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Static and dynamic structural analysis of aluminium craft deck structures, subjected to repeated impact load

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Abstract

This paper presents the results of an investigation on the response of the deck structure of a high-speed aluminium craft to the repeated impact load. This type of load is produced by operating the equipment which is installed on the deck structure, reinforced by the longitudinal stiffeners and transverse frames. Finite Element Method is used to analyse the stress distribution on the deck structure. Using the commercial FEM-based software ANSYS, a certain region of the deck is modelled. The impact load is simulated as a reaction of the stiffened deck. Different angles of the impact load are considered in relation to the vertical plane, which led to the critical loading conditions. The stress distributions and deflection patterns within the deck induced by the repeated impact load are obtained through transient dynamic FE analyses. Furthermore, the recommendation of one of the ship classification agencies concerning such cases is pursued and investigated. It was concluded that the static analysis based on this recommendation does not explain the behaviour of the deck structure subjected to such local impact loads well. The detailed results of dynamic transient analysis show very complex modes of deflection and stress contours at each interval of loading. The results also indicate that the accumulation of induced stresses over time may finally lead to the collapse of the deck structure. The horizontal direction of the repeated impact load generates the most critical stresses and deflections in the deck structure.

Keywords

stiffened plate, aluminium, impact load, static, dynamic, FE analysis

1 INTRODUCTION

A deck structure of a ship is the only certain location for installing the devices and equipment, which are vital for a satisfactory safety and operation of the ship (see Figure 1). These devices and equipment could produce either static or dynamic loads during their operation. Ship structural designers should take into account all the effects resulting from any type of load. The available rules and recommendations of Ship Classification Agencies [1, 5, 7] are taking into consideration these types of loads. They include the formulations or procedures for estimating simple acting loads and examining their effects on the ship structural elements.

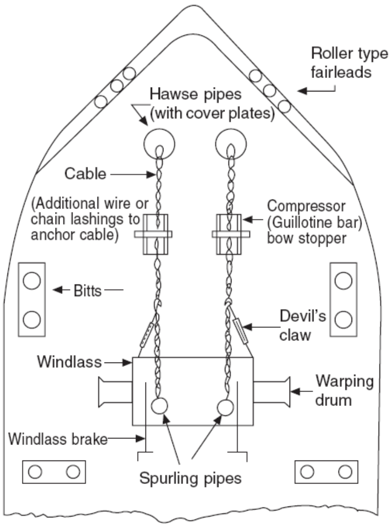


Figure 1 View of deck of a merchant vessel showing a number of deck equipments.

In recent years, there has been an increasing tendency towards high-speed marine transportation. Thus, many new designs of high-speed crafts have been developed by naval architects around the world. This implies that existing rules should be applied giving special attention and care to such cases, as they do not consider such loadings yet. Design problems arise especially when lightweight materials such as aluminium alloys or composite materials are used in the hull construction of these weight-sensitive crafts. Furthermore, the loads on the hull structure of these crafts generally depend on their mission, payload and operational environment. For the classification and strength evaluation, a number of missionrelated loads must be accounted for in addition to other routine loads and pressures. In calculating the load effects, the structure and associated load effects may be subdivided to primary, secondary and tertiary levels [9, 10]:

a) primary level

b) secondary level

c) tertiary level.

Figure 2 illustrates these three levels in ship structures where the primary level relates to the response of the entire ship's hull, as a beam under bending or twisting moments. The secondary level is associated with the load effects of a stiffened panel such as the outer bottom shell of the double bottom structure between the two adjacent transverse bulkheads. The boundaries of the secondary structure, i.e. stiffened panels, are usually formed by other secondary structures like the side shell or bulkheads. The tertiary level represents the load effects of the individual plating between stiffeners. The boundaries of the tertiary structure i.e. plating are formed by the stiffeners of the secondary structure of the stiffened panel.

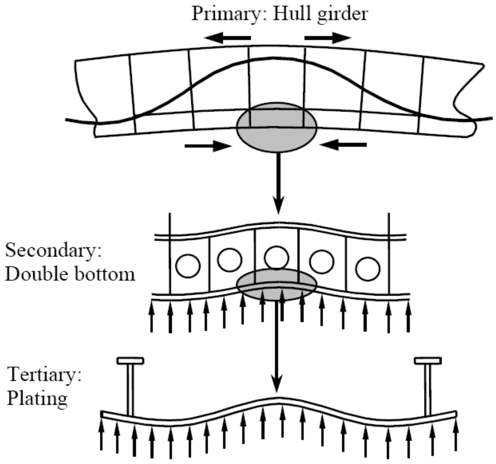


Figure 2 Three structural response levels and their associated load: primary, secondary and tertiary [9].

Some specific regions of the high-speed crafts are subjected to severe dynamic loads such as slamming loads and also to the repeated impact loads induced as a result of operating the deck equipments. As a very specific case, a reference can be made to the case of naval vessels when a deck gun is operating. Strength analysis in the corresponding regions of these crafts, subjected to such loads, is a main task of the structural designers. This paper deals with the effect of dynamic load on the deck structure of a high-speed aluminium craft. The load is assumed to be of the repeated impact type, produced as a result of operating a device that is installed on the deck, where several loads are applied in short time intervals to the deck structure. The direction angle of the repeated impact load may change in the vertical plane. It is recommended by the ship classification agencies, such as the American Bureau of Shipping (ABS) rules for the high-speed naval crafts [2], that an elastic static analysis of the deck structure around the deck equipment be performed. In such an analysis, an equivalent static force replaces the load of the repeated impact load. However, it would be better if a dynamic analysis be carried out at and around the location of the deck equipment. Through such an analysis, it could be possible to capture and understand the deck structural response better during the operation of the deck equipment. In addition, this would make it easier to predict any probable failure mode, such as tearing of the local plate panels in the deck structure. Such an analysis may help in designing the deck to absorb the repeated impact load better.

The strength of un-stiffened or stiffened metallic plates under either in-plane or lateral loads has gained great attention by many authors. Guedes Soares [18] studied the characteristics of un-stiffened plates under the static in-plane longitudinal compression and finally a design equation can be derived for estimating the ultimate strength of such plates. More detailed studies on un-stiffened plates under the different combinations of static loads were performed by Paik et al. [17] and Cui et al. [4]. Fujikubo et al. [6] studied the characteristics of the stiffened steel plates under the static in-plane and lateral loads.

Besides, there are numerous studies on the strength characteristics of unstiffened and stiffened plates under the lateral impact loads. As some examples, reference can be made to the works of Yuen, Nurick and Langdon [16, 19] on the identification of failure behaviour of stiffened steel plates under the lateral uniform or localized blast loads. An experimental and analytical study was also presented by Langdon et al. [15] of the inelastic deformation and failure (rupture) of the clamped aluminium plates under the pulse pressure loading.

Based on the survey and knowledge of the authors, there is not any study in the literature that reports on the response of stiffened plate structures subject to the lateral repeating impact loads. The main focus of this research is to identify the deflection and stress characteristics inside the deck stiffened plate structures as a result of repeating local impact forces. Stress and strain distributions within the deck structure are analysed applying Finite Element Method (FEM). The research includes a detailed modelling of the repeated impact load on the deck for both rule-based static and dynamic analysis. Based on the obtained results, some recommendations are given which are believed to be of importance to the structural designers and could be considered in future rules of such structures.

2 LOADS ON SHIPS

The classification of the loads on ships is according to the type of structure at which they act, as some loads influence the structure at just one of the three structural level responses defined earlier. In addition, the classification of loads is also according to the way they vary during the time; static, slowly or rapidly -varying in time. Therefore, in calculating the load effects on the ship structure, three types of structural analysis corresponding to static, quasi-static and dynamic loads should be considered. In a dynamic analysis, the effects of the time variation of the loading are fully accounted for. A quasi-static analysis is simply a static analysis in which the motions are estimated and their effect on the structure is accounted for, approximately by including some representative coefficient for the applied forces. Therefore, there is no essential difference between the static and quasi-static analyses.

In terms of three defined load types, the principal loads acting on the ships are summarised according to their variation in time [8]:

- **Static loads:** are the surrounding still water, dry-docking and thermal loads, respectively. The magnitude or direction of such loads does not change in time or their changes are minor.

- **Slowly varying loads:** are wave-induced dynamic pressure distributions on the hull, sloshing of liquid cargoes, and shipping of green seas on deck, wave slap on sides and foredecks, inertial, launching, berthing and ice-breaking loads at the hull level. These are primary loads acting on the ship hull girder. Their magnitude or direction changes slowly over the time.

- **Rapidly varying loads:** are slamming, forced vibration, ice-impact at secondary and tertiary levels, underwater explosion, grounding, collision, gun foundation and gun muzzle blast loads. These loads may act on the ship hull girder during the accidental occasions. They usually have a short duration of action and a large amplitude or magnitude. As a result of their action, different local or global failure modes may suffer the ship hull girder.

3 FINITE ELEMENT MODELLING AND ANALYSIS

3.1 Statement of the problem and extent of the model

The kind of equipment and device, attached to the foredeck of a high-speed aluminium craft and shown in Figure 1, produces a repeated impact load. The direction angle of the impact load may change in relation to the vertical plane. The equipment is attached to an interface rigid lightweight structure. The lower flange of the interface structure is fixed securely to a cylindrical foundation with an upper and lower flange by four bolts. The location of deck equipment in relation to the position of the transverse bulkheads is shown in Figure 3, where different parts of the connection between the equipment and the deck structure can be seen.

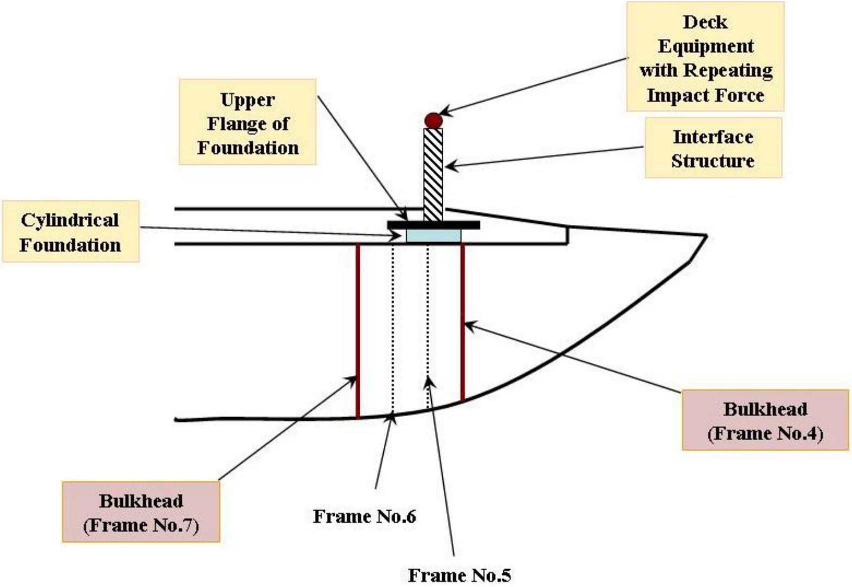


Figure 3 Location of deck equipment with repeated impact force in relation to the position of the transverse bulkheads.

One of the main objectives of this investigation is to establish the static and dynamic structural response of the deck during the equipment operation. General arrangement of the deck in the vicinity of the equipment, in addition to the details of the cylindrical foundation, is shown in Figure 4. The region under consideration for the analysis lies between the transversal bulkheads located at transverse frames No. 4 and No. 7; measuring 2250 mm (see Figs. 3 and 4). There is a centre girder attached to just beneath the deck along its centre line. The extent of the model in the transverse direction includes an interval of 2000 mm (1000 mm on either side of the deck centre girder). An analysis of ship deck of this extent by FE could give the extreme load deflection and stress distribution and pattern induced during the operation of the deck device.

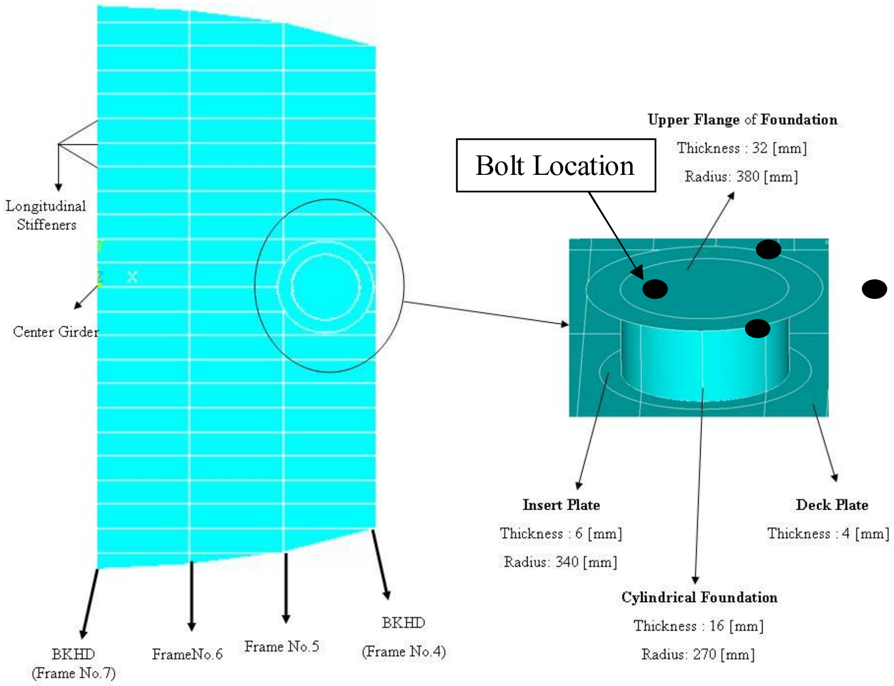


Figure 4 General arrangement of the deck in the vicinity of the equipment and the details of foundation.

3.2 Material properties

Interface connecting structure, cylindrical foundation and the craft structures are made of the aluminium alloy Al 5083-H321. The mechanical properties of the considered alloy are given in Table 1. Un-welded condition of the aluminium in Table 1 refers to the state of pure aluminium alloy before any thermal process like welding. On the other hand, when stiffeners are welded into the plate, in the neighbourhood of plate-stiffener junction material softens and as a result its mechanical properties are weakened. The region in which such a kind of weakness in mechanical properties happens is called “heat-affected zone” or simply HAZ. Un-welded condition of the mechanical properties in Table 1 is relevant to the material inside HAZ. Based on the obtained results from Ref. [12], the induced stresses fall well below the yield strength of the aluminium alloy materials. Therefore, only the modulus of elasticity of the aluminium alloy is considered as the dominant parameter in both static and dynamic analyses.

Table 1 Mechanical properties of Al 5083-H321 [1, 5].

Property	Symbol	Welded condition	Un-welded condition
Tensile yield stress (N/mm^2)	σ_Y	125	215
Tensile ultimate strength (N/mm^2)	σ_{ult}	275	305
Modulus of elasticity (N/mm^2)	E	70000	70000
Poisson's ratio	ν	0.33	0.33

3.3 Characteristics of the deck equipment

The principal characteristics of the deck equipment are listed in Table 2. The cylindrical foundation has a height of 286 mm. Longitudinal stiffeners are of aluminium flat-bar with the cross-sectional dimensions of $40mm \times 4mm$. The centre girder has a flat-bar of cross-sectional dimensions of $225mm \times 10mm$. Other structural dimensions are presented in Figure 4.

Table 2 Deck equipment characteristics.

Characteristic	Value or range
Weight (kg)	56
Range of direction angle in vertical plane for the repeated impact force (Degree)-Positive anticlockwise	(-12)-(+85)
Rate of repeated impact force (1/Second)	1.3
Height of interface structure (mm)	933
Maximum magnitude of the repeated impact force (kN)	26.6

3.4 Finite Element discretization

SHELL63 and BEAM188 elements are used from the library of the finite element code ANSYS [3] in the descretization of the deck structure and the attached foundation. SHELL63 elements, as shown in Figure 5, are used to depict the modelling of the deck plating and foundation. The elements have four nodes and six degrees of freedom at each node; translations in the nodal x, y, and z directions and rotations about the nodal x, y and z-axes. Stress stiffening and large deflection for both in-plane and normal loads are considered.

BEAM188 elements, as shown in Figure 6, are used for the modelling of stiffeners. These elements are suitable for analysing the slender to moderately thick beam structures. The

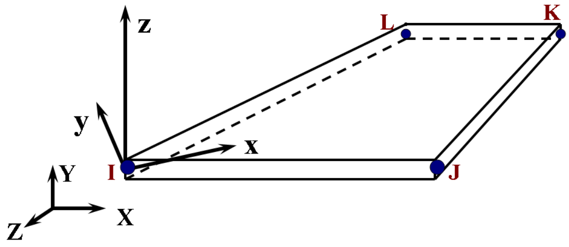


Figure 5 SHELL63 element.

element is based on the Timoshenko beam theory. Shear deformation effects are included. BEAM188 is a linear (2-node) or a quadratic beam element in 3-D and has six or seven degrees of freedom at each node, which includes the translations in the x, y, and z directions and rotations about the x, y, and z directions. A seventh degree of freedom (warping) is also considered. This element is well-suited for the linear, large rotation, and/or large strain nonlinear behaviour.

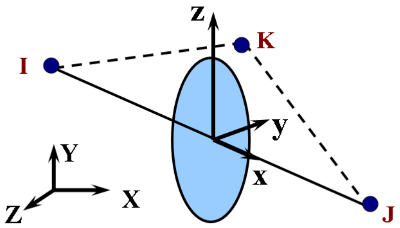


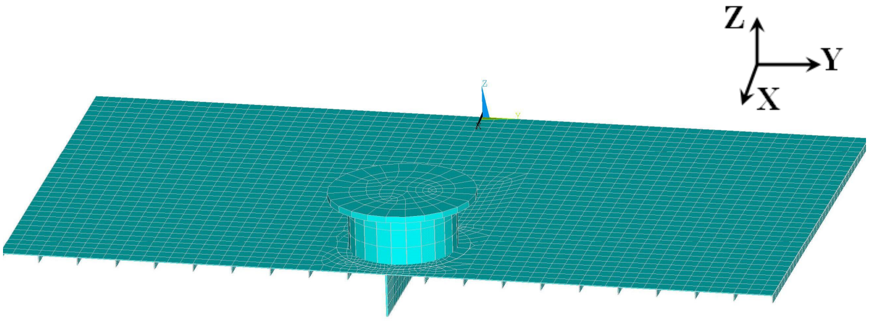
Figure 6 BEAM188 element.

3.5 Boundary Conditions

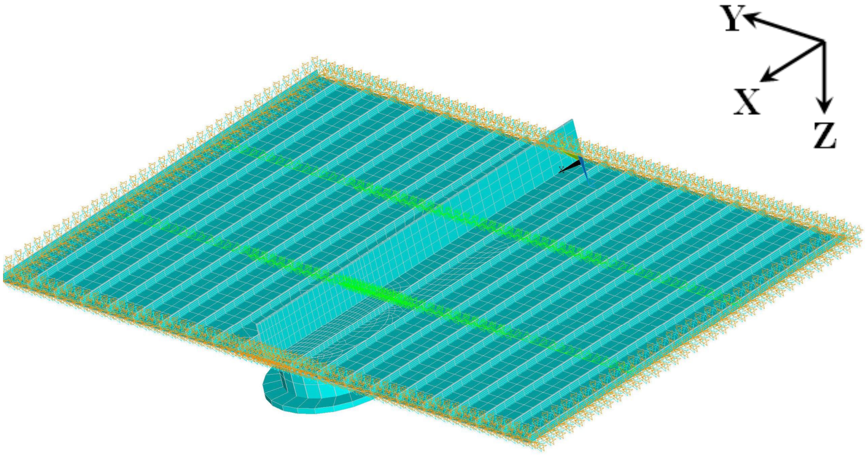
Due to the relatively stiff connection of the deck structures to the surrounding structures (side shell structure as well as the transverse watertight bulkheads), the edges of the deck structure in the model are considered to be fully restrained from the connections to the side structure or transverse bulkheads.

In order to keep simplicity, the transverse frames No. 5 and No. 6 (Figure 4) are not modelled here. These elements have generally smaller rigidities than those of the transverse bulkheads. That is why; just the longitudinal displacement movement of the nodes on these two transverse frames No. 5 and No. 6 (see Figures 3 and 4) are coupled with each other. The reason behind this and not imposing other conditions on the model is due to the fact that the nodes lying on these two frames may have lateral deflection. So, constraining the vertical motion of the deck along with the lines of transverse frames No. 5 and No. 6 may lead to the incorrect results.

The boundary conditions imposed on the finite element model from a topsidedown view are shown in Figure 7.



(a) 3D view



(b) Topside-down view of considered deck structure and cylinder including the boundary conditions

Figure 7 FE model of the deck.

Created finite element model consists of 3479 shell elements and 800 beam elements. The connection between the shell elements are considered to be ideal. Also, beam elements are defined in the interfaces of planes of different structural elements. Probable failures or detaching in the bolt joints are not considered in this study since their investigation was not included in the outline of the research. Therefore, all joint connections are considered to remain ideal throughout the analyses. For a detailed modeling of the bolt joints and also the study of possible failure modes in their locations, more detailed modelling schemes using other types of elements like contact elements are needed. This is left to a future work.

3.6 Load modelling in static analysis

For the analysis of the high-speed naval crafts, equivalent load for the static analysis from the ABS recommendations [2] was developed and adopted for both the commercial and naval high-speed crafts. Based on the ABS recommendation, the dynamic repeated impact load produced during the operation on deck equipments can be replaced by an equivalent static load. The total equivalent static force has only a vertical component and its value (F_w) is calculated using Eq. (1), where W is the weight of the deck equipment, R is the value of the repeated impact force produced during the operation, and nxx is the vertical acceleration of the craft at the location of the deck equipment, respectively.

$$F_w = W\left(1 + 0.5n_{xx}\right) + 1.3R \tag{1}$$

The n_{xx} in Eq. (1) is calculated using Eq. (2).

$$n_{xx} = n_{cg}.K_v \tag{2}$$

The n_{cg} in Eq.(2) is the craft vertical acceleration at its centre of gravity and K_v is a factor considering the distribution of the vertical acceleration along the craft [2] and is calculated using expression (3):

$$K_v = \begin{cases} 1 & \text{for } x/L \le 0.5 \\ 2x/L & \text{for } x/L > 0.5 \end{cases} \tag{3}$$

where x and L are respectively the longitudinal coordinate of the considered section from the after-perpendicular of the craft and the length of the craft.

The total calculated equivalent force on the foundation (F_w) is to be distributed equally among the bolt locations in the upper flange of the foundation as demonstrated in Figure 8.

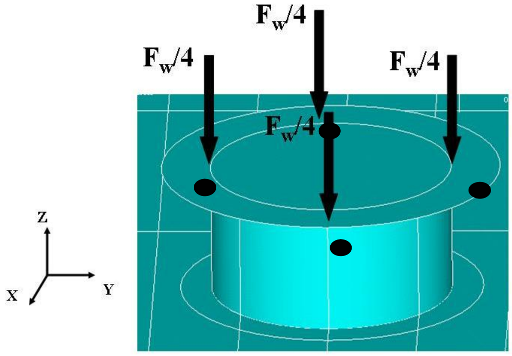


Figure 8 Static equivalent loading scheme applied to four bolts.

3.7 Load modelling in dynamic analysis

In the dynamic loading scheme, the time interval and direction angle of the repeated impact load applied to the deck structure, beside the weight of the deck equipment were considered. Let x and y coordinates represent the longitudinal and transversal directions of the craft and z represents the direction perpendicular to the craft deck. The deck equipment is attached by means of four bolts to the upper flange of the cylindrical foundation as shown in Figure 4.

For any direction angle of the repeated impact load (α), the maximum magnitude of the reaction load is denoted by R in Figure 9. The horizontal component of the reaction force, $R.\cos\alpha$, is distributed equally between the two bolts fixed on the x-direction as demonstrated in Figure 10. Each of these two forces is ramped from zero to their real values ($R.\cos\alpha/2$) in the time interval. At the end of each time interval, these forces are suddenly reduced to zero. The number of load ramps is set equal to the times of repeating the load. The time interval between the successive load ramps can be calculated based on the deck equipment characteristics.

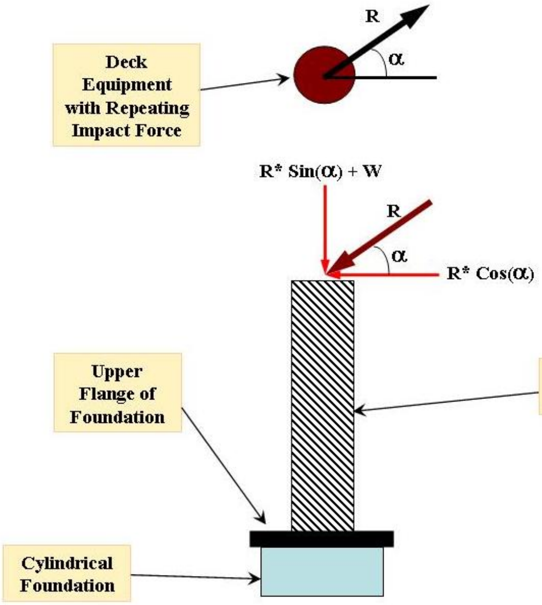


Figure 9 Repeated impact force of deck equipment, its reaction and components.

Four more forces are exerted on the bolt locations in the upper flange of the foundation. Two are the weight of the deck equipment (W) which include the vertical component of the reaction force ($R.\sin\alpha$). Again, during each time interval, the values of these two forces are ramped from the half of the weight ($W/2$) to their corresponding maximum values ($(W + R.\sin\alpha)/2$) and at the end of each time interval, they are decreased to zero. The other two vertical forces are related to the bending moment created by the horizontal component of the reaction force. This bending moment, calculated by $(R.\cos\alpha.h)/D$, is the function of the reaction force (R), the direction angle of the repeated load (α), the height of the interface structure (h) and the diameter of the foundation cylinder (D). The two forces representing the effects of this bending moment are also applied in a ramped trend. The complete loading scheme is shown in details in Figure 10 [11, 13, 14].

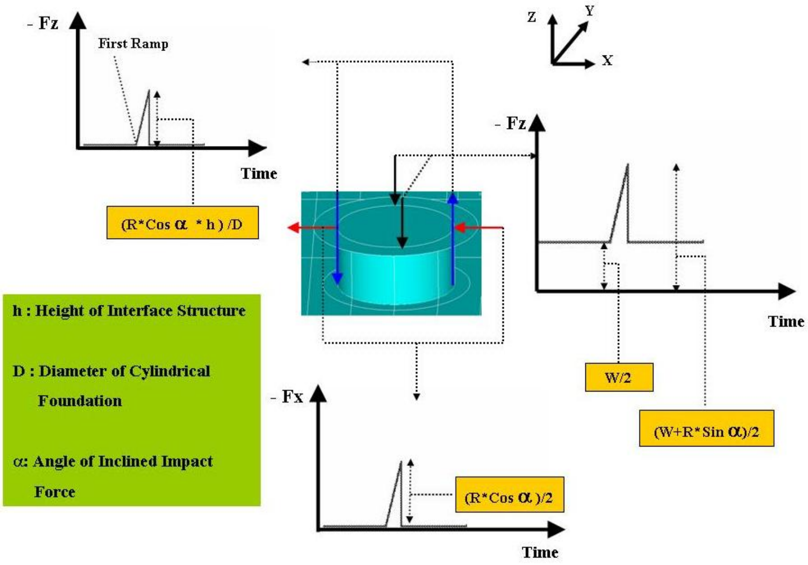


Figure 10 Dynamic loading scheme.

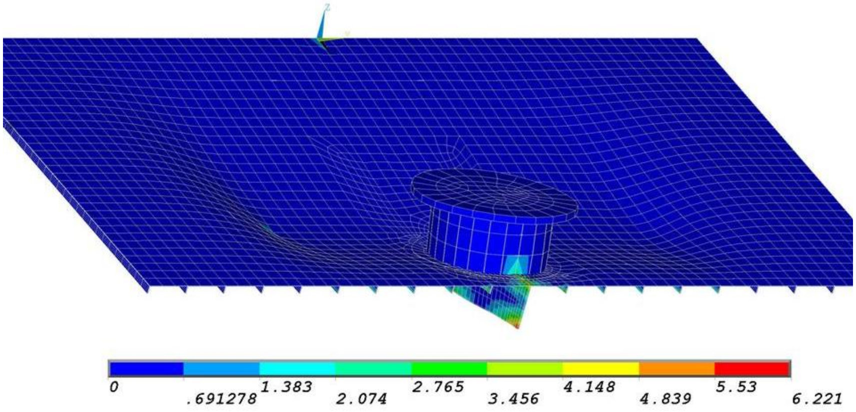
4 RESULTS AND DISCUSSIONS

4.1 Static analysis

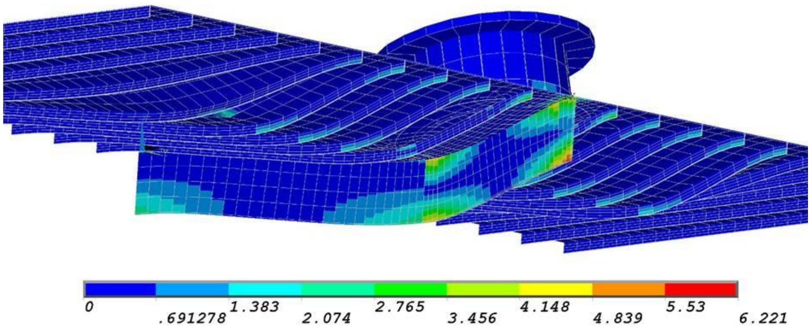
Table 3 presents a summary of the results based on the finite element analysis of the deck model (Figure 7) for the static rule-based loading (Figure 8). Stress and deflection modes for the deck under the equivalent static load system are shown in Figure 11. As can be seen from the results in Table 3, the maximum values of deflection and equivalent Von-Mises stress are below the allowable limits stated by the rules [2]. It should be noted that the unit of stress on the plots in Figure 11 and also other figures is in kgf/mm^2. As observed from the detailed stress plots in Figure 11, highly stressed areas are produced at the fore end of the bolted junction between the foundation and the deck structure, and at the centre girder and around the longitudinal stiffeners.

Table 3 Comparison of obtained results from static analysis with the allowable limits stated in the rules of ABS [1].

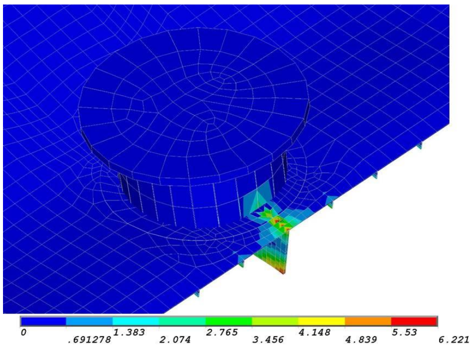
Result	Symbol	Value	Allowable limit	Symbol	Value
Maximum calculated out-of-plane deflection of the plate by FEM (mm)	$U_{Z,max}^{FEM}$	1.016	Maximum allowable out-of-plane deflection of the plate by the rules (mm)	U_Z^{All}	2.000
Maximum calculated Von-Mises equivalent stress of the plate by FEM (MPa)	σ_{max}	62.2	Maximum allowable Von-Mises equivalent stress of the plate by rules (MPa)	σ_{All}	62.5



(a) Perspective view



(b) Underside view



(c) Detailed view

Figure 11 Stress and deflection modes for the deck under equivalent static load system.

4.2 Dynamic analysis

The distributions of maximum Von-Mises equivalent stress and also maximum deflection at successive load intervals and different direction angles of the repeated load are shown in Figures 12 and 13.

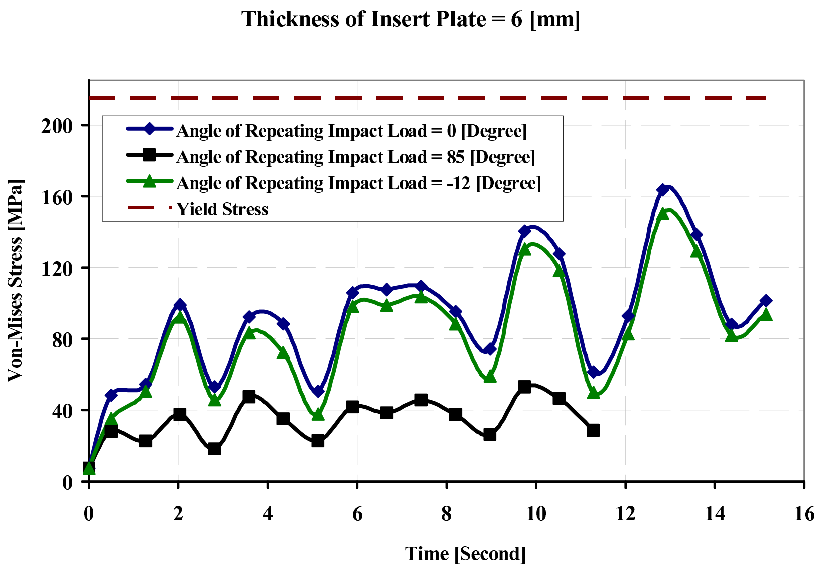


Figure 12 Distribution of maximum Von-Mises stress versus time for different angles of impact load of the deck equipment.

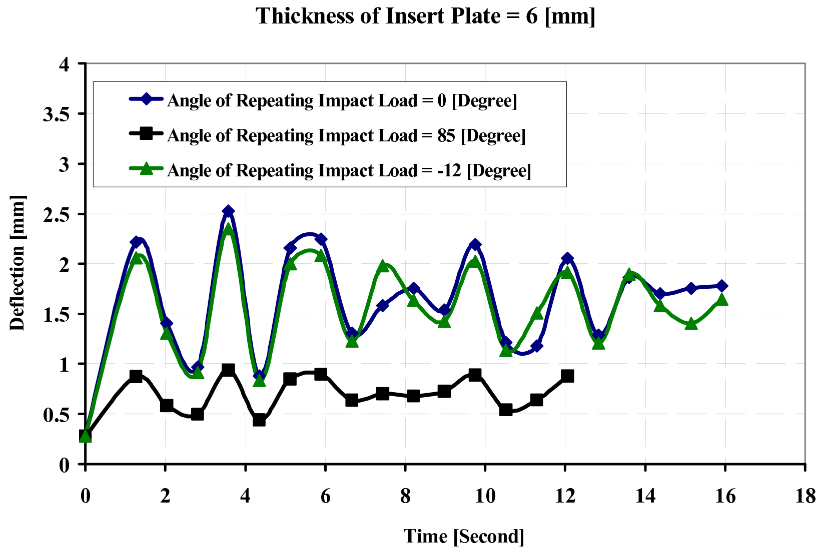


Figure 13 Distribution of maximum deflection versus time for different angles of impact load of the deck equipment.

Since the deflections and stresses are relatively high for the zero-degree of direction angle for the repeated impact load, the deflection modes and equivalent stress contours of the deck obtained by the finite element dynamic analysis are shown in Figures 14 and 15, respectively, for ten successive impact load intervals.

It should be noted that the maximum magnitudes of deflection and equivalent stress in different load steps are not devoted to one specific element or node inside the model. In other words, the location where has the maximum deflection defers from one load step to another one. This is also true in the case of the location of maximum equivalent stresses. Therefore, the values reported in the Figures 12 and 13 are not relevant to any specific element or node inside the model.

The behaviour of the deck structure is almost the same when the direction angle of the repeated impact load is either 0^o or -12^o as can be observed in Figures 12 and 13. The deflections and stresses are the greatest in the case of zero degree angles and accordingly this case is the most critical one. The upper limit of the direction angle, 85^o, is not critical since the maximum stress and deflection are much less than those values for the zero and -12 degrees.

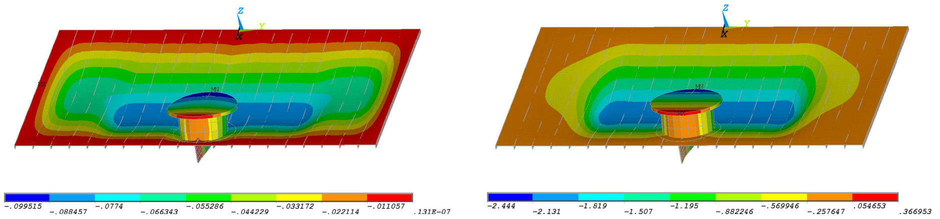
It is an important phenomenon observed in Figures 12 and 13 that the decrease of the stress level in the load intervals corresponds to the increase of the deflection and vice-versa. Based on the results shown in Figure 14, any relatively large deflection in Figure 13 corresponds to the large deflection of the local plate panels lying either between frames 5 and 6 or between frames 6 and 7. It can be assumed that a large deflection in the deck happens farther away from the foundation. Also, when maximum stresses are captured in Figure 12, an overall deck deflection occurs between the two rigid transverse bulkheads at frames 4 and 7.

The results indicate that with a further increase in the number of repeated load intervals, the maximum values of the equivalent stress tend to increase while those of the deflection tend to decrease. Thus, the evidence supports the fact that as a result of successive load intervals, the resulting stresses are added to the residual stresses within the deck. This may lead to a limit state or critical condition for the total stresses and may finally cause the failure in the deck structure.

A comparison of the results in Figures 11 and 15 illustrates a great difference between the response of the deck in both static and dynamic analyses. The deflection mode and stress distribution around the foundation in the results of static analysis are different from those in the dynamic one. This suggests the need to perform the dynamic analysis instead of static analysis to reach a realistic view on the response of the deck to the rapidly varying foundation loads.

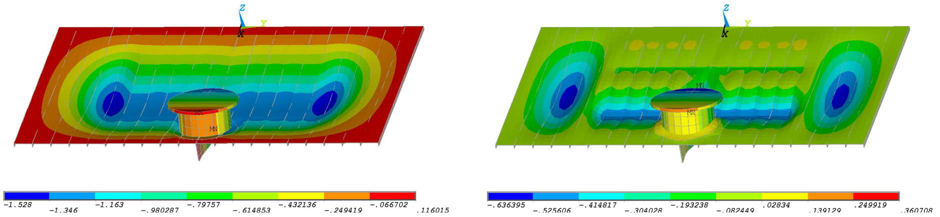
5 CONCLUSIONS

The deck structure response of a high-speed aluminium craft to the repeated impact load was investigated applying Finite Element Method. The impact load was simulated properly in a rational manner. The recommendation of one of the ship classification agencies was also assessed.



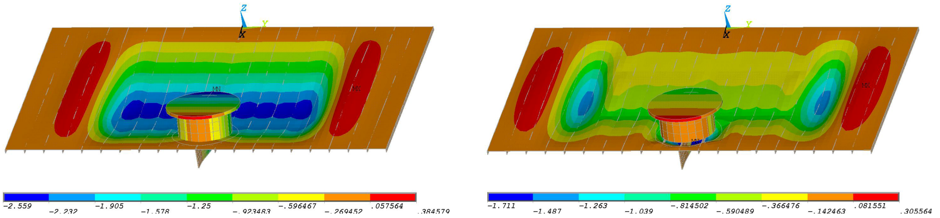
(a) Impact Load Interval No.1, Time= 0.5015 Second

(b) Impact Load Interval No.2, Time= 1.272 Second



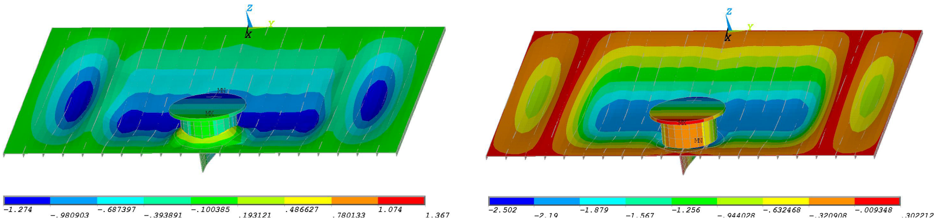
(c) Impact Load Interval No.3, Time= 1.575 Second

(d) Impact Load Interval No.4, Time= 2.813 Second



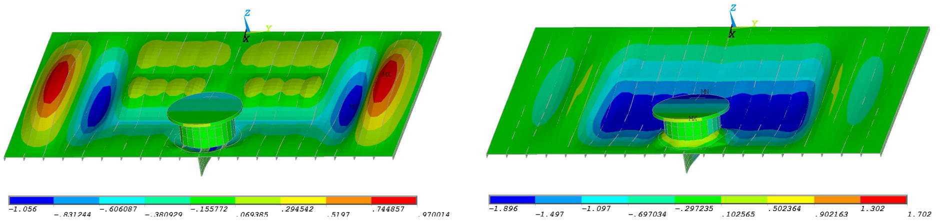
(e) Impact Load Interval No.5, Time= 3.583 Second

(f) Impact Load Interval No.6, Time= 4.354 Second



(g) Impact Load Interval No.7, Time= 5.124 Second

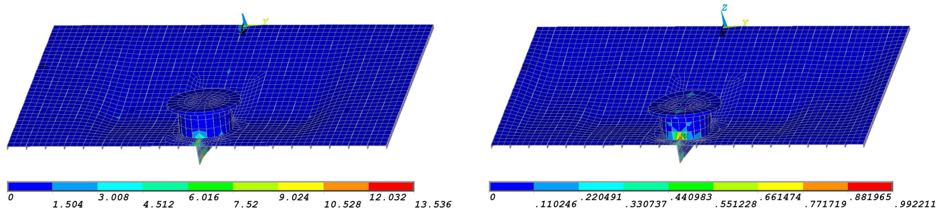
(h) Impact Load Interval No.8, Time= 5.895 Second



(i) Impact Load Interval No.9, Time= 6.666 Second

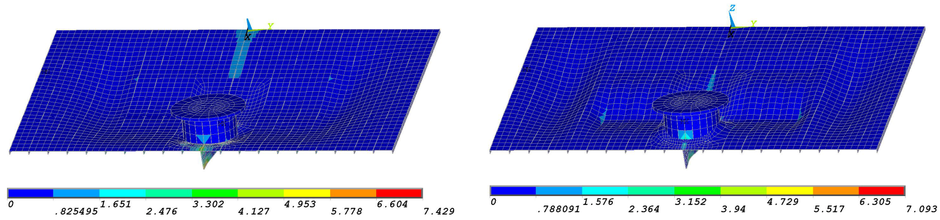
(j) Impact Load Interval No.10, Time= 7.436 Second

Figure 14 Deflection contours of the deck obtained by dynamic finite element analysis.



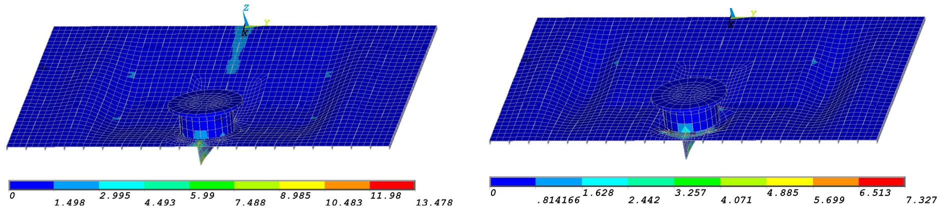
(a) Impact Load Interval No.1, Time= 0.5015 Second

(b) Impact Load Interval No.2, Time= 1.272 Second



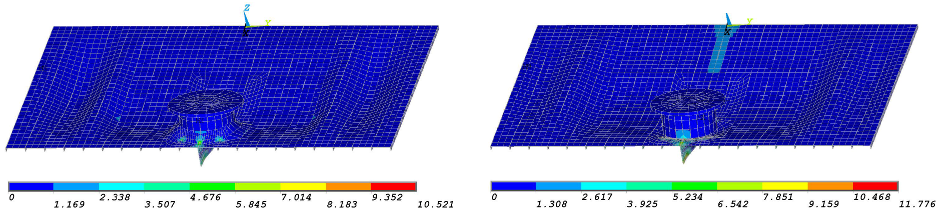
(c) Impact Load Interval No.3, Time= 1.575 Second

(d) Impact Load Interval No.4, Time= 2.813 Second



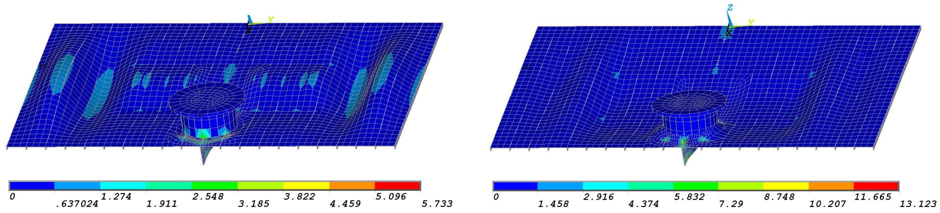
(e) Impact Load Interval No.5, Time= 3.583 Second

(f) Impact Load Interval No.6, Time= 4.354 Second



(g) Impact Load Interval No.7, Time= 5.124 Second

(h) Impact Load Interval No.8, Time= 5.895 Second



(i) Impact Load Interval No.9, Time= 6.666 Second

(j) Impact Load Interval No.10, Time= 7.436 Second

Figure 15 Equivalent stress contours of the deck obtained by dynamic finite element analysis.

The following conclusions were drawn from the results of the present investigation:

- Static analysis based on the recommendation of the ABS does not explain the behaviour of the deck structure subjected to such local impact loads in a proper manner. Performing the dynamic transient analyses helps effectively in understanding the behaviour of deck structure under high-speed repeated impact loads.
- The analysis of the behaviour of the foundation is not possible by just referring to one time interval of the load and it is necessary to consider successive time intervals.
- With an increasing number of loading time intervals, residual stresses are accumulated and, as a result, the total stress increases.
- Large local panel deflections apart from the foundation may happen in some cases. Contrary to this, an overall deck deflection is observed when large stresses are applied to the deck structure.

Further studies should be carried out to help in more accurate prediction of the failure modes at the foundation. In addition, the effect of different foundations on the deck response should be examined.

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