A DISCUSSION OF PRACTICAL ASPECTS OF REELED FLOWLINE INSTALLATION

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ABSTRACT
Reeling is a fast, reliable and cost effective method for installing subsea flowline systems up to 20 inch in diameter. The individual flowline joints are lined up and welded together onshore to make long stalks of pipe before being spooled onto the large reels of reel lay vessels. On arrival in the field offshore, it is spooled off, straightened and laid on the seabed up to 10 times faster than conventional S-lay or J-lay methods. The ability to carry out the fabrication and welding onshore, off-line from the vessel critical path, allows very high quality welding and coating to be achieved.

Over the last few years, it is evident that the engineering fundamentals, mechanics and cost effectiveness of the reeling process are now well understood within different quarters of the offshore industry as many major pipelaying Contractors own, or are planning to own, a reel lay vessel. What is apparently missing, however, is the implications and practical aspects of the reeling process when it comes to implementation during project execution.

This paper reviews the engineering fundamentals of the reeling process first and then discusses the practical aspects and applications of reeling mechanics from spoolbase fabrication to spooling-on process up to the offshore campaign and spooling-off process and subsea installation.

INTRODUCTION
The reeled installation technique is a well established method for installation of subsea rigid flowlines, including single flowline and Pipe-In-Pipe (PIP) systems. The basic process of loading stalks of line pipe that have been prefabricated onshore onto large reels (spooling-on or reeling-on process) before transit to the offshore field location, unspooling, straightening and laying on the seabed (reeled-off process) is generally well understood.

In recent years, many major pipelaying Contractors have built, or considering to build, reel lay vessels. Table 1 shows the reel lay vessels that are available in the market and those that are coming to the market in near future (2012-2013).

Table 1 - Existing and under construction reel ships

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Reel Diameter (m)</th>
<th>Pipe Diameter Range (in)</th>
<th>Main Reel Capacity (t)</th>
<th>Top Tension (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technip[17, 22]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apache II</td>
<td>16.5</td>
<td>4 - 16</td>
<td>2000</td>
<td>197</td>
</tr>
<tr>
<td>Deep Blue</td>
<td>19.5</td>
<td>4 - 18</td>
<td>5600</td>
<td>550</td>
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<td>Deep Energy</td>
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<td>5600</td>
<td>450</td>
</tr>
<tr>
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<td>4 - 18</td>
<td>6350</td>
<td>544</td>
</tr>
<tr>
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<td>4 - 12</td>
<td>2267</td>
<td>N/A</td>
</tr>
<tr>
<td>Subsea7[19]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seven Navica</td>
<td>15.0</td>
<td>2 - 16</td>
<td>2200</td>
<td>205</td>
</tr>
<tr>
<td>Seven Oceans</td>
<td>18.0</td>
<td>6 - 16</td>
<td>3500</td>
<td>450</td>
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<tr>
<td>McDermott[20]</td>
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<td>1601</td>
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<tr>
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<td>12.21</td>
<td>3.5 - 10</td>
<td>1550</td>
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<tr>
<td>Aegir</td>
<td>161</td>
<td>4 - 16</td>
<td>4000</td>
<td>800</td>
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<tr>
<td>EMAS AMC</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Lewek Constellation</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>800</td>
</tr>
</tbody>
</table>

1 Estimated values based on available information
2 Under construction

This paper has been structured in such a manner to address the practical issues that arise during design, fabrication and installation of reeled flowlines during a typical project execution as follows:

- A brief description of the reeling mechanism;
- Line pipe procurement requirements;
- Selection of suitable anti corrosion coating and thermal insulation system (where applicable);
- Reelable wall thickness
- Local buckling during reeling process
- Stalk fabrication;
- Spooling-on process and required tension
- Straightening process and required back tension
- Special consideration for PIP systems
Topics that are discussed in this paper are applicable to seamless and seam-welded (DSAW and HFI) steel pipes as well as metallurgically bonded (claded) lined pipes. Although similarities to mechanically lined pipes exist, special considerations shall be made where mechanically lined pipes are installed using the reeling method, see [2].

MECHANICS OF REELING

The reeled installation technique is well described in Fig. 1 using the Moment-Curvature curve. The reeling process is comprised of five steps; see [1]:

Step 1: The prefabricated pipeline is spooled onto the reel from the quayside of the spoolbase under applied spooling-on tension. This is referred to as spooling-on or reeling-on process. The spooling-on tension is a combination of self weight frictional force (between pipe and rollers) and applied frictional force as pipeline passes through the tensioner. During this step, the pipeline is plasticized and passing the yield point (point A) until it finally adopts a maximum curvature (point B), equivalent to the radius of the reel hub. The radius of curvature increases as more pipe is spooled onto the reel.

Step 2: During spooling-off or reeling-off process that takes place offshore, the pipeline first spans from the reel to the aligner. Through this stage, the pipeline is approximately straight in the span (point D) due to the combination of pipe self weight and applied back tension. The back tension is applied by precise positioning of the aligner wheel with respect to reel. There is a reverse plastic deformation associated with this straightening process (point C), but some residual curvature remains in the pipeline.

Step 3: The pipeline is then re-bent over the aligner wheel in the same direction as it was originally plasticized. The curvature is always equivalent to the radius of the aligner wheel (point E), irrespective of whether it is at the start or end of the pipeline stalks.

Step 4: The pipeline is then subjected to a reverse plastic bending (point F) in the three-point straightener arrangement. This reverse curvature is carefully selected in order to ensure that, when the pipe is relaxed, it is physically straight.

Step 5: The reeling process ends with relaxation of the pipeline to a degree of straightness within the limits defined in the line pipe supply specifications that has been used to govern the steel line pipe procurement from the mills.

LINE PIPE PROCUREMENT

The line pipe material properties have a profound effect on the reeling process. As the pipeline is subjected to two cycles of reverse plasticization (plastic straining) during the reeling process, the post yield properties of the material shall be selected such that an appropriate strain hardening is achieved.

For seamless line pipes, the additional requirements to that of API 5L / ISO 3183 [3] has been set out in [1] as follows:

- Maximum yield strength and tensile strength of no greater than SMYS+100 MPa and SMTS+100 MPa, respectively
- Yield strength spread of actual production run no greater than 100 MPa
- Wall thickness tolerance limited to ±12.5% of wall thickness for seamless pipe. Tighter tolerance, however, may be required depending on the method of Non Destructive Examination (NDE) for welds
- Yield to tensile ratio (i.e. the hardening factor) of no greater than 0.89 (DNV-OS-F101 [4] considers this to be 0.90)
- As a minimum, the percentage of elongation shall be 25%
- Strain aged testing of parent pipe material shall be performed to the level experienced during reeling process

For longitudinally welded line pipes (mainly DSAW and HFI pipes), as shown in [5], line pipes can be produced with tighter wall thickness and yield stress tolerance although there is generally a compromise on the yield to tensile ratio and values of closer to 0.92 and higher are common.

In addition, for longitudinally welded line pipes, special considerations should be made to ensure that longitudinal weld, Heat Affected Zone (HAZ) and base material of pipes are fit for intended use after significant straining and that the weld metal strength of the line pipe longitudinal weld overmatches the strength of the parent material. It is further recommended to have a limited cap reinforcement of the longitudinal weld in order to avoid strain concentrations.
For seam welded line pipes, therefore, tighter and more comprehensive Material Procedure Qualification (MPQ) trials are normally required, especially on the toughness of the weld and HAZ.

**SELECTION OF SUITABLE ANTI CORROSION COATING AND THERMAL INSULATION SYSTEM**

Reeled flowline systems are coated against corrosion. The corrosion coating system can vary from a thin (fraction of millimeter thickness) Fusion Bonded Epoxy (FBE) layer to multiple polypropylene (PP), polyurethane (PU) or polyethylene (PE) layers depending on the specific application. These polymeric based materials are far softer than steel but they can withstand higher strain levels.

Reeled flowlines may also be thermally insulated to meet flow assurance requirements. In terms of thermally insulated flowlines that are made of multilayer systems, the criteria for selecting a system depends on, inter alia, the Overall Heat Transfer Coefficient (OHTC) requirements, hydrostatic collapse resistance (dictated by water depth), thermal creep performance, water ingress under prolonged operational conditions, stiffness variation between individual insulation layers and steel pipe, choice of Field Joint Coating (FJC) system, and overall pipeline Specific Gravity (SG).

![Fig. 2 – Local buckling of thick PU based insulated flowline after bending in Heriot-Watt University bending rig [6].](image1)

The choice of FJC is generally limited to either PP and PU based systems, except where the parent coating is FBE only. Apart from (hot applied) tape wrap systems, FJCs are applied using hot injection moulding and allowed to set. The application of hot IMPP and IMPU based FJCs can have a profound effect on the reeling process if it is not well controlled. The preheating process of steel pipe (for accelerated curing) and hot application of FJC will soften the underlying steel pipe, and in presence of geometrical and / or material originated mismatch, local buckling can occur as the pipe is bent on the reel. For example, as shown in [6], the change in stiffness, purely due to application of PU based FJC, can cause curvatures that are significantly higher than the curvature of the reel leading to local buckling (see Fig. 2). It was also stated in [6] that geometrical mismatch (variation of the wall thickness) on an uncoated, or fully coated pipe, could have a significantly lower impact on the pipe local buckling behavior than the application of the hot PP based coating with a PU based FJC on a perfectly uniform (i.e. with no mismatch) pipe.

Furthermore, the quality and bonding of the insulation system and steel pipe should be carefully controlled. Figs. 3 to 6 show the de-bonding of the steel pipe and insulation system, crack within the insulation interlayer and failure of the FJC under bending.

Attention should also be made to the insulation / coating system cut-back length and chamfer angle of the parent insulation system to ensure that it aligns with the requirement of the automatic welding track and AUT heads. For automatic welding, a minimum cut back length of circa 225 mm is recommended, although it is case dependent and should be checked in advance with welding Contractors. A staggered (asymmetric) cut back length could also be requested by some welding Contractors.

![Fig. 3 – Catastrophic failure and de-bonding of the insulation system on the reel.](image2)

![Fig. 4 – De-bonding of the steel and insulation layer (courtesy of Heriot-Watt University).](image3)
REELABLE WALL THICKNESS

The two most widely used codes of practice and standards for subsea pipelines, API-RP-1111 [7] and DNV-OS-F101 [4] provide guidance on the selection of reelable wall thickness. In both codes, the reelable wall thickness is obtained from the relationship that has been put forward for combined bending and external over pressure criterion. To derive a minimum wall thickness for reeling as a function of pipeline outside diameter and reel hub radius, zero differential pressure across the section is assumed.

As discussed in [1], these equations are derived from consideration of the pure bending moment theory and cannot therefore take into account the beneficial effects of spooling-on (reeling-on) tension. Furthermore, the strain concentration due to presence of geometrical and material originated mismatches should be considered using a combination of reliability based techniques and FEA as described in detail in [8] and [9]. In the 2009 edition of API-RP-1111 [7], this has been recognized by stating that “bending strains are not simply nominal (global) bending strains and shall include an allowance for possible strain concentrations”. The strain concentration can stem from, inter alia, mismatch of wall thickness and yield strength of adjacent pipe joints, mismatch of wall thickness and yield strength of pipe joints and integral buckle arrestors [13] and variation between the FJC stiffness and its parent insulation material.

As discussed in [1], a specific criteria (developed by Technip) has been put forward which has been validated over the years and calibrated using series of detailed FEA, full scale testing and reliability based approach.

Provided the line pipe procurement requirements set out above are strictly followed and implemented, for a given pipe outside diameter, the required nominal reelable wall thickness is defined as; see Eqs. (1) to (3):

\[
\begin{align*}
\frac{t_{\text{nom}}}{t_{\text{tol}}} & = \frac{t_{\text{min}}}{1+t_{\text{tol}}} \quad (1) \\
\frac{t_{\text{min}}}{\epsilon_{\text{b-nom}}} & = 2D_{\text{nom}} \quad (2) \\
\epsilon_{\text{b-nom}} & = \frac{D_{\text{nom}}}{2R_{\text{reel}} + D_{\text{nom}} + 2t_{\text{coating}}} \quad (3)
\end{align*}
\]

In the case of negative wall thickness manufacturing tolerance of 12.5%, Eq. (1) becomes:

\[
t_{\text{nom}} = t_{\text{min}} \frac{0.875}{1.14} = 1.14t_{\text{min}} \quad (4)
\]

Fig. 7 compares API (considering the bending safety factor of 1.0), DNV (considering condition load effect factor of 0.82), and the above mentioned relationships for reelable wall thickness. Also included are the DNV based relationship with condition load effect factor of 0.77 (derived based on a series of reliability based analyses and FEA) and Technip’s ApacheII track record (as of 2008).

Fig. 7 – Technip Apache II track record comparison with API, DNV and above mention criterion (after [1] with additional information).
For the HFI pipes, due to higher hardening factor (yield to tensile ratio $\geq 0.92$), the traditional approach has been to calculate the reelable wall thickness from Eq. (4) and add extra 1-3 mm to the calculated wall thickness. As it has been shown in [5], this crude approach ignores the beneficial effect of much better wall thickness tolerance and yield and tensile strength variation of actual production run of the HFI line pipes. A detailed FEA can confirm, whether or not, a higher hardening factor of $\geq 0.92$ combined with much tighter yield strength spread (e.g. 60 MPa) and tighter wall thickness tolerance (e.g., $\pm 5\%$) is acceptable.

LOCAL BUCKLING DURING REELING

Local buckling during reeling takes place on the reel where pipe is subjected to the maximum curvature (minimum radius of curvature). As discussed in detail in [10] and [11], this occurs when a weaker pipe joint follows a stronger pipe joint onto the reel as illustrated in Fig. 8.

The bending moment required to bend the strong pipe joint is provided by the trailing weaker pipe joint. As shown in Fig. 8, this increase in the bending moment cannot be supported by the weaker pipe joint without localized increase in its curvature (“lift off” from the reel) and hence developing compressive strain. Therefore, the weaker pipe joint locally buckles if the bending moment required to bend the stronger pipe joint is higher than its bending moment capacity. The extent of the local buckling is generally limited to one or two diameter length from the girth weld and is visible on the vessel or bending rig.

Rather than analyzing the moment-curvature curve, the level of peak strain (in the weak pipe joint) is a more deterministic value to gauge whether or not pipe has the buckling tendency. This level is strongly dependent on the pipe $D/t$ ratio, material strain hardening and its ultimate tensile strain value. The ultimate tensile strain is lower than its compressive counterpart and should be considered here. A good practice suggests a fraction (e.g. 40-50% or factor of safety of $\geq 2$) of the ultimate tensile strain to be adopted as an acceptable strain limit even though wrinkles and onset of local buckling have been noted at much higher levels of strain and closer to the ultimate tensile strain. This, of course, is case dependent and application of higher spooling-on tension is always a good remedy.

The pipe wall is more susceptible to necking and plastic collapse at higher levels of axial strain, and these effects are usually visually evident when viewing FEA results or full scale test. In cases with axial strain higher than 40-50% of ultimate strain, the level of necking and bulging of the pipe wall is evaluated by a more thorough examination of the FEA and / or test results and the acceptability for reeling is determined. As an example, Fig. 9 shows the FEA result of mismatch pipe analysis with $D/t$ ratio of 23. As it can be seen, even though the strain levels are limited below 4% (tensile and compressive) and seems to be acceptable, the compressive strain took place at the inner wall of the pipe, suggesting the onset of bulging phenomenon.

STALK FABRICATION

As it was mentioned above, the most attractive aspect of reeled installation method is the ability to perform more than 98% of the welds onshore in the spoolbase, ensuring high quality welding, with statistically less repair rate and utilizing weld and inspection techniques / apparatuses that might not be easily handled offshore on board of the vessel. Same applies to the application of FJC's as application of injection moulded system offshore is more challenging. However, diligent preparation is required prior to welding.

Due to the nature of reeling process, it is to be ensured that the weld tensile properties are overmatched to that of the parent pipe material, typically to 20% higher than the actual production run. This is to ensure that the strain concentration does not occur in the weld material, resulting in unwelcomed weld fracture. The welding process should achieve low defect
size, minimum root profile and minimum weld repair. In addition, it should be made sure that the mismatch between two adjacent pipes does not exceed the level set during the design phase.

There are also cases where detailed FEA shows that the likelihood of local buckling on the reel is high or improved fatigue response during operation is desired. Therefore, it is necessary to minimize the mismatch between the joints where other mitigation measures (e.g. enhanced procurement specification or applying higher spooling-on tension) are not feasible. One of the methods that can be adopted during the stalk fabrication is pipe sorting. Pipe sorting will also minimize the misalignment (Hi-Lo), avoiding stress concentration and minimizing the chance of weld root defect. The typical acceptable misalignment is 0.5-1.0 mm, although higher values of up to 2.0 mm have been reeled based on specific project requirements. The Hi-Lo of 0.5 mm is a typical target value for reeled Steel Catenary Risers (SCRs).

If pipe sorting is required, pipe ends are circumferentially scanned within e.g. 200 mm depth along the length and their internal diameter and wall thicknesses are measured and recorded within a database. A dedicated computer program can then select adjacent pipes (“pipe fit up”) such that pipes with nearest wall thickness are welded together (reducing the mismatch) as well as minimizing the misalignment. The geometrical database combined with the individual pipe production heat number can also lead to minimizing the mismatch further.

In cases where pipe sorting or fit up cannot achieve the desired outcome or where the operational requirements need improved fatigue performance, the pipe end internal machining or counterboring is performed. Typical example that Client is insisting on counterboring are reeled SCRs (see [12]). Limitation of the counterboring machines and the extent it can be performed is an important factor that has to be defined during the design phase. Recent field proven laser measurement technique enables achieving high precision counterboring up to 200 mm depth in one step, see Fig. 10. For longer sections, a multi step counterboring is needed and the availability of this capability needs to be checked before design is finalized.

**SPOOLING-ON PROCESS AND REQUIRED TENSION**

Spooling operation is an important operation in which pipe is plastically bent onto the reel drum (highest curvature during the reeling process). In order to plastically bend a pipe over the reel drum, as shown in Fig. 11, a tensile force is needed. This tensile force, called spooling-on (reeling-on) tension, can be calculated by; see Eqs. (5) and (6):

\[
T_{\text{spooling}} = f_{\text{spooling}} \frac{M_p}{R_{\text{reel}}} \tag{5}
\]

\[
M_p = \frac{1}{6} \sigma_{y,\text{mean}} \left(D_{\text{nom}}^3 - (D_{\text{nom}} - 2t_{\text{nom}})^3 \right) \tag{6}
\]

Note that in order to calculate the plastic moment, the mean yield strength has been used. Considering the line pipe procurement requirements set out earlier, this becomes “SMYS+50 MPa”. The plastic moment is the moment in which the full cross-section of the pipe is plasticized. The spooling factor \(f_{\text{spooling}}\) is taken as 1.5 as a minimum. This is to account for variation in yield strength and wall thickness. However, in most cases, the spooling-on tension is higher than that of Eq. (5) in order to achieve efficient reel packing and to minimize the chance of local buckling on the reel. Even the onset of local buckling can result in localized lift off of the pipe from the reel which complicates the reel packing operation.

**Fig. 11 – Schematic of spooling-on process.**

\[
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\]

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\]

![Fig. 11 – Schematic of spooling-on process.](image)

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**Fig. 12 – Seven Navica during spooling-on. Note the long stalk (courtesy of Subsea7).**

Line pipe stalks are spooled onto the vessel either by a dedicated spooling-on tensioner (e.g. Deep Blue) or by passing the pipe through the pipelay spread (e.g. Seven Ocean). The tension that can be applied by passing through the pipelay
spread is higher and can be beneficial when reeling very thick pipes, geometrically dissimilar sections (e.g. integral buckle arrestors [13], transition joints). In addition, there is an element of frictional force between the line pipe stalk and rollers in the spoolbase (see Fig. 12) which increases the applied tension during spooling-on operations.

One of the important aspect of the spooling-on operation and reel packing is the spooling head design. The spooling head is the first section of the pipe that is transferred onto the reel using cranes and winches and then secured onto the reel in order to retain the spooling-on tension. The design of the spooling head can be as simple as a modified blind flange with pad eyes (see Fig. 13) to a purpose built “pawn head”.

Reel packing is then performed as required by laterally moving (fleeting) the pipelay ramp / spooling-on tensioner in order to pack the product on the reel flange to flange. At strategic locations (e.g. close to the reel flange or transition joints), wooden blocks are placed between spooled pipes as required; see Fig. 14. The pipeline is continuously monitored during the spooling-on operation and any damage to the coating / insulation system is either repaired or recorded for repair during pipelay operations.

When the spooling-on operation is finished, the initiation head (the first head that goes into the water) is either left in the ramp and connected to the first end structure (PLET or PLR) or secured onto the reel flange using the spooling head (see Fig. 15).

**TRANSITION JOINTS**

There are occasions where different pipe sizes with a sizable change in diameter (and wall thickness) are continuously spooled onto the reel using a specially made piece called “transition joint”. Transition joints are (conically shaped) pieces with dissimilar diameter at either end to match adjoining pipes. The wall thickness of the transition joint is either equal or very close to the pipe joints welded onto. Transition joints are varied depending on pipe diameter, wall thickness, function, length, shape and method of fabrication.

For permanent transition joints which are installed subsea, the variation in pipe sizes are small and are mainly fabricated by counterbored joints or a forged piece. For the temporary transition pieces, however, two conical halves are made by cold rolling and forming of structural steel plates. The two halves are then longitudinally welded together. It is to be ensured that the longitudinal welds as well as girth welds to pipes are fit-for-service as it is going through the reeling cycle.

Transition joints are designed using a combination of past experience and detailed FEA (see Figs. 16 and 17). Apart from controlling the peak strain in the transition joint, one other limiting factor in design is the lift off from the reel. By its nature, there will be a lift off in the smaller end of the transition joint. However, the acceptable limit of lift off is normally set as a percentage of the larger pipe diameter which has to be controlled. Ensuring that the spooling-on tension is maintained has been shown to be a key in avoiding local buckling.
In addition, as most transition joints are fabricated by cold forming of structural steel plates, it is important to check its properties, tolerances, strain hardening and weld quality. During design, the acceptable tolerances and material properties of the fabricated transition joint is identified. Therefore, the as-built measurements of the fabricated joint should be carried out to ensure it is within the acceptable design limit. Past experience has shown that the transition joint’s failure has mainly occurred as a result of poor fabrication in terms of inadequate wall thickness and poor quality of longitudinal welds.

Fig. 17 shows a typical transition joint reeled onto the vessel. Although increasing the transition joint length generally reduces the strain concentration (peak strain) in the transition joint, pipelay equipment constraints and geometry will limit the length of transition joint.

**STRAIGHTENING PROCESS AND REQUIRED BACK TENSION**

After the pipeline is spooled onto the reel and a straightening trial is performed, the vessel sails away to the offshore location to start the pipelaying. On arrival, an initiation operation is performed in which an anchorage point is established on the seabed. In order to commence pipelaying, the pipe needs to be transferred from the reel to the aligner. This is a precise operation in which high tension is required to bring the pipe onto the aligner wheel, the so-called “aligning operation”; see Fig. 18. If the distance between reel and aligner is not enough, pipe may subject to a high curvature and cannot be brought to aligner and even buckle. This is due to the nature of reeling process explained earlier (see Fig. 1) in which the pipe is reverse bent in the span between the reel and aligner.

![Fig. 16 – Axial strain distribution of a typical long transition joint (courtesy of Technip).](image1)

**Fig. 16 –** Axial strain distribution of a typical long transition joint (courtesy of Technip).

![Fig. 17 – Transition joint spooled onto the reel (courtesy of Technip).](image2)

**Fig. 17 –** Transition joint spooled onto the reel (courtesy of Technip).

Once the pipe has been brought to the aligner, it passes through the straightener. The straightening principle is based on three point bending in which the pipe is plastically bent in the reverse direction of the aligner curvature. Pipes are then passed through tensioners and ready to leave the vessel into the water.

There are two important factors that affect the spooling-off and straightening process. The first is the required back tension (which is defined as the tension between the reel and aligner) is to be controlled and maintained throughout the laying process. This is a necessity to ensure that the pipe does not buckle in the reel to aligner span. This is achieved by combination of manual / automatic control of the reel surge and the aligner positioning. In vessels with aligner wheel (e.g. Deep Blue, Seven Ocean), the aligner positioning is maintained using specially designed balancing cylinders where the hydraulic cylinders will keep the aligner in the predetermined position and adjust itself with pipelaying rate and vessel movement. A variation in the pressure (and hence positioning) of the aligner wheel is allowed and considered in the design and pipelaying. The back tension is almost transferred over the aligner to top of the straightener on its entirety ignoring the losses due to friction and bending of pipe.

The second important factor is the straightener setting and vessel straightening capacity. The straightener curvature is set by a combination of FEA results, past project experience and
straightening trials. There are two hydraulically controlled tracks where the top track applies the reverse curvature and the bottom track supports and guides the pipe.

The straightener capacity governs whether the pipe can be straightened after plasticization. This sometimes dictates whether a vessel can install a particular pipeline or not. The straightener capacity is calculated by the plastic moment formula defined in Eq. (6) for both steel pipe and insulation / coating system, if present.

There is a notion within some segments of the industry that as pipe has been plasticized and strain hardened, the mean yield strength in Eq. (6) should be replaced by the corresponding strain hardened yield strength of the material. However, it is to be noted that the plastic moment formula assumes that the entire pipe cross section has reached the yield point, which does not happen in reality as there would be a plastic neutral axis, as explained in [15]. Kirkemo [14] showed that the equivalent plastic moment of a 2.0% strain hardened pipe (considering Ramberg-Osgood relationship) can be expressed as:

\[ M_H = M_p \left( 0.70 + \frac{0.30}{\alpha_h} \right) \]  

For the typical hardening factor \( \alpha_h \) range of 0.85 to 0.90 for reeled pipes, the plastic moment increase is between 3-5%. Therefore, using Eq. (6) to calculate the straightening capacity is judged to be justified provided a safety margin of e.g. 10% to that of vessel straightening capacity is considered in design. Otherwise upgrading the straightener tracks and capacity should be envisaged.

Following passing through the straightener, the pipe enters the vessel tensioner. The primary functions of tensioner are to hold the pipe catenary weight, impose tension throughout the suspended section of the pipe and applying the tension downstream of the aligner, ensuring that pipe is always under tension. Tensioners consist of a number of caterpillar tracks mounted in a frame. The tracks are activated by paying in / out and squeezing the pipe using hydraulic cylinders to generate enough friction to hold it. The tensioner frames are designed so that it can be opened by rotating one or more tracks, enabling the pipe out of the tensioner or allowing special pieces (e.g. transition joints, spooling head) to pass.

Tensioner tracks can be vulnerable to the sudden step change in the pipe size, e.g. FJC up-stand, integral buckle arrestors and transition joints. Care must be taken, especially in the case of heavy pipes and ultra deepwater operations, as the full grip of the tracks (track pads) may not be achieved and pipe may slip over the tracks. PU based rubber pads are generally used and preferred over the metal pads.

**SPECIAL CONSIDERATION FOR PIP SYSTEMS**

Reeled PIP systems have become more and more common in different parts of the world. More than 30 reeled PIP systems have been installed worldwide by Technip and three by Helix (as of 2012). The primary objective of using PIP systems is the flow assurance requirements (preventing wax and hydrate formation) and low OHTC value. However, PIP systems are increasingly considered as an additional protective layer against loss of containment or to withstand the impact force due to third party or trawl / fishing gear interaction.

Design of reeled PIP systems brings new challenges during fabrication and installation, some of which are discussed here.

**Stalk fabrication.** During stalk fabrication, the inner pipe and outer pipe stalks are fabricated separately. As described in [16], inner pipe stalks are transferred to the firing line in the spoolbase where insulation materials (in the form of short panels) are wrapped around the inner pipe and centralizers are bolted in place at predetermined intervals. The prefabricated inner pipe stalk is then inserted into the prefabricated outer pipe stalk using the pushing machine to make a PIP stalk. Individual PIP stalks that are stored in the spoolbase are then spooled onto the reel, each connected by tie-in welds; see [16].

When PIP stalks are spooled-onto the reel, due to the different radius of curvatures adopted by the inner and outer pipes, the inner pipe is protruding from the outer pipe and this is to be considered during stalk tie-in weld operation. If excessive protruding takes place and the pushing machine cannot close the extra gap between the outer pipes of PIP stalks, a section of inner pipe is cut.

**Waterstop joint fabrication.** Waterstops are fitted in the annulus between the inner and outer pipe at approximately one stalk intervals in order to minimize the damage to the insulation system in case a wet buckle happens. The use of mechanically clamped waterstop systems are now common after its first time success in Petrobras Canapu project (see [16]) and design for annular gap of as low as 20 mm has been achieved in more recent projects. However, due to significant additional stiffness of the waterstop joint, it is to be ensured that the high spooling-tension is maintained and extra centralizers are fitted in the vicinity of the waterstop as shown in Fig. 19. The distance between waterstop edge and centralizer depends on the outer...
pipe diameter, annular gap, reeling curvature and thickness of the waterstop.

**Inner pipe tension.** During installation, the vessel pipelaying equipment is in contact with the outer pipe and due to the nature of PIP fabrication, the inner pipe can move relatively freely inside the outer pipe with constraint applied only by end bulkheads positioned at each end of the pipeline. Fig. 20 shows a typical tension distribution during the reeling process. It can be seen that when installation commences (reeling-off the vessel), the inner and outer pipes share the axial tension, i.e. both under tension, in the span between the reel and the aligner. However, after passing over the aligner and straightener, the outer pipe tension approaches zero at a location above the tensioners, whilst the inner pipe remains under considerable tension. In other words, the applied tension by pipelaying equipment is shared between the two whilst the sum of tension is what has been applied by the vessel. If, at any stage from the lifting off the reel up to passing over the aligner and straightener, outer pipe goes into compression, there is high chance of local buckling. Understanding of this phenomenon to set the vessel equipment (considering variations) in order to apply enough tension and predicting the loads on end bulkheads are vital. In the event the inner pipe is subjected to excessive tension (and hence the outer pipe is under very low tension or even compression), the use of intermediate bulkheads or load sharers is required.

Fig. 20 – Example of inner and outer pipes tension distribution during reeling [16].

**Spooling-on operation.** As mentioned before, preserving tension during every aspect of reeling and unreeling operation is important. During the spooling-on operation, the inner and outer pipes need to be connected to one another so that the tension can be transferred. Bulkheads (forged pieces providing transition from a PIP system to single pipe) are used. Fig. 21 shows a schematic of reelable bulkhead.

An alternative to reelable bulkhead is the use of a “sailors cap” (see Fig. 22 and [18]) which is used to secure the PIP to the extremity of the main reel flange. The benefit of the sailors cap is that the PIP end bulkheads can be stored and installed without being plasticized. A straight section of 4-6 m towards the PIP end can be achieved. This is a viable solution if the annulus of the PIP system is vacuumed to achieve lower OHTC and therefore the PIP stalks cannot be cut during the lay down operation.

Fig. 21 – Schematic of the reelable bulkhead.

Fig. 22 – Sailors cap arrangement (courtesy of Subsea7).

**Cut-to-length operation.** During lay down operation and abandonment / termination, the inner and outer pipes need to be individually welded to the end bulkhead which itself is welded to the second end structure. In order to perform welding, the inner pipe needs to be protruded and secured in place. This can be achieved using the “wedge system”. The wedge system consists of three (or four) specially designed steel rings (wedge blocks) which are fitted around the annular gap between the inner and outer pipes. The wedge blocks are made of two moving parts; upper part and lower part, which are moved upwards and downwards with respect to one another, using a set of screws. The inner surface of the wedge blocks (lower section) has finished with threads to allow a firm grip over the inner pipe. After outer pipe was cut, wedges are placed inside the annular space between the inner and outer pipes, the upper section is moved upwards to fully contain the annular space and...
comes into contact with the internal surface of the outer pipe. Then, it is firmly tightened in place and prevents the free movement of the inner pipe inside the outer pipe. This allows the inner pipe to be welded to the end bulkhead. The outer pipe is then pulled back to cover the length exposed and welded to the bulkhead. This method excludes the use of half shells which requires two additional girth welds and two additional longitudinal welds.

CONCLUSION

This paper discussed some of the most important practical aspects that need to be taken into consideration when reeled flowline systems are installed. It was shown that the reeled flowline systems can be installed efficiently and reliably by considering the following:

- Design for the reelable wall thickness is performed based on the specific supplementary requirements for line pipe procurement;
- High weld quality with minimized defect size and yield strength overmatching of the weld material is achieved;
- Minimizing the likelihood of local buckling is achieved by minimizing the mismatch between the two consecutive joints, maintaining the spooling-on / back tension during spooling-on / spooling-off operations and, applying a suitable insulation system with reeling compatible FJC and low up-stand;
- Ensure that the strain localization takes place away from the weld and that its value is limited to a percentage of the pipe ultimate tensile strain limit;
- When spooling flowlines with different sizes, a suitable and adequately short transition joint is designed with well controlled geometrical tolerances and material properties with respect to the adjoining pipes;
- Consider the straightening capacity of the vessel from the beginning of the project and allow circa 10% margin based on the maximum straightening capacity;
- When installing PIP systems, ensure that the inner pipe tension is well estimated, use the intermediate bulkheads or load sharers if necessary and, qualify PIP specific items such as waterstops, inner pipe holding wedge system and reelable bulkheads.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Dnom</td>
<td>Nominal outside diameter</td>
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<tr>
<td>fspooling</td>
<td>Spooling-on factor</td>
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<td>MPlastic</td>
<td>Plastic moment accounting for hardening</td>
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<tr>
<td>MP</td>
<td>Plastic moment</td>
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<tr>
<td>RH</td>
<td>Reel hub radius</td>
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<td>tcoating</td>
<td>Thickness of coating / insulation</td>
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<td>tmin</td>
<td>Minimum reelable wall thickness</td>
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<td>(strain) hardening factor</td>
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<td>sy</td>
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<td>AUT</td>
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<td>IMPU</td>
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<td>Specified Minimum Tensile Strength</td>
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<td>SMYS</td>
<td>Specified Minimum Yield Strength</td>
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REFERENCES

Offshore Technology Conference (OTC 21487), Houston, Texas, USA.


