An Overview of Railway Damage with the Finite Element Analysis

Ridwan[1](✉), Maejar Bacthiar[1], Bayu Ridwan[1], and Aditya Rio Prabowo[2]

[1] Department of Mechanical Engineering, Universitas Merdeka Madiun, Madiun 63133, Indonesia
ridwan@unmer-madiun.ac.id
[2] Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Abstract. In this paper, reviews of several fractures and damage to railway construction in their application to daily use are presented. An overview of technology and application usage of finite element analysis in assessing railways damage is also presented. As happened on the train track, the fatigue mechanism and the high thermal condition can cause fracture and damage. Damage to the railway also can occur due to the heightened interaction between the rail and the wheel. Furthermore, finite element analysis in the last decade seems to become extremely essential, for instance, assessing rail-wheel interaction events to improve passenger safety. Prevention and lessons that can be drawn from these several circumstances are encouraging things to avoid similar incidents in the future.

Keywords: Railway · finite element analysis · failure analysis · thermally buckled track · fatigue crack

1 Introduction

The train is public transportation that is widely used in all parts of the world. Fast and comfortable transportation is something that passengers desire. The train accommodates a large enough number of passengers to take to a place at once. Trains use their lanes called railway. Construction errors and failures on railway can cause severe catastrophes. The loss of life of many people can occur due to train accidents, one of which can occur due to broken railway.

Because of its importance, several studies have been carried out to improve rail safety. One of them is in the railway' construction. The railway superstructure and the rolling stock build a complex mechanical design. Nejad (2014) [1] studied the residual stresses in the rail wheel caused by the stress field from the heat treatment process of a railway wheel, and the contour plots of the von Mises stress were determined. Furthermore, Gras et al. (2018) [2] found that local heterogeneity had an effect on a railway track. In the following year, Ciotlaus et al. (2019) [3] found that Rail-wheel interaction can affect rail and wheel wear. Skrypnyk et al. (2020) [4] conducted research on the simulation methodology for the prediction of rail damage and the long-term

W. A. Wirawan et al. (Eds.): ICORT 2022, AER 220, pp. 3–12, 2023.
https://doi.org/10.2991/978-94-6463-126-5_2

plastic deformation and wear in an explosion depth hardened manganese crossing were quantified. However, there are still many studies that combine several methods, such as experiments and simulations that have been confirmed, but there are still many that have not been recognized. And also Understanding the improvement in railway construction is also vital to enhance and improve safety.

In this study, an overview of railway technology, failures, and application usage of finite element analysis are presented. Imperfections in the examination and development of railway will also be discussed. Furthermore, several causes of fracture and damage to the railway are presented, such as the fatigue crack and buckled track caused by the high thermal condition. This paper also includes several studies related to railway safety using the finite element method to estimate the event of interaction between railway and the wheels to improve safety.

2 Railway Infrastructure

Public transport such as trains or also known as rail transport is a wheeled means of transportation that runs on rails that carry passengers and goods. This transportation is different from road transportation, where trains run on a prepared flat surface, and railroad vehicles (rolling stock) are guided directionally by the rails on which they run. Usually, the track consists of steel rails, installed on sleepers (ties) which are also mounted on ballast, on which the rolling stocks, are usually equipped with metal wheels. Navikas and Sivilevičius (2017) [5] summarized the properties of material utilized for railway track construction as presented in Table 1. Furthermore, the materials properties in railway track components also studied by Zakeri and Ghorbani (2011) [6], Table 2.

In the train, a permanent track with minimum maintenance cost is extremely needed and should deliver a comfortable and safe ride at the maximum allowable speed. The permanent track should have the following characteristics to accomplish those purposes as suggested by Chandra and Agarwal (2003) [7].

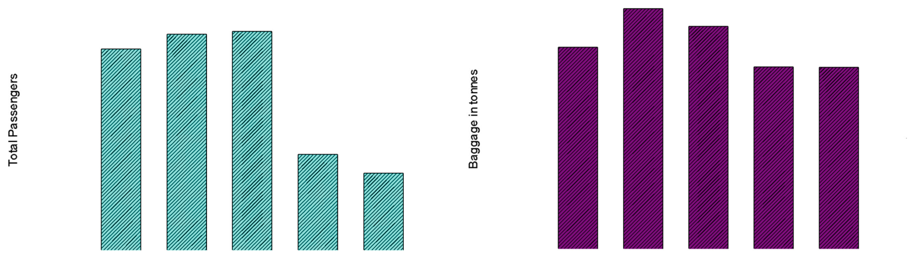
In Indonesia, the use of rail public transportation in the last five years has experienced an increase and decrease in total passengers. The increase in passengers occurred from 2017 until 2019 [8], Fig. 1. In 2017, the total number of passengers reached 386361.

Table 1. Materials properties utilized for railway track construction [5].

Parameters	Density of dry soil (kg/m^3)	Thermal conductivity (J/(day·m·C))	Specific Heat Capacity of Solid Component (J/kg·C)	Phase Change Temperature From C	Phase Change Temperature To C	Water content	Initial temperature
Natural ground	1770	103680	1582	−0.01	−0.5	0.157	7.3
Humus	1800	120960	1000	−0.01	−0.5	0.2	3
Subgrade	2081	129945	1585	−0.01	−0.5	0.175	6.29
Sub-ballast	2130	94176	1276	−0.01	−0.5	0.039	3.22
Ballast	2198	172800	1095	−0.01	−0.5	0.015	2

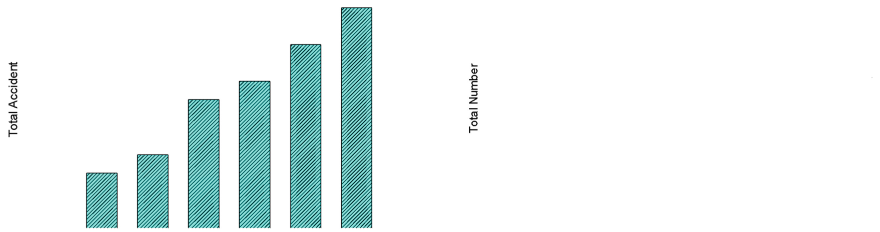
Table 2. Properties of material in railway track components [6].

Component track		Mass [kg/m]	Stiffness [kN/m]	Damping [kN·S/m]
Ballasted track	Rail (UIC60)	60	–	–
	Railpad	–	200 × 103	28
	Sleeper	320	–	–
	Ballast	–	46 × 103	180
Slabtrack	Railpad	–	375 × 103	135
	Slab	1876	–	–
	subgrade	–	60 × 103	180



(a) (b)

Fig. 1. (a) Total passenger and (b) total baggage being transported in the last five years [8].



(a) (b)

Fig. 2. (a) Total accident and (b) cause of accident involved the train transportation in 2020 [9].

This total has been increased at around 419878 passengers at the end of 2019. However, it can be seen in Fig. 1a, that the decline in passengers occurred from 2020 to 2021.

At the end of 2021, the total number of train passengers was only around 147521. This decline occurred due to the restrictions on outdoor activities caused by the COVID-19 pandemic disease in Indonesia. However, the number of accidents on public transportation tends to increase every month as present in 2020 [9]. The number of accidents and cause of accidents in 2020 can be seen in Fig. 2.

3 Fracture in Railway

Failure in the construction of railway is very dangerous. This failure can cause the train to fall while it is moving. This catastrophe can cause the death of the passengers. Orringer et al. (1984) [10] showed that damage to railway can occur due to high thermal conditions. This condition can trigger a buckle on the railway as shown in Fig. 3. Furthermore, Orringer et al. (1986) [11, 38] showed fatigue failure also often occurs in steel railway as presented in Fig. 3a. It found that the analysis of the fracture surface from fatigue failure usually shows characteristics typically referred to as beach marks. This phenomenon suggests that the propagation of the crack can be seen from the initial crack. Moreover, once the crack size reaches a critical level, the crack will propagate extremely fast until the fracture is complete. Figure 3a shows the fatigue striations on the fracture surface of the rail.

Steel Materials used in railway construction are very important and crucial. The difference in mechanical properties makes the strength of the railway also different. Recently, studies conducted by Godefroid et al. (2020) [12] suggest that fracture toughness, fatigue crack resistance, and wear resistance of two railroad steels are affected by the chemical composition of the steel to be operated. Table 3 summarized the performed analysis of the rail steels along with the average chemical composition (wt%) [12]. It can be seen that the composition of Manganese (Mn) in common steel is less than that of micro-alloyed steel. This phenomenon shows that there is a difference of 0.2 wt% of higher Manganese (Mn) in micro-alloyed steel. Also, some chemical composition is not present in these two materials. For instance, Copper (Cu) and Molybdenum (Mo) are not available in common steel (CS) and micro-alloyed steel (MS), respectively. Figure 4

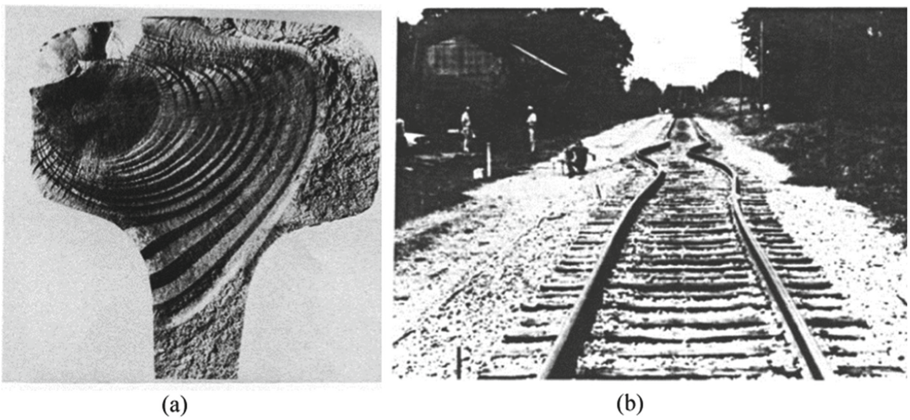
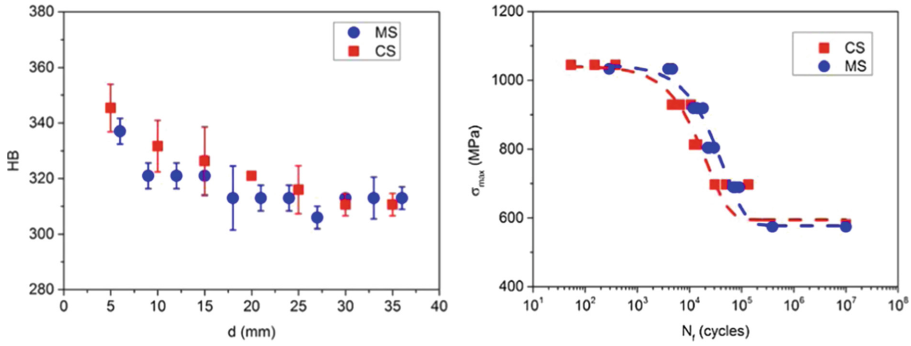


Fig. 3. (a) Fracture surface on the rail [11] and (b) buckled track caused by the high thermal condition [10].

Table 3. Analysis of the rail steels: average chemical composition (wt%) [12].

	Mn	C	P	Si	Cr	Cu	S	Ni	Mo	Nb	V
CS	0.84	0.72	0.02	0.24	0.08	–	0.01	0.01	0.01	0.003	0.002
MS	1.04	0.77	0.01	0.47	0.01	0.01	0.02	0.01	–	0.03	0.06



(a) (b)

Fig. 4. (a) Profiles of the railhead microhardness [12] and (b) maximum stress for common steel (CS) and micro alloyed steel (MS) [12].

presents the differences of the hardness profiles from the railhead and the maximum stress for both common steel (CS) and micro-alloyed steel (MS). Considering these phenomena, these steels meet the standard requirements of American Railway Engineering and Maintenance-of-Way Association [13] and European Committee for Standardization [14] for railroad applications for the hardness, tensile and fracture toughness.

4 Structural Analysis of Railway Using the Finite Element Method

Engineering problem modeled with finite elements requires the assembly of element characteristic of stiffness matrices and element force vectors. This indicates the global system of equations as written:

$$Ku = F \tag{1}$$

where K is the assembly of element stiffness matrices, and F is the assembly of force vectors. Here, u is the vector of nodal unknowns. For, the global system matrix K, it can be obtained by summation in form of the "expanded" element co-efficient matrices, $k^{(e)}$ as [15]

$$K = \sum_{e=1}^{E} k^{(e)} \tag{2}$$

The finite element method is often used to analyze a structural component under various load conditions [16–25]. In the finite element method, the structure even with the complex geometry is divided into N_e elements with a set of N_n nodes. This process is usually called meshing, which is accomplished using so-called pre-processors. The elements then comprise the entire domain of the problem without any gap or overlapping.

The finite element method formulation is required to be based on a coordinate system. In finite element method formulation for elements, employing a local coordinate system is defined for an element in reference to the global coordinate system that is usually prescribed for the whole structure. Based on this condition, the displacement within the element can be determined by polynomial interpolation operating the displacements at its nodes or nodal displacements as follow [26].

$$U^h(x, y, z) = \sum_{i=1}^{n_d} N_i(x, y, z)d_i = N(x, y, z)d_e \tag{3}$$

here the superscript h represents for approximation, n_d is the number of nodes comprising the element, d_i is nodal displacement at the i_{th} node and can be described as

$$\begin{aligned} d_i = \left\{ d_1 d_2 \vdots d_{n_f} \right\} &\rightarrow \textit{displacement component} 1 \\ &\rightarrow \textit{displacement component } 2 \vdots \\ &\rightarrow \textit{displacement component } n_f \end{aligned} \tag{4}$$

where n_f is the number of Degrees of Freedom (DOF) at a certain node. Here, n_f is equal to 3 for 3D solids, and

$$\begin{aligned} d_i = \{u_i v_i w_i\} &\rightarrow \textit{displacement in the } x - \textit{direction} \\ &\rightarrow \textit{displacement in the } y - \textit{direction} \\ &\rightarrow \textit{displacement in the } z - \textit{direction} \end{aligned} \tag{5}$$

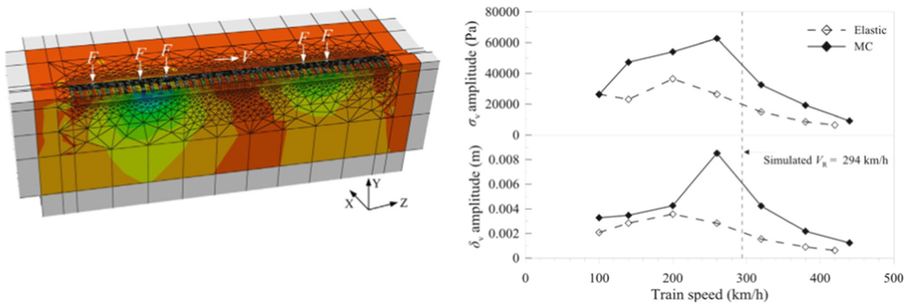
Here, the displacement components can also consist of rotations for structures of beams and plates. In this condition, the vector d_e in Eq. (3) represents the displacement vector for the whole element and has the condition as

$$\begin{aligned} d_e = \left\{ d_1 d_2 \vdots d_{n_d} \right\} &\rightarrow \textit{displacement at node } 1 \\ &\rightarrow \textit{displacement at node } 2 \vdots \\ &\rightarrow \textit{displacement at node } n_d \end{aligned} \tag{6}$$

Thus, the total Degrees of Freedom (DOF) for the entire element is $n_d * n_f$.

N in Eq. (3) can be defined as a matrix of shape functions for the nodes in the element, which are pre-defined to assume the shapes of the displacement variations regarding the coordinates. It has the relation

$$\begin{aligned} &N(x, y, z) = [N_1(x, y, z) N_2(x, y, z) \cdots N_{nd}(x, y, z) \downarrow\downarrow \cdots \\ &\downarrow \textit{ for node } 1 \textit{ for node } 1 \cdots \textit{for node } n_d \end{aligned} \tag{7}$$



(a) (b)

Fig. 5. (a) Distribution of stress in vertical direction of ballasted railway models under moving load [27] and (b) Response amplitudes under moving load with different train speeds [27].

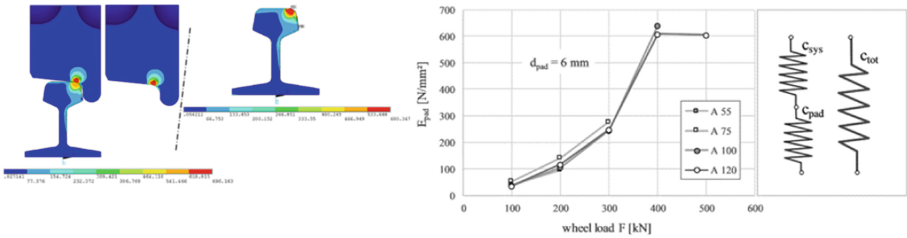
Here, N_i is a sub-matrix of shape functions for displacement components, and can be described as

$$N_i = \left[N_{i1}\ 0000\ N_{i2}0000 \ddots 0000N_{in_f} \right] \tag{8}$$

where N_{ik} is the shape function for the k_{th} displacement component and Degrees of Freedom (DOF) at the i_{th} node. For 3D solids [26], $N_{i1} = N_{i2} = N_{i3} = N_i$.

Recently, the finite element method has been widely used to analyze the response of the permanent track construction [27]. Li et al. (2018) [27] studied the ballasted railway considering the effects of moving train loads and Rayleigh waves using the finite element method. The study showed that higher frequency triggers a secondary vibration peak for ballast and sub-ballast layers. Furthermore, the Elasto-plastic materials showed greater dynamic responses to the stresses and displacements conditions compared to elastic materials. Figure 5 shows the distribution of stress in the vertical direction of ballasted railway models under moving load and the response amplitudes under moving load with different train speeds which were presented in [27]. Arslan and Kayabaşi (2012) [28] examined the 3D rail–wheel contact analysis using the finite element method. The rail–wheel contact with the distribution of Von Mises stress is presented in Fig. 6a. They noted that the maximum stress was located at the contact point of the rail with the wheel.

Further study on the wheel loads from runway cranes based on rail strain measurement has been conducted by Kettler et al. (2020) [29]. The study suggests that two novel mechanical concepts which are the two additional horizontal strain gauges on the rail can predict the actual wheel loads quite accurately for cases with and without an elastomeric rail pad. These mechanical concepts have been validated by comparing the result based on the experiment and finite element method. The study showed that when the load of F = 200 kN applied on the rail, the first and second test produced 167.9 and 199.7 kN of load, respectively. Further, the result obtained from the finite element method showed at 192.4 and 204.8 kN. Further study related to the transportation examination especially ship-ship during collision accident using finite element analysis can be seen in the [30–37]. The finite element method is really concerned with selecting the size of the mesh



(a) (b)

Fig. 6. (a) Distribution of Von Mises stress of the railway under load [28] and (b) stiffness parameters of elastomeric bearing pad [29].

and the boundary condition. This limitation can be prevented by applying benchmarking based on experimental data and conditions. In addition, research that applies both models become important to accomplish in the future.

5 Conclusion

Several reviews have been done on the railway's technology and the failure phenomenon on the train track. One of these failure mechanisms is caused by the high thermal condition which resulting the buckled track phenomena. Moreover, selecting the material for the railway's construction is an essential part and it has influenced the fatigue crack resistance. For instance, the composition of Manganese (Mn) in common steel is less than that of micro-alloyed steel. It shows that there is a difference of 0.2 wt% of higher Manganese (Mn) in micro-alloyed steel. Besides, the use of the finite element method to improve railway construction is essentially important in the last decade. The rail–wheel contact with the distribution of Von Mises stress can be seen in the finite element method. The analysis can be used to determine the highest stress caused by the rail-wheels interaction. However, the development of railway is still challenging since the passengers need trains that are faster and safer.

References

1. Nejad, R.M.: Using three-dimensional finite element analysis for simulation of residual stresses in railway wheels, Eng. Fail. Anal. 45, 449–455 (2014).
2. Gras, T., Hamdi, M.A., Tahar, M.B., O. Tanneau, O., Beaubatie, L.: On a coupling between the Finite Element (FE) and the Wave Finite Element (WFE) method to study the effect of a local heterogeneity within a railway track, J. Sound Vib. 429, 45–62 (2018).
3. Ciotlaus, M., Kollo, G., Marusceac, V., Orban, G.: Rail-wheel Interaction and Its Influence on Rail and Wheels Wear, Procedia Manuf. 32, 895–900 (2019).
4. Skrypnyk, R., Ossberger, U., Pålsson, B.A., Ekh, M., Nielsen, J.C.O.: Long-term rail profile damage in a railway crossing: Field measurements and numerical simulations, Wear. 472–473, 203331 (2021).
5. Navikas, D., Sivilevičius, H.: Modelling of Snow Cover Thickness Influence on the Railway Construction Temperature Regime under Variable Weather Conditions, Procedia Eng. 187, 124–134 (2017).

6. Zakeri, J.A., Ghorbani, V.: Investigation on dynamic behavior of railway track in transition zone, J. Mech. Sci. Technol. 25, 287–292 (2011).
7. Chandra, S., Agarwal, M.M.: Railway Engineering. Oxford University Press, New Delhi (2003).
8. BPS (Badan Pusat Statistik).: Statistik Transportasi Darat 2020. Badan Pusat Statistik, Jakarta (2020).
9. DJKA (Direktorat Jenderal Perkerataapian).: Buku Statistik Semester 1 Tahun 2020. Direktorat Jenderal Perkerataapian, Jakarta (2020).
10. Orringer, O., Morris, J.M., Steele, R.K.: Applied research on rail fatigue and fracture in the United States, Theor. Appl. Fract. Mech. 1, 23–49 (1984).
11. Orringer, O., Morris, J.M., Jeong, D.Y.: Detail fracture growth in rails: Test results, Theor. Appl. Fract. Mech. 5, 63–95 (1986).
12. Godefroid, L.B., Souza, A.T., Pinto, M.A.: Fracture toughness, fatigue crack resistance and wear resistance of two railroad steels, J. Mater. Res. Technol. 9, 9588–9597 (2020).
13. AREMA.: American Railway Engineering and Maintenance-of-Way Association, Manual for Railway Engineering, Vol. 1 – Track. AREMA, Lanham (2019).
14. CEN.: European Committee for Standardization, EN 13674-1, Railway Applications – Track – Rail. CEN, Brussels (2017).
15. Madenci, E., Guven, I.: The Finite Element Method and Applications in Engineering Using ANSYS ®. Springer, New York (2015).
16. Prabowo, A.R., Tuswan, T., Ridwan, R.: Advanced development of sensors' roles in maritime-based industry and research: From field monitoring to high-risk phenomenon measurement, Appl. Sci. 11, 3954 (2021).
17. Prabowo, A.R., Tuswan, T., Prabowoputra, D.M., Ridwan, R.: Deformation of designed steel plates: An optimisation of the side hull structure using the finite element approach, Open Eng. 11, 1034–1047 (2021).
18. Prabowo, A.R., Ridwan, R., Tuswan, T., Sohn, J.M., Surojo, E., Imaduddin, F.: Effect of the selected parameters in idealizing material failures under tensile loads: Benchmarks for damage analysis on thin-walled structures, Curved Layer. Struct. 9, 258–285 (2022).
19. Ridwan.: Failure Assessment of Ship Hull Materials Under Tension Loading as Part of Impact Phenomena Using Finite Element Approach [Master thesis]. Universitas Sebelas Maret, Surakarta (2021).
20. Ridwan, R., Prabowo, A.R., Muhayat, N., Putranto, T., Sohn, J.M.: Tensile analysis and assessment of carbon and alloy steels using fe approach as an idealization of material fractures under collision and grounding, Curved Layer. Struct. 7, 188–198 (2020).
21. Dzulfiqar, M.F., Prabowo, A.R., Ridwan, R., Nubli, H.: Assessment on the designed structural frame of the automatic thickness checking machine - Numerical validation in FE method, Procedia Struct. Integr. 33, 59–66 (2021).
22. Prabowo, A.R., Ridwan, R., Muttaqie, T.: On the Resistance to Buckling Loads of Idealized Hull Structures: FE Analysis on Designed-Stiffened Plates, Designs. 6, 46 (2022).
23. Ridwan, Putranto, T., Laksono, F.B., Prabowo, A.R.: Fracture and Damage to the Material accounting for Transportation Crash and Accident, Procedia Struct. Integr. 27, 38–45 (2020).
24. Ridwan, R., Nuriana, W., Prabowo, A.R.: Energy absorption behaviors of designed metallic square tubes under axial loading: Experiment - based benchmarking and finite element calculation, J. Mech. Behav. Mater. 31, 443–461 (2022).
25. Alwan, F.H.A., Prabowo, A.R., Muttaqie, T., Muhayat, N., Ridwan R., Laksono, F.B.: Assessment of ballistic impact damage on aluminum and magnesium alloys against high velocity bullets by dynamic FE simulations, J. Mech. Behav. Mater. 31, 595–616 (2022).
26. Liu, G.R., Quek, S.S.: The Finite Element Method. 2nd Edition. Butterworth-Heinemann, Elsevier, Oxford, United Kingdom (2013).

27. Li, L., Nimbalkar, S., Zhong, R.: Finite element model of ballasted railway with infinite boundaries considering effects of moving train loads and Rayleigh waves, Soil Dyn. Earthq. Eng. 114, 147–153 (2018).
28. Arslan, M.A., Kayabaşi, O.: 3-D Rail-Wheel contact analysis using FEA, Adv. Eng. Softw. 45, 325–331 (2012).
29. Kettler, M., Zauchner, P., Unterweger, H.: Determination of wheel loads from runway cranes based on rail strain measurement, Eng. Struct. 213, 110546 (2020).
30. Prabowo, A.R., Bae, D.M., Sohn, J.M., Zakki, A.F., Cao, B., Cho, J.H.: Effects of the rebounding of a striking ship on structural crashworthiness during ship-ship collision, Thin-Walled Struct. 115, 225–239 (2017).
31. Bae, D.M., Prabowo, A.R., Cao, B., Sohn, J.M., Zakki, A.F., Wang, Q.: Numerical simulation for the collision between side structure and level ice in event of side impact scenario, Lat. Am. J. Solids Struct. 13, 2691–2704 (2016).
32. Prabowo, A.R., Cho, H.J., Lee, S.G., Baek, S.J., Byeon, J.H., Bae, D.M., Sohn, J.M., Harsritanto, B.I.: Evaluating structural crashworthiness and progressive failure of double hull tanker under accidental grounding: Bottom raking case, Open Eng. 8, 193–204 (2018).
33. Prabowo, A.R., Cho, H.J., Lee, S.G., Bae, D.M., Sohn, J.M., Cho, J.H.: Investigation on the Structural Damage of a Double-Hull Ship, Part II - Grounding Impact, Procedia Struct. Integr. 5, 943–950 (2017).
34. Prabowo, A.R., Cahyono, S.I., Sohn, J.M.: Crashworthiness assessment of thin-walled double bottom tanker: A variety of ship grounding incidents, Theor. Appl. Mech. Lett. 9, 320–327 (2019).
35. Prabowo, A.R., Laksono, F.B., Sohn, J.M.: Investigation of structural performance subjected to impact loading using finite element approach: Case of ship-container collision, Curved Layer. Struct. 7, 17–28 (2020).
36. Tuswan, T., Abdullah, K., Zubaydi, A., Budipriyanto, A.: Finite-element analysis for structural strength assessment of marine sandwich material on ship side-shell structure, Mater. Today Proc. 13, 109–114 (2019).
37. Tuswan, Zubaydi, A., Piscesa, B., Ismail, A.: Dynamic characteristic of partially debonded sandwich of ferry ro-ro's car deck: A numerical modeling, Open Eng. 10, 424–433 (2020).
38. A. Zulkarnain, W. A. Wirawan, H. Boedi Wahjono, and I. Puspitasari Aldoko, "The Effect of Air Pressure in the Electric Train's (KRL) Braking System on Wheel Damage," *J. Phys. Conf. Ser.*, vol. 1273, no. 1, 2019, https://doi.org/10.1088/1742-6596/1273/1/012077.