Majalah Ilmiah Pengkajian Industri
(Journal of Industrial Research and Innovation)
Vol. 16, No.1 April 2022 – (1-10)
Journal homepage: https://ejurnal.bppt.go.id/index.php/MIPI/index

The Fatigue Life Assessment of Sideboard on Deck Barge Using Finite Element Methods

Alamsyah[1*], Amalia Ika Wulandari[1], Nugroho Septianda Oktaparo[1], M Uswah Pawara[1], Muhammad Riyadi[2]

[1] *Naval Architecture Program, Kalimantan Institute of Technology, Balikpapan, Indonesia*
[2] *Naval Architecture and Marine Engineering, Yildiz Teknik University, Besiktas/Istanbul, 34349, Turkey*
*Correspondence E-mail: alamsyah@lecturer.itk.ac.id

ABSTRACTS

A Deck barge is a type of ship that has a flat hull used to transport large amounts of cargo such as wood, coal, sand, etc. The deck barge uses retaining walls to transport bulk loads on deck known as sideboards which can collapse due to fatigue life. The purpose of this research is to determine the maximum stress and fatigue life of the sideboard construction based on the height of the bulk load on the sideboard using coal as the bulk load. The method used in this research is the finite element method with a high load case of coal loading to the sideboard is 2.24 m, 2.60 m, and 2.96 m. The results showed that a high load case of 2.24 m detected a maximum stress value of 79.25 MPa and a fatigue life of 81.16 years with 10 x 10^5 cycles. Load case with a high load of 2.60 m detected a maximum stress value of 110.11 MPa and a fatigue life of 24.72 years with 3.53 x 10^5 cycle. For a high load case of 2.96 m, a maximum stress value of 146.80 MPa was detected and a fatigue life of 9.28 years with 2 x 10^5 cycle. There is an increasing stress value by the rise of the load height against the sideboard and there is a decrease in the fatigue life in the construction.

ARTICLE INFO

Article History:
Received 21 Jan 2022
Revised 22 Feb 2022
Accepted 07 Mar 2022

Keyword:
Barge,
Fatigue Life.
Sideboard,
Stress.

INTRODUCTION

Puspitasari 2018 stated that a barge or pontoon is a type of ship that has a flat hull in the shape of a large box that is used to transport goods and towed by tugboats or used to accommodate the tides, such as on a floating dock [1]. The barge is also used to transport crude palm oil [2]. The deck barge transports large quantities of cargo placed on the deck as well, such as wood, coal, sand, and others. Barges do not have a propulsion system like ships in general, but there are also badges that have their own propulsion system, such as Self-Propelled Barge. This type of barge is different because it has its own propulsion and the shape of the hull is the same as the one which is usually operated in shallow waters and inland waterways [3]. The characteristics of the Deck Barge are: only transporting commodities on the deck; unmanned; without its own propulsion; does not have hatch holes in the deck except for manholes which are closed and lined with gaskets; has a ratio breadth to the height of (B/H) ≤ 3; has a block coefficient of 0.9 or more [4]. Research on the fatigue limit of the barge structure is an important concern because it is one of the

***Corresponding Author | Alamsyah|🖂 alamsyah@lecturer.itkac.id**

modes of transportation of goods and bulk cargo in large quantities.

Previous research conducted by Arswendo *et al.* showed the maximum stress value that occurs in constructing the 1036 DWT coal deck barge under the influence of calm water [4]. Another research by Mulyatno et al. showed the maximum stress value in deck construction with other types of vessels [5]. Also, Adnyani has conducted research on deck strength on the Deck Barge 10070 DWT by simulating two load cases during operation [6]. Riyanto et al. examined the strength of the deck barge due to changes in the distribution of load on the deck in calm water conditions [7]. Pratama et al. examined the strength of the ship deck due to changes in load distributed [8]. In his research, the deck construction is loaded vertically, in the same direction as the y-axis, which is the loading from the load. The loading is defined as linear static, with fixed ordinate axes in numerical calculations [9]. All of the previous research used the finite element method. The purpose of those research is to ensure that the deck strength of the ship is still sufficient. One of the assessments carried out is to determine the strength of the construction. It is conducted by detecting the stress ratio in which it is compared to the working stress that occurs in the construction due to external loads that happened on the ship with the allowable stress of the material [10]. To fulfill the allowable stress (yield strength), the modulus of construction is increased by increasing the thickness of the plate or longitudinal carling [11]. The strength of the construction, given a continuous load, its material will reach the point of fatigue which results in permanent damage as a process of changing the permanent structure at one point becoming a crack. [12].

Material properties, geometric properties, and manufacturing processes can affect the quality of a design [13] so that the selection of the right material can affect the performance of ship construction. The fatigue fracture mechanism consists of 3 stages, namely: crack initiation, crack propagation, and final fracture [14]. The rate of crack propagation is proportional to the stress range and is usually represented by the stress intensity ΔK, which is a function of stress magnitude, size, fracture geometry, and structural geometry [15]. Alamsyah et al. detected the local stress and fatigue life of the pontoon lift using numerical simulations with the defines the number of cycles to failure, N(S), when a material is repeatedly cycled through a given stress range S (S-N curves approach), based on the weld joint model, and the profile section model [16]. Pangestu *et a*l., examined the fatigue life of ship construction using the Simplified Fatigue Analysis method [17]. Alamsyah et al. detected hotspot stress and fatigue life on structures using numerical simulations and the Palmgren-Miner cumulative linear damage theory [18] [19]. Misbah et al. estimated the fatigue life of ships using the Mean Value First Order Second Moment method [20]. The same results on the use of the MVFOSM method and the FORM First Order Reliability Method (FORM) were also shown by Liu et al. in optimizing the reliability-based missile suspension structure [21]. The research was conducted not only to ensure the eligibility of the strength of the vessel structure but also to predict the fatigue life of the construction. Determining the fatigue life can be done by doing a stress analysis on the construction first.

In 2006, the International Association of Classification Societies (IACS) developed a new regulation for the construction of tankers and bulk carriers, namely Common Structural Rules (CSR) [22]. Repetitive loads that occur continuously can result in fatigue on the ship's structure. Fatigue is a type of failure (fracture) in a component due to repeated and changing dynamic loads. It is estimated that 50%-90% of mechanical failure occurs due to fatigue [23]**.** Fatigue is a process of the cycle after cycle of damage accumulated in structures that are subjected to fluctuating stresses, through several stages starting from the initial crack free to the failure state. The most influential load parameter is the fluctuation of the stress component or commonly referred to as the stress range [24]. There are two types of fatigue, Low-cycle fatigue that occurs for a low number of cycles less than $5x10^3$ cycles, and High-cycle fatigue that occurs for a high number of cycles. Fatigue life is calculated based on the total calculation of fatigue damage from stress hotspots which produces a cumulative fatigue damage index. This index is then used as input to calculate the fatigue life of the structure based on the fatigue life equation where the design life according to CSR is 25 years [22]. To determine the value of "D" or Accumulated Fatigue Damage, the S-N curve approach by applying the Palmgren-Miner cumulative linear damage theory is used [25] [26]. To predict fatigue life, we must know the value of fatigue damage by using the simplified fatigue analysis equation determined by DNVGL-RP-0005: 2014-06 [27].

This study uses finite element (FE) methods where numerical procedures can be used to find solutions to various problems in engineering [28]. The numerical analysis discusses several aspects that have particular relevance to the response of ship structures, including the importance of determining the weld model, the effect of failure criteria, material relations in complex structural simulations, and application of the scaling law in assessing the impact of full-scale structural response [29]. An accident collapsed case has occurred in constructing a sideboard of deck barge 10486 DWT while transferring coal [30]. The initial hypothesis was due to construction fatigue. The accident shows an important study regarding sideboard construction on the deck barge, including strength, fatigue life, the form of construction, and external factors such as corrosion, pressure from the load, etc. In this study, an analysis of the strength of the barge sideboard construction was carried out, and the fatigue life of the construction was estimated. The benefits of the research results are expected to become a reference in the barge sideboard design process and as a reference to determine the construction replacement time correctly.

METHODS

The stress analysis uses numerical simulation. The finite element method is applied in the calculation with the load case based on the height of the load on the sideboard, which is equal to 2.96 m, 2.60 m, and 2.24 m. Hence, the size of the deck barge is shown. The length, width, load height, and DWT are 90.44 m, 24.00 m, 5.4 m, 4.2 m, and 10,486 tons, respectively. The sideboard size is also shown in **Table 1**.

Table 1. The components construction of the sideboard.

Components	Details	
	dimension	**units**
Stiffener 1	200x70x6	mm
Stiffener 2	100x70x6	mm
Stanchion	200x200x8x12	mm
Support Stanchion	200x200x8x12	mm
Plate Thickness 1	8	mm
Plate Thickness 2	10	mm

The type of material used is BKI standard steel with the notation KI-A36 [31], with presented properties. Modulus of Elasticity, Shear Modulus, Poisson Ratio, Density, Yield stress, and Ultimate Stress are 200 GPa, 79.3 GPa, 0.3, 7850 kg / m^3, 250 MPa, and 400 MPa, respectively. **Figure 1** shows the details of the 2D sideboard construction, which is the object of research—3D modelling using FE with reference to 2D images. 3D modelling is shown in **Figure 2**.

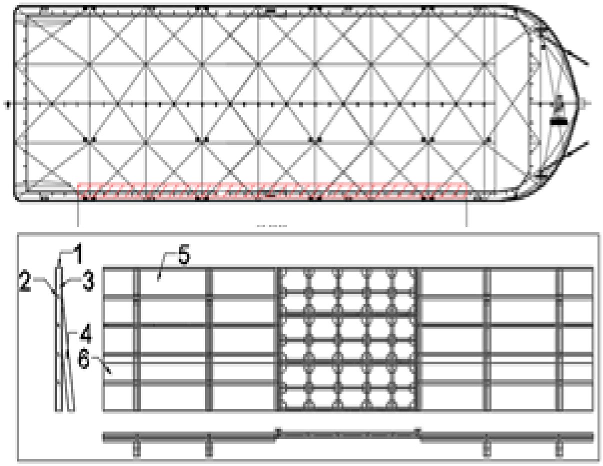


Figure 1. The object of research.

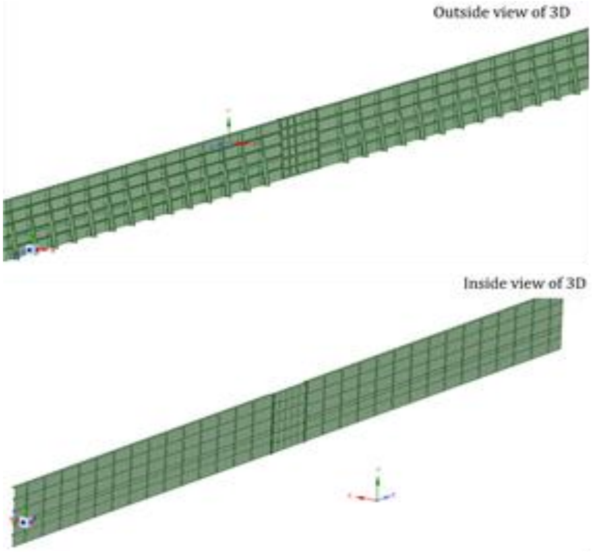


Figure 2. Inside & Outside view of 3D sideboard with FE.

The next stage is using FE, namely meshing of 3D modelling. It determines how many nodes (points) and elements there are in 3D modelling. The mesh size, number of nodes, and number of elements are 120 mm, 345,672 nodes, and 170,392 elements, respectively. The mesh stages in FE are shown in **Figure 3**

.

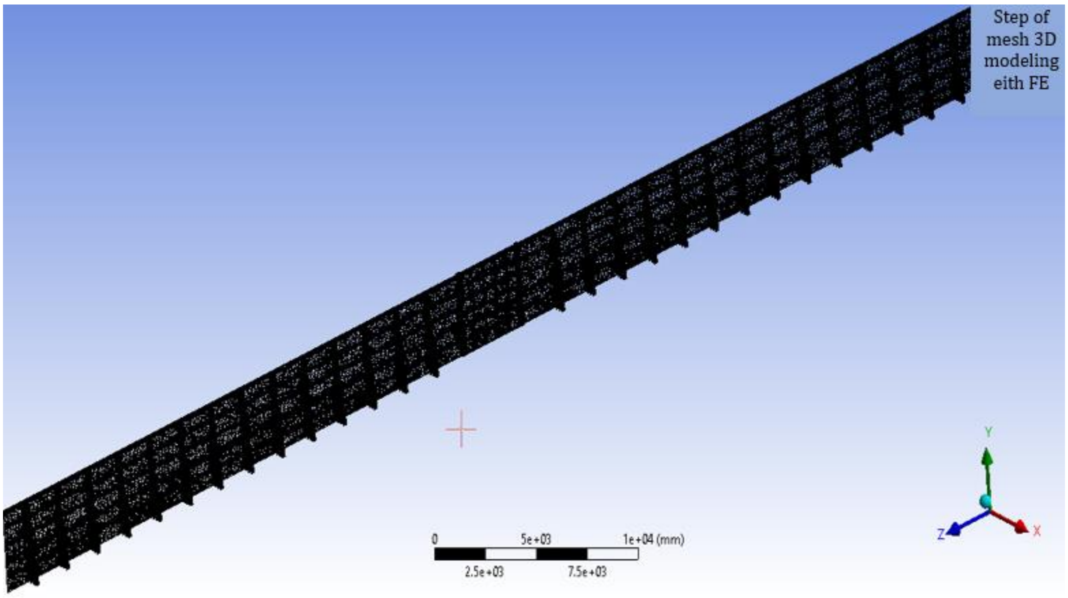


Figure 3. The meshing of 3D Sideboard with FE.

The next stage is using FE, which is the input displacement on 3D modelling in the form of fixed support and load according to the load case that was planned at the beginning. The provision of fixed support is shown in **Figure 4**.

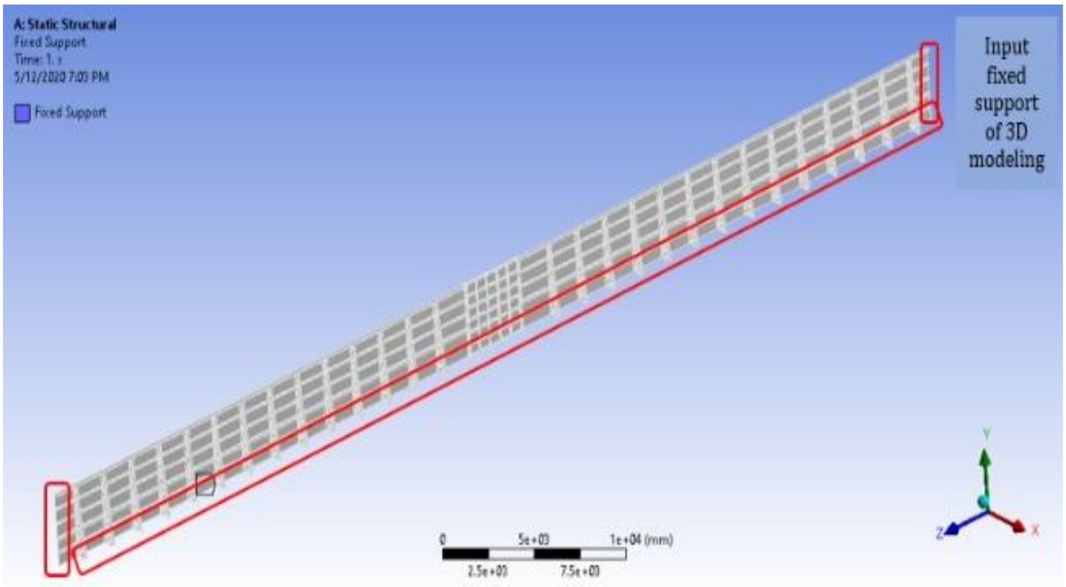


Figure 4. Input Fixed Support on 3D Sideboard with FE.

The load input which is the amount of pressure on the sideboard construction is determined based on the active soil pressure of the Rankine method [32] with a sloping ground surface. The pressure that occurs on the sideboard uses the equation (1) for lateral pressure (P_a). Therefore, the required variables for each are shown, they are the density of coal (γ) 8.1634 Kn/m^3 [33], load height to the sideboard (H), and the active pressure of coal coefficient (K_A). Illustration of coal loading case is shown in **Figure 5**.

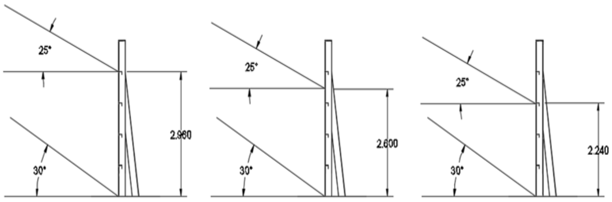


Figure 5. Load case on 2D Sideboard.

$$P_a = \gamma\ H\ K_A \tag{1}$$

$$K_A = \cos\beta \times \frac{\cos\beta - \sqrt{cos^2\beta - cos^2\phi}}{\cos\beta + \sqrt{cos^2\beta - cos^2\phi}} \quad (2)$$

The case is where the angle of surcharge of bulk coal [34] is (β) = 25°. Anup K Swain provides the angle of internal friction value for bulk coal [35], which is (ϕ) = 30° so that the load given in the FE 3D model is shown in **Figures 6**, **7**, and **8**.

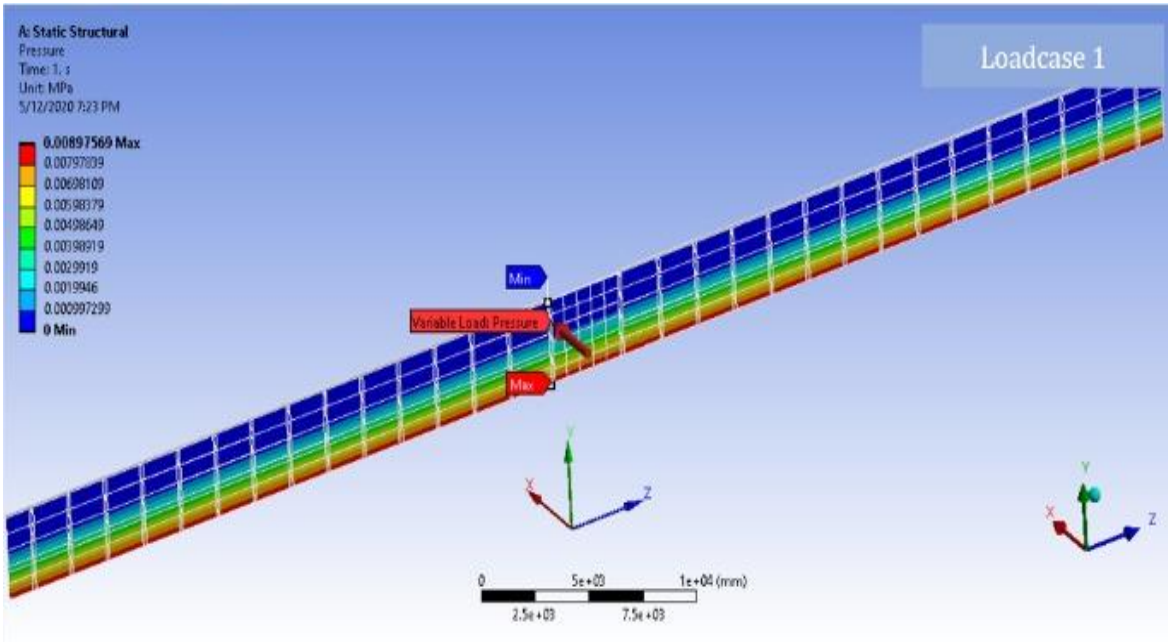


Figure 6. Load case 1 with 2.24 meters.

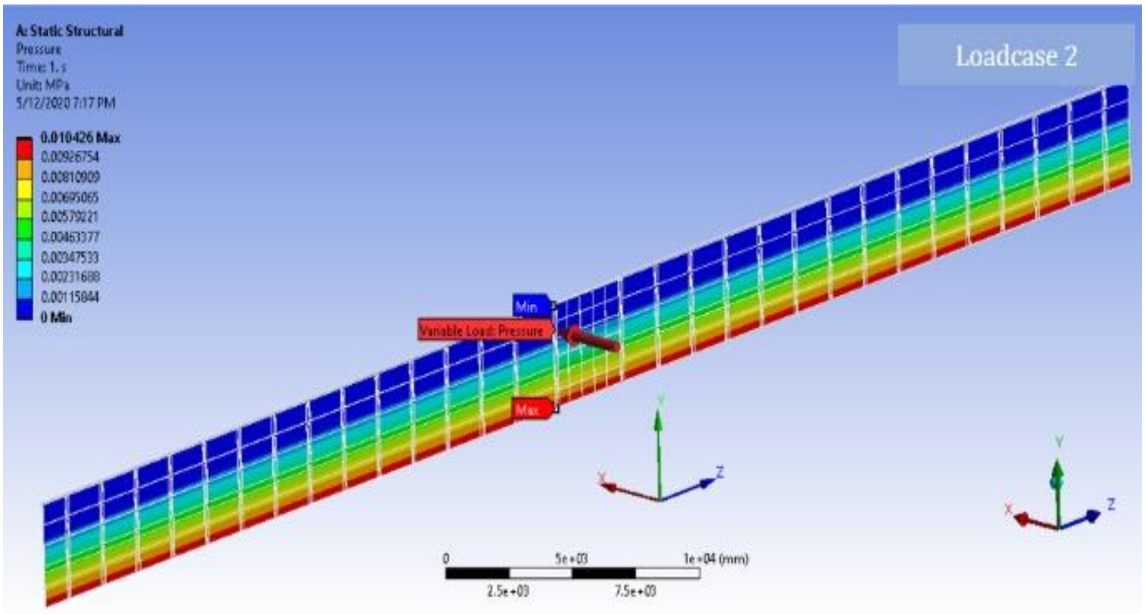


Figure 7. Load case 2 with 2.60 meters.

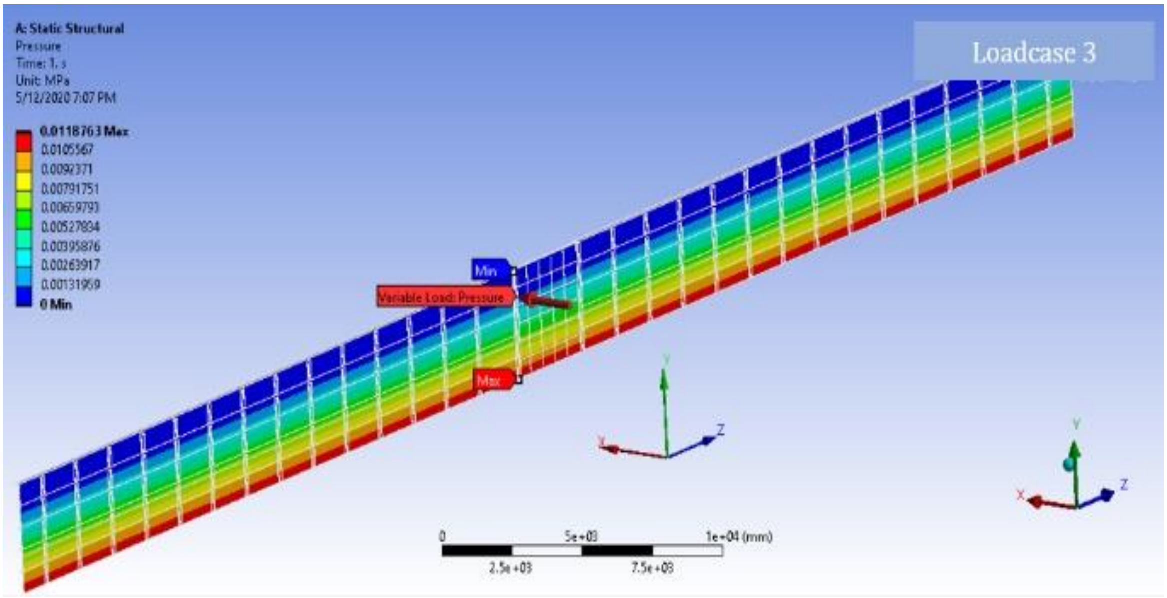


Figure 8. Load case 3 with 2.96 meters.

Fixed support input and pressure on the sideboard will produce the maximum stress of the construction. The stress that occurs is obtained from numerical analysis using the finite element approach [36]. After getting the maximum stress, the next step is to determine the fatigue life of the sideboard construction. The calculation of fatigue life uses the simplified fatigue analysis equation "Fatigue Assessment of Ship Structures" [27]. Then from the maximum stress, we can choose the type of S-N curve to determine the number of cycles. The selection of the S-N curve type is based on the position of the maximum stress, the shape of the weld joint, the type of construction profile section, and the size of the profile section. The basic parameter of loading fatigue is the stress range, in which cracking depends on the number of cycles (S-N diagram) [37]. The S-N curve is shown in **Figure 9**.

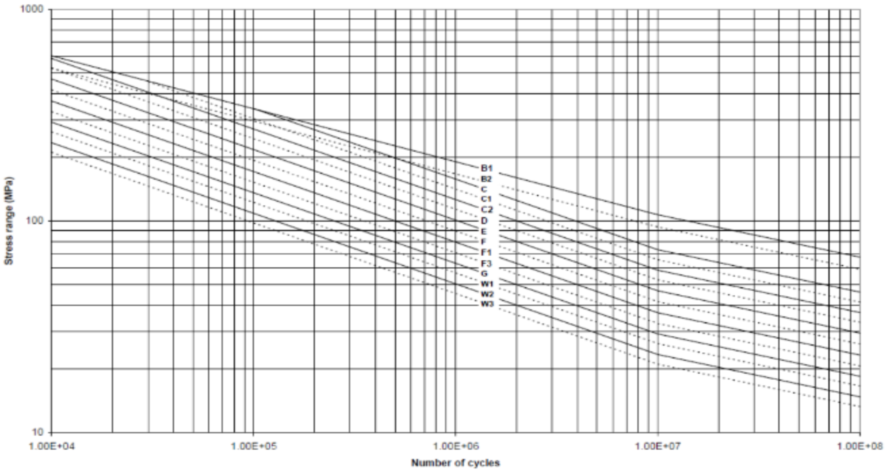


Figure 9. S-N curve [27].

Fatigue life is determined by first calculating the value of fatigue damage using Eq. (3)

$$D = \frac{v_0 T_d}{\bar{a}} q^m r \left(1 + \frac{m}{n}\right) \leq \eta \tag{3}$$

$$v_0 = \frac{1}{4.\log_{10}(L)} \tag{4}$$

$$q = \frac{\Delta\sigma_0}{(In\, n_0)^{1/h}} \tag{5}$$

$$h_0 = 2.21 - 0.54 log_{10}(L) \tag{6}$$

$$h = h_0 + \frac{h_a \times z}{T_{act}} - 0.005(T_{act} - z) \tag{7}$$

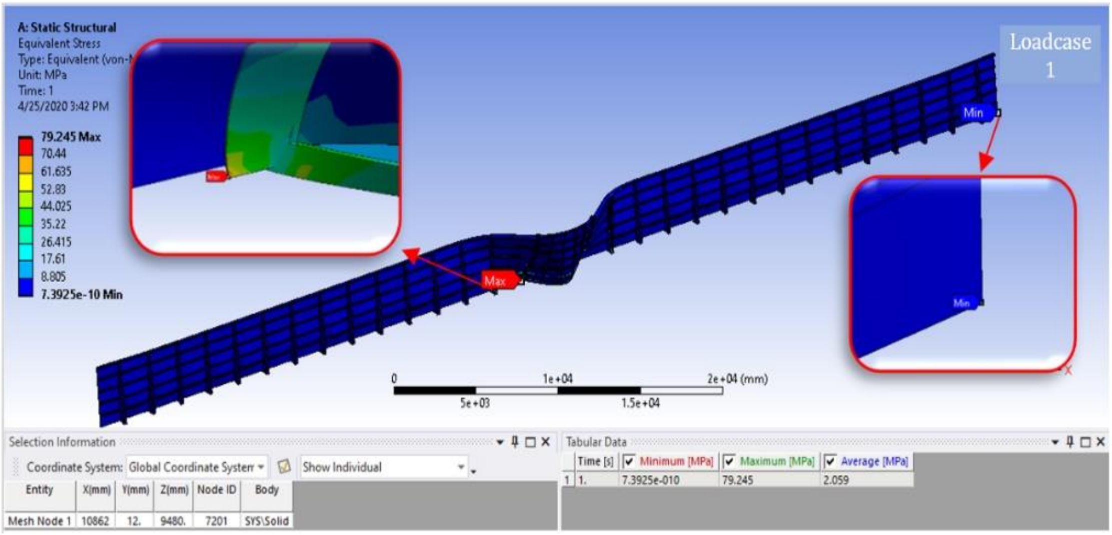
$$Fatigue\ Life = \frac{Design\ Life}{D} \times years \tag{8}$$

where D = Accumulated Fatigue Damage ; $\bar{\boldsymbol{a}}$ = intercept of the design S-N curve with the log N axis; m = negative inverse slope of the S-N curve; $\boldsymbol{v_0}$ = Average zero up-crossing frequency; $\boldsymbol{n_i}$= number of stress cycle over time period; q = Weibull stress range scale distribution parameter; T_d = Design life of ship in seconds (20 yrs = 6.3 x 10^8 sec); $\Gamma\left(\boldsymbol{1}+\frac{\boldsymbol{m}}{\boldsymbol{h}}\right)$ = Gamma function; and Design life = 20 years referred to Det Norske Veritas (DNV) rules.

RESULTS AND DISCUSSION

Research Results

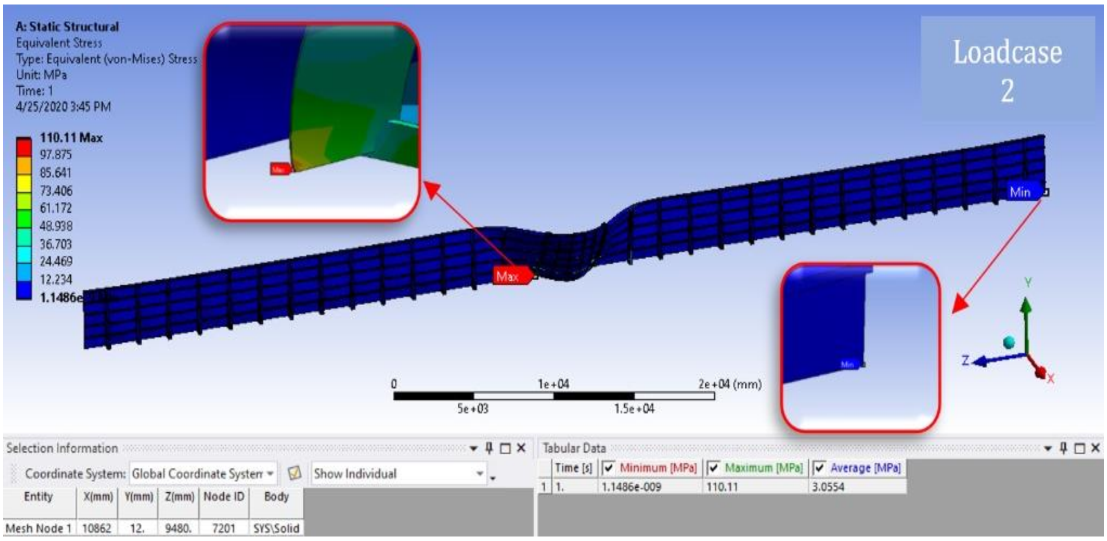
Sideboard 3D models show predicted stress distributions, and hence the maximum stress positions may be identified. Then the numerical simulation results of FE for each load case are displayed as shown in **Figures 10**, **11**, and **12**.



Entity	X(mm)	Y(mm)	Z(mm)	Node ID	Body
Mesh Node 1	10862	12.	9480.	7201	SYS\Solid

	Time [s]	☑ Minimum [MPa]	☑ Maximum [MPa]	☑ Average [MPa]
1	1.	7.3925e-010	79.245	2.059

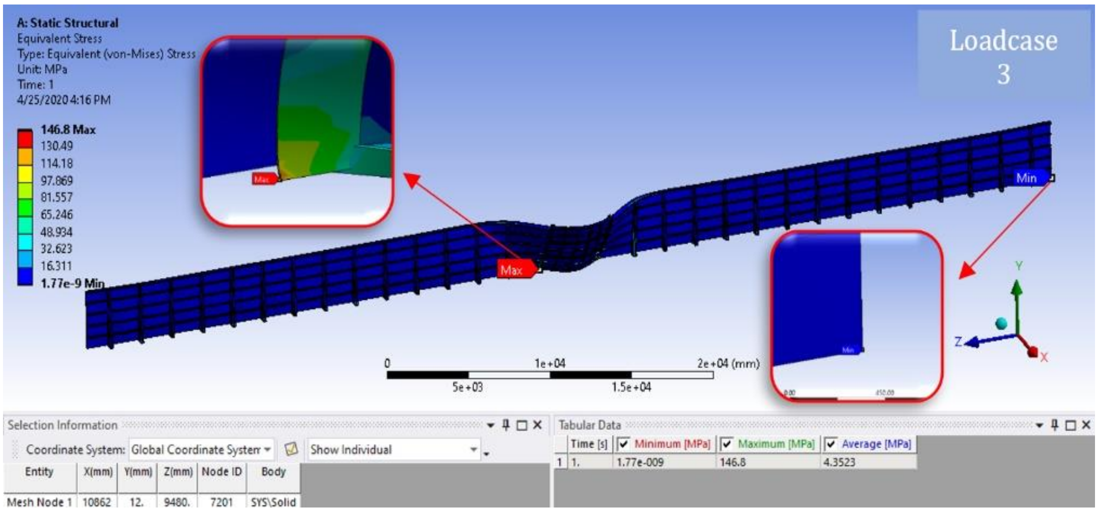
Figure 10. Von misses stress of load case 1.



Entity	X(mm)	Y(mm)	Z(mm)	Node ID	Body
Mesh Node 1	10862	12.	9480.	7201	SYS\Solid

	Time [s]	☑ Minimum [MPa]	☑ Maximum [MPa]	☑ Average [MPa]
1	1.	1.1486e-009	110.11	3.0554

Figure 11. Von misses stress of load case 2.



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
4/25/2020 4:16 PM

Coordinate System: Global Coordinate System

Entity	X(mm)	Y(mm)	Z(mm)	Node ID	Body
Mesh Node 1	10862	12.	9480.	7201	SYS\Solid

	Time [s]	☑ Minimum [MPa]	☑ Maximum [MPa]	☑ Average [MPa]
1	1.	1.77e-009	146.8	4.3523

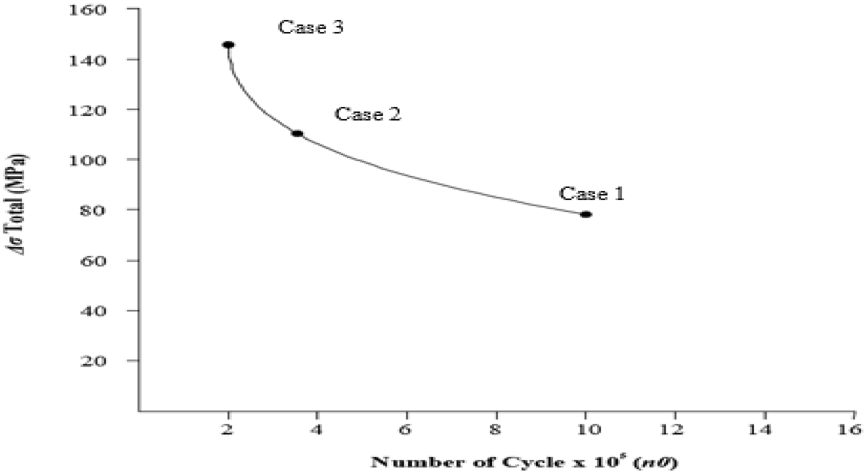
Figure 12. Von misses stress of load case 3.

Figure 10 shows the maximum stress in the X direction at the height of the coal load of 2.24 m against the sideboard of 79.25 MPa. The stresses in the Y and Z directions were insignificant so that they did not have any effect on the sideboard structure. The stress lies in the construction of the stanchions, which are located at the bottom center of the sideboard. The minimum stress detected at the end of the sideboard is 73.925×10^{-11} MPa. **Figure 11** shows the maximum stress in the X direction at the height of the coal load of 2.60 m against the sideboard of 110.11 MPa. The stresses in the Y and Z directions are detected as so small that they do not have any effect on the sideboard structure. The stress lies in the construction of the stanchions, which are located at the bottom center of the sideboard. The minimum stress detected at the end of the sideboard is 11.486×10^{-9} MPa. Whereas **Figure 12** shows the maximum stress in the X direction at the height of the coal load of 2.96 m against the sideboard of 146.8 MPa. The stresses in the Y and Z directions were detected as so small that they did not have any effect on the sideboard structure. The stress lies in the construction of the stanchions, which are located at the bottom center of the sideboard. The minimum stress detected at the end of the sideboard is 17.7×10^{-10} MPa.

Discussions

From all three of the load cases to the sideboard, the S-N Curve shape obtained is as shown in **Figure 13**. The calculation of fatigue life is determined by Eq. (8). Accumulated Fatigue Damage is calculated first using **Equations**. **(3), (4), (5), (6),** and **(7)**. The calculation results are shown in **Table 2**.

Table 2 shows the fatigue damage to the load case on the height of the coal load against the 2.96 m sideboard, which is above 1 (one), which in this condition will cause the structure to fail. Therefore, it is not recommended to apply the load case when the deck barge is operating.



.**Figure 13.** S-N curve of sideboard.

Table 2. The Fatigue Life of Sideboard Construction.

Load Height (m)	Number of Cycle	Fatigue Damage	Fatigue Life (years)
2.24	1,000,000	0.25	81.16
2.60	353,000	0.81	24.72
2.96	200,000	2.16	9.28

CONCLUSION

From the research conducted, it can be concluded that coal at a load height of 2.24 m against the sideboard has a maximum stress of 79.25 MPa and a fatigue life of 81.16 years. Coal at a load height of 2.60 m against the sideboard has a maximum stress of 110.11 MPa and a fatigue life of 24.68 years. Coal at a load height of 2.96 m against the sideboard has a maximum stress of 146.80 MPa and a fatigue life of 9.28 years. There is an increasing value of stress with the increase of height of the load against the sideboard wall, and there is a decreasing value of the fatigue life with the increase of stress values in the construction. The safe limit of the coal load height on the barge can be referred to in case 2. The load height results in a sideboard age prediction of around 25 years. This is in line with the design life of the barge, which is 25 years. This sideboard age prediction result can be used for sizes under 300 feet.

AUTHOR INFORMATION

Corresponding Authors
Email: alamsyah@lecturer.itk.ac.id
Phone:+62 85242800578
Email: 09161015@student.itk.ac.id

Author Contributions

Main contributor of this research is Alamsyah, the other authors is, Nugroho, Amalia Ika Wulandari, M U Pawara, and Muhammad Riyadi are supporting contributors.

ACKNOWLEDGMENTS

The authors would like to thank the Naval Architecture program of Kalimantan Institute of Technology for facilitating this research. Also, thank to the anonymous reviewer who has provided constructive input and suggestions so that this paper is worthy of publication.

REFERENCES

[1] D. A. Puspitasari, Desain Floating Power Plant Dengan Tenaga Panel Surya Untuk Masyarakat Maluku Utara. Theses, Departemen Teknik Perkapalan Fakultas Teknologi Kelautan Institut Teknologi Sepuluh Nopember Surabaya, 2018.

[2] S. M. Chougle, S., & Walke, "Generations of Crude Oil.," *Am. Int. J. Res. Sci. Technol. Eng. Math.*, vol. 4, no. 10, pp. 309–313, 2015.

[3] N. B. Prayoga & W. D. Aryawan, "Desain Self-Propelled Oil Barge (SPOB) Untuk Distribusi Crude Oil di Kabupaten Sorong, Papua Barat," *J. Tek. ITS*, vol. 5, no. 1, pp. G19–G24, 2016.

[4] B. A. Adietya & B. Arifin, "ANALISA KEKUATAN DECK PADA PONTON BATUBARA PRAWIRAMAS PURI PRIMA II 1036 DWT DENGAN SOFTWARE BERBASIS METODE ELEMEN HINGGA," *KAPAL J. Ilmu Pengetah. Teknol. Kelaut.*, vol. 8, no. 1, pp. 1–5, 2011.

[5] I.P.Mulyatno, B.A. Adietya and R.A.Maulana, "Strength Analysis of Peti kemas Geladak Construction MV. Sinar Demak Efect of Charges Peti kemas Using Finite Element Method," *Kapal J. Ilmu Pengetah. dan Teknol. Kelaut.*, vol. 9, no. 1, pp. 24–29, 2013.

[6] L. Adnyani, N. Aisyah, S. Sulistijiono R. G. Harahap, A. Dianiswara and Nurmawati, "Analisa Kekuatan Deck BARGE NANIA 10070 DWT Dengan Dua Metode Pembebanan," *KAPAL J. Ilmu Pengetah. dan Teknol. Kelaut.*, vol. 16, no. 2, pp. 49–55, 2019.

[7] N. S. Riyanto, H. Yudo, and A. Trimulyono, "Analisa Kekuatan Deck Akibat Perubahan Muatan Pada Tongkang TK. NELLY – 34," *J. Tek. Perkapalan*, vol. 8, no. 3, pp. 454–460, 2020.

[8] M. H. Pratama, H. Yudo, and I.P. Mulyanto, "Analisis Kekuatan Konstruksi Car Deck Kapal Penyeberangan 1000 GT Akibat Perubahan Muatan Dengan Metode Elemen Hingga," *J. Tek. Perkapalan*, vol. 8, no. 3, pp. 426–434, 2020.

[9] F. F. Rosid, I.P. Mulyatno, dan E.S. Hadi"Analisa Kekuatan Konstruksi Kapal Landing Craft Tank Teluk Katurei Akibat Perubahan Framing System Dengan Metode Elemen Hingga," *J. Tek. Perkapalan*, vol. 5, no. 3, pp. 502–508, 2017.

[10] R. Munandar, A. Ardianti, G. Sitepu, A.M. Nugraha, Hamzah and M.I. Hayatuddin, "Study on Transverse Strength of the Deck-Container Ships Due to Laying All Containers on Deck," *EPI Int. J. Eng.*, vol. 2, no. 2, pp. 178–184, 2019, doi: 10.25042/epi-ije.082019.14.

[11] A.M. Nugraha, Hamzah, G. Sitepu, A. Ardianti, Ifhanuddin and S. Baso, "Strength Behavior Analysis of Insert Plate for Placing Corner Fitting due to Container Load," 2019, doi: 10.1088/1757-899X/875/1/012074.

[12] M. Muharnif and R. Septiawan, "Analisa Pengujian Lelah Material Stainless Steel 304 Dengan Menggunakan Rotary Bending Fatigue Machine," *J. Rekayasa Mater. Manufaktur dan Energi*, vol. 1, no. 1, pp. 64–73, 2018.

[13] Y. M. Zhang, X. D. He, Q. L. Liu and B. C. Wen, "Reliability-Based Optimization and Robust Design of a Coil Tube-Spring with Non-Normal Distribution Parameters," *J. Mech. Eng. Sci.*, vol. 219, no. 6, pp. 567–575, 2005.

[14] Rahmatullah & R. Ahmad, "Analisa Pengujian Lelah Material Bronze Dengan Menggunakan Rotary Bending Fatigue Machine," *J. Rekayasa Mater. Manufaktur dan Energi*, vol. 1, no. 1, pp. 1–11, 2018.

[15] S. T. Rolfe and J. M. Barsom., *Fracture and Fatigue Control in Structures — Applications of Fracture Mechanics*. Englewood Cliffs, N.J.: Prentice-Hall, Inc, 1977.

[16] Alamsyah, W.Setiawan, N. S. Oktavaro, R. J. Ikhwani, A.I. Wulandari and M.E.H.A. Purba., "An Analyze of Fatigue Life Construction of Lifting Poonton for Small Vessel," in *3rd Bicame*, 2020, pp. 95–101, [Online]. Available: https://www.scientific.net/AST.104.95.pdf.

[17] A. Pangestu, M. N. Misbah and D. Setyawan, "Analisis Fatigue Life Konstruksi Kapal Tanker 17500 DWT Menggunakan Metode Simplified Fatigue Analysis," *J. Tek. ITS*, vol. 8, no. 1, pp. G52–G57, 2019.

[18] Alamsyah, A.I. Wulandari and I. Fadillah "The Strength Analysis of and Fatigue Life of Spob Propeller Shaft,, "The Strength Analysis of and Fatigue Life of Spob Propeller Shaft," *Wave J. Ilm. Teknol. Marit.*, vol. 13, no. 2, pp. 91–98, 2019, doi: 10.29122/jurnalwave.v13i2.4162.

[19] Alamsyah, A.I. Wulandari, R.J. Ikhwani and J.A. Saka., "The Fatigue Life Analysis of TB Ship. 27 M the Shaft Using the Finite Element Method," *Inovtek Polbeng*, vol. 10, no. 2, pp. 144–151, 2020, doi: 10.35314/ip.v10i2.1653.

[20] M. N. Misbah, D. Setyawan and A. Soleh, "Perkiraan Umur Lelah Struktur Kapal Berbasis Keandalan dengan Metode Mean Value First Order Second Moment," *KAPAL J. Ilmu Pengetah. dan Teknol. Kelaut.*, vol. 16, no. 2, pp. 74–80, 2019.

[21] Z. Liu, Y. Zhang and W. Wang "Fatigue Life Reliability Based Design Optimization for The Missile Suspension Structure," *Multidiscip. Model. Mater. Struct.*, vol. 8, no. 1, pp. 120–129, 2012.

[22] I. A. of C. S. (IACS), *Common structural rules for double hull oil tanker*. 2014.

[23] A. Akuan, *Kelelahan logam*. 2007.

[24] O. F. Hughes & J. K. Paik., *Ship structural analysis and design*. New Jersey: Society of Naval Architects and Marine Engineers (SNAME)., 2010.

[25] K. Hectors and W. D. Waele, "Cumulative Damage and Life Prediction Models for High-Cycle Fatigue of Metals: A Review," *Metals.*, vol. 11, pp. 1 – 32, 2021.

[26] M. Jimenez Martinez, "Fatigue of offshore structures: A review of statistical fatigue damage assessment for stochastic loadings," *Int. J. Fatigue*, 2020.

[27] DNVGL, *Fatigue design of offshore steel structures*. AS: DNVGL, 2014.

[28] S. Moaveni, Finite Elemen Analisis : Theory And Application With ANSYS., *United States of America: Pearson Prentice Hall, 2008*.

[29] M. Zhang, J. Liu, Z. Hu, and Y. Zhao, "Experimental and numerical investigation of the responses of scaled tanker side double-hull structures laterally punched by conical and knife edge indenters," *Mar. Struct.*, vol. 61, pp. 62–84, 2018.

[30] Yovanda, "Batu Bara dan Buldoser Jatuh ke Laut di Kaltim Saat Diangkut Kapal Tongkang," *detikNews*, Kutai Kartanegara, Dec. 2019.

[31] B. K. Indonesia, *Rules For Hull : Rules Classif. Constr., vol. II*. 2018.

[32] V. Murthy, *Principles and Practices of Soil Mechanics and Foundation Engineering*. New York: Marcel Dekker, 2002.

[33] Anom, "Berat volume batubara." https://www.aqua-calc.com/page/density-table.

[34] P. Kulinowski and P. Kasza, *Properties Bulk Solids*. Department of Mining, Dressing and Transport Machines AGH, 2014.

[35] A. Swain, H. Patra and G.K. Roy, *Mechanical Operations*. McGraw Hill Education, 2010.

[36] M. H. Nubly and H. Yudo, "Strength Analysis of Propeller Shafting on Orca Class Fisheries Inspection Boat using Finite Element Method," *Int. J. Civ. Eng. Technol.*, vol. 8, no. 10, pp. 1599-1610., 2017.

[37] P. Caridis, *Inspection, repair and maintenance of ship structures*, 2th ed. London: Witherby, 2009.