STUDY OF SANDWICH PANEL APPLICATION ON SIDE HULL OF CRUDE OIL TANKER

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A lightweight sandwich plate system (SPS) consisted of steel faceplate and polyurethane elastomer composite cores have excellent potential to be applied on the ship structure. Steel faceplate and polyurethane elastomer (PU) cores are frequently applied, but PU has a relatively high material cost. More economical material can be achieved by combining PU with fiberglass as a fiberglass reinforced polyurethane elastomer (FRPU) composite. In this study, the sandwich consisting of steel faceplate and FRPU composite core material is applied in the tanker side hull by investigating the structural performance and weight saving analysis using finite element analysis (FEA). Four sandwich side hull models using different stiffener configurations are compared with the conventional stiffened plate model. The results show the promising SPS application on structural strength and weight reduction. The remarkable stress reduction, deformation, and structural weight reduction due to SPS application are discussed. Therefore, its weight reduction can increase the ship payload so that ship operations will be cost-effective.

Key words: sandwich plate system, polyurethane elastomer composite, weight reduction, structural strength, side hull

INTRODUCTION

The need for lightweight ship structures is the main purpose in the ship design to increase ships payload, protect the environment, reduce fuel consumption and CO_2 emissions. Lightweight structures are developed by changing the existing construction dimension or installing lightweight materials on the possible structural parts. One of the latest breakthroughs of lightweight material in ship structures is Sandwich Plate System (SPS). It has been widely applied in the worldwide shipbuilding industries.

The purpose of the lightweight SPS application is to increase the ship cargo-carrying capacity. However, sandwich plate applications are still limited to naval ships and non-structural components in commercial ships [1]. A few studies on the SPS application in ship construction have shown superiority in increasing the ratio of strength and weight and reducing the complexity of ship construction arrangements [2].

SPS consists of 3 layers: the upper faceplate layer, the middle core layer, and the bottom faceplate layer. The faceplate layers are made of high strength, high density, but low thickness material. Otherwise, the core layer is made of low strength, low density, but very high thickness material. Combining these two material characteristics creates a sandwich effect that provides a very efficient ratio of stiffness-to-weight [3,4,5], which is an important characteristic for light structures in the ship's construction [6].

In terms of the development of SPS for ship structure, several core materials have been analyzed, such as the combination of unsaturated polyester resin (UPR) with talc powder [7], bio-resin using vinyl ester and vegetable oil [8,9], UPR with a clamshell powder [10], UPR with an eggshell powder [11], epoxy resin [6], and polyurethane elastomer (PU) [12,13,14]. Steel faceplates and room temperature cured polyurethane elastomer core are commercial materials of SPS for ship structure [2,15].

However, room temperature cured polyurethane elastomer is relatively expensive and is not available in many countries. High-cost materials prevent applying the material in the industry, so a low-cost core material that meets the Lloyd's Register (LR) [16] criteria is required. PU casting has a lower price and is available in many countries. PU casting can also be reinforced with fiberglass to obtain a fiberglass reinforced polyurethane elastomer (FRPU) composite. FRPU composite has been applied as the core material of SPS because it meets LR criteria, including density, hardness, ultimate tensile strength, and elongation at break [17,18].

An extensive range of research studies about the application of sandwich structure on static behavior and weight-reduction investigation in the few structural part was introduced, such as in the ship deck [17,19,20], hull structure [10,18], and car deck [11,21,22], and other various structures. Brooking & Kennedy [15] conducted a Finite Element Analysis (FEA) on applying SPS to several flat plate constructions on tankers. Based on this numerical study, it has been found that the stresses in SPS have a smaller value than the allowable stress [15]. Weight analysis of conventional barge construction and SPS barge construction has also been performed [23]. Other research has been conducted on FEA and the weight reduction gained by applying SPS [10,11,18].

The above-mentioned analysis results that the application of SPS can increase strength-to-weight ratio by reducing the use of stiffener. The implementation of SPS can reduce the need for stiffeners [19,23], so weight reduction and payload can be obtained. However, the optimal configuration of stiffeners to obtain the lightest possible construction weight and strength that meets the criteria has not been widely carried out.

In this paper, the potential implementation of SPS, which uses FRPU composite as the core material on the side hull of 17500 DWT crude oil tanker model toward static behavior using FEA, is investigated. FEA was performed on the conventional side hull and SPS side hull to evaluate structural strength compared to strength criteria. Structural strength (including stress and deformation) and structural weight were also conducted to determine the benefits of applying SPS compared to conventional construction. A total of five different configuration models based on the configuration of stiffener are investigated. Five numerical models based on the stiffener configuration are carried out.

MODELLING DESCRIPTION OF APPLICATION OF SPS

The reference model used in this study was a conventionally stiffened side hull of a 17500 DWT crude oil tanker. The principal dimension of the crude oil tanker is presented in Table 1. The side hull consists of a stiffened steel plate and a configuration of stiffeners. The conventional hull consists of the side plate, web frames (T profile), side stringer (T profile), mainframe (L profile), and side longitudinal (L profile). The scantling dimension is mentioned in Table 1. In this study, the side hull's stiffened steel plate was replaced by SPS with different stiffener configurations. The SPS model consists of a steel faceplate and FRPU core material. The application study of SPS was conducted by comparing the structural strength and weight between conventional and sandwich side hull models.

Table 1: Principal dimension of crude oil tanker and structural part dimension of conventional side hull

Principal dimension	Value	Unit
Length of All (LOA)	157.5	m
Length Between Perpendicular (LBP)	149.5	m
Beam MLD	27.7	m
Depth MLD	12	m
Draft	7	m
Structural part	**Dimension**	**Unit**
Side hull	21.75 x 9	m
Side stringer	21.75 x 1.48	m
Web frame	T 1250 x 12 x 300 x 16	mm
Main frame	L 200 x 42 x 10 x 22	mm
Side longitudinal	L 200 x 42 x 10 x 22	mm
	L 200 x 43 x 11 x 22	mm
	L 216 x 46 x 11 x 25	mm

Initially, the side hull modulus needs to be calculated to determine the faceplate and core thickness. The faceplate and core thickness were calculated based on Lloyd's Register standard using strength index (R), where the R-value must be less than 1 [16]. Based on the calculation, faceplate thickness of 4 mm and a core thickness of 20 mm were chosen. Four sandwich side hull models using different stiffener frame spacings were compared to the conventional model. Model A was the sandwich side hull without changing the stiffener configuration. Model B was the sandwich hull and enlarged the side longitudinal frame spacing from 650 mm to 700 mm while the other stiffener was fixed. Model C and D were the sandwich hull by enlarging the side longitudinal frame spacing to 750 mm and 800 mm. The SPS application description and the technical drawing of the conventional model and model A were illustrated in Fig. 1.

FEA FOR STRUCTURAL STRENGTH ASSESSMENT

The application of SPS on the side hull of Tanker is analyzed by investigating structural behavior between conventional hull and sandwich side hull using FEA software ABAQUS. The parameter used as structural behavior is stress and deformation. In the discretization of finite element model, the side hull can be simulated using the layer-wise solid/shell element. LR notices that the faceplate layers are interpreted by shell elements and the core material by solid elements [16]. The faceplate layers were simulated using the eight-node quadrilateral shell element (SC8R), while the core material was simulated using the eight-node hexahedral element (3D8I). The stiffeners, including mainframe, web frame, side longitudinal, and side stringer, were modeled by shell elements (SC8R).

There are three steps in finite element analysis, namely: (1) pre-processing, including modeling the structural geometry, meshing, and input the load; (2) FE analysis to get a structural response; and (3) post-processing to investigate stress and deformation of the model. The contact modeling between faceplate and core and between structural elements were modeled by tie constraints so that there is not any relative motion. Meanwhile, the boundary condition is assumed clamped in all sides of the hull (CCCC). Table 2 shows the material properties of steel faceplate and fiberglass reinforced polyurethane elastomer (FRPU) composite cores.

The side hull model has been loaded by dynamic wave pressure, according to the International Association of

Table 2: Material properties of steel faceplate and FRPU core

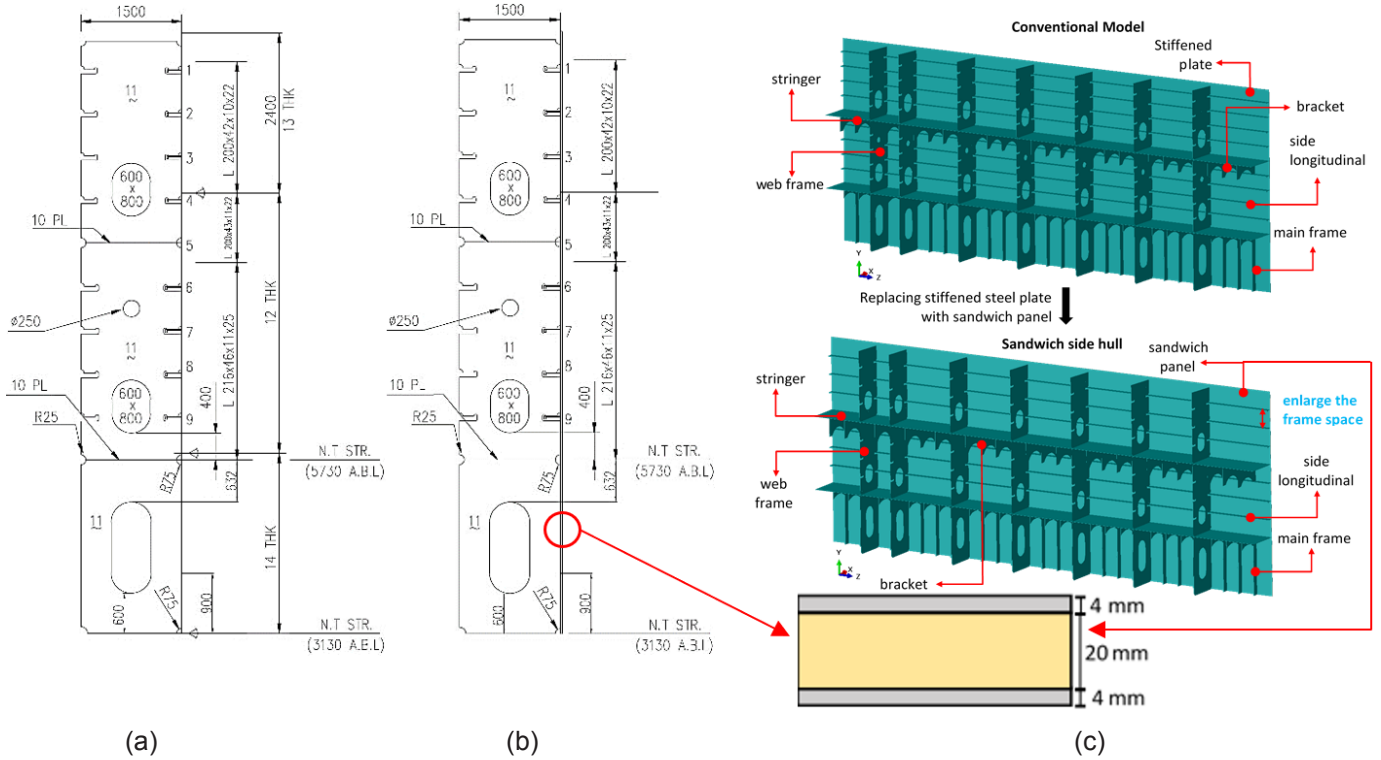| Material	Density (kg m^{-3})	Elastic Modulus (MPa)	Poisson Ratio
Face plate (Steel)	7850	206000	0.3
Core material (FRPU)	1098	901.95	0.36

(a) (b) (c)

Figure 1: (a) Technical drawing of conventional model, (b) technical drawing of model A,
(c) illustration of SPS application on side hull of tanker

Classification Societies (IACS) rules [24]. The loading applied to the side structure is dynamic wave pressure (P_{ex-dyn}). P_{ex-dyn} is the largest value between pressure for load case 1 (P_1) and pressure for load case 2 (P_2), which can be calculated using the equation (1) and (2). P_{11} can be calculated using equation (3). Clamped in all sides of the hull or fully clamped boundary condition and the applied load locations are illustrated in Fig. 2.

$$P_1 = 2f_{prob}f_{nl-P1}\left[\left(P_{11} + \frac{135B_{local}}{4(B-75)} - 1.2(T_{LC} - z)\right)f_1 + \frac{135B_{local}}{4(B+75)}\ f_2\right] \tag{1}$$

$$P_2 = 26f_{prob}f_{nl-P2}\left[\left(\frac{B_{local}}{8}\theta + f_T C_b\frac{0.25B_{local} + 0.8C_{wv}}{14}\left(0.7 + \frac{2z}{T_{LC}}\right)\right)f_1 + \left(\frac{B_{local}}{8}\theta + f_T C_b\frac{0.25B_{local}}{14}\left(0.7 + \frac{2z}{T_{LC}}\right)\right)f_2\right] \tag{2}$$

$$P_{11} = (3f_s + 0.8)\ C_{wv} \tag{3}$$

where: B_{local} is local breadth at the waterline (m); θ is roll angel; C_{wv} is wave coefficient; B is moulded breadth (m); T_{LC} is draught in the loading condition being considered (m); C_b is block coefficient; f_{prob} is probability coefficient; f_{nl-P1} is coefficient considering non-linear effects for load case 1; f_{nl-P2} is coefficient considering non-linear effects for load case 2; z is vertical coordinate (m).

The equation for static analysis can be seen in equation (4). Equations (5), (6), and (7) are variables associated with static analysis.

$$\{F\}\ =\ [K]\ \{U\} \tag{4}$$

$$\sigma = \frac{F}{A} \tag{5}$$

$$\tau = \frac{F}{A} \tag{6}$$

$$\in = \frac{\delta}{L} \tag{7}$$

where: $\{F\}$ is force (N); $[K]$ is stiffness (Nm^{-1}), $\{U\}$ is displacements (m); σ is the normal stress (Pa); A is the surface area perpendicular to the force (m2); τ is the shear stress (Pa); ϵ is the strain; δ is the deformation (m); L is the length (m).
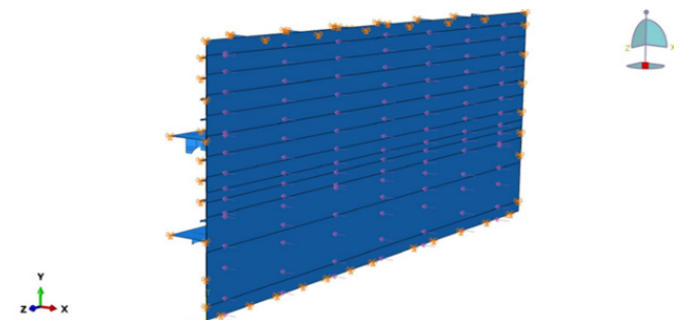

Figure 2: Clamped in all sides of the hull
and applied load locations

RESULT AND DISCUSSION

Convergence study

Meshing is the process of partitioning a model into smaller elements. The smaller the mesh element, the greater the number of elements. Generally, a high number of elements makes a numerical analysis more precise. However, a high number of mesh elements increases the computer's workload and increases the analysis's running time. Therefore, it is necessary to conduct a convergence analysis to find the optimal number of mesh elements. The expected result is a result that is closer to the true value with the least number of elements possible. In this investigation, the difference between the second trial's output should be less than 2% compared to the first trial.

The convergence study was conducted on two variables, namely stress and deformation. Both variables must meet the 2% convergent requirement for the results to be considered valid. The 2% convergent requirement in this study is better than the 5% convergent requirement used by Wang [25]. In the conventional side-shell model, convergence value occurs at a mesh size of 0.0135 m and the number of elements 2775600. The graph of this convergence can be seen in Fig. 3 (a). In the side-shell sandwich model, the convergence value occurs at

a mesh size of 0.018 m, and the number of elements is 2772050. The graph of the convergence study on the sandwich hull model is illustrated in Fig. 3 (b). Mesh elements illustration of the conventional and sandwich model can be seen in Fig. 4.

Comparison of deformation

The challenge of SPS application is its sensitivity to severe load, which may cause damage. Therefore, the strength analyses of the side hull are essential as a further assessment of SPS's application. In this section, the results of FEA are shown to entirely analysis the deformation comparison between conventional and sandwich side hull with various stiffener configurations.

The comparison of maximum deformation between conventional and sandwich hull models is illustrated in Fig. 5. The results show that the application of SPS can reduce deformation significantly. The reduction percentage of deformation is in the range between 17.2 – 17.8%. It also can be shown that the enlarging the frame space of side longitudinal results in little deformation reduction percentage, as can be shown in model A, model B, model C, and model D.

The deformation contour between the conventional and all sandwich side hull model is depicted in Fig. 6. It shows that the application of SPS removes the sourc-
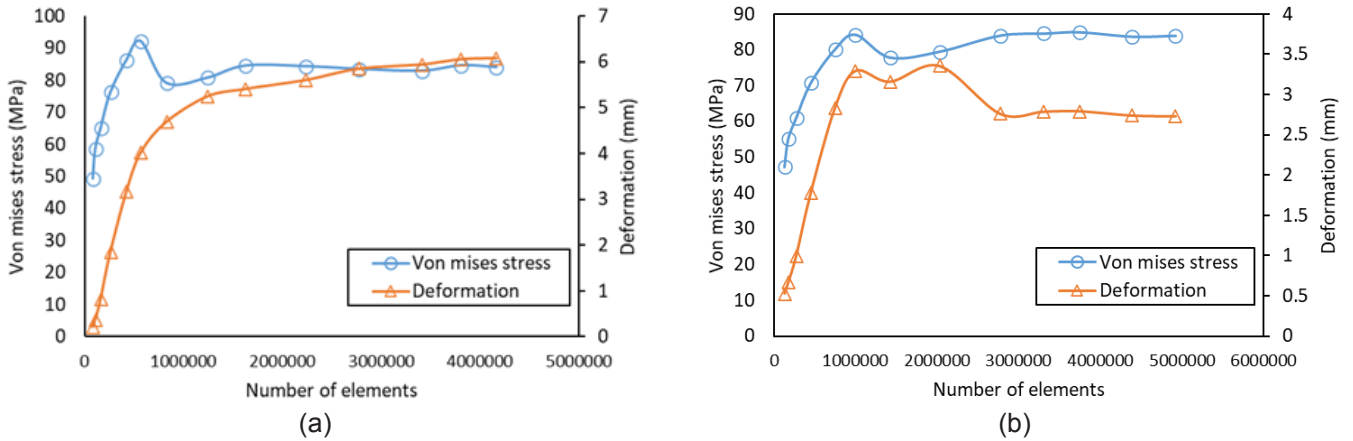

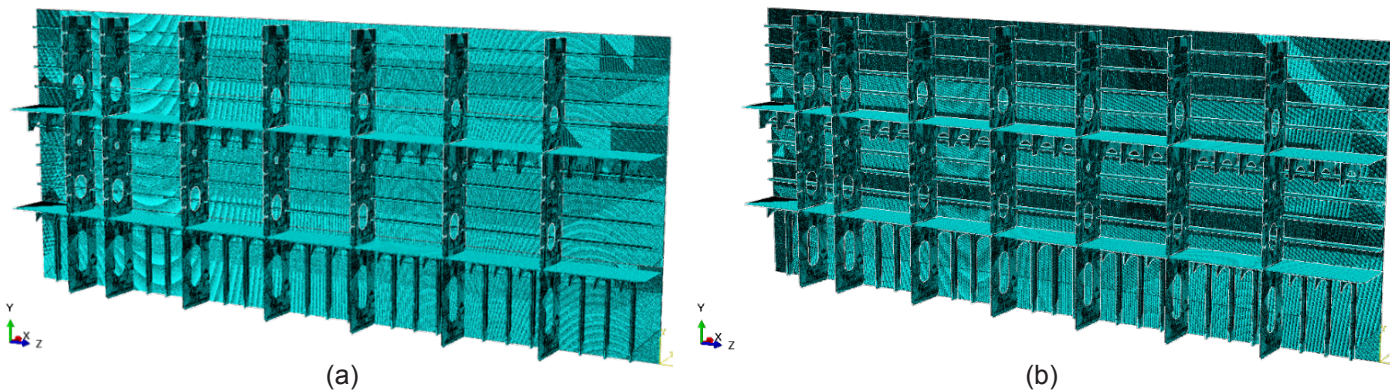*Figure 3: Convergence analysis between (a) conventional model and (b) Model A*

Figure 4: Mesh elements illustration of (a) the conventional and (b) sandwich model

es of deformation concentration, so it can decrease the high deformation that occurred in the structure. In the conventional model, deformation concentration occurs on the side plate. Nevertheless, in sandwich hull models, deformation concentration occurs on the mainframe because of the sandwich plate's high thickness.

The outstanding reduction of deformation due to SPS implementation is affected by the dissimilarity of thickness design between stiffened steel plates and sandwich plates. The splitting of the faceplates by an FRPU core serves to remarkably expand the section modulus, improving the material cross-section's bending stiffness. So, SPS implementation will eliminate the deformation concentration.
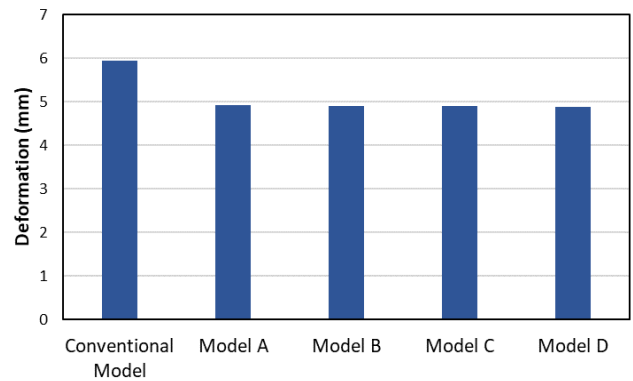

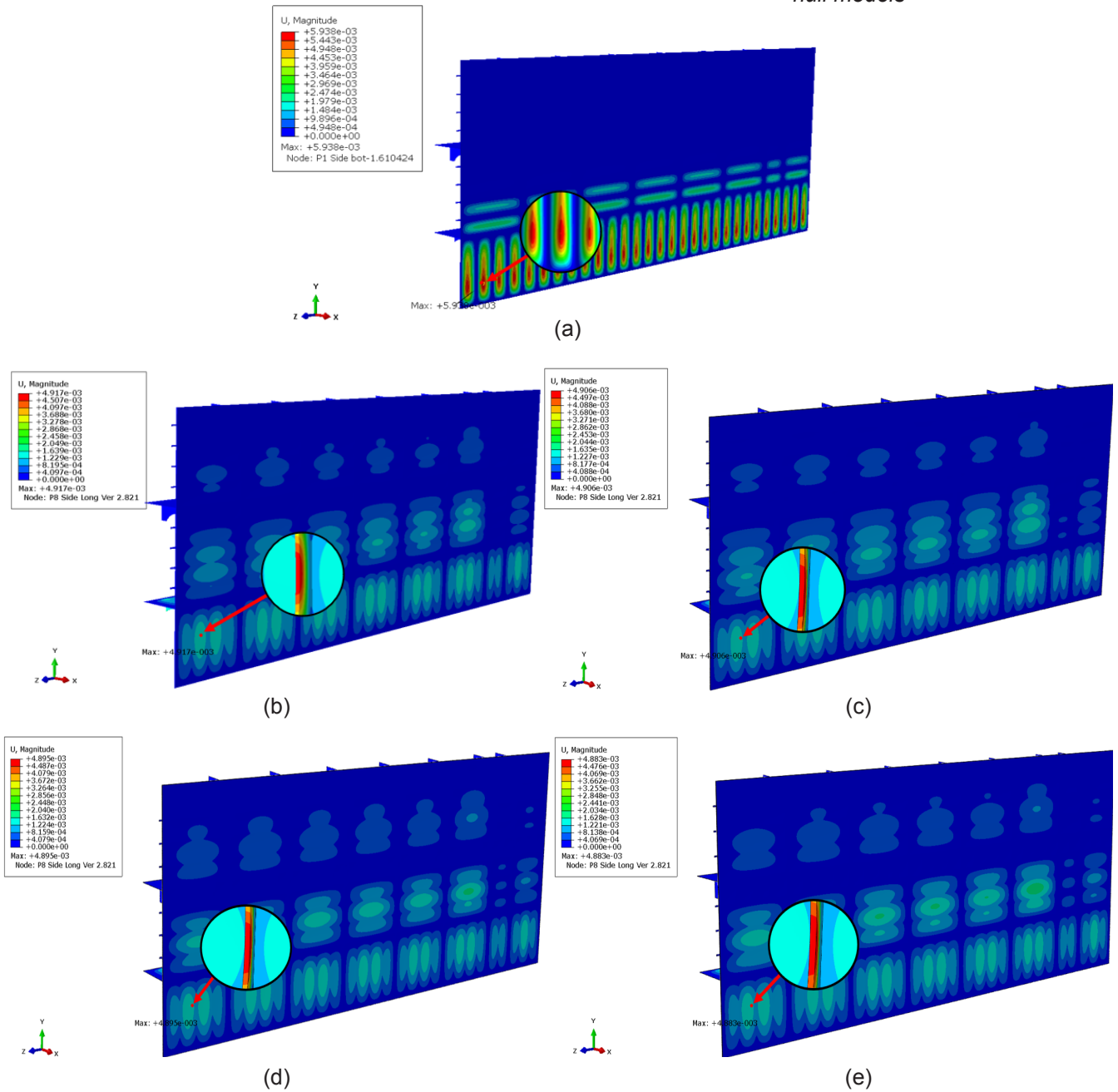*Figure 5: Deformation of conventional and sandwich hull models*

Figure 6: Deformation contour of (a) conventional, (b) model A, (c) model B, (d) model C, (e) model D

Comparison of structural strength

Further, the FEA simulation is conducted to investigate structural strength by comparing the von Mises stress between conventional and sandwich side hull models. The comparison of the maximum von Mises stress between conventional and all sandwich side hull models is depicted in Fig. 7. It shows that the application of SPS reduces the von Mises stress. The reduction percentage of stress is in the range between 20.8 – 27.9%. The higher the frame space of the longitudinal side, the higher the von mises stress. It is because the unsupported area results in increased stress. An I-beam where the flanges distribute the bending and in-plane loads is similar to the working principle of a sandwich plate. Simultaneously, the web supports transverse shear, reallocates concentrated normal to the surface forces, and defends the structural strength.

The application of SPS removes the sources of stress concentration [2,26], as depicted in Fig. 8. The yield strength of steel is 235 MPa [27,28] and the allowable stress of steel, according to BV, is 70% of the yield strength [28] or 164.5 MPa. 70% of the steel yield strength is a safety factor that is also considered as essential parameters in static analysis for engineering structure. The safety factor of sandwich panels with poly-urethane elastomer cores for ship and bridge structure is also developed from the yield strength of steel [26,29]. All sandwich models meet the BV criteria [28], including Model D, which has von mises stress very close to the allowable stress, 162.4 MPa. In other studies, the sandwich model's maximum stress was smaller than the strength requirement [11,19,26] and the conventional model [11,19].
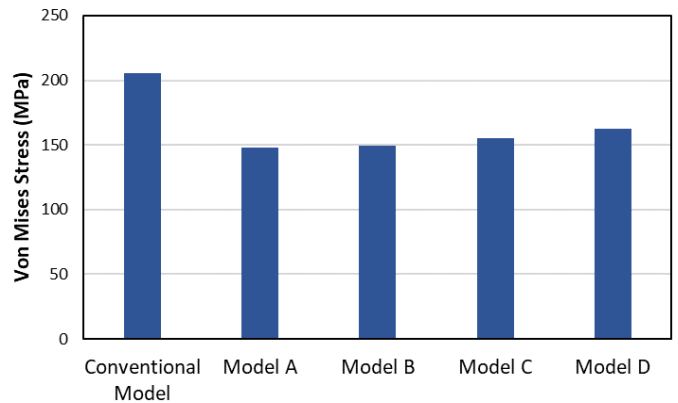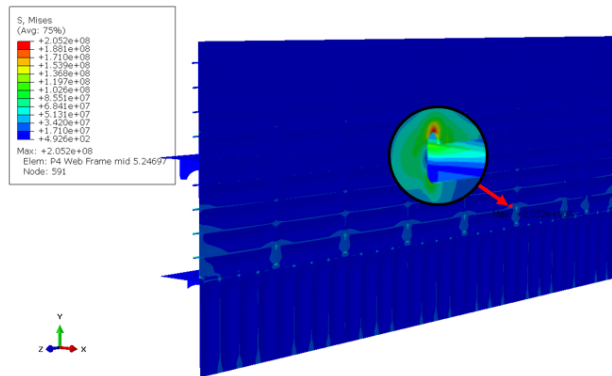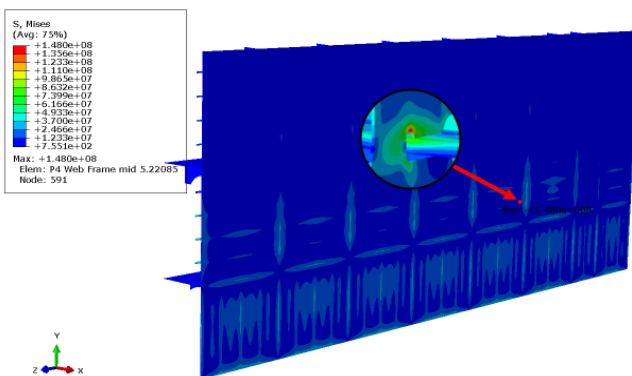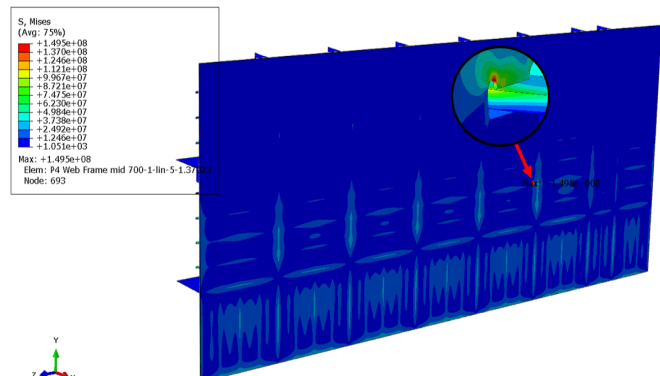

Figure 7: Von Mises Stress of conventional and sandwich hull models
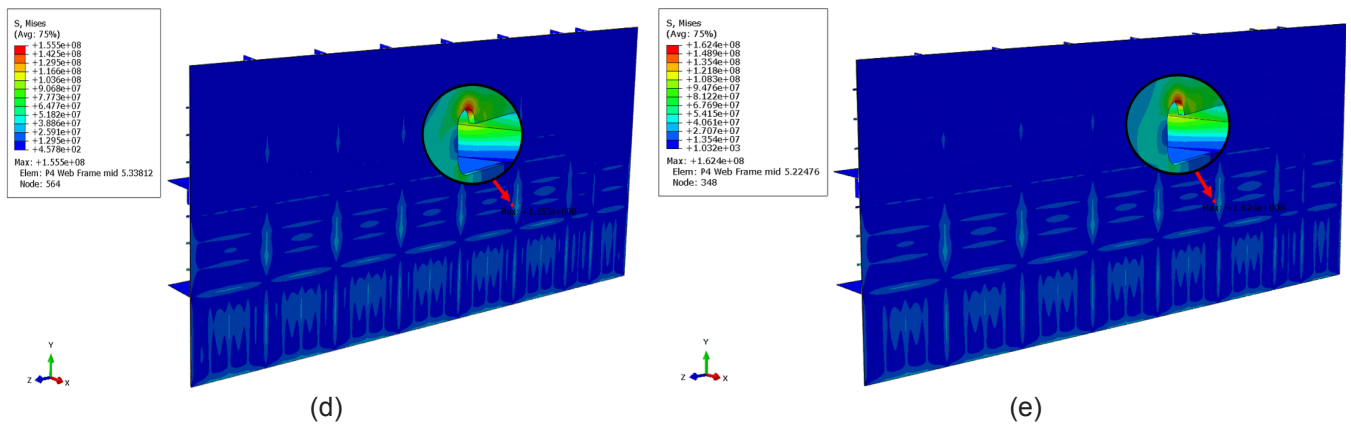

(a)

(b)

(c)

Figure 8: Von Mises stress contour of (a) conventional, (b) model A, (c) model B, (d) model C, (e) model D

Comparison of structural weight

Prior to applying SPS to the side hull, strength calculation and structural weight estimation are conducted to ensure that its application will produce essential benefits for the shipyard management and the shipowner. Weight reduction should be high enough to compensate for the unpredicted technical and financial difficulties during SPS assembly [11].

Structural weight is the relation of the material density and how much space it takes up. The comparison of structural weight between the conventional model and sandwich hull models is illustrated in Fig. 9. It is noted that the implementation of an SPS in the side hull comprehensively reduces the structural weight. Compared to the conventional model, the application of SPS in model A without changing the stiffener configuration shows a decrease in the weight up to 4.2%. Moreover, enlarging the frame space of the side longitudinal in model B, model C, and model D causes weight reduction where the highest reduction, about 8.8%, occurred in model D. Other studies confirmed these results that most sandwich models produce a weight reduction of 5 – 8% compared to conventional models [23].

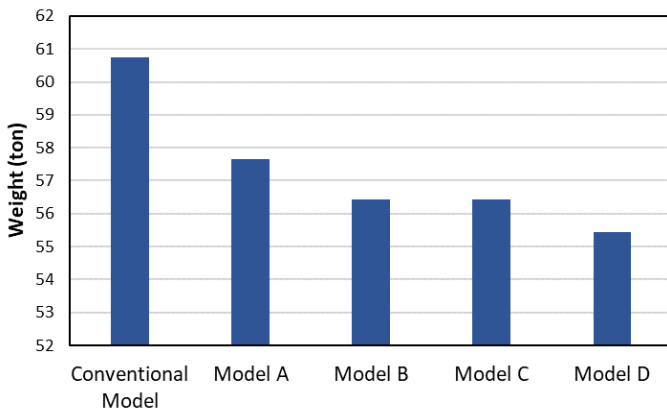Compared with the related study about the sandwich panel implementation in a container ship, SPS's application in the hull structure was mentioned in [10]. The weight reduction was up to 17%. [10]. Another study shows that the SPS's implementation, which uses synthetic resin as the core material in the ferry car deck, reduces the deck panel's weight by about 12% [19]. Moreover, the investigation in [11] presented that the weight reduction can reach between 8.87% – 11.6% in the car deck structure.

Generally, the weight reduction obtained can be different, depending on the ship's structural part and type of sandwich panel. In the future, the ship structure's optimization is needed to get the best weight reduction and meet the strength criteria. There are not many papers on optimizing secondary stiffener configuration on sandwich panels to obtain optimal weight reduction and meet the strength requirements. Besides, research on the economic aspects of SPS application on ship structures is also still limited. Methods for assessing the reliability [30] and durability [31] of SPS also need to be developed in the future. A composite sandwich panel [32] is also interesting to be applied as a ship's material.

CONCLUSION

The primary observation due to SPS's application on the side hull of Tanker on the static behavior using finite element software ABAQUS is summarized. A total of four sandwich hull model using different stiffener configuration is compared with the conventional stiffened model using von mises stress, deformation, and structural weight parameters. Taking into account the assumptions made and the limitations of work concerning the computation of SPS implementation, the preliminary analysis show promising outcomes in structural strength enhancement and structural weight reduction. SPS application provides to the increase in the structural strength and removes the stress concentration. The remarkable reduction of stress due to SPS application is 20.8 – 27.9%. Moreover, the SPS application reduces the structural weight in the range between 4.2 – 8.8%. Its weight reduction can increase the ship payload so that ship operations will be cost-effective.

Figure 9: Structural weight between conventional and sandwich hull models

REFERENCES

1. Tuswan, Zubaydi, A., Piscesa, B., Ismail, A. (2020). Influence of application of sandwich panel on static and dynamic behaviour of ferry ro-ro ramp door. Journal of Applied Engineering Science. (in press)

2. Ramakrishnan, K.V., Kumar D.P.G. (2016). Applications of sandwich plate system for ship structures. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 83-90.

3. Yang, J.-S., Ma, L., Schmidt, R., Qi, G., Schröder, K.-U., Xiong, J., Wu, L.-Z. (2016). Hybrid lightweight composite pyramidal truss sandwich panels with high damping and stiffness efficiency. Composite Structures, vol. 148, 85–96, DOI: 10.1016/j.compstruct.2016.03.056

4. Zhang, X., Zhou, H., Shi, W., Zeng, F., Zeng, H., Chen, G. (2018). Vibration tests of 3D printed satellite structure made of lattice sandwich panels. AIAA Journal, 1–5, DOI: 10.2514/1.j057241

5. Li, C., Shen, H.-S., Wang, H. (2019). Nonlinear bending of sandwich beams with functionally graded negative Poisson's ratio honeycomb core. Composite Structures vol. 212, 317-325. DOI: 10.1016/j.compstruct.2019.01.020

6. Ismail, A., Zubaydi, A., Budipriyanto, A., Yudiono. (2018). Damage identification of the sandwich plate having core from rice husk-epoxy for ship deck structure. The 3rd International Conference on Marine Technology, p. 112–118. DOI: 10.5220/0008543301120118

7. Arianto, P.Y., Zubaydi, A., Piscesa, B., Tuswan. (2019). Experimental and numerical bending analysis of steel/resin-talk sandwich material. IPTEK The Journal for Technology and Science, vol. 30, no. 3, 123-128, DOI: 10.12962/j20882033.v30i3.5496

8. Ardhyananta, H., Sari, E.N., Wicaksono, S.T., Ismail, H., Tuswan, Ismail, A. (2019). Characterization of vinyl ester bio-resin for core material sandwich panel construction of ship structure application: Effect of palm oil and sesame oil. AIP Conference Proceedings, p. 1-5, DOI: 10.1063/1.5141664

9. Tuswan, Zubaydi, A., Piscesa, B., Sari, E.N., Ismail, A. (2020). Core sandwich material development based on vinyl ester bioresin for ship structure application. IOP Conference Series: Materials Science and Engineering. (in press)

10. Tuswan, Abdullah, K., Zubaydi, A., Budipriyanto, A. (2019). Finite-element analysis for structural strength assessment of marine sandwich material on ship side-shell structure. Materials Today: Proceedings, vol. 13, no. 1, p. 109–11, DOI: 10.1016/j.matpr.2019.03.197

11. Tuswan, Zubaydi, A., Budipriyanto, A., Sujiatanti, S.H. (2018). Comparative study on ferry ro-ro's car deck structural strength by means of application of sandwich materials. The 3rd International Conference on Marine Technology, vol. 1, p. 87-96, DOI:10.5220/0008542800870096

12. Ismail, A., Zubaydi, A., Piscesa, B., Ariesta, R.C., Tuswan. (2020). Vibration-based damage identification for ship sandwich plate using finite element method. Open Engineering, vol. 10, 744–752, DOI: 10.1515/eng-2020-0086

13. Yazici, M., Wright, J., Bertin, D., Shukla, A. (2014). Experimental and numerical study of foam filled corrugated core steel sandwich structures subjected to blast loading. Composite Structures, vol. 110, 98–109. DOI: 10.1016/j.compstruct.2013.11.016

14. Shan, C., Yi, Y. (2016). Stress concentration analysis of an orthotropic sandwich bridge deck under wheel loading. Journal of Constructional Steel Research, vol. 122, 488–494. DOI: 10.1016/j.jcsr.2016.04.011

15. Brooking, M., Kennedy, S. (2004). The performance, safety and production benefits of SPS structures for double hull tankers. Proceedings of the RINA Conference on Double Hull Tankers.

16. Lloyd's Register (2020). Rules for the application of sandwich panel construction to ship structure. Lloyd's Register Group Limited, London.

17. Ismail, A., Zubaydi, A., Piscesa, B., Panangian, E., Ariesta, R.C., Tuswan. (2020). A strength analysis of conventional and sandwich plate deck using finite element method. IOP Conference Series: Materials Science and Engineering. (in press)

18. Ismail, A., Zubaydi, A., Piscesa, B., Panangian, E., Ariesta, R.C., Tuswan. (2020). A comparative study of conventional and sandwich plate side-shell using finite element method. IOP Conference Series: Materials Science and Engineering. (in press)

19. Sujiatanti, S.H., Zubaydi, A., Budipriyanto, A. (2018). Finite element analysis of ship deck sandwich panel. Applied Mechanics and Materials, vol. 874, 134–139, DOI: 10.4028/www.scientific.net/AMM.874.134

20. Andric, J., Kitarovic, S., Radolovic, V., Prebeg, P. (2019). Structural analysis and design of a car carrier with composite sandwich deck panels. Ships and Offshore Structures, 1–16. DOI: 10.1080/17445302.2018.1564536

21. Tuswan, Zubaydi, A., Piscesa, B., Ismail, A. (2020). Dynamic characteristic of partially debonded sandwich of ferry ro-ro's car deck: a numerical modelling. Open Engineering, vol. 10, 424-433, DOI: 10.1515/eng-2020-0051

22. Tuswan, Zubaydi, A., Piscesa, B., Ismail, A., Ilham, M.F. (2020). Free vibration analysis of interfacial debonded sandwich of ferry ro-ro's stern ramp door. Procedia Structural Integrity, vol. 27, p. 22-29, DOI: 10.1016/j.prostr.2020.07.004

23. Momčilović, N., Motok, M. (2009). Estimation of ship lightweight reduction by means of application of sandwich plate system. FME Transactions, vol. 37, no. 3, 123–128.

24. International Association of Classification Societies (2012). Common structural rules for double hull oil tankers. International Association of Classification Societies, London.

25. Wang, I. T. (2014). Numerical and experimental verification of finite element mesh convergence under explosion loading. Journal of Vibroengineering, vol 16, 1786–1798

26. Kennedy, S. J., Bond, J., Braun, D., Noble, P. G., Forsyth, J. D. (2003). An innovative "no hot work" approach to hull repair on in-service FPSOs using sandwich plate system overlay. Offshore Technology Conference 15315.

27. Lloyd's Register (2014). Rules for the manufacture, testing and certification of materials. Lloyd's Register Group Limited, London.

28. Bureau Veritas (2019). Rules on materials and welding for the classification of marine units. Bureau Veritas, Paris.

29. De Freitas, S.T., Kolstein, H., & Bijlaard, F. (2010). Sandwich system for renovation of orthotropic steel bridge decks. Journal of Sandwich Structures & Materials, vol. 13, 279–301. DOI: 10.1177/1099636210386848

30. Tomić, R., Petrović, P., Petrović, M. (2012). Contribution to the evaluation of the compliance for new products with aspect reliability and maintenance. Journal of Applied Engineering Science, vol. 10, 201-208.

31. Vladimirovna, T. P., Nikolaevna, M. U., Vladimirovich A. E., Mishchenko E., Nikolaevna O. A. (2020). Improving the reliability of durability prediction of building materials and structures as one of the factors of sustainable economic development. Journal of Applied Engineering Science, vol. 18, 463-466.

32. Trombeva-Gavriloska, A., Lazarevska, M., Cvetkovska, M. (2016). Experimental testing of composite sandwich panels with different face sheets. Journal of Applied Engineering Science, vol. 14, 163-168.