Finite Element Analysis for Structural Performance of Offshore Platforms

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Abstract: Finite element analysis (FEA) technology has become an increasingly important tool for evaluating the structural performance of offshore platforms. This includes using FEA to perform strength and stability checks and optimization of structural design when subjected to design loads such as gravity, wind and waves, and also to perform failure investigation for offshore platforms when subjected to special loading conditions such as earthquakes and vessel impacts. Modeling of offshore platforms has been challenging due to the complexity of structural designs and the large volume of elements used in the model. This paper reviews design approaches and requirements for offshore platforms, and presents several considerations in modeling the structural performance of offshore platforms using Abaqus, including selection of element types for various components, selection of material models, modeling of masses, modeling of foundations, and simulation of various load conditions. A numerical example with a generic GBS (gravity based structures) offshore platform is included to demonstrate the use of the proposed modeling approach.

Keywords: Accident Load, Beams, Bending, Buckling, Constitutive Model, Contact Interaction, Design Optimization, Drilling, Dynamics, Earthquake Load, Failure Investigation, GBS (Gravity Based Structure), Gravity Loading, Impact, Mechanisms, Naval Architecture, Offshore Drilling, Offshore Platform, Rig, Ring Girders, Semi-submersible, Simulation-based Design, Skin Plates, Soils, Soil-Structure Interaction, Stick Models, Stiffeners, Substructures, TLP (Tension Leg Platform), Vessel Impact, VPD (Virtual Product Development), Wave Load, Wind Load.

1. Introduction

An offshore platform is a large structure with facilities to drill wells, extract and process oil and natural gas from under the seabed, and temporarily store product until it can be brought to shore for refining and marketing.

Although submerged oil wells were drilled from platforms as early as 1890s, the first modern offshore drilling/production platform was installed in 1947 off the coast of Louisiana at a depth of 6.1 m (Offshore, 1997). To date several thousand offshore platforms have been installed around the world. The safely producing depth of water has reached to 2,100 m, and the safely drilling depth to 3,050 m (Utt, 2004).

There are mainly five different types of oil platforms and rigs.

- **Fixed platforms** are typically built on concrete and/or steel legs anchored directly onto the seabed, supporting decks with space for drilling rigs, production facilities, and crew quarters. Conventional fixed platforms include steel jacket and compliant towers. In addition, GBSs (Gravity Based Structures) can be considered as an unconventional type of the fixed platform.

- **Tension leg platforms (TLP)** are floating facilities that are tied down to the seabed by vertical steel tubes called tethers.
- **Semi-submersibles** have hulls (columns and pontoons) of sufficient buoyancy to cause the structure to float, but of weight sufficient to keep the structure upright.
- **Spars** are large diameter single vertical cylinders supporting decks, moored to the seabed.
- **Floating production systems** often refer to FPSO (floating production, storage, and offloading systems) consisting of large monohull structures equipped with processing facilities.

Figure 1 shows two examples of typical offshore platforms (GBS and semi-submersible) based on public domain information.

(a) Troll A GBS platform off the west coast of Norway (Wikipedia, 2012a)

(b) P-51 semi-submersible platform off the Brazilian coast (Wikipedia, 2012b)

Figure 1. Examples of offshore platforms.

This paper presents a review of design approaches for offshore platforms, focusing on several considerations in development of FEA models for offshore platforms. An analysis example for a GBS platform is included to demonstrate the application of the proposed approach.

2. Design Considerations

2.1 Design Requirements and Design Loads

Design of an offshore platform often involves three steps: foundation design, naval architecture, and structural design.

Foundation Design

For fixed platforms, the loads resulting from structural weight and environmental conditions must be resisted by the piles or the bases at and/or below the seabed. The design of pile penetration for piled structures and the design of base size for GBSs will depend on the weight of platforms, environmental loads and soil characteristics. A geotechnical report is required based on studies of in-situ and laboratory tests of soil samples from the desired locations.

Naval Architecture

Naval architecture of an offshore platform includes tasks to address hydrostatics requirements (a structure's ability to maintain afloat while it rests in water) and hydrodynamics requirements (a structure's resistance towards motion due to flow of water around). The design needs to examine static stability, which is the ability of a structure to restore itself to an upright position after being inclined by wind, wave, or other loading conditions. Intact stability design requires the righting (stabilizing) moment of a structure be sufficient to withstand wind/wave moments in normal operational configuration. Damaged stability design requires a structure withstand flooding of designated compartments with wind/wave moments, which is often referred as analytical "worst intact condition".

Structural Design

Structural design involves conducting structural analysis for design validation, and selection of construction materials based on the validation results.

Structural design validation typically includes a strength check to ensure sufficient structural resistance related to material yield strength for all structural components, a stability check to ensure the sufficient resistance to buckling for all structural components under compression, and a joint check to ensure sufficient connecting capacities between various components. In addition, advanced design validations may be required for fatigue and corrosion resistances, and impact of special and accidental loads.

The design loads for offshore platforms typically include the following:

- Static loads:
    - Dead weights (weights of structure in air, equipment permanently installed on platform, and ballast, etc.)
    - Hydrostatic forces (buoyancy and hydrostatic pressure on structural components below waterline, etc.)
- Dynamic loads:
    - Operational loads (weights of drilling/production facilities and living quarters, and forces generated from operations such as drilling and crane operation, etc.)
    - Environmental loads (wind, wave, ice, thermal and earthquake, etc.)
    - Construction loads (loads arising from fabrication and installation of the platform and its components)
    - Accidental loads (e.g. collision with vessel, dropping objects, fire or explosion, etc.)

Environmental loads, especially wave loads, usually dominate the design of offshore platforms.

Codes, standards and recommended practices typically used for designing offshore structures include BS 6235 (1982), API RP 2A-WSD (2000), and DNV-OS-C101 (2011) for steel structures and DNV-OS-C502 (2010) for concrete structures.

2.2 Simulation-based Designs

Traditional approaches for designing offshore platforms were primarily based on experience, by distributing global loads to individual components and assessing each component's resistance to loading. This traditional approach may still exist to some extent, but industry has increasingly relied on simulation-based design.

The use of finite element analysis (FEA) in the marine and offshore industry stretches back to the late 1950s when a computer model was used to analyze curved grillages of ship bulkheads (McVee and Reijmers, 2005). The development of commercial FEA programs in 1970s and 1980s, especially the addition of contact algorithms and the introduction of CAE/CAD systems in 1990s, allowed engineers to use more sophisticated analysis tools to solve more complicated structural problems in offshore structures. During that period, analysis range expanded from linear elastic modeling to non-linear analyses such as plastic deformation, buckling, fatigue, and impact of contacting objects. Today, virtual product development (VPD) environments are well established for the marine and offshore industry, and FEA relating to all aspects of computational structural mechanics (e.g. strength and buckling), computational fluid dynamics (CFD), and multiphysics is an important part of VPD process. Noticeably, the FEA program Abaqus has played a significant role in simulating marine and offshore structures (Simulia, 2009).

After a few decades of practice, FEA technology has proven to provide more rational designs with increased safety and reduced construction and operation cost for offshore structures. Yet challenges remain as offshore structures typically involve numerous complex structural components such as trusses, beams, plates, girders and ring-beams; and numerous mass elements such as self masses and added masses. Putting all these structural and mass components in one model for the static and dynamic analyses is a difficult task. Model optimization and management are required, and reasonable assumptions should be made in the development of FEA models for offshore platforms.

3. FEA Modeling Considerations

3.1 Modeling Requirements

Development of an FEA model requires considerations for modeling structures (including foundation), modeling material behavior, modeling masses, and modeling loads. Considerations for modeling structures (e.g. selecting element types), materials and masses will be presented in the following sections. Considerations for modeling loads will be described in an example case with selected load cases. To better describe the proposed modeling approach, a generic GBS platform is presented as an analytical example. Note that the modeling approach described in this paper is presented as a general concept and is suitable for other types of platforms.

A gravity-based structure (GBS) is a support structure held in place by gravity. GBS offshore platforms are often constructed of steel and reinforced concrete, with tanks or cells which can be used to control buoyancy. When a GBS platform is built, it is towed to its intended location and sunk to the seabed. The structural columns/legs of the GBS are used to support the top operating deck which is often called the topsides. Figure 2 shows a schematic of an analytical generic steel GBS platform that has the topsides (represented by a simple framework) supported by four drilling/utility legs (by stiffened plates) connected to the base on the seabed.

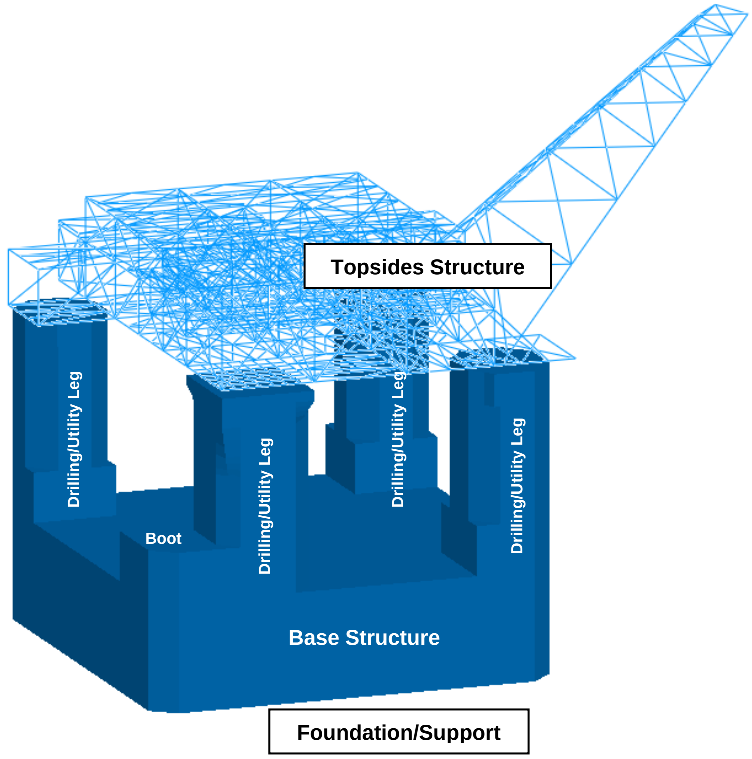


Figure 2. Schematics of a steel GBS platform.

3.2 Considerations for Modeling Structures

3.2.1 Overall Considerations

The primary purpose of developing an FEA model for an offshore platform has been to perform strength check related to material yield of all structural components. It is also desirable that an FEA model can be used to predict the global and local buckling of various structural components under compressive stress conditions. In addition, special analyses may be required for fatigue, pushover, vessel impact assessments, etc.

For the purpose of the above mentioned analyses, all structural and mass elements must be well represented in the model. Therefore, simplifications and assumptions must be made to keep the integrated model size to a manageable level. For example, low order element types and coarse mesh can be used for areas of less importance/concern. In general, element meshes should be refined enough to capture stress concentration where geometric sharp corners may exist; and local buckling where members are under compressive stress conditions. Several sensitivity analyses may be required to determine the final mesh to be used in the model.

In order to capture the buckling of compressed members, the effect of non-linear geometry has to be considered in the analysis.

3.2.2 Topsides Structure

Topsides structure refers to the surface hardware installed, including the oil production plant, the accommodation block and the drilling rig. Stick models using beam elements are extensively used for modeling the topsides structures.

Element type of 2-node linear beam in space is recommended for modeling the topsides. The connections between the topsides and the legs can be modeled using kinematic constraint equations.

3.2.3 Legs and Base

The legs and the base are the primary structural components supporting the topsides in a GBS platform. Depending on the materials (concrete or steel) used, modeling considerations can be different as described in the following.

Concrete Caisson

Concrete GBS platforms are often built as caisson type supported directly by the uppermost layers of soils. The water-tight caisson provides buoyancy during construction and towing, and also acts as a foundation structure during operation. Reinforcements and/or pre-stressed reinforcements are often used in building concrete caissons.

Element type of linear three-dimensional continuum (solid) is recommended for modeling the concrete caisson. These elements can be coupled with REBAR option to model the presence of reinforcements. The pre-stressed reinforcement can be defined using the initial stress conditions combined with the REBAR option for these elements.

Steel Leg and Base

For steel GBS platforms, the topsides structure is typically supported by steel legs that are connected to a steel base on the seabed. There are also corbels near the top section of legs to enhance the support to the topsides, and boots near the bottom section to connect to the base. Steel legs, including corbels and boots, are built with stiffened plates combined with closely-spaced ring girders and vertical and horizontal beams.

A steel base, typically rectangular, is composed of several bulkheads in both directions of the base. The bulkheads in the base are also built with stiffened plates.

Element type of 4-node shell is recommended for the steel plates, while element type of 2-node linear beam in space for the ring-girders. Since the ring-girders are often attached to the stiffened plates, the beam elements can be defined using offset nodes next to the shell element family.

Beam elements can also be used to model the stiffeners for the stiffened plates. However, due to very close stiffener spacing, typically less than 1 meter apart, it virtually impossible to use beam elements here. Alternatively, the REBAR option can be used to model the stiffeners. The area of rebar in shell elements can be defined to match the stiffener area, while the fractional distances of rebar can be defined to match the out-of-plane bending stiffness of the stiffeners.

3.2.4 Foundation

The soil foundation to support GBS platform is often modeled using spring elements in vertical and two horizontal directions. Linear and/or non-linear spring properties can be defined to the spring elements.

3.3 Consideration for Modeling Materials

For design validation analyses, elastic material models, defined by Young's modulus and Poisson's ratio, are often used. A designer will review the analysis results to examine whether the effective stress in steel members reaches steel yield capacity, or whether the tensile stress in concrete members reaches tensile stress limit to initiate cracking.

When advanced analyses are required to further examine the offshore platform performance beyond steel yielding and/or concrete cracking, inelastic material models must be used. For steel members, isotropic/kinematic hardening material models are recommended with the post-yield behavior calibrated using coupon test results. For concrete members, smeared cracking material models are recommended with the compressive yield behavior calibrated using uniaxial and confined compressive coupon tests, and the tension stiffening effect calibrated using fracture energy test results.

3.4 Consideration for Modeling Masses

3.4.1 Self Masses

Self masses here refer to dead weights in air of structural members comprising the platform. They can be defined as densities of members through the property definition, and activated during the gravity analysis step.

3.4.2 Added Masses

Added masses here refer to additional masses attached or potentially attached to the structural members. The added masses include entrained masses such as ballasts, water tanks and dumps, and potentially attached masses such as a volume of water outside the structure that may potentially move with the structure during vibration.

Added masses are typically modeled as directional point masses using lumped mass elements.

4. Analysis of Example Steel GBS Platform

4.1 Example Model

A generic steel GBS platform as shown in Figure 2 is analyzed here to demonstrate the application of the presented modeling approach. The base is assumed to be 90×90 meters wide and 25 meters deep (the bottom of base is 45 meters below the water level), while the legs are assumed to be 18×18 meters wide and 45 meters deep (with 20 meters below the water level). The stiffened plates used for the legs and the base are assumed to be composed of skin plates of 30 mm thick and T-section stiffeners spaced at 1 meter apart. The total weight of the structure (including added masses) in the vertical direction is assumed to be approximately 300 Mt. The steel material is assumed to have Young's modulus of 200 GPa, Poisson's ratio of 0.3, and yield strength of 360 MPa.

The FEA model for the generic example platform uses approximately 30,000 shell elements with rebars for stiffened plates, over 20,000 beam elements for topsides frameworks and leg ring-girders, and over 10,000 soil spring elements for the foundation. In addition, over 20,000 point mass elements are used to model added masses.

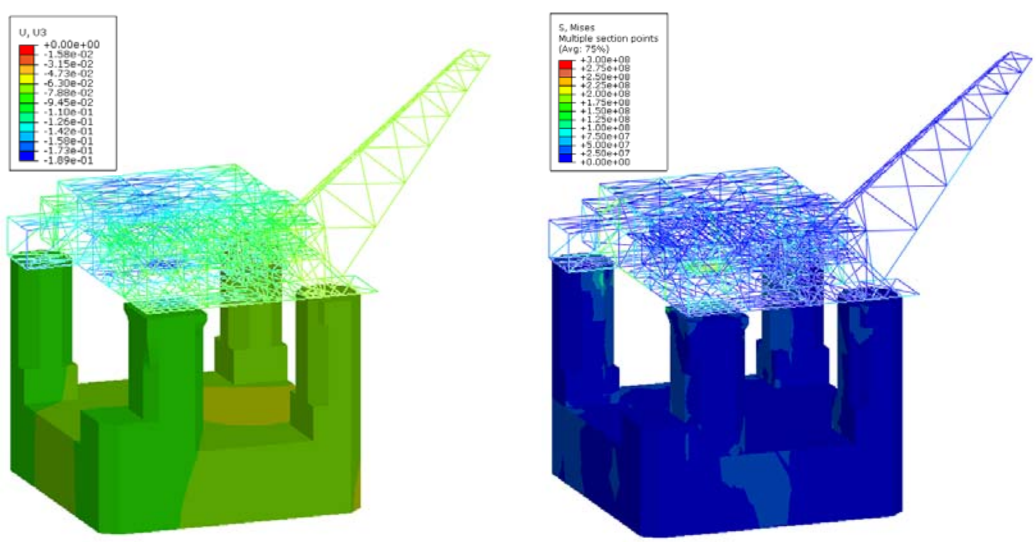
The following sections present a few selected analysis load cases including gravity loads, natural vibration, and vessel impact. Since the model size was optimized, these analyses were performed using Abaqus v.6.11 on personal computers. The gravity load and natural vibration analyses used CPU time of approximately 1 minute, and the vessel impact analysis used approximately 10 minutes.

4.2 Gravity Load

One of the most important load cases is gravity load, which is often modeled using static analysis as the first load step in order to activate self masses in the model and determine the initial settlement of the platform under the dead weight and buoyancy loading. While all the mass elements will be activated in the analysis, all the exterior surfaces below the water level will be subjected to hydrostatic pressures to simulate the buoyancy effect.

Figure 3 presents the contour plots of vertical displacement and effective stress resulting from the gravity load. The left side of Figure 3 shows relatively uniform vertical displacement of the base ranging from 0.06 m to 0.08 m downwards, suggesting the gravity load had overcome the buoyancy load and the GBS is able to relatively uniformly settle on the seabed. Note that the topsides structure shows more vertical displacement with the maximum movement of 0.19 m downwards.

The right side of Figure 3 shows the maximum effective stresses in the legs and the base is less than 100 MPa, which is significantly less than the assumed yield strength, suggesting all the leg and base members are satisfied for the strength check under the gravity loading. No buckling (column buckling or plate buckling) is observed for any member under the gravity loading.



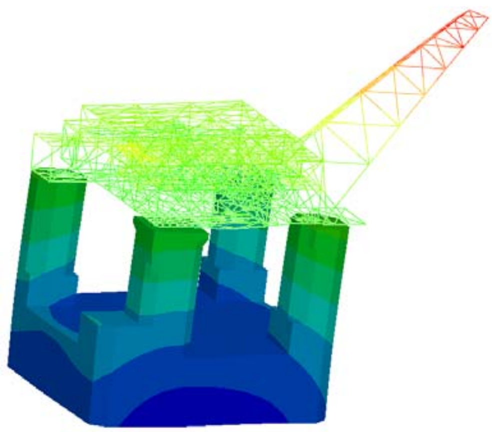
vertical displacement (m) effective stress (N/m^2)

Figure 3. Vertical displacement and effective stress under gravity loads.

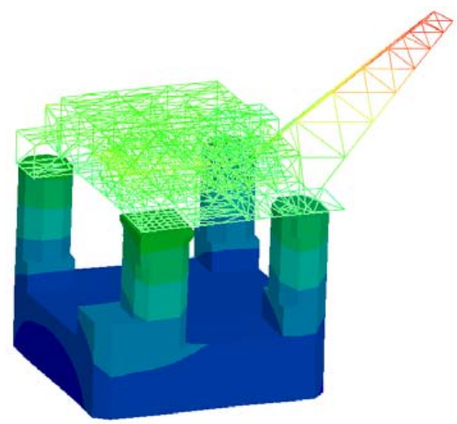
4.3 Natural Vibration

Once the masses in the structure are activated, natural vibration analysis can be performed. The natural vibration analysis identifies the primary vibration modes with associated frequencies. The results can be further used for the modal analysis to simulate the wind, wave and earthquake loading effects.

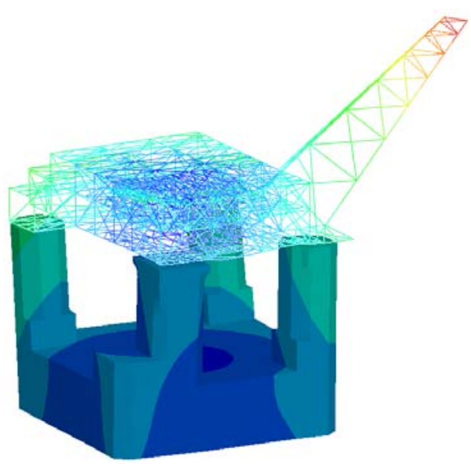
Figure 4 shows the first four vibration modes with the associated frequencies of 0.603, 0.648, 0.903 and 1.28 s^{-1}. As shown in the figure, the first two vibration modes are global rotating of GBS about horizontal axes. The third vibration mode shows twisting of the system, and the fourth mode shows bending motion.



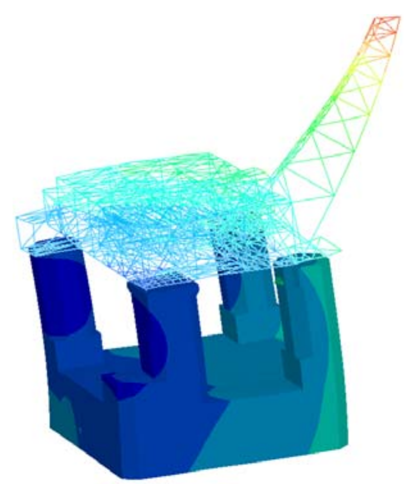
Mode 1 (Frequency = 0.603 s^{-1})



Mode 2 (Frequency = 0.648 s^{-1})



Mode 3 (Frequency = 0.903 s^{-1})



Mode 4 (Frequency = 1.28 s^{-1})

Figure 4. First four modes and associated frequencies for natural vibration.

4.4 Vessel Collision Impact

A non-linear dynamic analysis using time integration was performed for a special load case where a vessel accidently collides one of the legs of the platform. The vessel was assumed to have a lump mass of 5 kt with an initial speed of 3 m/s. In the model, the vessel was modeled as a rigid surface with a spherical head of 2 meter radius. During the impact, the interaction between the ship and the leg structure was modeled by contact surfaces.

Figure 5 shows the analysis results of vessel speed and impact force as a function of time. As shown in the figure, the impact period is less than 0.3 second, as the vessel speed changes from 3 m/s advancing towards the leg to -1.6 m/s moving away from the leg after the impact. The maximum impact force was found to be 230 MN.

Figure 6 shows the contour plots of effective stress at three different stages of the event: prior to the impact, at the maximum impact loading, and after the impact. It shows that at the maximum impact loading, the effective stress rises significantly over the entire impacted leg and towards part of the base next to the leg. The peak effective stress exceeds the yield strength of 360 MPa, causing plastic deformation in the impacted area. As a result, the effective stresses are not fully relieved in the damaged area even after the vessel moves away from the leg.

This example demonstrates that vessel collision can potentially cause permanent damage to legs, and should be considered in the design. Another important result to examine would be the shear force transferred from the impacted leg to the topsides. This shear force can be used to assess whether the connection capacity between the legs and the topsides is sufficient to sustain the vessel impact.

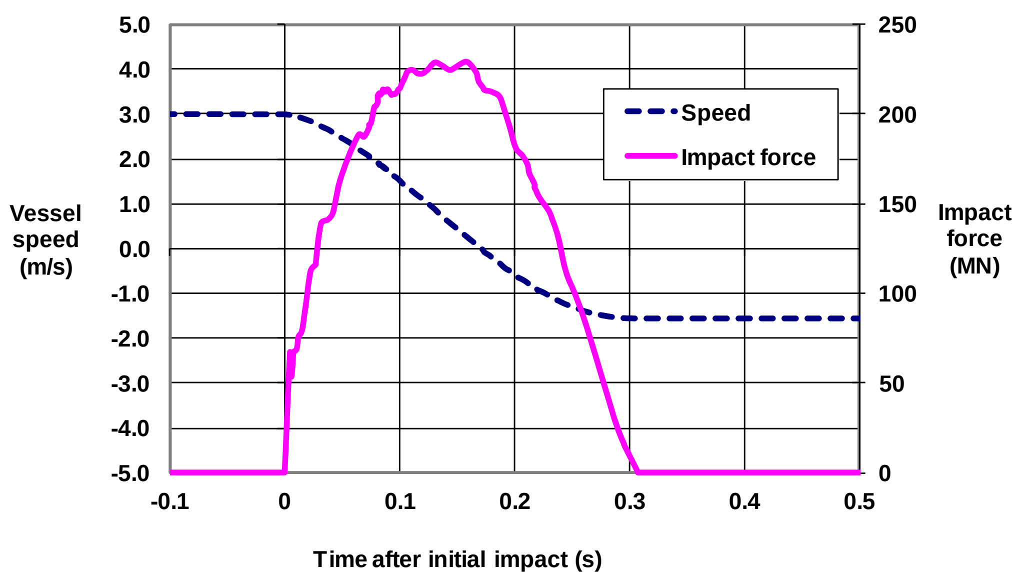
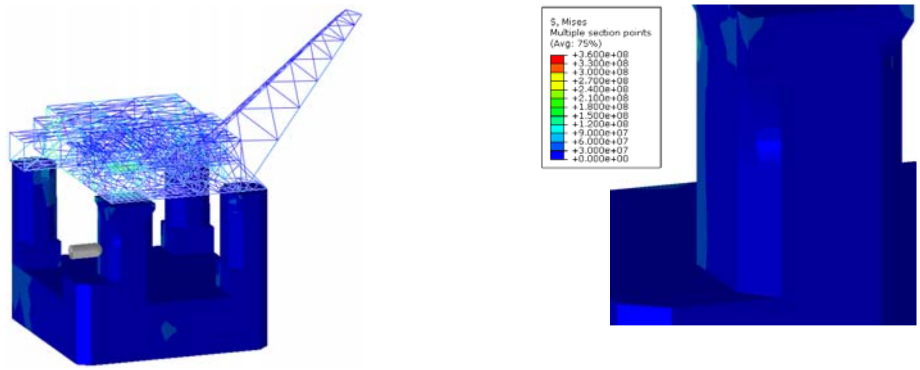
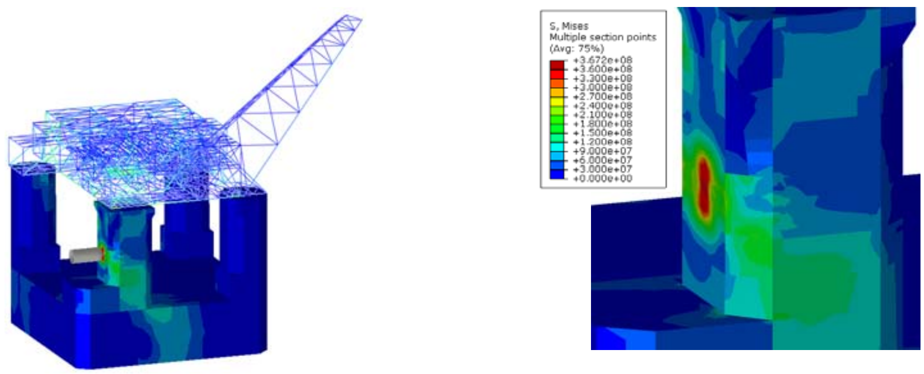


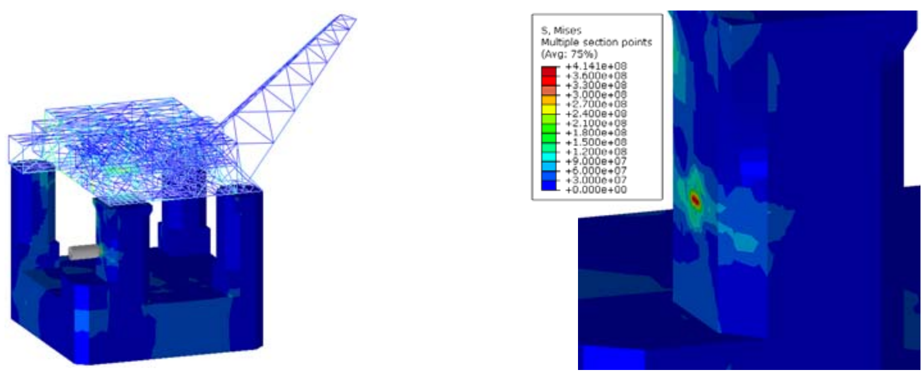
Figure 5. Vessel speed and impact force as function of time.



(a) prior to impact



(b) at maximum impact



(c) after impact

Figure 6. Effective stress (N/m^2) at three different stages of vessel impact.

5. Summary and Conclusions

This paper reviews design approaches and requirements for offshore platforms, and presents several considerations in modeling the structural performance of offshore platforms using Abaqus, including selection of element types for various components, selection of material models, modeling of masses, modeling of foundations, and simulation of various load conditions.

To demonstrate the use of the proposed modeling approach, a numerical example with a generic steel GBS (gravity based structures) offshore platform is presented. The analysis results suggest that under gravity loads, the example generic platform shows uniform settlement on the seabed, which is a typical required feature of GBS platforms. The natural vibration analysis shows that the primary vibration modes of a GBS platform can consist of global rotating, twisting and bending. Modal analysis can further be performed to examine the impact of wind, wave and earthquake loads. The vessel impact analysis suggests that the impact of a vessel can cause permanent damage to legs, and should be included in the design considerations of offshore platforms.

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