© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

The Effect of Layer Thickness on Stress Ratio and Fatigue Service Life of Plain Concrete Slab Track Structure

Emeralda Insani Nuansa Singgasana Pelangi Jelita Dialiran Sungai Pasadena[1*], Willy Barasa[1], Hanafi Isnanta Prabawa[1], Thiya Fiantika[1], Wimpie Agoeng Noegroho Aspar[1], Suci Putri Primadiyanti[1], A B Waseso[1], Bambang Piscesa[2], Dwi Agus Purnomo[1]

[1]Research Center for Transportation Technology,
National Research and Innovation Agency, Tangerang Selatan, 15314, INDONESIA

[2]Civil Engineering Department,
Institut Teknologi Sepuluh Nopember, Surabaya, 60111, INDONESIA

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2023.15.06.021
Received 16 July 2023; Accepted 30 September 2023; Available online 21 December 2023

Abstract: Indonesia has been developing a high-speed railway. Therefore, it is necessary to study slab track design configuration, which is convenient and efficient, by considering the country's environmental, geological, and geographical conditions. This paper discusses the effect of the layer thickness on the stress ratio and fatigue service life of slab track layers. The finite element method (FEM) analysis was performed to numerically simulate the maximum moment caused by 180 kN of axle load. Subsequently, the classic calculation of stress ratio and fatigue service life was conducted for various layer thicknesses. The same materials specifications, axle load, and the value of subgrade reaction were applied for all slab track configurations with various thicknesses. The results indicate that the thicker each layer is, the lower stress ratio and the higher fatigue service life. The thicknesses influence the contribution of each layer in resisting the axle load in the slab track system. The slab track design is still conservative because friction between each layer of the slab track design configuration was not considered. The analysis was conducted for plain concrete slab without any reinforcement. The results are interesting for practicing engineers and researchers, and more case studies might be beneficial.

Keywords: Concrete slab track, stress ratio, fatigue service life, finite element method (FEM)

1. Introduction

Infrastructure development is one of the strategic preferences to accelerate the growth and equity of the Indonesian economy. In order to improve the position of infrastructure competitiveness, it is necessary to accelerate infrastructure development to support the development of various cities. This strategy is in line with urbanization development in Indonesia. In addition, infrastructure development could support basic services and economic and urban development. The development aim was stated in National Medium-Term Development Plan for 2020 - 2024.

The main strategic issues and targets of national economic infrastructure development are railways connectivity to support the main cities' urban agglomerations and conurbation corridors. This strategy has a high level of demand for intercity travel. Furthermore, the strategic issue and target of urban infrastructure development are the need for the availability of an urban mass public transport system in six metropolitan areas in Indonesia such as Jakarta, Surabaya, Bandung, Medan, Semarang, and Makassar [1].

*Corresponding author: emer001@brin.go.id

In Indonesia, the speed of travel time is needed as part of railway transportation services to create reliable connectivity. The maximum speed rate of the railway is determined based on the lowest full speed between the maximum speed of the tracking capability and the train [2]. The average railway speed in Sumatera ranges from 25 to 40 km/h for inner-city lines and from 45 to 55 km/h for regional lines, and the maximum allowable speed is only around 70 km/h [3]. In Java, the average train speed reaches 70-90 km/h. However, the maximum allowable speed limit is 120 km/h [4]. This speed limitation is influenced by the ability of locomotives and infrastructure availability, such as rail lines with a rail width of 1.067 mm, rail lines with ballast - sub-ballast that do not the requirements comply, locations at several points that are prone to landslides and prone to subsidence, level crossings and vertical alignments.

With a faster train trip time, it will further increase community mobility. The acceleration of the travel time can be created by increasing the speed of the infrastructure traversed by the train. It means the railway facilities such as locomotives and trains can go faster on the same path yet still prioritize the safety of the trip. Several efforts can be made to improve the quality of train travel. One of which is the construction of a double-track on the southern route of Java which eliminates railroad crossings to speed up travel times. In addition, there are optimizing train speeds on curved tracks according to the curved design. Make improvements according to the optimal design on the arch so that the train's speed can be increased and also engineer the operating pattern by rearrangement of the duration of the stopping train at the station. Existing railway lines were carried out to improve the quality of rail materials, such as replacing bearings, rails, and drafts. Rail bearings that were originally still using wood or steel have now been replaced with concrete. Subsequently, the previously unfit rails have been repaired, and the R.42 or R.50 type rails are replaced with R.54 type rails which can accommodate higher train speeds. Another innovation that can be implemented is to replace the rail track ballast system with a ballast-less track system that uses a track slab as a place for rails to rest.

Slab track systems have many advantages, including the capabilities to serve these high-speed routes more efficiently than ballasted tracks, mainly due to their higher structural stability, significantly lower need for maintenance, and longer life cycle [5]-[7]. Higher track availability for the operator as a result of fewer maintenance requirements, superior stability and track alignment/geometry characteristics, and trafficability with road vehicles [8] may reduce noise and vibration in urban areas, minimize track maintenance costs and maintain track geometry [9].

This paper analyses of various thicknesses of slab track layers to find the relationship between the stress ratio and the fatigue service life for each layer. This paper is expected to accelerate railway development technology in Indonesia, especially for the high-speed railway technology.

2. Methodology

2.1 Slab Track Specifications

The main structural components of slab track consist of rail, surface layer, middle layer, and bottom layer of slab track, as shown in Fig. 1 [10]. Design requirements, model geometry, and mechanical properties are needed to define the slab track. The data obtained are from the literature review. The properties for all the structural components needed to build the model are clearly shown in Table 1. These numbers were used to simulate numerically and adapted with the applicable standards. The constitutive equation for concrete design only consisted of elastic concrete material with a specific concrete compressive strength, Young's modulus, and Poisson's ratio. The Young's modulus input in SAP2000 was computed using ACI 318-19/SNI 2847-19 standard for the ultimate strength criteria.

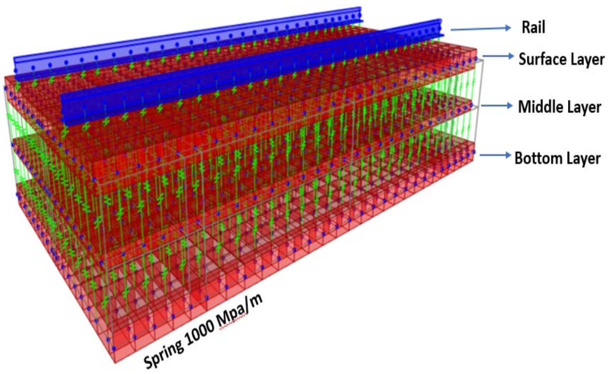


Fig. 1 - Components of track slabs [10]

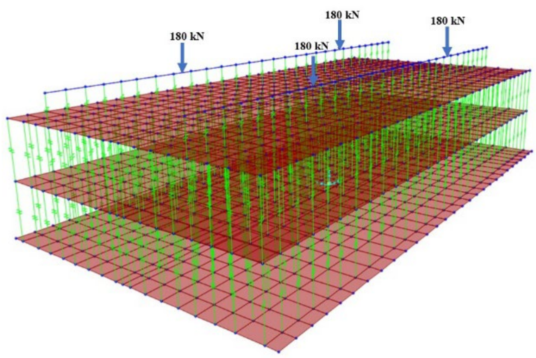


Fig. 2 - Loading of slab track model

2.2 Finite Element Analysis

In order to study the characteristics of slab track, an analysis model was established by three-dimensional finite element software [10]-[14]. The components of the slab track were simulated by various elements, respectively. Rail was simulated by beam element, and solid element will be used to model the surface layer, middle layer, and bottom layer of slab track. Every layer is connected with two joint roller rigid links to transfer the load from the upper layer to the bottom layer. In the finite element model, the bottom surface, which is the bed plate, is constrained by spring with a value of stiffness is 62,500 N/mm.

Numerical analysis using the finite element method was done by inputting all parameters (model, mechanical properties, load, and load combination). In this case, the static load is used to analyse the numerical simulation. For the dynamic moving load analysis, a dynamic load allowance (DLA) was known and was used to scale up the static axle load in the analysis for design purposes. Fig. 2 illustrates the loads applied in a static model with 180 kN in each axle loads with a 0.5 dynamic load factor. In case of the fatigue simulation, the load combination used from Indonesian National Standard (SNI) 1725:2016 about loading for bridges which is 1.0 D + 1 (1.0 + 0.5) L and the ultimate load combination is 1.3D + 1.8 (1.0 + 0.5) L; where D represents dead load and L represents live-load.

2.3 Stress Control

According to the numerical simulation results, the mechanical characteristics of the structure can be defined. The stress and moment of each component become the main elements for design optimization calculations. The stress was then investigated by calculating the stress ratio. The stress ratio can be affected by the modulus of rupture and maximum stress from the result of numerical simulation. In the ACI 318-19 Code, the calculation of modulus rupture can be defined in eq. (1) [15], and the stress ratio is calculated by eq. (2). According to the numerical simulation result, the maximum structure moment is needed to calculate the stress ratio. In Asia, the value of the stress ratio is less than 0.4.

$$f_{rup} = 0.62\sqrt{f'c} \tag{1}$$

$$R = \frac{\sigma_{\max}}{f_{rup}} \tag{2}$$

where f_{rup} = modulus rupture, f'_c = compressive strength of concrete, R = stress ratio, and s_{max} = maximum stress of the structure.

Table 1 - Properties of the slab track model components

Components	Length (mm)	Width (mm)	Height (mm)	Concrete Strength	Elasticity Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)	Stiffness (MPa/m)
Track Slab	5,000	2,500	200	F'c 50	33,234	0.2	2,500	
SCC	5,000	2,500	100	F'c 30	25,742	0.2	2,500	
Bed Plate	5,000	2,700	200	F'c 25	23,500	0.2	2,500	
Support Layer								1,000

2.4 Fatigue Check-In Concrete

Fatigue in concrete can be defined as the incremental damage due to subsequent propagation of cracks under repeat loading [16]. Fatigue in concrete can be performed by laboratory tests with an investigation of the behaviour of concrete under cyclic tension [17] and presented in eq. (3).

$$f_{rd} = k_{1f} f_d \left((1-\sigma_p) / f_d (1 - \frac{\log N}{K}) \right) \tag{3}$$

where f_{rd} = design fatigue strength, k_{1f} = may be determined for compression and flexural compression (k_{1f} = 0.85) and for tension and flexural tension (k_{1f} = 1.0), f_d = design strength of concrete, σ_p = stress due to permanent loads, $N = \leq 2 \times 10^6$, and K = shall be taken as 10 for normal concrete.

2.5 Thickness Adjustment

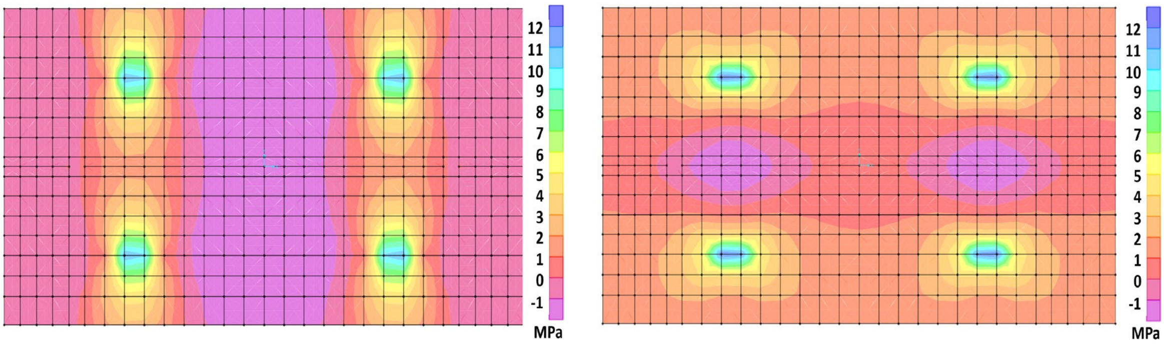
The thickness of each component of the slab track greatly affects the design result, particularly the service life of the structure. Simulation of each layer was done many times by iterating value thickness to obtain the optimal thickness. While the track slab layer analysis was performed, the other layers were at a constant thickness. Therefore, in this paper, three results show the relationship between the thickness and stress ratio and also the relationship between the thickness and service life of slab track.

3. Results and Discussion

3.1 Surface Layer of Slab Track Analysis

The FEM model was established to obtain the maximum moment caused by 180 kN of axle load for each configuration. Subsequently, the stress ratio and fatigue life service calculation for plain concrete slabs were conducted. Therefore, the relationship graph will be exhibited between the thickness of each layer and the stress ratio. The stress value was determined by the maximum moment caused by the load located on the nodal axle load. The color of the surface layer of the slab track represents what occurs. For instance, the blue color shows that stress is a positive result, while the purple color is a negative result. The results depend on the color scale, as shown in Fig. 3.

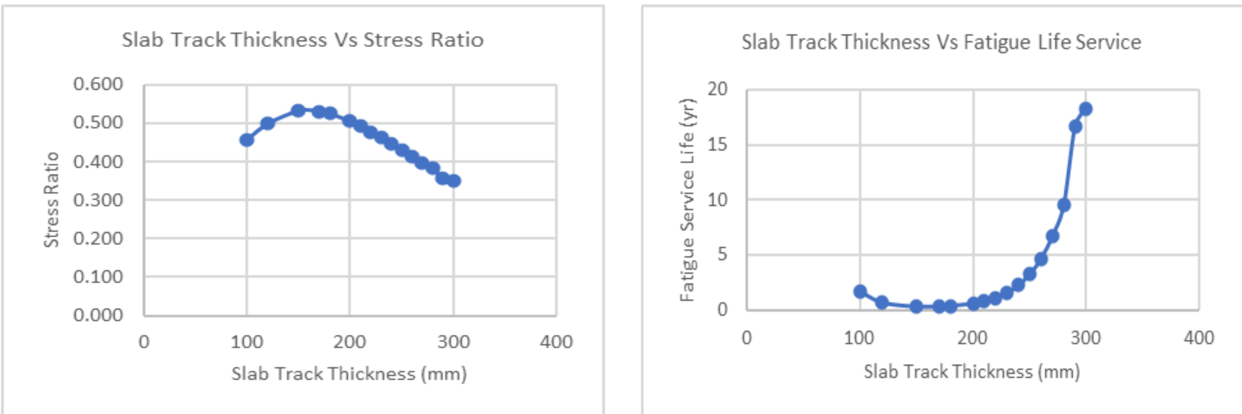
The slab track has become the most important layer in the system because it is the first layer to withstand the axle load from a high-speed train. Thus, it is necessary to consider the track slab thickness according to the maximum stress allowed in the concrete slab. The idea that the stress brought on by load is less than the flexural strength of the slab concrete guides the calculation of the slab thickness [18]. However, it is also necessary to consider the fatigue life of the concrete. The relationship between track slab layer thickness and the stress ratio, also with fatigue life service, is shown in Fig. 4. It can be seen that the stress ratio initially builds up as the slab track thickness increases. However, after the stress ratio reaches the maximum value, subsequently the stress ratio drops even though the slab track thickness is getting bigger. As the thickness of the slab track increases, the fatigue service life also increases and shows a higher number.



(a) (b)

Fig. 3 - Stresses at the surface layer of slab track under loading type of 1.0D + 1.5L (a) M11 stress in a surface layer of slab track on an X-axis, and; (b) M22 stress in a surface layer of slab track on a Y-axis

This phenomenon occurred because the slab track configuration consists of three functional layers that withstand the load altogether. When the track slab layer is thinner, the maximum moment caused by axle load will be in the thicker layer, such as the bed plate and SCC. Therefore, the bed plate will significantly contribute to resisting the applied load. It is because of the thickest layer in the track slab system. In this case, the slab track does not really give a contribution to resisting the applied load. However, after reaching 150 mm thickness, the slab track layer will gradually increase the stress ratio and fatigue life service.



(a) (b)

Fig. 4 - Influence of slab track thickness (a) stress ratio, and; (b) fatigue service life

The R-value, as shown in Fig. 4(a) influenced by the maximum service stress carried out by the track slab and the modulus of rupture of the concrete (f_{rup}). Furthermore, the modulus of rupture value is influenced by the compressive strength of concrete, which is the critical factor affecting the slab's ability to resist failure [15]. The safety limit on R-value is 0.4; thus, if R > 0.4, it is necessary to conduct fatigue stress control to find out the fatigue service life. Fatigue design analysis follows Standard Specification for Concrete Structures (2007) by Japan Society of Civil Engineers, where the fatigue strength for concrete in compression, flexural compression, tension, and flexural tension, expressed as a function of fatigue life N cycle and stress due to permanent loads [17].

Fig. 4(b) illustrates the relationship between track slab thickness and fatigue service life. It is seen that the thicker the track slab layer is, the longer the fatigue service life could be. This can be understood because the *N* cycle value influences the fatigue life of the concrete. The *N* cycle will increase if the life service also gets increases. However, it is necessary to conduct more studies to find the reinforcement needed. Thus, the minimum track slab thickness and reinforcement area needed according to the fatigue service life plan can be inferred.

3.2 Middle Layer of Slab Track Analysis

The middle layer of the slab track will be controlled against cyclic loads and allowable stresses. The main focus of finding out the check is to make changes in the thickness of the middle layer of the slab track ranging thickness from 50 mm to 150 mm. When the thickness of the middle layer of the slab track is changed, other layers above and below it, such as the surface layer and bottom layer of the slab track, remain with a thickness of 200 mm. The maximum moment caused by the load is shown in Fig. 5. The relationship between the middle layer of slab track thickness and stress ratio, also with the stress shown in Fig. 6.

With a thickness of 50 to 150 mm, the middle layer of the slab track is strong enough to be loaded with an unlimited number of cyclic loads. Nevertheless, it is still required to check against its planned life. It was assumed that the slab track operated for 50 years. With a plan life of 50 years and varying middle layer of slab track thickness, it is necessary to check the stress on the middle layer of slab track with the allowable stress. From the results of the analysis, it was found that with a thickness greater than 130 mm, the stress on the middle layer of slab track is smaller than the allowable stress according to the Japan Society of Civil Engineers - Standard Specification for Concrete Structure 2007. Therefore, the layer thickness starting from 130 mm is not appropriate to be applied on the slab track. This is due to as the thickness of the middle layer of the slab track increases, and the service stress gets larger. This is also supported by the increase in the magnitude of the bending moment on the middle layer of the slab track, yet the bending moment on the track slab layer and bed plate is reduced so that a stress concentration occurs.

3.3 Bottom Layer of Slab Track Analysis

The bottom layer is located on the base of the track slab structure. This layer works to transmit the load from the upper structure to the subgrade or other structure on elevated construction. Besides the axle load from the train, this layer withstands extra dead load from the surface layer and middle layer structure itself. Similar to the other layers, the maximum moment of the bottom layer is located on the nodal axel load, as shown in Fig. 7.

The calculation results of various thicknesses in the bottom layer are shown in Fig. 8. The results indicate that the 100 mm bottom layer has the smallest stress ratio, which is 0.3631. Based on the calculation to find out the design service life. It is known that the design age is 14.3 years which is also the longest design age for the bottom layer. In the beginning, the design age of the bottom layer suddenly dropped as the bottom layer thickness increased from 100 mm to 200 mm. Subsequently, design age gradually increases as the bottom layer thickness increases, and it continuously increases. The bottom layer with 200 mm thickness has the biggest stress ratio, which is 0.5051. However, its design age is the least at 0.55 years only. After 200 mm, then continuously add the thickness until 300 mm. In the thickness range of 200 mm to 300 mm, the stress ratio decreases to 0.4167.

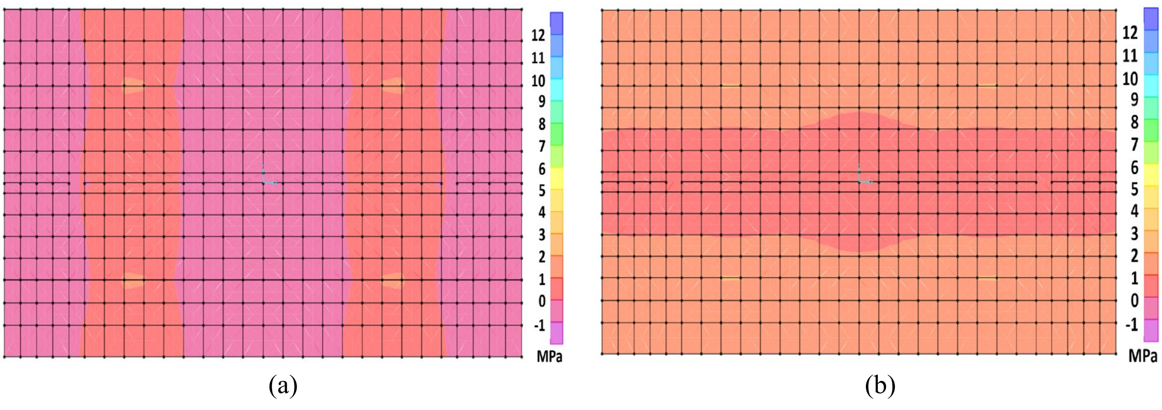
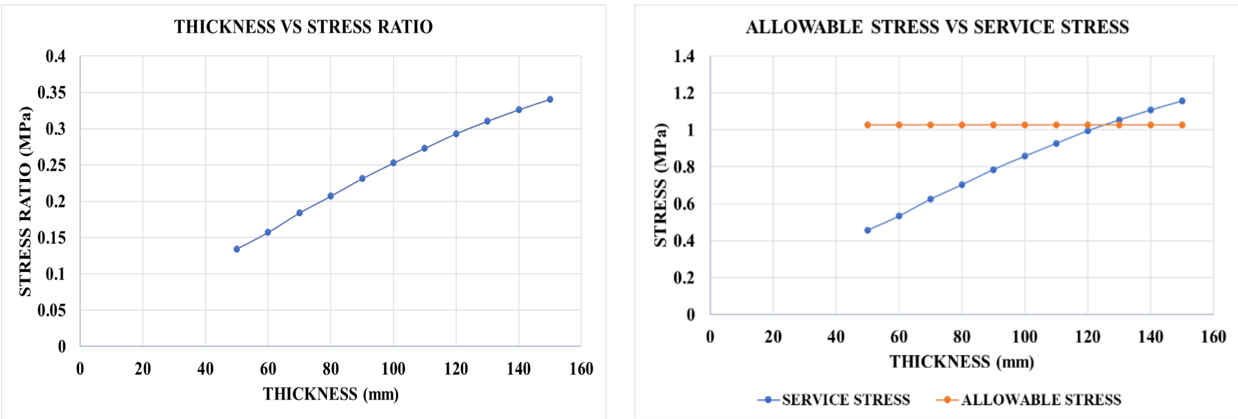


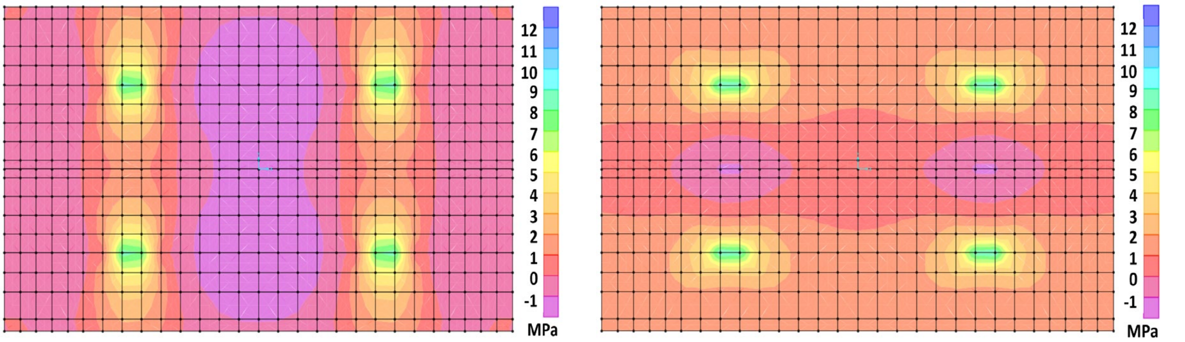
Fig. 5 - The stress of the middle layer of slab track on loading type 1.0D + 1.5L (a) M11 stress in the middle layer of slab track in the X-axis, and; (b) M22 stress in the middle layer of slab track in the Y-axis



(a) (b)

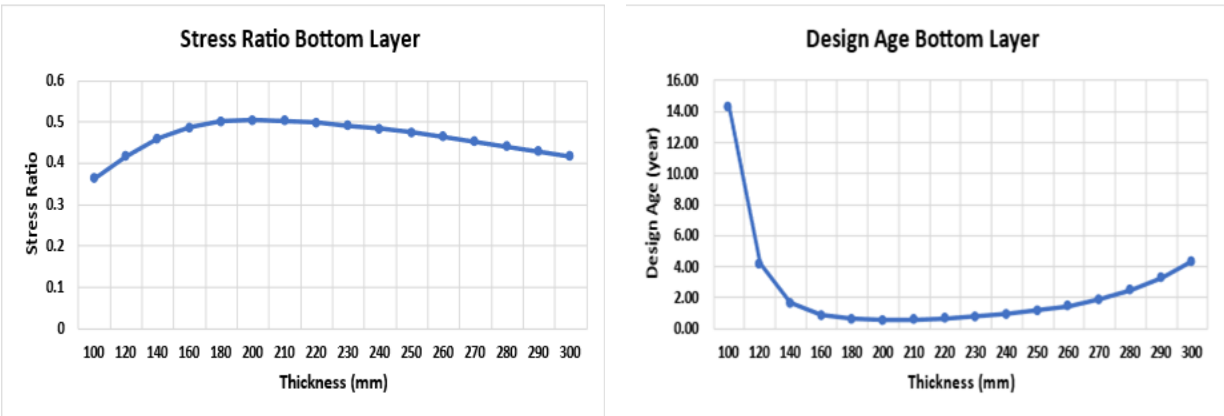
Fig. 6 - The comparison of thickness middle layer of slab track with stress ratio and stress (a) thickness vs. stress ratio, and; (b) allowable stress vs. service stress

On the thickness of 100 mm, the moment that occurs on the bottom layer doesn't really affect the track slab system that consists of the bottom layer, middle layer, and surface layer. This is because the bottom layer's thickness is smaller than two other layers, so the moment that impact, the slab track system spreads on the thicker layer. However, if the thickness of the bottom layer is more than 200 mm, this layer is quite influential because of the biggest thickness of other layers.



(a) (b)

Fig. 7 - The stress of the bottom layer of slab track on loading type 1.0D + 1.5L (a) M11 stress in the bottom layer of slab track in the X-axis, and; (b) M22 stress in the bottom layer of slab track in the Y-axis



(a) (b)

Fig. 8 - The comparison of the bottom layer thickness of the slab track with stress ratio and design age (a) stress ratio on the bottom layer; (b) design age on the bottom layer

4. Concluding Remarks

The facts of the study concerning the effect of layer thickness on stress ratio and fatigue service life of plain concrete slab track structure is obtained and presented as the following.

This paper describes aspects of layer thickness to the stress ratio and the design age of the slab track and life service. The results obtained from the analysis indicate that each layer has its proportional thickness to contribute to withstand the load altogether in the track slab structure configuration. For the slab track layer, the minimum thickness needed is 150 mm with an R-value of 0.533. The Middle layer of the slab track's function transfers the load to the bed plate and ties the layers between the track slab and bed plate. SCC needs to be limited the thickness to 120 mm due to the allowable stress calculated.

The minimum thickness depends on the stress value resisted by the bed plate. For the bottom layer of the slab track, the minimum thickness is 200 mm with an R-value of 0.5051. If the R-value for minimum thickness exceeds 0.4, it is necessary to add the reinforcement to achieve unlimited cycle loading or obtain the fatigue service life plan.

The thickness for each layer needs to be adjusted for all the layers that could contribute to withstand the load altogether. However, more study about slab track configuration needs to be conducted regarding reinforcement and fatigue service life plan.

Acknowledgement

This work is part of the research study carried out in the Research Centre for Transportation Technology (PR TT), National Research and Innovation Agency - BRIN, Jakarta, Indonesia. BRIN financed the study via National Research Budget, Research and Innovation for Advanced Indonesia scheme, and LPDP grants. The authors are grateful for the financial support provided by the institutions. The authors would appreciate reviewers who provided constructive suggestions.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that the publication of this paper does not constitute a conflict of interest.

References

[1] Republic of Indonesia (2020). The National Medium-Term Development Plan For 2020-2024. Appendix Presidential Regulation Number 18 of 2020. Indonesia. pp. I.3 - IX.35.

[2] Kementerian Perhubungan Republik Indonesia (2009). Government Regulation PP No. 72. Railway Traffic and Transportation. https://djka.dephub.go.id/regulasi?lang=en_.

[3] Setiawan D. M. (2016). Pembatasan kecepatan maksimum dan kaitannya terhadap kapasitas lintas jalur kereta api Muara Enim- Lahat, Sumatera Selatan. Prosiding Seminar Nasional Teknik Sipil 2016, Surakarta, Indonesia, pp. 36-46.

[4] PT. KAI (2021). Percepatan waktu tempuh KA sebagai peningkatan pelayanan KAI. https://www.kai.id/information/full_news/5098.

[5] Michas G. (2012). Track Slab Systems for High-Speed Railways. MSc Thesis, KTH Royal Institute of Technology.

[6] Esveld C. (2003). Recent developments in slab track. European Railway Review, 9(2), 81-85.

[7] Matias S. R. & Ferreira P. A. (2020). Railway slab track systems: Review and research potentials. Structure and Infrastructure Engineering, 16(12), 1635-1653.

[8] Thuer G. & Vocks H. (2012). Track Slab System Technology in Australia: Innovation Challenges Based On European Long Term Experiences. AuRAIL 2012 Rail's Role Society, pp. 27-28.

[9] Tayabji S. D. & Bilow D. (2001). Concrete track slab state of the practice. Transportation Research Record, 1742, 87-96.

[10] Yu Z., Xie Y., Shan Z. & Li X. (2018). Fatigue performance of CRTS III slab ballastless track structure under high-speed train load based on concrete fatigue damage constitutive law. Journal of Advanced Concrete Technology, 16(5), 233-249.

[11] Zhu K., Zeng Z., Wu B. & Wei W. (2016). Influence of interface bond damage on the dynamic characteristic of CRTS III track slab. Proceedings of the 6th International Conference on Electronic, Mechanical, Information and Management Society, https://dx.doi.org/10.2991/emim-16.2016.364.

[12] Pradnyanita P., Piscesa B., Attard M. & Samani A. (2020). Numerical investigation of HSC column under axial and flexural loading using 3D-NLFEA. IOP Conference Series: Materials Science and Engineering, doi:10.1088/1757-899X/930/1/012057.

[13] Prasetyo A. D., Piscesa B., Al Rasyid H. & Prasetya D. (2020). 3D non-linear finite element analysis of concentrically loaded high strength reinforced concrete column with GFRP bar. Journal of Civil Engineering, http://dx.doi.org/10.12962/j20861206.v35i1.7750.

[14] Piscesa B., Attard M. M. & Samani A. K. (2017). Three-dimensional finite element analysis of circular reinforced concrete column confined with FRP using plasticity model, Procedia Engineering, 171, 847-856.

[15] Issa C. A., Gerges N. N. & Fawaz S. (2014). The effect of concrete vertical construction joints on the modulus of rupture, Case Studies in Construction Materials, doi: 10.1016/j.cscm.2013.12.001.
[16] Maitra S. R., Reddy K. S. & Ramachandra L. S. (2020). Material and size effect on fatigue damage of concrete for pavement application. Transportation Research Procedia, doi: 10.1016/j.trpro.2020.08.071.
[17] Uomoto T., Ishibashi T., Nobuta Y., Satoh T., Kawano H., Takewak K. & Uji, K. (2008). Standard specifications for concrete structures-2007 by Japan Society of Civil Engineers. Concrete Journal, doi: 10.3151/coj1975.46.7_3.
[18] Liu X., Zhao P. & Dai F. (2011). Advances in design theories of high-speed railway ballastless tracks. Journal of Modern Transportation, doi: 10.1007/bf03325753.