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Finite Element Analysis of Floating, Production, Storage and Offloading (FPSO) Vessel Subjected to Sudden Crash (Impact) Load

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Abstract- The need for deep-water development and continuous exploitation of depleting shallow water reserves has spawned new forms of offshore structures like FPSO (Floating, Processing, Storage and Offloading) vessel for production and storage of oil or gas. Many offshore structures have been designed to cater for these needs but FPSO due to its storage capacity and ease of installation is suitable for smaller fields which can be depleted quickly and avoids the need for installing permanent and expensive pipelines. However, for continuous production and offloading of oil, DP shuttle tanker which has flexibility of loading and transporting oil to any destination is required since FPSO would not hold crude products for a longer period. Thus, tandem offloading operation from FPSO to DP shuttle tanker is essential. This work aimed at studying the effect of crash (impact) load on FPSO in tandem offloading operation was achieved by modeling an FPSO using SolidWorks then subjected to impact/collision at different velocities of DP shuttle tanker which ranges between 0.6m/s to 200m/s. ANSYS Explicit Dynamics was used to analyze parameters like deformation/displacement, stress and equivalent elastic strain under the impact (collision) loading. The results obtained from the simulation reveled that at DP shuttle tanker velocities 5m/s and 20m/s the crash load did not reached the damage point on both FPSO and DP shuttle tanker. At velocities above 20m/s there is a great damage after collision. In addition, as the velocity of DP shuttle tanker increases, the values of those parameters also increase. This implies that at low velocity of DP shuttle tanker in tandem offloading operation, the risk of damage after impact/collision is lesser and at velocity greater than 20m/s there is tendency of heavy damage after collision resulting to stern damage on FPSO and consequent penetration and flooding in the machine room.

Key Words: FPSO, DP shuttle tanker, Pipelines, Tandem offloading, ANSYS Explicit Dynamics

I. Introduction

FPSO simply means Floating, Production, Storage and Offloading which is a ship-shaped vessel similar to trading tanker, is one of the offshore platforms currently being used in the offshore industries. The development of the offshore industry commenced with the use of fixed structures. As development accelerated with the discovery of oil and gas in deeper water, the use of floating structure have become popular and commonplace, among those floating structure is FPSO. This ship-shaped floating structure has ability to produce, store and offloading the oil but it does not have the drilling capability [1]. FPSO system represents an important solution for the exploitation of the deep-water oil and fields. The floating type of platform used designed to gather oil or gas produced from the seabed as well as from nearby platforms and to store it until the oil or the gas are offloaded onto shuttle tanker or sent through a pipeline.

The main reasons for choosing FPSO as the offshore platform are due to its storage capacity and the provision of large topsides particularly in marginal deep water fields. Offloading operations require a safe relative positioning between two vessels under the action of environmental forces such as wind, waves and current. These can subject the vessel to quartering or beam seas that can significantly influence the response of FPSO [2]. A transportable platform, FPSO vessels are popular as they can be easily moved and installed to nearby platforms and also allow for easy transportation of oil to tankers or pipelines. Once an existing field has been depleted FPSO can then be moved to other locations. This makes them suitable for smaller fields which can be depleted quickly and avoids the need for installing permanent expensive pipelines.

An FPSO vessel is fixed to a central anchoring point by means of the mooring system, which permits free rotation of the unit to account for wind and wave action. The crude oil is pumped onto the FPSO vessel through riser lines fastened to the seabed. Once on board, the oil is passed through separators to separate the gas and to remove water and sand, after which the product is stored. Typically, the tank capacity is one million barrels. At regular intervals, a shuttle tanker calls to collect the crude oil for processing ashore [3]. A Shuttle tanker is a specialized ship designed to transport oil from offshore oil field to onshore refineries. Shuttle tankers are often used as an alternative to pipelines in harsh climates, remote locations or deep waters [4].

Loads on Offshore Structures

Loads are generally estimated using the classification rules or by direct hydrodynamic calculations. The loads that an offshore Structure experiences can be roughly divided into two parts [5];

Static Loads: These consist of loads, which do not vary with time, or even if they vary, the effect of time could be neglected. The hydrostatic pressure, Weights of the offshore platform components, Cargo and Ballast loads come under this category. In addition to these, wave moments and forces coming due to component parts are also considered as static loads.

All these loads can be group into Dead weight e.g. weights of structure in air, ballast and Hydrostatic forces.

Dynamic Loads: These are the loads, which vary with time, and the variation is substantially large because a dynamic analysis is generally required. The hydrodynamic Pressure due to waves, wind Loads and other operational loads like loads due to underwater Explosion, Machinery operational loads etc., are the loads which are considered as dynamic loads.

Dynamic loads can be group into; Operational Loads: this includes the weights of drilling/production facilities, living quarters and forces generated from operations such as drilling and crane operation.

Environmental Loads: this includes the wind, wave, ocean current, ice, thermal and earthquake. These loads especially the wave loads usually dominate the design of offshore platform.

Construction Loads: these are the loads arising from fabrication and installation of the platform and its components.

Accidental Loads: it includes Ship collision hazards, Dropped object hazards, Fire hazards and Blast hazards. Both the above categories of loads, would act on offshore structures/vessels and its components from time to time.

Impact Load/Collision. Impact load is dynamic load i.e. it varies with time. An example is caused by ships collision. Impact occurs when one object strikes another, such that large forces are developed between the objects during a very short period of time. In ship impacts on offshore structures/vessels, the loads are governed by the kinetic energy of the striking ship. The kinetic energy may be estimated from the mass of the ship, including the hydrodynamic added mass, and the speed of the ship at the instant of impact. If the collision is non-central, a part of the kinetic energy may remain as kinetic energy after the impact. The remainder of the kinetic energy has to be dissipated as strain energy in the installation and in the vessel. Generally this involves large plastic strains and significant structural damage to the installation, the ship or both. Given that the collision event takes place, the loads and consequences of the collision event must be determined. A number of analysis tools and procedures for collision analyses have been developed and presented during the last decades.

The main concern in ship impacts on fixed platforms is the reduction of structural strength and possible progressive structural failure. However, the main effect for buoyant structures is damage that can lead to flooding and, hence, loss of buoyancy. The measure of such damages is the maximum indentation implying loss of water tightness. However, in the case of large damage, reduction of structural strength, as expressed by the indentation, is also a concern for floating structures [6].

Contact incidents between FPSO/FSU and shuttle tanker have clearly demonstrated a high likelihood of contact between vessels in tandem offloading. The large masses involved, i.e. the high potential impact energy, make the collision risk large.

Hence it becomes essential to consider the loads correctly and analyze the structure accordingly. Use of ANSYS software which is a finite element analysis tool, makes the process of application of load very simple and manageable and also the chances of errors in combining the loads are eliminated.

Finite Element Analysis

The finite element method (FEM) is the most popular simulation method to predict the physical behavior of systems and structures. Since analytical solutions are in general not available for most daily problems in engineering sciences, least square approximation techniques and numerical methods have been evolved to find a solution for the governing equations of the individual problem [7-9]. This research investigated and analyzed the displacement/deformation, force, stress and strain on 3-D model of FPSO and DP shuttle tanker after impact/collision in tandem offloading operation using finite element analysis software known as ANSYS® Explicit Dynamics.

ANSYS® Explicit Dynamics. If your product needs to survive impacts or short-duration high-pressure loadings, you can improve its design with ANSYS® explicit dynamics. The ANSYS explicit dynamics suite enables you to capture the physics of short-duration events for products that undergo highly nonlinear, transient dynamic forces. ANSYS® explicit dynamics software is an extension to ANSYS® structural mechanics suite, it shares the same graphical user interface (GUI), serving mechanical engineers who need to study highly complex problems especially ones with high strain rates and other complications that are difficult to solve with general-purpose implicit solution methods [10].

FPSO in Tandem Offloading Operation

The tandem offloading means that the shuttle tanker is positioned at some distance, e.g. 80 m, behind the FPSO as shown in Fig. 1. The two vessels are physically connected by a mooring hawser and a loading hose through which cargo is offloaded. The tanker may position itself by its own dynamic positioning system so that the hawser is not tensioned (DP mode), or by applying certain astern thrust and maintain a small tension on hawser (Taut hawser mode). Tug or standby vessel assistance may be required for taut hawser mode. The DP tankers have greater uptime in harsh environments and therefore are widely applied in the North Sea. FPSO and DP shuttle tanker in tandem offloading operation can in principle be summarized into the following five operational phases, from the point of view of the tanker [11].

1. Approach: tanker approaches FPSO stern and stops at a wanted distance.
2. Connection: messenger line, hawser and loading hose are connected.
3. Loading: oil is transferred from FPSO to tanker.
4. Disconnection: manifold is flushed, and loading hose and hawser are disconnected.
5. Departure: tanker reverses away from FPSO stern while sending back hawser messenger line, and finally sails away from field.

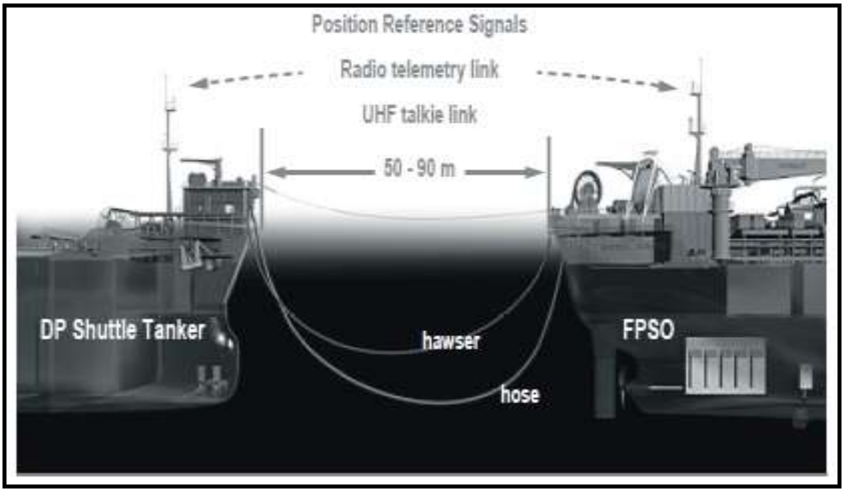


Fig.1 A Typical FPSO and DP Shuttle tanker in a tandem offloading operation

II. Methodology

Material Data

Since both the FPSO and offloading tanker are ship-like offshore platforms, structural steel, which has the building material properties for both FPSO and DP shuttle tanker, is selected. Table 1 and Table 2 show the material properties of Structural Steel.

Table 1 Structural Steel Constants

Density	7.85e-006 kg/mm^3
Coefficient of Thermal Expansion	1.2e-005 C^{-1}
Specific Heat	4.34e005 mJ/ kg C
Thermal Conductivity	6.05e-002 W/ mm C
Resistivity	1.7e-004 ohm mm

Table 2 Structural Steel Isotropic Elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
22	2.0e+005	0.3	1.6667e+005	76923

Assumptions

i. The FPSO structure is assumed to be inside water.
ii. The FPSO is fixed.
iii. The DP shuttle tanker collides with the FPSO in tandem offloading operation.
iv. The Impact occurs in tandem offloading operation between FPSO to DP shuttle tanker.

Governing Equations

Considering the law of conservation of Momentum

$$M_1V_1 + M_2V_2 = (M_1 + M_2)V \qquad (1)$$

where M_1 =FPSO mass
M_2 = Offloading tanker mass

V_1= FPSO velocity

V_2= Offloading tanker velocity

V= Velocity after impact

Since the FPSO is fixed during tandem offloading operation, equation (1) becomes

$$V = M_2V_2/(M_1 + M_2) \qquad (2)$$

Impulse

$$Ft = M * V \qquad (3)$$

where F= Impact Load/force which is very high

t= time of impact which is very small

$M= M_1+M_2$

From eqn. (3), Impact force/load can be calculated.

To calculate the deformation/displacement, stress and equivalent elastic strain of FPSO after impact, theory of Elasticity is used [12].

Considering an infinitesimal element on the FPSO after impact as shown in Fig. 2, the summation of forces in vertical and horizontal axes gives;

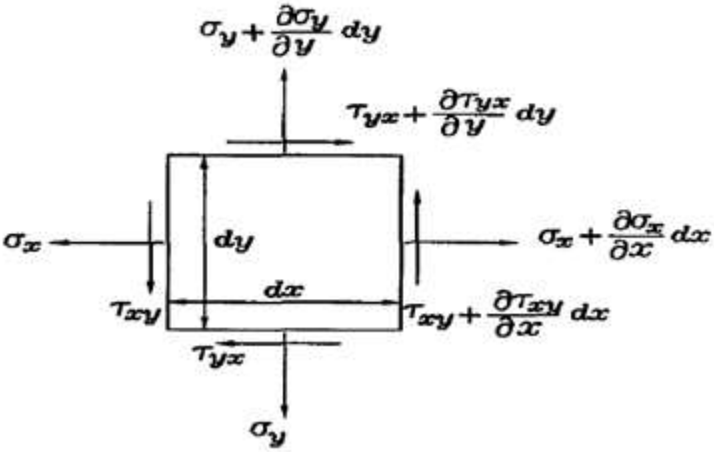


Fig. 2 Free body diagram of infinitesimal element

$$\sum F_x = \left(\sigma_x + \frac{\partial \sigma_x}{\partial x}\right) dxdy - \sigma_x dxdy + \left(\tau_{xy} + \frac{\partial \tau_{xy}}{\partial y}\right) dxdy - \tau_{xy} dxdy + f_x dxdy = 0 \qquad (4)$$

$$\sum F_y = \left(\tau_{xy} + \frac{\partial \tau_{xy}}{\partial y}\right) dxdy - \tau_{xy} dxdy + \left(\sigma_x + \frac{\partial \sigma_x}{\partial x}\right) dxdy - \sigma_y dxdy + f_y dxdy = 0 \qquad (5)$$

Simplifying eqns. (4) and (5) yield

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + f_x = 0 \qquad (6)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y = 0 \qquad (7)$$

For an Isotropic material, the constitutive equation which relates stresses and strains together is

$$\{\sigma\} = [D]\{\epsilon\} \qquad (8)$$

where $\{\sigma\} = \{\sigma_x \sigma_y \tau_{xy}\}^T$ denotes the stress and $\{\epsilon\} = \{\epsilon_x \epsilon_y \gamma_{xy}\}^T$ is the strain

The material property matrix $[D] = \frac{E}{1-v^2}\begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \frac{1-v}{2} \end{bmatrix}$ is for plane stress condition (9) and

$$[D] = \frac{E(1-v)}{(1+v)(1-2v)}\begin{bmatrix} 1 & \frac{v}{1-v} & 0 \\ \frac{v}{1-v} & 1 & 0 \\ 0 & 0 & \frac{1-2v}{2(1-v)} \end{bmatrix}$$

for plane strain condition (10)

where *E*= Elastic Modulus
v = Poisson's ratio

The kinematic equation which relates strain to displacement can be expressed as

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \tau_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} \qquad (11)$$

Where *u* and *v* are displacements in the x and y directions respectively.

Combining eqns (6), (7), (8) and (11) give eight unknowns (three stresses, three strains and two displacements) for eight equations (two equilibrium, three constitutive and three kinematic equations).

To develop the finite element formulation for the elasticity problem, apply Gallerkin's method by applying weighted residual function to equations (6) and (7) and writing them together yield

$$\int_\Omega \begin{Bmatrix} w_1 \left(\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y}\right) \\ w_2 \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y}\right) \end{Bmatrix} d\Omega + \int_\Omega \begin{Bmatrix} w_1 f_x \\ w_2 f_y \end{Bmatrix} d\Omega - \int_{\Gamma_e} \begin{Bmatrix} w_1 \Phi_x \\ w_2 \Phi_y \end{Bmatrix} d\Gamma = 0 \qquad (12)$$

Where Γ_e is the Boundary for essential condition and $w_i\ (i = 1,2)$ is the weighting function.

Applying integration by part to the terms in the first integral of eqn (12) gives

$$-\int_\Omega \begin{Bmatrix} \left(\frac{\partial w_1}{\partial x}\sigma_x + \frac{\partial w_1}{\partial y}\tau_{xy}\right) \\ \left(\frac{\partial w_2}{\partial x}\tau_{xy} + \frac{\partial w_2}{\partial y}\sigma_y\right) \end{Bmatrix} d\Omega + \int_\Omega \begin{Bmatrix} w_1 f_x \\ w_2 f_y \end{Bmatrix} d\Omega + \int_{\Gamma_n} \begin{Bmatrix} w_1 \Phi_x \\ w_2 \Phi_y \end{Bmatrix} d\Gamma = 0 \qquad (13)$$

Where Γ_n is the boundary for natural conditions and eqn (13) can be rearrange and rewritten as

$$\int_\Omega \begin{bmatrix} \frac{\partial w_1}{\partial x} & 0 & \frac{\partial w_1}{\partial y} \\ 0 & \frac{\partial w_2}{\partial y} & \frac{\partial w_2}{\partial x} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} d\Omega + = \int_\Omega \begin{Bmatrix} w_1 f_x \\ w_2 f_y \end{Bmatrix} d\Omega + \int_{\Gamma_n} \begin{Bmatrix} w_1 \Phi_x \\ w_2 \Phi_y \end{Bmatrix} d\Gamma \qquad (14)$$

Substitution of the constitutive equation to eqn (14) gives

$$\int_\Omega \begin{bmatrix} \frac{\partial w_1}{\partial x} & 0 & \frac{\partial w_1}{\partial y} \\ 0 & \frac{\partial w_2}{\partial y} & \frac{\partial w_2}{\partial x} \end{bmatrix} [D] \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \tau_{xy} \end{Bmatrix} d\Omega = \int_\Omega \begin{Bmatrix} w_1 f_x \\ w_2 f_y \end{Bmatrix} d\Omega + \int_{\Gamma_n} \begin{Bmatrix} w_1 \Phi_x \\ w_2 \Phi_y \end{Bmatrix} d\Gamma \qquad (15)$$

Then substitution of kinematic equation to eqn (15) yields

$$\int_\Omega \begin{bmatrix} \frac{\partial w_1}{\partial x} & 0 & \frac{\partial w_1}{\partial y} \\ 0 & \frac{\partial w_2}{\partial y} & \frac{\partial w_2}{\partial x} \end{bmatrix} [D] \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} d\Omega = \int_\Omega \begin{Bmatrix} w_1 f_x \\ w_2 f_y \end{Bmatrix} d\Omega + \int_{\Gamma_n} \begin{Bmatrix} w_1 \Phi_x \\ w_2 \Phi_y \end{Bmatrix} d\Gamma \qquad (16)$$

Using triangular linear element and interpolating the displacements ***u*** and ***v*** using shape function as

$$u(x,y) = \textstyle\sum_{i=1}^{3} H_i(x,y)u_i \qquad (17)$$

$$v(x,y) = \textstyle\sum_{i=1}^{3} H_i(x,y)v_i \qquad (18)$$

where H_i is the shape function and the displacement can also be expressed as

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{bmatrix} H_1 & 0 & H_2 & 0 & H_3 & 0 \\ 0 & H_1 & 0 & H_2 & 0 & H_3 \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \end{Bmatrix} = [N]\{d\} \qquad (19)$$

Where $\{d\} = \{u_1 \quad v_1 \quad u_2 \quad v_2 \quad u_3 \quad v_3\}^T$ is the nodal displacement vector, using this expression for strains yield

$$\begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = \begin{bmatrix} \frac{\partial H_1}{\partial x} & 0 & \frac{\partial H_2}{\partial x} & 0 & \frac{\partial H_3}{\partial x} & 0 \\ 0 & \frac{\partial H_1}{\partial y} & 0 & \frac{\partial H_2}{\partial y} & 0 & \frac{\partial H_3}{\partial y} \\ \frac{\partial H_1}{\partial y} & \frac{\partial H_1}{\partial x} & \frac{\partial H_2}{\partial y} & \frac{\partial H_2}{\partial x} & \frac{\partial H_3}{\partial y} & \frac{\partial H_3}{\partial x} \end{bmatrix} \{d\} \qquad (20)$$

Using symbol **[B]** to denote the matrix expression in on the right hand side of eqn (20) i.e.

$$\{\epsilon\} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = [B]\{d\} \qquad (21)$$

Since Gallerkin's method states that $w_i = H_i$ (i =1, 2, 3) and $w_2 = H_i$ (i =1, 2, 3), applying these weighting functions and putting eqn (20) into eqn (16) gives for the finite element domain integral

$$\int_{\Omega^e} [\mathrm{B}]^{\mathrm{T}} [\mathrm{D}][\mathrm{B}] d\Omega \{\mathrm{d}\} \qquad (22)$$

where Ω^e is the element domain and therefore the element stiffness matrix for elasticity is expressed as

$$[K^e] = \int_{\Omega^e} [B]^T [D][B] d\Omega \qquad (23)$$

Eqn (23) holds for any kind of element and dimension.

Evaluation of linear shape function provide

$$[B] = \frac{1}{2A} \begin{bmatrix} (y_2 - y_3) & 0 & (y_3 - y_1) & 0 & (y_1 - y_2) & 0 \\ 0 & (x_3 - x_2) & 0 & (x_1 - x_3) & 0 & (x_2 - x_1) \\ (x_3 - x_2) & (y_2 - y_3) & (x_1 - x_3) & (y_3 - y_1) & (x_2 - x_1) & (y_1 - y_2) \end{bmatrix} \qquad (24)$$

Substituting eqn (24) in eqn (23) results in

$$[K^e] = \int_{\Omega^e} [B]^T [D][B] d\Omega = [B]^T [D][B] A \qquad (25)$$

where A is the Area of the element.

Eqn (25) is true for both plane stress and plane strain conditions. The material properties [D] are selected for both plane stress or plane strain accordingly. A unit thickness is assumed for plane stress condition because the solution is independent of thickness direction. However the thickness can be included by multiplying the matrix by the thickness.

The Force Vector

The two right handed terms of eqn 16 are the forced vector. The first is the term due to body force which is zero since there is no initial force before impact and the other is due to tractions which is the Impact force *F* that is gotten from the impulse formula in eqn (3). Therefore the governing eqn for this project work is

$$[F] = [K][U] \qquad (26)$$

where *[F]* is the Impact/ load force as in eqn. (3)

[K] is $[K] = \int_{\Omega^e}[B]^T[D][B]d\Omega = [B]^T[D][B]A$

Stiffness matrix

[U] is $\{d\} = \{u_1 \quad v_1 \quad u_2 \quad v_2 \quad u_3 \quad v_3\}^T$

Deformation / Displacement

Analysis Procedures

The procedures include a 3D model of both FPSO and DP shuttle tanker using SolidWorks which was then imported into ANSYS Explicit Dynamics for analysis as shown in Fig. 3-6. Assumed masses of 50000000kg and 30000000kg were added to both FPSO and DP shuttle tanker respectively. The geometry was discretized into 5880 elements with 2901nodes when meshed. The FPSO is fixed while the DP Shuttle tanker is dynamically positioned with velocities ranging from 0.6m/s to 200m/s as the initial condition. The end time of impact, number of cycles and time step safety factor are set as 0.05seconds, 100000000 and 0.9, respectively. All other parameters were set as program controlled in the analysis settings before solving. After the establishment of analysis settings, explicit dynamic solver (AUTODYN) utilized these data in solving the total deformation/deflection, elastic strain and equivalent stress on the FPSO after impact.

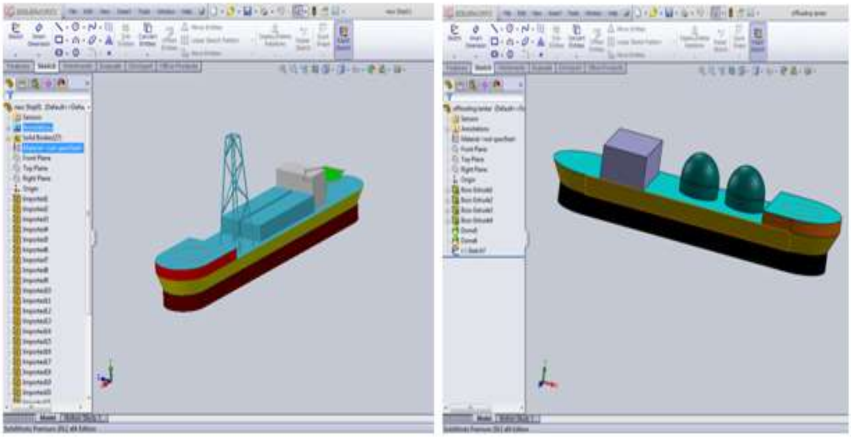


Fig. 3 Geometry of Both FPSO and DP Shuttle Tanker in SolidWorks

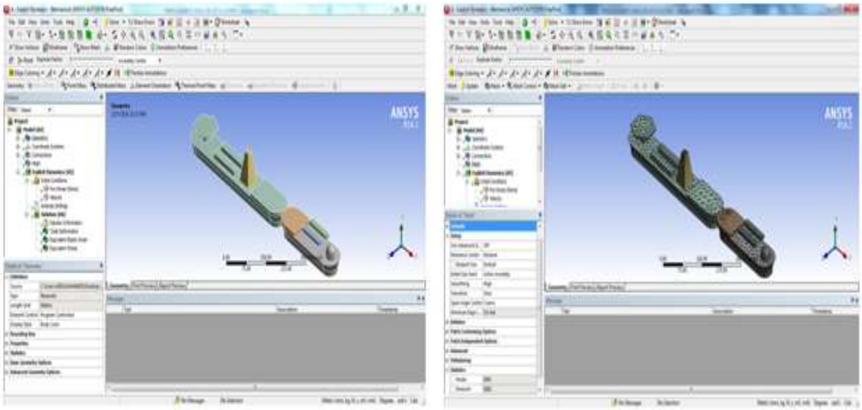
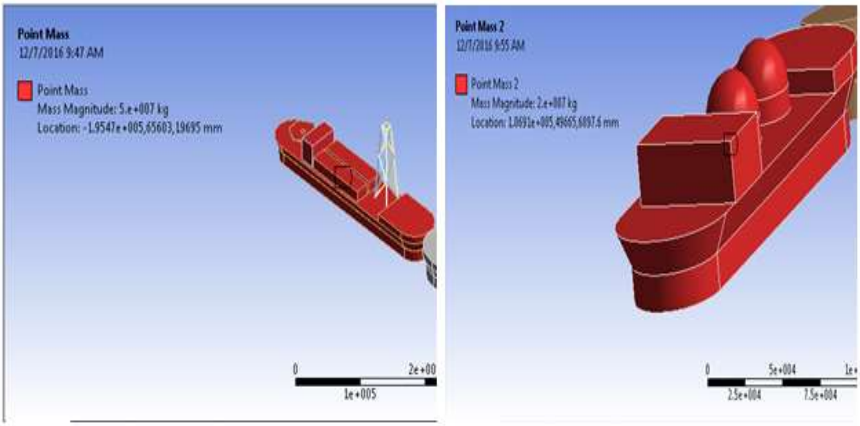


Fig. 4 Model Imported into ANSYS and Meshed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Point Mass
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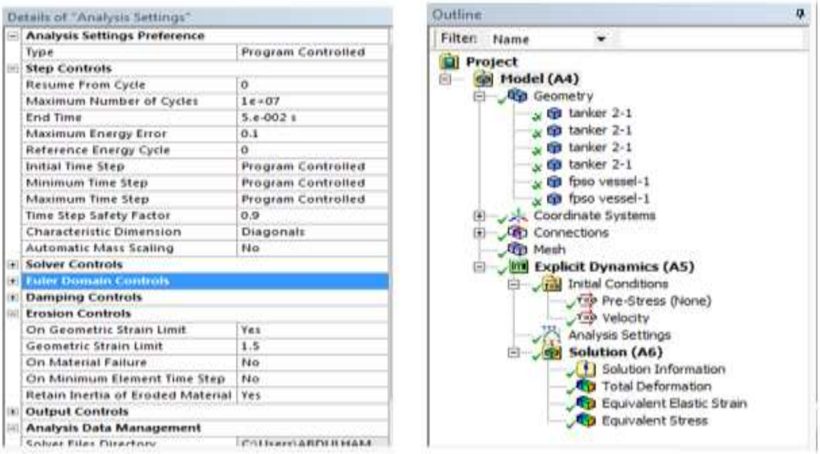
Location: -1.9547e+005,65603,19695 mm

Point Mass 2
12/7/2016 9:55 AM
Point Mass 2
Mass Magnitude: 2.e+007 kg
Location: 1.0691e+005,48665,6097.6 mm

Fig. 5 Masses Added to Both FPSO and DP Shuttle Tanker


Details of "Analysis Settings"

Analysis Settings Preference	
Type	Program Controlled
Step Controls	
Resume From Cycle	0
Maximum Number of Cycles	1e+07
End Time	5.e-002 s
Maximum Energy Error	0.1
Reference Energy Cycle	0
Initial Time Step	Program Controlled
Minimum Time Step	Program Controlled
Maximum Time Step	Program Controlled
Time Step Safety Factor	0.9
Characteristic Dimension	Diagonals
Automatic Mass Scaling	No
Solver Controls	
Euler Domain Controls	
Damping Controls	
Erosion Controls	
On Geometric Strain Limit	Yes
Geometric Strain Limit	1.5
On Material Failure	No
On Minimum Element Time Step	No
Retain Inertia of Eroded Material	Yes
Output Controls	
Analysis Data Management	
Solver Files Directory	C:\Users\ABDULHAM

Outline

Filter: Name

- **Project**
  - **Model (A4)**
    - Geometry
      - tanker 2-1
      - tanker 2-1
      - tanker 2-1
      - tanker 2-1
      - fpso vessel-1
      - fpso vessel-1
    - Coordinate Systems
    - Connections
    - Mesh
    - **Explicit Dynamics (A5)**
      - Initial Conditions
        - Pre-Stress (None)
        - Velocity
      - Analysis Settings
      - **Solution (A6)**
        - Solution Information
        - Total Deformation
        - Equivalent Elastic Strain
        - Equivalent Stress

Fig. 6 Analysis Setting and the Project Tree showing Solution Information

III. Results and Discussion

The results obtained from the analysis which include, the deformation/ displacement resulting from the impact, equivalent elastic strain and equivalent stress after the collision or impact, are presented as follows.

Effect of DP Tanker velocity on deformation/displacement

As obtained in Table 4, FPSO at velocity of 5m/s has no deformation since it is fixed and that the collision is initiated by the DP shuttle tanker with a maximum deformation/ displacement of 341.58mm. This is an indication that before impact (at time t=0) there is no displacement. As the time of collision increases the deformation/ displacement increases until all the energy generated due to collision is lost. Thus, the result obtained in table 5 revealed that the DP shuttle tanker has a maximum deformation/ displacement of 770.98 mm at velocity of 20m/s while the FPSO remained fixed. This indicates that as velocity increases the deformation also increases (Fig. 8).

Table 4 Solution Results at velocity v= 5m/s

Definition					
Type	Total Deformation	Directional Deformation		Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Orientation		X Axis	Y Axis		
Coordinate System		Global Coordinate System			
Results					
Minimum	0. mm	-1.4741e-004 mm	-142.25 mm	1.9944e-007 mm/mm	1.6572e-002 MPa
Maximum	341.58 mm	323mm	136.01 mm	8.9638e-004 mm/mm	177.54 MPa
Minimum Occurs On	fpso vessel		DP Shuttle tanker		
Maximum Occurs On	DP Shuttle tanker			fpso vessel	

Table 5 Solution Results at velocity v= 20m/s

Definition					
Type	Total Deformation	Directional Deformation		Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Orientation		X Axis	Y Axis		
Coordinate System		Global Coordinate System			
Results					
Minimum	0. mm	-1.8548e-004 mm	-93.091 mm	3.8361e-007 mm/mm	7.3299e-002 MPa
Maximum	770.98 mm	765.32 mm	157.32 mm	1.3063e-003 mm/mm	247.48 MPa

Minimum Occurs On	fpso vessel	DP Shuttle tanker
Maximum Occurs On	DP Shuttle tanker	fpso vessel

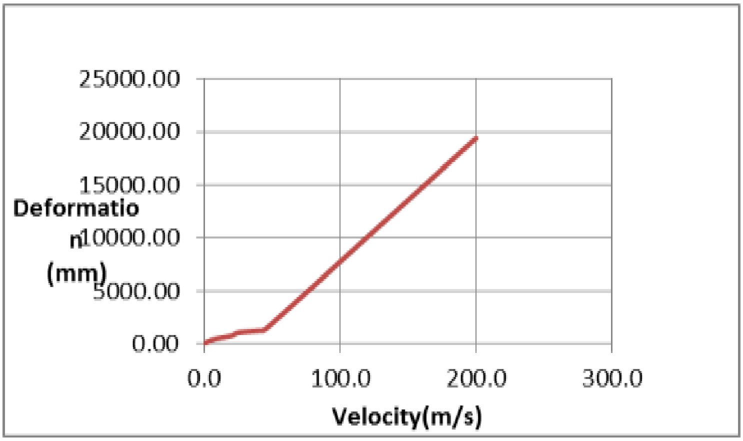


Fig. 8 Plot of Maximum Deformation/displacement against velocity

Effect of DP Tanker velocity on elastic strain

From Table 4, the minimum and maximum strains values of 1.9944e-007 and 8.9638e-004 occurred at the DP shuttle tanker and FPSO, respectively at 5m/s. This has no significant effect on the elastic strain since the value of the velocity is too small. The FPSO is having the maximum value because it is a relatively fixed vessel compared to the DP shuttle tanker during impact and also it is the DP shuttle tanker that is colliding with the FPSO.

In addition, the minimum and maximum strains values of 3.8361e-007 and 1.3063e-003 as observed in Table 5 occurred at the DP shuttle tanker and FPSO, respectively at 20m/s. This implies that as velocity increases, the elastic strain also increases (Fig. 9).

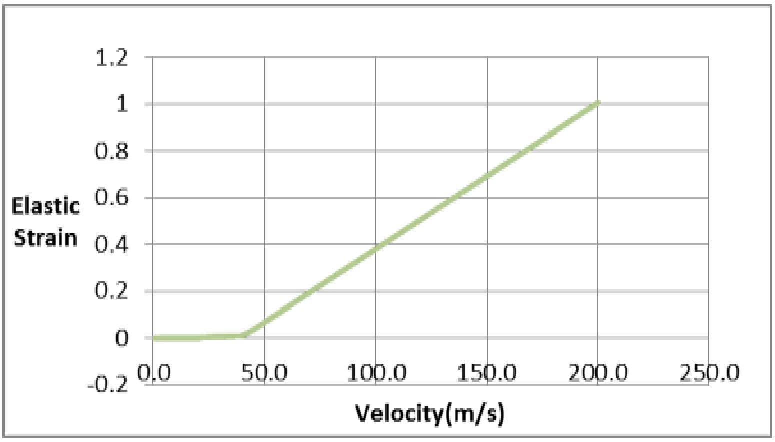


Fig. 9 Plot of Equivalent Elastic Strain against Velocity

Effect of DP Tanker velocity on equivalent stress

From Table 4, the minimum and maximum stress values of 1.6572e-002 MPa and 177.54 MPa is occurring at DP shuttle tanker on the FPSO. This value (177.54MPa) is smaller compared to 250MPa which is the yield strength of the material at 5m/s. Therefore at velocity of 5m/s the both the FPSO and the DP shuttle tanker will not have massive crash.

In addition, the minimum and maximum equivalent stress values of 7.3299e-002 MPa and 247.48 MPa is obtained at DP shuttle on the FPSO as observed in Table 5 at 20m/s. This value (177.54MPa) is almost equivalent to 250MPa which is the yield strength of the material that both FPSO and DP shuttle tanker is made-up. Therefore at velocity of 20m/s the both the FPSO and the DP shuttle tanker will not yield or fail massively. Thus as velocity increases, the equivalent stresses also increase (Fig. 10).

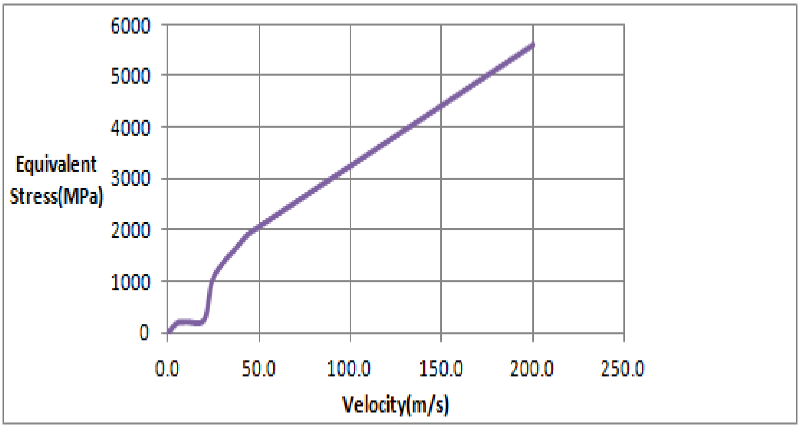


Fig. 10: Plot of Maximum Equivalent Stress against velocity

Effect of velocity above 20m/s on displacement, strain and equivalent stress

Table 6 shows the maximum values of deformation/displacement, equivalent stress and equivalent elastic strain at different velocities of DP shuttle tanker result after simulation. It can be seen that from v=25m/s and above the outcome for maximum deformations/deflections, maximum equivalent stresses and maximum equivalent elastic strains are relatively high and also as the velocity increases from v=25m/s there is significant increase in the values of deformation/displacement, equivalent stress and equivalent elastic strain. This is substantiated with Fig. 8-10.

In summary, the results generated using velocities 5m/s and 20m/s showed that there are no significant deformation/displacement on both FPSO and DP shuttle tanker at velocities of 0.6m/s and 1.0m/s. Also above 20m/s, the results outcomes for equivalent stress have exceeded the yield strength of the material for both vessels. The application of this could be found in RPG (Rocket Propelled Grenade). For instance, when RPG is fired at FPSO at a speed of 200m/s will cause a great damage.

Table 6 Different DP Shuttle Tanker Velocities Considered For Simulation

Velocity (m/s)	Maximum Total Deformation (mm)	Maximum Equivalent Stress (MPa)	Maximum Equivalent Elastic Strain
0.6	30.00	13.31	0.00003773
1.0	102.46	25.79	0.00009841
5.0	341.58	177.54	0.0008964
10.0	516.78	201.89	0.0010569
20.0	770.98	247.48	0.0013063
25.0	1068.30	1072.60	0.005412
40.0	1246.20	1747.90	0.01147
45.0	1398.90	1938.22	0.03621
200.0	19405.77	5592.00	1.0049

IV. Conclusions

This research work has analyzed the deformation/displacement, equivalent stress and equivalent elastic strain developed in crash (impact) load between FPSO and DP shuttle tanker in tandem offloading operation. ANSYS Explicit Dynamics was used to analyze those parameters and the results obtained reveled that at DP shuttle tanker velocities 5m/s and 20m/s the crash load did not reached the damage point on both FPSO and DP shuttle tanker. At velocities above 20m/s there is a great damage after collision. In addition, as the velocity of DP shuttle tanker increases, the values of those parameters also increase. This implies that at low velocity of DP shuttle tanker in tandem offloading operation, the risk of damage after impact/collision is lesser and at velocity greater than 20m/s there is tendency of heavy damage after collision resulting to stern damage on FPSO and consequent penetration and flooding in the machine room.

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