Effects of Reeling on the Mechanical Properties of HFI Welded Pipes

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Abstract

In the offshore oil and gas industry project cost and schedule considerations remain of prime importance, leading operators to seek more competitive field development solutions. The High Frequency Induction (HFI) production process is the most economical method for the manufacture of steel pipeline material and, when installed by the reeling method, delivers significant savings in terms of cost and lead-time. In recognition of this Corus and Subsea 7 have entered into a technology development program to prove the suitability of HFI welded linepipe for installation by the reeling process.

During the research program a sequence of pipes were cut and fabricated such that each spool contained a single girth weld at the mid point. These pipe spools were then subjected to simulated reeling trials using a bending former representative of the reeling vessel Seven Navica. The test programme was designed to determine the evolution of tensile, Charpy impact and fracture toughness properties of the pipe material following the application of the reeling process. To understand how the properties of the pipe evolve in relation to the strain history, actual strains were measured at various locations along the length of the spool. Particular account was taken of the girth weld location and positioning of the longitudinal seam weld.

Evaluation of the test results demonstrated that pipe properties after reeling were well within accepted norms for offshore pipe specification and construction. To complement this the work performed supports the specification of HFI linepipe for reeled installation when accompanied by appropriate testing data and best practice in design.

1.0 Introduction

The reel-lay process is one of the most effective installation methods of pipelines for offshore oil and gas applications and is typically applied to pipe diameters of between 3” and 16”. There is a perception that only seamless linepipe is suitable for reeling, however, time and technology has changed and the experience and knowledge of the HFI product for the offshore industry is far greater.

HFI is growing in popularity and is expected to play a major role in reducing the unit cost of large scale, long distance pipeline projects. In addition to delivering a consistently shorter procurement schedule and lower unit costs, it can reduce
material requirements and offshore construction activity; through the tighter manufacturing tolerances offered. The superior shape control during the manufacture of HFI enables faster fabrication of pipe stalks and reduces the risk of pipe buckling during reeling.

Subsea 7 were seeking to utilise the advantages of HFI but needed to understand more fully how the material responds during the multiple straining cycles which occur during the reeling process. From the research conducted a specification for the manufacture of HFI linepipe could be generated to assure the pipe would be consistently produced to the required quality.

2.0 Mechanics of the reeling process

A typical reeled pipe installation process is shown schematically in Figure 1 and complemented by an image of the Subsea 7 vessel, Seven Navica. During reeling, and subsequent installation, the pipe is subjected to a number of subsequent elastic plastic bending cycles of different magnitude. A typical moment-curvature plot as shown in Figure 2 illustrates this.

The points indicated on Figure 2 illustrate the main steps in the reeling cycle are as follows:

1 → 2: The pipe is applied to the reel. The curvature increases until first yield occurs in the outer fibres of the pipe. When point 2 is reached, the pipe curvature is equal to that of the reel.

2 → 3: During unreeling the pipe begins to straighten as it moves between the reel and the aligner, curvature being reduced.

3 → 4: As the pipe begins to conform to the aligner, reloading occurs leading to the second elastic-plastic cycle.

4 → 5: The pipe is reverse bent in the straightener producing a negative curvature.

5 → 1 Once through the straightener, elastic unloading occurs to return the pipe theoretically to the zero moment – zero curvature point.

It should be noted that the schematic shown in Figure 2 is a simplification of the more complex actual loading applied to the pipe. Apart from the bending component, the pipe is subjected to the axial load applied by the tensioner (in order to prevent the pipe buckling) as well as contacts loads. However it has been demonstrated [1,2], that the bending moment remains the primary loading mode controlling mechanical behaviour of the pipe.

Due to the nature of the reeling process, the material along the pipe circumference will have different loading (and stress-strain) histories. At the extrados position the material in Figure 2 will experience two major positive strain increments: during
reeling-on (1-2) and during bending over the aligner (3-4). However, the stress-strain history is different for the intrados position where the material is subjected first to compression and will then experience the positive strains during reeling-off and straightening.

In order to understand the overall pipeline mechanical response during installation and to predict its reliability in service, it is necessary to know how mechanical properties of the pipe material change with the application of cyclic plastic strains and the resultant pipe properties during the pipeline service life.

3.0 Full-scale reeling simulations

For the purposes of this investigation, full-scale reeling trials were performed at Heriot Watt University, using a test rig shown schematically in Figure 3. In the test rig the pipe spools were bent with one end fixed and the other end free to move horizontally when loaded by a mobile crane.

The test matrix for the reeling simulations consisted of 9 spools fabricated from three pipe grades X52, X60 and X65. Each test spool was nominally 12m in length with a girth weld at the mid point. The test matrix is summarised in Table 1. The seam welds were positioned at the intrados of the bend at the pull end and the extrados at the anchor end of each spool. This enabled the performance of the seam weld in the two planes of maximum strain to be evaluated. As a control point one spool of each grade was evaluated in the unstrained condition; the X60 grade spool not being subjected to destructive mechanical testing but successfully reeled without buckle.

After completion of the reeling simulations, the spools were transferred to Corus Tubes’ Pipe Mill in Hartlepool, UK where ultrasonic testing and ovality measurements were completed. Test coupons for mechanical testing were also taken at this point from the anchor end of the spools.

4.0 Mechanical characterisation of HFI welded pipes

Following reeling a sequence of mechanical destructive tests was taken from the strained pipe spools; a summary of the test programme is shown in Table 2. All mechanical characterisation specimens from the strained pipes were taken from the fixed end, where the weld is at the extrados of the bend during the reeling process (points of maximum positive strain corresponding to points two and four on Figure 2). Mechanical test samples were taken at four positions around the pipe circumference, each area having undergone a different strain history. In this paper these positions are referred to as “clock” positions with 12 o’clock being at the weld (See Figure 4).
4.1 Effect of straining

Figure 5 shows the stress-strain curves recorded on the longitudinal specimens machined from the fixed end of the strained spool HFI-2 (API 5L grade X65). As expected, the application of the reel-lay straining cycle has changed both the yield strength and shape of the stress-strain curves.

It is evident that tensile properties of the pipe material after reel-lay installation strongly depend on the straining path. Due to the fact that the pipe material at different points over the pipe circumference is subjected to different straining histories, the resultant tensile properties will vary with the clock position around the pipe. The yield strength $R_{0.5}$ before and after reeling was compared at different positions around the pipe. This comparison was presented as a ratio (after reeling/before reeling) and the distribution of results shown in Figure 6. It is worth noting that the evolution of the yield strength of the material of both grades is similar and strongly dependent on the straining path. While the yield strength of the pipe material decreases at 11 and 12 o’clock positions (the extrados of the bend) due to the Bauschinger effect, the yield strength of the pipe material at the 6 o’clock position increases.

4.2 Elastic-plastic cyclic behaviour of the pipe material

Round bar low cycle fatigue specimens were extracted from three different o’clock positions (6, 11 and 12 o’clock) in order to investigate the material’s elastic-plastic cyclic behaviour. The applied total strain magnitude was +2% in tension and -0.5% in compression. This is a typical nominal strain range experienced by a pipe in the reel-lay installation on the Seven Navica.

The main aim of the tests was to establish the material’s response to the applied cyclic strains in the first ten cycles of the applied load. Figure 7 shows stress-strain hysteresis loops recorded on longitudinal specimens taken from three different o’clock positions of the pipes HFI-1 and HFI-5. It can be seen that while in the first half-cycle of the applied load the pipe material exhibits discontinuous yielding (the Luder’s plateau), the shape of the stress-strain curve in the second and subsequent cycles is “round-house” with the yield strength decreased due to the Bauschinger effect. Similar elastic-plastic cyclic behaviour was registered on the transverse specimens machined from the pipe HFI-1.
4.3  Charpy properties of HFI pipes

A comprehensive characterisation of the Charpy properties of the pipes in both unstrained and strained conditions was carried out. The specimens were tested over a temperature range in order to generate full transition curve and enable subsequent estimation of the indexing temperature $T_{27J}$ which is the temperature for an energy of 27 J measured in a standard 10 x 10 mm Charpy V-notch specimen.

Figure 8 represents the Charpy transition curves generated using the transverse and longitudinal Charpy specimens taken from five different o’clock positions of the strained pipe HFI-2. It is quite remarkable that the material from the strained pipe at 11 and 12 o’clock positions showed better Charpy properties compared to other o’clock positions. It can possibly be explained by the fact that the material’s yield strength at 11 and 12 o’clock position at the fixed end of the pipe decreases as a result of the cyclic straining due to the Bauschinger effect enhancing the material’s ability for strain hardening.

Strain history obviously has an effect on Charpy Impact performance as seen by the variation in the results shown in Figure 7. However, in general, it has been shown that after five cycles no significant change in toughness was noted.

4.4  Fracture toughness properties of HFI pipes

Fracture toughness properties were investigated using three-point bend specimens taken from three different o’clock positions over the pipes circumference, namely 3, 11 and 12 o’clock positions. The fracture toughness values obtained are given in terms of the Crack Tip Opening Displacement (CTOD).

The fracture toughness test results followed the trend established in Charpy tests. Figures 9 and 10 provide comparison of the fracture toughness of X65 and X52 at the fusion line before and after straining. Even after cyclic elastic-plastic straining, it is quite clear that the pipe material at the 12 o’clock position exhibits excellent fracture toughness properties. “M-type” fracture behaviour occurred in all the tests conducted. Fracture toughness of the strained material at the 6 o’clock position is affected by plastic pre-straining that is manifested in lower CTOD values registered in the tests. Again, results showed that changes in fracture toughness properties during straining were within pipeline design requirements.
5.0 Engineering critical assessment of HFI welded pipes

In order to demonstrate the integrity of HFI welded pipes under repeated strains experienced during the reel-lay installation process, an Engineering Critical Assessment (ECA) of the pipes containing axial and circumferential flaws was conducted. The assessment was carried out following the recommendations provided in BS 7910:2005 [3]. In this standard, structural acceptability of a component containing an actual or postulated crack-like flaw is assessed by use of the Failure Assessment Diagram. The FAD defines the envelope for achievement of a limiting condition for loading of the cracked structure, and assessment points lying on or within this envelope indicate that the structure, as assessed, is acceptable against this limiting condition. According to the principles of an ECA, the following information is required for the analysis:

- size, position and orientation of flaw,
- stresses acting on the region containing the flaw,
- toughness and tensile properties of the region containing the flaw

Taking material and stress data from the reeling investigation it was assumed that a surface axial flaw was present at the fusion line of the seam weld was present to complete the ECA. A separate analysis was performed for a surface circumferential flaw located at the 12 o’clock position (fusion line) of the pipe. The analysis was carried out using the latest version of the TWI software Crackwise 4, an example of which is shown in Figure 11.

Through the performance of the detailed ECA it was shown that the tolerable flaw sizes are well within the capability of the NDT system employed at Corus Tubes’ pipe mill. This was assuming a flaw size acceptance criteria of 5% of the wall thickness of the pipe. This is common in offshore and onshore pressure pipe applications.

6.0 Conclusion

Nine HFI spools were tested on the Heriot Watt bending rig without experiencing failure or buckling. Comprehensive mechanical characterisation of the HFI welded pipes in as received and reeled conditions was carried out. Tensile properties, Charpy transition behaviour, elastic-plastic cyclic behaviour and fracture toughness properties of the pipe material were thoroughly investigated on the test pieces taken demonstrating that HFI welded pipes can be reeled and subsequently maintain mechanical properties at the level required to ensure structural integrity.

Through an ECA it is indicated that integrity of the HFI welded seam during reel-lay installation process can be assured; the tolerable defect sizes calculated being greater than the allowable maximum defects in the pipe mill acceptance criteria.
Both Corus and Subsea7 believe that this study will support confident use of HFI for reeled installation allowing them to take advantage of the significant economic benefits it affords.

7.0 Author biographies

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8.0 References


9.0 Glossary

HFI – High frequency induction welding method of pipe manufacture  
Intrados – the interior curve of an arch, in this paper relating to the bent pipe spool  
Extrados - the exterior curve of an arch, in this paper relating to the bent pipe spool  
$R_{0.5}$ – The Yield strength of the pipe at 0.5% strain  
$T_{27J}$ – temperature for an energy of 27 J measured in a standard 10 x 10 mm Charpy V-notch specimen
10.0 Figures

Figure 1a – Schematic of the reel-lay installation process and Figure 1b - Photograph of Subsea 7 vessel – Seven Navica

Figure 2 – Bending moment in the pipe during reeling process (plan view)

Figure 3 – Full scale reeling test arrangements
Figure 4 – Cutting plan for mechanical test samples

Figure 5: Tensile stress-strain curves, pipe HFI-2 (X65 strained pipe) longitudinal specimens

Figure 6: Evolution of the longitudinal yield strength due to the reel-lay cycle, X65 and X52 steel grades
Figure 7: Elastic-plastic cyclic behaviour of the X65 and X52 steel, longitudinal specimens

Figure 8 – Charpy test data for pipe HFI-2 (X65, strained), longitudinal and transverse specimens

Figure 9: Evolution of fracture toughness of X65 grade steel due to the straining cycle, Transverse specimens, 12 o’clock position
10: Evolution of fracture toughness of X52 grade steel due to the straining cycle, Transverse specimens, 12 o’clock position

Figure 11 – Failure assessment diagram
12.0 Tables

Table 1: Test matrix for the full-scale reeling simulations

<table>
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<th>Pipe ID</th>
<th>Grade</th>
<th>Diameter (inches)</th>
<th>Wall Thickness</th>
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Table 2 – Mechanical characterisation tests

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<th>Charpy test</th>
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