The Latest Advances in the use of Advanced Engineering for the Design and Simulation of LNG Subsea Loading Pipelines

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Abstract

The design of LNG subsea pipelines and risers presents real challenges such as low operating temperatures, multiple pipe walls, and differential expansion of materials. This paper gives an overview of how Advanced Engineering, through the use of finite element analysis (FEA) tools, can be used to undertake the complex design and simulation of subsea LNG pipelines, risers and components.

Traditionally LNG loading lines are placed above the waterline on trestles, which are expensive and prone to environmental conditions. Significant project cost savings and security enhancement can occur if the pipelines are placed subsea. Also, there is increased security and protection of the subsea LNG pipeline, if it is trenched and buried, as compared to an exposed pipeline above the water.

Through the use of FEA tools, described within this paper, it is possible to design LNG pipelines subsea. Pond & Co. has been involved a recent subsea LNG project which involved a comprehensive FEA model of a triple-walled (PIPIP) LNG system including both pipelines and risers. This paper covers the latest main findings in the use of Advanced Engineering for the design and simulation of subsea LNG loading lines.

The first part looks at the design considerations and challenges when designing LNG pipelines and risers. The second part looks at the 'global' analysis of LNG pipelines and risers using a highly non-linear finite element (FE) program. Two FEA models are presented, 1. An ABAQUS model that is sed to investigate the pipeline and riser stresses and displacements, and 2. an ORCAFLEX model to look at effects of environmental loading (wave and current) on the risers to determine riser clamp loads and clamp sping. These tools can be used to undertake the PIPIP response, pipe/soil interaction, expansion/span analysis, and determine stress, displacements, and anchor clamp loads.

Using the above-mentioned FEA models, an example is then given that demonstrates how these FEA tools have been used.

Introduction

The LNG LPG markets are beginning to grow, and this is set to continue for the foreseeable future. The existing method for off-loading LNG is to have transfer arms linked to shore by insulated pipes laid on a trestle. However, this has inherent disadvantages for long trestles such as high cost, security risks, and significant environmental impact. An alternative approach is to use subsea insulated LNG loading lines, which can lead to significant cost savings of the LNG. The subsea pipeline option decreases environmental impact, eliminates disruptions of local marine traffic, and improves security.

The PIP system consists of an inner pipe, 4-in dual rated 304/304L Seamless pipe, to transport the LNG, separated by a vacuum to provide thermal insulation, and an outer 6-inch is dual rated 316/316L EFW with HD polyethylene (PE) coating. The 4-inch/6-inch pipe-in-pipe is then inserted in a protective conduit pipe, such as a 10 and 12-inch carbon steel (X42) pipe. This type of system provides the required thermal insulation for the transportation of the LNG, by the 4-in/6-in pipes, and the required protection from environmental by the use of the outer 10 or 12-in pipe.

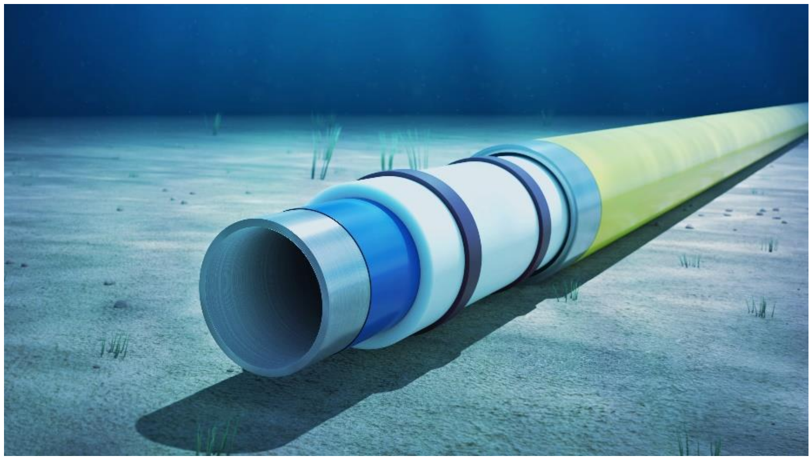

Figure 1 An LNG PIP System (Conduit outer pipe not shown for clarity)

Figure *1* shows a PIP configuration for LNG applications. The PIP would be placed inside a conduit pipe (not shown for clarity) for protection purposes, making it a Pipe-in-Pipe-in-Pipe (PIPIP), and the pipeline would also be trenched and buried.

Technical Considerations of LNG Systems

There are a number of technical design considerations that need to be taken into account when designing subsea LNG lines. Low operating temperatures can present issues to consider with the mechanical design and the choice of appropriate materials. Cryogenic pipelines are relative complex to design because of the multiple pipe walls, differential expansion of materials, and pipe-soil interaction. Also, the pipeline is connected to the risers, which may be at both ends of the pipeline, and the riser needs to be included in the design. One riser will generally be at the offshore end, connected to the jacket of offshore structure, while the other end may have an onshore riser tie-in into the existing onshore pipeline.

The main technical considerations to be taken into account when design cryogenic pipelines are the following:

- **Low Operating Temperatures.** The temperature LNG is very cold at --265 °F and this can present challenges such as thermal performance, boil-off, and safety. To minimize operation boil-off gas the pipeline solution consists of a thermally efficient PIP system. These low temperatures can present real challenges in the choice of materials, in terms of material toughness at low temperature, and creation of contraction forces.

- **Large Contraction Forces.** Due to the presence of the cold LNG at approximately -265 °F the contraction forces can be relatively large, and these forces need to be accommodated in the design. For LNG, these high contraction forces can be either overcome by the use of bulkheads at each end of the pipeline, or by the use of bellows. In this paper, the inner pipe is a 4-in dual rated 304/304L Seamless pipe with the inclusion of bellows in the pipeline. These bellow act as springs and alleviate the high axial contraction, from the presence of cold temperatures, on the inner pipe.

- **Differing Expansions.** The pipes are uncoupled, except at the bulkhead locations, and there is some friction between the pipes. Differing temperature, internal pressures, and material properties, especially coefficients of thermal expansion, for each pipe can lead to different loads in each of the pipes. The interaction of the loads is more complex at the bulkhead locations, and warrants the use of FEA to accurately determine the loads.

- **Global FEA**. There is a requirement for a global model to obtain the loads for the pipeline design, bellows design and loads to the risers at the end of each line. Also, the loads are used for the design of the risers and riser clamps at each end of the pipelines. The global model allows the accurate determination of the loads, and displacements, in the system to ensure a safe and robust design, while saving time and reducing computation requirements.

- **Pipe-Soil Interaction**. Pipe-soil interaction has to be included in the FEA to adequately predict end movements of the pipeline and subsequent forces at the tie-in locations. The pipe-soil interaction is included within the FEA model presented within this paper.

- **Riser Analysis**. The riser should be included in an analysis to accurately assess the reaction loads between the riser and the pipeline. The riser is loaded with environmental loads that need to be taken into account as part of the design. This is undertaken by running riser analysis FEA models.

- **Design Codes.** There are no pipeline codes that specifically address the needs of subsea LNG pipeline design. Hence ASME B31.3, stress limits are used for the design of the pipelines, and close attention to the NFPA 59a design code.

- **Long Distances.** The distances of the loading lines can be on the order of km's. This requires a very thermally efficient pipeline, with a low overall heat transfer coefficient (OHTC), to maintain the temperatures so that content boil-off does not occur.

- **Low Risk Tolerance.** The pipeline must have environmental and loading risks reduced to a minimum, and the design must be robust and reliable. Structural, thermal, and fatigue loads are checked against codes.

Advanced Engineering

As the LNG pipeline system is complex, Advanced Engineering through the use of Finite Element Analysis (FEA), is used to undertake the design of the PIP system. A flow assurance analysis is undertaken first to determine the Overall Heat Transfer Coefficient (OHTC) for the system, and to determine the temperature profiles in each of the three pipes. The main aim of the flow assurance is to ensure that the vacuum between the 4-in and 6-in pipe is sufficient to avoid freezing temperatures of the 6-in pipe, and to ensure no boil off of the LNG over the given length of the pipeline.

Two models are created to undertake the design, one for the subsea pipeline using ABAQUS, and Risers, and a second model using ORCAFLEX to look at the global loads on the risers due to environmental loading.

Model 1. LNG Pipeline FEA Model using ABAQUS

The finite element analysis package, ABAQUS, was used to simulate the subsea PIP system inside the outer conduit pipe. The models allow for non-linearities such as material, large displacement, pipe-soil interaction and 3-D route geometries.

A global, 3D FEA model has been created to assess the pipeline expansion/contraction and the stress and load response under extreme ambient and operational loading conditions. Each pipe is modelled in ABAQUS, 4-in, 6-in and 10-in. Centralized between the 4-in and 6-in pipe are also included, and bellows are included on the 4-in pipeline at predetermined spacing distances.

As the pipeline will be trenched and buried, with 4-ft cover, the soil is also included in the FEA model. In accordance with NFPA 591, vacuum breaks were included in the design to break up the length of the annulus.

Figure *2* shows a global FEA model schematic.

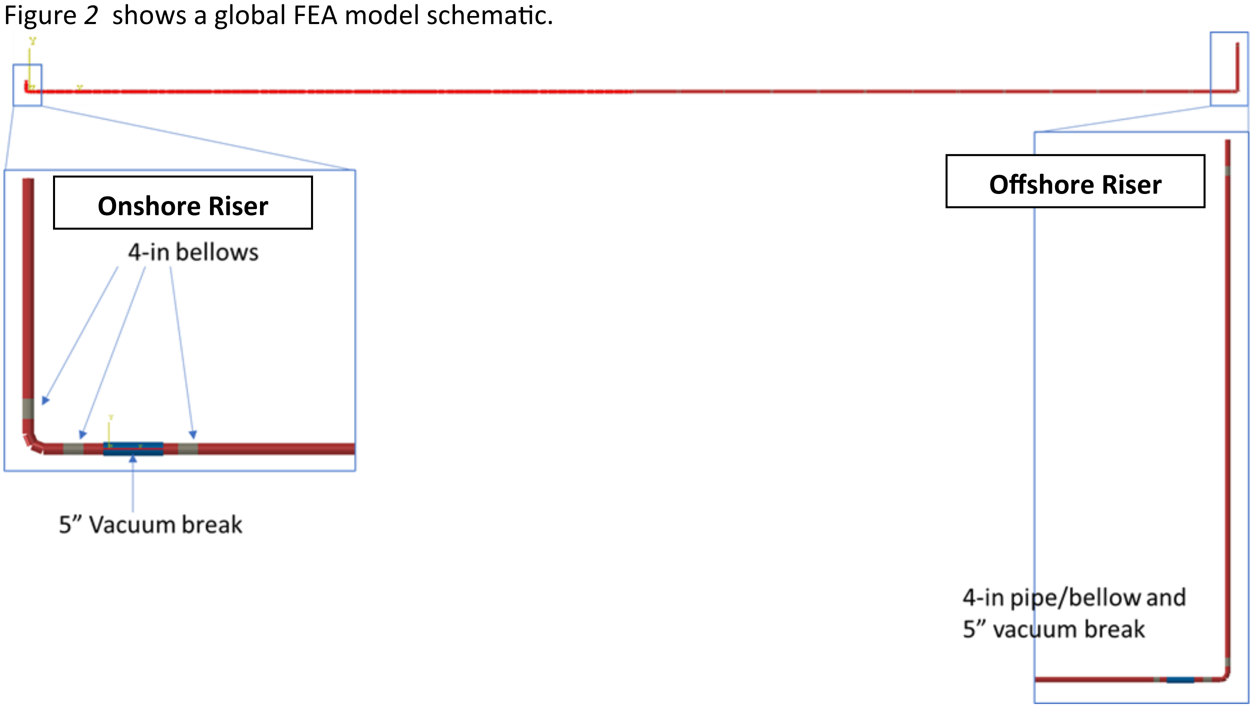

Figure 2 Simplified Longitudinal Design of the LNG Subsea Pipeline System.

A global, 3D FEA model has been created to assess the pipeline expansion/contraction and the stress and load response under extreme ambient and operational loading conditions. Boundary Conditions of the pipeline is assumed to be fixed boundary conditions at the top of the risers at the tie-in locations. At one end, the offshore end, an expansion spool was included at the top of the riser system to give the system some flexibility.

The FE elements used in the FEA model are PIPE31H, which are the hybrid formulation pipe elements within ABAQUS/Standard. These elements are selected because they are particularly well suited to modeling long, slender pipelines with better convergence behavior than the standard pipe elements.

The FE global model is initially created using the ABAQUS pre-processor (ABAQUS/CAE), which is a user friendly graphical interface, to generate the riser and bend curvature. For simulation efficiency, the load case runs are conducted using input decks and restart techniques.

Two-node 3D pipe elements are used to model all three (3) pipes. All of the nodes and elements of the three pipes are assumed to be concentric initially. The intermediate pipe and inner pipe then naturally settle to their correct positions. Thus, any bending moments associated with the eccentricities of the pipes are accounted for in the model.

The interactions between the three pipes are modeled with contact elements with friction effects. Single-node connector elements are used to model the restraints of the onshore tie-in, bottom anchor mechanism, and riser clamps.

A general view of the offshore riser end is shown below in Figure *3*.

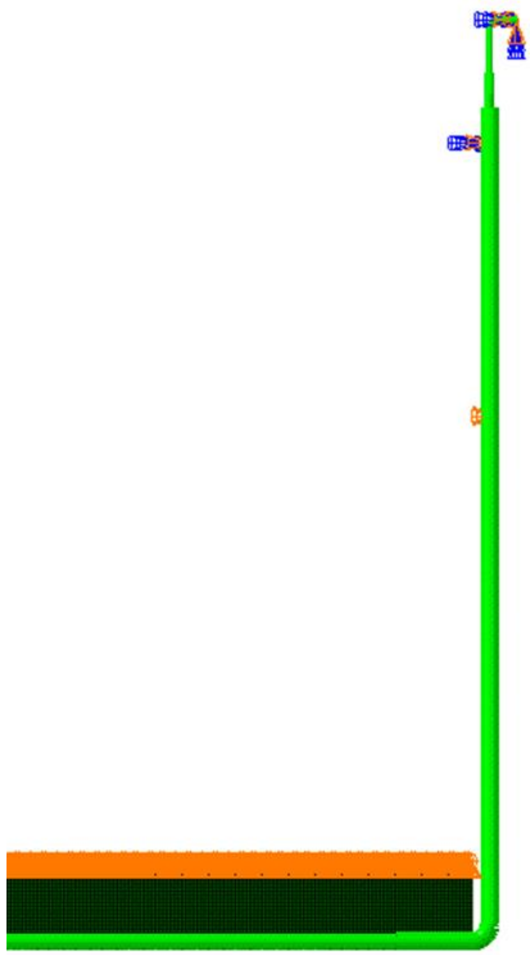

Figure 3 General arrangement at the offshore Riser end, and the boundary conditions.

The same Abaqus model is used to model the risers to look at displacements and stress in the 4-in and 6-in pipes.

Model 2. LNG Riser model using ORCAFLEX

To investigate the effects of environment loading, due to wave and current loading, another model was develop using the commercial software ORCAFLEX. The model is shown below in Figure 4. The model is used to apply wave and current loading, due to environmental loading, on the pipeline system to determine the loads at the riser clamp locations. The 100-yr storm condition is considered as the worst case.

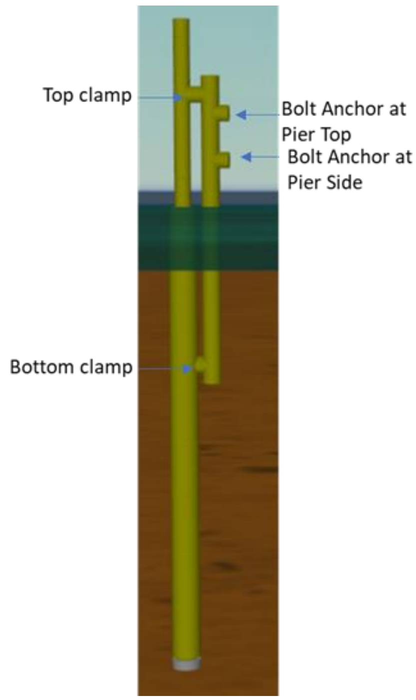

Figure 4 Riser model in Orcaflex to determine Riser Clamp loads

The riser clamp spacing was determined in accordance with design codes to ensure that the riser at the Pier does not undergo any vortex induced vibrations (VIV). The riser vortex shedding analysis is carried out to determine the critical riser spans. This analysis is performed to ensure that the riser clamp spacing and locations are such that critical spans - which may cause vortex shedding vibration - are limited. The critical span lengths are calculated in accordance with DNV CN 30.5. The top riser span is considered a fixed-pinned configuration.

The top hanger clamp is defined as the fixed support, and the second clamp, which is a sliding clamp, is considered as pinned. The touchdown of the riser, protected with 4-ft soil burial, is considered as a pinned support. The effective spans of the riser are taken from the riser drawing.

The velocities passing over the riser spans are calculated using the 100-yr wave and currents design conditions. This total wave and current velocity are then applied to riser span to calculate the in line and cross flow vortex shedding frequencies. These frequencies are compared to the natural frequency of the riser span to whether they fall within ranges provided by the DNV CN 30.5 Code for vortex shedding.

Fatigue checks were undertaken in accordance with DNV RP C203

Riser Clamps Spacing Verification

The riser vortex shedding analysis is carried out to determine the safe riser spans. This analysis is performed to ensure that the riser clamp spacing, and locations are such that vortex induced vibrations will not occur. The critical span lengths are calculated in accordance with DNV 30.5. The top riser span is considered a fixed-pinned configuration. The top hanger clamp is defined as the fixed support, and the second clamp which is a sliding clamp considered as pinned. The bottom of the riser, protected with 4 feet sand/ grout bag burial, is considered as a pinned support. The effective spans of the riser are taken from the riser drawing.

The velocities passing over the riser spans are calculated using the 100-year wave and currents design conditions. This total wave and current velocity are then applied to riser span to calculate the in line and cross flow vortex shedding frequencies. These frequencies are compared to the natural frequency of the riser span and determining whether they fell within ranges provided by the DNV 30.5. From this comparison, it was found that the riser is not subject to vortex shedding frequencies.

Riser Clamps Structural Design Verification

Riser clamps structural design is performed in compliance with AISC ASD design safety factors. The riser design loads are summarized in the tables below. Riser at Pier C is exposed to external environment and the 100-year storm condition was used for the determination of the maximum riser clamp loads. The resultant loads on the clamps include environmental load and static dead weight. Details of the clamp load determination using the FEA software ORCAFLEX. The results show that the riser clamp design meets the design requirements.

Results

The FEA models mentioned in the previous section was used to determine the stress and displacements in the 4-in and 6-in pipe of the LNG system. The displacements and stresses in both the 4-in and 6-in were examined. The more critical pipe in the 4-in, as this is seeing the cold LNG temperatures, and the stresses are shown in Figure 5.

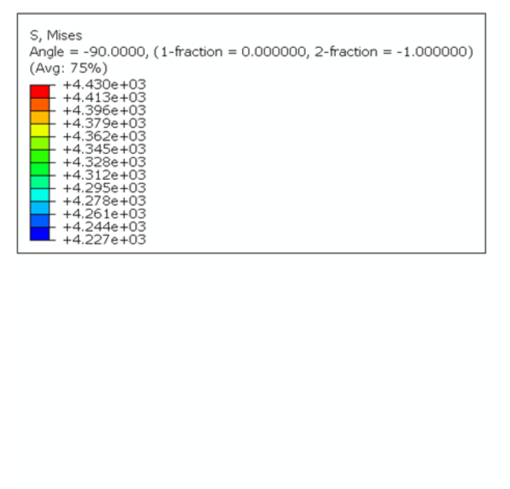

Figure 5 Von Mises Stress Profile in 4-inch Pipeline

Two cases were run. Case 1 with a perfect vacuum, i.e. no transfer of LNG temperatures to the 6-in pipe. Case 2 with a partial vacuum, which is more realistic of practical case. The results are shown in Table 1.

Table 1 – Summary Table of Stress Analysis Results

Riser		Load Case 1[1]			Load Case 2[2]		
		4"	6"	12"	4"	6"	12"
Riser (Offshore end)	Stress (ksi)	4.43	4.48	1.68	4.45	3.30	2.97
	% SMYS	14.7%	14.9%	4.0%	14.8%	11.0%	7.1%
	% Allowable B31.3	26.5%	26.9%	8.4%	26.6%	19.8%	14.8%
Riser (Onshore end)	Stress (ksi)	5.37	4.54	1.00	11.7	14.19	3.72
	% SMYS	17.9%	15.1%	2.4%	39.0%	47.3%	8.8%
	% Allowable B31.3	32.2%	27.2%	5.0%	70.0%	85.0%	18.6%

Notes:
1. Load Case 1: Perfect vacuum
2. Load Case 2: Partial vacuum

Based on the results, the following key findings and recommendations are summarized:

- Stresses of each component of the pipe-in-pipe assembly are within allowable limits of B31.3.
- Displacements of the expansion bellows in 4-inch pipe are within allowable limits.
- Overall, the pipeline design is suitable for the operating pressure and temperature.

Based on the above, the LNG transfer pipeline is considered safe for the normal operating condition, and compliant with design codes B31.3 (2018) and NFPA 59a (2016).

Discussion

Based on the stress analysis results, the findings and riser design are listed below:

- Stress. Stresses are within allowable limits for each component of the pipe-in-pipe-in-pipe bundle. Overall, the pipeline design is suitable for the normal operating condition. The stresses are within allowable limits of B31.3.
- Vortex-Induced-Vibrations. The riser at the offshore end was checked for vortex induced vibrations (VIV) in accordance with DNV CN 30.5, and the length of the riser does not induce either in-line or cross-flow VIV.
- Fatigue. A fatigue analysis of the risers in operation has been conducted according to DNV RP C203. The allowable number of complete thermal and pressure cycles is orders of magnitude beyond what is expected (600 cycles with LNG offloading twice per month for 25-years).
- 100-yr Storm Condition at offshore end. Clamp loads and loads on supports were determined for the 100-yr storm conditions, and these will be used to design the supports at the top of the offshore pier.

- Splash Zone. The extent of the splash zone was determined in accordance with DNVGL-OS-C201, so as to reduce the corrosion of the riser and the clamps. The distance of the first clamp, above MSL, was calculated to be 6-ft (to bottom of clamp).
- Riser Clamp Loads. Riser clamps structural design is performed in compliance with AISC ASD design safety factors. Riser at the offshore end is exposed to external environment and the 100-year storm condition was used for the determination of the maximum riser clamp loads.

Based on the above, the LNG transfer pipeline is considered safe for the normal operating condition, and compliant with design codes B31.3 (2008) and NFPA 59a (2016).

Conclusion

LNG loading lines are extremely complex to design due to the presence of the cold cryogenic temperatures and the high level of contraction on the inner pipe. This warrants the use of Advanced Engineering, such as the use of Finite element analysis (FEA), to determined the loads and displacement s in the PIP system.

An FEA analysis has been presented in this paper that uses both ABAQUS, to look at the global displacements and stresses and, ORCAFLEX model to look at the environment loading on the offshore riser. The main conclusions are as follows:

- Stress. Stresses are within allowable limits for each component of the pipe-in-pipe-in-pipe bundle. Overall, the pipeline design is suitable for normal operating conditions. The stresses are within allowable limits of B31.3.
- Fatigue. A fatigue analysis of the risers in operation has been conducted according to DNV RP C203. The allowable number of complete thermal and pressure cycles is orders of magnitude beyond what is expected (600 cycles with LNG offloading twice per month for 25-years). The bellows with allowable 5,077 cycles also exceed the expected load cycles.

These FEA models presented within this paper allow safe and reliability designs to be undertaken. Significant project cost savings and security enhancement can occur if the cryogenic pipelines are placed subsea. Through the use of FEA tools, described within this paper, it is possible to design LNG pipelines subsea.

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