, usually that of the hub radius, is generated from the pipe immediately following it onto the reel. In the case of a connection where a weaker pipe follows a stronger one, the necessary moment cannot be supported by the trailing one without a localised increase in curvature, as shown in the diagram. The actual distribution of curvature is a complex function of the relative plastic moments of the two sections, the reeling configuration, the hub radius and the back tension applied to the pipe. However, the diagram above is used to illustrate the general effect of inhomogeneity between adjacent pipe ends.

Variability in Pipeline Materials

Pipelines are constructed from individual joints of pipe welded together; these joints are generally limited to 12.2m (40ft) in length for road transportation purposes. The basic properties of line pipe, both in range of mechanical performance and dimensional tolerances, are limited by pipeline specifications, the most commonly used being API 5L [3].

The properties that impact upon the ovalisation of a pipeline during reeling that are controlled by API 5L include outside diameter and wall thickness tolerances and the allowable range of yield strength. There are other factors that affect the response of a pipe to the reeling process, for example post-yield hardening behaviour, however these are not explicitly covered by the codes.

The out-of-roundness of a pipe, its ovality, is described within API and DNV codes [3,1] by the following two definitions:

$$\Delta_{API} = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \tag{2}$$

$$\Delta_{DNV} = f_o = \frac{D_{\max} - D_{\min}}{D_{nom}} \tag{3}$$

For the same pipe geometry the API definition (2) will produce a value for ovalisation approximately half that of DNV (3). For clarity, all subsequent values of ovality will use the API definition.

The maximum allowable ovality of line pipe as delivered to the spoolbase is limited by the pipeline specification. A large quantity of project line pipe has been measured to assess its initial shape using the internal ovality tool, described below. The preliminary results of this work have shown that the spread in ovality readings is small, as is the mean value; in fact much smaller that the specified maximum allowable of Δ_{API} 0.75%.

Validation of Finite Element Analysis by Bending Trial

General

The finite element analysis of the reeling process has been validated using full-scale bending simulations of pipe joints. Advanced measurement techniques have been used to provide high quality ovality data.

Two pipes were welded together with deliberately mismatched yield strengths then subjected to a bending trial on a rig specifically designed to mimic aspects of the reeling process at Heriot Watt University, Edinburgh, Scotland,. The magnitude of the mismatch was selected to induce significant and measurable local deformations during bending, in order to provide an improved understanding of the mechanisms involved and to provide data for validation of the finite element modelling. The tight specification and control of pipe properties during procurement means that a mismatch of this size does not occur in practice.

While preparing for the trial all possible parameters of interest are measured to provide the maximum amount of information for validation of the finite element model; during the trial itself detailed measurements of both pipe shape and strain are taken at each stage.

Test Preparations

The pipes procured for the trial were both produced by the High Frequency Induction (HFI) method. Material produced by this process was selected because it is known that there is generally little variation in wall thickness around the circumference, thus minimising the risk of a geometrical mismatch masking the effect of the intended material one.

A section of the end of each pipe joint was removed prior to welding and was sent for material testing. The nominal properties of the test pipes are presented in Table 1 below together with the measured yield strength from the removed sample:

Test Pipe	Anchor End	Pull End
Nominal Outside Diameter	10” (273.1 mm)	10” (273.1 mm)
Wall Thickness	0.5” (12.7 mm)	0.5” (12.7 mm)
Measured Yield Strength	528 MPa	435 MPa

Table 1- Bending Trial Pipe Properties

The two pipe sections were cut to length and welded together using approved procedures. The root pass employed the Gas Tungsten Arc Welding (GTAW) process and Shielded Metal Arc Welding (SMAW) was used for the fill. Formal non-destructive examination of the weld was performed. The seam welds on each pipe were positioned 180° apart.

The welded pipe section was marked with a series of axial lines and circumferential rings to create a mesh along the section. At the intersection of the axial line that marks the principal axial of bending with each circumferential line, a pock mark was made to assist with longitudinal strain measurements.

The initial spacing of the pock marks was recorded with a calibrated digital vernier gauge, the initial pipe shape was recorded with a novel ovality tool (described below) and the wall thickness at each node on the mesh was measured using an ultrasonic probe.

The bend test rig, was configured with a bending former of 9.75 m, to match that of the CSO Deep Blue, and an associated reverse former to produce straight pipe. Holes were drilled in the ends of the test section to allow attachment of the restraining pins.

Internal Ovality Measurement Tool

In order to obtain the capability to validate accurately the finite element modelling activities undertaken as part of the development programme, a means of measuring pipe shape throughout the bending trial process, described below, was required. During the plastic bending of a steel pipe section around a former the test piece is relatively inaccessible for detailed dimension survey from the outside. The most effective way to obtain the accurate shape of the section is from within the pipe. The Optical Metrology Centre (OMC) [4] was engaged to produce a laser measurement tool for this purpose, see Figure 3.

Figure 3 - Laser Profiling Tool

The profiler measures internal shapes from 140 to 480 mm diameter. A profile is created using a laser triangulation probe that is rotated through 360 degrees. The angle of the probe is recorded by an optical encoder. A typical profile will usually consist of 2000 measurements, and takes about three seconds to collect. Variations in surface colour are taken into account automatically, allowing the profiler to measure objects from black to white. An internal inclinometer ensures that all profiles can be referred to vertical regardless of the rotation of the device. An odometer wheel is fitted to the rear of the device to record the longitudinal position of the tool.

Bend Test Procedure

With reference to the diagram of the bending rig, see Figure 4, the anchor end is equivalent to the leading pipe onto the reel and the pull-end is that of the trailing pipe. To produce the most onerous loading condition, the stronger pipe (X65) was positioned at the anchor end. The pipe is bent onto each former twice to provide a conservative simulation of the reeling process described in Figure 1.

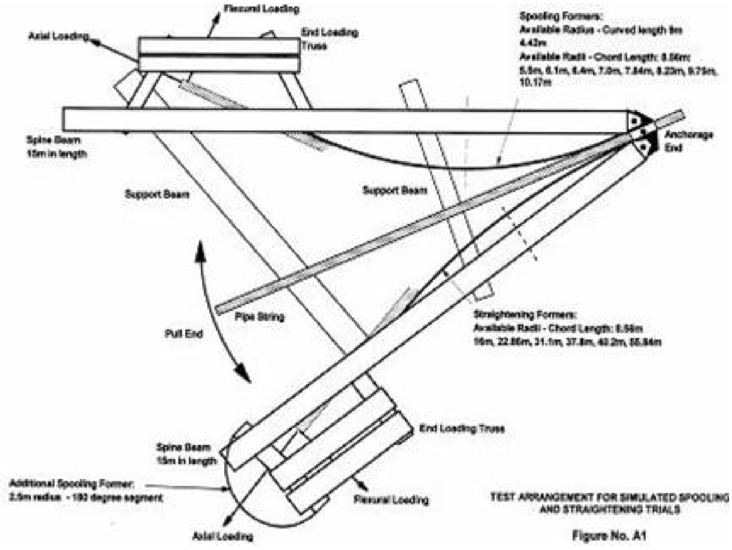


Figure 4 - Schematic of Bending Test Rig

At each key stage in the process the internal ovality tool was passed up the inside of the pipe to provide a survey of the shape of the section at regular points along the test piece. Using a tool such as this, for the first time it has been possible to obtain an accurate understanding of pipe shape while bent around the former. A survey of the pockmarks was also performed to give an indication of the distribution of longitudinal strain between the pipe material either side of the weld.

Finite Element Analysis of Bending Trial

A detailed 3D FEA model of the Heriot Watt University test rig was generated. This model exactly represents the geometry of the test rig to ensure that the simulation is as realistic as possible. The model includes even minor details such as the clearances between the test pipe and the formers as apparently inconsequential details have been shown to have an effect.

This model was used to plan and verify that the test was feasible with the large mismatch present. Sensitivity studies were performed to ensure that the probability of a buckling failure was minimal. The test was planned using finite element analysis (FEA) to push the deformation to the point just before a buckle would occur. The test results obtained have been used to carefully correlate detailed aspects of the simulation.

The validation of the predictive ability of the FEA techniques employed in the design process is a key part of the development of the design process.

Comparison of Results

The trial described above has produced a large quantity of data. It is not possible to present all of the data in detail in this paper. The results below are only intended to show the value of the bending trial as a validation of complex finite element modelling of the reeling process. The methodical mechanical and geometrical survey of the bending trial is essential to enable this validation.

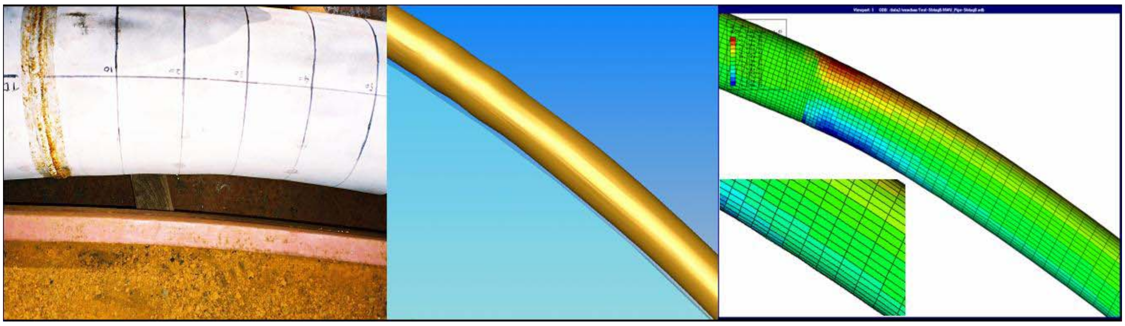
Pipe Shape in Reeled Position

The graphical results presented as Figure 5 below, show three representations of the pipe at Stage 3 of the bending trial process; this is when the pipe is bent to the CSO Deep Blue hub radius former for the second time (note this is conservative; in practice the pipe is bent to the radius of the aligner which is greater, or lower curvature, than the reel hub).

1. The first image is a visual photograph of the bulge seen in the weaker pipe close to the weld location.

2. The second image is generated from the dimensional data produced by the laser tool. The profile of each section has been imported into SolidWorks. Each section profile has been positioned on a curve of radius equal to that of the reel hub in accordance with its measured longitudinal position and rotated to be normal to this line. A technique known as lofting has been used to interpolate a surface between these profiles.

3. The third image is the shape predicted by the finite element model described above.



Figures 5a, b and c - Images of the Bulge

Whilst it is not straightforward to compare the shapes presented above, the images are shown to illustrate the detail in which the laser tool can survey an area for validation of finite element modelling.

Assessment of Final Pipeline Ovality

The obvious bulge that could be seen during the second bending on the hub former disappears during the final straightening operation. A full internal survey of the pipe was undertaken to measure any residual changes in local pipe shape. These measurements were compared to the predictions made by the finite element model of the process and are plotted on the graph presented as Figure 6, below.

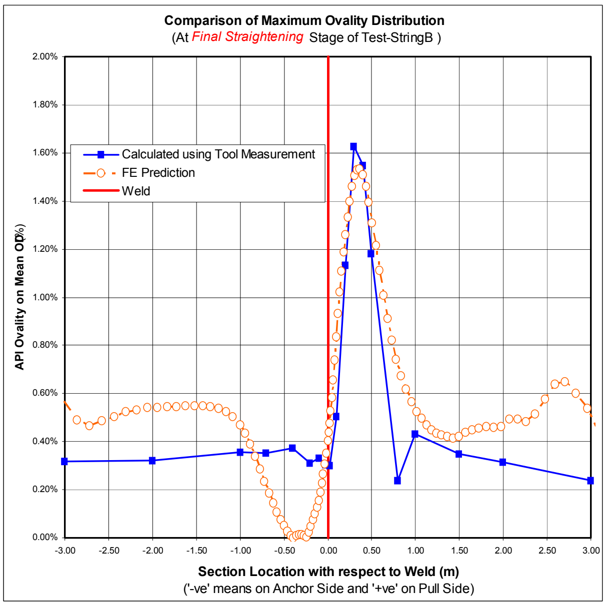


Figure 6 - Comparison of Final Pipeline Ovality

It can be seen that the curves are largely in agreement, and that the finite element model captures both the general shape of the residual feature and the absolute values of ovality predicted.

It should be noted that localised ovality peaks are a potential concern for pipeline collapse, but do not have the same effect as uniform pipe ovality of the same magnitude.

Results of Strain Distribution Assessment

The nominal longitudinal strain experienced by the extreme fibres of a pipe during the reeling process is described by Equation 4. The introduction of a mismatch, as intended in the trial above, locally alters the distribution around the feature.

$$\varepsilon = \frac{D}{R} \tag{4}$$

The results of the pock mark strain assessment are presented on Figure 7. It should be noted that the weld material is overmatched in terms of yield strength when compared to the pipeline material. This means that the extent of straining in the weld metal itself is much lower than that seen in the adjacent pipes. The detailed distribution of strain in the weld and heat affect zone has been investigated by Technip in separated studies, however it should be noted that this is not captured by the measurements presented below.

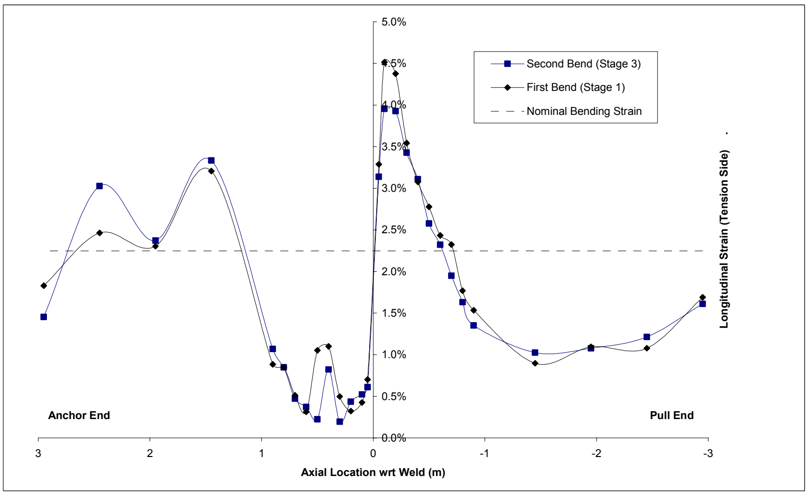


Figure 7 - Longitudinal Strain Distribution

Conclusions

It has been shown in this paper that the traditional assessments of stability during reeling are not sufficiently representative of the detailed mechanics of the reeling process. Technip have undertaken a detailed development programme of testing and analysis to improve understanding of these mechanisms. The validated tools and techniques developed can be applied to optimisation of reeled pipeline design in deep water.

References

1. ‘Offshore Standard OS-F101 - Submarine Pipeline Systems’ DNV 2000.
2. ‘Ultimate Pipe Strength Under Bending, Collapse, and Fatigue’ Murphey C, Langner C., OMAE 1985
3. ‘Specification for Line Pipe’ API 5L, 2000
4. www.optical-metrology-centre.com