Structural simulation of a Horizontal Pressure Vessel for predicting stress under extreme weather conditions

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Abstract: Offshore containers are exposed to the movement caused by wind, ocean currents, and unpredictable weather conditions so a good structural resistance is required for them. A dynamic analysis has been developed using Abaqus/Explicit to study the structural response of a horizontal pressure vessel mounted in Floating Production Storage and Offloading (FPSO) topsides in the Gulf of Mexico (GOM) coast. The model includes fluid behavior of crude oil inside the container for which the linear Us-Up Hugoniot equation of state is used. The viscosity of the oil was varied according to temperature. A single adaptive meshing rule is also used to prevent distortion of fluid elements.

The structural resistance of the horizontal pressure vessel must satisfy the ASTM, ASME and API Standards to prevent catastrophic failure under extreme weather conditions. The vessel is made of a SA516-70 steel, for which mechanical properties are taken into account. The analysis considers thermal effects of fluid and weather conditions by using an appropriate heat transfer coefficient. Wind velocity is expressed in terms of an external pressure load. Stress results have been compared with a stress distribution obtained from a simulation of a pressure vessel located on a fixed platform. This type of simulation is very important since no historical data exist for this FPSO location.

Keywords: Offshore, FPSO (Floating Production, Storage and Offloading), pressure vessel, FEM (Finite Element Model).

1. Introduction

Oil exploration and production companies are exploring further out into the sea and deeper under the ocean floor, at depths greater than 900 m to tap into pockets of oil and natural gas around the world. Since 1975 oil industry started exploring in deepwater to obtain energy resource developing new technology equipment. The FPSO (Floating Production Storage and Offloading System), a floating platform as shown in Figure 1a, receives the fluid from the undersea oil reservoir via flexible risers through a turret mounted swivel, then the fluid is separated to oil, gas, and water by the process equipment, and usually packaged into modules and secured on the deck of the vessel (*production function*). The separated oil is stowed in the vessel's tanks (*storage* *function*) for periodic offloading to a shuttle tanker (*offloading function*) in deepwater's. In addition to these functions, the FPSO system has other functional components to ensure that the unit can be operated in a safely offshore (Gámez, 2007). The mooring system and turret are required to keep on station the FPSO, the riser and swivel receive the fluid; but they will not be consider in this study. Topside structures are composed of different equipment such as pumps, vessels, pipes, as well as other components whose principal function is to separate, compress and mix oil extracted from undersea obtaining the grade needed.

A determination of maximum stress in pressure vessels of the FPSO is required since they are subjected to a different set of conditions that are established by design (ASTM) and operation (ASME) standards. These containers are located on floating platforms in the Gulf of Mexico and they are exposed to movement caused by wind, ocean current and varying weather conditions, increasing its structural resistance in susceptible areas. Due to the complex geometry, loads and boundary conditions of this kind of containers, it is necessary to perform a simulation using the Finite Element Method (FEM).

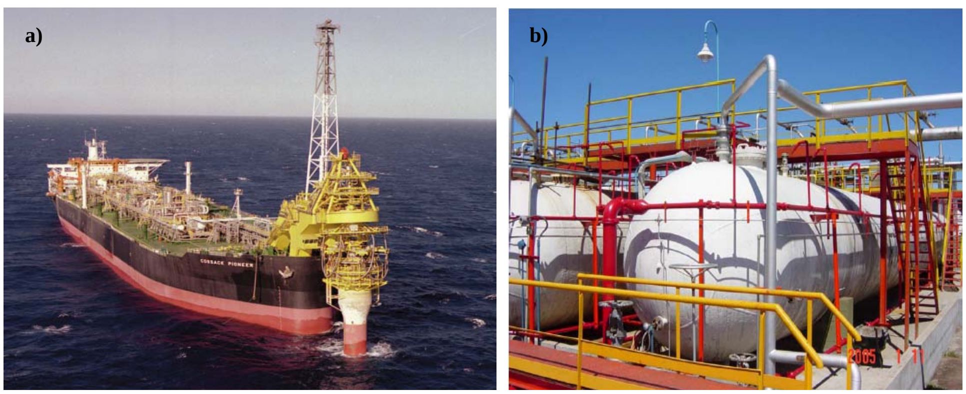

Figure 1. a) Mexico FPSO, b) Pressure vessel under study.

2. Environment conditions

It is necessary to consider the FPSO locations. These floating platforms are designed to be operating 20 years before failure assuring reliability in each of the components that compose them; actually some disconnectable mooring systems are in service in Chinese and Australian waters so evacuation is possible in the event of an incoming typhoon or cyclone. However, due to their complex installation procedures and costs**,** these kind of mooring systems have become a less preferred option. The FPSO "Yùum K'ak'náab" is located on the Gulf of Mexico coast sea at 105 miles off the coast of Ciudad del Carmen of the Campeche Sound (Shimamura, 2002). The name of the vessel means "Lord of the Sea". It will be the first FPSO in the Gulf of Mexico and will handle 15- 20% of Mexico's oil production.

2.1 Climate Review

Climate conditions are important variables to determine the reliability of equipment. In the Campeche Sound, rains are abundant during the summer with temperatures ranging from 10 to 40ºC during the year. Figure 2 shows the recorded wind speed of the last 20 years. Wind reached velocities up to 111 km/hr according to Weather Underground.

Wind speed is used as input to understand the evolution of stresses in susceptible areas of failure on the process equipment (vessels) of the FPSO. To take into account the effect of wind velocity the concept of kinetic energy (KE) per unit volume is used Equation 1:

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\rho V v^2 \qquad (1)$$

Where V is the volume and v is the velocity. Kinetic energy per unit volume gives the total pressure which will be applied at the surface of the vessel.

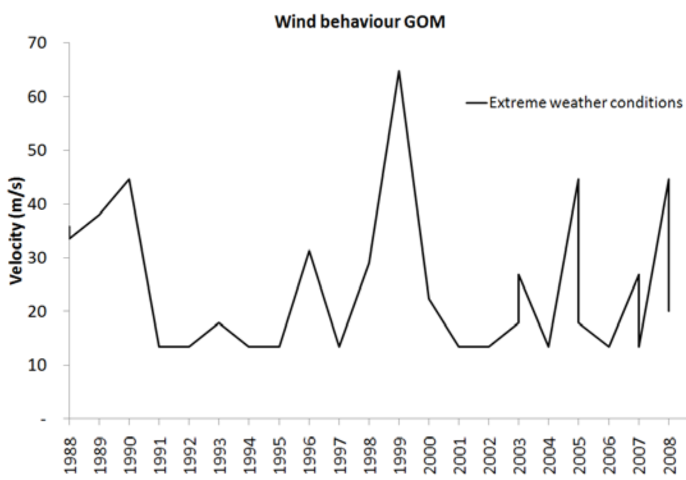

Figure 2. Wind velocity over last 20 years.

The other variable to consider is the weather temperature. Convection to air is considered for this analysis. The heat transfer coefficient, *h*, is calculated using Equation 2:

$$h = Nu(k/D) \qquad (2)$$

Where Nu is the Nusselt's number, *k* is the thermal conductivity, and *D* is the vessel diameter. The complicated flow pattern across a cylinder greatly influences heat transfer. The average Nusselt number for cross flow over a cylinder is calculated by using Equation 3 (Cengel, 2003):

$$Nu = CRe^m Pr^n \qquad (3)$$

Where C is a constant, Re is the Reynolds' number, Pr is the Prandtl's number, m and n depend of flow pattern. Table 1 shows the air properties considered for this work.

Table 1. Air properties.

Temperature (°C)	Density (kg/m^3)	Thermal Conductivity (W/m°C)	Kinematic Viscosity (Pa-sec)	Prandtl Number
10	1.246	0.02439	1.43E-05	0.7336
20	1.204	0.02514	1.52E-05	0.7309
30	1.164	0.02588	1.61E-05	0.7282
40	1.127	0.02662	1.70E-05	0.7255
50	1.092	0.02735	1.80E-05	0.7228

3. Component selected for the study

3.1. Oil cylinder

The oil cylinders under ASTM specification are available in four grades having different strength levels. The vessel (here referred to TH-0) is made of a SA516-Gr70 steel, with a specified yield strength of 207 MPa and a specified ultimate tensile strength of 620 MPa. The vessels are designed for usage with a maximum allowable pressure of 1.186MPa. Figure 3 illustrate the dimensions of the container and Table 2 shows the parameters considered for this study.

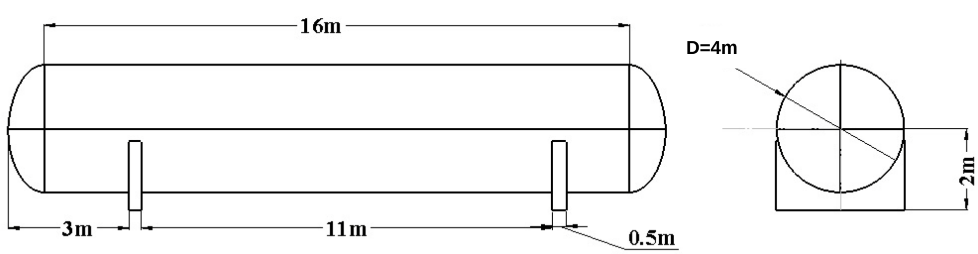

Figure 3. Lateral and front view of oil cylinder TH-01.

Table 2. Parameters of the vessel.

TH-01 (Oil buffer tank)	
Diameter	4.03 m
Wall thickness	0.01 m
Total length	18.2 m
Total capacity	223.3 m^3
Operation pressure	1.08 MPa
Operation temperature	43 °C
Maximum operating temperature	73 °C
Contents	Crude oil

3.2 Crude oil

The model includes fluid behavior of crude oil which is considered as an incompressible and inviscid material. To model such behavior, an equation of state (EOS) is used. For this problem the linear U_s-U_p Hugoniot equation of state is used (Hibbit, 2008). This equation has the form:

$$p = \frac{\rho_0 c_0^2 \eta}{(1-s\eta)^2}\left[1-\frac{\Gamma_0 \eta}{2}\right]+\Gamma_0 \rho_0 E_m \quad (4)$$

$$\eta = 1-\frac{\rho_0}{\rho} \quad (5)$$

Where p is the pressure, $K=\rho_0 c_0^2$ is the elastic bulk modulus, and ρ_0 is the density. In order to get a hydrostatic bulk response, s and Γ_o are considered to be zero.

The wave speed (c_0) of crude oil is 1481.16 m/s considering a bulk modulus of 1.93 GPa (Shashi, 2004); but to control the distortions of fluid elements a value of three orders of magnitude less was chosen so the wave speed is 47.65 m/s and the crude oil will still behave as an incompressible medium. This will avoid an overly stiff response. The deviatoric response of the fluid is governed by Newtonian viscous fluid model using Eos shear, viscous option available in Abaqus.

Hourglass control forces are calculated based on the shear stiffness of the material. Thus, in materials with extremely low or zero shear stress such as inviscid fluids, de hourglass forces calculated based on the default parameters are insufficient to prevent spurious hourglass modes. Therefore, a sufficiently high hourglass scaling factor is used to increase the resistance of such modes.

Table 3 shows the kinematic viscosity in centistokes as function of temperature. Density of crude oils ranges from 820 to 880 Kg/m^3 a maximum value is selected. From this value the shear viscosity is calculated (in Pa-sec) from Table 3.

Table 3. Kinematic viscosity of crude oil as function of density and temperature (Buryakovsky, 2001).

Average Density (kg/m^3)	Temperature (ºC)				
	10	**20**	**30**	**40**	**50**
820	5.6	4.2	2.8	2.8	1.4
830	5.6	5.6	4.5	3.9	2.5
840	11.2	9.9	5.6	5.74	4.3
850	14	12.9	7.9	5.8	5.2
860	20.5	13.7	9.4	6.5	5.6
870	22.4	20.3	12.4	10.5	7.6
880	39.2	23.2	18.3	11.7	10.3

4. Modeling

A dynamic thermo-mechanical analysis was developed to evaluate the structural response of the vessel. Abaqus/Explicit scheme was selected due to the facility to handle complex contact interactions.

Under excessive static and dynamic internal pressure, the vessels may experience severe plastic deformation and eventually may collapse (Nakayama, 1980), so this study will help to find techniques to prevent failure and to ensure safe operation of pressure vessels considering temperature changes. This can be performed by limiting the stress, strains and design loads of vessels within the allowable values after the failure modes of vessels have been determined.

4.1 Geometry

The vessel geometry with constant thickness is shown in Figure 2. Each part was created in a CAD software and then exported and assembled in Abaqus/CAE. The container is mounted on the bases foundation plate located on the floating platform.

4.2 Materials

The vessel is made of SA516-70 steel. Table 4 shows the mechanical and thermal properties considered for this steel (ASME code, 2007). The thermal properties are average values and these are not considered dependent of temperature.

Table 4. Steel Properties.

SA516-70 steel	
Mechanical properties	**Thermal properties**
E=207 GPa	Thermal conductivity=50 W/mºC
v=0.3	Specific heat=460 J/KgºC
Yield stress=207 MPa	Density=7800 Kg/m^3

4.3 Mesh

The fluid and the supports are modeled with C3D8RT elements (8-node thermally coupled brick), and the vessel and the base plate are modeled with S4RT (4-node thermally coupled doubly curved shell) elements. For fluid elements the following parameters were used in the input file:

```
*SECTION CONTROLS, NAME=oil_set, KINEMATIC SPLIT=orthogonal,
HOURGLASS=stiffness
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The total number of elements considered in the analysis is 107267 and the total number of nodes is 118812. Figure 5a shows the discretized model.

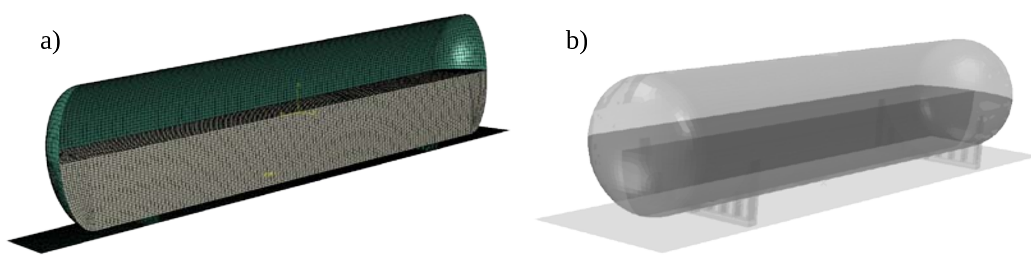

Figure 5. a) Discretized model, b) Oil vessel modeled in a virtual environment.

A single adaptive mesh domain that incorporates the oil is defined. A frequency parameter on the *ADAPTIVE MESH value of 5 increments was selected, and the number of mesh sweeps used to smooth the mesh is increased to 3 from a default value of 1. The default values are used for all other parameters and controls. No mass scaling was considered.

5. Loads and boundary conditions

5.1 Loads

A determination of the internal distribution of stresses is required in civil and mechanical engineering, for the study and design of structures, tunnels, dams, mechanical parts, and structural frames among others, under prescribed or expected loads.

The internal pressure is calculated by Abaqus using Equation 4. Also an external pressure which considers the wind velocity is a applied following the description in section 2.1. Figure 4 shows the pressure loading conditions.

Frictionless contact is defined between the fluid and the tank using the general contact algorithm in Abaqus/Explicit. The crude oil is subjected to gravity load.

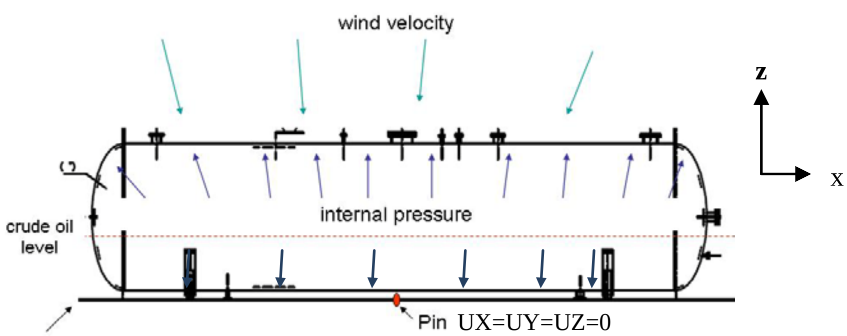

Figure 4. Vessel boundary conditions.

5.2 Initial and boundary conditions

Symmetry boundary conditions are used to model only half of the geometry in order to reduce computational time. The vessel was exposed to a rotary motion about a pin node (for which UY=UX=UZ=0, where U is the displacement) through a periodic function constraining the base plate in the middle. The rotation was prescribed as:

$$UR2 = 0.01396 cos 5.5t \quad (6)$$

Where UR2 is the rotation about Y axis. An initial geostatic stress field is defined to equilibrate the stresses caused by the self-weight of the oil. Thermal convection to air was calculated as mentioned in section 2.1. For crude oil the initial temperature has a value of 43 °C and for the container the value is 26°C as shown in Figure 5.

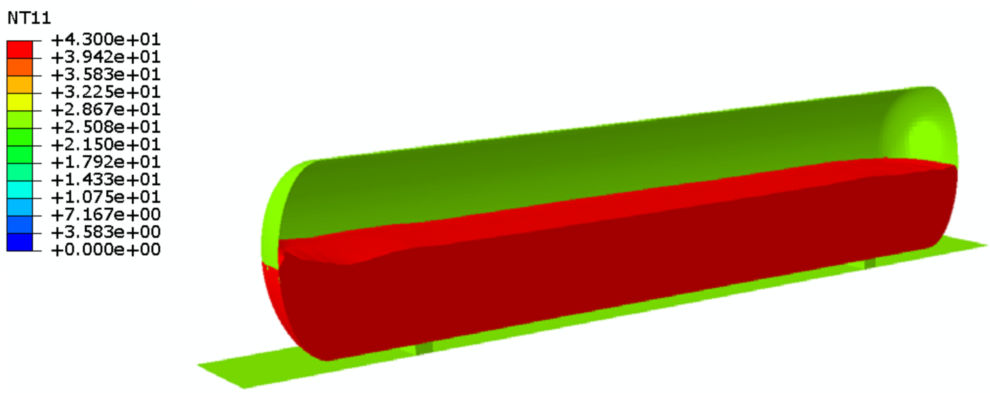

Figure 5. Initial temperature distribution (in °C).

5.3 Simulation

The procedure of this study takes FEM as a starting point for the optimization of pressure vessel design. Simulations were done using Abaqus/Explicit to analyse the stress distribution of the vessel under operation conditions plus environment media (wind velocity, temperature and floating platform). Parameters such as material type, design loads, internal pressure, temperature and fluid behaviour were taken into consideration for the numerical analysis as explained in sections 5.1 and 5.2. The first simulation considered the base plate as fixed (static simulation) and the other one considered a periodic rotation assigned to the reference point (pin node) of the base plate. These simulations were used for comparison.

6. Results

For the first simulation (fixed platform) a maximum von Misses stress of 105 MPa was found at near supports. Figure 6 shows the von Mises stress distribution (in Pascals). This result is due to the fact that the supports receive all the loading of crude oil weight plus wind pressure conditions while keeping the base plate fixed.

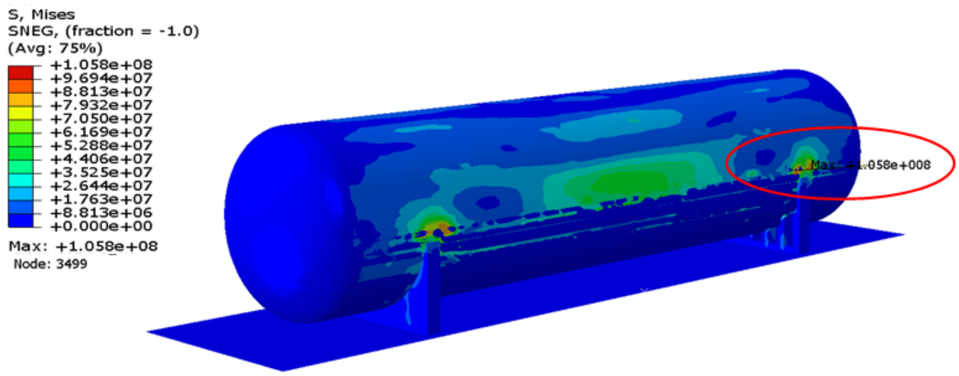

Figure 6. Static vessel results.

Figure 7 shows von Mises stress distribution (in Pascals) for the second simulation (dynamic case) showing a maximum stress value found near the junction of the vessel with the supports (marked with a red line). It can be seen that a maximum value of 175 MPa is reached at that location.

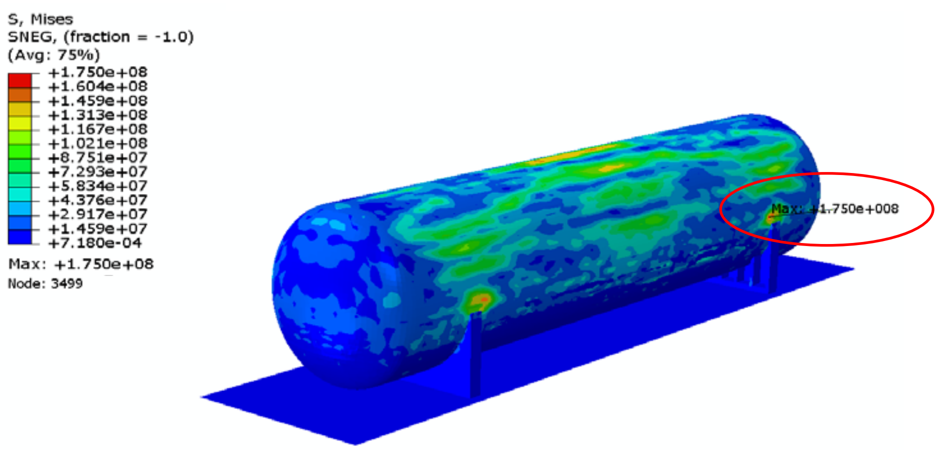

Figure 7 . Von Mises stress distribution (in Pascals) considering wavy motion of base plate.

Figure 8 shows the magnitude of the vertical displacement (in meters) during the simulation showing oil movement considering wavy motion of base plate.

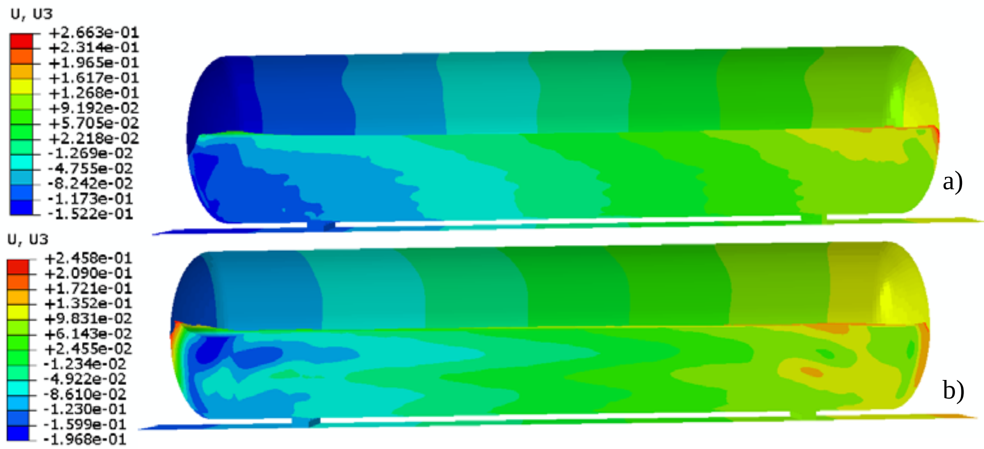

Figure 8. a) Vertical displacement distribution (in meters) at 30% of total simulation time b) Vertical displacement distribution (in meters) at 85% of total simulation time.

7. Conclusions and future work

This study has shown an alternative manner to analyze the structural behavior of pressure vessels located in FPSO systems. The results of stresses in the dynamic simulation were more critical than for the static case, therefore this will help in suggesting to ASTM, ASME and API codes a new methodology for the design and maintenance of containers considering another materials with different mechanical properties and more complex weather conditions in order that containers located in a floating platform can support operational and load design conditions.

More work has to be carried out considering mechanical and thermal cycle loads to perform a fatigue analysis to get more realistic and quantitative results.

8. Acknowledgements

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