Konversi Energi dan Manufaktur

P-ISSN : 2339-2029
E-ISSN : 2622-5565

Jurnal Konversi Energi dan Manufaktur
Volume 10 Number 1 – January 2025 Page 61-69
Website : http://journal.unj.ac.id/unj/index.php/jkem DOI: https://doi.org/10.21009/JKEM.10.1.7

Structural Strength Analysis of Car Deck Re-Layout Impact on Ro-Ro Ships Using Structural Analysis Method

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Article information - : Received : 19-11-2024; Revised : 17-01-2025; Accepted : 21-01-2025

Abstract

This study focuses on analyzing the structural strength of car deck construction in roll-on/roll-off (ro-ro) passenger ships. Ro-ro ships are designed to transport both vehicles and passengers, in which vehicles can drive in and out under their own power. While these ships are operational, there is a potential for improvement in their construction strength, particularly in the car deck area. The car deck is a critical structural component as it bears both vehicle loads and supports the upper decks. This research analyzes the car deck's structural integrity, which was initially designed for trucks and sport utility vehicles (SUV), under various conditions including calm water, sagging, and hogging scenarios. Using both finite element method (FEM) analysis through ANSYS software and manual calculations via Excel, the study evaluates maximum stress points and deflection. The 3D modeling was completed using Fusion 360, while 2D drawings were created in AutoCAD. Results revealed that the highest stress occurs during hogging conditions with truck loads, showing 188.23 MPa stress and 0.077128 m deflection. With a safety factor of 1.3281, these values comply with Indonesian Classification Bureau (BKI) standards, which require stress below 250 MPa and a safety factor above 1.

Keywords: stress; deflection; ANSYS software; safety factor; BKI rules.

1. Introduction

In Indonesia, ship construction design is a crucial aspect in the maritime world [1]. Efficient and robust construction is essential to ensure ship safety, performance, and sustainability [2], [3]. A roll-on/roll-off (ro-ro) ship is a vessel capable of loading vehicles that can drive in and out of the ship under their own power [4], hence a roll-on/roll-off ship is abbreviated as ro-ro [5]. Every ship construction has critical construction areas, which are locations identified based on calculations requiring monitoring or based on the vessel's operational history [6], [7].

Car deck construction requires special attention as this structure is designed to withstand loads from vehicles and deck houses above it [8]. The car deck is also a critical location in ro-ro ships during collision events [9] . To prevent structural failure, the finite element method (FEM) has become a reliable solution used by many researchers [10], [11]. Currently, the FEM serves as a powerful tool for analyzing ship structural responses by modeling the actual ship at a smaller scale for easier analysis [12] - [14]. This research will contribute significantly to the knowledge and understanding of car deck structural strength analysis to ensure ships are strong, robust, and innovative. This study focuses on using structural analysis methods in ship design, aiming to enhance structural strength in accordance with Indonesian Classification Bureau (BKI) rules. This research will employ both manual calculations and finite element methods to determine maximum stress after analysis.

The study proposes a novel approach to evaluating the structural performance of car decks in ro-ro ships that combines finite element analysis and human calculations, with a special emphasis on the influence of re-layout scenarios with different vehicle loads. In contrast to earlier research that mainly focused on static or dynamic vehicle-deck interactions [15], [16], this study integrates stress and deflection analysis across several operational situations (such as hogging and sagging) to add to previous research [17], [18]. Additionally, the results offer important insights into BKI standard compliance as well as useful suggestions for improving vehicle deck designs to increase load-bearing capacity and guarantee maritime safety.

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2. Experimental Methods

A ro-ro ship is designed to accommodate vehicles that can drive in or out of the ship under their own power, hence called ro-ro. Ro-ro vessels can transport trucks, passengers, and cars [19]. The characteristics of these ships include having ramp access at the bow and stern, featuring long vehicle deck lanes, and multiple ventilators on the upper deck for vehicle exhaust disposal [20]. The car deck is a deck or platform on ships used to accommodate vehicle cargo, typically found on ferries or ro-ro ships [21]. The car deck is a vital structural component as it does not only accommodate vehicle cargo but also supports the decks above it. The vehicles in question range from two-wheeled to six-wheeled motor vehicles [22].

The FEM has become a common method in engineering [23]. It is an analytical method for predicting the response of an engineering system by dividing a continuous form into several finite parts. These parts are called elements, where each element connected by nodes. Mathematical equations then become representations of the object. Design problems can be solved through mathematical and numerical methods. For objects with irregular shapes (isoparametric elements), solutions using mathematical methods become difficult. Therefore, numerical methods need to be used, which in their development are called the FEM [24].

This research conducts variations in car deck modeling where the car deck receives vertical loads or loads along the y-axis from vehicle cargo. The loading is defined as linear static, with a fixed ordinate axis in numerical calculations. In this study, three loading conditions as seen on table 1 are used for load variations [25].

Table 1. Loading Variations [26]

No.	Load Configuration	Vehicle Load	Total Weight (tons)
1	Loading Variation 1	24 SUVs	84
2	Loading Variation 2	12 Trucks	120
3	Loading Variation 3	15 SUVs and Trucks	112.5

The analysis uses an SUV weight of 3.5 tons and truck weight of 10 tons [27], [28]. The load is concentrated on vehicle wheels (4 wheels for SUV, 6 wheels for truck), with distributed loading on the ship's car deck as illustrated in Figure 1 below.

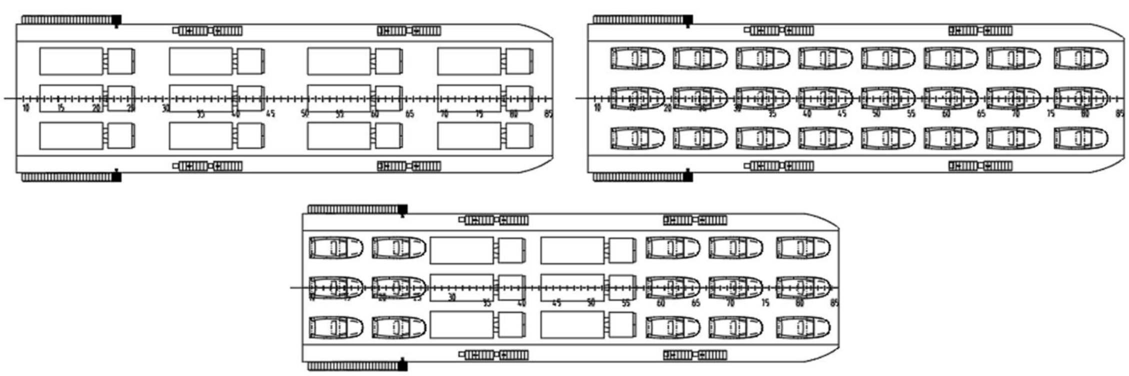

Figure 1. Loading variations of the car deck

The model used in this research is a cross-section of the ro-ro ship's car deck, using data from KM. Mahkota Nusantara. The modeling data is presented in Table 2.

Konversi Energi dan Manufaktur

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Table 2. Main dimensions of KM. mahkota nusantara

Description	Value	Unit
Length overall (LOA)	123.00	m
Length between perpendiculars (LPP)	115.50	m
Width	18.00	m
Height	12.30	m
Fully loaded draft	6.25	m
Block coefficient	0.70	-

3. Results and Discussion

The modeling was conducted using AutoCAD for 2D design and Fusion for 3D design, with the 3D design shown in Figure 2.

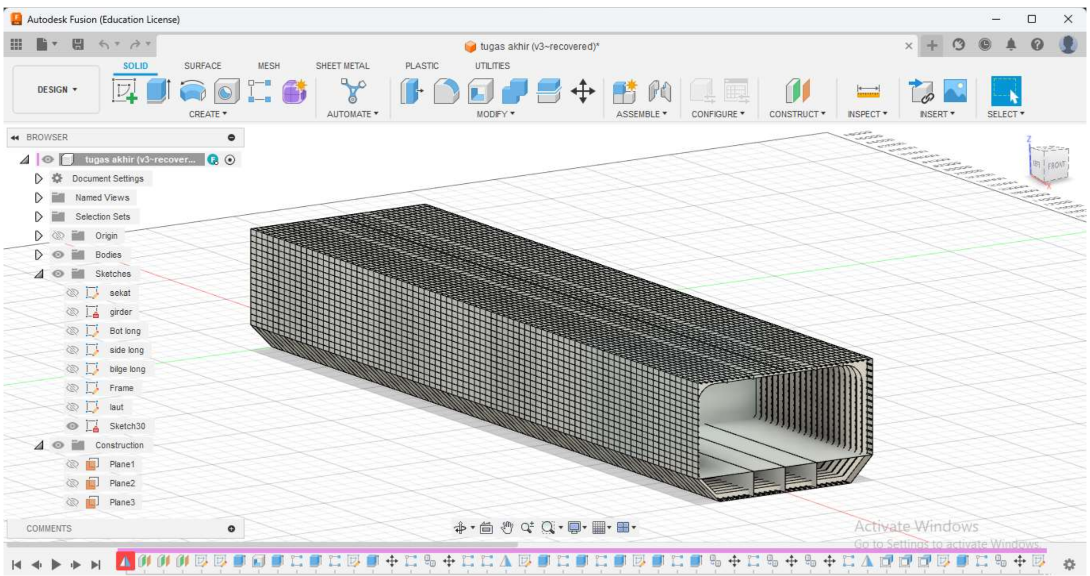

Figure 2. 3D model of car deck

3.1. Meshing

Meshing is a FEM stage that converts the solution domain into discrete elements. The principle is dividing complex structures into smaller elements to capture structural behavior. Following American Bureau of Shipping (ABS) guidelines for coarse global models, acceptable global meshing requires approximately 10,000 elements minimum, with element sizes varying from 2 to 6 longitudinal stiffener spacing depending on ship type and size [29]. For this research, a mesh size of 500 mm was used with an 80,000 mm model length. Figure 3 shows the 600 mm meshing results with grid patterns conforming to class requirements.

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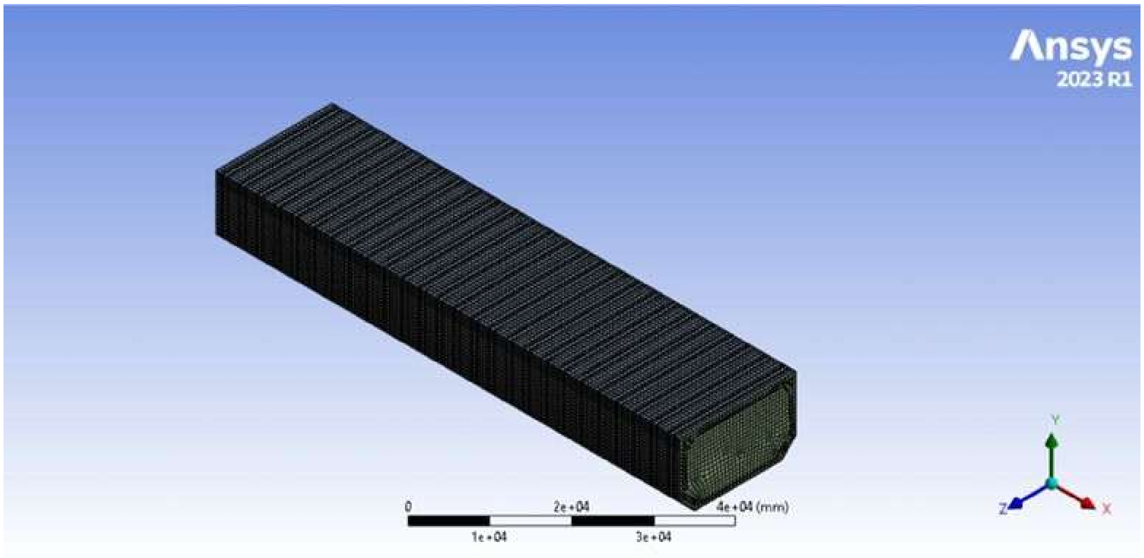

Figure 3. Meshing results

3.2. Convergence Test

Convergence testing was performed to select appropriate element sizes in finite element modeling, ensuring valid results. The process compared various element quantities, using natural frequency values for the first mode as reference. Convergence test results are shown in Table 3.

Table 3. Convergence test

No.	Mesh (mm)	Manual (mm)	FEM (MPa)	Deformation
1	300	53.28	53.72	8
2	400	53.28	53.16	8.30
3	500	53.28	53.20	8.35
4	600	53.28	53.81	8.36
5	800	53.28	54.12	8.60
6	900	53.28	54.45	8.68
7	1000	53.28	54.28	8.73

3.3. FEM Running Result

The stress analysis results shown in Figure 4 demonstrate that under the first loading variation (single SUV), the ship's car deck experiences a maximum stress of 0.14243 MPa, occurring along the deck longitudinal between frames 12 and 84.

Konversi Energi dan Manufaktur

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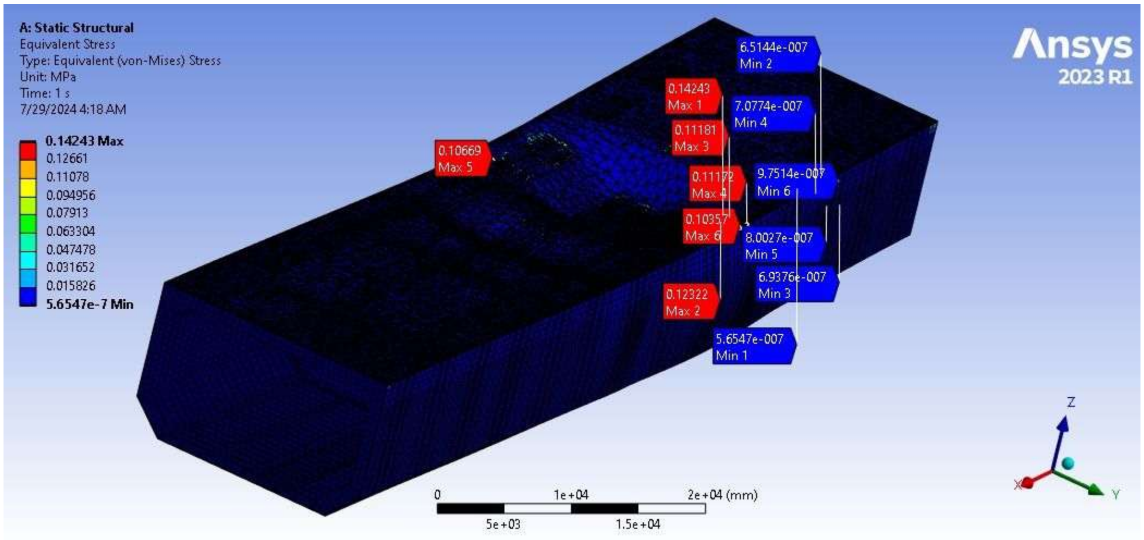

Figure 4. Loading variation 1: SUV

The stress analysis results shown in Figure 5 demonstrate that under the second loading variation (truck loading), the ship's car deck experiences a maximum stress of 7.6711 MPa, located along the deck longitudinal between frames 12 and 84.

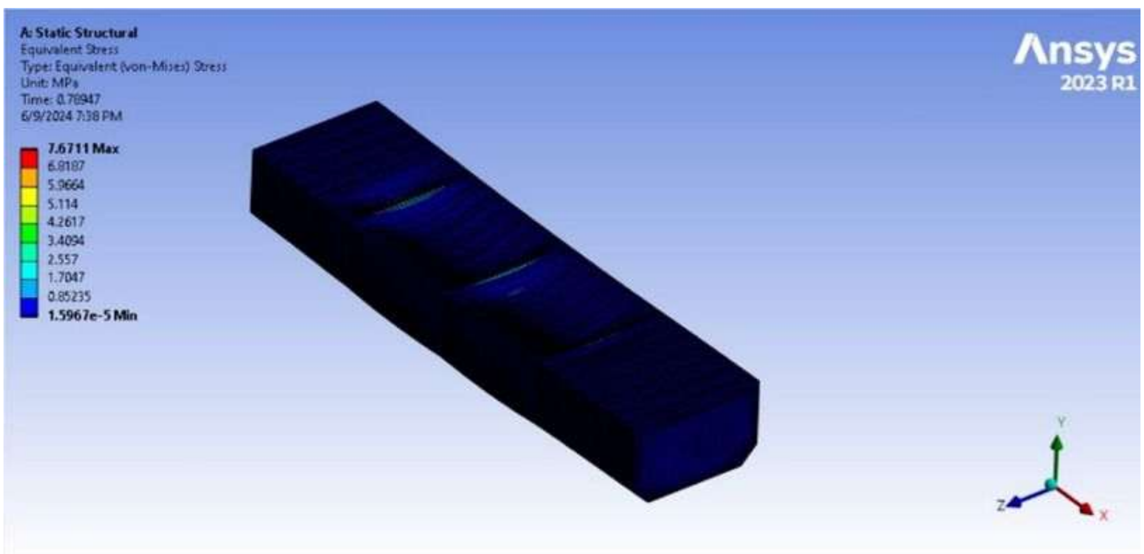

Figure 5. Loading variation 2: truck

Figure 6 shows the stress analysis results of the ship's car deck under loading variation 3 (combined SUV and truck loading), which produces a maximum stress value of 2.7284 MPa, located on the deck longitudinal between frames 12 - 84. The loading arrangement consists of SUVs positioned between frames 12 - 35 and frames 63 - 84, while the truck is positioned between frames 35 - 63.

Konversi Energi dan Manufaktur

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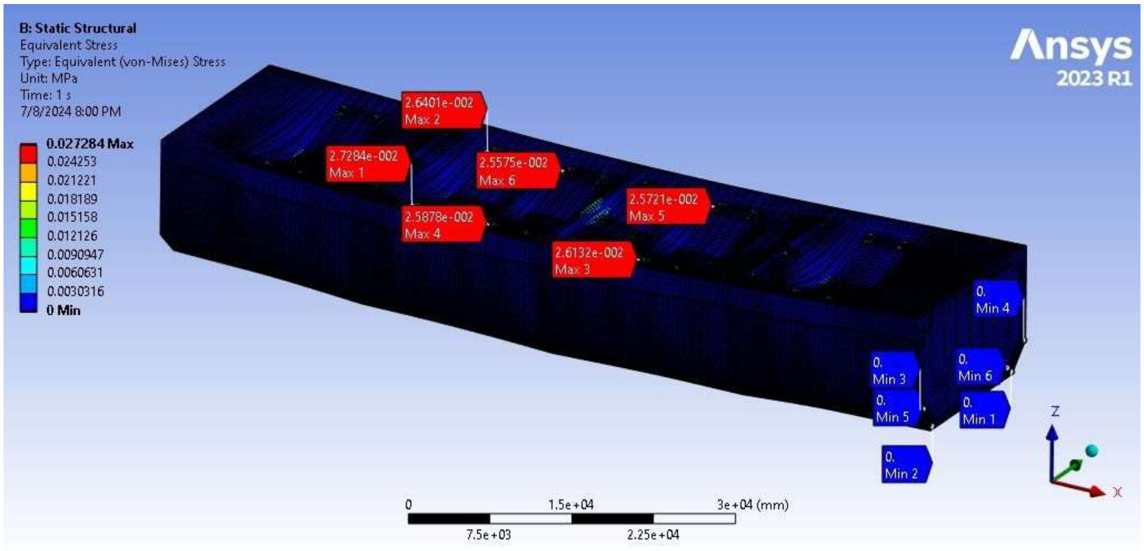

Figure 6. Loading variation 3: SUV and truck

3.4. Safety Factor

The Safety Factor represents a material's ability to withstand various external loads [30], including compressive loads (pushing forces) and tensile loads (pulling forces). A structure is considered safe when its Safety Factor (Sf) value is greater than or equal to 1 [31].

Table 4. Safety factor values

Condition	Σ Max (MPa)	Safety factor	Description
SUV	0.14243	175.248	Pass
Truck	7.6711	32.847	Pass
SUV and Truck	2.7284	91.628	Pass

The Safety Factor values derived from the FEM analysis are shown in Table 3. The analysis revealed the highest Safety Factor under SUV loading conditions, with an Sf value of 175.248, which significantly surpasses the BKI regulatory requirement of Sf ≥ 1 [32].

To demonstrate the uniqueness and efficacy of this study, its results contrasted with of related investigations. The previous investigation [33] had a safety factor of 1.25 and a maximum stress of 200 MPa. In contrast, our study's finer meshing and specific operational situations (hogging and sagging) resulted in a greater safety factor (1.3281) and a lower maximum stress (188.23 MPa). These improvements offer a more comprehensive view of vehicle deck performance in a range of operational scenarios.

Another study [16] used novel sandwich materials to lower weight and enhance structural performance in 300 GT Ferry ro-ro ships. Sandwich materials are useful for reducing stress, but their applicability is limited by their high cost and complexity. Our study, which employed traditional materials, was cost-effective while still meeting BKI requirements. This method is more feasible for real-world applications since it guarantees pragmatism and conforms to industry norms.

4. Conclusion

The structural strength analysis of the ro-ro ship's car deck under various re-layout scenarios using the FEM reveals compliance with BKI standards in terms of maximum stress and safety factors. The study demonstrates that under SUV, truck, and combined vehicle loadings, the car deck maintains structural integrity with maximum stresses well below the 250 MPa limit and safety factors significantly exceeding 1. This research provides insights

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into optimizing car deck designs for better load distribution and structural efficiency. Future studies could explore dynamic loading conditions, material alternatives, or further enhancements in design methodologies to improve operational safety and efficiency.

5. Acknowledgments

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