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Analysis of Fatigue Life of Tugboat Towing Hook Construction Using Finite Element Method

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Abstract

The towing hook on the tugboat has a function to pull the barge. Because of this ability, a good towing hook construction is needed to work optimally. Indications for the good construction is the value of fatigue life, which is more than the value of design life of 20 years. A towing hook detail on tugboat from PT. Asia Aditama Shipyard – Balikpapan was selected as an example. This study aims to obtain the value of fatigue life based on the total resistance calculated by BHP data in full, 75%, and 50% of the total displacement volume and estimate the maximum size of a barge, based on maximal towing pull capacity. The benefits of this research are providing information about the fatigue life of a towing hook, analyzing several possible load cases, and giving the recommendation of the maximum principal dimensions of the barge that the towing hook can be pulled. The method used in this study is the finite element method using ANSYS, the fatigue life calculation approach is the Palmgren–Miner cumulative damage method and refers to the DNVGL rule. The results of the calculation of fatigue life in the maximum towing pull condition are 22 years, 22 years, and 23 years at 100%, 75%, and 50%, respectively. The main size of barges that can be towed by Tugboats under maximum towing pull conditions are LOA = 147m, LWL = 144,529m, B = 35m, H = 13m, T = 11m.

1. Introduction

Many industries require the calculation of structural fatigue life. These industries are not only in the shipbuilding industry [1],[2],[3], but also aircraft [4], the automotive industry [5], or manufacture [6]. Therefore, it is important to study and calculate the fatigue life of a structure. These studies are especially the failure related to structural fatigue that can trigger an accident.

Some accidents that occur are caused by fatigue. One of them is the failure of the towing system, which caused an accident on the truck vehicles on the road [7]. Based on visual inspection and accident modelling, the researchers found the accident's cause, which is the failure of the eyebolt connected to the hook on the A-frame trailer, after one year of use. Bolts undergo a rapid degradation process due to wear and cyclic loads, thereby increasing excess gaps. A failure like this can also happen to ships [8].

Moan [8] explained that the first rule for offshore structures that included fatigue requirements was published around 1970. This rule was refined after the failure of Ranger I and Alexander L. Kielland's semi-submersible jack-ups in 1979 and 1980. This accident made the fatigue analysis and calculation of fatigue life on ships essential.

Fatigue is an important criterion for evaluating ship structure. There are two methods for calculating fatigue life, namely deterministic and spectral methods. With a spectral approach, calculation of the vertical and horizontal bending moments induced by waves under two loading conditions, and the non-operating time is taken into account [9]. In this research, the fatigue life calculation approach using Palmgren–Miner cumulative damage was carried out. One other method used to predict fatigue life is to consider crack growth, especially in weld joints [10].

Calculation of fatigue life is usually done at weld joints. In the welded joint, there are effects of material properties, loading, geometric shapes, residual stress, and the consequences of failure in welding [11]. This failure has led to much research focused on improving welding techniques in ship structures while increasing cost efficiency in ship maintenance [12], [13].

In the East Kalimantan area, many tugboats are operated. The tugboat is a ship whose function is to pull, push, or hold other ships such as coal barges. Tugboats around the Mahakam and Barito rivers are used to towing barges loaded with coal, wood, and others. In towing conditions, the towing hook functions as a hook to pull the barge.

The pulling load generated on the tugboat causes excessive pressure around the towing hook. Pressure on the towing hook area causes the towing hook construction to experience stress distribution. Tugboat's pulling force can cause fatigue in the construction that receives the force's distribution, namely towing hook construction.

Rizky et al. [14] analyzed fatigue life using MSC Nastran Patran and MSC Fatigue software. Both software calculated the stress and damage of the main deck construction and towing hook support. A Fatigue life calculation uses the Palmgren – Miner cumulative damage method and using BKI and DNV rules. The analysis obtained a construction fatigue life of 19 years.

Damanik et al. [15] investigated local stress analysis using a numerical finite element method (FEM). The analysis used a static load analysis derived from the towing pull force to determine the stress characteristics and the maximum stress based on a four-load case, namely lightweight barge, lightweight barge, deadweight barge, and sagging (full load), and hogging (full load). The result is stress maximum occurs in full load sagging conditions.

Besides MSC Nastran Patran and MSC Fatigue software, another software can be used to obtain the structure's stress, namely ANSYS. This paper provides information about the use of ANSYS for the finite element method to simulate the towing hook. Based on the towing hook pull capacity data, the maximum principal dimensions of the barge are also recommended.

This study aims to calculate the fatigue life of the tugboat towing hook in which its data was obtained from the shipyard. Towing hook construction is needed and was modelled in finite element software. The result is the fatigue life of tugboat towing hook construction, whether the construction is satisfied or unsatisfied compared to design life. As the design life of the towing hook, we assumed that the value is 20 years. The benefits of this research are providing information about the fatigue life of a towing hook, analyzing several possible load cases, and giving the recommendation of the maximum principal dimensions of the barge that the towing hook can pull.

2. Methods

This study's method includes calculating the total resistance, modelling towing hook construction using the finite element method, meshing, analyzing using software based on the finite element, calculating the fatigue life, and determining the main size of the barge. In the present work, a case study will be performed on the fatigue life prediction of a towing hook structural detail in order to identify the fatigue life using the deterministic method. Visualization of a Tugboat Pulling a Barge is presented in Figure 1. Fatigue analysis is used to review hotspot stress in the area that highly experienced cracking.

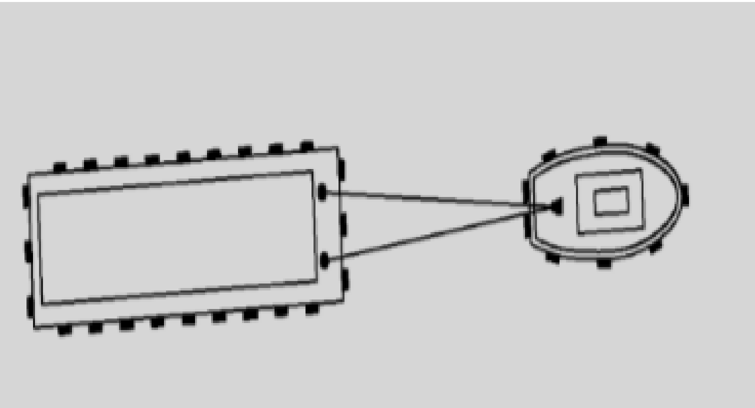

Figure 1. Visualization of a Tugboat Pulling a Barge [15]

2.1. Principal Dimension of Tugboat and Barge

Data collection of the tugboat was obtained from PT. Asia Aditama Shipyard – Balikpapan such as principal dimension (Table 1), general arrangement, construction profile, and towing hook detail.

Table 1. Tugboat Principal Dimension

Dimension	Value
Length Overall	27.00 m
Breadth Moulded	8.00 m
Depth Moulded	3.80 m
Design Draft	3.00 m
Complement	10.00 m
Gear Box Rotation	5.04 : 1
Genset	40 kW
Port Of Registry	Balikpapan
Flag	Indonesia
Class	RINA

2.2. Towing Hook

The modelled part of the towing hook is the construction part, which is welded with a tugboat bulkhead (Figure 2). This part experienced the tensile force based on the pull capacity data, but the towing hook was not modelled in detail. The red circle is the towing hook construction modelled in this paper, while the hook itself (construction with blue colour in Figure 3) was neglected and altered by the tensile force in two sections with a red arrow. Based on this picture taken from PT. Asia Aditama Shipyard, the construction is modelled in Autocad to measure the dimension (Figure 4).

Figure 2. Towing Hook Construction

Figure 3. Model of Towing Hook Construction In Red Circle

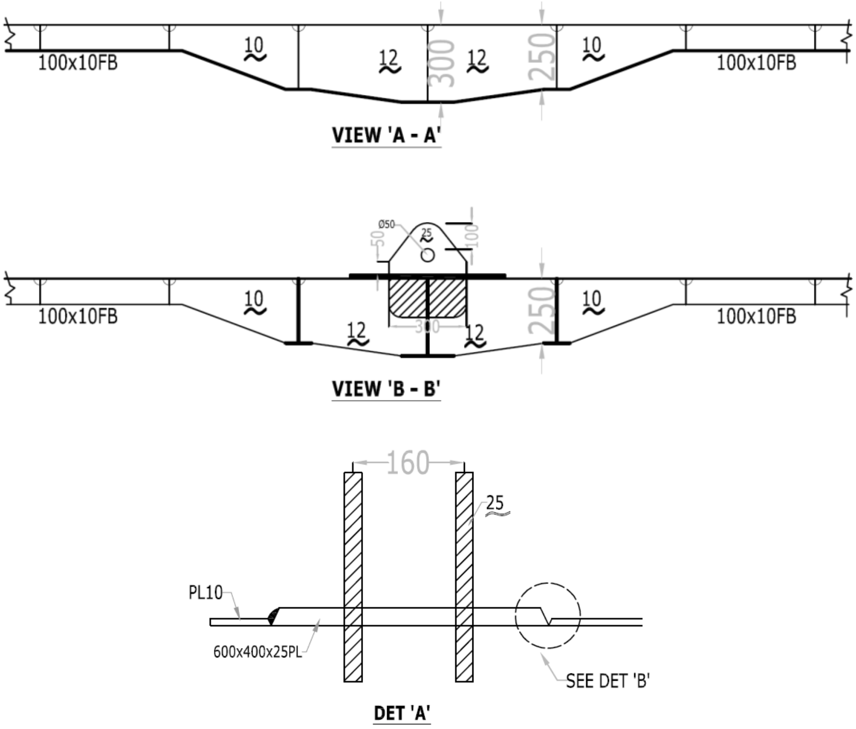

Figure 4. Detail of Towing Hook Construction

2.3. Load

Loads received by the tugboat are static loads that are assumed to originate from the loading of barges. Input loading properties entered in the finite element-based program because the analysis used is static structural. The types of loads on the ship include a) Static loads change when the total weight of the ship changes, as a result of loading and unloading activities, fuel use, or changes in the ship itself. Static loading is a type of fixed loading; in this case, this load is assumed unchanged. b) Dynamic loads change with time in a specific frequency that causes a vibration response to the ship's structure. c) Impact loads occur due to slamming or pounding waves on the keel, bow, or other parts of the ship, including the green water [15].

In this paper, the load input into the ANSYS is the total resistance in different loads of case condition, such as 100%, 75%, and 50% displacement. This fatigue life value may be used to evaluate a state of towing hook construction that is still suitable for use or in damaged conditions.

2.3.1. Towing Speed Vs Brake Horse Power

Towing speed Vs. Brake horsepower aims to discover how fast the barge's speed when pulled by a tugboat with a specific BHP owned by a Tugboat as shown in Eq. 1 and Figure 5.

$$Kts = 1.43 \times BHP^{0.21} \tag{1}$$

where Kts is Speed in Knots, BHP is the maximum value of brake horsepower from the engine. While the amount of 1.43 is the assessment value that was obtained by Dave Geer. This assessment based on the approach that is taken. The value of 0.21 is a rank of the maximum value of the brake horsepower maximum of the engine [16].

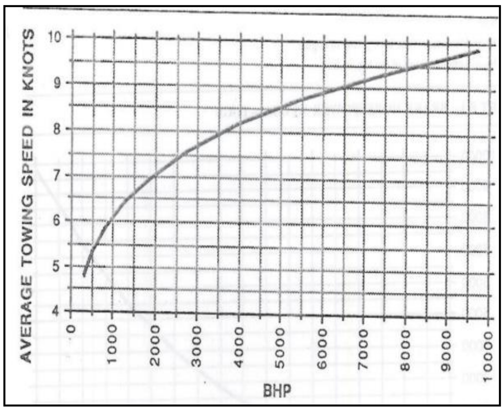

Figure 5. Towing Speed Vs Brake Horsepower Graph [16]

2.3.2. Ship Resistance

Ship resistance at a certain speed is the fluid's force acting on the ship in such a way as to counteract its movements. The resistance will be the same as the fluid force component which works parallel to the ship's axis of motion. The term "Resistance" often used in ship hydrodynamics, while "Drag" is commonly used in aerodynamics and for loads immersed in water [17] as shown in Eq. 2.

$$VR_T = R_F(1 + k_1) + R_{App} + R_w + R_B + R_{TR} + R_A \quad (2)$$

where R_F is calculated using the ITTC formula 1957; $(1+k_1)$ is a form factor; R_{APP} is complementary or additional resistance; R_W is the wave resistance; and R_B is an additional resistance due to the existence of a bulbous bow and ship models that include effects such as roughness and air resistance [18].

2.4. Finite Element Method

A numerical method that is very suitable for digital computers is the finite element method. This method is an elastic continuum in which a structure is discretized into several elements. Then, the element is used in the matrix, while the deflection of each node will be associated with loading such as material properties, geometric properties, and others. The finite element method has been widely used to solve various mechanical problems with complex geometry. This method is mostly used because computationally it is very efficient, providing a variety of accurate solutions to complex problems [19].

2.4.1. Model Geometry

A 3D model of a towing hook construction was performed by using the Pro-Engineering software, widely used in design and mechanical engineering (Figure 6). In the 3D modelling, only the towing hook construction that was welded with tugboat bulkhead was taken into account. The hook was not modelled but was applied by pulling force directly in the Ansys Workbench. The finite element analysis was performed by using the Ansys Workbench software. The 2D finite elements that model profiles and plate as they are given in the model were assigned material properties, including the thickness of each component.

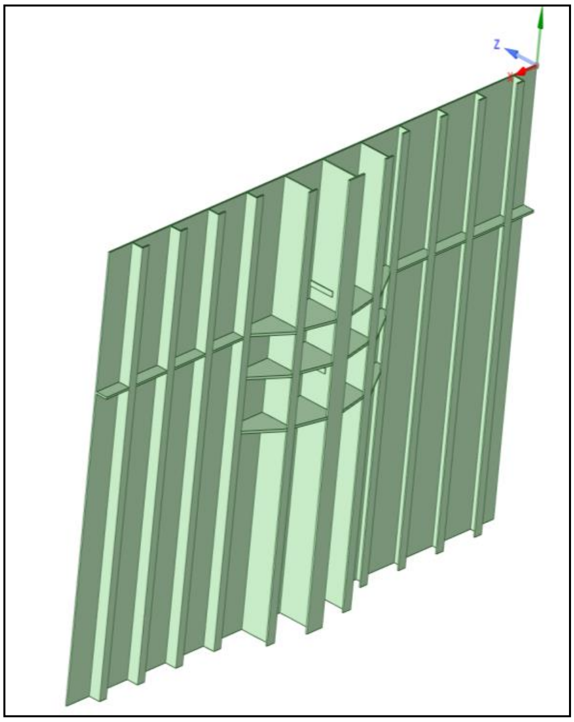

Figure 6. 3D Model of Towing Hook Construction in ANSYS Workbench

2.4.2. Boundary Condition

Regarding the boundary condition for the analysis, the fixed support is applied in the welding section. The towing hook construction consists of a plate, T profile, and C profile. The links with the blade, i.e., with the grader frame, were made using rigid elements fixed in all degrees of freedom. Besides, the force was applied in normal direction to the working surface of the towing hook construction (Figure 7).

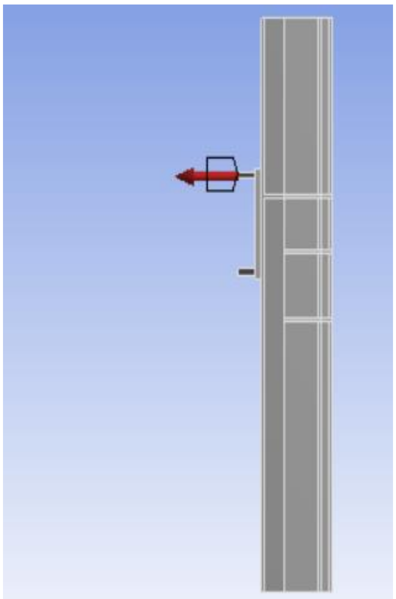

Figure 7. Force Applied in Towing Hook Construction

2.4.3. Meshing

Meshing aims to set the distance between elements that must be performed to use finite element-based software through the pre-processing stage before carrying out the analysis. After determining the Meshing Size and the number of elements and nodes in this modelling, the meshing process is done to get the results of Figure 8. The type element in this research was tetrahedral. A meshing sensitivity analysis was conducted to illustrate uncertainties in the simulation results arising from the mesh size and stress.

Based on meshing sensitivity analysis, we can determine the element size that can obtain consistent stress. Regarding computer limitation, in this meshing, the authors uses 9.0 mm Element Size and 4.8 million elements as shown in Figure 9. If the meshing process runs smoothly without error, it can proceed to the next step, the solving step in finite element-based software.

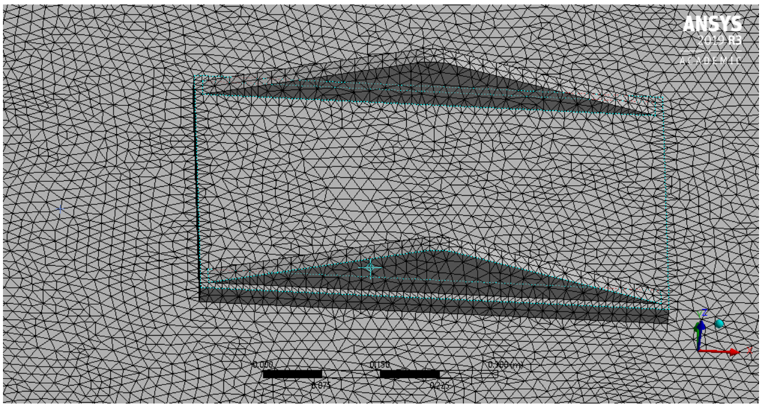

Figure 8. Meshing Modelling

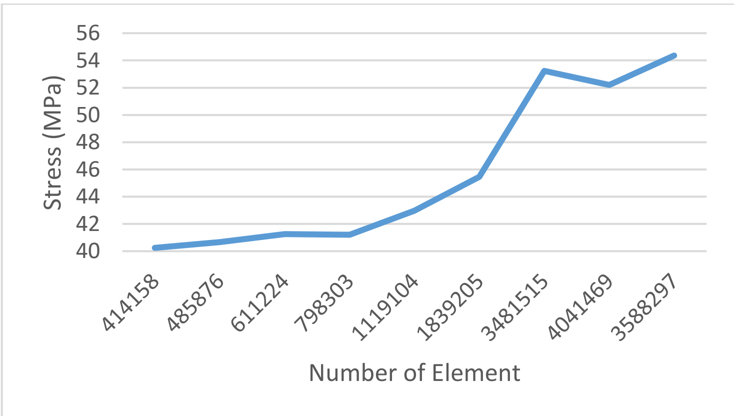

Figure 9. Stress Compare to the Element Size

2.5. Fatigue Life Calculation

The fatigue calculation of the existing structure on this tugboat is based on the application of the Palmgren–Miner cumulative damage rule. This rule used the fatigue damage ratio. D has a value more than once; it can be ascertained that the structure is not accepted (appendix of JTP Common Structural Rules, 2006). DM values are obtained through Eq. 3.

$$D = \frac{v_0 \times T_d}{\bar{a}} \times q^m \times \neg\left(1 + \frac{m}{h}\right) \le n \tag{3}$$

Where D is Accumulated Fatigue Damage; V_0 is Average zero up-crossing frequency; T_d is Design life in seconds; $\bar{a}$ is the intercept of the design S-N curve with the log N axis; q is Weibull stress range scale distribution parameter; h is Weibull stress range shape distribution parameter and $\neg\left(1+\frac{m}{h}\right)$ is Gamma function [20].

The stress-cycle concept (S-N) is the first approach taken to understand the phenomenon of fatigue (Figure 10). This S-N curve is widely used in material design applications where stresses occur in elastic regions, and fatigue life is long enough. This S-N curve method cannot be used in reverse conditions (stress in plastic regions and relatively short fatigue life) [21].

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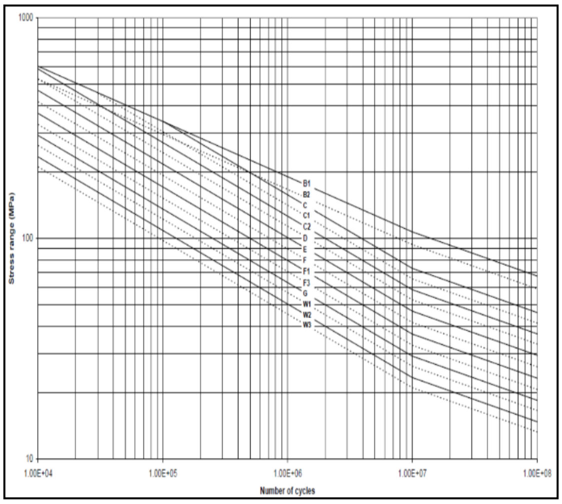

Figure 10. S-N Curve In Air [22]

Where D is Accumulated Fatigue Damage; V_0 is Average zero up-crossing frequency; T_d is Design life in seconds; $\bar{a}$ is the intercept of the design S-N curve with the log N axis; q is Weibull stress range scale distribution parameter; h is Weibull stress range shape distribution parameter and $\neg\left(1+\frac{m}{h}\right)$ is Gamma function [20]. Formula (4) calculates the fatigue damage where the value is used to find the value of fatigue life. The formulas were obtained from Det Norske Veritas (Norway) and Germanischer Lloyd (Germany) or abbreviated with DNV-GL [22]. Fatigue life is calculated using Eq. 4, where design life is 20 years as DNV regulation and D is Accumulated fatigue damage.

$$Fatigue\ life = \frac{Design\ life}{D}\ x\ years \tag{4}$$

3. Results and Discussion

3.1. Total Resistance

The total resistance on a barge certainly has a varying value due to variations in loading, which have been calculated in the previous sub-chapter. The results of total resistance's calculations are based on variations in loading that are at 100% of the total displacement volume, 75% and 50% of the total displacement volume, as shown in Table 2.

Table 2. Results from the Calculation of Total Resistance

Load Combination	Speed (Knot)	Draft (m)	Resistance total (kN)	Equivalent Stress (MPa)	Number Of Cycles	Fatigue Damage	Fatigue Life
100 %	7.1	11.000	173.0	96.628	2,017,412.206	0.909	22
75%	7.1	10.443	172.3	96.237	2,114,306.19	0.892	22
50 %	7.1	9.886	171.6	95.846	2,224,076.42	0.875	23

3.2. Stress Analysis Using Finite Element Software

Calculating the stress value in finite element software requires data in the form of a total resistance value and also the availability of a model or construction. The model has been designed in Finite element software owned by each loading variation. The value of barges resistance has been calculated in the previous sub-chapter. From the data that has been calculated, the following stress values are obtained as shown in Table 2.

3.2.1. Stress Distribution

Static stress analysis is done for the towing hook construction with pulling force acting on it. The analysis shows that the maximum equivalent stress developed in the towing hook construction is lesser than the component material allowable (250 MPa).

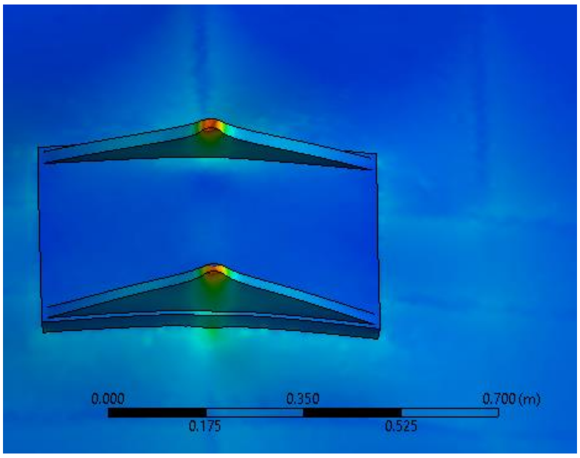

Figure 11. Example of Maximum Principal Stress Results

Figure 11 shows the maximum equivalent stress in the towing hook construction, where the force is applied as figured in red arrow Figure 3. The equivalent structural stresses are correlated to experimental fatigue data to predict the fatigue life of the spot-welded joints. This equivalent structural stress was developed based on popular equivalent stress that is the von Mises equation stress with the equation as below [23].

$$\sigma_q^i = \frac{1}{\sqrt{2}}\left[\left(\sigma_x^i - \sigma_y^i\right)^2 + \left(\sigma_y^i - \sigma_z^i\right)^2 + \left(\sigma_z^i - \sigma_x^i\right)^2 + 6\left(\left(\tau_{xy}^i\right)^2 + \left(\tau_{yz}^i\right)^2 + \left(\tau_{zx}^i\right)^2\right)\right]^{\frac{1}{2}} \tag{5}$$

3.3. Fatigue Life Calculation

In the calculation of fatigue life, the formula used has been explained in the previous chapter. Calculation of fatigue life can be calculated after getting the stress and accumulated fatigue damage value, which can be determined using the Eq. 4. The value of the stress can be determined in the finite element method software, as shown in Table 2.

In Table 2, we get the value of fatigue damage with a variety of loading 100% of the total displacement volume or maximum Towing Pull (with 7.1 knots speed, 11 meters draft, 173.0 kN total resistance, 96,628 Mpa stress, 2,017,412,206 some cycles) is 0.909. The value of fatigue damage with a variety of loading 75% of the total displacement volume (with 7.1 knots speed, 10.443 meters draft, 172.3 kN total resistance, 96,237 Mpa stress, and 2,114,306.19 number of cycles) is 0.892. The value of fatigue damage with a 50% loading variation of the total displacement volume (with 7.1 knots speed, 9.886 meters draft, 171.6 kN total resistance, 95,846 MPa stress and 2,224,076.42 number of cycles) is 0.875.

After getting the D or Accumulated fatigue damage, we can determine the fatigue life of the towing hook construction, as shown in Table 2.

3.4. Calculation of Maximum Principal Dimension of Barge

Based on the towing hook's catalogue, the maximum towing pull capacity is 173 KN. This value was used to model and optimize the barge size in Maxsurf Resistance that obtained the total resistance equivalent with 173 KN. The result is validated with the ship registration data and the optimal barge size that can be pulled by a tugboat, as shown in Table 3.

Table 3. Barge Principal Dimension

Dimension	Value
Length Overall	147.00 m
LWL	144.259 m
B	35.00 m
H	13.00 m
T	11.00 m
Displacement	16,845.112 ton

4. Conclusion

Based on the analysis results, the following conclusions are obtained: the value of fatigue life in the towing hook construction of the tugboat Asia Tirta 2005 under conditions of 100%, 75%, and 50% displacement volume is 22 (Twenty-two) years, 22 (Twenty-Two) Years and 23 (Twenty-Three) Years, respectively. The maximum size of a barge that can be towed by the tugboat at the maximum towing pull conditions are Length overall (Loa) = 147m, Length on the waterline (Lwl) = 144.529m, Beam (B) = 35m, Height (H) = 13m, Draft (T) = 11m.

Besides MSC Nastran Patran and MSC Fatigue software or ANSYS, other software may be used to model finite element models such as ABAQUS, POSEIDON, or Maestro Marine. The use of this software may add the knowledge in the finite element method and ensure the result consistency. In this paper, green water effect and slamming are neglected, for the future work, these parameters need to be added.

Moreover, some numerical or physical parameters, such as mesh size and different force conditions, significantly impact the simulation accuracy. We recommend using meshing sensitivity analysis to estimate and reduce the magnitude of errors related to numerical solution methods.

References

[1] K. Kwon and D. M. Frangopol, "Fatigue life assessment and lifetime management of aluminum ships using life-cycle optimization," *Journal of ship research,* vol. 56, no. 2, pp. 91-105, 2012.

[2] W. Fricke, H. Petershagen, and H. Paetzold, "Fatigue Strength of Ship Structures," *Part I: Basic Principles, Germanischer Lloyd, Hamburg,* pp. 34-36, 1997.

[3] N. Veritas, *Fatigue assessment of ship structures*. Det Norske Veritas, 2001.

[4] N. Ferreira, J. S. Jesus, J. A. M. Ferreira, C. Capela, J. M. Costa, and A. C. Batista, "Effect of bead characteristics on the fatigue life of shot peened Al 7475-T7351 specimens," *International Journal of Fatigue,* vol. 134, p. 105521, 2020/05/01/ 2020.

[5] H. Chandra and B. Sianturi, "Analysis of Fatigue Life and Crack Propagation Characterization of Gray Cast Iron under Normalizing Process," in *Journal of Physics: Conference Series*, 2019, vol. 1198, no. 3: IOP Publishing, p. 032006.

[6] H. Wan, Q. Wang, C. Jia, and Z. Zhang, "Multi-scale damage mechanics method for fatigue life prediction of additive manufacture structures of Ti-6Al-4V," *Materials Science and Engineering: A,* vol. 669, pp. 269-278, 2016.

[7] J. L. Otegui, "Fatigue damage leads to a serious traffic accident," *Engineering Failure Analysis,* vol. 9, no. 1, pp. 109-122, 2002/02/01/ 2002.

[8] T. Moan, "Fatigue reliability of marine structures, from the Alexander Kielland accident to life cycle assessment," *International Journal of Offshore and Polar Engineering,* vol. 17, no. 01, 2007.

[9] Y. Wang, "Spectral fatigue analysis of a ship structural detail – A practical case study," *International Journal of Fatigue,* vol. 32, no. 2, pp. 310-317, 2010/02/01/ 2010.

[10] G. F. M. Souza and B. M. Ayyub, "Probabilistic Fatigue Life Prediction for Ship Structures Using Fracture Mechanics," *Naval Engineers Journal,* vol. 112, 4, pp. 375-397(23), 2000.

[11] D. Guan, "A method of predicting the fatigue life curve for misaligned welded joints," *International Journal of Fatigue,* vol. 18, no. 4, pp. 221-226, 1996.

[12] K. J. Kirkhope, R. Bell, L. Caron, R. I. Basu, and K. T. Ma, "Weld detail fatigue life improvement techniques. Part 1: review," *Marine Structures,* vol. 12, no. 6, pp. 447-474, 1999.

[13] K. J. Kirkhope, R. Bell, L. Caron, R. I. Basu, and K. T. Ma, "Weld detail fatigue life improvement techniques. Part 2: application to ship structures," *Marine Structures,* vol. 12, no. 7, pp. 477-496, 1999.

[14] A. P. Rizky, I. P. Mulyatno, and S. Jokosisworo, "ANALISA FATIGUE KONTRUKSI MAIN DECK SEBAGAI PENUMPU TOWING HOOK AKIBAT BEBAN TARIK PADA KAPAL TUG BOAT 2 x 800 HP DENGAN METODE ELEMEN HINGGA," *Jurnal Teknik Perkapalan,* vol. 4, no. 1, 2016.

[15] L. Damanik, I. P. Mulyatno, and B. A. Adietya, "KAJIAN TEKNIK KEKUATAN KONSTRUKSI KAPAL TUGBOAT 2 x 800 HP DENGAN METODE ELEMEN HINGGA," *Jurnal Teknik Perkapalan,* vol. 4, no. 1, 2016.

[16] G. Dave, "Propeller Handbook The Complete Reference for choosing, instaling and Understanding Boat Propeller," ed: The McGrew-Hill Companies. USA, 1989.

[17] A. SV, "Harvald," *Resistance and Propulsion of Ships. Denmark: John Weiley & Sons,* 1983.

[18] A. F. Molland, S. R. Turnock, and D. A. Hudson, *Ship resistance and propulsion*. Cambridge university press, 2017.

[19] M. Alam and M. Wahab, "Finite Element Modeling of Fatigue Crack Growth in Curved-Welded Joints Using Interface Elements," ed: University of Illinois. Illinois, 2005.

[20] G. DNV, "Fatigue design of offshore steel structures," *Recommended Practice DNVGL-RP-C203,* vol. 20, 2016.

[21] S. Jokosisworo and J. Sebastian, "Analisa Fatigue Kekuatan Stern Ramp Door Akibat Beban Dinamis Pada KM. KIRANA I Dengan Metode Elemen Hingga Diskrit Elemen Segitiga Plane Stress," *Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan,* vol. 8, no. 3, pp. 119-125, 2011.

[22] D. N. Veritas, "Fatigue design of offshore steel structures," *DNV Recommended Practice DNV-RP-C203,* 2010.

[23] H. T. Kang, "Fatigue prediction of spot welded joints using equivalent structural stress," *Materials & Design,* vol. 28, no. 3, pp. 837-843, 2007/01/01/ 2007.