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Structural Assessment of an Offshore Platform Subjected to a Ship Collision

*Eman O. Younis[1, *], Ehab R. Tolba[2], Sherif El. Abdellah[3], Elsayed M. Galal[4]*

[1] *Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: eman95505@eng.psu.edu.eg,*
[2] *Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: prof.tolba@eng.psu.edu.eg,*
[3] *Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: sherifabdellah@yahoo.com,*
[4] *Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: elsayed.galal@eng.psu.edu.eg,*
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ABSTRACT

Oil and gas platforms are exposed to ship accidents, which is an unavoidable event. Ships have been developed recently, where it becomes larger and more equipped. Design standards established guidelines that take into consideration collision energy into design calculations. Researchers have been calling for an update since 2004, as these criteria have remained unchanged for a long time. In 2019, the Det Norske Veritas (DNV) standard revised the standard vessel mass to be 6500–10,000 tons displacement, and the updates are continuing to the other relevant standards. Another standard calculated the collision energy using a standard vessel with a displacement of 5,000 tons moving with speed 2 m/s. This paper investigates and analyzes a jack-up platform that is impacted by a standard vessel using the ductility design principle. The collision is numerically modeled using ABAQUS software. Three different scenarios are considered. The results of displacement, impact force, and energy have been assessed and explained to each member. The members suffered considerable damage after being impacted by a vessel of 5,000 tons. This study can help in the development of standards for offshore structures that consider higher collision energies.

Keywords: Ship-platform collision; Offshore structures; Jack-up platform; Ductility design; FE-modeling; Abaqus; Impact energy; Local and global responses.

1 INTRODUCTION

The Gulf of Suez is a vital transportation route for oil and commercial services or products. It is located northwest of the Red Sea in Egypt. This basin has a maximum water depth of around 80 m. As shown in figure 1, the Gulf of Suez region is abundant with onshore and offshore oil fields, producing about 75% of Egypt's total oil output. The Gulf has approximately 80 offshore oil fields with great future potential for additional offshore development. The main drilling offshore platforms in the Gulf of Suez are jack-up platforms [1-3].

Offshore platforms are huge structures that are used for exploration, drilling, extracting, processing, and transporting. There are fixed and movable types of platforms depending on the water depth and usage. They are exposed to hard environmental conditions like currents, wind, storms, waves, and functional loads. Also, these structures are subjected to accidental loads like ship collisions and possible technical failure [4, 5].

Since the 1980s, researchers have paid great attention to ship-platform collisions as they are unavoidable events which lead to major structural problems and affect people’s lives, production continuity, and economic consequences. The repairing process of the platform or replacing the damaged members is expensive and difficult. Reported accident statistics (OTO 1999 052) [6] showed that a majority of 66% of ship collisions with installations were caused by supply vessels. Between 2001 and 2011, 26 collisions on the Norwegian Continental Shelf were reported [7].

In 2005, a multipurpose support vessel collided with the Mumbai High North platform, rupturing the gas risers. The collision led to a major explosion, the loss of many lives, and the collapse of the platform.

In 2009, on the Norwegian continental shelf in the North Sea, the well workover vessel Big Orange XVIII collided with the Ekofisk 2/4–W tripod jacket. The vessel has a displacement of 6,000 tons. It had a speed of

4.5–4.8 m/s, resulting in a collision energy of about 70 MJ. As shown in figure 2, the collision caused significant damage to both the platform and the vessel, with no personal injuries [8].

Many papers like [7, 9-11] included numerical modeling for tubular members of a fixed platform structure subjected to ship impact. The resultant impact force and energy were concluded.

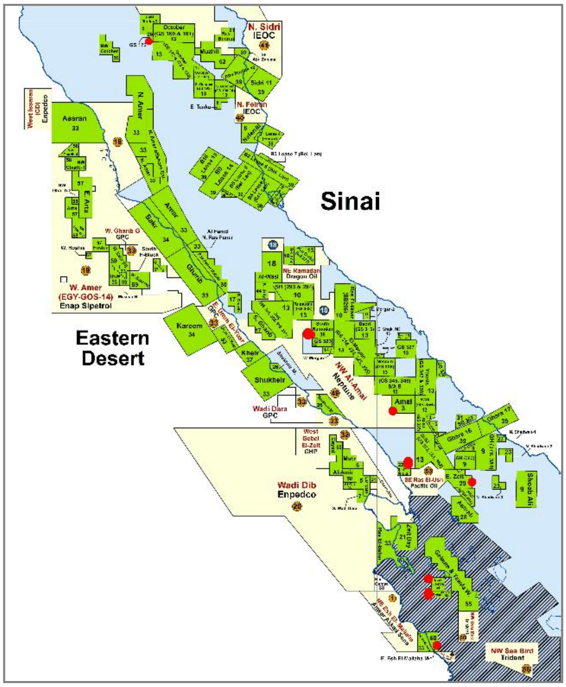


Figure 1: The oil and gas fields in the Gulf of Suez in 2022 (offshore platforms in red color).
Source: based on [12].

Figure 2: The Big Orange XVIII-Ekofisk 2/4-W platform collision.
Source: based on [7].

Yu and Amdahl [13] reviewed the state-of-the-art of offshore structures subjected to ship impacts and discussed the factors which affect the platform response.

Some of the literature was based on real case studies like Maritime and Soegaard [14], which described the accident that happened in the North Sea. Also, Rigueiro and Ribeiro [15] analyzed the deformation of a platform structure located in Brazil and subjected to a ship impact at different speeds using ABAQUS software.

Other researchers studied different scenarios for the collision event, like Zhang and Pedersen [16], who performed different scenarios for a jack-up platform subjected to a supply vessel collision and analyzed the resulting local damage. Also, Storheim and Amdahl [17] used the nonlinear finite element method and presented curves for the contact force and deformation. Ning and Zhang [18] used a numerical approach to study a collision between a spar hull and a supply vessel. They used ABAQUS software to analyze the collision energy, the impact force, and the damage shape. However, Ma and Kim [19] used another software (ANSYS) to analyze the collision between a jack-up rig and a 20,000 tons supply vessel and recommended that the standards concerned with collision for jack-up rig should be developed.

The presence of offshore installations in the Gulf of Suez increases the accidents probability. Hurghada is a tourist city on the Red Sea coast, about 50 miles from the Gulf of Suez. As a result, any accident might result in an oil leak, affecting the seashores [1, 2]. Therefore, collision energy should be considered at the design phase of jack-up offshore structures for proper structure safety.

In this study, the finite element analysis (FEA) program "ABAQUS" is used to perform a structural assessment of a jack-up rig platform subjected to a ship collision. The assessment includes determining the displacement and collision energy for the platform structure elements due to the ship's bow collision. The main issues that might occur during a collision incident are denting and dismantling of elements. This program enables simulation of the accident and modification of the conditions for future prediction.

2 OFFSHORE PLATFORM AND SUPPLY VESSEL

2.1 Offshore Platform

The studied platform is AL YASAT, which was built in 1979 and is located in the Persian Gulf, as shown in figure 3. It is a mobile jack-up rig which can be moved from its current location to the Gulf of Suez. It consists of a hull and three truss-type legs. It is fixed to the seabed by spud cans, which penetrate the seabed by 4.3 m. The platform’s water depth from the seabed is 68.75 m.

The hull is 7.75 m in height and is located at 4.25 m above sea level. The leg of the platform has three cylindrical steel chords with a length of 86 m and a diameter of 762 mm. The chord thickness varies along its length. The chords are braced horizontally and diagonally to form 16 bays of 5.1 m each, with two gear racks on each side, as shown in figure 4. Also, both the horizontal and diagonal bracing members have a variable thickness along the leg bays, as shown in table 1. Figure 5 shows a detailed view of the studied platform. The jack-up platform is made of steel. Each element has elastic modulus of $210*10^9$ N/mm2, a poisson ratio of 0.3, and a density of 7850 kg/m^3.

The platforms are subject to a variety of loads caused by the environment and gravity. This paper focuses on the impact load that results from a ship's collision with a platform.

Figure 3: The jack-up platform and its supply vessel.

Source: based on [20].

Table 1. Structural details of the jack-up platform members.

Member	Chord	Horizontal	Diagonal Brace
Yield Stress (N/mm^2)	$690*10^6$	$345*10^6$	$490*10^6$
Length (m)	5.1	8.0	9.063
Diameter (mm)	762	323.9	406.4
Thickness (mm)	30 up to 56 m length 32 for the rest	14 up to Bay 10 16 from Bay 11 to 16	18 up to Bay 11 21 from Bay 12 to 16

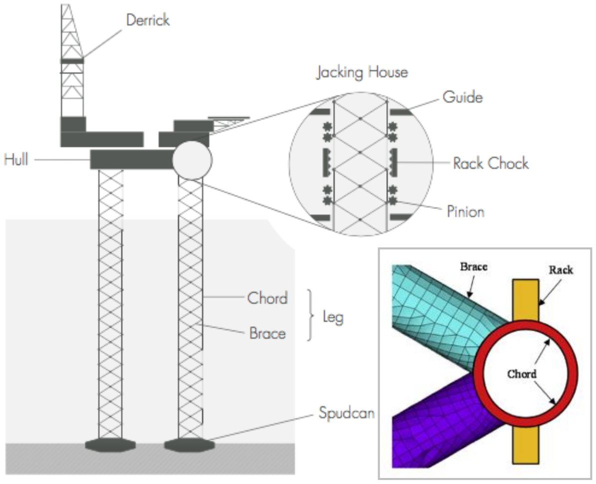
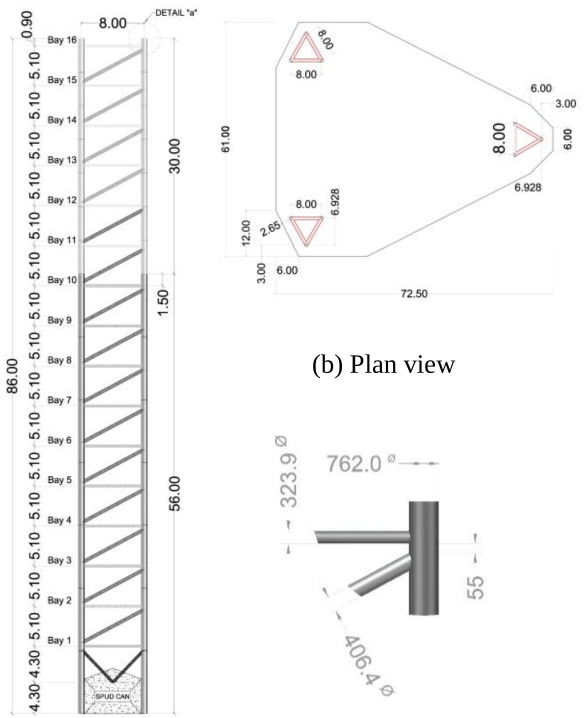


Figure 4: A jack-up platform's general assembly. Source: based on [19, 21].



(a) Elevation view

(b) Plan view

(c) Detail "a"

Figure 5: Jack-up platform details view.

2.2 Supply Vessel

Vessel profile and breadth plan are shown in figure 6. The length of the supply vessel is 32.5 m, the breadth is 9 m, and the draft is 4 m. It has a displacement of 5,000 tons. Table 2 presents the material properties of the reference supply vessel.

Table 2. Material properties of the supply vessel.

Density (kg/m^3)	Elastic Modulus (N/mm^2)	Poisson Ratio
7850	$210*10^9$	0.3

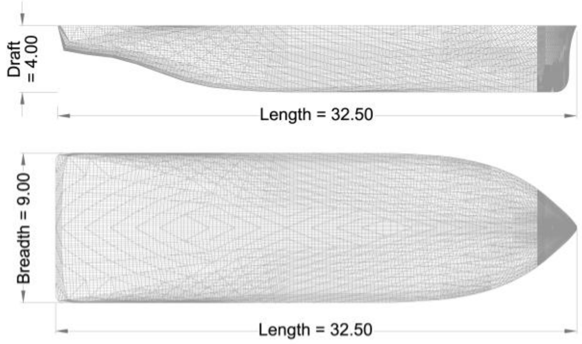


Figure 6: Supply vessel section view.

3 METHODOLOGY

There are three design principles for the ship-platform collision event depends on their relative strength, as shown in figure 7.

- Strength design: The platform is strong enough to withstand the collision. The ship dissipates most of the collision energy, causing significant damage to its body.
- Ductility design: The platform is subjected to large plastic deformations as it dissipates most of the collision energy.
- Shared energy design: Both the platform and the ship are subjected to deformations as they dissipate the collision energy.

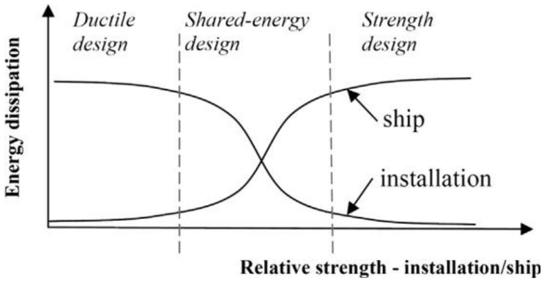


Figure 7: The design principles according to NORSOK (N-004) standard. Source: based on [24].

In this study, the non-linear finite element method was used to analyze the behavior of the platform's members during the ship-platform collision. The ductility design principle is applied in this analysis, where the ship is not allowed to deform. In reality, the ship and the platform will share the dissipation of the collision energy, and the weakest body will be damaged. NORSOK proposes using the ductility design approach when designing and assessing the platform braces. The advantage of this principle is that there is no need to know or model all the colliding ship's structural details; it just needs the outer shape of the ship's bow. The results of this principle are adequate for comparative analysis and are of pessimistic nature.

Different scenarios were developed based on the shell elements method as it is used for both global and local structure responses [19]. Figure 8 shows that there are three main scenarios for the ship-platform collision proposed and studied: (1) individual members; (2) five bays from one leg of the platform; and (3) the whole platform. The leg elements were analyzed and evaluated for each main scenario after being impacted by a ship in the middle of their length.

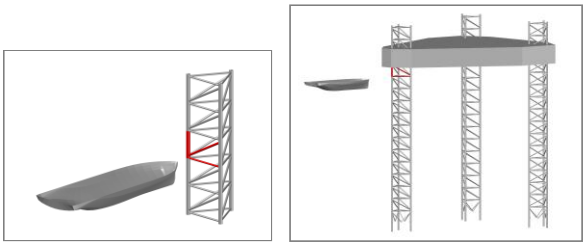


Figure 8: The collision scenarios of five bays from the platform (left) the whole platform (right).

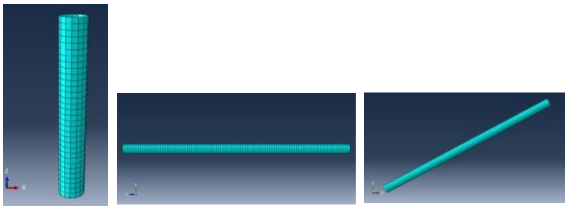


Figure 9: The meshing model of the vertical, horizontal, and diagonal bracing members (from left).

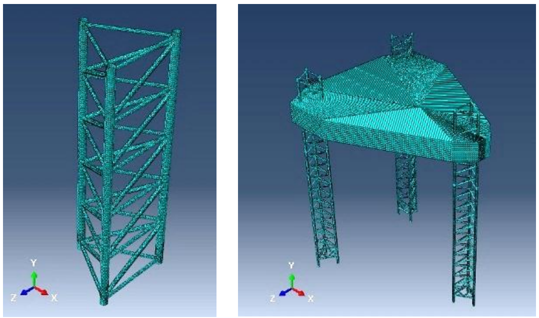


Figure 10: The meshing model of five bays from the platform (left) the whole platform (right).

4 NUMERICAL MODELING

In general, there are four steps for computational modeling with finite element method (FEM): (1) body geometry modeling; (2) element meshing; (3) material property definition; and (4) boundary condition specification [22]. For this study, the supply vessel is proposed to have a speed of 2 m/s, as recommended by the DNV [23] and NORSOK N004 [24]. The collision energy (E) is calculated using equation (1.1) [11].

$$E = \frac{1}{2}\,(M + m_{ad}).v^2 \qquad (1.1)$$

The design collision energy for a supply vessel with a displacement (M) of 5,000 tons moving towards the platform at a speed (v) of 2 m/s and 10% added hydrodynamic mass (m_{ad}) for the ship's bow impacts is 11 MJ.

The ship impacts the platform's leg between bays number 12 and 13. A dynamic/explicit solver is used to implement the collision simulation. Hard-contact algorithms are used to model the contact between the ship and the platform [25]. As shown in figures 9 and 10, the whole model is meshed using S4R shell finite elements and uses an elastoplastic material model with isotropic hardening to define the members' material. The ship is modeled as a rigid body. According to [26], the pinned end support condition is the appropriate assumption for the boundary conditions of the members' ends in scenarios (1) and (2). It has also been proposed for scenario (3) to model the spud can foundations using the pinned end support boundary condition since the flexibility of the rotational degree is the best way to represent them in ABAQUS software. The results of the displacement, impact force, and energy will be presented and explained for each case.

Model validation was carried out to ensure the accuracy of the ABAQUS program results. Ning and Zhang [17] investigated a collision between a spar hull and a supply vessel weighing 10,000 tons with 10% added hydrodynamic mass and moving at 3 m/s. The ductility design approach was used to model a rigid bulbous bow impacting a deformable spar hull structure. Using the provided input data and software solver, the collision model was recreated and compared to the output values. Some input data was not provided in detail, particularly for the structure's geometry model, which affected the output accuracy. The missing input data was logically and wisely assumed. As shown in Table 3, the variation in result values is very small, and the structural response of the two models is similar. Based on that, the model is built.

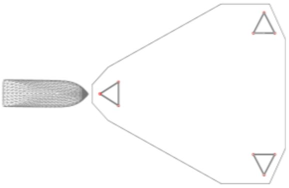
Table 3. The results of Ning, Zhang (2013) [17] and the model validation.

Results	Internal Energy (MJ)	Penetration (m)	Impact Force (MN)
Ning, Zhang (2013) [17]	46.9	2.208	40.7
New Model for Validation	48.0	2.269	50

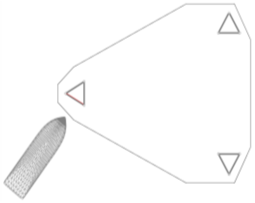
5 RESULTS AND DISCUSSION

The numerical modeling results for the platform elements' responses to the ship collision have been studied and analyzed for three different scenarios. Each member has different mechanical and structural properties. When the ship hits it and stops traveling, each member reaches its maximum displacement. The displacement retracts due to the member's elastic behavior, and the member subsequently gets its final deformed shape.

Unlike the other scenarios, the displacement curve in scenario (3) does not stabilize at a certain point because the whole platform deflects just after the member gets its final deformed shape. As the impacted members in the same bay absorb the majority of the collision energy, the value of the entire platform deflection is small. The difference in this value between scenarios depends on the configuration of the platform with the vessel during the collision, as shown in figure 11. The moment of inertia is inversely proportional to deflection, so the deflection of the entire platform is less in vertical chord collision than in horizontal and diagonal bracing members collision.



(a) Vertical chord collision.



(b) Horizontal and diagonal bracing members collision.

Figure 11: The configuration of the impacted platform with the vessel (plan

The stronger a member is, the less damage it suffers. The impact force value fluctuates with time because of the evolution of the member's localized damage. When the impact force curve reaches zero, the member no longer resists, and the member gets a final deformation shape. In scenarios (2) and (3), the impact force value fluctuates less because the impacted member does not resist the ship collision individually.

The collision energy includes the impacted member's internal energy (total strain energy), absorbed kinetic energy (the portion of structural members pushed to move by the ship’s impact), and viscous dissipation (the damping effects due to external or internal friction). The internal energy part is the largest and it dissipates in the distorted shape of the impacted member. The values of kinetic energy and viscous dissipation are low. The velocity has been computed, and the friction can be neglected. Therefore, research focuses on and assesses internal energy. The results of displacement, impact force, and energy follow the same way in all three collision scenarios.

5.1 Vertical Chord Member

When the member becomes longer, it buckles more and provides less resistance to the ship's collision. As shown in table 4, the displacement of the vertical chord member has increased through the different scenarios. Thus, the impact force value has decreased, as seen in figure 13. The displacement curve became steady following retraction from the maximum to the final displacement of the member, except for scenario (3), as shown in figure 12. The displacement curve became unstable because the entire platform deflected by about 4 cm. The deflection value is very small because of the assumed configuration of the platform with the vessel during the collision, as explained before.

Table 4. The results of displacement, impact force, and energy for the vertical chord.

Vertical Chord	Individual Member	Five Bays	Whole Platform
Displacement (m)	0.67	0.69	0.83
Impact Force (MN)	46.36	21.59	19.71
Internal Energy (MJ)	10.65	6.57	5.12

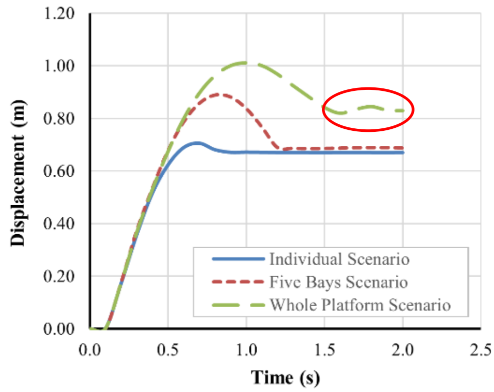


Figure 12: The displacement of the vertical chord in different scenarios.

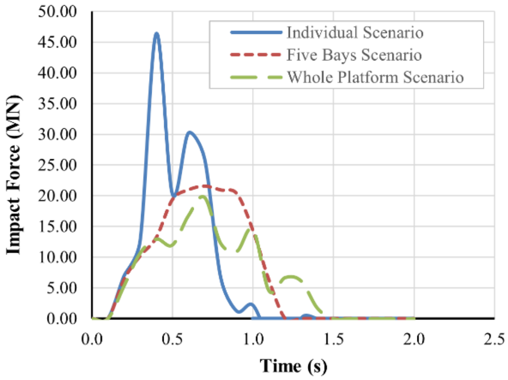


Figure 13. The impact force of the vertical chord in different scenarios.

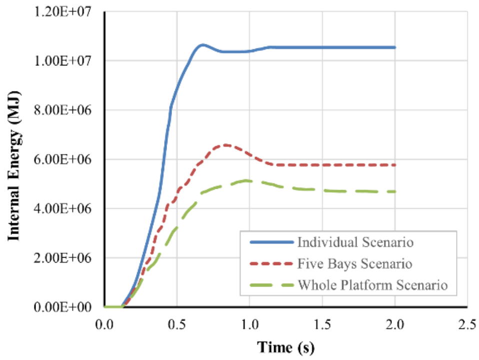
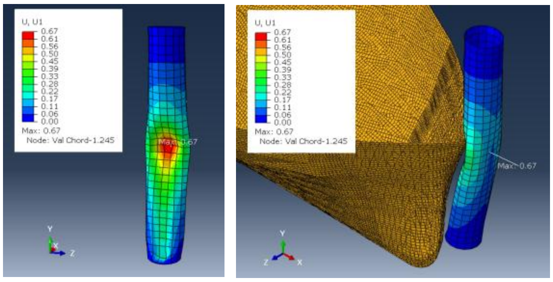
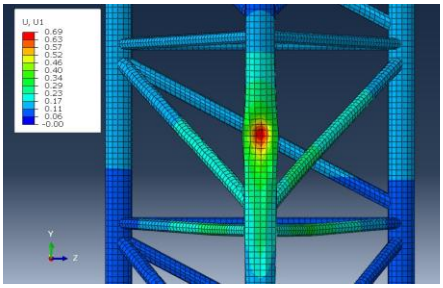


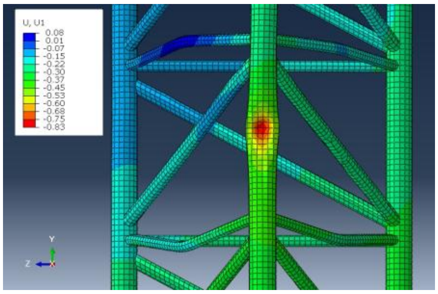
Figure 14. The internal energy of the vertical chord in different scenarios.



(a) Scenario (1)



(b) Scenario (2)



(c) Scenario (3)

Figure 15. The final deformed shape of the vertical chord in different scenarios.

previously stated, the collision energy for the model is 11 MJ. As shown in figure 14, in scenarios (1), (2), and (3), the internal energy of the vertical chord member accounts for about 97%, 60%, and 46.5% of the collision energy, respectively. The remaining portion is distributed among the structure's other members. Figure 15 shows how the member resists the impact in the different scenarios by having a denting region in the middle.

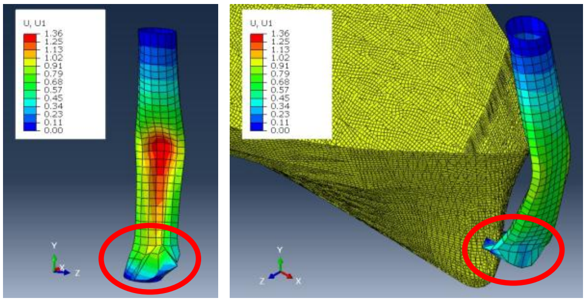


Figure 16. The final deformed shape of the vertical chord member.

Individual vertical chord member was tested under different conditions until it collapsed. At each time, the only variable was the ship's velocity. It can withstand ship velocities of 3 and 4 m/s without collapsing. It did, however, collapse at the ship's velocity of 5 m/s, with a total impact energy of 68.75 MJ, as shown in figure 16.

5.2 Horizontal Member

The horizontal member is the weakest in the studied platform. It has less strength (yield stress), diameter, and thickness than the other members. It shows the same performance in all scenarios. As shown in Figure 18, the ship slides down the horizontal member after the collision. This phenomenon occurs due to the ship's relatively high speed and the member's small diameter. Therefore, the horizontal member is displaced in directions other than the impact direction.

In scenario (1), denting damage is sustained by the member in the middle by about 2.96 m. The ship eventually collides with both ends of the member, forcing it to collapse. However, because of the ship's depth in scenarios (2) and (3), the horizontal and diagonal bracing members are both affected by the ship's collision, which prevents the structure from collapsing. As shown in figure 17, in scenario (3), the displacement curve continues to develop over time as the platform deflects by about 25 cm.

As shown in Table 5, the impact force of the horizontal member is low, revealing that it has low resistance. In scenario (1), the impact force is small until the member collapse begins at t = 3.6 sec. The curve then increases dramatically to around 23.73 MN and drops again below zero.

Table 5. The results of displacement, impact force, and energy for the horizontal member.

Horizontal	Individual Member	Five Bays	Whole Platform
Displacement (m)	2.96	0.88	0.82
Impact Force (MN)	23.73	7.6	9.59
Internal Energy (MJ)	9.45	1.6	1.4

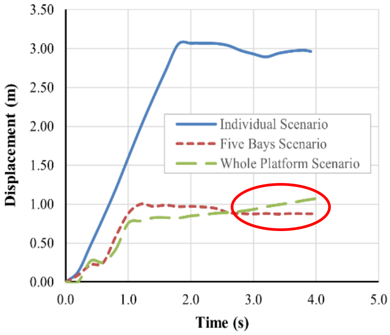
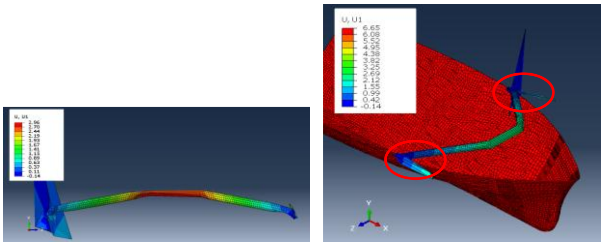
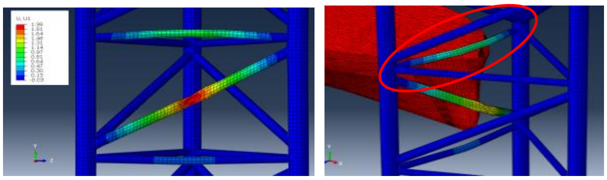


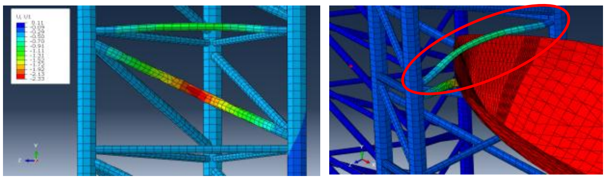
Figure 17. The displacement of the horizontal in different member scenarios.



(a) Scenario (1)



(b) Scenario (2)



(c) Scenario (3)

Figure 18. The final deformed shape of the horizontal member in different scenarios.

In scenario (3), there is a drop in the middle of the curve values at t = 1.6 sec, as shown in figure 19. The horizontal member gets its maximum and final displacements at t = 1.6 sec and t = 1.8 sec, respectively. At this point in the collision, the diagonal bracing member is resisting the impact. As a result, the impact force curve drops at t = 1.6 sec and then rises again. At t = 2.8 sec, the impact force curve drops to zero when the diagonal bracing member reaches its final displacement.

As shown in figure 20, in scenarios (1), (2), and (3), the internal energy of the horizontal member accounts for about 86%, 14.5%, and 12.7% of the collision energy, respectively. In scenarios (2) and (3), the diagonal bracing member absorbs more impact energy and suffers more damage than the horizontal, as shown in figure 18 (b, c).

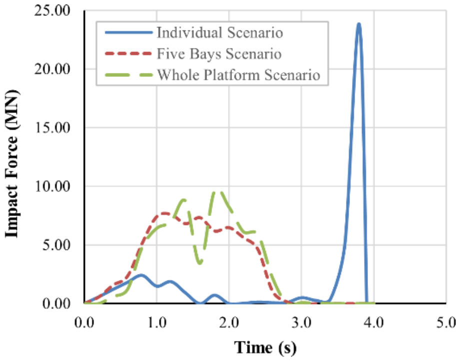


Figure 19. The impact force of the horizontal member in different scenarios.

The horizontal member collapsed in the first scenario, so it was assessed again individually. As shown in figure 21, the member is subjected to the same ship but with a velocity of 0.5 m/s. It resisted the ship's collision, resulting in a displacement of 0.72 m without collapsing. In the other scenarios, the member is linked to other members of the structure. Thus, it could endure a collision with the ship's velocity of 2 m/s.

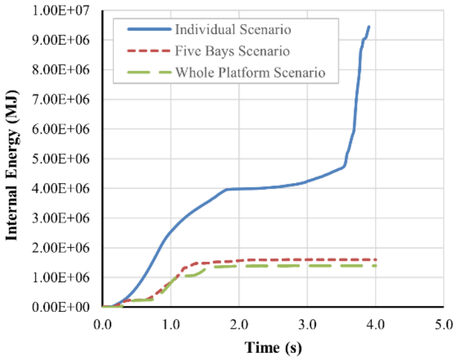


Figure 20. The internal energy of the horizontal member in different scenarios.

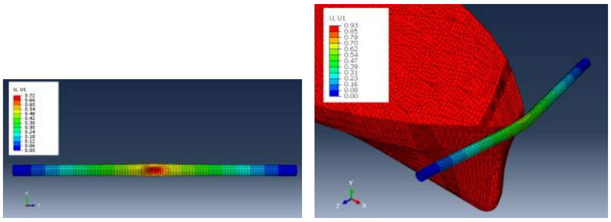


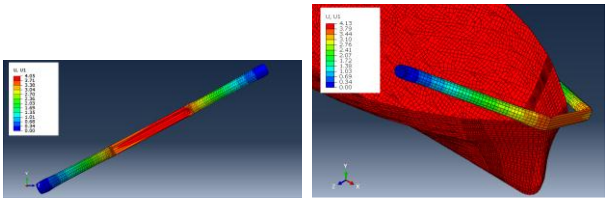
Figure 21. The final deformed shape of the horizontal member (scenario 1) at a ship velocity of 0.5 m/s.

5.3 Diagonal Bracing Member

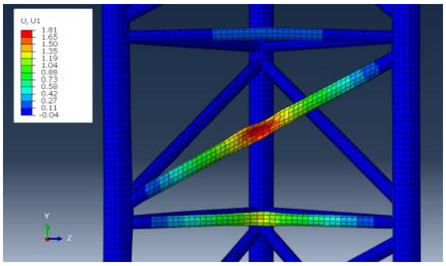
In scenario (1), the displacement of the diagonal bracing member increases, and the member sustains significant damage with no apparent elastic behavior. The impact force value is low because the member's middle part is stretched to withstand the impact, as shown in figure 24. In scenarios (2) and (3), the diagonal bracing member has more damage than the horizontal, but neither has collapsed. Because of the ship's depth, the collision affected both the horizontal and diagonal bracing members, as shown in figure 22. Figure 23 shows that the overall platform was deflected by approximately 23 cm in scenario (3).

Table 6. The results of displacement, impact force, and energy for the diagonal bracing.

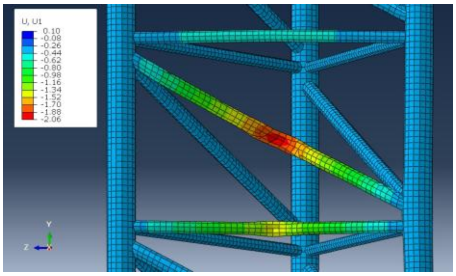
Diagonal Bracing	Individual Member	Five Bays	Whole Platform
Displacement (m)	4.14	1.8	1.83
Impact Force (MN)	4.49	10.6	12.28
Internal Energy (MJ)	11.92	6.8	6.21



(a) Scenario (1)



(b) Scenario (2)



(c) Scenario (3)

Figure 22. The final deformed shape of the diagonal bracing in different scenarios.

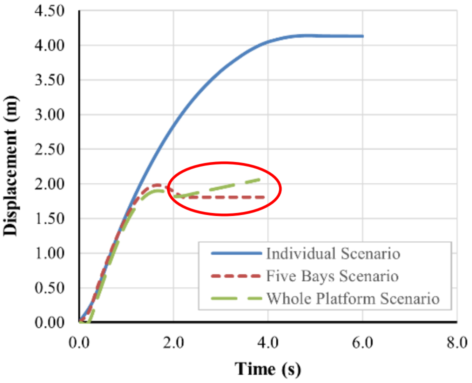


Figure 23. The displacement of the diagonal bracing in different scenarios.

As shown in figure 25, The internal energy of the diagonal bracing member in scenario (1) is high, around 11.92 MJ. The member suffers severe, permanent damage. It absorbs about 62 % and 56.5 % of the collision energy in scenarios (2) and (3), respectively. The remaining percentage is distributed to the other platform members.

As seen in table 6, the diagonal bracing member has higher displacement values than the other members throughout the assumed collision scenarios. However, the diagonal bracing member could withstand the ship's collision without collapsing as its position, strength, diameter, and thickness kept it from collapsing or sliding like the horizontal member. When the ship's velocity was reduced to 0.5 m/s, the diagonal member experienced a local deformation of around 0.42 m, as shown in figure 26.

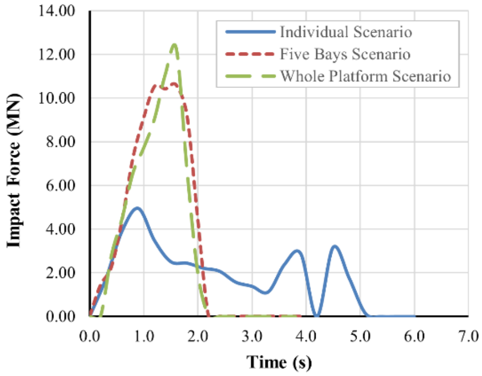


Figure 24. The impact force of the diagonal bracing in different scenarios.

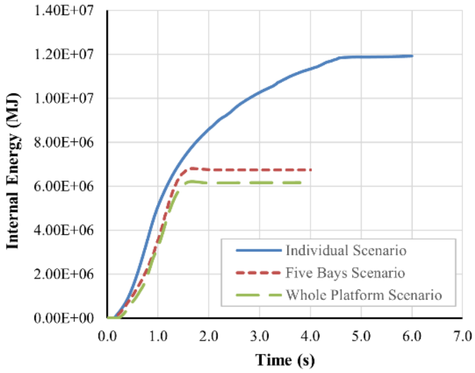


Figure 25. The internal energy of the diagonal bracing in different scenarios.

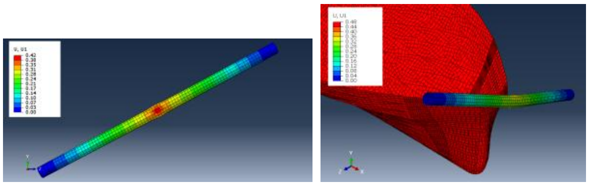


Figure 26 The final deformed shape of the diagonal bracing (scenario 1) at a ship velocity of 0.5 m/s.

In this research, each main member was evaluated and studied in three different scenarios. Figure 27 summarizes the final displacement results of the platform members in meters. The vertical chord member is the strongest against the ship's collision, while the diagonal bracing has the largest displacement in all three scenarios.

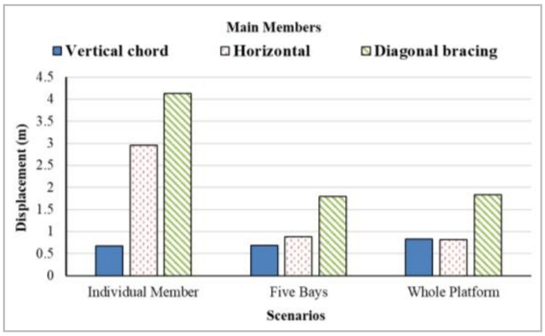


Figure 27. The members' displacement in the three scenarios.

6 CONCLUSIONS

In Suez Gulf, jack-up platforms are used for drilling and extracting oil. This basin is economically valuable to Egypt. The main reason for potential platform collisions is supply vessels traffic. This study aims to assess the ability of a jack-up platform to sustain a standard vessel collision. The response of the platform's members to a 5,000 tons ship's bow impact moving at 2 m/s is numerically modeled using ABAQUS software. The collision damage is studied and assessed for the impacted members using different collision scenarios.

The jack-up platform did not collapse during the collision scenarios with the standard ship, although the members sustained significant denting damage. However, the accidents recorded in recent years have higher collision energies than the analyzed collision (11 MJ).

As a result, the potential collision energy caused by modern ships should be considered throughout the platform and ship design phases. That reduces long-term repair costs, makes the platform and ship's structure safer, protects the environment, and saves lives. It is recommended to study proper collision protection systems with the appropriate fender type for each site's tide conditions.

7 LIST OF SYMBOLS AND ABBREVIATIONS

cm	: Centimetres
DNV	: Det Norske Veritas
FE	: Finite element
FEA	: Finite element analysis
FEM	: Finite element method
Kg	: Kilogram
m	: Metres
MJ	: Mega Joule
mm	: Milli Metres
MN	: Mega Newton
NORSOK	: Norsk Sokkels Konkurranseposisjon
OTO	: Offshore Technology Report
sec	: Seconds
t	: Time
Ø	: Diameter

Credit Authorship Contribution Statement:

Eman Osama: Methodology, Writing Original Draft, Software.

Ehab Tolba: Conceptualization, Review and Editing, Supervision.

Sherif Abdellah: Supervision, Review and Editing.

Elsayed Galal: Supervision, Review and Editing.

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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