The Strength and Fatigue Life analysis of Sedan Car Ramp of The Ferry Ro-Ro 5000 GT Using Finite Element Method

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Article Info	Abstract
	The Ferry Ro-Ro 5000GT has three levels of car deck that are connected by internal ramps. Two issues that have to be paid attention during the operation of the internal ramp there are the strength capacity and the design fatigue life of the internal ramp structure. The purpose of the research is to determine the strength and fatigue life of the internal ramp construction. The method used the Finite Element Method using a static load by load case of point load at top girder and between girders. Results of the research detected the maximum stress value is in the load case of the point load (three sedan car) at between of the girder is 52.143 MPa with the fatigue life is 44.47 years with the load cycle is 7300000 cycle while the minimum stress value detected at the load case of the point load (two sedan cars) at top girder is 34.199 MPa with the fatigue life is 195.92 years with the load cycle is 50000000 cycle. For the safety factor, ramp construction 6.08 ~ 10.38. The safety factor value above is still in safe condition because the value is SF > 1.

1. Introduction

The Ferry Ro-Ro 5000 GT operates in the Sunda Strait with the Merak-Bakauheni Port shipping route capable of carrying many passengers and vehicles. Based on data from PT. ASDP Indonesia Ferry, the number of passengers at Christmas 2019 and New Year 2020 at Merak-Bakauheni Port was recorded as 21,699 passengers. In addition, the number of vehicles was recorded as 3,784 units consisting of 605 motorbikes, 2,281 units of four-wheeled vehicles, 179 buses, and 719 trucks [1]. Ro-Ro passenger ship is equipped with a loading ramp to enable vehicles to roll on and roll off the ship. It is classified into two categories: open and enclosed space of Ro-Ro (BKI 2020 Guidance for class notations 2020) [2]. Usually, a ramp is made at the stern of the ship, and in some vessels, there are also on the bow and side of the ship [2].

The Ferry Ro-Ro 5000 GT has a three-tiered deck construction to make it easy for vehicles to be transferred to the upper or lower decks. The Ro-Ro Ferry is equipped with an internal ramp construction. The internal ramp is a bridge to place vehicles from the car deck to the inner second deck. An internal ramp is needed to simplify the process of loading and unloading vehicles from the car deck to the second deck and vice versa. There are two types of ramp internal drive systems: a hydraulic system and a steel wire rope system [3]. The design of the ramp door must be able to guarantee that the construction is under stress allowed and can be accepted by the construction and has sufficient elastic stiffness, and does not cause excessive elastic deformation [4]. Based on Biro Klasifikasi Indonesia (BKI) 2014 Rules, Vol. 2, the ship construction must be designed to be sturdy and lightweight [5]. In addition, the construction should comply with the minimum requirement of the classification society. Ship construction plays a vital role because the ship is a means of marine transportation. The design must meet the safety standards of the ship's crew, passengers and cargo so that accidents do not occur.

Vehicles usually transported by Ro-Ro ferries are cars of various types, one of which is a sedan. This shows that the load intensity that works on the internal construction of the ramp when loading and unloading are very high. Based on this, the internal ramp construction planning must have a stress level at the allowable limit. The finite element method is used in the present study, a numerical method for solving engineering problems and mathematical physics. Typical problems of fields of interest in engineering and mathematical physics that can be solved using the finite element method include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential [6]. The basic idea in the finite element method is to find solutions to complex problems by replacing them with simpler ones. Because the real problem will be

simplified, and we can finally find approximate solutions and get the right solution [7]. Finite element analysis (FEA) is a numerical technique for solving complex problems, such as varying shapes, boundary conditions, and loads maintained as they are, but the solution obtained is only an estimate [8]. Chord from this research is expected to obtain information about the prediction of fatigue life of internal ramp construction, which can be used as a reference in repairing or replacing the construction. In addition to working stress, the internal construction of the ramp can also experience structural fatigue due to cyclic loads, which impacts durability and construction life. It is estimated that 50% – 90% of mechanical failure is caused by fatigue [9]. The determination of construction fatigue life follows procedures in the rules by considering the S-N Curve [10].

For fatigue life analysis, the procedure of the response amplitude operator was applied [11]. Lotsber (2006) presents a comparison based on similar calculated hot spot stresses using the two procedures [12]. In general, the presence of a size effect was agreed upon; the size effect is considered dependent on the plate thickness at the considered hot spot in addition to the size of the attachment plate and type of dynamic loading [13]. One of the methods used in determining fatigue is the probabilistic method [14]. Therefore, an alternative assessment method based on notch stress and very fine element meshes have been used to assess target hot spot stress values to calculate the best estimates of fatigue lives [15]. Based on the review of fatigue assessment methods of welded details in steel structures [16]. Meneghetti (2021) compares the fatigue behaviour of EN-GJS-1050 austempered ductile iron-to-S355J2 steel dissimilar joints to the categories of the corresponding homogeneous steel welded joints, as suggested in International Standards and Recommendations [17]. Bartsch (2020) presented at longitudinal welded carried out fatigue tests in connection with numerical simulations in order to be able to evaluate the fatigue strength with better accuracy [18]. In the present study, the strength and fatigue life of the internal ramp construction is investigated, the load cases are given to determine the strength and fatigue life of the ramp.

2. Methods

In general, the research stage is contained in the flow diagram shown in Figure 1. and will be explained comprehensively step by step.
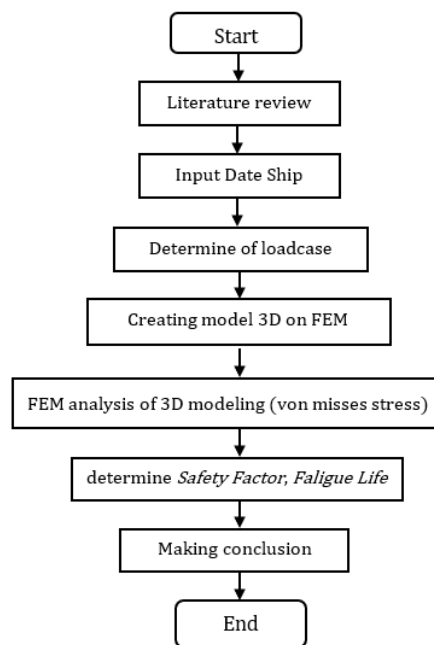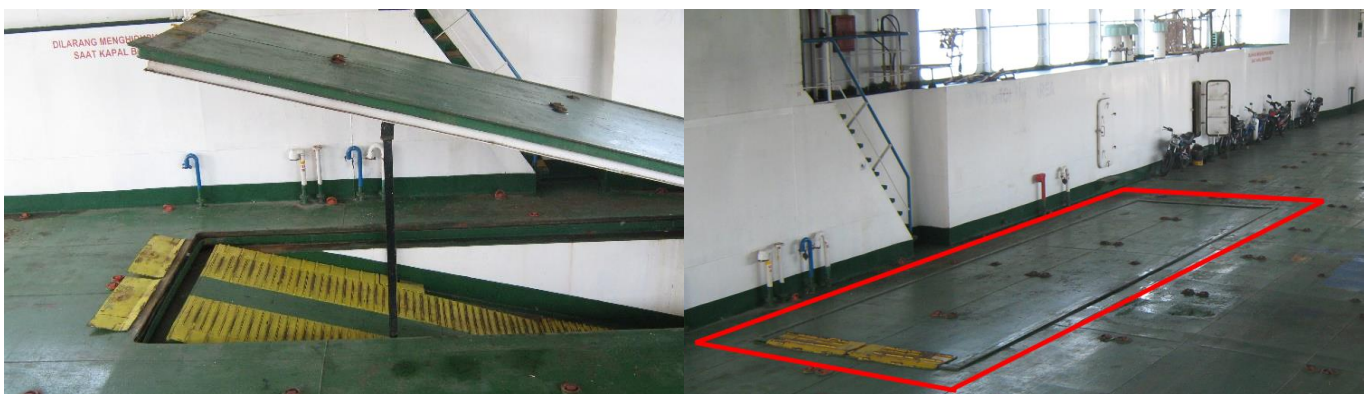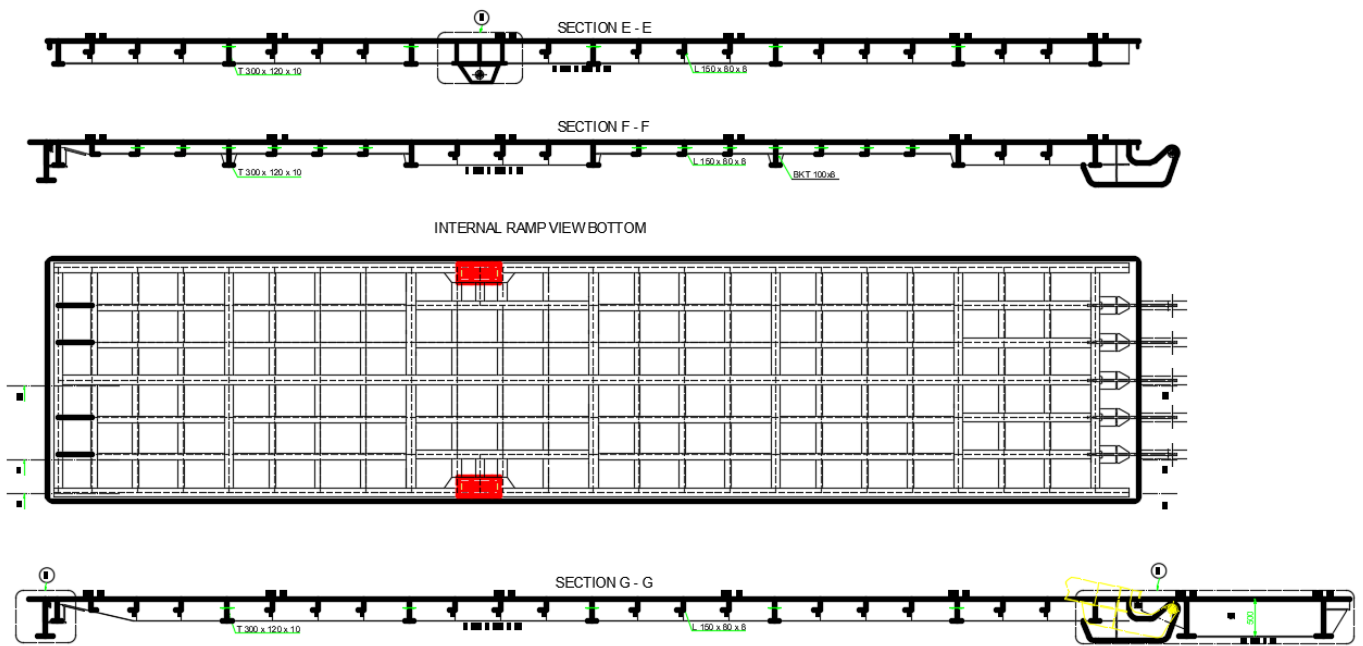

Figure 1. Research Flow Chart

The appearance of the research object and the main size data for the internal ramp are shown in Figure 2. and Table 1

(a)

(b)

Figure 2. a) Internal ramp on ferry Ro-Ro5000 GT; b) 2D of internal ramp

Table 1. Dimension Internal Ramp of Ferry Ro-Ro 5000 GT

Dimension	value	Unit
L	3.0	meters
B	5.0	meters
H	0.3	meters
Elevation	14.14	degree
T bar	300x120x10	mm
L bar	150x80x8	mm

The model to be analyzed uses a sedan car vehicle load Jumalia [19] gives a load sedan car of 1.5 tons, distributed as a point load according to the number of wheels of the vehicle shown in Table 2.

Table 2. Poin Load of Internal Ramp of Ferry Ro-Ro 5000 GT [19]

Vehicle type	Weight of car (tons)	Weight of car (Newton)	Car of dimension, L x B (m)	Point load (Newton)
Sedan car	1.5	15000	4.7 x 1.9	3750

3D modelling uses a finite element application using the x, y and z axes. The x-axis represents the width of the model design, the y-axis represents the length of the model design, and the z-axis represents the thickness or height of the model design. The next step is to determine the stress value in the internal construction of the ramp, which is defined as the force of unity of the cross-sectional area of the object. Suppose two beams are of the same material, but their cross-sectional area is different, and they are both subjected to a force. In that case, the two beams experience different stresses, where a beam with a small cross-section will experience large stress compared to a larger cross-section, then the stress is smaller. Stress is symbolized by σ or read as sigma. Mathematically, stress can be formulated as follows Eq. (1) [20].

$$\sigma = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A}$$

(1)

Where: σ = stress which is a force acting perpendicular to the cross-section;
          A = the area with regard to Normal Stress that causes tension.

Strain is a change in shape experienced by material where two opposing forces (in the centre) are subjected to the ends of the material. As the stress increase, the strain is bigger, which means an increase in length takes place. Tension and stress are taken into account in determining the material properties that support construction. The strain is the ratio between the change in the material length to its original length. It can be formulated as follows [21].

$$\varepsilon = \frac{\Delta}{L} \qquad (2)$$

Where: ε = strain Δ = total length L = original length
          The next step is to determine the value of the construction safety factor by comparing the results of the maximum working stress that occurs in the construction with the yield stress of the materials used in the construction. Eq. (3) is used to calculate the safety factor.

$$SF = \frac{\sigma_{yield}}{\sigma_{v\ maximum}} \qquad (3)$$

Where σ_{yield} is the yield stress of the material, σ_v Maximum is the von mises stress acting on the construction, and SF is the safety factor (SF> 1) [22]. This ratio is called the factor of safety and must be greater than one. This factor is also identical to the ratio between the ultimate stress and the allowable stress of the tensile rod [23].
          The next stage is to determine the fatigue life due to cyclic loads from the environment (waves, wind currents) that work continuously. Fatigue strength analysis is applied to all structures that are predominantly subject to cyclic loads to ensure the structure's integrity and study the possibility of fatigue damage as the basis for an efficient inspection method. Cyclic loads are the main cause of fatigue in ship structure which is caused primarily by waves. However, other cyclic loads also affect fatigue failure and must be taken into account. The model to be analyzed uses a sedan car vehicle load distributed as a point load according to the number of wheels of the vehicle. The fatigue life of the internal ramp structure is estimated considering the Palmgren-Miner rule of cumulative damage. The foremost treatment of cumulative fatigue damage is the linear damage rule (LDR), which is the Palmgren-Miner rule. In this rule, cumulative fatigue damage is progressively linear, and it is assumed that the cumulative damage at failure is 1.0 [10]. The fatigue life can be calculated based on the S-N fatigue approach using the following DNVGL [10] formula:

$$D = \frac{v_0 T_d}{\bar{a}} q^m r \left(1 + \frac{m}{n}\right) \leq \eta \qquad (4)$$

$$v_0 = \frac{1}{4.\log_{10}(L)} \qquad (5)$$

$$q = \frac{\Delta\sigma_0}{(In\ n_0)^{1/h}} \qquad (6)$$

$$h_0 = 2.21 - 0.54 log_{10}(L) \qquad (7)$$

$$h = h_0 + \frac{h_a \times z}{T_{act}} - 0.005(T_{act} - z) \qquad (8)$$

D is accumulated fatigue damage, v_0 is average zero up-crossing frequency, q is Weibull stress range scale distribution parameter, h is Weibull stress range shape distribution parameter, Td is the design service life of the ship, $r(1+m/h)$ is gamma function, $\bar{a}$ is the intercept of the design S-N curve with the $log\ N\ axis$, and $\Delta\sigma_0$ is the largest stress range out of no cycles. Value D is used to determine the fatigue life of the ramp structure by calculating the fatigue life Eq. (9).

$$Fatigue\ Life = \frac{Design\ Life}{D} \qquad (9)$$

Where: Fatigue life = material fatigue

          Design life = 20 years according to DNV regulations [24],

                    D = fatigue damage

After fatigue life is determined in the present study, the correlation graph between stress range per load case and fatigue life for the inner ramp structure is produced. It is used to analyse the fatigue life of the ramp.

3.   Results and Discussion

Vehicle weight is shown in Table 2. To simplify the analysis, it is assumed that, in the load case, the load is equally distributed to all wheels of the vehicle point of load. Each load centre point on the internal ramp is given a load of 3.750 N

per node. The extent of the load per variation can be calculated according to the number of cars which are assumed to be as follows.

a. For load cases, load 3 cars are placed on the girders and between the girders (see Figure 5b). This shows that the internal ramp door is given 3 loads of 4-wheeled vehicles so that the load given is 12 concentrated loads which are symbolized by a red arrow pointing downward. On the load of 3 sedans, there are 12 load centre points, where the load centre points are the car tires. The 12 load centre points are obtained from the number of tires on the car multiplied by the number of cars. Then the weight of the load at each load centre point is 3.750 N. Then, the total load is 45.000 N or equivalent to 4.5 tons.

b. For load cases, 2 cars are placed on the girders and between the girders (see Figure 5c). This shows that the internal ramp door is given 2 loads of 4-wheeled vehicles so that the load given is 8 concentrated loads which are symbolized by a red arrow pointing downward. On the load of 2 sedan cars, the results are 8 load centre points, where the load centre point is the car tire. 8 load centre points are obtained from the number of tires on the car multiplied by the number of cars. Then the weight of the load at each load centre point is 3.750 N. Then, the total load is 30.000 N or equivalent to 3 tons. 3D modelling of the internal construction of the 5000 GT Ro-Ro ferry ramp using finite elements is shown in Figure 3.
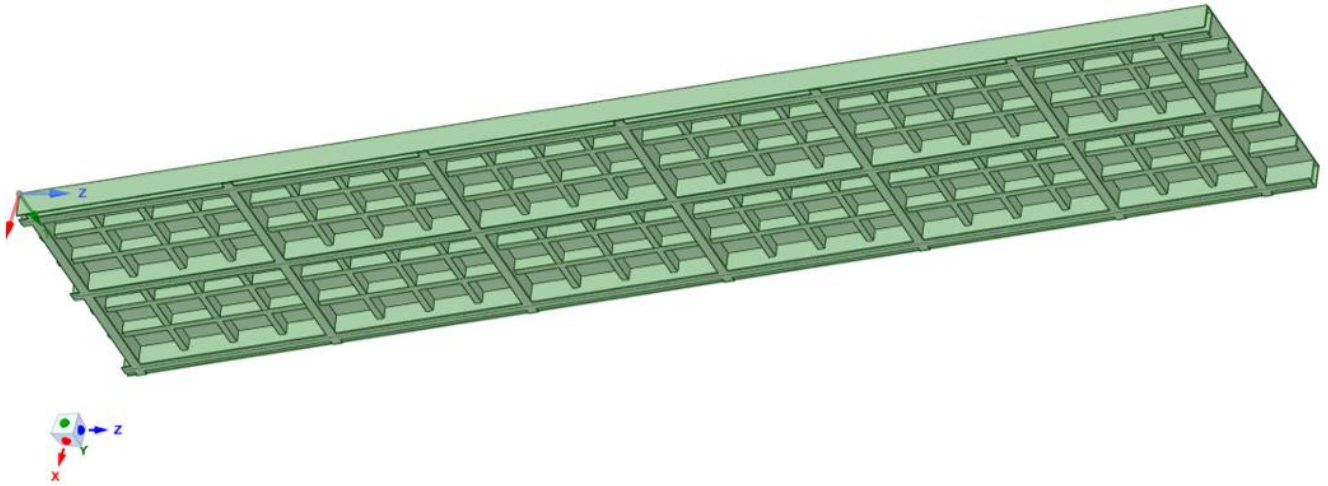

Figure 3. Three dimensional internal ramp ferry Ro-Ro by FEM.

Input mechanical properties material internal ramp ferry Ro-Ro 5000 GT. Material data used for the Ferry Ro-Ro ship structure uses ABS Grade AH36 steel with the following specifications as shown in Table 3. [25].

Table 3. The mechanical properties of AH36

Physical properties	value	Units
Elastic Modulus	210 x 10^3	MPa
Density	7850	kg/m^3
Ultimate tensile stress	490-620	MPa
Poisson's Rattio	0.3	–
Yield Strength	355	MPa
Tangent Modulus	675	MPa

The meshing process is a series in the finite element method where the 3D model undergoes a nodal division treatment of smaller finite elements that are connected to each other. The ideal selected mesh size has mesh sensitivity where the resulting stress value does not change significantly and tends to be stagnant. Because the internal construction of the ramp is very complex, the size element value used is 150 mm and considering the minimal capabilities of the PC. The meshing result of the internal ramp 3D model is shown in Figure 4. In this study, the support used follows the actual conditions, namely, using fixed support and roll support. While the load case that is given is a point load which consists of a point load placed on the girder and a point load placed between the girders. The support and load cases inputted to the internal ramp model are shown in Figure 5.
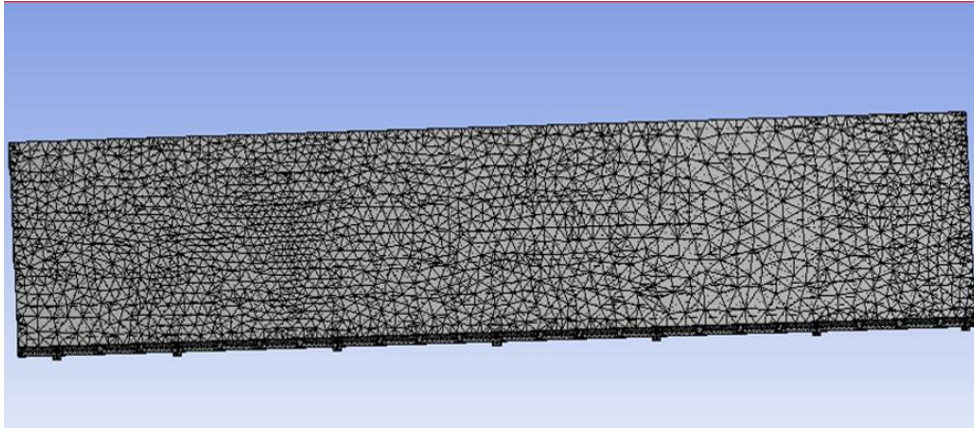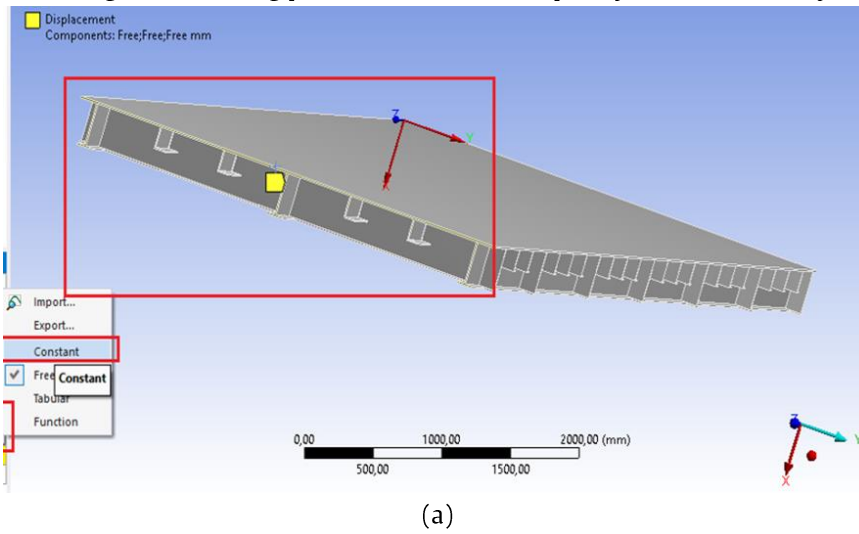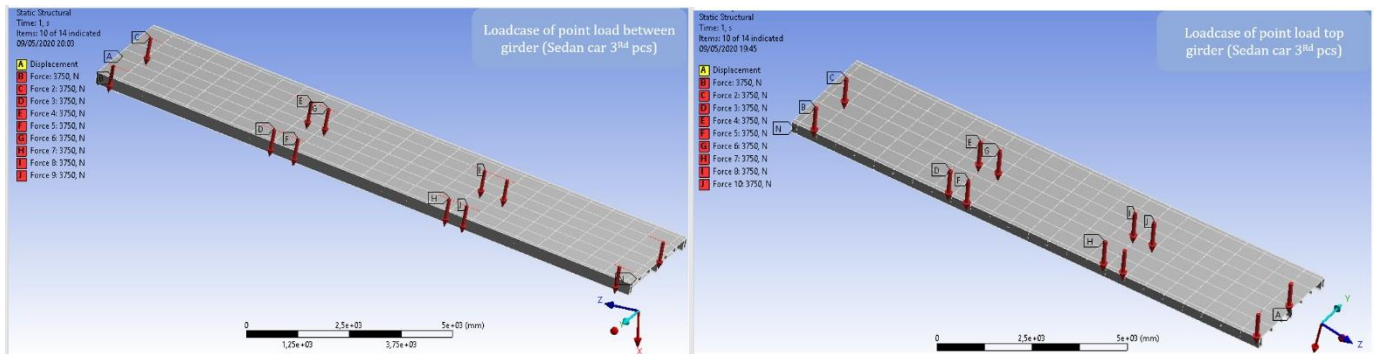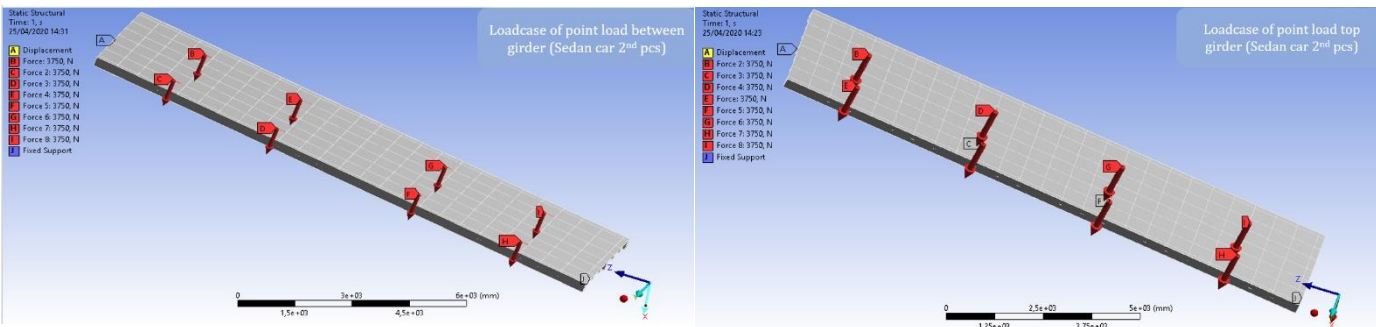
Figure 4. Meshing procces 3D internal ramp ferry Ro-Ro 5000 GT by FEM

(a)

(b)

(c)

Figure 5. a) Input displacement; b) Input loadcase 3rd pcs of sedan car; c) input loadcase 2nd pcs of sedan car.
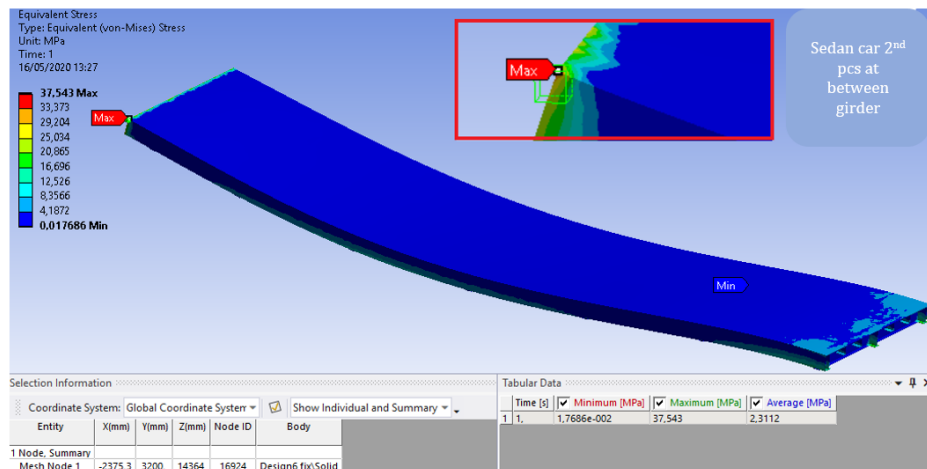
After input displacement and load case are carried out, general postprocessing is carried out, which is the final stage of FEM. The results of general postprocessing obtained the equivalent stress value (von misses stress). The maximum and minimum working stress are shown in Figure 6.
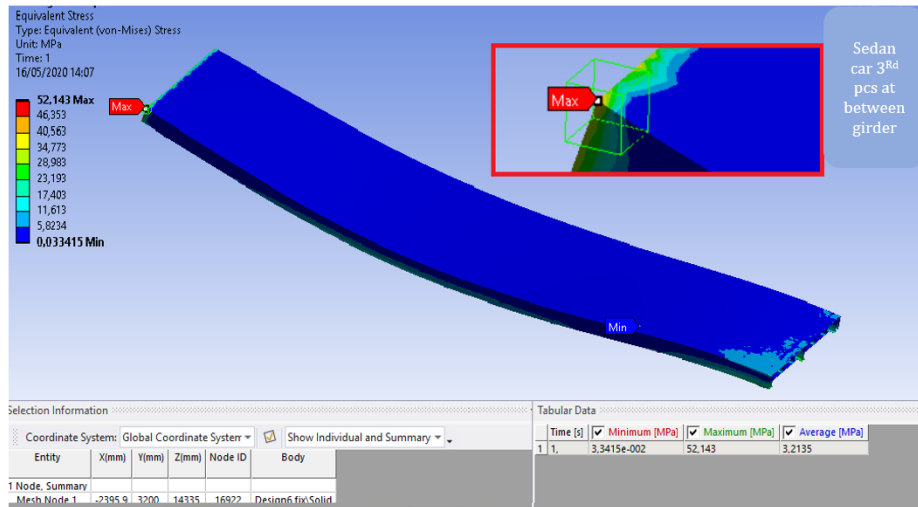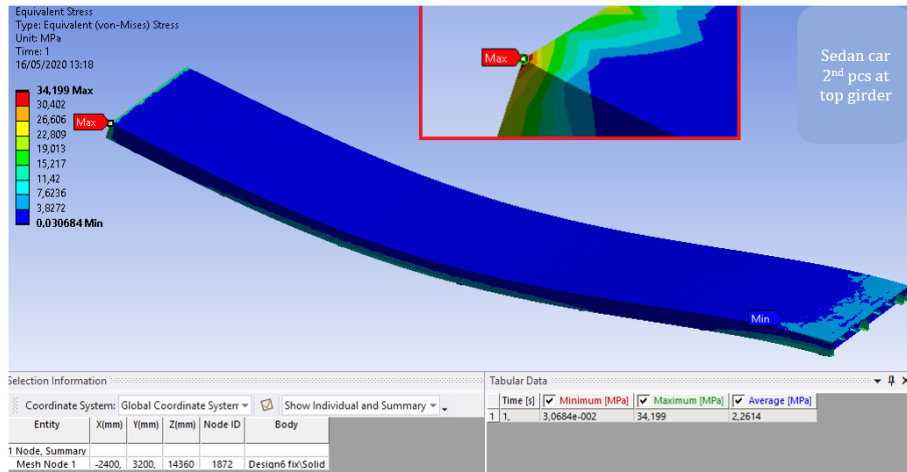

(a)
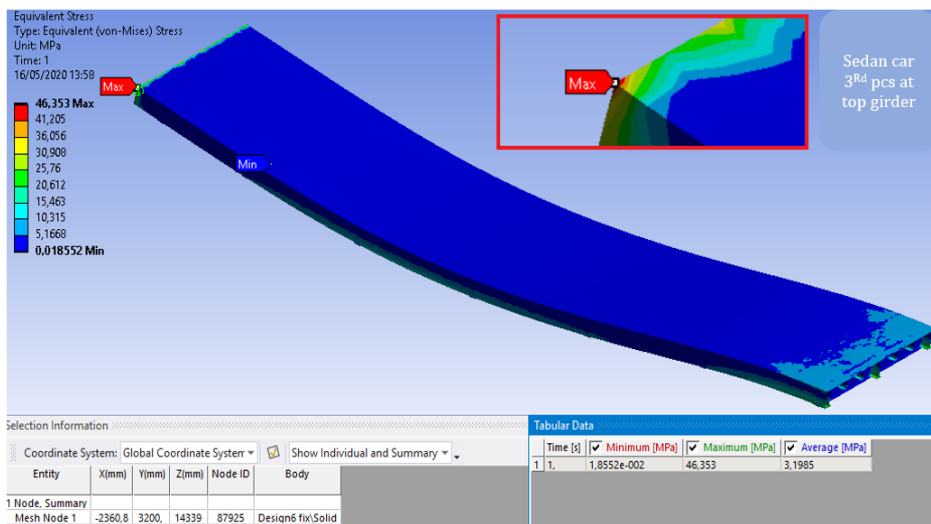
(b)

(c)

(d)

Figure 6. a) stress equivalent of 3 pcs sedan car load case between girder; b) stress equivalent of 3 pcs sedan car load case top girder; c) stress equivalent of 2 pcs sedan car load case between girder; d) stress equivalent of 3 pcs sedan car load case top girder.

Based on the results from finite element analysis software in variations of 3 cars in caseload position that is not supported, the stress value located between girder and at the top of girder is 52.143 MPa at node 16922 and 46.353 MPa at node 87925, respectively. As for The variations of 2 cars, the stress value is 37.543 MPa at node 16924 and 34.199 MPa at node 1872, respectively. The recapitulation of equivalent stress of the internal ramp is shown in Table 4.

Table 4. Equivalent stress of loadcase

Loadcase	Force (N)	Von misses stress (MPa)
3 pcs at between of girder	45.000	52.143
3 pcs at top of girder	45.000	46.353
2 pcs at between of girder	30.000	37.543
2 pcs at top of girder	30.000	34.199

The next step is to determine the safety factor using Eq. (3), so that the safety factor is obtained as shown in Table 5.

Table 5. The safety factor of internal ramp constructions

Loadcase	σ_{yield} (MPa)	σv_{max} (MPa)	SF
3 pcs at between of girder	355	52.143	6.08
3 pcs at top of girder	355	46.353	7.65
2 pcs at between of girder	355	37.543	9.45
2 pcs at top of girder	355	34.199	10.38

Table 5 shows the value of the construction safety factor when the maximum von mises stress occurs for all loadcases, namely SF > 1, so it can be concluded that the internal construction of the ramp is eligible. The final stage of this research is to determine the fatigue life of construction using Eq. (4), (5), (6), (7), (8) and (9). The values of *v0, q, h, r(1+m/h),* a show in Table 6. The values of fatigue damage and fatigue life for each of the maximum working stresses are shown in Table 7.

Table 6. The support variable of fatigue damage of S-N Curve Class type E

Loadcase	v0	q	h	r(1+m/h)	a
3 pcs at between of girder	0.22	12.3	1.58	1.82	1.02×10^{12}
3 pcs at top of girder	0.22	10.8	1.58	1.82	1.02×10^{12}

2 pcs at between of girder	0.22	8.39	1.58	1.82	1.02×10^{12}
2 pcs at top of girder	0.22	7.5	1.58	1.82	1.02×10^{12}

Table 7. The fatigue life of internal ramp constructions

Loadcase	σv max (MPa)	Number of cycle (cycle)	Fatigue damage (D)	Fatigue life (years)
3 pcs at between of girder	52.143	7300.000	0.45	44.47
3 pcs at top of girder	46.353	10.000.000	0.30	65.71
2 pcs at between of girder	37.543	30.000.000	0.14	140.14
2 pcs at top of girder	34.199	50.000.000	0.10	195.92

Table 7 shows the value of fatigue life on the load case of 3 sedans, which is not supported with the value of fatigue damage of 0.45 is 44.47 years, the value of fatigue life in the load case of 3 sedan cars is supported by the value of fatigue damage of 0.30 is 65.71 years, the value of fatigue life in load case 2 sedan cars not supported by the fatigue damage value of 0.14 is 140.14 years, and the value of fatigue life on the load case 2 sedan cars is supported by the fatigue damage value of 0.10 is 195.92 years. The next step represents the von mises stress and cycles relationships for all load case simulations shown in the S-N curve. The form of the S-N Curve internal ramp constructions is shown in Figure 7.
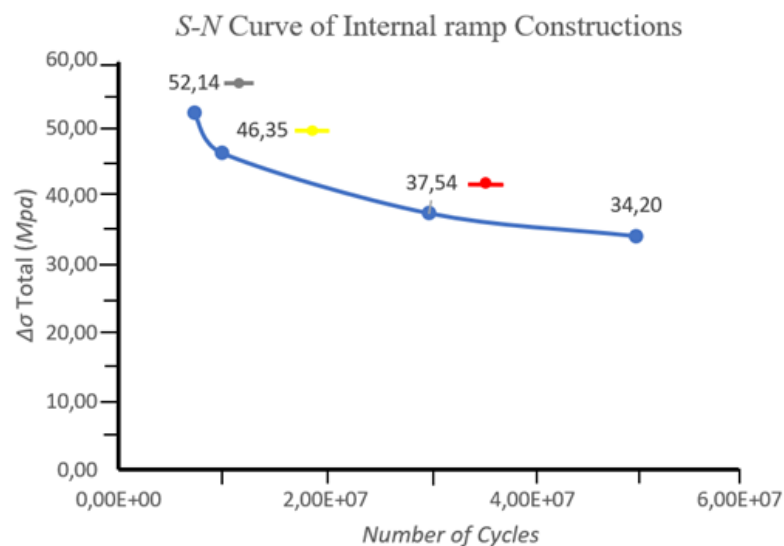

Figure 7. The correlation graph between stress range per load case and fatigue life for inner ramp structure.

4. Conclusion

The maximum stress value on the internal construction of the ramp detected in the load case of 3 sedans between the girders is 52.143 MPa with a safety factor value of 6.08. The minimum stress value in the load case of 2 sedan cars top girder is 34.199 MPa with a safety factor value of 10.38, which can be concluded that the internal ramp is eligible because SF > 1. This also proves that the stress will increase when the sedan is between the girders, and the stress will be reduced when the sedan car shifts just above the girder. The value of fatigue life in the construction of the internal ramp in a vulnerable time of 44.47 ~ 195.92 with a cycle of 700.000 ~ 50.000.000 cycles

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