A Survey of ABAQUS Simulations in Technip USA Deepwater Pipeline Engineering

B.W. Duffy

Technip

Abstract: The production of hydrocarbons from deepwater reservoirs requires the fabrication and installation of massive infrastructure. As the global energy industry targets hydrocarbon reservoirs in ever deeper water, the use of remote subsea wells to access the reserves and deepwater flowlines to transport the produced hydrocarbons back to floating production platforms will increase. Technip pipeline engineers utilize a number of simulation tools, including ABAQUS, to ensure that the deepwater pipelines and subsea equipment are designed, fabricated and installed to meet the demanding environmental and operating conditions. Some of the various simulations Technip performs with ABAQUS include: global pipeline thermal buckling and fatigue simulations; analyses of the installation of the pipeline end termination (PLET) structure and its connection to the suction piles that restrain the pipeline (these simulations provide the highly nonlinear force deflection curve for use as the boundary conditions in the global pipeline thermal buckling simulation); cavity radiation simulations of the heat transfer between multiple flowlines/umbilicals in the turret of floating production platforms; and thermal management simulations to ensure that the pipelines insulation design will maintain adequate hydrocarbon temperatures during shut-down conditions.

Keywords: Buckling, Fatigue, Pipes, Pipeline, Submarine Pipeline, Cavity Radiation, Transient Heat Transfer, Pipeline Flow Assurance, Pipe-Soil Interaction, Soil-Structure Interaction, Reliability.

1. Introduction

The production of hydrocarbons from deepwater reservoirs requires the fabrication and installation of very expensive infrastructure. The cost just to drill a deepwater well can easily exceed $70-100 million. The various components needed to support long-term production of deepwater hydrocarbons (the production platform, subsea wellheads, pipelines, and control systems) can be a $1 to $3 billion (or more) investment. Given this huge capital expenditure and the volatility of hydrocarbon pricing, there is tremendous pressure in the energy industry to deploy highly reliable and cost effective equipment for such deepwater projects.

Advanced simulations help ensure that the designs of deepwater equipment can withstand the severe environmental and operating conditions and that the installation procedures can get the hardware on location safely. The variety of simulations Technip performs with ABAQUS include: global pipeline thermal buckling and fatigue simulations; analyses of the installation of the pipeline end termination (PLET) structure and its connection to the suction piles that restrain the pipeline (these simulations provide the highly nonlinear force-deflection curves for use as the boundary conditions in the global pipeline thermal buckling simulation); cavity radiation simulations of the heat transfer between multiple flowlines/umbilicals in the turret of floating production platforms; thermal management simulations to ensure that the pipeline insulation design will maintain hydrocarbon temperatures during long shut-down conditions; and impact simulations to ensure that subsea structures can survive dropped object events.

2. Components of Deepwater Pipeline Systems

Unlike an onshore pipeline, a deepwater pipeline usually consists of more than just steel pipe, some valves and several compressor stations. A general layout of a deepwater pipeline system is shown in Figure 1. A deepwater pipeline is often attached at each end to a structure called a PLET (“Pipeline End Termination”). The PLET is connected to other components of the subsea development, such as a wellhead manifold, subsea tree or a riser base, by a secondary pipe structure called a jumper. The pipeline, often referred to as a flowline, may be a either a flexible composite structure or a rigid steel pipe. All of the examples discussed here in this paper are steel pipeline designs. The maintenance of the hydrocarbon fluid temperature is an important design consideration for deepwater pipeline systems. Various types of insulation designs are used to mitigate heat loss to the very cold ocean water. Umbilicals, which are not shown in Figure 1, are another important component of the deepwater production system. Umbilicals provide hydraulic fluid, electric power, chemical injection and data transmission to the subsea trees, pipelines, valves, sensors and other control instruments in the system.

2.1 The Flowline

Deepwater flowlines often have low diameter to wall thickness (D/t) ratios to meet the pressure containment requirements and collapse loads. The D/t ratios for deepwater flowlines range from 20 down to l0 or less. Given this D/t range most steel flowlines are manufactured from seamless pipe.

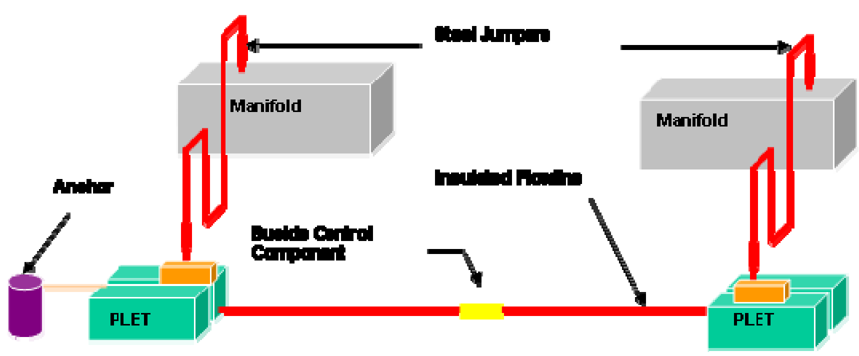

Figure 1. Schematic of deepwater pipeline system components.

The girth welds that join each joint of pipe (a joint being approximately 12 meters long) are the locations of greatest concern for fatigue damage.

2.2 Coatings: Thermal and Corrosion Design

Polymer/plastic coatings are applied to the outer surfaces of most deepwater flowlines to minimize the corrosion risks. In many long, deepwater production flowlines, maintaining an appropriate temperature of the hydrocarbons (especially during long periods of no flow) is a critical design objective. Warm hydrocarbon fluids ensure their ability to flow. In relatively short production flowlines (less than 8 km) the insulation is often strong, hard syntactic foam attached or bonded to the outside of the flowline. However, for longer flowlines or situations where temperature control is critical, deepwater projects will utilize a pipe-in-pipe (PIP) design. The gap between the inner (carrier pipeline) and the outer protective pipeline is filled with an insulation material to maintain adequate hydrocarbon temperature during shut-ins. A PIP flowline design will often have several steel bulkheads that are welded to both the inner and outer pipes at several locations to constrain relative axial motion fully. These bulkheads can present a thermal design challenge.

2.3 PLETs and Jumpers

The difficulty of working more than 5000 feet below the surface of the ocean and other operating requirements means that a deepwater pipeline cannot be attached directly to a subsea wellhead or riser. Instead the ends of deepwater pipelines are attached to structures called PLETs. As shown in Figure 1, a jumper then connects the PLET to the subsea wellhead. The PLET and jumper together must be designed to withstand the deflections and loads caused by the pipeline expansion.

A deepwater PLET can easily measure 5 by 15 meters and weigh 50-75 tonnes. A deepwater PLET is shown in Figure 2. The large chain seen in the figure is used to attach the PLET to a suction pile embedded into the ocean floor. The flowline is attached to a pivoting hub, seen at the top of the photo. The hub pivots for installation purposes.

2.4 Umbilicals

Umbilicals are bundles of individual hydraulic tubes, electrical conductors, chemical injection tubes and fiber optic lines wrapped inside of a protective outer casing. The design and fabrication of umbilicals is an impressive engineering activity and is not covered in this paper. An example of an umbilical cross section layout is shown in Figure 3. A good overview of the use of FEA in design of umbilicals was published by DUCO, Ltd, a Technip subsidiary (Probyn, 2007).

3. Assessment of PLET Anchor System Stiffness

The main function of the PLET is to provide a connection point to other subsea infrastructure. A PLET is a very large structure, and yet for many deepwater pipeline systems the PLET itself must be anchored to a pile embedded in the seafloor to provide the resistance to the pipeline walking loads. In shorter pipelines subjected to many thermal cycles, the pipeline walking loads can become quite large.

Figure 2. Typical PLET for a deepwater pipeline system.

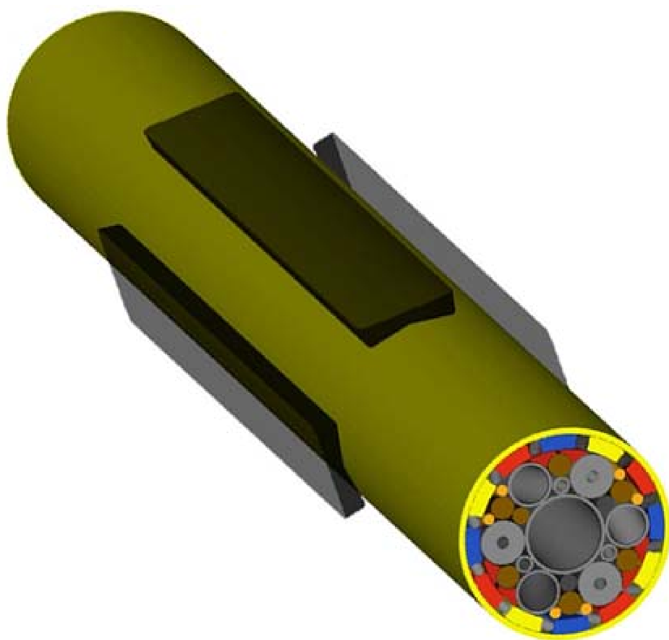

Figure 3. Example of an umbilical layout.

3.1 Simulation Objective

The axial expansion at each end of a deepwater pipeline caused by the thermal loads can be very large. The temperature of the hydrocarbon fluid as it enters the pipeline can be as much as 125^{o} C. Depending on the pipe-soil interaction and the configuration of the pipeline, the end expansion of the flowline can be 1 to 2.5 meters as it heats up from the ambient seafloor temperature to its operational temperature. The PLET and jumpers must be designed to accommodate such expansions without creating excessive loads or stresses that would fatigue the pipeline. A sliding carriage design on the PLET is commonly used to absorb such axial expansions.

The flowline expansion-contraction cycles and the seafloor topology can create a situation where the entire flowline tends to accumulate axial displacement in a particular direction, i.e. the flowline begins walking/ratcheting. If the tendency of the flowline is to walk away from the PLET, the resistance to this motion is a strong function of the tension that remains in the anchor chain connected to the suction pile after the PLET and flowline are installed. The first objective of the simulation is to create the full nonlinear force-displacement curve for the PLET as a function of the installed bottom tension. The second objective is to provide the installation team with the installed bottom tension required to ensure that the displacement of the PLET sliding mechanism remains within the limits. The final objective is to develop an understanding of how the touchdown angle of the PLET mudmat varies as a function of the installed bottom tension.

3.2 Summary of Simulation Model and Loading

The model is currently 2D because transverse currents are deemed too small to impact the deflections. The anchor chain, which has no inherent bending stiffness, is modeled with hybrid truss elements. The anchor pile stiffness under horizontal loads (i.e. the lateral bearing resistance) is modeled with a nonlinear spring. An analytical model was used to define the seafloor-anchor interaction in the vertical direction. The data from that model defined a piecewise linear,"softened contact", penetration curve. Little axial motion of the anchor chain is expected so no friction was included in the contact interaction model. The seafloor was modeled as a flat rigid surface.

The various components of the PLET are modeled as rigid bodies. The reference node for each PLET component was located at the component's center of gravity. The submerged weight of each component was applied to the component's reference node. The model is shown in Figure 4.

The following loading sequence is used in the PLET stiffness simulation:

1. Pull on the PLET horizontally; creating tension in the anchor chain
2. Apply gravity to the anchor chain and establish contact with seafloor
3. Lift PLET 25 ft above the seafloor.
4. Apply submerged weight to the PLET components and increase horizontal load on PLET to the "installed bottom tension" magnitude.
5. Lower PLET to seafloor
6. Slide PLET to determine nonlinear force-deflection curve as PLET slides axially.

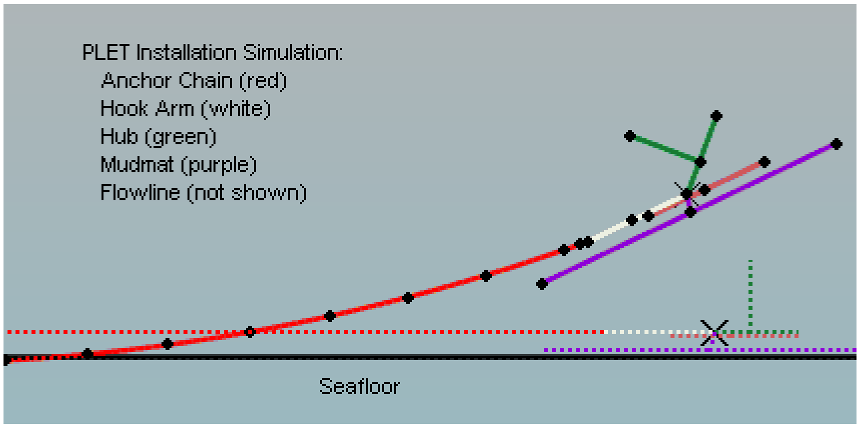

Figure 4. Configuration of PLET system simulation.

3.3 Results

The nonlinear force-deflection curves for a PLET anchor system with a very long chain, over 210 feet, are shown in Figure 5. The installed bottom tension in the system dictates how much initial sag is in the chain. At lower installed tensions, considerable pipeline walking must occur before the chain becomes taut. Once the chain is taut further resistance to pipeline walking is provided primarily by the suction pile.

The results for the second objective are shown in Figure 6. The yellow box defines the acceptable operating zone for the PLET sliding mechanism under flowline walking loads. The operator was particularly adamant that no more than 6 inches of “forward” or "walking" motion be experienced by the PLET under normal operating conditions. Thermal stress simulation of the entire pipeline system showed that the flowline might exert walking loads on the PLET as high as 325 kips. As shown in Figure 6, the PLET anchor system must be installed with a bottom tension of at least 50 kips to satisfy this performance objective.

The third objective of these simulations is to define the relationship between the angle of the PLET relative to the seafloor at initial touchdown and the installed bottom tension. Significant damage to the PLET can occur if it lands on the seafloor at too steep of an angle. The simulations discussed in this section easily provided the data needed to establish a functional relationship between installed bottom tension and the angle of the PLET at touchdown. Figure 7 shows the predicted configuration of the PLET and the anchor chain at touchdown at two extreme bottom tension values. When the installed bottom tension is only 30 kips, the PLET angle is considered too large to land the structure safely.

4. Pipeline Lateral Buckling Simulations

Assessing the ability of a deepwater pipeline design to meet the fatigue performance targets requires the use of a detailed, global model of the flowline and its route along the seafloor.

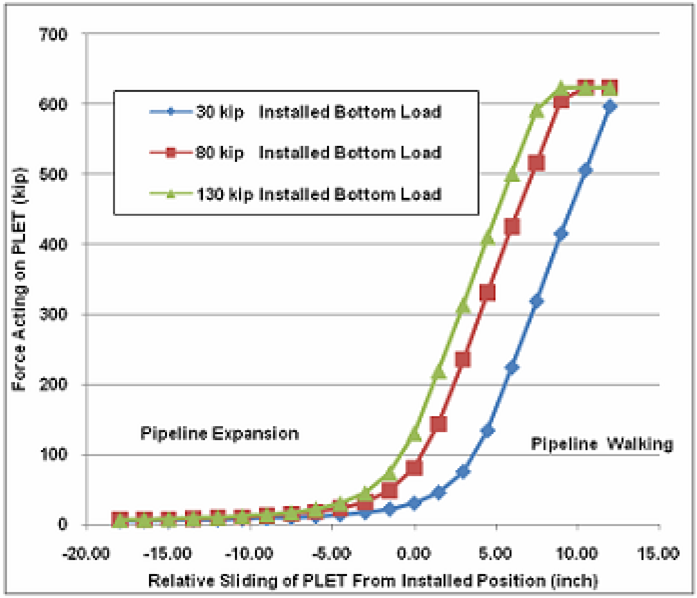

Figure 5. Nonlinear force-deflection curves for a PLET anchor system that has a 210 foot chain length between the PLET and anchor pile.

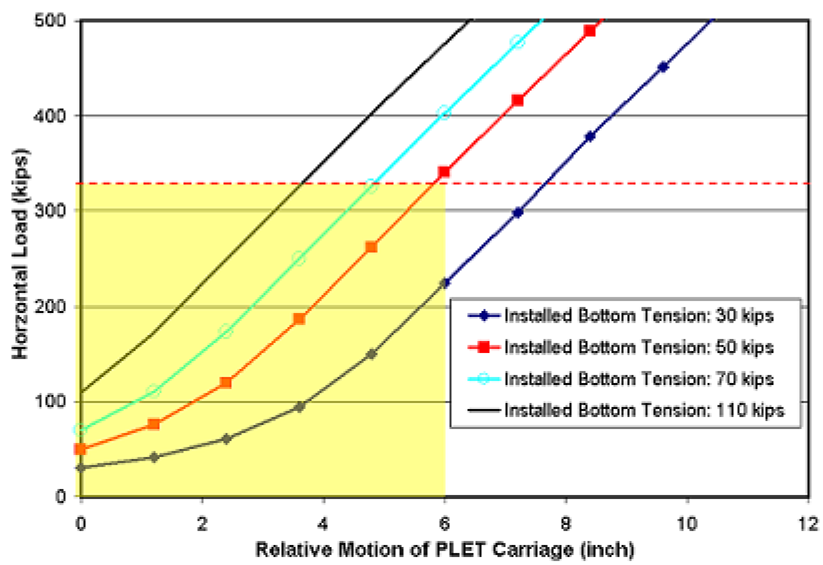

Figure 6. Allowable operating range for the PLET sliding mechanism.

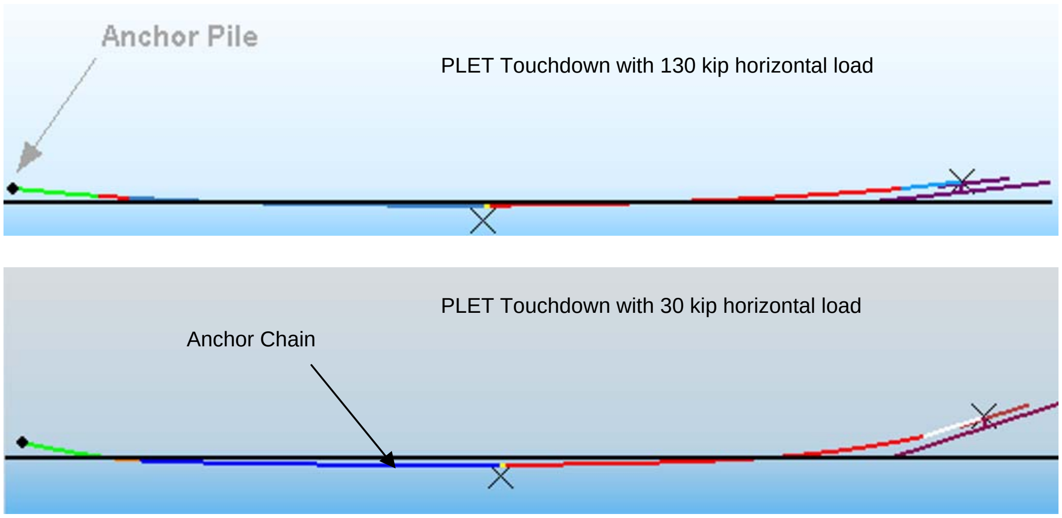

Figure 7. Comparison of PLET touchdown angle with different installation loads

For many deepwater projects, the 3D seafloor topography along the flowline route is used in the simulation. A proper fatigue study requires simulation of the installation and testing processes before studying the flowline's response to the complex cyclic loads created during operations.

4.1 Simulation Objective

Experience with deepwater flowline design has shown that the axial fatigue of the flowline, at the girth welds is one of the more difficult performance objectives to meet. While the thermal transients in the flowline generate large axial forces, these axial forces alone do not contribute all that much fatigue damage. Instead it is the tendency of these large forces to cause global lateral (or upheaval) buckling of the flowline, as seen in Figure 8, that pose the extreme fatigue design challenge. The main objective of the large global flowline simulation is to understand where and how the flowline will form lateral buckles and to assess the fatigue damage the buckles create. These simulations can also provide data on the potential for free spans to exist in the flowline after installation. Such free spans can pose an additional fatigue risk if they are subject to vortex-induced vibrations, created by ocean currents flowing across the span.

4.2 Summary of Simulation Model and Loading

The seafloor is modeled with rigid elements. The topography of the seafloor is obtained from sonar data and is typically formatted as elevation profiles parallel to the proposed pipeline route. The softened contact interaction model is used to simulate the nonlinear embedment vs. contact pressure relationship for the flowline. Depending on the properties of the soil forming the seafloor, the flowline's resistance to axial and lateral slip can have a very complex, nonlinear form. In many cases the `FRIC` user subroutine must be used to define the axial and lateral pipeline-seafloor friction.

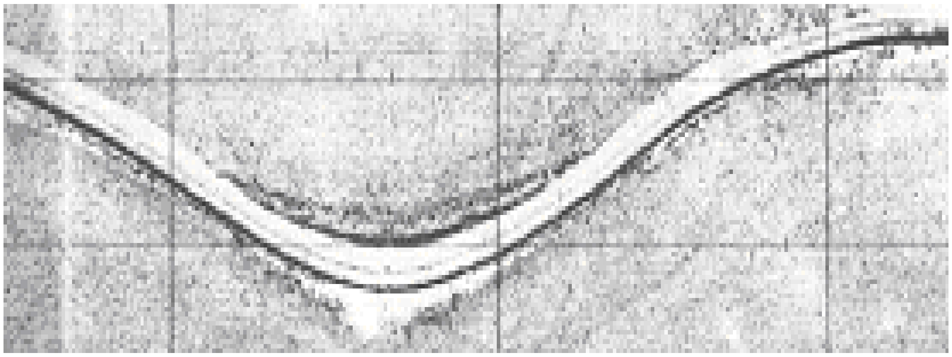

Figure 8. Observed flowline lateral buckling on seabed (plan view)

The flowline is modeled with PIPE31H elements. Twelve or sixteen sections points are used to capture the circumferential variation of stress and strain in the flowline. This increase in computational cost is needed to model unpredictable bending deformations in the lateral buckles.

The response of PLET anchor system is represented with a nonlinear spring element attached to the ends of the PIPE31H mesh. During the installation steps of the simulation, these spring elements representing the PLET anchor system are removed from the model. After the flowline has been installed on the seafloor they are added back into the model before the hydrotest and operational loads are applied. The hydrotest of the pipeline system is one of the last qualification activities before starting up the system. The test applies a very large internal pressure, using water, to ensure system integrity. The hydrotest pressure is much higher than the maximum allowable operating pressure (MAOP). Considerable axial and lateral deformations can occur during the test as large effective axial forces are created in the flowline. The operational loads, temperature and internal pressure profiles along the entire flowline, are determined using flow assurance simulation tools. The profile data are then used as loading conditions in the Abaqus simulation.

Obtaining convergence in a deepwater flowline simulation can be challenging because of the highly nonlinear interactions between the flowline and seafloor and the general instability of the flowline itself (the structure may be less than 35 cm across and yet is 20 km long). Experience has demonstrated that judicious modifications to the `HCRIT` value, to the convergence controls on the rotational degrees-of-freedom, and to the time incrementation parameters can improve the convergence rate with minimal impact to the solution's accuracy. In addition, the automatic static stabilization algorithm is used to help control the unstable lateral buckling displacements.

4.3 Results

The deformed configuration of a typical deepwater flowline is shown in Figure 9. The center image in the figure is a “global” view of one segment of the flowline mesh. The edges of the seafloor elements are displayed only when the “feature angle” is greater than 1 degree. Thus edges in the image indicate significant discontinuities in seafloor slope. The close up views in top right and bottom left corners of Figure 9 provide better views of the two lateral buckles that form in this segment of the flowline. The distance between the nodes shown on the flowline is approximately 75 feet; not all nodes are shown in Figure 9. The element length is approximately 3 ft in this model.

The design approach often used at Technip to satisfy the fatigue requirements in deepwater flowlines is to trigger controlled lateral deflections intentionally at appropriate intervals along the flowline route. Doing so provides greater confidence that Technip's flowline designs will achieve the reliability needed to operate safely for their design life, which may be 20 years or more. The controlled lateral deflections help ensure that the stress range during each loading cycle is minimal, thus limiting the fatigue damage. With uncontrolled buckling of a deepwater flowline, curvatures of the pipeline in the buckle can be much larger/sharper, increasing the stress and fatigue damage experienced.

Various methods exist for perturbing the flowline geometry so that lateral deflections reliably form at designated locations. "Sleepers" (short vertical upsets) can be placed under the flowline or a distribution of buoyancy module can be placed around the flowline to "lift" it off of the seafloor.

The effective axial force profiles along a flowline simulation are plotted in Figure 10. In this model, a buoyancy module is placed at a distance of 1500 meters from one end of the flowline. The flowline does not effectively buckle during the first operational cycle. However, the lateral deformations during the hydrotest and the early operational cycles accumulate and trigger a large global buckle in the third cycle. The buckle relieves much of the compressive force in the middle of the flowline. Ideally the buckle control measures used in a deepwater pipeline system lower the

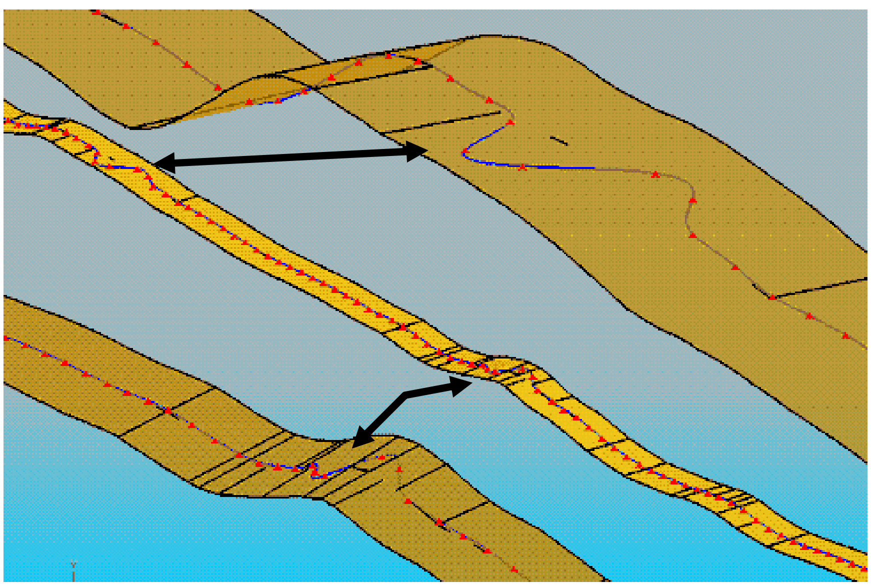

Figure 9. Changes in the slope of the seafloor trigger lateral buckles.

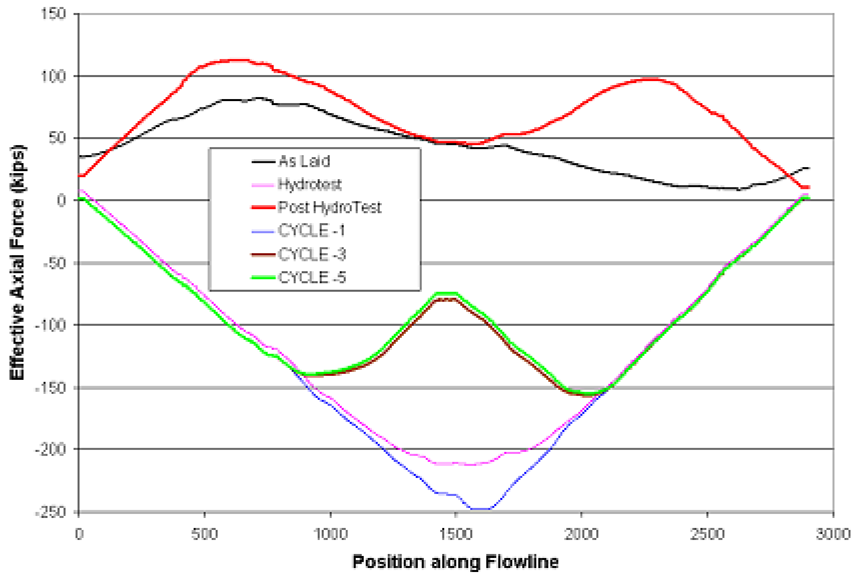

Figure 10. Effective axial force profiles in the flowline during various load steps in the simulation. A buoyancy module at position 1500 triggers a lateral buckle.

fatigue loads (i.e. stress ranges) to a level where the accumulated fatigue damage is within the tolerances for the flowline's girth welds.

Over the past year,Technip has begun creating scripting tools to mine the vast amount of simulation results created during a global lateral buckling simulation. The current tools search every section point in every flowline (PIPE31H) element to locate the largest stress range during each loading cycle. A loading cycle includes the heating and pressurization of the flowline, simulating "normal" operation, and the depressurization and cooling down seen when the pipeline system is shut down. The magnitude and location of the maximum stress range is noted and used in the fatigue calculations. Figure 11 shows the history of stress at two locations along the pipeline. These are locations with the largest predicted stress range in the flowline at different loading cycles. In the early loading cycles, the lateral deflections of the flowline were minimal and the largest stress range was predicted to be at the flowline-PLET connection. With each loading cycle lateral displacements were accumulating at a critical location along the flowline. Eventually, at about the 25th loading cycle, the perturbation of the flowline's geometry became large enough that a large buckle formed and the magnitude of stress range (and fatigue damage) increased greatly. Results like those in Figure 11 have caused a reassessment of how many loading cycles must be included in lateral buckling/fatigue design simulations.

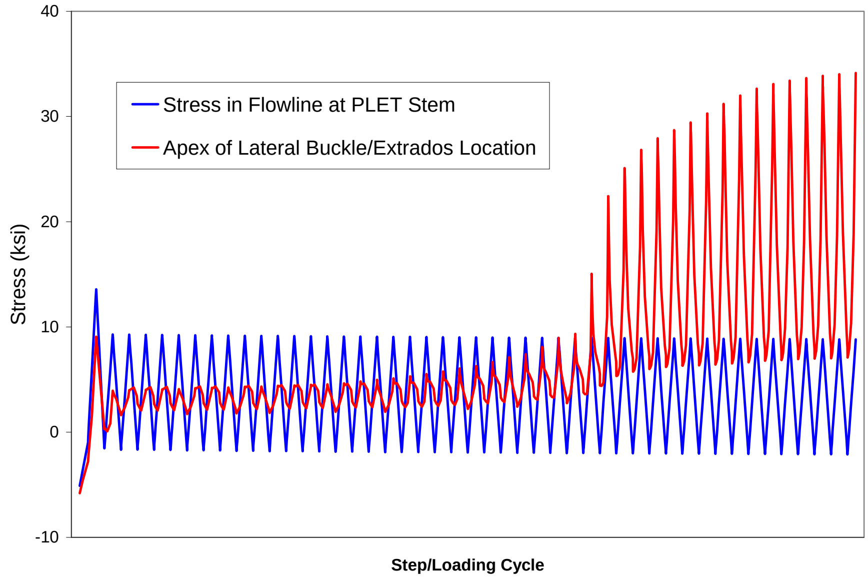

Figure 11. Axial stress history at two locations along the flowline.

5. Thermal Management of Deepwater Flowlines

5.1 Simulation Objectives

In many long, deepwater, production flowlines, maintaining the appropriate hydrocarbon temperature (even during long periods of no flow) is a critical design objective. Warm hydrocarbon fluids ensure their ability to flow by preventing hydrate formation or wax deposition. Deepwater projects will utilize a pipe-in-pipe (PIP) design for longer flowlines or situations where temperature control is critical and difficult to achieve. With a PIP design, the air and insulation materials in the gap between the inner (carrier pipeline) and the outer protective pipeline limit the heat loss from hydrocarbon fluid to the cold ocean water. However a PIP design can have several steel bulkheads that are welded to both the inner and outer pipes to constrain the relative axial motion of the two pipelines fully. These bulkheads can present a thermal design challenge as they rapidly conduct heat from the hydrocarbon to the cold outer surface of the PIP. A transient heat transfer simulation is used in ABAQUS to ensure that enough insulation is used around the bulkhead to maintain adequate hydrocarbon temperatures during a 22 hour no-flow condition.

5.2 Summary of Simulation Model and Loading

An axisymmetric model is used in the simulation. Only half of the bulkhead is modeled. A swept view of the mesh is shown in Figure 12. The pink material is the insulation applied over the PIP bulkhead. The air gap is shown in yellow, and the hydrocarbon fluid is shown in dark grey. Complete temperature continuity is assumed between the insulation layer and the outer pipeline. Thermal contact is used between the steel of the bulkhead and the air gap and between the inner wall of the carrier pipeline and the hydrocarbon fluid. Only conductive heat transfer is modeled in this simulation; no convection is allowed in either fluid. The thermal conductivity of the hydrocarbon is increased from its actual value in an attempt to offset this assumption. This class of design simulation is well suited for a Fluid Structure Interaction (FSI) simulation, and Technip will likely develop such models in the near future.

The outer surface of the insulation and the exposed outer pipe are assigned the temperature of the surrounding seawater, which is approximately 4^{o} C. The entire mass of hydrocarbon fluid is given an initial temperature of 43^{o} C. A steady step heat transfer step is used to calculate the thermal profile under “flowing conditions”. The initial temperature constraint on the hydrocarbon fluidis released and a transient heat transfer step is performed to predict the cooling of the hydrocarbon as heat is lost to the ocean.

5.3 Results

The thermal transients for a series of insulation designs, with increasing thickness, are shown in Figure 13. The temperature profiles are shown for both the inner diameter of the inner pipeline and the centerline of the hydrocarbon fluid. This data allowed the operator to select the most effective and cost efficient insulation material and design for the project’s requirements.

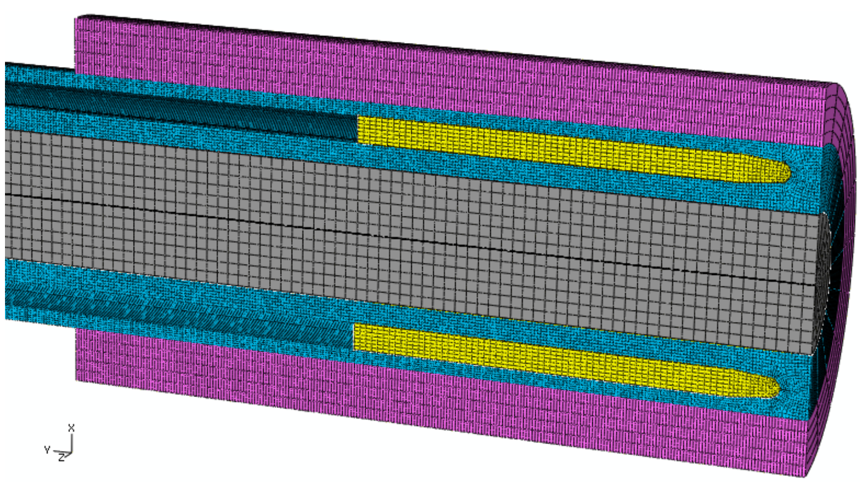

Figure 12. PIP bulkhead mesh (revolved through 180 degrees).

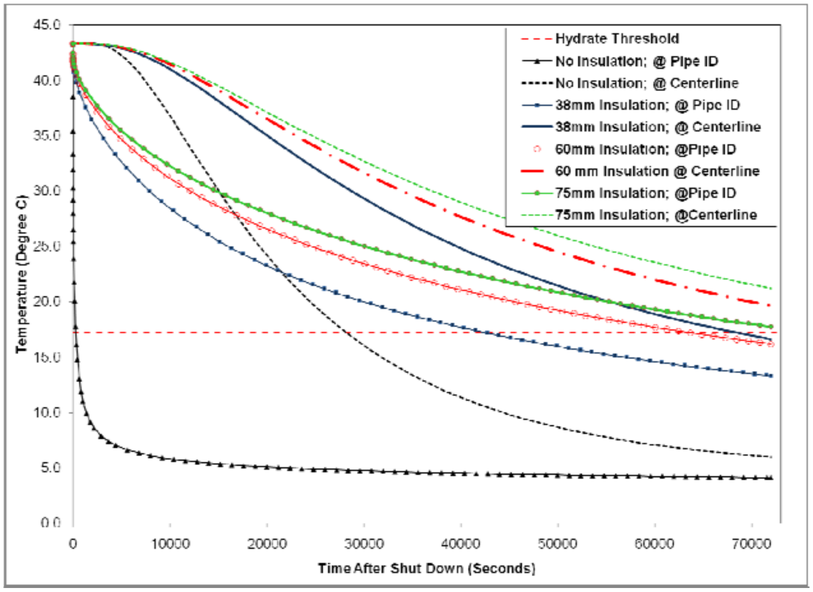

Figure 13. Thermal transient data for various insulation designs for the PIP bulkhead

6. Cavity Radiation Analysis of Riser Turret

Ultimately the objective of any deepwater project is to recover the hydrocarbons to the surface of the ocean. The structure that connects the surface facility, whatever its configuration, to the subsea components is called a riser. A floating production, storage and offloading strucutre, an FPSO, is one class of deepwater floating facility. It is basically a very large ship, typically with no propeller. It is quite common with an FPSO configuration to have a single riser convey all of the production flowlines, water or gas injection lines and umbilicals within a single, very large riser. There may be more than 10 individual pipelines in the riser to convey fluids or power to or from the subsea equipment.

6.1 Simulation Objective

As is so often the case in large complex projects, initial designs are created with one set of data and assumptions only to discover later in the project that data and assumptions have changed. The configuration of flowlines within the riser for one deepwater project is shown in Figure 14. The temperature (in degree C) of the four production risers and the gas export line are indicated in the figure; the export line is the coldest. The other four structures in the riser are the umbilicals that supply hydraulic power and electricity to the subsea equipment. These umbilicals cannot be subject to excessive temperatures. After fabrication of the riser components had begun, it was determined that the production flowlines would be 20% hotter than the initial design considered. The objective was to determine if the umbilicals would exceed their maximum allowable temperature.

6.2 Summary of Simulation Model and Loading

This simulation was conducted in ABAQUS because of its cavity radiation functionality. The simulation was a simple, 2D, steady state heat transfer analysis. The air between the flowlines and umbilical was modeled only with conductive heat transfer. A thermal contact model was used to provide for heat transfer from the flowlines to the air gap.

6.3 Results

Contours of the radiation flux from the production flowlines are shown in Figure 15. These contours pass the reality check; considerably more radiation heat flux occurs between the cold outer shell of the riser turret and the hot production flowlines than is seen between those flowlines and the warmer umbilicals. The variation of the umbilical surface temperatures are shown in Figure 16. There is a very large temperature gradient around the surfaces of the umbilicals. This simulation predicts that the umbilical surface temperatures could exceed 85 ^{o} C. The umbilical engineering team and the flow assurance team will utilize this data to determine if forced convective cooling needs to be retrofitted to the riser turret design.

Such a change in thermal management methodology would be a strong driver to create an FSI model for this deepwater design challenge.

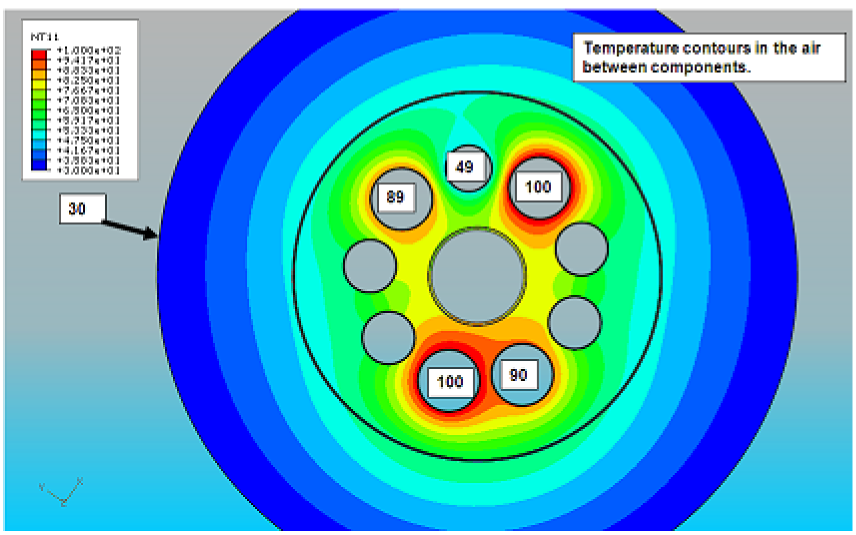

Figure 14. Temperatures assigned to the (4) production flowlines and the gas export line in the riser turret model.

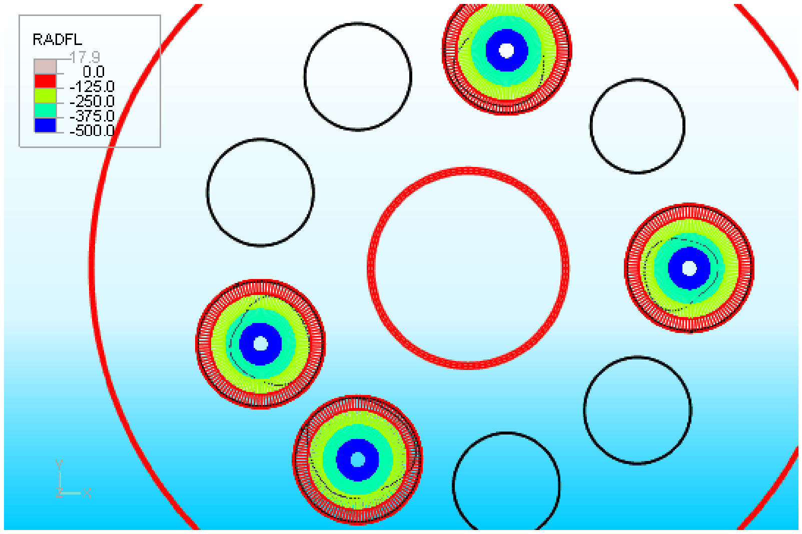

Figure 15. Contours of radiation heat flux from surface of the production flowlines.

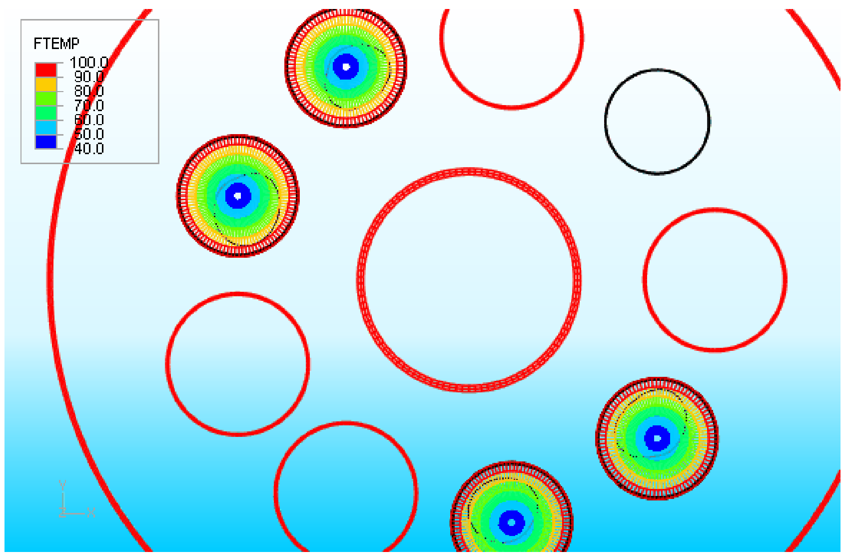

Figure 16. Umbilical surface temperature (C).

7. The Future of Simulation at Technip

Technip as an organization has a distinguished 50 year history of developing and deploying technologies that unlock new growth opportunities. Both the company's technical experts and corporate executives recognize the import role that advanced engineering simulations play in all of Technip's major business activities, not just the deepwater hydrocarbon market. Management strongly encourages collaboration between simulation experts from various engineering disciplines: flow assurance, pipeline engineering, onshore process engineering, subsea installation and manufacturing. Technical seminars that bring together staff from across Technip's global offices to share knowledge and new ideas are rapidly becoming an annual tradition. Considerable expense is being taken to develop and deploy internal technical training to capture the intellectual property and hard learned experience of Technip's network of experts. Such training will help prepare future Technip staff to continue expanding use of advanced engineering simulations.

8. References

1. Probyn, I, A. Dobson, and M. Martinez "Advances in 3-D FEA Techniques for Metallic Tube Umbilicals" Proceedings of the 7th International Offshore and Polar Engineering Conference., pp. 848-861, Lisbon, 2007.

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