Comparative Study on Ferry Ro-Ro's Car Deck Structural Strength by Means of Application of Sandwich Materials

Tuswan[1], Achmad Zubaydi[1], Agung Budipriyanto[2] and Septia Hardy Sujiatanti[1]
[1]*Department of Naval Architecture, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember (ITS), Jl. Arief Rahman Hakim, Surabaya, Indonesia*
[2]*Department of Civil Infrastructure Engineering, Faculty of Vocational Studies, Institut Teknologi Sepuluh Nopember (ITS), Jl. Menur 127, Surabaya, Indonesia*

Keywords: Car Deck, Structural Strength, Sandwich, Ferry Ro-Ro.

Abstract: This paper presents results of investigation on car deck performances by means of application of sandwich materials for 300 GT Ferry Ro-Ro. Strength performance was examined utilizing finite element method and compared to design criteria. Four finite element models of the ship deck were developed; three of them were modification of existing ship structure with different configurations of stiffeners. Two design load cases were considered in the analysis. Design load scenario was assumed to be in seagoing condition where the pressures were due to the static and dynamic distributed loads. In this research, sandwich materials were fabricated from steel face sheets and core materials which were made from two filler materials, one core was from clamshell powder and the other was from eggshell powder. The synthetic resin was used as the matrix and epoxy resin was applied as the adhesive layer. The results were promising in terms of structural strength and weight savings. The strength of car deck sandwich structure having no deck beam was found to be met with the allowable strength criteria and contributed to reducing the stress approximately 14.6%. Moreover, its application led to the weight saving ranged from 8.87% to 11.6%.

1 INTRODUCTION

The lightweight material is urgently required. Therefore, research effort concerning the application of the lightweight material in ship's deck structures has recently attracted many researchers. Reducing the mass of deck structures is the predominant intention, but its application seems to be a major benefit to decrease the ship lightweight due to a large number of decks. Strength and stability of the structure and weight reduction are a major consideration. Consequently, in the most general cases, the lightweight material is frequently selected instead of increasing existing material thickness.

Lightweight materials (e.g. aluminium, composite, and sandwich panel) have been investigated as alternative materials in deck structure. Gunnarsson and Hedlund (1994) investigated the possibility the use of sandwich structure made from extruded aluminium profiles in the ship's car deck to achieve a lower weight. However, the design was too costly to be implemented. It was also assembled and proved with acceptable results regarding structural strength by Hanson (2000). Noury et al. (2005) studied the comparison of a conventional stiffened plate structure and the steel sandwich structure in the hoistable car deck. The results indicated that weight saving was about 10%. It was also showed that the laser-welded sandwich panels offered high stiffness and strength both local and global directions. Momčilovic and Motok (2009) assessed the application of sandwich plate system (SPS) in general cargo barge and offered weight reduction from 5 to 15% in comparison to conventionally built one. Weight reductions of the SPS bulk carrier and SPS container barge were even less: 6 to 13% and 4 to 12%, serially. Based on the issues, it was hard to find that it could be greater than 15%, mostly varying between 5 and 8%. Kortenoeven et al. (2008) also noticed that the application of sandwich material could reduce the structural weight up to 39% in a specific part (e.g. decks) of a dredging ship. Weight reduction for FRP sandwiches could be more than 70% and average 39% for steel sandwich applications. Hybrid sandwich (steel-polymer-steel) has also been inspected, but the issues indicated that

Tuswan, ., Zubaydi, A., Budipriyanto, A. and Sujiatanti, S.
Comparative Study on Ferry Ro-Ro's Car Deck Structural Strength by Means of Application of Sandwich Materials.
DOI: 10.5220/0008542800870096
In *Proceedings of the 3rd International Conference on Marine Technology (SENTA 2018)*, pages 87-96
ISBN: 978-989-758-436-7

there was no cost or weight advantage for internal decks and bulkheads mainly because of the small plate thickness needed in the existing structure. Sandwich panels were also more excellent in terms of weight savings than single-skin panels in most structural parts of the ship, with an exception in bottom structures constructed for high design pressures, single skin panels were more recommended as asserted by Johnson and Ringsberg (2017).

Until now, more than 35,000 m2 of SPS are currently in operation in the marine and construction sectors. SPS has found substantial applications in ship repair (e.g. ramps and Ro-Ro decks) using the overlay technique. Further, it was a viable alternative to conventional stiffened plates with further enhance before it could be used in the construction of a new car deck structure. SPS was a robust design that reduces weld volumes by up to 60% compared to stiffened plates (SAND.CORe, 2013). Its application in ship structure also could (a) remove the need for secondary stiffeners (Sujiatanti, et al., 2018), (b) reduce the lightship weight (Brooking & Kennedy, 2004), (c) offer high strength to weight ratio (Castanié, et al., 2008; Wadley, 2006; Mamalis, et al., 2002; Belouettar, et al., 2009), and (d) improve crashworthiness in structure (Reis & Rizkalla, 2008).

This paper presents the main issues to evaluate the possibility of replacing today's conventional steel car deck panels in Ferry RO-RO vessels with alternative lightweight sandwich materials. These materials were satisfying the design requirements of scantlings, as well as the classification society DNV-GL structural strength for car deck panels (DNV-GL, 2015). The design loads were calculated by adopting the DNV-GL standard (DNV-GL, 2017). This paper is organized as follow, aims and the used methodology are explained. Then the reference model, load case applied, material selection, and car deck's modified models are described. Next, the analyses and results of structural strength and weight estimation are systematically presented and discussed. This article is concluded with conclusions.

2 DESCRIPTION OF MODEL DEVELOPMENT

2.1 Reference Model

The ship used as a reference in this research was a Ferry RO-RO with approximately corresponding to the total car deck area of 381.8 m2. The car deck panel comprised of two main parts; the stiffened plate system and the beam system as illustrated in Figure 1.

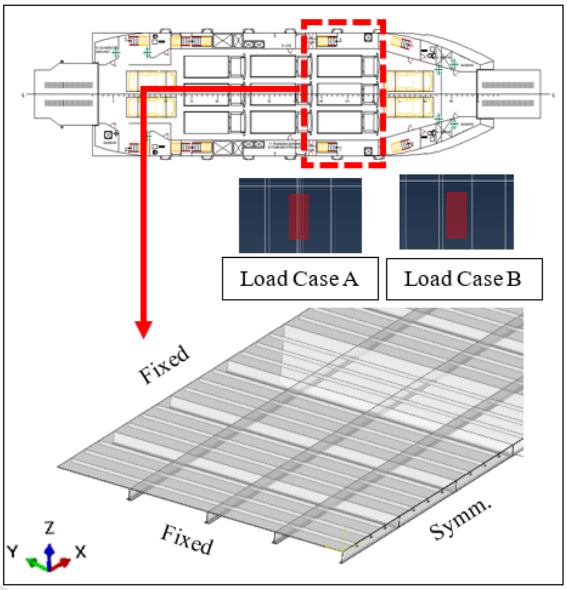


Figure 1: Half-modelled reference car deck symmetric with respect to x-axis with boundary condition and load case variation.

The car deck structure investigated in this study was located in the parallel mid-body between two bulkheads; the dimension was 14 m in length and 11 m in breadth. In this research, the existing car deck scantling consisted of deck girder and strong beam with T profile (T 180x90x8 mm) and deck beam with L profile (L 60x60x6 mm). The face sheet and core thickness must be designed in accordance with the strength index (R) by DNV-GL criteria (DNV-GL, 2016). The reference car deck thickness was 12 mm. In this study, the sandwich thickness configuration clearly calculated of 4 mm thin faceplate and 20 mm thick core.

The modified models were based on the configuration of stiffeners. Car Deck A was the sandwich plate without changing the existing stiffener, while Car Deck B was the car deck with sandwich plate and diminished whole deck beams without changing the strong beams and girder spacing. Another modification was Car Deck C with have similar configuration to Car Deck B but the strong beam and deck girder's frame spacing be enlarged.

The finite element simulations were implemented to analyze structural strength by comparing the von Mises, normal stress, shear stress, and deflection value between the existing steel structure and modified models. Eight-node solid linear brick elements with reduced integration and hourglass control (C3D8R) having six degrees of freedom per node was used to model the core material, A 4-node doubly curved thin or thick shell with reduced integration and hourglass control (S4R) was selected to model steel plates, and a 2-node linear beam element (B31) with six degrees of freedom per node was used to model the stiffeners.

A node-surface based tie constraint was applied to provide the interaction between the deck plate and stiffener while surface to surface based tie constraint was chosen to give interaction between faceplate and core material as cohesive interaction. Meanwhile, the assumption of boundary condition should be organized in such a way that could be similar to the real conditions. The boundary conditions applied in the model were fixed in the side of car deck structure, a pinned constraint in the connection between the bulkhead and car deck, and symmetry constraint was applied in the centre line of car deck structure.

2.2 Material Selection

The face sheets are comparatively thin and are usually constructed by a high strength material. The core is relatively thick and supports sufficient stiffness and strength in the direction normal to the plane of the face sheet.

In this study, both the conventional stiffened steel plate car deck structure and the application of sandwich material were systematically investigated. The sandwich materials were manufactured by steel facing plates and the core made from waste materials. Two core materials were developed; one core material was made synthetic resin and clamshell powder and the other was made from synthetic resin and eggshell powder. Many researchers were being interested in eggshell and clam shell's abilities as potential fillers (Manshuri & Amalina, 2014; Hassan, , et al., 2012). The most valuable properties including hardness, water absorbent qualities, tensile strength were found to be satisfied by using different sea shells (Ramnath, et al., 2018). The filler was mixed with unsaturated polyester resin (UPR) as matrix, methyl ethyl ketone peroxide as a catalyst with different weight compositions. The previous research (Abdullah, et al., 2017; Mula, et al., 2017) stated that filler ranged from 20% to 30% of the total core weight of both clamshell and eggshell was the most optimum composition core material properties and fulfilled the DNV-GL Criteria (DNV-GL, 2016) and Lloyd's Register (Llyod's Register, 2015).

Sandwich flexural tests in previous research were performed to obtain core material properties of both clamshell (Abdullah, et al., 2018) and eggshell (Mula, et al., 2018) based on ASTM standard (ASTM C 393, 2016). Meanwhile, the mechanical properties of steel were based on DNV-GL standard (DNV-GL, 2016). The steel and core material properties used in finite element modelling was obtained from previous research, see in detail in (Abdullah, et al., 2018; Mula, et al., 2018).

2.3 Load Estimation

Design load scenarios for strength calculation of car deck in normal operation at sea were calculated. The pressure due to the distributed load for the static and dynamic design load scenario should be derived for each dynamic load case and calculated as depicted in Equation 1 (DNV-GL, 2017).

$$P_{dl} = P_{dl\text{-}s} + P_{dl\text{-}d} \tag{1}$$

where $P_{dl\text{-}s}$ is a static pressure due to the distributed load. Dynamic pressure ($P_{dl\text{-}d}$) due to the distributed load is calculated by ($P_{dl\text{-}s} \cdot a_z/g$), where a_z represent vertical envelope acceleration.

The load was assumed to in the seagoing condition where the total load was the sum of static pressure ($P_{dl\text{-}s}$) from and dynamic pressure ($P_{dl\text{-}d}$) represented the motion of the ship. The panel was loaded with a uniformly distributed load of 250 kg/m^2 and the self-weight of the panel. The total load was calculated as self-weight= 131.7 tonne. Hence, the dynamic factor was 1.5 in accordance with DNV-GL (DNV-GL, 2017), and was added to the loads when evaluating stresses. Therefore, arising due to the motion of the ship increased the load to 197.55 tonne.

For stowed position load case, the local loaded panel for a heavy truck was lifted to the stowed position. In this load case, dynamic factor was not used as a added load. The wheel load was designed when the wheels from three heavy trucks were situated in the top op stiffener (real contact between tires and stiffener), hereinafter referred to as load case A. Another case was situated exactly in the middle between stiffener (axle parallel to stiffener), hereinafter referred to as load case B, as depicted in Figure 1.

For individual vehicles with specified arrangement and dimensions of footprints, the local design pressure ($P_{dl\text{-}s}$) was, in general, to be taken as (DNV-GL, 2015):

$$p_{dl\text{-}s} = \frac{Q}{N_o\, ab}(9.81 + 0.5a_v) \tag{2}$$

where Q represents maximum axle load in tones, n_o is number of load areas on the axle, a is the extent of the load area parallel to the stiffeners in m, b is extent of the load area perpendicular to the stiffeners in m, a_v is used for moving cargo handling vehicles, is assumed to be 0. The load area dimensions are in general to be taken as:

$$\mathrm{a} = \sqrt{kA}\,;\; b = \sqrt{\mathrm{A/k}} \qquad (3)$$

where k is 2.0 for single wheel, 2.0 for multiple wheels with axle parallel to stiffeners. A is calculated by ($9.81wQ/n_op_o$). Where n_o is assumed to be 2 unless otherwise specified. w value equals to 1.0 in general, p_o is divided by two load prints i.e. front load print and rear load print which represent maximum tire pressure in kN/m^2. The summary of wheel loading was presented in Table 1.

Table 1: Wheel loading of car deck.

Load Prints	Chassis Weight (tonnes)	Weight Capacity (tonnes)	n_o	p_o (kN/m^2)
front	2.22	2.29	2	342.74
rear	1.66	4.51	2	234.54

The load prints (in red area) of three heavy truck used double wheel with dimension 0.3 x 0.425 m in rear wheel and single wheel with dimension 0.3 x 0.215 m in front wheel as illustrated in Figure 2.

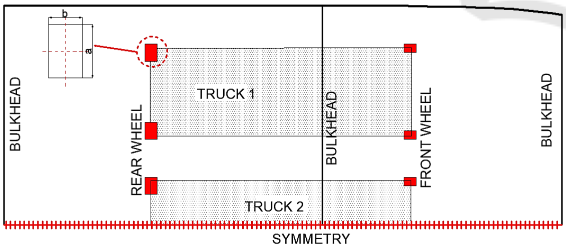


Figure 2: Working position of wheel loading of half-modelled symmetric with respect to x-axis.

2.4 Design Criteria

Since the car deck structure was assumed to be subjected to a pure vertical force, the only stress that was evaluated in the initial design was normal bending stress and bending shear stress. The normal bending stress, denoted σ_x was calculated with Equation 4.

$$\sigma_x = \frac{M_y}{I_y}\, z \qquad (4)$$

where I_y is the moment of inertia for the cross-section, M_y is the bending moment, and z is the distance from the neutral axis to the fiber currently being studied in the cross section (Thelandersson, 1987).

The bending shear stress (τ_{xz}) in the structure due to a load of tire was calculated using Equation 5.

$$\tau_{xz} = \frac{\mathrm{v_y\, s_z}}{\mathrm{t.I_z}} \qquad (5)$$

where v_y is the load, s_z is the static moment, I_z is the moment of inertia, and t is the thickness where the shear stress is evaluated.

Besides normal and shear bending stress, and von Mises stresses will occur when the profile was unevenly loaded. Consequently, the equivalent von Mises stress is evaluated with Equation 6. Where $\sigma_y = \sigma_z = \tau_{yz} = \tau_{xy} = 0$, this assumption was decided since the profile will be subjected to pure bending in this load case. The von Mises stress was calculated with Equation 6 below.

$$\sigma_{vm} = \sqrt{\sigma_x^2 + 3\tau_{xz}^2} \qquad (6)$$

Design criteria for analyzing structural strength has to be defined. These criteria are determined in this study by the classification society DNV GL (Kortenoeven, et al., 2008). The maximum stresses that are allowed to occur in the structural elements were calculated according to DNV rules for existing car deck. Maximum allowable stresses with regards to load conditions for the existing car deck were normal bending stress (σ_x) is assumed 222 MPa, bending shear stress (τ_{xz}) was assumed 125 MPa, and von Mises stress was assumed 250 MPa.

To determine the permissible stress of modified models by means of application of sandwich material, the flexural test based on ASTM C393 (2016) standard was conducted to obtain maximum sandwich bending stress as permissible criteria. Flexure tests on flat sandwich construction were conducted to determine maximum face bending stress (σ_{nu}) and core shear stress (τ_u). The permissible criteria of modified models were summarized in Table 2.

Table 2: Permissible stress of sandwich structure for different core compositions.

Permissible criteria for sandwich with core made from			
20% Eggshell	30% Eggshell	20% Clamshell	30% Clamshell
90.7 MPa	95.2 MPa	67.6 MPa	71.4 MPa

The design criteria for deflection was assumed that when the panel deflects, a certain free height above the below car deck has to remain. Thus, a certain limiting value could not be assigned precisely for deflection (Ringsberg, 2015.). The maximum edge deflection criteria of the lowest points of the panel (δ) which must not exceed 50 mm was applied. It applies to keep the difference in edge heights between two adjacent loaded and unloaded car decks’ minimum. This was to ensure the safe passage of vehicle from one panel to another.

2.5 Mesh Convergence Study

Mesh convergence is an important issue that needs to be addressed in most of linear problem. During performing an FE-analysis, there were possible sources for error, for example, the mesh might be too coarse. In order to obtain reliable results, a mesh convergence study was carried out in order to confirm the accuracy of the results. The method of establishing mesh convergence required a curve of a critical result parameter (von Mises stress), to be plotted against global mesh size as can be seen from the Figure 3.

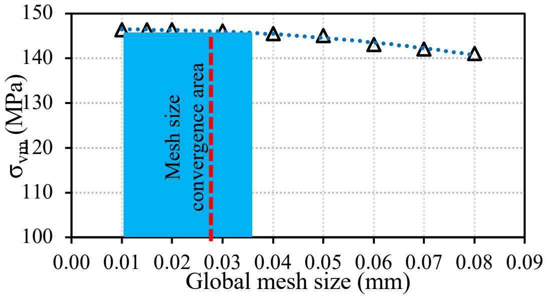


Figure 3: Convergence study of reference model.

The vertical dashed line represented the optimum global mesh size for the model. It was evident that the solution converges for mesh sizes between 0.035 and 0.01 as illustrated by blue area in the Figure 3. For the analysis, a global mesh size of 0.03 was applied in finite element analysis.

3 RESULT AND DISCUSSION

Prior to the application of sandwich structure to ship construction, preliminary strength analysis and weight estimation were conducted to ensure that the specific sandwich application in deck structure would lead to substantial benefits for the shipyard as well as the ship owner. Weight saving should be significant to compensate the unforeseen technical, practical and financial problems during the engineering and production of sandwich applications and to assure ship owner, classification societies and management of the shipyard to actually decide to apply sandwich panels.

Structure weight (m) is the relationship between the density of the substance (ρ) and how much space it takes up (v). The car deck total area as depicted in Figure 1 was 381.8 m^2 and the density of the material was reported in (Abdullah, et al., 2018; Mula, et al., 2018).

The weight comparisons between the reference car deck and three models of sandwich structures by means of application of sandwich material and configuration of stiffener are illustrated in Figure 4. From the illustrated diagram, it could be reviewed that the application of sandwich material both of using clamshell and eggshell core material considerably decreased the car deck weight. It could be concluded that core material with 20% eggshell which had the lowest density was the most significant weight reduction compared to the others. In another hand, the core material with 30% had the lowest weight savings. Regarding the modified models, Car Deck A without changing the configuration of stiffener showed the marginally decrease the weight from 1.7% to 4.5% in compared with existing car deck. A similar report was also given in Car Deck B, weight saving was in the range between 8.87% and 11.6%. Moreover, Car Deck C indicated the highest weight reduction was about 15.8%.

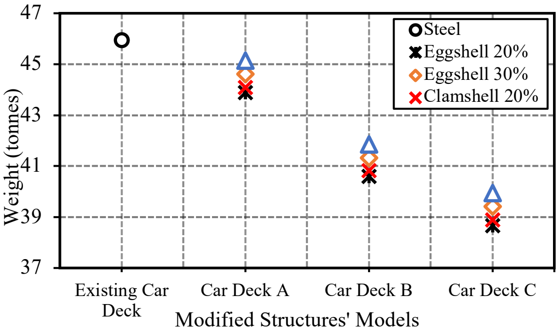


Figure 4: Comparison of weight estimation to whole models.

Compared with similar reports regarding the application of sandwich plate using synthetic resin, Sujiatanti et al. (2018 stated that the result of the study showed that the application of sandwich panel which used core material from synthetic resin in Ro-Ro's car deck reduced the structural deck about 12%. It was a correct projection of application of a waste material as a filler in core material as a comparable result regarding weight reduction. However, one has to consider the reality that even though SPS proposes valuable benefits, the rough weight reduction even greater than 50% that can be occasionally discovered in application of SPS in ship structure as argued by Momčilović & Motok (2009).

With the weight reduction of the ship, an increase in the ship's payload can be carried out in ship operations, so that it can carry more cargo. It provides meaningful benefits to the ship owner and shipyard.

Taking into consideration of sandwich application, preliminary strength calculations used finite element analysis was performed in the next section and need further investigation to decide to implement sandwich panels in car deck structures.

3.1 Structural Strength Analyses

One of the challenges for sandwich panel structures is its sensitivity to point loads, i.e. concentrated loads may break the material and cause delamination. Therefore, besides weight analysis, the structural strength analyses of the car deck by means of application of sandwich material is substantially important as an advance thorough check to study the implementation of sandwich material.

In this section, the finite element analysis results were presented to thoroughly observe the comparison of structural strengths between existing car deck and modified structures' models where there were different core material properties, and the number of stiffener configurations. Permissible criteria for different models, to investigate their performance and to correlate them with each other, have to be defined in Section 2.3.

The results from the FE analyses between two different load cases showed in Figure 5-8. Figure 5-7 presented in sequence the comparison of von Mises stress (σ_{vm}), normal bending stress (σ_x), and shear bending stress (τ_{xz}) between existing model and modification models. From those illustrated diagrams, in comparison between the existing model and Car Deck A which have similar stiffener configuration, the application of sandwich material could reduce von Mises stress in the range from 13% to 15.8% in load case A, and from 1.3% to 9.5% in load case B, respectively. It could be reviewed that Load Case B which wheel load was situated exactly in the middle between stiffeners (axle parallel to stiffener) identified as the most critical concern. This is not a standard cargo configuration and will occur very seldom.

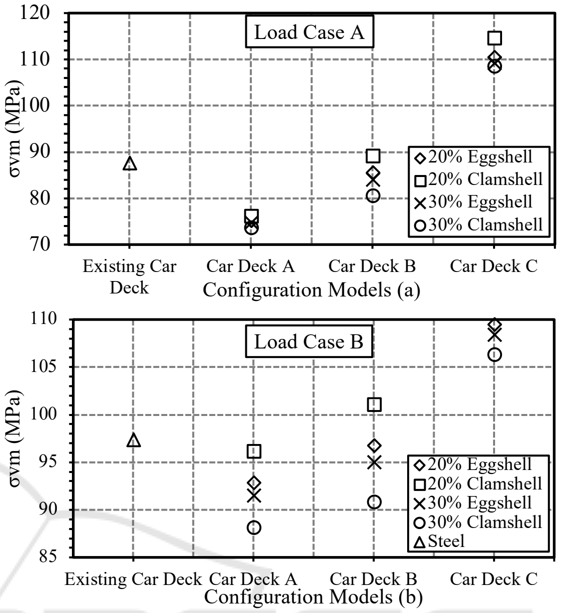


Figure 5: von Mises Stress between existing and modified structures' models under (a) Load Case A (b) Load Case B.

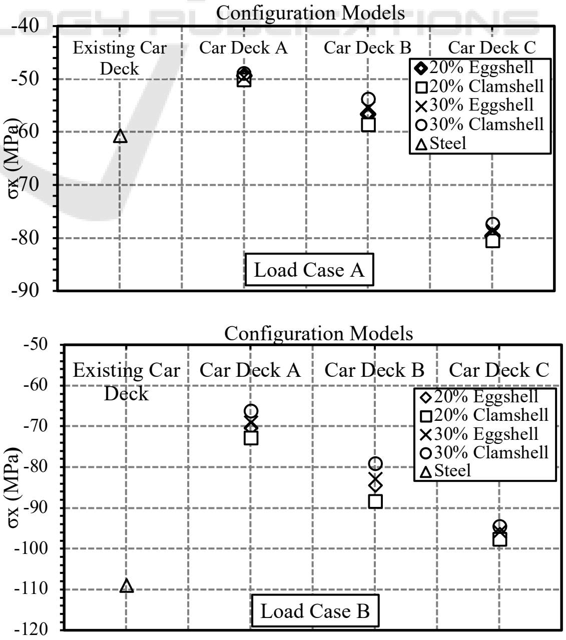


Figure 6: Normal bending stress between existing and modified structures' models under (a) Load Case A (b) Load Case B.

The reduction of stress by sandwich application is influenced by the difference in thickness configuration between steel and sandwich plates and separation of the face plates by a lightweight core acts to significantly increase sectional modulus and sectional area which can improve bending stiffness of the material cross-section. Its application will also remove the sources of stress concentrations so that can decrease the stress which occurs in the structure.

In comparison with design criteria in the existing model, the von Mises stress, normal bending stress, and shear bending stress which occurred in the existing structure were still below than design criteria. In addition, concerning the von Mises stress occurred in modified models for each load case, the possible modification model was effective in Car Deck B. The stress occurred in whole sandwich types in Car Deck C exceed the permissible criteria. In Car Deck B, only sandwich with 30% eggshell had stress value below the permissible criteria for each load case with stress reduction about 14.6% in load case A, and 6% in load case B, serially. Figure 5 also showed that diminishing the stiffener in modification model will increase the von Mises stress. Compared with existing model, the same study was carried out by Zubaydi et al. (2018) who studied the application of sandwich plate for redesigning the car deck. There was no weight saving calculation in this research. The core consisted of unsaturated polyester resin and talc with four filler variations was used. The stress reduction was mostly varying between 19.9% and 20.7%. The higher weight reduction was caused by using thicker sandwich thickness compared with this project.

It can be further noticed in Figure 6 and Figure 7 which showed the comparison of normal bending stress (σ_x) and shear bending stress (τ_{xz}) in whole models. Comparing the existing structure and Car Deck A, the application of sandwich material in car deck structure will decrease the normal bending stress and increase the shear bending stress. Zero normal bending stress will occur in the neutral axis and the stress level will increase as the distance from the neutral axis increases.

Further, Figure 8 illustrated the deflection value which occurred in whole models. The main consideration for investigating the deflection is to evaluate how a car will react while passing a panel. If the deflection is large, the car will experience an up and down motion of the vehicle, which can be uncomfortable. Another goal for investigating the deflection is for visualization function. If the deflection is large and visible to the eye, the structure could be noticed as unreliable, which is unsatisfactory for the ship owner.

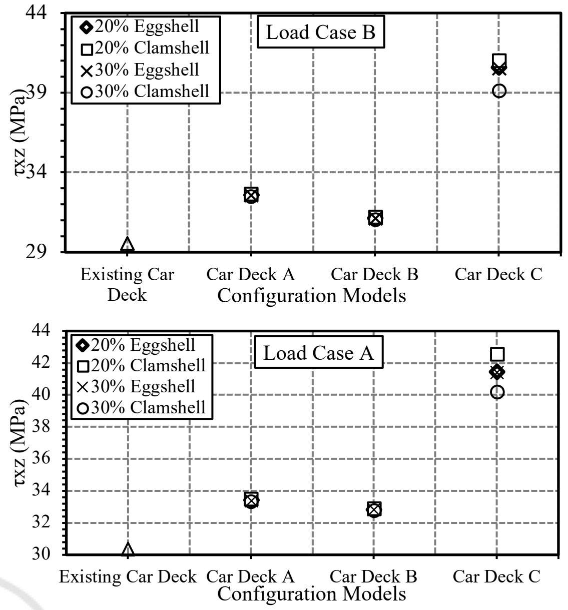


Figure 7: Shear bending stress between existing and modified structures' models (a) Load Case A (b) Load Case B.

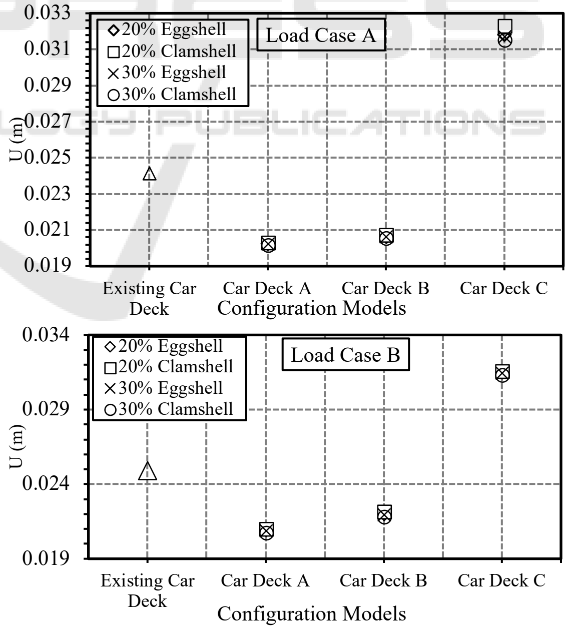
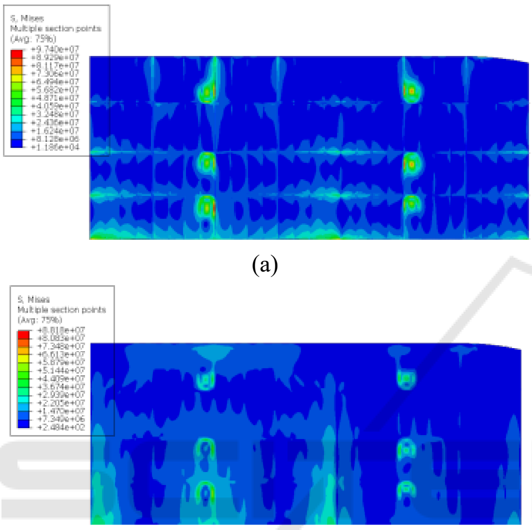


Figure 8: Maximum deflections between existing and modified structures' models under (a) Load Case A (b) Load Case B.

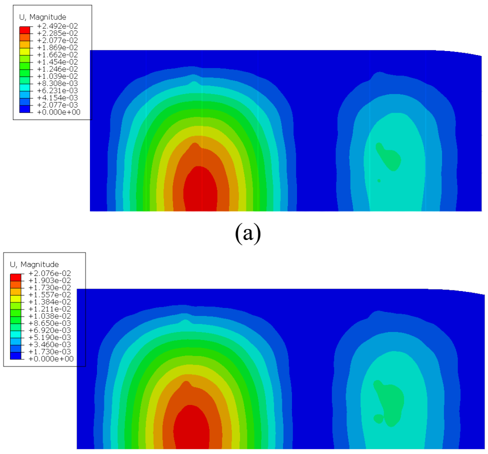
The stiffness of the structure is dependent on the cross-section, and the lower the stiffness is the higher will the deflection be. Figure 7 represented that application of sandwich material in car deck structure could increase the stiffness by reducing the deflection compared to existing model; 15.9%-16.5% in load case A, 15.7%-16.7% in load case B, respectively. Compared with permissible criteria, all models in each load case fulfilled the maximum edge deflection criteria of the lowest points of the panel (δ). It also reviewed that deflection in Car Deck A and Car Deck B was still lower than the existing model. Further, the deflection in Car Deck C significantly increased the deflection compared to existing model.



(a)

(b)

Figure 9: Comparison of half-modelled von Mises stress contour in Load B (a) Existing (b) Car Deck A with 30% Clamshell.



(a)

(b)

Figure 10: Comparison of half-modelled deflection contour in Load B (a) Existing (b) Car Deck A with 30% Clamshell.

The comparison of half-modelled von Mises stress and deflection contour between existing model and Car Deck A in Load Case A was figure out in Figure 9 and Figure 10. From the illustrated figure, it showed that the highest stress occurred in the connection of deck plating and stiffener near wheel load. The application of sandwich material removes the sources of stress concentration as depicted in Figure 9b so that can decrease the stress occurred in the structure. Similarly, the comparison of deflection contour by means of application of sandwich materials was also presented in Figure 10. It was clearly seen that the application of sandwich material could significantly decrease the deflection value. The deflection contour presented that the highest maximum deflection has occurred in an area which experienced the rear wheel loading. It was affected because the in the rear wheel had the higher load print than in the front wheel.

4 CONCLUSIONS

This is to summarized primary observations and conclusions from this research, considering the assumptions made and work limitation regarding the projection of application of sandwich material in car deck structure. The preliminary study regarding the application of sandwich material as an alternative solution in deck structure indicated a very promising results in terms of structural strength and weight saving. The FE method had been utilized to model and analyze the influence of sandwich application on a reference car deck with respect to design criteria such as the normal, shear, von Mises stresses, and deflection occurring in the structure. The best car deck configuration was obtained by eliminating all the deck beams by using sandwich with 30% eggshell. Its application contributed to stress reduction about 14.6% in load case A, and 6% in load case B. However, Load case B was not a standard cargo configuration and would occur very rarely. In terms of rough weight estimation, its application showed that the weight savings were in the range of 8.87% and 11.6%.

Further studies on parametric design and cost optimization need to be carried out. By utilizing optimization techniques, a relatively better solution could be reached as the optimum dimensions for car deck configuration is found.

ACKNOWLEDGEMENTS

This research was funded by Directorate of Research and Community Services, Ministry of Research, Technology and Higher Education, The Republic of Indonesia under PUPT research scheme. The first author would like to thank for the support provided by the Ministry through The Master’s Degree Program Leading to Doctoral Degree for Excellent Bachelor Graduates (PMDSU).

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