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Seismic Design of Subsea Spool per ISO: Part III- Analysis & Design

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ABSTRACT

This is the final part of a three-part paper that presents the methodology, data needed, code check of 12-inch ID rigid pools, describing the design methodology, and key design parameters for performing the analyses. Discussion of the state of art regarding the soil data is covered in Part I. Part II is dedicated to describing ISO 19901 and 19902 seismic qualification and the derivation of design time histories.

For each cluster end, there are two parallel flowlines each individually terminated with a Flowline Termination Assembly (FTA). The FTA is free to move axially on its foundation to absorb movement caused by the flowline expansion and walking. Lateral movement is restricted by lateral stops on the foundation. Two separate spools will then be connected to a single Pigging Loop Module with a piled foundation. A diver-less horizontal collet connector system will be used for the tie-in at both ends of the spool.

The analysis methodology which assumes the seabed is a compliant plate, is described in this paper. For validation purposes, a couple of configurations were used to create a full three-dimensional model where the soil was modeled using the solid element with Moh-Columb behavior. These results are not presented in this paper.

1. Introduction

This is the Part III of a three-part paper [12 and 13] which describes the spool design, FE analyses, and the resulting geometrical configuration and also covers the following areas:

- Detailed design by analyses demonstrating spools are fit for purpose
- Checks of spool-ends reaction loads at connection-points to PMA and FTA under operational and seismic events

The following issues are not addressed here

- Assessment of the susceptibility of spools to VIV and FIV
- Fatigue due to flowline cyclic thermal expansion and contraction
- The design of the connector system, PMA, and foundation.

A typical layout of the manifold and well clusters including the PMA to FTA & PMA to PMA spools is shown in Figure 1.

The design methodology to be employed in the spool design is present in this part.

There are several design constraints imposed by the current architecture and installation equipment which limit the spool size.

Chang et al [5] and Peng et al [11] described in some detail the effect of ISO code on the seismic design; see also [9] and [10].

2. Key design parameters

Key design parameters are given in this section. It is to be noted that all of these parameters were used in the design of spools. There were many hundreds of analysis, but only a handful of results are given in this paper.

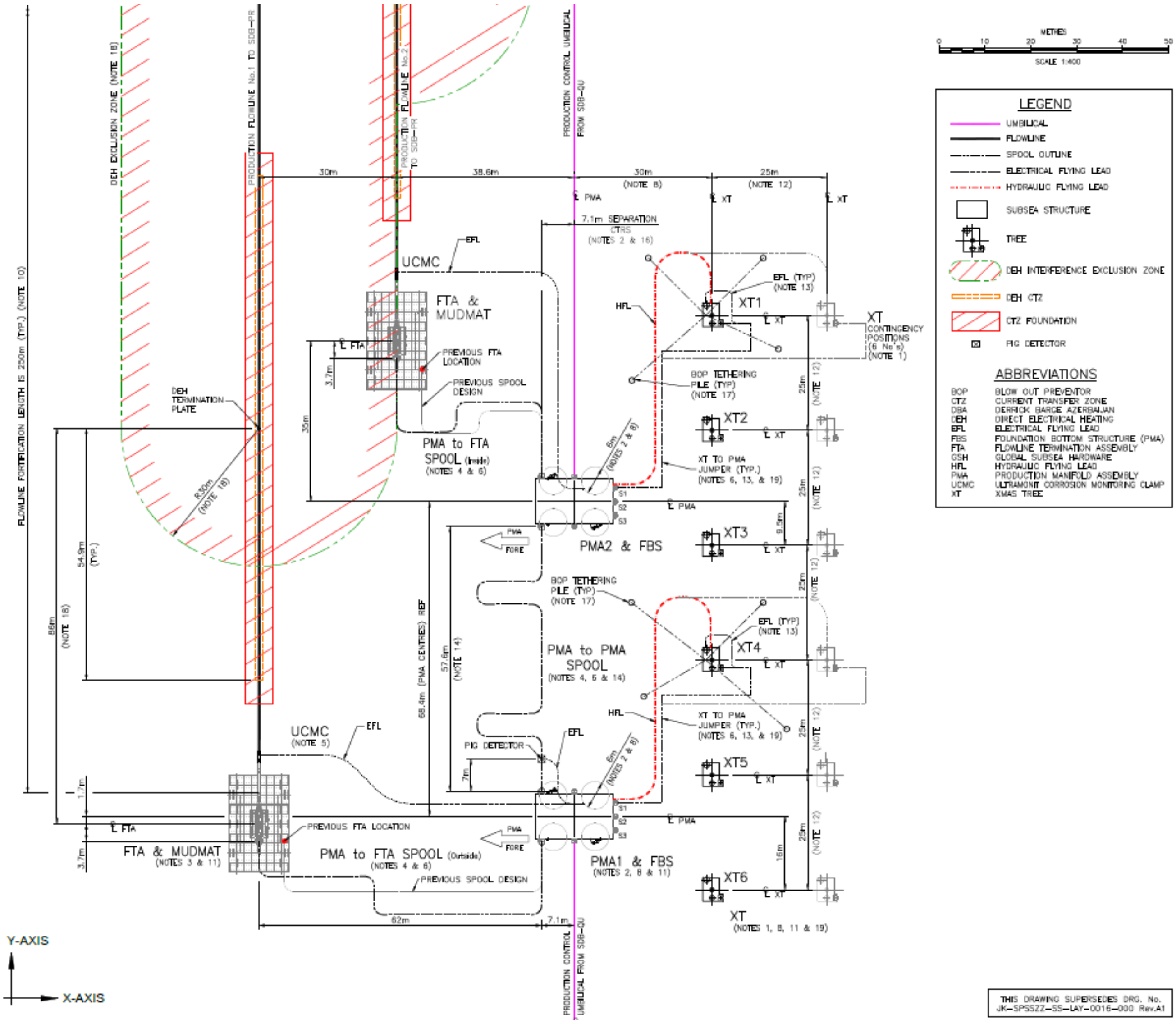

Figure 1: Cluster Layout – Plan View

Design Code-Spools were designed using "Design by Analysis Method" following ASME VIII 2011a, Div. 2 Part 5 [3].

Table 1: Material Data

Parameter	**Value**
Pipe	SMLS
Grade	X65
Steel Density	7850 kg/m^3
Young's Modulus @ 20°C	207 GPa
Poisson ratio	0.3
SMYS @ 20°C	450 MPa
SMTS @ 20°C	535 MPa
Thermal Expansion Coefficient	11.7 x 10^{-6}
Thermal Conductivity	45 W/m.K
Ovality	1% OD (Max. 4mm)
Wall Thickness Tolerance	+/-12.3%

Table 2: Wall Thickness Data

Parameter	**PMA to FTA Spool and FTA Piping**
Nominal Diameter	304.8mm ID 391.3mm OD
Nominal Wall Thickness	38.75mm +/-12.3%
CRA Total Overlay	4.5mm
CRA overlay wastage allowance	3mm

Material Data -The pipe material data for the spools and the flowlines are presented in Table 1

Spool Wall Thickness- The spool wall thickness determination has employed a 'no burst' criteria at SIWHP (785 barg). The nominal design wall thickness is 36mm however due to manufacturing limitations a suitably sized pipe has been selected (Table 2). An internal Corrosion Resistant Alloy overlay of Alloy 625 (UNS N06625) is attached to the carbon steel pipe. The CRA strength has not been accounted for in the wall thickness determination. The thickness selected is based on a predicted accumulated erosion loss of 3mm over the entire field life. The spools shall be of constant ID to allow the passage of intelligence pigs.

Design Pressure and Temperature- Pressure and temperature data for the FTA spools are presented in Table 3.

Table Error! No text of specified style in document.**: Pressure and Temperature Data.**

Parameter	Value
Design Pressure	325barg
Burst Pressure Rating	785barg (SIWHP)
Max Design Temp	90 °C
Min Design Temp	-29 °C

Table4: Process Conditions

Analyzed Loading Condition	Pressure (barg)	Temperature (°C)	Density (kg/m^3)
Installation (Flooded)	0	ambient	1010
Leak test	358	ambient	1010
Design	325	90 (1)	50-200 (1120 (2))
SIWHP	785	90	200
Seismic	325	90	200
Shutdown/restart (3)	0 to 325	-29°C to 90°C	50-1120

Notes: 1) Maximum expected FTA inlet temperature during normal operation is 62°C, 2) Maximum operation density used in the analysis is taken as MEG density, 3) Operating values can be considered instead of these values.

Loading and Process Data- Table 4 shows the loading conditions to be analyzed and the respective pressure and temperatures that have been rationalized for each load condition considered in the design for the design conditions including start-up and shut down.

Product Densities- The assumed content densities of the flowlines in various conditions are given in Table 5

Temperature De-rating No de-rating of the steel is required for in the spool design as per ASME VIII, whereby de-rating of the steel does not occur until 121°C (250°F), [4]. However, the current analyses conservatively consider de-rating (SMYS de-rated from 450MPa to 435MPa @ 62°C).

Table 5. Content Densities

Condition	Density (kg/m3)
Empty	0
Flooded / Hydro-test	1010
Production Flowlines Operation(1)	50 to 200
MEG90	1120

Notes: 1) Typical operational variation excluding liquid slugs potentially accumulated during shutdown/restart.

Wave and Current data - Omni-directional wave data with an associated current and design currents with associated waves have been presented for each location. This has been rationalized to a single set of Metocean data applicable for a generic spool design as shown in Table 6.

Table 6: Simplified Metocean Data to be applied to all Flowlines (Design Current and Associated Wave)

Parameter	1 Yr	10 Yr	100 Yr
Hmax (m) (Most Probable)	9.0	11.6	13.9
THmax (s) (Best Estimate)	7.9	9.0	9.7
Current at 1m above seabed (m/s)	0.49	0.68	0.88
Current at 3m above seabed (m/s)	0.58	0.80	1.03
Current at 5m above seabed (m/s)	0.59	0.83	1.07

Marine Growth- The marine growth will be 30mm with a density of 1325 kg/M^3 which is included in the weight calculations.

Table 7: Summary of Embedment, Axial, and Lateral Friction Factors

Parameter	For Manifolds		
	LB	BE	UB
Embedment **(%/D_{oc} 1)**	8%	26%	39%
Axial Friction Factor	0.20	0.39	0.97
Lateral Breakout Friction Factor	0.20	0.33	0.90
Lateral Residual Friction Factor	0.32	0.50	0.84

Note 1: Overall external diameter, D_{oc} is taken as 607.8 mm

Pipe-Soil Interaction Data - The non-linear spools-soil interaction responses using the recommendation of [14] methodology are presented as 'friction factors', μ (i.e. soil resistance divided by vertical pipe load). The evaluated spool embedment, axial, and lateral friction factors for the spools-piece are summarised in Table. These parameters are to be used in the PMA-FTA and

PMA-PMA spools-piece FE analysis design.

Seismic- Two levels of seismic activity (see Part II [12]) are used, namely:

- Extreme Level Earthquake (ELE);
- Abnormal Level Earthquake (ALE);

Time-domain direct integration analyses were used for seismic analyses. Each record has two horizontal and vertical acceleration components. Sets of seven 3-component time histories provided for ELE and ALE levels were used.

Initially, a set of 10 real strong-motion accelerograms was selected for the analysis. Table 8 lists the time-histories selected, and the specific components of each record used for the analysis. Out of these 10 records, seven histories were chosen to carry out seismic analyses. They are highlighted in blue in Table 8.

Manifold Interface Loads Limits- Connector loads limits on the inboard hub, inner support, and connector cradle at the PMA are provided by the manifold design for the different load cases.

Table 8: Earthquake Time Histories for Analysis

Event	Date	Country	Station	Mag.	Distance (km)	Comp	PGA (g)
Kern County	07/21/1952	USA	Taft Lincoln School Tunnel	7.4	43.5	Y	0.18
Loma Prieta	10/18/1989	USA	Saratoga-Aloha Ave	6.9	27.6	X	0.51
Northridge	01/17/1994	USA	Arleta-Nordhoff Ave. Fire Station	6.7	9.9	X	0.34
Tabas	09/16/1978	Iran	Tabas	7.4	52.0	Y	1.10
Ierissos	08/26/1983	Greece	Ierissos-Police Station	5.1	8.0	X	0.18
Kalamata	09/13/1986	Greece	Kalamata-OTE Building	5.9	11.0	Y	0.27
Imperial Valley	10/15/1979	USA	Cerro Prieto	6.5	26.7	X	0.17
Landers	06/28/1992	USA	Coolwater	7.3	23.0	Y	0.42
Landers	06/28/1992	USA	Desert Hot Spring	7.3	23.0	X	0.17
Izmit	08/17/1999	Turkey	Goynuk-Delvet Hastanesi	7.6	73.0	X	0.14

End Expansion- End expansions were determined in the flowline buckling and walking assessment. The recommended expansion/contraction at this stage is currently +2.2m/-1.0m respectively, to encompass a standard FTA and FTA to PMA spool design across the field.

Settlement- Due to the 'very soft' to 'soft' clays expected in the area with low shear strength, significant embedment may occur. Initial settlement of each structure will vary; a piled PMA structure will differ from a skirted mud-mat FTA foundation causing a greater spool misalignment. Differential settlement of the spool compared with the structures was considered in the spool design. Total long term FTA settlement is 135mm with short term settlement of 10mm, for the FTA, mud-mat, flowline. The maximum post-seismic settlement of FTA is estimated to be 260mm. For the PMA, a long term settlement of around 100mm has been used.

Tie-in Elevations- The PMA tie-in elevation from the seabed to hub centers has been taken as 2.5m with a tolerance of +1.7/-0.0m. The elevation of the center of the FTA inboard hub relative to the seabed is 1.5m, and therefore the minimum height from the seabed of 2.5m was used in the analyses conservatively.

3. Spool Design Methodology

3.1 General

The overall spool design methodology is as follows:

- Determine initial spool dimensions due to the field architecture constraints;
- Determine the shortest and longest spool dimension due to installation tolerances of the tie-in structures considering which legs of the spools will be variable and if any clashes would occur (Figure 2);
- Determine if spool size and weight is installable by available vessels/barges and satisfies crane lift capacities, crane reach, and spool transportation requirements;
- Review Operational safety including any dropped objects/fishing interaction and whether protection is required i.e. mattress protection;
- Review soil conditions to determine soil frictions and whether additional foundation/support is required; Consider end conditions, application of loads from/to interfacing parties;
- Determine boundary conditions (metrology/manufacturing tolerances including allowable tolerances for connector and connector stroking loads);
- Consider differential embedment of the structures and the spool piece. Initial and long term settlement should be considered;
- Perform static non-linear elastic FE analyses;
- Review connector loads and satisfies capacity

checks with interfacing party;

- Perform cyclic analysis, considering start-up and shut down;
- Perform seismic analysis;
- Determine the natural frequency for spool shape, for calculating allowable span lengths ascertaining if VIV may be an issue;
- Perform FIV and FLIP screening
- Perform fatigue assessment including ECA for the welds;
- Perform code stress checks following "Design by Analysis Method" ASME VIII 2011a, Div. 2 Part 5 [3].
- Use spool dimensions that provide the longest total length (including tolerances) to determine if suitable for Process conditions i.e. MEG volumes are feasible;
- Determine Anode requirements.

It is noted that spool wall thickness has been determined using a 'No burst' probability method [Ref. **Error! Reference source not found.**] that does not account for any additional benefit of the CRA strength. Weight and stiffness due to the thickness of the CRA are accounted for in the FE analyses; however, the CRA thickness is ignored in the stress calculations.

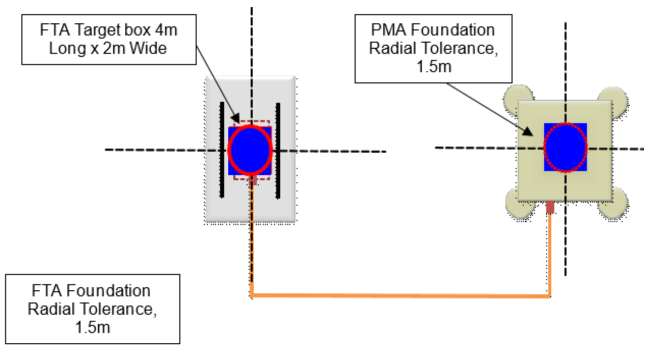

Figure 2 Installation tolerances at the PMA and FTA location

3.2 Design Constraints

There were several design constraints imposed by the combinations of operational and installation system requirements:

- Spool lengths are limited to the transportation barge envelope whereby the maximum envelope is 66m x 14m x 5.5m;
- Increasing spool lengths would impact MEG flush volumes and will have to be reassessed after determining final spool geometry;
- The current separation between FTA centers is approximately 30m laterally with an axial offset of approximately 10m. PMA center to the nearest FTA center separation is currently 30.0m laterally;
- Sizing and weight to remain within crane lift capacities;
- Loads at the PMA spool end has to be checked for limiting loads imposed by the PMA design.

Ensuring the design conforms to the constraints listed above resulted in a complex spool design, particularly for the inner spool. This is due to the minimum lengths required to clear the spool from the DEH influence zone and available space for spool routing whilst remaining within the installation barge envelope and avoiding clashes with the outer spool.

The spool design requires a long lever arm suitable for absorbing the large expansion loads which were challenging based on the current cluster configuration and barge limitations. A significant number of bends (complex geometry) was required to allow sufficient flexibility to avoid overstressing the spool or overloading connectors at the structure of the end (PMA/FTA) if they were to be designed according to ASME B31.8 [4]. An alternative to this (having complex geometry) was to allow for some yielding in the pipe wall following ASME Section VIII 2011a, Division 2 Part 5 [3] "Design by Analysis Method" which was adopted for our design.

Spool sizing has to be determined based on field layout with consideration given to the sizing as a result of installation tolerances.

3.3 Seismic Analyses Methodology

The time history direct integration method was used for seismic analyses. Each record has two horizontal and vertical acceleration components. Sets of seven 3-component time histories of the Manifold locations and for ELE and ALE levels were used to conduct seismic analyses [see part II]. These time histories were specifically produced for Cluster spools matching their fundamental natural period. The time histories have been scaled to the expected natural period of the cluster spools.

The design is in line with the ISO 19901-2 [8] requirements, where for the time history analysis method covering the ALE and ELE event all 7 events have been checked and the design should pass 4 of the 7, in line with the functional requirements associated with each.

Spool's FTA and PMA end were assumed to be connected to FTA and PMA via springs (Which represent FTA and PMA's connector stiffness in each direction) and after applying all static loads including pipeline walking to the FTA end, seismic acceleration records were applied to these two locations plus rigid surface's reference point where the seabed is modeled as rigid surface. Direct integration was conducted to calculate strain and stress at different times.

The main factor in seismic analyses of any structure is considering a suitable form of damping. Two sources of damping in any structure resting on soil are soil hysteretic damping and radiation damping, which are major sources of energy dissipation. These can be implemented by dashpots. Full details of all damping sources and their implementations in soil-structure interaction problems are explained in Appendix C.

In the design of spools, Equation 1(see Part I, [12]) was used to introduce dashpots into the model. In the axial, transverse, and vertical directions the dashpot constant is assumed to be

$$C_{rx} = C_{ry} = C_{rz} = D\rho V_s \qquad (1)$$

Here D is the spool diameter, ρ and v_s are Soil density and shear wave velocity [12]. The recommended values are half as much as recommended by some researchers [2], and less than 1/8 of allowed by ASCE4-98 (quoted Part I, [12]; see also Eurocode [7].

In this work damping related to the rotational degrees of freedom is neglected as per the Berger approach (see [6] and [12].

Using **Error! Reference source not found.** and assuming the following $\rho = 1340\,\frac{kg}{m^3}$ and $G_0 = 0.5$ MPa, and assuming the minimum possible ratio of $\frac{G}{G_0} = 0.1$, dashpot constant will be $C = 5000\ \frac{N}{m/s}\,/m$ and since element length is 0.250m, dashpot to be used is $C = 1250\ \frac{N}{m/s}$. This value was reduced again and value of $C = 750\ \frac{N}{m/s}$ was used in the Abaqus.

The added mass of the pipe, drag, and inertia forces are included in the analyses using Morrison Equations.

The seismic events are described in [13]

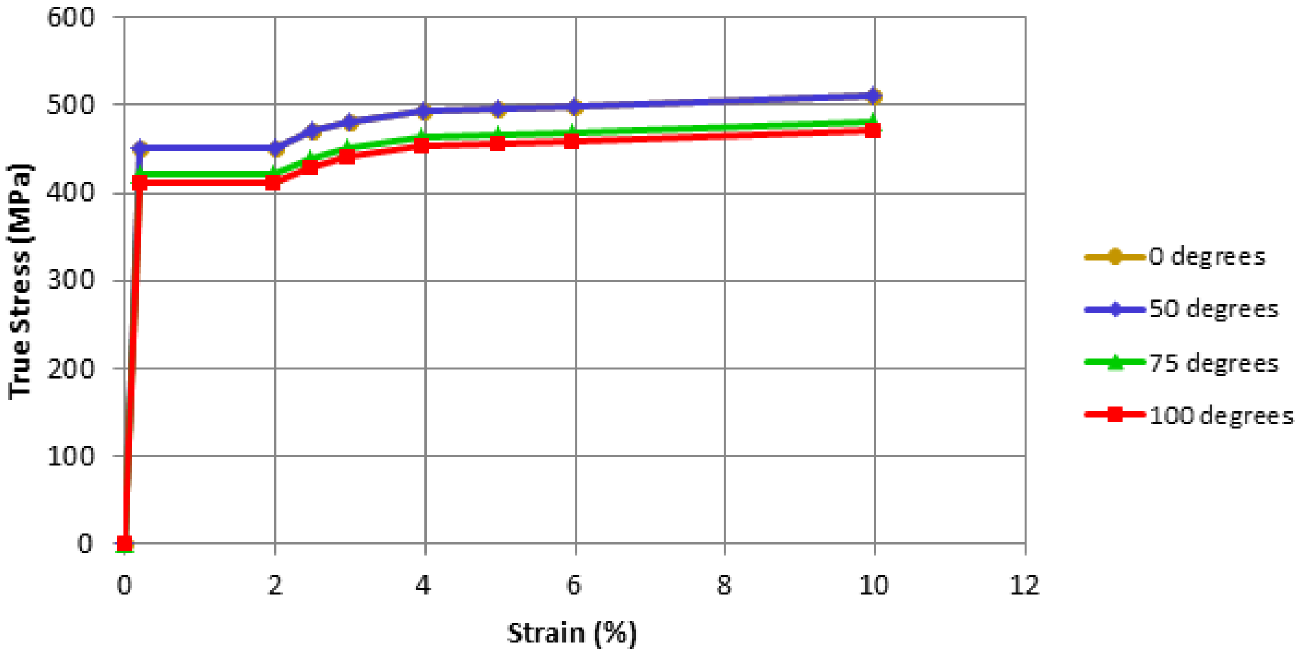

Figure 3: Engineering Stress-Strain Curve

3.4 ASME VIII acceptance criteria

ASME Section VIII 2011a, Division 2 Part 5 [3] "Design by Analysis Method" was used as the guiding code to demonstrate that the designed spools are fit for purpose. This is because as stated in Section 0 using ASME B31.8 [4] factors the spool design required a long lever arm suitable for absorbing the large expansion loads while the spool has to stay in the elastic region behaviour which was challenging based on the current cluster configuration and barge limitations. A significant number of bends (complex geometry) required to allow sufficient flexibility to avoid overstressing the spool. The alternative to this (having complex geometry) is to allow for some yielding in the pipe wall following ASME Section VIII 2011a, Division 2 Part 5 "Design by Analysis Method" [3].

Elastic-Plastic stress analyses following Section 5.2.4.of the code were performed. The assumed engineering stress-strain curves as shown in Figure 2, have been used. The stress-strain curves include the Lüder's plateau effect (typical for heat-treated pipes).

The design-by-analysis requirements are organized based on protection against the failure modes listed below. The component shall be evaluated for each applicable failure mode. If multiple assessment procedures are provided for a failure mode, only one of these procedures must be satisfied to qualify the design of a component. It is noted that the Limit-Load Analyses of 5.2.3 is not applicable as stated in 5.2.3.2

Limitation (b): "Components that experience a reduction in stiffness with deformation, e.g. a pipe elbow under in-plane bending, shall be evaluated using paragraph 5.2.4."; from [3]

(a) Protection against Plastic Collapse

(b) Protection against Local Failure

(c) Protection against Collapse from Buckling

(d) Protection against Failure from Cyclic Loading and temperature de-rating. The stress-strain curve at 62°C has been linearly interpolated and converted to the true stress-strain curve [1] to be used in the Abaqus modelling.

The material elastic perfectly plastic model is based on the minimum yield obtained from Fig 2 (and NOT the smallest of 1/3 SUT and 2/3SyT) hence:

450-14 (for de-rating case T for 62 degree Centigrade) = 436 MPa

The hysteresis loop stress-strain curve of material is schematically shown in Figure 4.

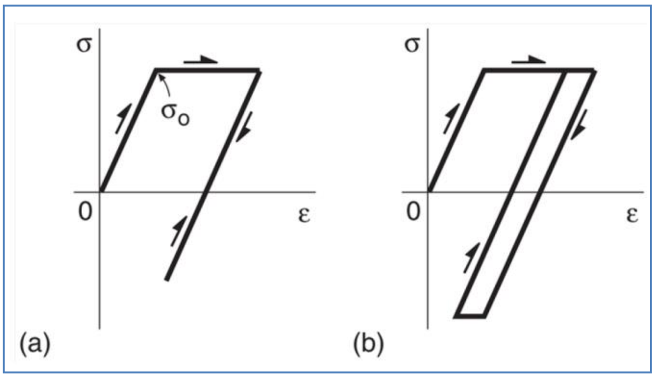

Figure 4: Cyclic Stress-Strain Hysteresis Model

The specific number of load cases due to combinations of the imposed end displacement (misalignment at the connectors due to fabrication and metrology tolerances) is 256 cases. These 256 were run with the identified soil characteristics a) Upper bound soil friction and b) Lower bound soil friction. It is also to be noted that due to installation tolerances (these are tolerances relating to the landing targets of the two ends structures that we can account for it by "cut to suit" during fabrication for each spool) there is a need to analyse two spool sizes, Short and Long spool for each "Inner FTA to PMA", "Outer FTA to PMA" and "PMA to PMA" spool. Therefore the required number of basic analysis runs for one spool is 256x2x2 = 1024 cases for each spool.

4. Abaqus Modeling

4.1 General

The spools were modelled in the general FE program Abaqus. The models were extended from the PMA to the FTA. PMA piping was not included in the model.

The pipe is modelled using a 2-node Elbow 31 element capable of predicting global spool behaviour, particularly in spool bends. Deformation nonlinearity as well as material nonlinearity was included in the analyses. A contact pair is established between the seabed, which is the master surface, and the spool elements which form the slave surface. The seabed reference node is fully fixed throughout the analysis. The seabed surface has the vertical stiffness in such a way to model pipe penetration and seabed friction is also used to provide axial and lateral restraint. The elastoplastic stress-strain relationship (Figure 3) is modelled with temperature de-rated SMYS and SMTS.

The spool analysis does not include any FTA and PMA piping, only the outboard hub of the connector was modelled by including a stiffer element than the spool pipe. The effects of FTA and PMA are modelled using 6 non-linear springs at each end to represent the effect of FTA and PMA stiffness.

Initial analysis will apply boundary conditions, operating loads, expansion, and walking conditions. These initial results will be used to determine a final geometry for developing more sophisticated models and applying seismic and cyclic load conditions.

The spool design will use a generic design for all cluster ends therefore, only three sets of spool geometry will be analyzed; namely inner and outer spools to connect the FTAs to the PMA and middle spool to connect PMA to PMA (see Figure 1).

Different combinations of boundary conditions from FTA and PMA end tolerances have been considered in the analyses. Having six degrees of freedom at each end will produce $(2^6)^2 = 4096$ load cases. To reduce the number of load cases and consider only the critical load cases, two assumptions are considered:

- Two series of analyses for each spool is carried out assuming lower bound friction between spool and seabed and upper bound values. In using lower bound friction values, two ends of the spool are raised vertically up by the total vertical tolerance value and in using upper bound friction values, two ends of the spool are pressed down by the total vertical tolerance. This is because assuming lower bound friction and pressing down two ends of spool does not produce critical results, and also, assuming upper bound friction and raising two ends of the spool is not critical as well.
- Within the connector itself the carrier pipe is free to rotate torsionally during the initial laydown of

the connector, only after tie-in is complete is the torsional movement restricted. So there is no need to consider this degree of freedom in the initial load cases.

Considering the above assumption the number of degrees of freedom to be applied in the analysis reduces from 6 to 4 at each end so the total number of critical load cases reduces to $(2^4)^2$=256 load cases for each of lower bound and upper bound friction factors.

The critical load case which gives higher von-Misses stress is used to perform seismic and cyclic analysis. The spools will be assessed for SIWHP to ensure no loss of containment occurs .i.e. strain-based design.

4.2 Soil Friction

Pipe-soil friction plays an important role in spool design. A typical plot of frictional resistance against displacement is shown in Figure 5 and Figure 6. In the FE analyses, a user subroutine is used to model both residual friction coefficients (axial and lateral) and breakout lateral resistance.

A typical axial pipe-soil interaction relationship used in the present study is defined in Figure 5.

A typical lateral pipe-soil interaction relationship used in the present study is defined in Figure 6.

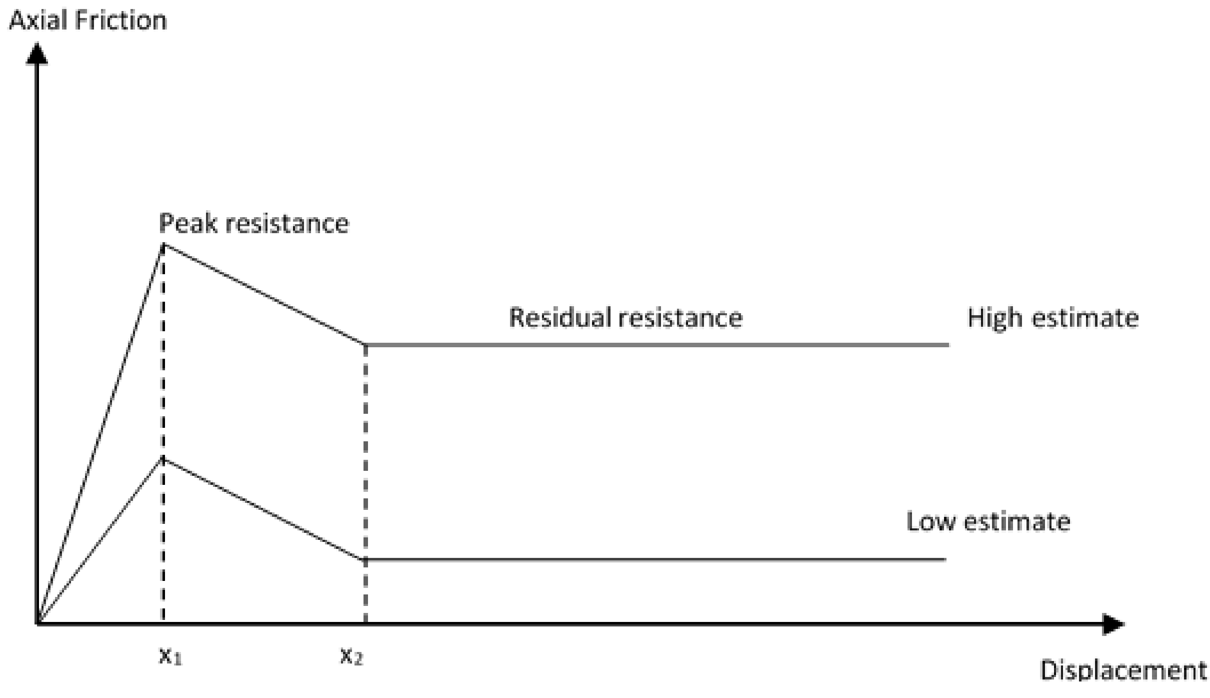

Figure 5: Typical Axial Friction Coefficients

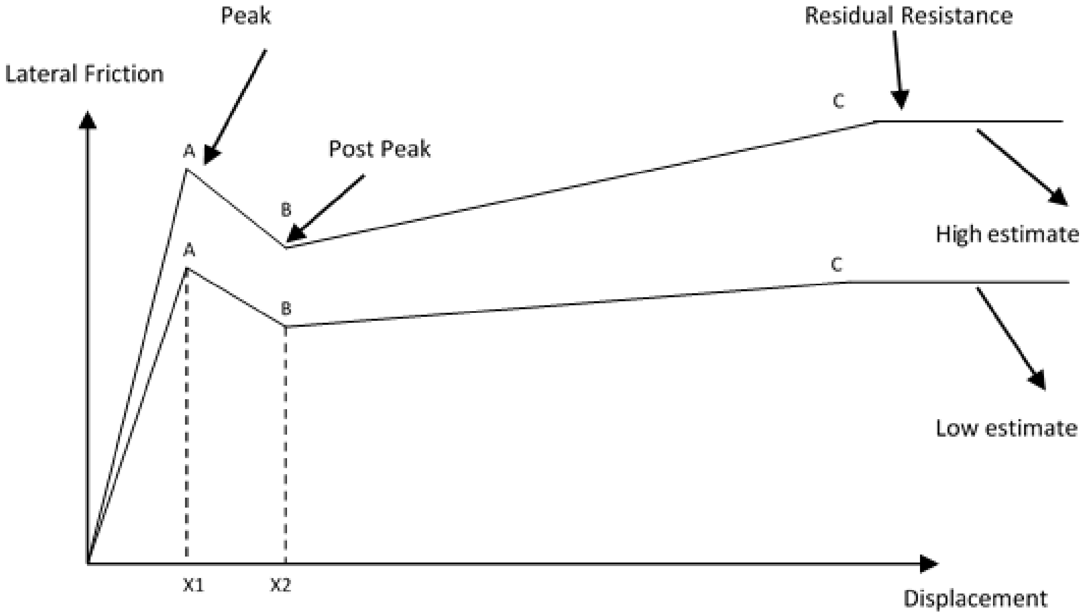

Figure 6: Typical Lateral Friction Coefficients

4.3 FTA and PMA Stiffness

Two ends of the spools are connected to FTA and PMA; both are assumed to be flexible. Assuming fixed ends for spool yield to very unrealistic spools end reactions, so both FTA and PMA stiffness are included in the analyses. Six independent springs at two ends of the spool are assumed to model FTA and PMA stiffness, each of them is to model stiffness of FTA and PMA in each direction (there are 6 degrees of freedom at each end of spool). FTA spring stiffness has been evaluated by JP Kenny Structural team and is in Ref. **Error! Reference source not found.** and PMA stiffness has been evaluated by FMC in Ref. **Error! Reference source not found.**.

4.4 Model geometry

The spool may be modelled using a 2-node Elbow 31 element [1]. Geometric nonlinearity, as well as material nonlinearity, must be accounted for in the analyses. The seabed can be modelled as a rigid analytical surface defined using finite elements. A contact pair is defined between the seabed, which is the master surface, and the spool elements which form the slave surface. The seabed reference node is fully fixed throughout the analysis. The seabed surface has the vertical stiffness to represent the soil vertical stiffness, but the spool is free to lift off. The friction at the interface of the spool and the seabed in axial and lateral directions are defined appropriately.

Different combinations of boundary conditions from FTA and PMA end tolerances have been considered in the analyses. Having six degrees of freedom at each end will produce (26)2 = 4096 load cases. To reduce the number of load cases and consider only the critical load cases, two assumptions are considered:

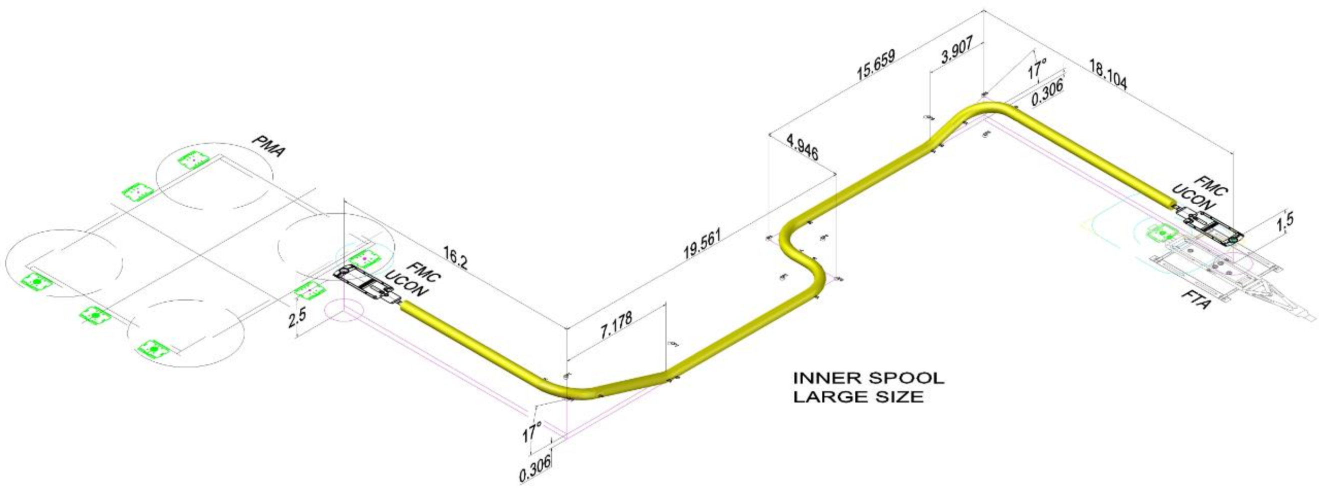

Figure 7: Configuration of Possible Largest Size of Outer Spool based on Installation Tolerances

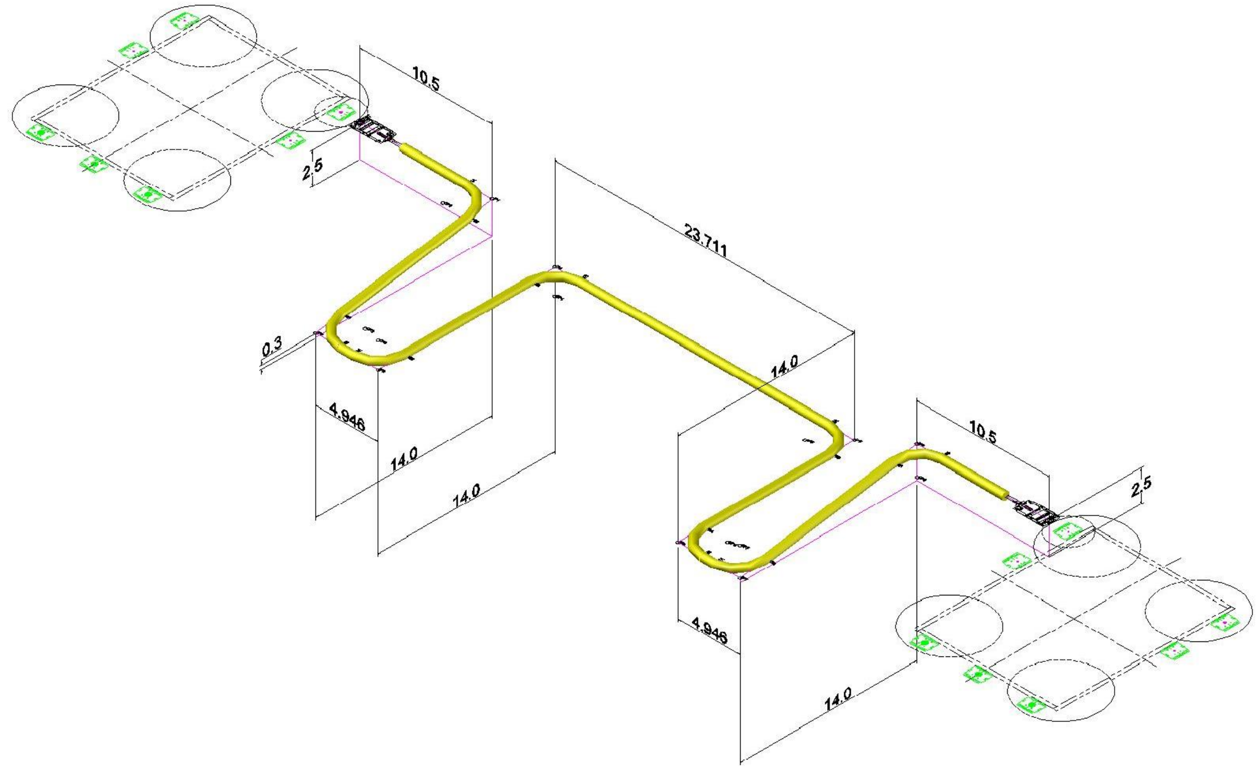

Figure 8: Configuration of Possible Smallest Size of Middle Spool based on Installation Tolerances

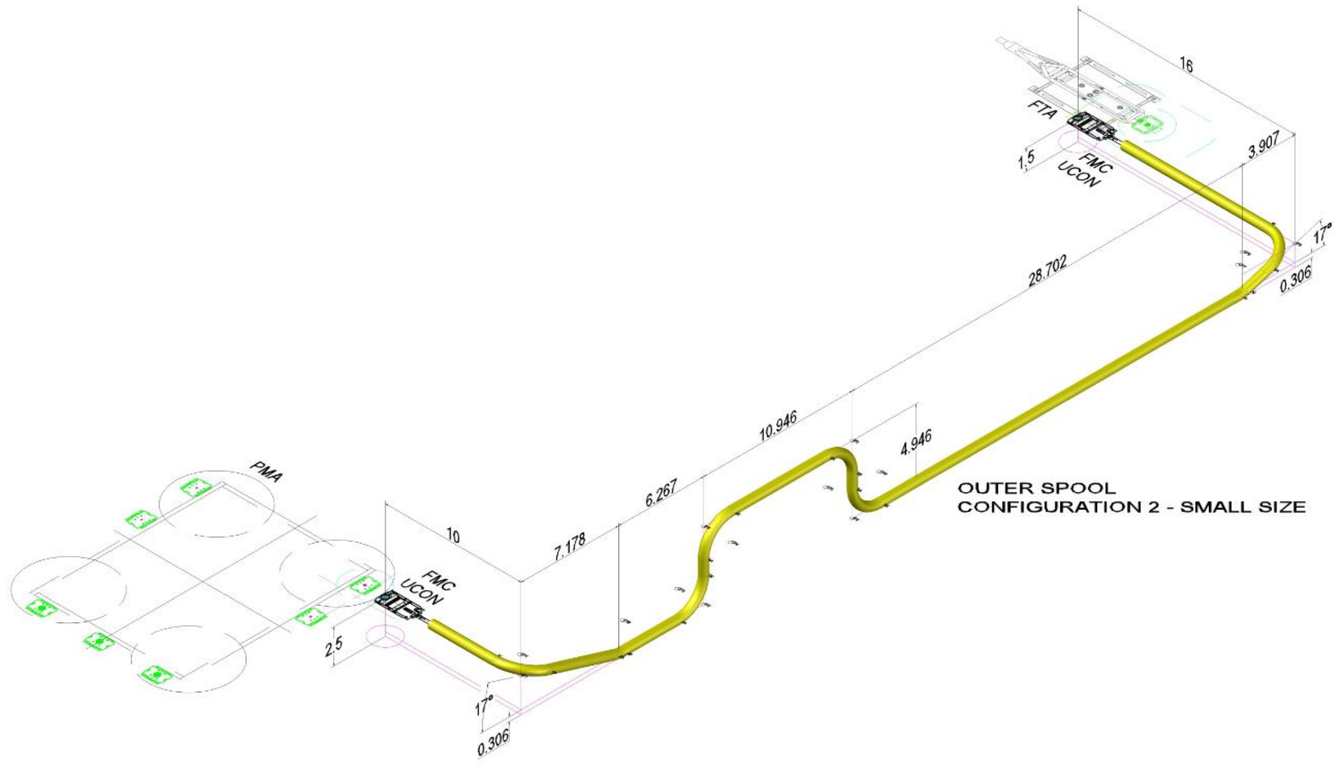

Figure 9: Configuration of Possible Smallest Size of Outer Spool– Configuration 2 based on Installation Tolerances

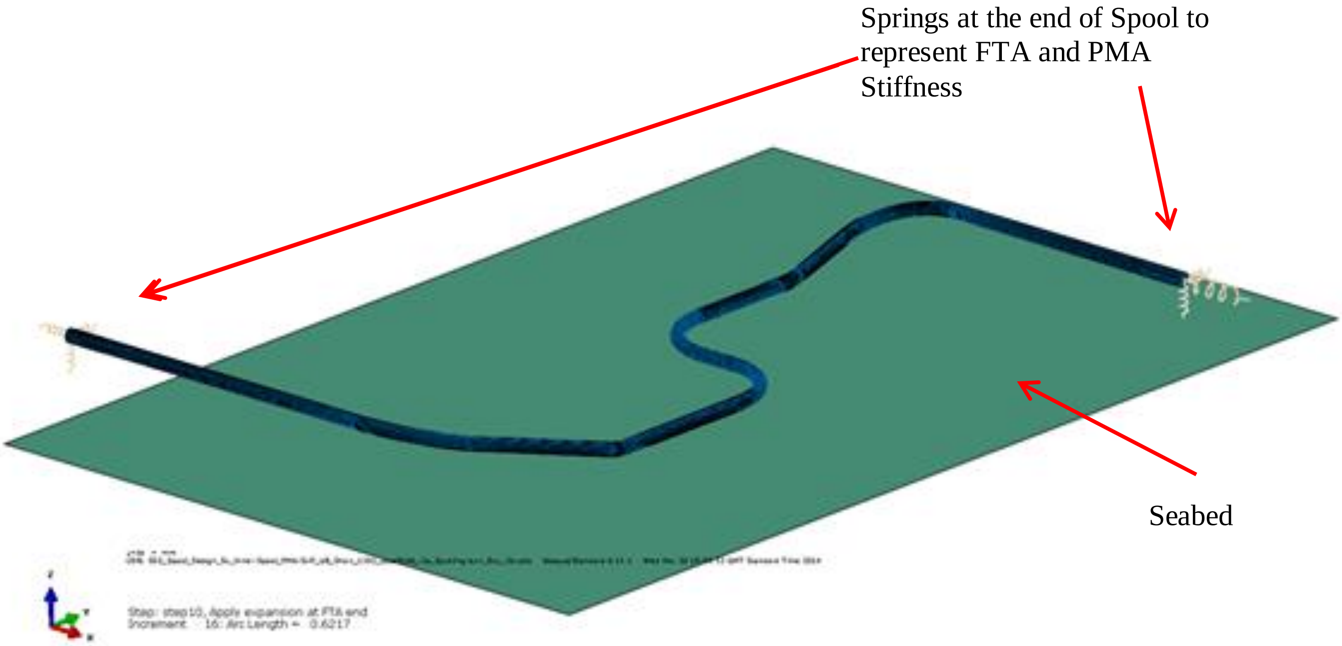

Figure 10- Finite Element Model of Inner Spool using 3D Shell Elements

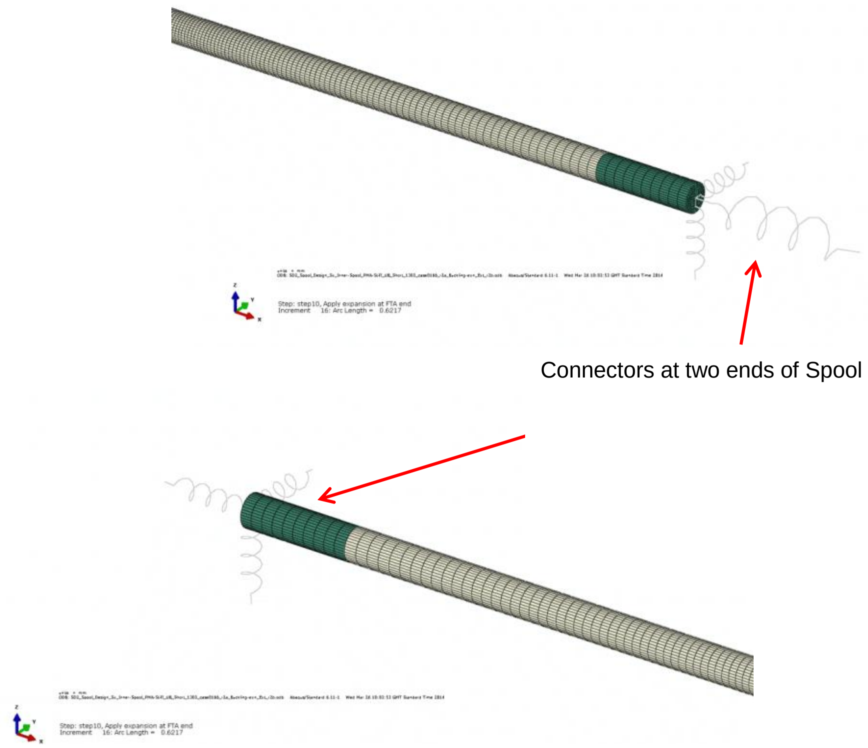

Figure 11- Finite Element Model of Inner Spool using 3D Shell Elements

The final configuration for each spool considering the smallest and longest possible sizes based on installation tolerances was modeled for inner, middle, and outer spools. Figures 7 to 9 show a few examples.

FTA and PMA ends of the spool are connected to 6 springs at each end to represent FTA and PMA stiffness in each degree of freedom (Figure 10). The seabed has been modeled using a rigid surface with vertical stiffness so that spool can embed into it and friction in longitudinal and lateral direction has been given between spool and seabed.

4.5 Abaqus Load Steps

The load steps to be applied in the Abaqus model for a realistic spool model:

1) Submerged weight in empty condition, zero friction, fit pipeline to the seabed;
2) Apply external pressure
3) Restore friction coefficients
4) Release restraints
5) Apply submerged weight in operational condition. For spool analyses, the water-filled spool is assumed.
6) Apply Metrology/ Fabrication/ Land Survey tolerances
7) Stroke FTA end of the spool
8) Stroke PMA end of the spool
9) Apply internal pressure and fix torsional degrees of freedom at two ends of the spool
10) Apply design temperature
11) Apply expansion and walking to FTA end
12) Reduce internal Pressure and temperature to shut-down condition
13) Apply pipeline contraction

Note that friction between pipe and seabed is set initially to zero to facilitate numerical convergence when settling the pipeline on seabed. This value is set to the appropriate value soon after the pipe is settled on the seabed.

Note that seabed was assumed flat in the analyses. Conservatively, the smallest value for PMA height (2.5m) was used. The true variation in height will be known after metrology and can be accounted for by combinations of slight changes to the angles before welding.

Figure11: Inner spool - Smallest Size – Envelope of Von-Mises Stress (MPa)

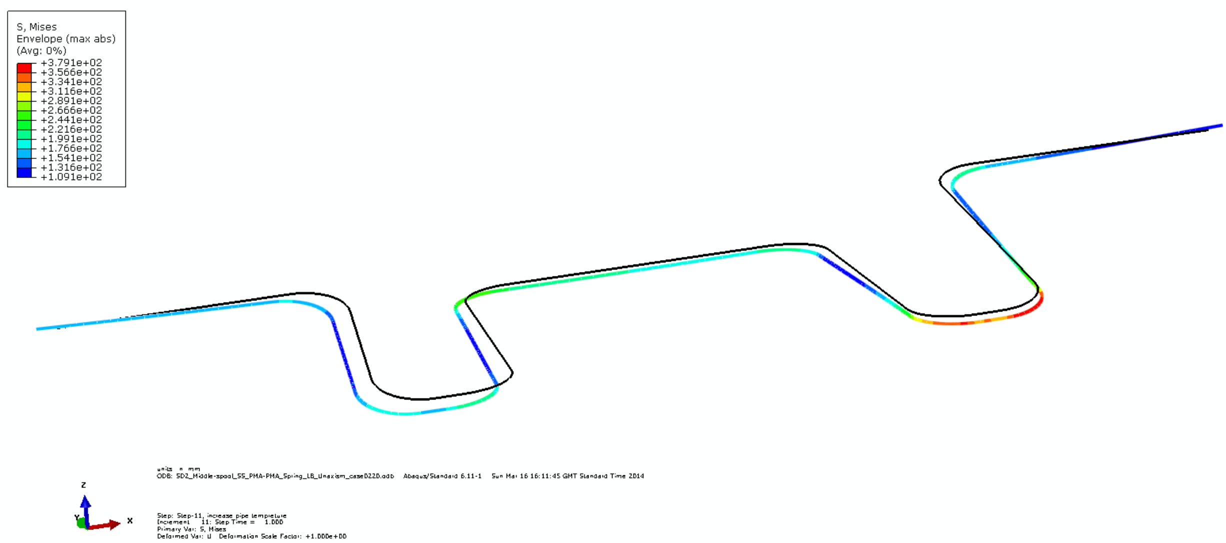

Figure 12: Middle spool - Smallest Size – Envelope of Von-Mises Stress (MPa)

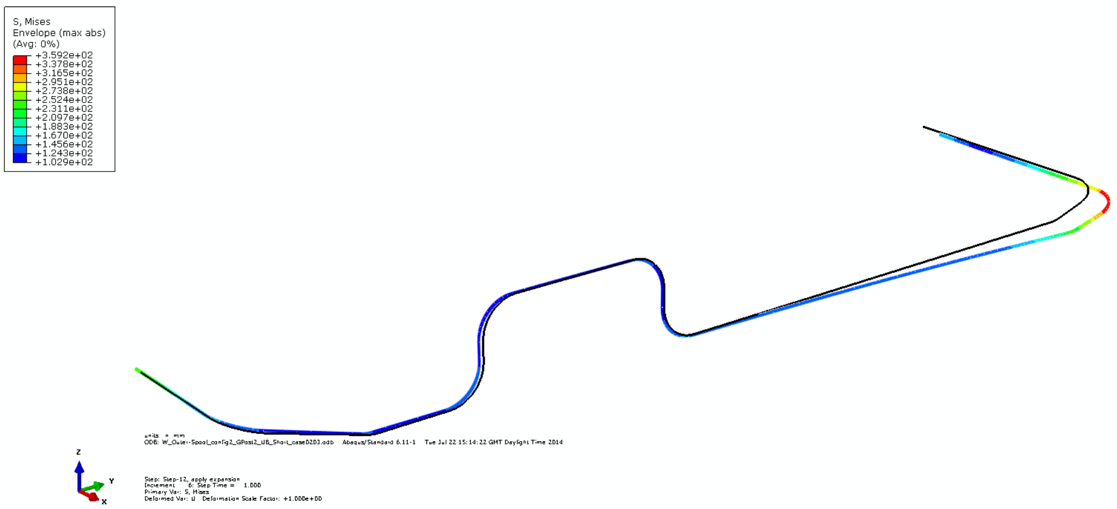

Figure 13: Outer spool – Configuration 2 – Envelope of Von-Mises Stress (MPa)

Figures 11 to 13 show examples of Abaqus' results

Two series of analyses for each spool is carried out assuming lower bound friction between spool and seabed and upper bound values. In using lower bound friction values, two ends of the spool are raised vertically up by the total vertical tolerance value and in using upper bound friction values, two ends of the spool are pressed down by the total vertical tolerance. This is because assuming lower bound friction and pressing down two ends of spool does not produce critical results, and also, assuming upper bound friction and raising two ends of the spool is not critical as well.

Within the connector itself the carrier pipe is free to rotate torsionally during the initial laydown of the connector, only after tie-in is complete is the torsional movement restricted. So there is no need to consider this degree of freedom in the initial load cases.

Considering the above assumption the number of degrees of freedom to be applied in the analysis reduces from 6 to 4 at each end so the total number of critical load cases reduces to $(2^4)^2$=256 load cases for each of lower bound and upper bound friction factors.

5. Concluding Remark

Seismic analysis of rigid spools was presented. Another check must be performed to ensure that the interface loads at the connector ends are compatible with the limiting conditions of the connectors. It is shown that to identify feasible geometries for spools that are fit for purpose according to Design by Analyses method of ASME Viii, Division 2, Part Five [3].

Results for a few of several hundred cases analyzed are presented in this paper. The following observations were made.

- It is reminded that the first step of the cluster spool design is to check spools end reactions against their allowable limit given by subsea connectors
- The shortest size of the Inner spool is the most critical spool in terms of end reactions.
- The reported case is a 12in ID pipe. If the thickness of the ID increases then a practical geometry may not exist, except if the tolerances are tightened or the capacity of the connector is increased. In such a situation flexible pipe might be necessary.
- The larger spool size has enough flexibility to pass the minimum requirement of 5 out of 7 records pass for ELE and ALE.
- As the length increase so does the margin to pass 6 out of 7 seismic records.
- Fatigue life calculations are not reported here, but as assessed using SN were satisfactory.
- Vortex indicated Vibration (VIV) screening checked (not reported here) no potential for VIV was detected.
- FLIP/FIV screening checked (not reported here) and passed, so there is no issue for FLIP/FIV.
- It was shown that suitable geometries can be found that pass the unity checks relating to the loads limit at the PMA for all spools and all conditions of operation and seismic events.
- all translational reactions (i.e. Resultant of FL, FT, and FV) were below allowable resultant of translational loads given by the connector vendor for different conditions,

- torsional reaction (ML) was compared against its corresponding value given by the vendor and resultant bending moment (i.e. Resultant of MT and MV) is compared with their allowable resultant bending moment provided by the vendor.

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Abbreviation/ Acronym	**Description**
A	Absolute
BPT	Ball Penetrometer Test
CD	Chart Datum
CDT	Cool Down Time
CPT	Cone Penetrometer Test
CRA	Corrosion Resistant Alloy
CMS	Corrosion Monitoring Spool
DEH	Direct Electrical Heating
ECA	Engineering Critically Assessment
FIV	Flow-Induced Vibration
FLIP	Flow-Induced Pulsation
FE	Finite Elements
FTA	Flowline Termination Assembly
ID	Inside Diameter
LB	Lower Bound
MEG	Mono Ethylene Glycol
PMA	Production Manifold Assembly
OD	Outside Diameter
SIWHP	Shut-in Wellhead Pressure
SMLS	Seamless
TBC	To be confirmed
UB	Upper Bound
VIV	Vortex-Induced Vibrations