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## Deepwater Installation Techniques for Pipe-in-Pipe Systems Incorporating Plastic Strains

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### Abstract

This paper presents a numerical and analytical study of pipe-in-pipe installation in deepwater by the J-lay and Steep S-lay methods. In particular it examines the amount and location on plasticity that may be allowed to occur during the installation phase of construction. The influence of the residual strain to operational performance of the line is discussed. The information in the paper provides guidelines for the installation of pipe-in-pipe systems in deepwater as well as indications of the critical areas that require detailed investigation.

A general limit of 1% strain during installation has industry acceptance although few projects have put this to the test. The results presented in the paper show this to be acceptable under certain circumstances and perhaps not so conservative in others. It also highlights the importance of understanding the numerical modeling techniques as well as the influence of assumptions in the loading and materials modeling.

### Introduction

With the flow assurance demands placed on flowline and riser systems in deepwater developments pipe-in-pipe is a technology widely used today and planned in the future due to the exceptional levels of thermal insulation they provide. As production progresses deeper though, pipe-in-pipe systems face the problem of becoming too heavy to install in a conventional manner. They therefore require thorough understanding of their structural response during installation to permit extension of the acceptable loading regime. In addition to plasticity the non-uniform geometries of typical deepwater field joints increases the complexity of the issue.

Flowline installation in deepwater is an area of considerable research at present, not so much in the form of joint industry projects but more internally within the installation contractors. This R & D focus falls into two categories:

- (1) Incremental improvements to installation layrates and reliability with existing vessels and equipment
- (2) Investigate and develop new methods for installation.

These two areas are not mutually exclusive and in a way the ideal extension to installation practice is one that offers a significant step forward for a small change in equipment.

In recent years pipeline and riser design codes have developed significantly to the point where limit states for the pipe are used to ensure safe installation and operation. This increased understanding within the design codes permits the extension of the installation envelope for traditional methods whilst providing a vehicle to assess new methods within an approved and acknowledged framework. It does however have the drawback of only being directly applicable to a single pipe with simple geometry.

Although the codes now provide enhanced assessment of the various pipe loading scenarios there is an increased requirement to understand and account for the effects of tolerances on the design. Additionally more complex geometries such as pipe-in-pipe systems require investigation through other means, typically finite element analysis, to supplement code assessment.

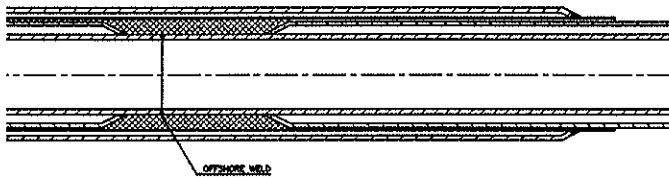
This paper examines in particular the assessment of the pipe-in-pipe field joint region during installation in both J-lay and S-lay including the Steep S-lay approach. The process makes use of the DnV 2000 pipelines design code<sup>(1)</sup> and ABAQUS non-linear finite element analysis.

### The Issue

The need for a more detailed and rigorous investigation of the pipe-in-pipe field joint area is driven by its geometry. Typically deepwater S-lay and J-lay utilize double or quad joints pre-fabricated onshore to speed up offshore construction. To further reduce offshore activities during installation there has been a push towards pipe-in-pipe

systems requiring the completion of only one offshore weld on the flowline, thereby eliminating the carrier (outer) pipe weld from the lay barge activities. Figure 1 shows a typical pipe-in-pipe arrangement based upon the system produced by ITP, achieving a single weld geometry at the field joint with the ends of the carrier pipe swaged down and fillet welded to the outer surface of the flowline. The simplified sequence of operations to complete a joint are as follows:

- (1) Load double or quad joint into firing line (near vertical for J-lay, near horizontal for S-lay)
- (2) Align weld faces of flowline and complete weld
- (3) X-ray weld
- (4) Slide external sleeve over field joint and secure in place. Depending on the field joint design insulation half shells may be attached between the swages of the carrier pipe (region A in Figure 1) prior to sliding of the external sleeve.
- (5) Wet insulation material injected into cavity between external sleeve and pipe-in-pipe welded area.



**Figure 1: Typical single weld pipe-in-pipe configuration**

The design of the external sleeve may be single or double walled (pipe-in-pipe) itself, the size and complexity dependent on the thermal performance requirements of the system, usually driven by the cooldown criterion to be met.

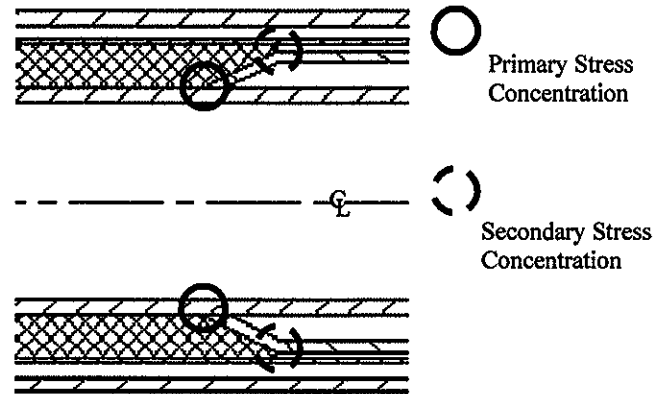
A critical path assessment of the installation operations is dependent on the number of weld stations available on the vessel. Typically only one station exists for J-lay with as many as 5 or 6 being available on S-lay vessels. This therefore leads to different critical path activities and activity durations for these two installation methods.

For J-lay the tension is the dominant loading as the weight of the pipe string suspended during laying is reacted almost entirely by the tensioners (dependent on tower angle of incline to the vertical). In S-lay, however, the suspended pipe is supported by a combination of vertical force from the stinger and horizontal force applied by the tensioners. The pipe is welded together in the near horizontal which results in significantly greater bending of the pipe in the overbend (stinger) and sagbend (near seabed) regions during installation.

High tension in J-lay, usually applied by the tensioners acting on the carrier pipe, and high bending in S-lay both result in stress concentrations in the field joint region for the geometry shown in Figure 1. The stress concentrations are different as the load applied to the field joint geometry causes differing

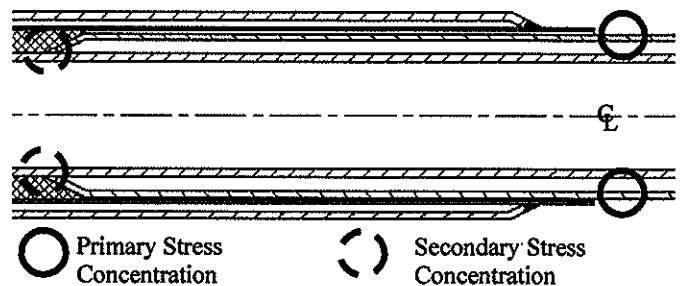
response. These are illustrated in Figures 2a and 2b for the J-lay and S-lay loading scenarios respectively.

As can be seen in Figure 2a the stress concentration occurs in the flowline at the toe of the fillet weld due to the rotation caused through application of tension to the carrier which is transferred to the flowline at the field joint via the swaged section.



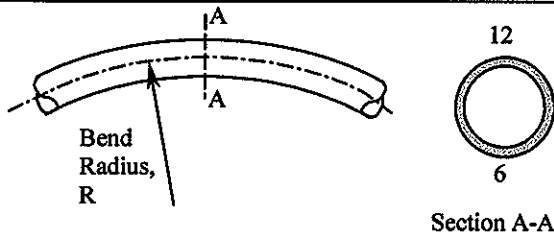
**Figure 2a: Stress concentrations during J-lay**

In Figure 2b the stress concentrations are seen to occur in the carrier pipe at locations where the external sleeve for the field joint ends. This is due to the significant discontinuity in bending stiffness between the main body of the system and the field joint with external sleeve. A secondary concentration can also be found at the toe of the fillet weld connecting the carrier and flowline but this is significantly less than those at the end of the external sleeve.



**Figure 2b: Stress concentrations during S-lay**

During the system design these stress concentrations must be evaluated and shown to be acceptable, preferably within the design code framework. For the high tension case (J-lay) this takes the form of weld assessment (fracture mechanics). For the case of bending strain concentrations occur in localized areas in the innermost and outermost regions of the pipe cross-section (described as the 12 and 6 o'clock positions, see Figure 3), the largest magnitudes and circumferential extent of which are dependent on cross-sectional bending stiffness, local geometry and the elasto-plastic material properties of the steel.



**Figure 3: Schematic showing regions of greatest magnitude stress in bending**

In bending several other important factors affect the severity of strain concentration, many of which are assessed for reeling installation. These factors are associated with tolerances of one variety or another, the main ones being:

- Pipe ovality
- Wall thickness variation
- Yield stress variation
- Weld misalignment

All of the above apply to the girth weld region whereas it is only ovality that realistically applies to a region of pipe within any given joint length. For the case of bending during installation of the pipe-in-pipe configuration shown in Figure 1 the weld-associated tolerances have little importance, although conventional single flowline or alternative pipe-in-pipe geometries the other factors must be considered to determine if they are influential.

The result of these tolerances on the system behaviour requires assessment of the following:

- Low cycle fatigue (weld fracture)
- Local pipe buckling

**Steep S-lay**

The Steep S-lay is an extension of conventional S-lay to permit pipe installation in deeper water through modification of the stinger and increased structural utilization of the pipe rather than the more expensive and complicated upgrading of the installation vessel's tension capacity.

Typically for an 8" flowline (wall thickness 16 mm) with a 12" carrier pipe (wall thickness 12 mm) the minimum bend radius during installation is circa 60m in the overbend region. This results in stress levels approaching yield in the carrier pipe without any consideration of ovality or strain concentrations due to the field joint geometry.

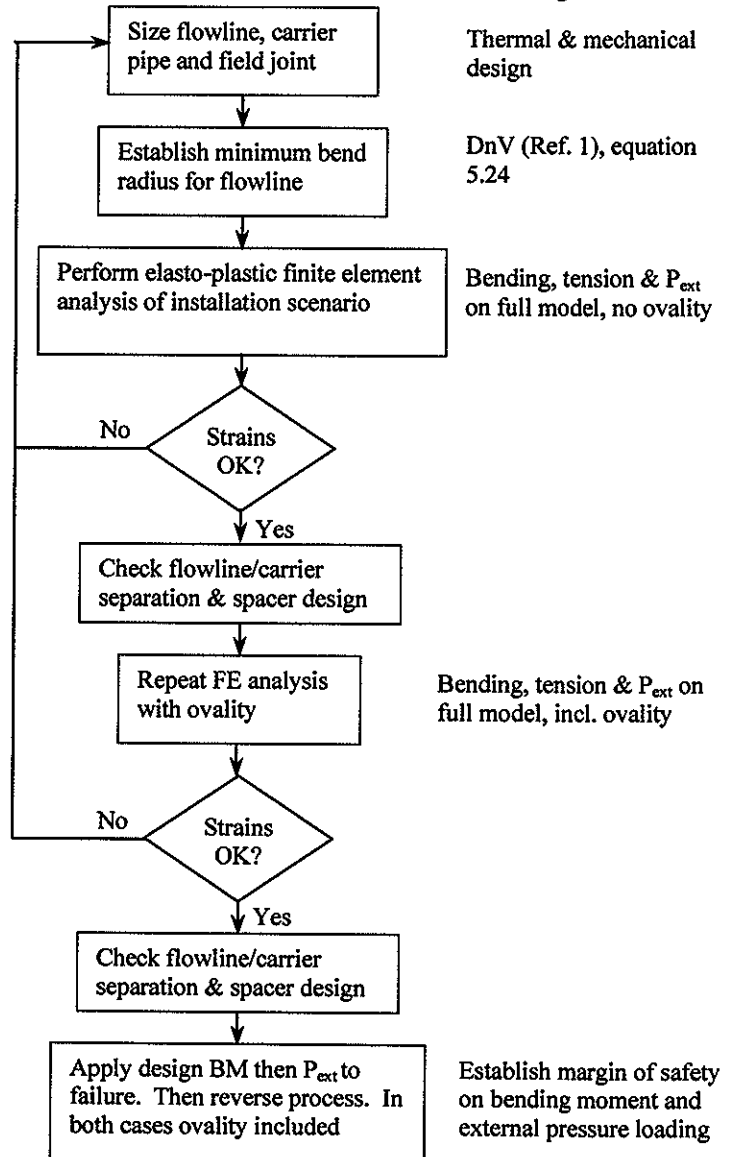
The flowline stress level is carefully controlled to satisfy DnV<sup>(1)</sup> code requirements thereby determining the minimum bend radius during installation. Table 1 shows the dimensions and stress levels in each component based on a simple linear bending stress calculation.

Component	Diameter (mm)	Wall Thickness (mm)	Stress @ 60m radius (MPa)	Yield Stress (MPa)
Flowline	219.1	16.0	378	448
Carrier	318.0	12.0	549	482
Inner former	341.7	6.0	589	448
Outer former	401.0	15.0	692	448

**Table 1: Component stresses at 60m bend radius**

**Design Process for Inclusion of Plastic Strains**

Figure 4 presents the flow chart for the design process to assess the system under extended installation loading.



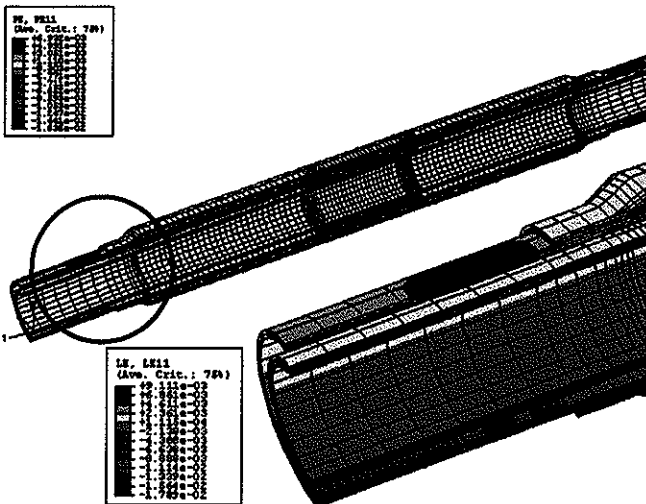
**Figure 4: Flowchart of design process**

The above process is structured such that the levels of strain seen during installation are firstly evaluated and then the complete assembly is assessed for stability under the bending and external pressure loads. The configuration is also checked for ovality as this is the most important of the tolerances in this scenario. Provided none of the system components buckle, particularly the carrier pipe, then the level of plastic strain is acceptable for installation purposes.

These analyses are all performed statically and the loading is assumed to be the worst case to be seen during installation. Should this condition be expected to be encountered more than once then the design must be assessed for low cycle fatigue. This is outside the scope of this paper.

**Case Study**

To illustrate the results obtained from finite element analysis of a single weld pipe-in-pipe field joint during Steep S-lay an 8" flowline (wall thickness 16 mm) with a 12" carrier pipe (wall thickness 12 mm) system is examined.



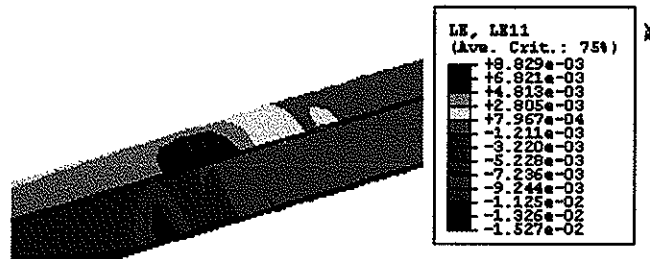
**Figure 5: Axial strain concentration at 60m bend radius**

The finite element modeling is performed with 3D brick elements and full representation of the elasto-plastic material properties of all metallic components. Figure 5 shows the axial strain concentrations at the end of the external sleeve. The greatest magnitude strain is -1.7% and is seen to be extremely localized, the regions of plastic strain extending a distance of approximately 0.16m axially. Circumferentially the plastic strain region extends to an angle of roughly 35°.

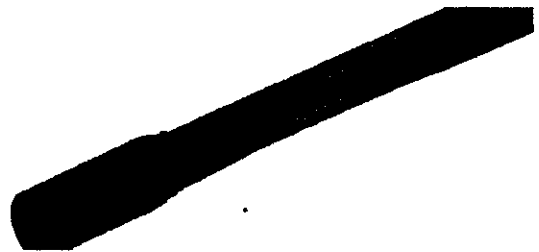
The application of tension offsets some of the negative strain concentration, approximately 0.25%. Figure 6 shows the strain concentration when bending and tension are applied.

Figure 7 shows the collapsed carrier pipe for the analysis where the design bending moment seen during installation is

firstly applied and then the external pressure is increased until the carrier pipe collapses. This establishes the margin of safety above the design external pressure.



**Figure 6: Strain concentrations under 60m bending and 200 Te tension**



**Figure 7: Collapse shape of carrier – design bending moment, external pressure increased until collapse**

Figure 8 is a plot of the buckled carrier pipe when the design external pressure is applied as the first load and then the bending moment is increased until the pipe buckles.



**Figure 8: Collapse shape of carrier – design external pressure, bending moment increased until collapse**

An interesting point to note is the fact that collapse of the pipe due to over-pressure occurs at a greater distance from the end of the external sleeve than buckling due to excessive bending moment application. This is due to the strain concentrations providing a hinge point for the bending-driven collapse whereas this region is effectively stiffer due to the presence of the external collar thereby resulting in external pressure collapse some distance into the main body of the pipe-in-pipe joint.

Figure 9 is a plot of the separation between flowline and carrier for two cases analysed, namely with and without insulation included. Additionally the effects of ovality on the annular gap closure is plotted.

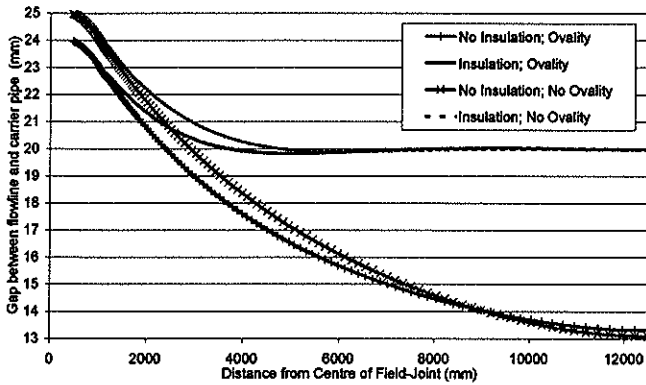


Figure 9: Plot of annular gap closure showing the effects of including the insulation material and ovality.

As one would expect, if no insulation is included then the annular gap reduces over a significant length of the joint due to the differing bend radii adopted by the flowline and carrier pipes respectively (note: no spacers are included in the double joint and centralization is therefore only provided by the swages at each end of the joint). The inclusion of the insulation material limits this and it can be seen that for over half the double joint length the insulation is in contact with the inner surface of the carrier pipe. Inclusion of ovality acts to increase this contact length slightly.

In regions where the insulation comes into contact with the carrier pipe it is necessary to evaluate the insulation under the radial compressive force to ensure this does not affect its thermo-physical material properties once installed.

**Comments on Design Codes**

The most relevant design code for pipelines subjected to plastic deformation during installation is DnV 2000<sup>(1)</sup>. DnV 2000 uses a limit state design to reduce the conservatism and associated cost in the design of pipelines. The standard is applicable for installation by S-lay, J-lay and laying methods introducing plastic deformations. The standard, other than the requirement to take into account of pre-stressing effects such as permanent curvature or elongation introduced during installation<sup>(1)</sup>, does not address in detail issues related to pipelines laid with residual strain or residual curvature. However, this design code proposes supplementary requirements which can be used to increase the confidence in the design of such pipelines. The following are the relevant supplementary requirements:

- Supplementary requirement P<sup>(3)&(4)</sup> relates to line pipe exposed to plastic deformation exceeding 2%. Such level of plastic deformations can arise in installation

intervention. For this requirement certain tolerances on the mechanical properties of line pipe<sup>(5)</sup> and certain mechanical tests<sup>(6)</sup> are specified.

- Supplementary requirement D<sup>(7)</sup> relates to enhanced dimensional tolerances
- Supplementary requirement U<sup>(8)</sup> relates to high utilisation

DnV 2000 and for material with SMYS>450MPa subjected to significant plastic straining during fabrication, installation and operation recommends that special considerations be given to environmentally assisted cracking including SCC and hydrogen induced cracking related to cathodic protection<sup>(9)</sup>.

DnV 2000 and in the presence of plastic strains requires that:

- Strain concentration factors are accounted for if plastic strain is experienced<sup>(10)</sup>.
- Large accumulated plastic strain are considered as these may aggravate local buckling<sup>(11)</sup>
- Effects of strain ageing are considered due to the accumulation of plastic strain<sup>(12)</sup>.
- An ECA is to be performed on installation girth welds for accumulated plastic strain exceeding 0.3%<sup>(13)</sup>
- The characteristic strain resistance is determined by testing such as full scale bending for accumulated plastic strain exceeding 2%<sup>(14) & (15)</sup>
- The pipe straightness, resulting from permanent deformation during construction, is determined together with due considerations of effects of instability, positioning of components and operation<sup>(16)</sup>.
- For accumulated plastic strains exceeding 2% the specific problems associated with these installation methods are addressed in the installation and testing specification<sup>(17)</sup>
- For accumulated plastic strains exceeding 2% the sequence of pipes including the pipe string is controlled such that variation in stiffness on both sides of weld are maintained within the assumptions made in the design<sup>(18)</sup>
- Girth welds exposed to accumulated plastic strain are qualified to demonstrate that the weld and the adjacent base material have as uniform mechanical properties as possible<sup>(19)</sup>.

(1) Section 4 B108  
 (2) Section 5 B502  
 (3) Section 6 D300  
 (4) This requirement is supposed to be difficult to meet for material grades with SMYS exceeding 415 MPa  
 (5) The finished line pipe is recommended to meet the following requirement:  
 -The measured yield strength of base metal should not exceed SMYS by 100MPa  
 -The YS/TS ratio should not exceed 0.85  
 -The elongation should be minimum 25%  
 (6) Uniaxial tension and compression followed by a measurement of certain parameters  
 (7) Section 6 D400  
 (8) Section 6 D500  
 (9) Section 5 B507  
 (10) Section 5 C402  
 (11) Section 5 D502. Section 5D deals with issues related to accumulated

- plastic strain.*
- (12) Section 5 D1002
  - (13) Section 5 D1005
  - (14) Section 5 D1006
  - (15) Section 9E deals with additional requirements for pipeline installation methods introducing plastic deformations
  - (16) Section 5 H200
  - (17) Section 9 E102
  - (18) Section 9 E104
  - (19) Appendix C E600

Issues related to pipelines subjected to plastic deformation has also been addressed in the DEEPIPE JIP<sup>(2)</sup>. The JIP was focused on the installation of pipelines in water depths from 500 to 1500m, pipes up to 20" and total strains between 0.5% and 1%. The conclusions of this JIP was that if the pipe is evenly supported on the lay barge/stinger, strains up to 1% (including all relevant strain concentration effects) may be accepted under conditions of displacement controlled loading. The following is the generally acceptable criteria for the condition of displacement controlled loading to be fulfilled:

- The pipe section shall be evenly supported over the entire section exceeding allowable elastic stress/strain limits including at least one roller/support beyond this area on each side
- The pipe shall not touch the last stinger roller/support or if the pipe touches the last stinger roller/support, the roller reaction force shall be controlled by a load cell or equivalent and compared to load controlled criteria

## Conclusions

Considerable cost savings could be realized by using less stringent strain limits for the installation of pipelines. This can be realized in combination with a higher level of engineering and analysis than that conventionally used to consider in greater detail

- Strain concentrations
- Dynamic effects for fatigue calculations including:
  - Direct wave and current load induced deformations
  - Installation vessel induced deformation
  - Vortex shedding induced vibrations
- The effect of residual bending moment/strain on all further design checks
- The effect of permanent plastic strain on:
  - Local buckling
  - Global buckling
  - Free span design, static and dynamic
  - Fatigue and fracture

Moving to strain-based design does require a greater amount of sophisticated analysis. The associated engineering cost however is more than compensated for the reduction in installation cost as well as the increased certainty in the design.

## References

- (1) DnV 2000 Submarine Pipeline Systems OS-F101, January 2000
- (2) Submarine Pipelines DEEPIPE JIP, STF22 F99675, SINTEFF, June 2000