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STRUCTURAL ASSESSMENT OF THE HULL RESPONSE OF AN FPSO UNIT TO DROPPED OBJECTS: A CASE STUDY

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ABSTRACT

Offshore structures are exposed to the risk of damage caused by various types of extreme and accidental events, such as fire, explosion, collision, and dropped objects. These events cause structural damage in the impact area, including yielding of materials, local buckling, and in some cases local failure and penetration. The structural response of an FPSO hull subjected to events involving dropped objects is investigated in this study, and non-linear finite element analyses are carried out using an explicit dynamic code written LS-DYNA software. The scenarios involving dropped objects are based on the impact from the fall of a container and rigid mechanical equipment. Impact analyses of the dropped objects demonstrated that even though some structural members were permanently deformed by drop loads, no failure took place in accordance with the plastic strain criteria, as per NORSOK standards. The findings and insights derived from the present study may be informative in the safe design of floating offshore structures.

Keywords: Drop object, Hull response,Impact analysis,Offshore structures

INTRODUCTION

Offshore structures are exposed to the risk of damage caused by vessel impacts or dropped objects. Accidents involving dropped objects often occur during operations on offshore units. Dropped objects generally have relatively high velocities in the most critical cases, and the influence of inertia forces on the response of the impacted structure is large.

The load from a dropped object is described by its kinetic energy, which is governed by the mass of the object, including the hydrodynamic added mass, and the speed of the object at the immediate point of impact [3]. Under most conditions, the major part of the kinetic energy must be dissipated as strain energy within the impacted component, and possibly within the dropped object. The most significant threat to global structural integrity is likely to be damage to the tanks, which could impair the intactness and stability of the floating offshore facilities [4].

The structural members of the deck need to be designed so that the load bearing capacity of the whole ship is intact after an accidental load occurs. The impact resistance of a deck depends on the plate thickness and the size and spacing of the supporting stringers. The structural integrity of the whole ship is normally not compromised due to dropped loads, but local damage and the consequences of this damage may lead to catastrophic results [5].

Jung et al. [11] focused on grated-steel deck structures subjected to dropped objects. An experimental study was undertaken in a dropped object test facility, and nonlinear finite element computations using LS-DYNA were also performed for the corresponding test models.

Sun et al. [14] studied items dropped on offshore units in order to investigate the overall falling process using nonlinear FEM software. The geometry of the dropped items, the horizontal speed of the dropped items, whether they were dropped into water, and various boundary conditions were accounted for.

Ingve [10] performed impact analyses for dropped objects in accordance with the typical NOKSOK N-004 standards for accidental actions. Different shapes, sizes and weights and various impact positions were used to simulate the dropped object, and analyses were carried out using the nonlinear finite element program USFOS.

Ahn et al. [1] investigated the effect of the conditions under which an object is dropped, using a parametric study. This study examined the methodology, conditions, and design aspects of dropped object calculations using a non-linear dynamics FEM analysis. Based on a comparison of the findings from direct FEM analyses with those from a simplified energy method using the Offshore Code DNVGL-RP-C204 [4], the findings were affected by the application of failure criteria in accordance with the requirements of the Code, the application of material properties, the location of the dropped object, and the condition of the object.

Moan [12] described the lessons learnt from accidents on offshore structures, and then gave a brief outline of general principles for safety management based on these experiences. Emphasis was placed on the Accidental Limit State (ALS) criteria.

Bergstad [3] evaluated the resistance of the deck structures in ship hulls to impacts from objects, with particular application to falling containers, and found that the energy absorption and the deformation of the deck structure needed to be analyzed. In general, nonlinear finite element methods were required in addition to procedures for the estimation of absorbed energy.

The present paper aims to investigate the structural response of an FPSO hull exposed to dropped object events. This is achieved using the critical energy absorption and localized deformation to penetration of the deck structure exposed to impacts from falling containers and rigid equipment. The scope of this work includes all possible FPSO locations affected by dropped accidental loads. The effects of different types of material are also accounted for. Critical areas for dropped object events are determined based on a minimum drop direction of within 10o to the vertical direction, as per DNVGL-OS-C102 [7] requirements.

In order to assess the strength versus dropped objects, non-linear finite element analyses are performed using an explicit nonlinear software code in LS-DYNA. With respect to the hull structure of the FPSO, areas such as the main lay-down located on the poop deck, the galley and infill deck and cargo deck are included in the strength assessments.

FPSO DESIGN

A double-sided, single-bottom hull is designed. Three thrusters are provided for heading control, although not for propulsion, and these thrusters are not used to assist the natural weathervaning of the vessel, as shown in Fig. 1. Topside modules are installed onto module support stools that are fabricated and erected on the cargo deck. A moon pool is located between the cargo area and the fore part of the vessel for integration of the turret.

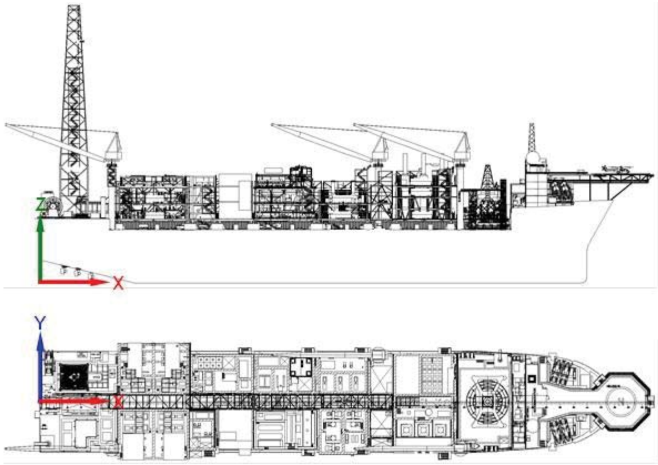

Fig. 1. General arrangement of the FPSO vessel

The principal dimensions of the FPSO are as follows:

- Length O.A. 335.6 m
- Length B.P. 320.0 m
- Breadth 58.8 m
- Depth 31.0 m
- Design Draft 21.5 m
- Scantling Draft 22.5 m
- Frame Spacing 0.8 m
- Web Frame Spacing 4.0 m

DROPPED OBJECT SCENARIOS

The dropping of objects during crane operations can cause damage to equipment and structural members such as the deck plating and walls. It is therefore necessary to check and validate the strength of structures for vulnerable areas against impact from dropping objects when the probability level is greater than 10^{-4} per year.

When modeling the worst case scenario of a dropped object load, the impact angle is essential. Zhang [16] performed extensive analyses to study the effect of impact angle in cases of ship collisions and dropped objects (the latter are of course more relevant in the present study). An object was dropped onto a plate at different impact angles, and the critical impact energy was found. As expected, a perpendicular impact was the most critical, as shown below in Fig. 2.

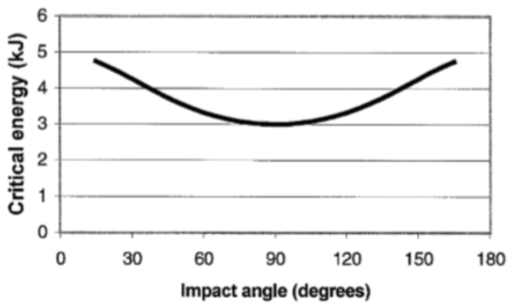

Fig. 2. Critical energy vs. impact angle of dropped object [16]

The rules applicable to the structural design of an impact load were reviewed, and specifically those rules relevant to dropped objects. DNV GL Offshore Standards and Recommended Practices are relevant and contain rules for the structural design of offshore ships and ALS design. According to these standards, all accidental loads that are relevant and have an annual frequency of occurrence greater than 10^{-4} need to be taken into account in the safety design [6]. The specific requirements concerning accidental loads are given in DNV GL-OS-A101 [6].

In this study, the design of the FPSO contains three main pedestal cranes and one knuckle boom crane. Pedestal crane 1 is the forward crane on the starboard side, while pedestal crane 2 is the forward crane on the port side and pedestal crane 3 is the aft crane on the starboard side. A knuckle boom crane is located on the infill deck, on the starboard side. Based on the design loads, drop height and swinging radii (defined by the characteristics and capacities of the cranes), the present study will assess the impact loads from dropped objects acting on the main lay-down area located on the poop deck. The crane layout, including the maximum and minimum reach of each crane, is shown in Fig. 3.

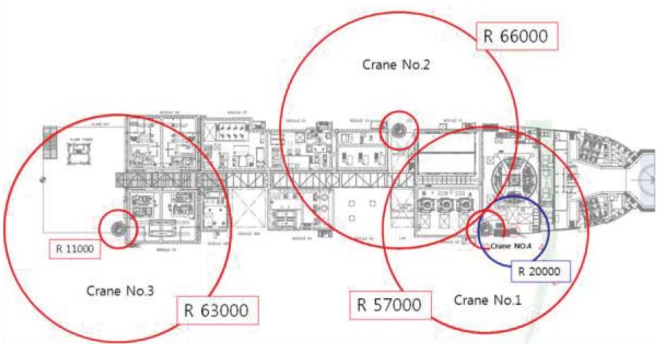

Fig. 3. General arrangement of the FPSO with crane layout

The acceptance criteria are that the structural areas around the impact locations of the dropped object may suffer plastic deformation, but no penetration is allowed. In other words, the critical failure strain should not be exceeded. For the other neighboring structures, the residual stress should be less than the allowable stress as per the DNV GL Class Rules [8], and deformation of the structure should not cause global collapse. In addition, the pillars must not be collapsed by buckling. In all cases, no collapse is allowed and the integrity of structures should be preserved.

To model the worst-case impact scenario, the container was dropped edge-first onto the deck at an impact angle of 90°. In the main analyses, the container was defined as an infinitely rigid shell, meaning that the impact energy was absorbed exclusively by the deck.

Dropping scenarios with regard to the impact of the container edge, such as large and small contact areas and one-corner contact are also examined. Information about the dropped objects and dropping heights considered here is summarized in Table 1. These impact locations are illustrated in Figs. 4 to 7. In all cases, a weak structure is assumed and a drop analysis is carried out.

Tab. 1. Design impact loads

Target area		Dropped object & condition	Impact area			Impact energy (KJ)	Height	Weight
Main lay-down area	Poop deck	20 foot ISO container (rigid)	D1	6.1 × 0.6 m	Small	518	2 m	26 ton
			D2	6.1 × 2.4 m	Large	765	3 m	26 ton
			D3	1.1 × 0.9 m	One corner	264	2 m	26 ton

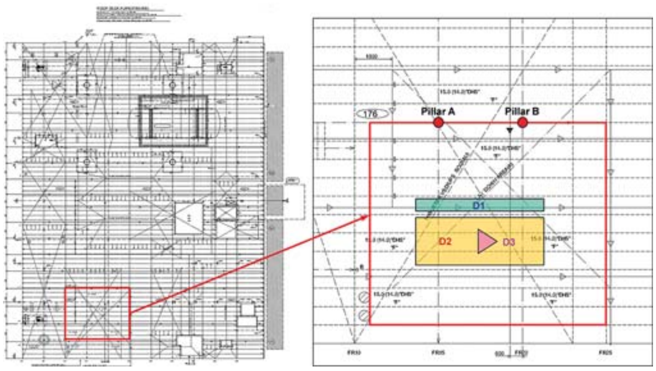

Fig. 4. Contact locations of the poop deck area – D1, D2 and D3 zones

Information on the structural scantling, such as the thicknesses and material grades of the plate, girder and stiffener, is given in detail in Tables 2 to 5.

Tab. 3. Poop deck area – D1, D2 and D3 zones

Gross plate thickness	15 mm
Longitudinal girder	800 × 12 + 200x20 (T-bar)
Longitudinal stiffener	250 × 90x10/15 (angle bar)
Material grade for plate	HT36
Material grade for longitudinal girder	HT36
Material grade for longitudinal stiffener	HT36

DESIGN CRITERIA

DNV GL and NORSOK give several recommendations concerning loads and the consequences of dropped objects. NORSOK N-004 [13] presents formulae for the determination of the impact velocity (in air and in water), as well as formulae for strain energy dissipation, associated damage (indentation or failure) and critical plastic strain with respect to typical steel material grades. The critical plastic strain adopted in the NORSOK Standards [13] will be used in the design acceptance check from the point of view of plastic strain. The value of the critical plastic strain for each steel grade is shown in Table 6. However, in this study, puncture of the deck plate is not acceptable over the full extent of the hull deck in the cargo area and above any hydrocarbon tank which may be outside of the cargo area, and the poop deck should not undergo more than 5% strain. Higher deformations can be specified for the lay-down areas or similar working decks, up to the following limits;

- Primary structures should not undergo more than 5% plastic strain; and
- The plastic deformation of secondary stiffeners should be limited to 10% strain.

For hull areas such as the hull deck, local details at the areas of interest can be modeled with an element mesh size of 100 × 100 mm in the analysis model. For a fine mesh FE model, the requirements given in DNV GL-OS-C102 [7] may be applicable. Usage factors are defined according to the mesh size, and the calculated usage factor based on the von Mises equivalent membrane stress at the centre of a shell element should not exceed the permissible peak usage factor, as shown in Table 6. Permissible peak usage factors (η_{peak}) given in DNV GL-OS-C102 [7] are defined based on the structural components, design method, load combination and applied mesh size.

The calculated usage factor based on the von Mises equivalent membrane stress at the centre of a plane element (shell or membrane) shall not exceed the permissible peak usage factor given in DNV GL-OS-C102 [7].

Tab. 6. Permissible peak usage factor for fine mesh FE analysis: $\sigma_{peak} = \eta_{peak} \cdot \sigma_{mateial\_yield\_stress}$ *[7]*

Permissible peak usage factors (η_{peak}) for fine mesh FE analysis	Mesh size		
	50 × 50 mm	100 × 100 mm	200 × 200 m
	1.7	1.48	1.25

A buckling capacity check is performed in accordance with the requirements given in the DNV GL Rules for Classification of Ships (Pt. 3, Ch. 1, Sec.13) [8]. The ideal elastic buckling strength without accepting any local distribution of the loads is used as a basis, together with the acceptance criteria given in the DNV GL Rules for Classification of Ships [8].

A buckling strength check is implemented to confirm the stability of the columns underneath the lay-down area with regard to catastrophic collapse under the impact load. Pillars under an impact load are subjected to two kinds of failure modes: buckling and yielding. Yielding does not lead to a catastrophic collapse of the pillars, since structural integrity will remain until rupture occurs. Thus, in order to avoid catastrophic pillar collapse from the impact load, buckling is checked using the Euler formula [8].

ASSESSMENT METHOD

In this study, we use FE analyses to assess the multitude of possible scenarios involving dropped objects and the structural configurations to be analyzed. An FE analysis is the most flexible method for this problem, as it can account for the possible effects that occur and assess the relevant factors such as impact energy, boundary conditions, material, and the different shapes and stiffnesses of indenters and the location of the indentation. An assessment of nonlinear material behavior is essential when determining the response of a structure.

To check whether the hull structures of an FPSO have sufficient strength to withstand dropped object events, nonlinear FE analyses are performed, including events involving large deformations of structures and elasto-plastic material properties. The strain hardening effect and the ultimate stress are considered in these analyses as a bi-linear strain-stress curve according to material grades, as shown in Fig. 5. Fracturing is determined on the basis of the critical plastic strain of the material used, as per the NORSOK Standard [13]. Fig. 6 shows the material properties used in the nonlinear simulations. The ultimate stress data are average values taken from online material information resources [6], and the critical strain data are taken from the NORSOK Standards [13].

For mild steel, these coefficients were originally determined experimentally by Paik [15] as C = 40.4 s^{-1} and q = 5. Alsos and Amdahl [2] suggested that the values of C would be greater for cases with large plastic deformations and high strain rates, and obtained better results when the coefficients had values of C = 4000 s^{-1} and q = 5.

DNV GL [4] recommends the same values (C = 4000 s^{-1} and q = 5) for typical offshore steels, if no other values are specified. Paik [17] also reports the coefficients for high tensile steel as C = 3200 s^{-1} and q = 5. As an initial configuration, the coefficients used in the ABAQUS model for mild and HT-36 steel were defined as C = 40.4 s^{-1} and q = 5. The Cowper-Symonds rate enhancement formula was used to model the effect of strain rate on the material properties, as shown in Fig. 6.

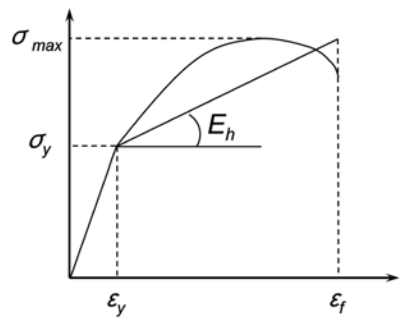

Fig. 5. Stress-strain curve for a bi-linear material

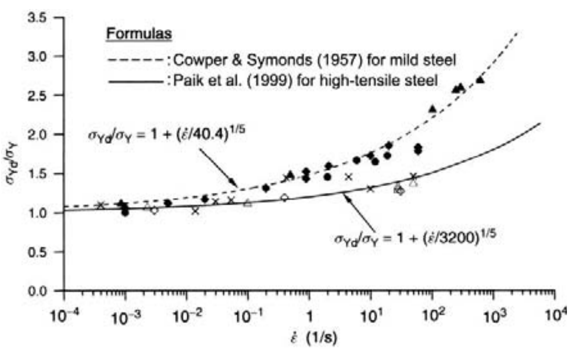

Fig. 6. Strain rate effect

$$\sigma_p = \sigma_y + \frac{EE_h}{E - E_h}\varepsilon_p \quad (1)$$

$$E_h = \frac{\sigma_{\max} - \sigma_y}{\varepsilon_f - \varepsilon_y} \quad (2)$$

where

σ_y = yield stress
E_h = Young's modulus
E_h = hardening modulus
σ_p, ε_p = plastic stress and plastic strain

$$\frac{\sigma_{yd}}{\sigma_y} = 1 + \left\{\frac{\varepsilon}{D}\right\}^{1/q} \quad (3)$$

Mild steel: D = 40.4, q = 5
HT steel: D = 3200, q = 5

Here, σ_{yd} is the dynamic yield stress, and σ_y is the static yield stress.

The material properties used in the initial configuration are based on the quality of the steel used for the decks of the FPSO. This includes mild, HT32 and HT36 grades of steel, as per the DNV GL code [5], which proposes engineering and true stress-strain parameters for these steel grades based on tests of different plate thicknesses. They recommend using the true stress-strain properties as input for FE analysis. Values for the plate thickness of t < 16 mm are applied in the material definition, as listed in Table 7.

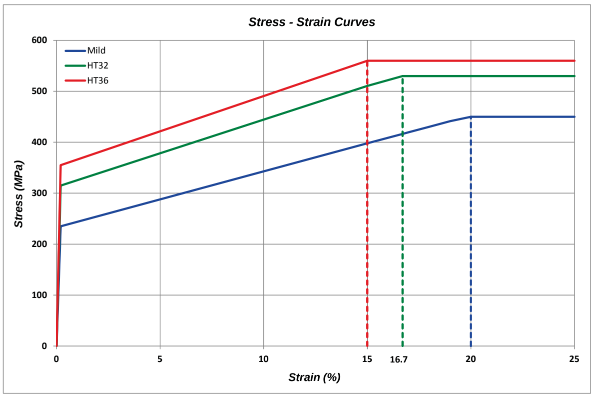

Fig. 7. Stress-strain curves for different steel grades

Tab. 7. Material properties used in the non-linear FE analyses [5]

Steel grade	Mild	HT 32	HT 36
Yield stress	235 MPa	315 MPa	355 MPa
Elastic strain	0.20%	0.20%	0.20%
Ultimate stress	450 MPa	530 MPa	560 MPa
Critical strain	20.0%	16.7%	15.0%
Density	7850 kg/m³	7850 kg/m³	7850 kg/m³
Young's modulus	2.06 × 1011 N/m²	2.06 ×1011 N/m²	2.06 x 1011 N/m²
Poisson's ratio	0.3	0.3	0.3
Tangent modulus	1085 MPa	1303 MPa	1385 MPa
Hardening parameter	1.0	1.0	1.0
Strain rate (C)	40.4 s^{-1}	3200 s^{-1}	3200 s^{-1}
Strain rate (P)	5.0 s^{-1}	5.0 s^{-1}	5.0 s^{-1}

FINITE ELEMENT MODELS

The mesh size of the FE model should fit with nonlinear FE analysis according to engineering judgment and nonlinear FE assumptions. For example, the areas of interest are modeled using very fine mesh size of around 100 × 100 mm, while the other areas have meshes of longitudinal stiffener spaced size. The dropped objects in all scenarios are assumed to be infinitely rigid, and all energies are therefore absorbed by the FPSO hull structure. FE models for each target area with rigid dropped objects are shown in Fig. 8.

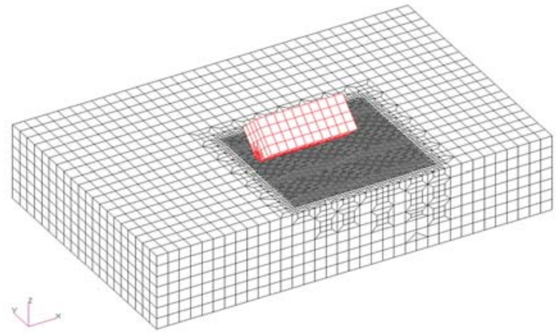

Fig. 8. FE model for drop impact analysis of the poop deck area

It is assumed that the FPSO vessel does not move during the drop events, which gives conservative results in terms of safety. The boundary conditions of the FPSO hull structure are therefore fixed. The boundary conditions applied to each area in the FE models are shown in Fig. 9.

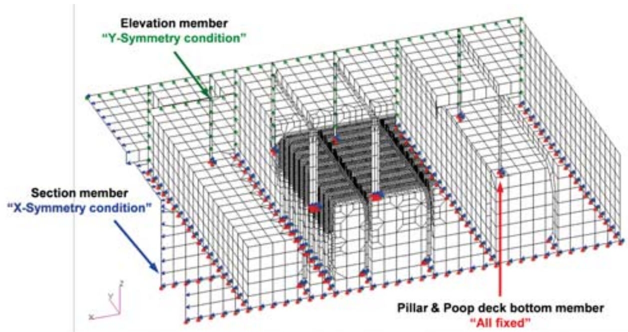

Fig. 9. Boundary conditions for the poop deck area

FINITE ELEMENT SIMULATIONS

Drop events are simulated by assigning various energy levels to the rigid body representing the dropped object, such as a container, and the equipment. During these drop events, the surface contact between the dropped objects and FPSO hull structure is taken into consideration. The contact is defined using an automatic single surface contact in LS-DYNA. Automatic contact, which may occur due to a large deformation of the FPSO structure, is also considered, and the initial shell thickness offset is always included. Impact energy is defined as the energy that a dropped object possesses just prior to impact. This is determined by conservation of energy, where it is assumed that all of the potential energy of the dropped object is converted to kinetic energy on impact, i.e. impact energy (J) = mass (kg) x acceleration due to gravity (m/s2) x height (m). This analysis considers the heavier lifts and compares these against the impact resistance strength of the target zone (TZ) decking. The decks in the identified TZs should be able to resist the impact energies associated with a dropped ISO container (with assumed mass 15 tons) from 3 m (442 kJ). This will significantly reduce the predicted frequency of deck failure, bringing it to below 10-4 per year. Contact areas are divided into three types: small, large and one-corner contact). A small contact area means that an inclined container is dropped, while a large contact area means the flat bottom of container. A small contact area can be occur when the wires of the two cranes are disconnected and the drop height is changed, as shown in Fig. 10. In a small contact area scenario, the sharp corner of the container will cause more conservative deformation and stress. The container also has a larger relative deformation energy, because it is less weak than the structural members. It is therefore important to calculate an appropriately small contact area. A one-corner contact means that one wire is disconnected in the small contact scenario. The one-corner and small contact areas can be calculated from the container deformation of dry drop simulation using the commercial analysis tool LS-DYNA.

Tab. 9. FE analysis results for drop impact events

	Target area		Dropped object	Load Case	Maximum plastic strain (%)					Max. reaction force	
					Primary member	Criterion	Second member	Criterion	Result	Location	Tons
Dropped object	Main lay-down area	Poop deck	Container	D1	3.1	5%	1.68	10%	Satisfied	Pillar B	405.4
				D2	2.91	5%	2.78	10%	Satisfied	Pillar B	391.1
				D3	2.41	5%	5.55	10%	Satisfied	Pillar A	151.7

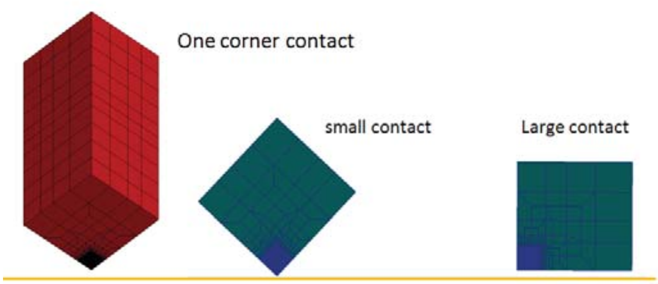

Fig. 10. Small, large and one-corner contact areas of the drop object

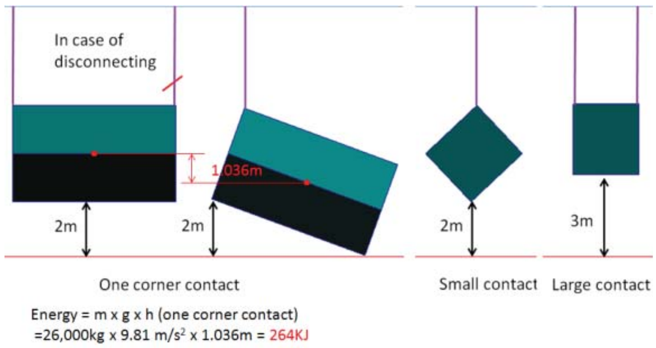

Fig. 11. Drop heights for small, large and one-corner contact scenarios

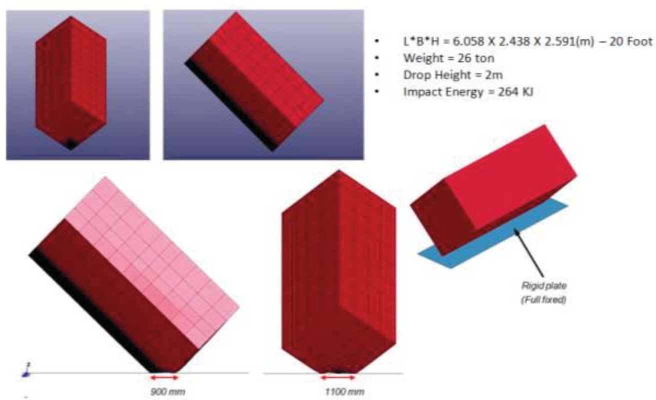

Fig. 12. Calculation of the contact area for one-corner contact

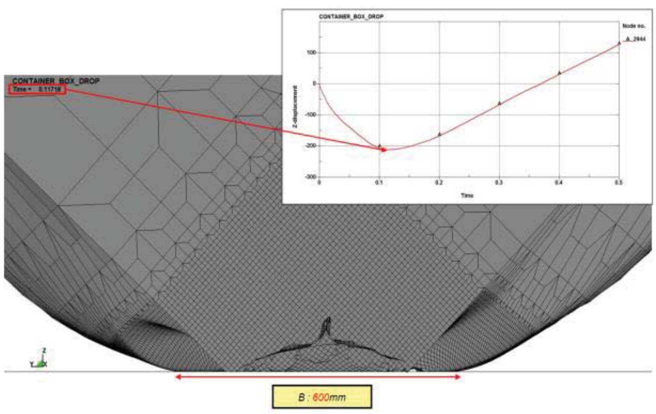

Fig. 13. Results of drop test for small contact area (deformation)

The findings of our calculations are shown in Figs. 14–19 for all cases studied, including plots of the deformed shape and plastic strain contours, and graphs of the penetration depth of the dropped object.

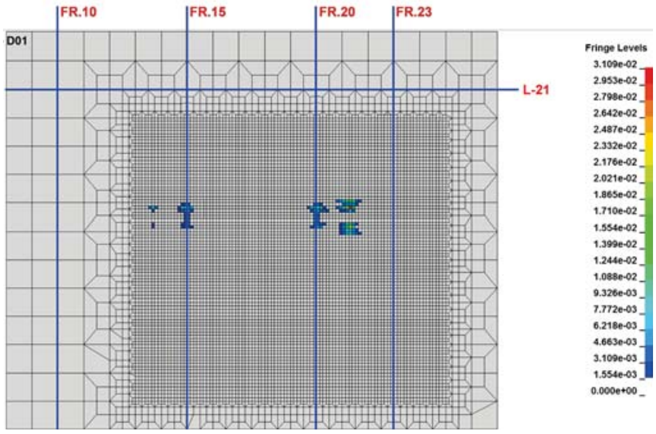

Fig. 14. Deformed shape and plastic strain contour – D1

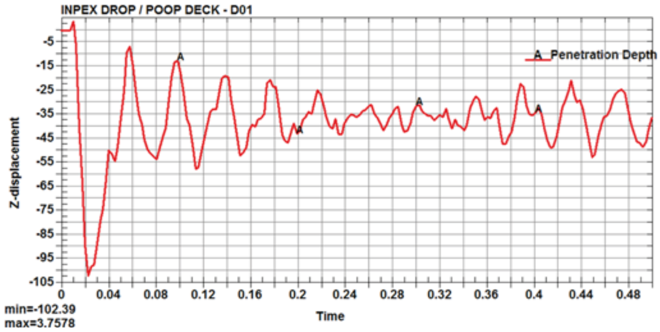

Fig. 15. Graph of penetration depth – D1

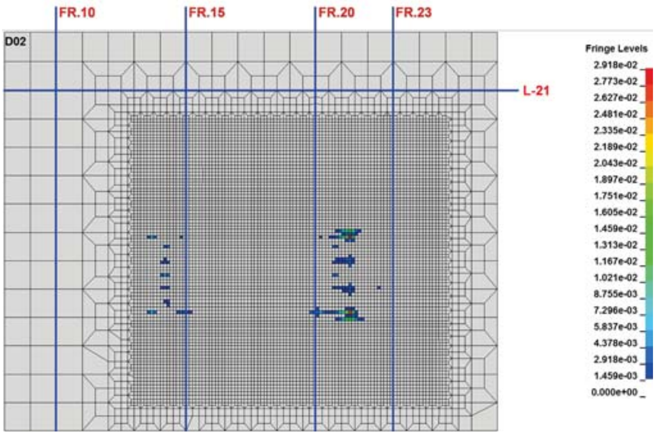

Fig. 16. Deformed shape and plastic strain contour – D2

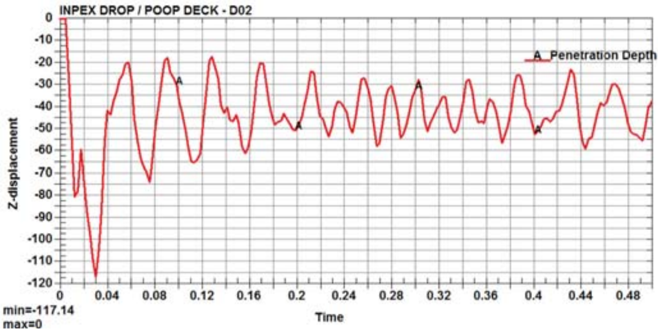

Fig. 17. Graph of penetration depth – D2

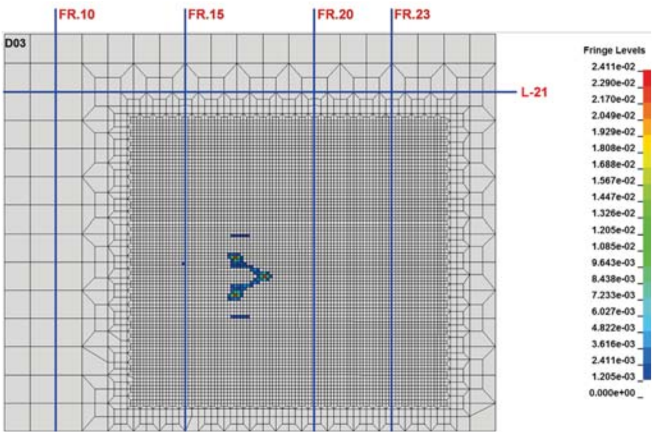

Fig. 18. Deformed shape and plastic strain contour – D3

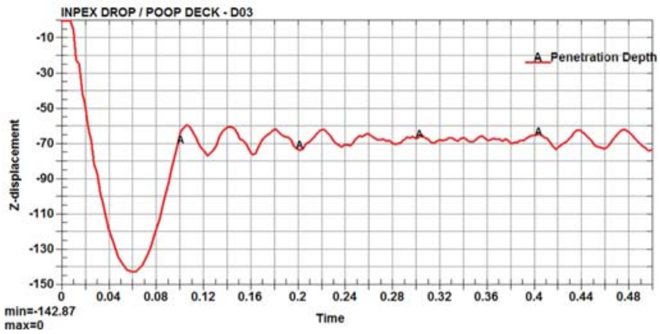

Fig. 19. Graph of penetration depth – D3

CONCLUSIONS

Drop impact analyses based on numerical impact simulations were carried out to investigate the safety of a FPSO hull structure during dropped object events. In all cases, the impacted structures suffered significant plastic deformation, but no failure occurred using the plastic strain criteria of the NORSOK Standards and the DNV GL Class Rule. Some structures were permanently deformed at the location of the drop event. However, the dropped objects did not breach the primary member. The maximum plastic strain of the cargo hull deck occurred at D11 and was 4.98%, i.e. within the allowable criteria of 5.0%. For the other neighboring structures, the equivalent stresses were less than the allowable stress set out in the DNV GL Class Rules, and structural deformation did not cause global collapse. Furthermore, the pillars supporting the main lay-down area did not suffer from buckling under the reaction forces. Finally, the findings and insights of the present study can be informative in the safety design of floating offshore structures. This article is useful from a practical engineering viewpoint, as containers are handled above FPSO units and an understanding of the effects of dropping one onto different types of deck is important from the point of view of safety assessment. The undertaken scope proves to be larger with all possible FPSO locations affected by dropped accidental loads. The effects of different material types are also accounted for. This study provides a technical basis for reducing the damage to FPSO deck structures and for taking reasonable protective actions based on the FE analyses carried out here.

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