Numerical Investigation of the Strength Assessment and Weight Reduction Sandwich Panel System on Barge Ship Structure

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The conversion from steel to sandwich material must comply with current regulations. This paper analyses three practical structural systems where the existing steel plate configuration has been converted to a sandwich material. The weight reduction of Light Weight Tonnage (LWT) can be calculated for each structure to find the best weight reduction and stress level that still fulfils the Biro Klasifikasi Indonesia (BKI) criteria. Numerical modelling methods are used through Finite Element Analysis (FEA) to determine the behaviour of the structure under loading conditions. The assumed loads on the model act on the deck, sides, bilge and bottom, then a calculation of the moments from the geometry of the load distribution. The calculation of the moments was used to obtain values for the deflection and the hogging condition as a comparison for the still water condition of the ship. Mesh convergence analysis on the existing model serves to validate the numerical modelling process. The stress and deformation values generated in the analysis compared the current model and three structural systems with sandwich plates. The stress value of the sandwich structure tends to be higher than the existing structure. However, the stress and displacement of the sandwich structure are slightly higher than that of the current structure, although the increase is negligible and there is a reduction in weight. The structural system using sandwich materials shows both high efficiency and cost effectiveness for ship barge.

KEY WORDS

~ Structural Systems
~ Weight Reduction
~ Numerical Modeling
~ Sandwich Materials
~ Ship Barge

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1. INTRODUCTION

Using composite materials is one of the most significant innovations in the shipping industry. Composites are lightweight materials used in structural applications by modifying existing structures where feasible. The Sandwich Plate System (SPS) is the latest lightweight material technology applied in ship structures. A barge analysis utilizing the sandwich panel system was conducted to evaluate weight reduction and structural strength, comparing the effects of eliminating stiffeners versus potential structural loss (Elsaka et al., 2020), Moreover, a dynamic assessment was performed on a 155-meter barge, analyzing various core types (Tuswan et al., 2023).

Using sandwich materials offers several advantages over conventional materials, such as reducing the need for stiffeners (Momčilović and Motok, 2009; Sujiatanti et al., 2018; Tuswan et al., 2021), enabling quicker and easier production (RamakrishnanKV and Kumar, 2016), and providing a higher crashworthiness value (CORe, 2013). The application of sandwich materials as a substitute for conventional steel is expected to reduce the overall weight of ship structures while maintaining the same main dimensions (Ismail et al., 2021b; Kim, 2020). This is possible due to the excellent strength-to-weight ratio of sandwich materials (Yang et al., 2016; Zhang et al., 2018). Several studies have demonstrated that using sandwich plates can significantly reduce structural weight while maintaining sufficient strength to meet design criteria [9, 10]. Additionally, numerous studies have explored sandwich plate applications, focusing on core material composition and the static and dynamic responses in various ship structures, such as decks (Ismail et al., 2021a), sides (Ariesta et al., 2022, 2021), inner bottoms (Baidowi et al., 2015; Regatama et al., 2019) and ramp doors (Tuswan et al., 2022).

However, while these benefits are well-documented, potential challenges and limitations associated with sandwich materials such as cost, durability, and manufacturing complexities are often overlooked. The studies mentioned above typically focus on modifying individual structural components rather than evaluating an entire ship compartment comprehensively in both existing and sandwich-based models.

Therefore, further research is needed to analyse the structural performance of an entire ship compartment using sandwich plates. Additionally, optimization studies are required to compare the strength to weight ratio of modified ship structural systems with that of conventional designs. The aim of this research is to evaluate the optimization of modified ship structural systems using sandwich plates by comparing stresses and deformations under various loading conditions, including cargo loads in still water, hogging, and sagging. The results will determine which structural system provides the best strength while meeting Biro Klasifkasi Indonesia (BKI) criteria (BKI, 2021).

2. METHODOLOGY

2.1. Sandwich Material Design

Sandwich material consisted of faceplate and core material. Generally, the faceplate used a solid and rigid material, while the core used a lightweight material (Llyod Register, 2020). This research uses steel as a faceplate and fiberglass-reinforced polyurethane (FRPU) as a core(Ismail et al., 2020). The material properties of these two materials can see on the Tabel.1.

Material	Density (kg/m^3)	Young Modulus (MPa)	Poisson's Ratio
Faceplate	7850	206000	0.30
Core	1098	901.95	0.36

Table 1. Material Properties of Sandwich Materials

The modification of the existing structure becomes sandwich material following Lloyd Register class rules. Several criteria must be accepted by classification rules, and then sandwich material can replace conventional steel, such as thickness allowance and strength index (R), to obtain the optimal thickness of the sandwich plate. Calculating the strength index can use equation (1) to determine the configuration of the sandwich plate used in accordance with the rules.

$$R = 0{,}01 \, . \, A_R \left[0{,}2 \, . \frac{b^2}{d(t_1+t_2)} + 11{,}7 \left(\frac{b.t_c}{d^2} \right)^{1{,}3} \right] k. \, P_{eq,R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where R is strength index, ($R \le 1$); A_R is $(\frac{a}{b})^{0.65}$; a is length of panel (mm); b is breadth of a panel (mm); d is $0.5(t_1 + t_2) + t_c$ (mm); t1 is top faceplate thickness (mm); t2 is bottom faceplate thickness (mm); tc is core thickness (mm); k is material factor; Peq,R is $0.0017 \frac{Z_{rule}}{l^2}$ (MPa).

2.2. Load and Loading Conditions

Calculation of the bottom, bilge, and submerged side load used Bureau Veritas (BV) regulation by using the hydrostatic pressure equation according to equation (2).

$$P_s = \rho \, g \, (T_1 - z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where Ps is side load (kN/m^2); ρ = density (kg/m^3); g is gravity (m/s^2); T1 is draught (m); z is vertical distance from the center of the load to the baseline (m). For the deck load calculation acting on the barge, coal with an angle of repose of 30° is assumed to have a rectangular pyramid shape. The load volume is then calculated and multiplied by the coal's density and gravitational acceleration to determine the total load acting on the deck. Illustrations for hogging and sagging conditions are shown in Figure 1.

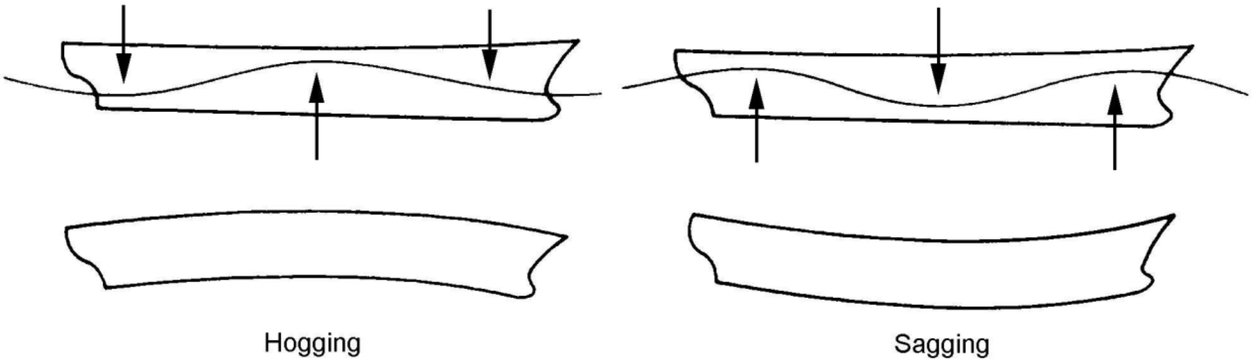

Figure 1. Hogging and sagging conditions

The deck load needs to be considered when evaluating the longitudinal strength of the ship, particularly the modulus of the deck and bottom under extreme hogging and sagging conditions. Hogging occurs when the water pressure is greater at the midship than the ship's weight, causing the hull to curve upwards in that area. Conversely, sagging happens when the water pressure is lower at the midship than the ship's weight, bending the hull downwards in the midship section.

2.3. Finite Element Method

The finite element method is one of the numerical methods used to solve engineering problems by dividing the structure into finite elements (Logan, 2007). In general, the finite element method relies on computers, and the memory capacity of the computer limits both the model size and the running time. Convergence analysis uses a specific set of elements, but each analysis inevitably produces slightly different results. This is due to the inherent approximation of the finite element method. The validity of a finite element model is judged by the error tolerance of its results. In other words, a valid model provides results with a deviation that is within an acceptable error limit. The ideal result is a model with as few elements as possible that still produces results that are very close to the actual value. In this study, the difference between the results of the second and first experiment should be less than 2%. To ensure accurate results within a reasonable computation time, a convergence test is required to determine the optimal model size.

In this study, the analysis was performed using the finite element method. The analysis configuration was performed by comparing three structural variants with the existing structure. The design variants of the barge in conversion are designed with longitudinal, transverse and mixed frame systems. Each variant has a different weight, but also a different strength. The aim is to determine the lowest possible weight while ensuring that the loads remain within acceptable criteria. The analysis involves simulating structural comparisons between different types of structural systems. The structural systems considered in this study are shown in Figure 3: (a) existing structural system modified into (b) longitudinal frame system, (c) transverse frame system, and (d) mixed frame system.

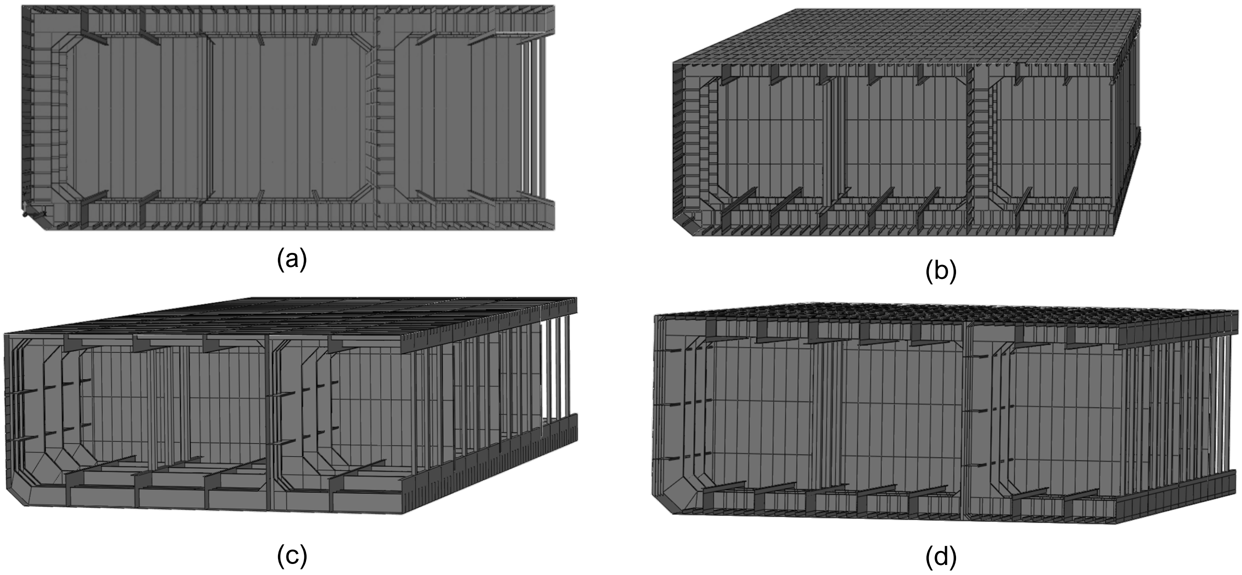
(a)
(b)
(c)
(d)

Figure 3. Variation of Barge Structure Design: (a) Existing; (b) Longitudinal; (c) Transverse, and (d) Mix Framing System

In essence, finite element simulation will obtain the minimum number of elements used with high accuracy to obtain simulation results that are close to the exact solution. This is illustrated by computational analysis results that are close to linear lines to verify the results and show the stability of the elements in a finite element method simulation (Logan, 2007). This technique was used to obtain the appropriate element type and structure configuration. The element size will be finding to obtain best dimension for reduce lack of time in computational that convergence condition as shown Figure 4.

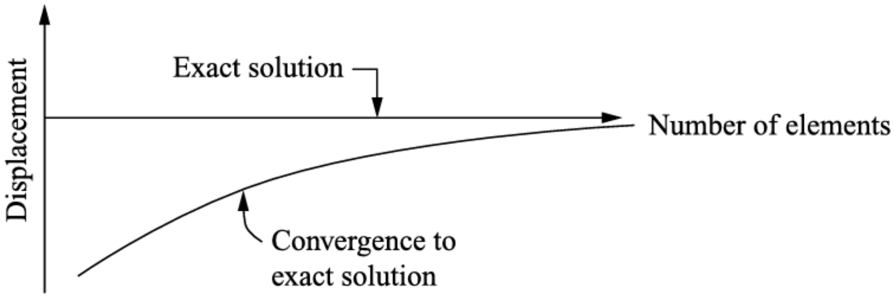

Figure 4. Convergency Study of Finite Element Analysis (Logan, 2007)

The boundary conditions in this analysis include pinned supports at both ends, restricting translation along the X-axis, Y-axis, and Z-axis. To optimize computational efficiency the model, define in symmetry model, that able to apply symmetry boundary conditions XSYMM or X-Symmetry, also ensuring that the left and right sides of the model behave identically. This allows the analysis to be performed on only half of the structure while maintaining accuracy.

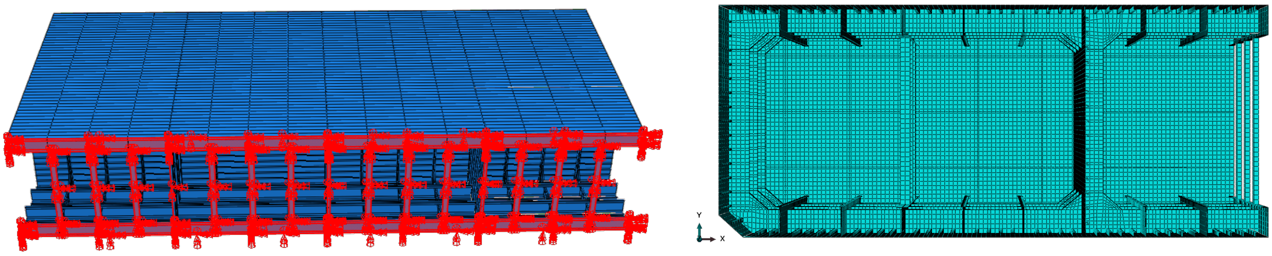

Figure 5. XSYMM constraints and Meshing Structure

Figure 5 are showing global meshing, 2D elements are used, employing a hexahedral meshing technique. The S4R or shell element structural mesh type is applied to the faceplate, while the C3D8R or solid element type is used for the core material, ensuring an efficient and precise representation of the structure. Details of the mesh conditions and XSYMM constraints.

2.4. Stress and Deformation

Stress is a force acting on an infinitely small area in a piece that has both magnitude and direction. The stress can be formulated according to the equation (3).

$$\sigma = \frac{F}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where σ is stress (N/m^2); F is force (N); A is area (m^2). Furthermore, von Mises stress can occur when the energy in a material is distorted, and the material reaches a particular critical value. Von Mises stress is used to determine whether a material will fracture (Hibbeler, 2019). To find the value of the von Mises stress can use the equation (4).

$$\sigma_v = \sqrt{\frac{(\sigma_z-\sigma_r)+(\sigma_z-\sigma_\vartheta)+(\sigma_\vartheta-\sigma_r)}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where σ_v is von mises stress (N/m^2); σ_z is Axial stress (N/m^2); σ_r is Radial stress (N/m^2); σ_θ is hope direction stress (N/m^2). Moreover, when a structure is stressed, it will experience a corresponding deformation phenomenon. Deformation is a change in shape that occurs when an object is subjected to a force. Initially, the object may undergo elastic deformation, where it returns to its original shape once the force is removed. However, if the force exceeds the object's yield point, it will undergo plastic deformation, resulting in a permanent change in shape. Based on this phenomenon, the extent of deformation in an object depends on the modulus of elasticity of the material used. The relationship between stress and deformation is shown by the equation (5).

$$\sigma = E.\varepsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where E is young modulus (N/m^2); ε is deformation.

2.5. Longitudinal Strength

The longitudinal strength of a ship is a measure of its ability to withstand forces acting along its length. These forces can come from cargo, the ship's own weight, and conditions like still water because this ship operating in river. It is calculated based on the modulus of the ship's cross-section, particularly with respect to the deck and bottom.

According to the Indonesian Classification Bureau's rules, the value of the cross-sectional modulus for the deck and bottom of the ship must be greater than a specified minimum value. This minimum value can be calculated using the equation (6).

$$W_{min} = k.C_0.L^2.B.(Cb + 0.7).10^{-6} \text{.................................} (6)$$

Where W min is minimum section modulus (cm^3); k is material factor; C_0 is wave coefficient; L is length of ship (m); B is breadth of ship (m); C_b is block coefficient. Then, the calculation of bending moments using the formula in accordance with the BKI rules is as follows: Bending moments on vertical waves Mwv [kNm] for sagging and hogging conditions can be determined by formula (7).

$$M_{wv} = L^2.B.c_0.c_1.c_L.c_M \quad \text{.................................} (7)$$

The total bending moment maximum (*hogging*) of the ship under each condition can be determined by the formula (8).

$$M_T = M_{SW,max} + M_{WV,hog} \text{ ....} (8)$$

The minimum bending moment (*sagging*) value can be calculated by equation (9):

$$M_T = M_{SW,min} + M_{WV,sag} \text{ ....} (9)$$

$$M_{SW,ini} = n_1.c_0.L^2.B.(0{,}123\text{-}0{,}015.C_B) \text{ ....} (10)$$

The analysis of longitudinal strength using rigid link constraints connected at the center of gravity of the ship in the Finite Element Analysis (FEA) modelling to obtain stress values on the deck and bottom structure of the ship.

3. RESULTS AND DISCUSSION

3.1. Configuration Sandwich Plate System (SPS)

Data gathering was carried out for the cargo barge with dimension shown in Table 2, and the cross-sectional area of the ship can be seen in Figure 6. With the existing ship data that has been obtained, the next step is to calculate the sandwich material to replace the steel material. In accordance with the rules of the Lloyd Register regarding the required strength index value following equation (1), the results of the sandwich material configuration check as shown in Table 3.

Description	**Value (m)**
Length Overall (L_{OA})	155.00
Length Perpendicular (L_{PP})	154.00
Breadth Molded (B)	45.00
Depth(D)	9.50
Draft(T)	6.10

Table 2. Main Dimensions of Ship

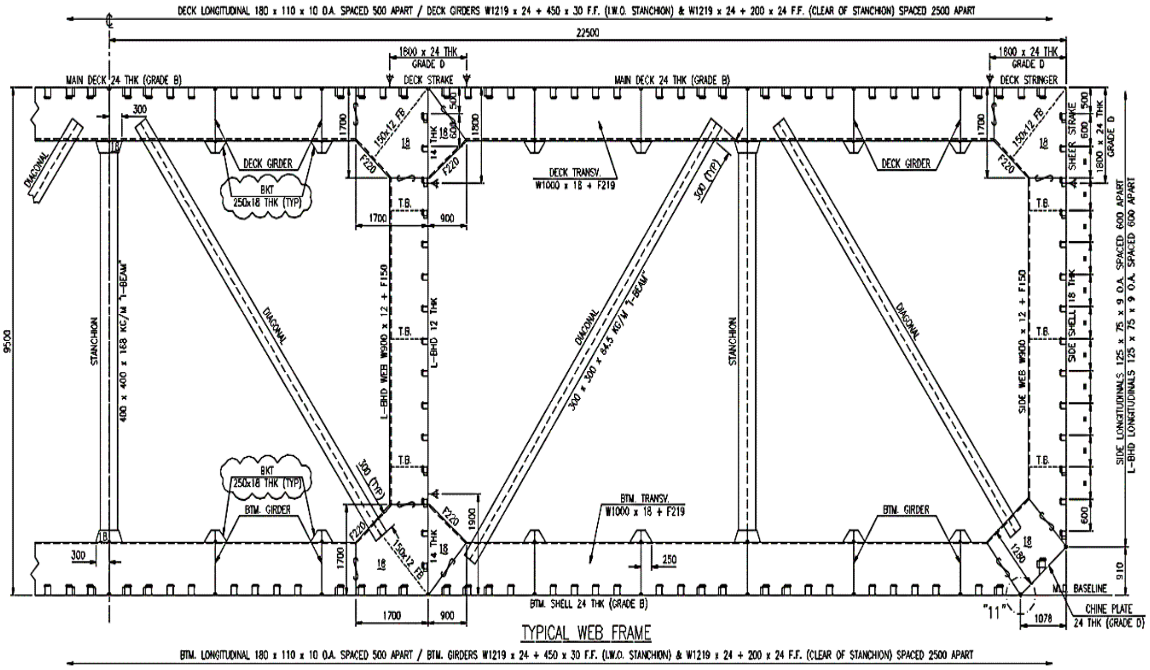

Figure 6. Midship Section

The sandwich plate structure configuration was checked to see if the thickness of the faceplate and core met the strength index criteria according to equation (1). The non-compliant and compliant parts are presented in Table 3. Using a check mark for structures that comply and cross structures that do not comply.

Sandwich Plate System Configuration	t_1	t_2	t_c	R	Check
Bottom	3	3	16	2.220	X
	4	4	16	1.626	X
	5	5	16	1.267	X
	6	6	16	1.027	X
	7	7	16	0.855	✓
	8	8	16	0.727	✓
	9	9	16	0.627	✓
	10	10	16	0.547	✓
Side	3	3	16	1.231	X
	4	4	16	0.906	✓
	5	5	16	0.708	✓
	6	6	16	0.576	✓
	7	7	16	0.481	✓
	8	8	16	0.409	✓
	9	9	16	0.354	✓
	10	10	16	0.309	✓
Deck	3	3	16	1.772	X
	4	4	16	1.304	X
	5	5	16	1.020	X
	6	6	16	0.829	✓
	7	7	16	0.692	✓
	8	8	16	0.589	✓
	9	9	16	0.509	✓
	10	10	16	0.445	✓

Table 3. Check Strength Index of Sandwich Plate System Configuration

In the modified structure, checks are also made on the ship's cross-sectional modulus and moment of inertia. It aims to see the longitudinal strength of the modified sandwich structure. All four types of structural geometries that were designed met the criteria required by BKI following Tables 4 and 5.

Structure Framing Systems	Modulus Bottom (cm^3)	Modulus Deck (cm^3)	Minimum Regulation (cm^3)	Check	
				Bottom	Deck
Existing	16783736	16015100	15152051	✓	✓
Longitudinal	20713105	20493175	15152051	✓	✓
Transverse	17358689	16105289	15152051	✓	✓
Mixed	20597571	20826421	15152051	✓	✓

Table 4. Check of Minimum Requirements of Section Modulus

Structure Framing system	Moment of Inertia Design (cm^4)	Moment Regulation (cm^4)	Check
Existing	7785445629	7000247656	✓
Longitudinal	9786212933	7000247656	✓
Transverse	7936545130	7000247656	✓
Mixed	9837897842	7000247656	✓

Table 5. Check of Minimum Requirements of Moment of Inertia Check

3.2. Verification of Convergency Study

The configuration of the material and the calculation of the load conditions, the structural systems modeling is carried out. The existing structural systems are made in Abaqus software and then meshed with a size of 0.5 m to 0.1 m. It aims to obtain a convergence graph. Convergence analysis is carried out using stress and deformation variables. There is convergence obtained in the mesh size of 0.1 m can be seen in Figure 7. with the number of elements 741528 and a margin of error of 2.8% for stress and 0.8% for deformation.

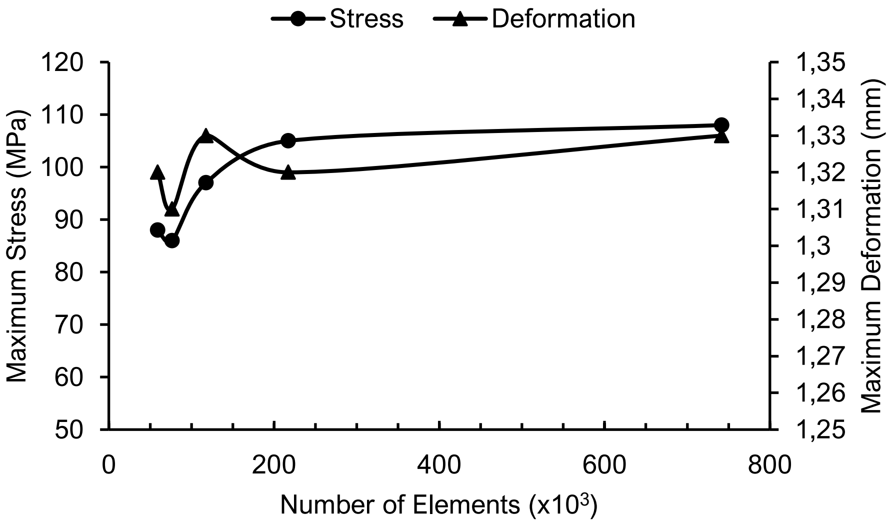

Figure 7. Convergency study of elements in stress and deformation

With the mesh size obtained that represented in Figure 7, an analysis of the application of the sandwich plate that will be used in the modified structural systems is carried out according to the thickness configuration obtained.

3.3. Influence of Structural Configuration on Stress, Deformation, and Weight Reduction

The load is applied based on operational conditions, where a 155 m × 45 m × 9 m barge transports a rectangular coal load. The coal load is modeled with a 30° angle of repose on the sloped side to determine the height of the coal being transported. Sandwich materials are utilized for the deck, side, and bottom structures, which experience forces from static loads in calm water, as well as bending moments due to sagging and hogging. These bending moments arise from specific loading conditions and weight distribution, given the barge's operational environment in a river.

Therefore, the anticipated structural response closely approximates real operational conditions. The application of loads to structural components and their subsequent responses in terms of stress and deformation are analyzed. Moreover, based on the outcomes of this study, the structure with the lowest weight is identified. According to the simulation results of the sandwich panel structure (SPS) configurations presented in Table 3, the corresponding stress and deformation responses are illustrated in Figure 8 and Figure 9.

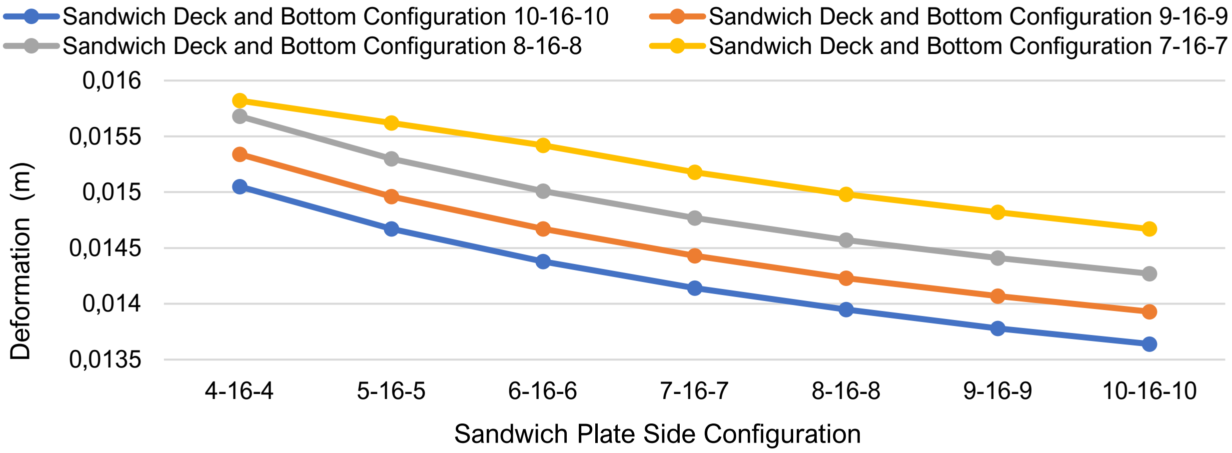

Figure 8. Comparison of Material sandwich in Deformation Response

Figure 8 demonstrates that the highest deformation values are found in the deck and bottom with the 7-16-7 configuration, and in the side configuration with 4-16-4. Deformation values decrease when thicker sandwich materials are used for the deck. Similarly, for the side plates, increasing the sandwich material thickness results in reduced deformation. This finding is also supported by the stress comparison data presented in Figure 9.

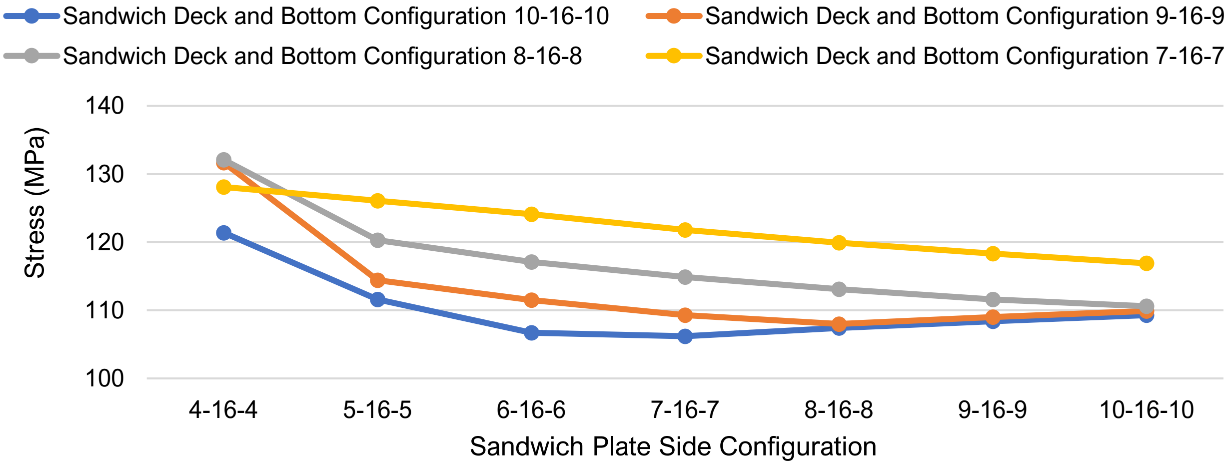

Figure 9. Comparison of Material sandwich in Stress Response

The greatest stress occurs in the deck and bottom configuration with 8-16-8 and the deck and bottom configuration with 9-16-9. The tension will be reduced according to the thickness at the tension condition of the sandwich deck size 7-16-7 meets the acceptance criteria for the thinnest side plate thickness combination stress which is 4-16-4. Considering the stress, deformation, and weight reduction achieved with the four sandwich configurations, the optimal choice is 9-16-9 for the bottom and deck structure, and 10-16-10 for the sides. Increasing the sandwich plate thickness of the ship block tangible reduces the stresses on the sides, deck, and bottom.

This is in line with the well-established principle that thicker materials offer greater strength and bearing capacity. This analysis also examines the weight reduction achieved with sandwich plates. Figure 10 shows an inverse relationship between faceplate thickness and weight reduction. In other words, thinner faceplates result in a more significant weight reduction in the overall structure.

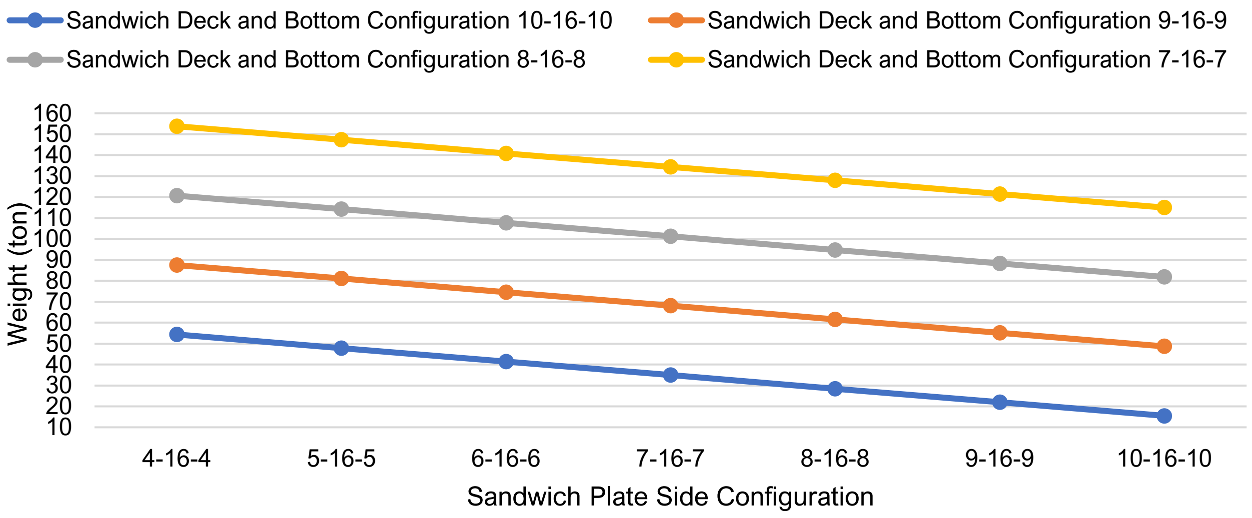

Figure 10. Comparison of Material sandwich in Weight Reduction

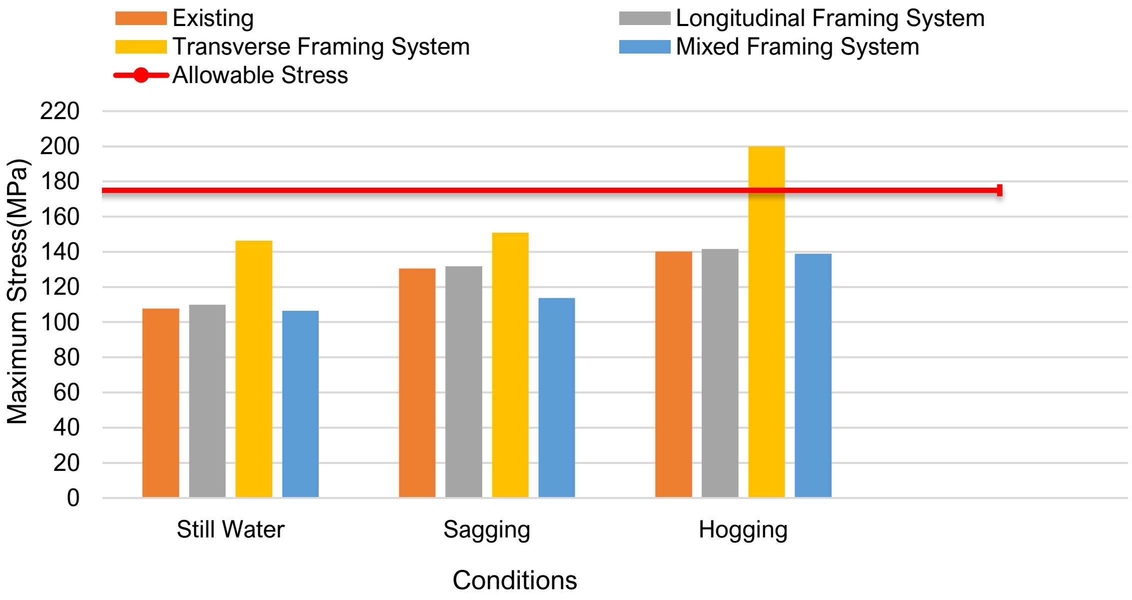

Figure 11. Stress Comparison Results

As shown in Figure 11, the transverse structure exceeds the allowable stress under hogging conditions. This occurs due to the limited number of longitudinal stiffeners, which leads to localized stress concentrations at the reinforced ends of the structure.

These stress concentrations can exceed the material's strength, potentially causing structural failure. Additionally, the transverse structure lacks an efficient load distribution compared to longitudinal structures. As a result, it is unable to effectively transfer loads when the ship experiences excessive bending forces. Furthermore, in line with the deformation behaviour due to bending moments, this structural configuration exhibits the highest deformation under bending load conditions.

To enhance structural strength, a mixed structural system can be utilized, as it allows for improved stress distribution, thereby increasing overall structural integrity. This is evident in the blue curve, which demonstrates that the mixed system consistently produces lower stress values across all loading conditions compared to the existing structural configuration and other structural types. Another approach involves reinforcing local structural elements in areas experiencing excessive stress. However, this method would increase the overall structural weight, which may impact the ship's performance.

The point is that this verifies that with BKI regulations which limit transverse structure to vessels under 90 metres in length, mixed structure is recommended for lengths between 90 and 100 meters. Analysis of the maximum stresses in the sandwich structure showed an increase compared to the existing design. According to the BKI regulations, the allowable stresses have certain criteria. In this study, the allowable stress limit is set at 175 MPa (BKI, 2021). The deformation analysis reflects the stress results, showing an increase in the deformation value of the sandwich structure which can be seen in detail in Figure 12.

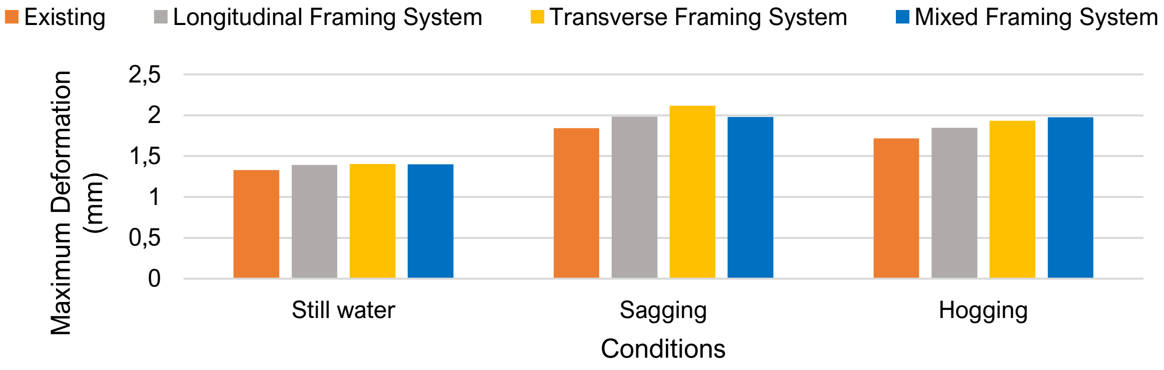

Figure 12. Deformation Total Comparison Results

From the analysis of the sandwich structure's static response and longitudinal strength, there is an increasing trend in stress and deformation while meeting the longitudinal strength requirements, except for transverse structures that exceed the allowable stresses of the class rules. However, the stress and deformation value of the sandwich plate application is increased; it is still offset by a decrease in the weight of the structure, which increases the load-carrying capability of the ship itself.

Weight loss can be seen in Table 6, where the longitudinal structure has a decrease of 5% from the existing structure. It happened because the modification of the longitudinal structure sandwich was only carried out on the deck plate, sides, and base. Unlike transverse or mixed sandwich structures with a 12% and 9% reduction, respectively, due to recalculation of the stiffeners used to match the analysed structural systems.

Structure framing system	Weight (ton)	Weight reduction (ton)	Weight reduction (%)
Existing	1049,56	-	-
Longitudinal	1000,91	48,66	5%
Transverse	921,28	128,28	12%
Mixed	951,22	98,34	9%

Table 6. Weight Reduction Results

The compensation applied in this condition can influence the cargo capacity, potentially increasing the amount of cargo that can be transported. However, it is essential to ensure compliance with the required acceptance criteria to maintain the safety of the cargo and prevent any adverse effects on the barge's performance.

4. CONSLUSION

The static behaviour of sandwich materials used in ship compartments was analysed and summarised using finite element software. The aim of this study was to evaluate the structural performance of a sandwich plate system as an alternative to conventional ship structures while ensuring compliance with classification standards. The results show that the optimum sandwich plate configuration is 9-16-9 mm for the deck and bottom and 10-16-10 mm for the sides. The modified sandwich plate system, which follows the BKI regulations, complies with the requirement that ships longer than 100 metres must use a longitudinal structure. The results show that the modified sandwich plate structure has a higher static behaviour than the existing structure. However, it still fulfils the BKI acceptance criteria. In calm water conditions, the stress in the longitudinal sandwich plate structure increases by 2% and the deformation by 4%. Under hogging and sagging conditions, the stress increases by 1%, while the deformation increases by 7%. In addition, the use of sandwich plates leads to a 5% reduction in overall weight, equivalent to 48.66 tonnes, compared to the existing structure.

Although the study confirms the feasibility of sandwich plate structures in shipbuilding, certain limitations must be recognised. The analysis focuses primarily on the static behaviour under idealised loading conditions, without considering the dynamic effects, fatigue performance or long-term durability in real operating environments. In addition, manufacturing costs, reparability and the potential challenges of large-scale implementation need to be further investigated.

The results have significant implications for ship design and operational efficiency. Reducing structural weight can increase cargo capacity and thus contribute to more sustainable maritime transport. However, the increase in deformation suggests that further optimisation may be required to improve structural integrity under extreme loading conditions.

Future research should investigate the fatigue performance of sandwich plate structures under cyclic loading, assess their hydrodynamic behaviour and investigate the economic feasibility of large-scale implementation. In addition, experimental validation through physical tests would be beneficial to substantiate the numerical results and refine the design recommendations.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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