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Material Parameters Effect and Optimization of Rail Clip Design for Heavy Haul Subjected to Different Axle Loads and Speeds

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Abstract

The fastening system, a critical component in railway engineering, serves the dual purpose of transferring the load from the rail to the sleeper while ensuring the rail's steadfast position. Due to increase of annual tonnage, concrete sleepers and fastening systems have been experiencing a wide variety of failures that include rail seat deterioration, insulator wear, shoulder deterioration, and worn rail pads. The mechanical behavior of fastening system is not fully investigated and further research need to be done. The primary objective of this research is to analyze the impact of varying axle loads and speeds on rail clips, considering various mechanical properties. The study aims to comprehensively assess their overall influence on the performance of the railway system. Finite element method is used for this analysis. Modal analysis is utilized to pinpoint areas of maximum deformation, specifically at the point of contact with the rail (front toes) and the lower two arches. Further insight is gained through frequency response analysis, conducted across varying speeds and axle loads. Additionally, the analysis extends to exploring the impact of altering mechanical properties such as density, Young's modulus, and Poisson's ratio. The results demonstrate that increasing the values of the mechanical properties leads to an increase in both the amplitude and corresponding frequencies. The relationship between speed, axle load, and the corresponding frequencies and amplitudes is determined. The results not only confirm expectations but introduce novel observations, providing a comprehensive understanding of how these factors interplay in the railway system.

Keywords: Rail clip, optimization, heavy haul, Finite element

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1. Introduction

One of the primary maintenance challenges facing the rail industry is the lack of compatibility between the life cycles of infrastructure components. If the life cycle of the materials that make up the rail seat and fastening system is not sufficient to match the life cycle of the rail, interim repairs of the rail seat may be necessary (Ryan et al., 2014). It has been shown that the majority of derailments are directly or indirectly caused by defects in rail-sleeper fastening systems (Sadeghi et al, 2010; Sadeghi ,2007).

Improved designs of track superstructure components are greatly needed, especially for heavy haul freight and high-speed rail lines. Significant attention should be given to the design of these components. These improved designs are particularly critical for joint heavy haul freight and high-speed passenger rail infrastructure, where loading demands are highest, track geometric requirements are most stringent, and track occupancy time is at a premium. Improvements in concrete crosstie and fastening system designs also help address the need to reduce track maintenance windows, thereby increasing rail capacity (Ryan et al., 2014).

The current design process is primarily based on practical experience and previous techniques, which fail to incorporate key variables related to actual field loading conditions. An example of designed components not meeting the requirements of current loading conditions is a study conducted at UIUC in 2012, which concluded that the average maximum freight static axle load exceeded the design axle load (Van et al. ,2012). Using this process often results in rail components not meeting their design life. While initially functional, they ultimately require more frequent maintenance or fail prematurely, leading to track outages, reduced capacity, and increased costs.
Recently, numerous studies have been conducted on rail fastening systems, but the mechanical behavior of these systems is not fully understood or investigated. The relationship between extreme loading events and failure mechanisms is not well-defined, making it difficult to determine the required robustness of the design (Van et al. ,2012).

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Due to vibration, noise, and increased dynamic loads in the traffic volume system, many broken rail clips have been found on some rail lines worldwide. Several studies have been reported on rail clips, including optimal design (Xiao and Zhao, 1995), influence of different materials on static properties (Yang and Pan, 2012), design parameter sensitivity (Li et al.,2016), geometry parameters (Hu et al.,2017), fatigue failure (Mohammdzedeh et al.,2014; Mohammdzedeh et al.,2014); Hasap et al.,2018); Hasap et al.,2018); Ferreno et al.,2019), modal and harmonic response (Xiao et al.,2017), and the influence of geometric parameters on clamping force and maximum stress (Hu et al.,2017). Additionally, Hu et al.,2017) revealed that the broken fastening system in railway lines is caused by fatigue failure accompanied by short-pitch rail (Liang et al.,2014).

Yung et al.,2014) studied the optimization design of rail clips in the Vossloh fastening system using experimental and finite element methods. They employed uniform design and grey relation analysis to present the strength and fatigue safety of a rail clip under a multi-objective optimization procedure. Ping et al. (2020) investigated the effects of clip material on the fatigue life of elastic rail clips under rail corrugation by considering optimal design and anti-corrugation design. However, limited research has been conducted on fatigue failure considering the mechanical properties by applying different axle loads and speeds.

Since the stiffness of a fastening system is one of the most important characteristics that directly impacts its long-term performance under repeated axle loading, research is needed to understand the effect of different loading scenarios with varying speeds. This analysis aims to examine the effect of applying different axle loads and speeds on rail clips to understand their overall impact on the performance of the railway system using the finite element method. Utilizing the finite element method is crucial as it allows for the visualization of spatial stress and deformation, identification of critical stress locations, and assessment of rail clip loading (Bartos et al.,2006).

2. Method and Data Sources

The dynamic analysis of the clip was performed using ANSYS software. All the components were considered as solid. The assembly consists of a Rail Clip, Bolt, Rail, and Guide Plate, as indicated in Figure 1. The fastening system W 40, Vossloh type was used as it can be used where speed is

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greater that 250km/h with axle load less than 30t. The speeds of 80, 100, 120 and 160 km/h have been considered. The speeds were chosen because most of the heavy haul lines are designed not to exceed a speed of 160km/h. The different wheel loads with different axle load and rail seat loads used were calculated based on the formulas presented in equations (1) to (3) from AREA quoted by N.F.Doyle, (1980) to account the dynamic factor as the speed increases, and the calculated values are presented in Table.1

In our days due to high demand there is an increase of the axle load. In order to capture the effect of axle load increment, the axle of 25, 30, 35, and 40t were chosen. They were chosen based on most used worldwide and future considerations, especially the 40t axle load. In the analysis a combination of lateral and vertical load was used with ratio of 0.1, 0.3 and 0.5 (lateral load to vertical load) by keeping the vertical load constant. The ratio was limited to 0.5 because it is believed that it's the worst case that may happen.

$$\phi = 1 + 5.21\frac{V}{D} \tag{1}$$

$$P = \frac{Axle\ \text{load}}{2} \times \phi \tag{2}$$

$$q_r = DF \times P \tag{3}$$

Where P is the design load in kN

Where V is speed (km/h)

ϕ is the dynamic factor

D is wheel diameter (mm) =864mm

q_r is rail seat load

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DF is a distribution factor, expressed as a percentage of the wheel load and for concrete sleepers was obtained as 51%. The mechanical properties used in this simulation are shown in Table 2. Modal and frequency response analyses were conducted to extract the principal modal shape characteristics and their corresponding frequencies, aiming to assess the dynamic characteristics of the rail clip. This analysis will help identify the modal deformation characteristics that cause stress concentration points on the clip. The first six modal shapes were extracted and are presented in Table 3.

The automatic meshing was carried out with an element size of 3mm, resulting in a total of 19,376 elements. For the boundary conditions, the clip was fixed on the side of the guide plate, and a compressive force was applied to the rail side. A preload force of 10kN was applied at the surface of the bolt. The compressive forces applied to the rail are presented in Table 1and calculation were made based on the presented formulas (1), (2) and (3) and the boundary conditions can be seen in Figure 1. The mechanical properties considered in the analysis are based on literature (Ping et al.,2020).

Table.1. Vertical load for different speeds

Speed (km/h)	Dynamic factor	Rail seat load (kN)			
		Axle load (t)			
		25t	30t	35t	40t
80	1.482	94.47	113.5	132.2	151.2
100	1.603	102.2	122.6	143.0	160.3
120	1.723	109.8	131.8	153.7	172.3
160	1.964	125.3	150.2	175.3	196.4

Table.2. Material properties of the model components for different cases

Properties	Cases	Rail	Rail clip	Bolt	Guide plate
Density (kg/m^3)	Case 1	7000	4500	4500	950
	Case 2	7900	7800	7900	1000

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Young's Modulus (GPa)	Case 1	150	100	100	2
	Case 2	220	200	220	4.5
Poisson's Ratio	Case 1	0.3	0.29	0.3	0.4
	Case 2	0.3	0.29	0.3	0.4

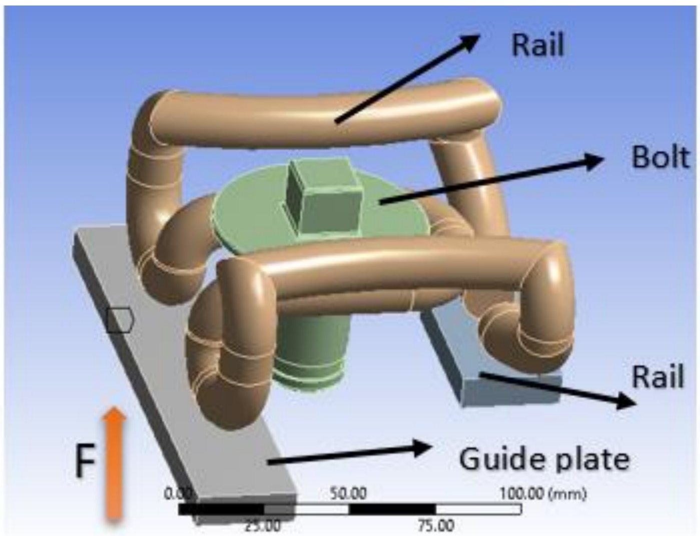

Figure. 1. Components of the fastening system model and boundary conditions.

3. Results Analysis and Discussions

Table 3 presents the 6 main frequency and its deformations from modal analysis. From the table, it can be observed that the deformation is high at the point of application with the rail (front toes) and at the lower two arches. For the mode 1 with frequency of 114.78 Hz, the deformations indicate that two low arches of the clip and the two front toes move vertically in the same direction. For the mode 2 with frequency of 221.78 Hz, two heels of the clip and the front toes move longitudinally in the same direction. For the mode 3 with frequency of 374.23 Hz, Low arch of the clip and the two front toes move vertically, but in different direction. For the mode 4 with frequency of 418.73 Hz, one high arch move vertically in different direction with the other high arch and one front toe move vertically in different direction with the other front toe. For the mode

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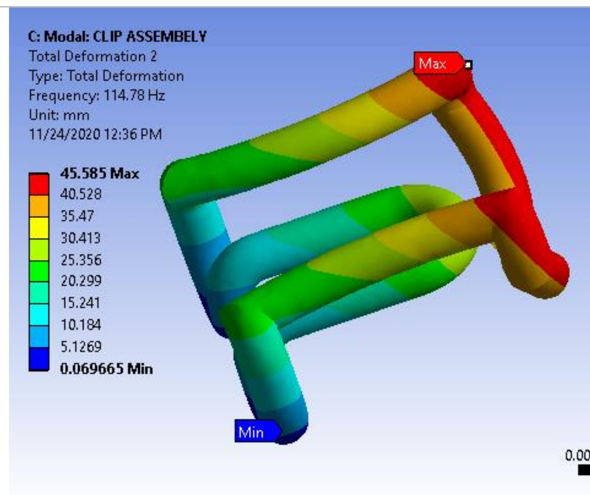
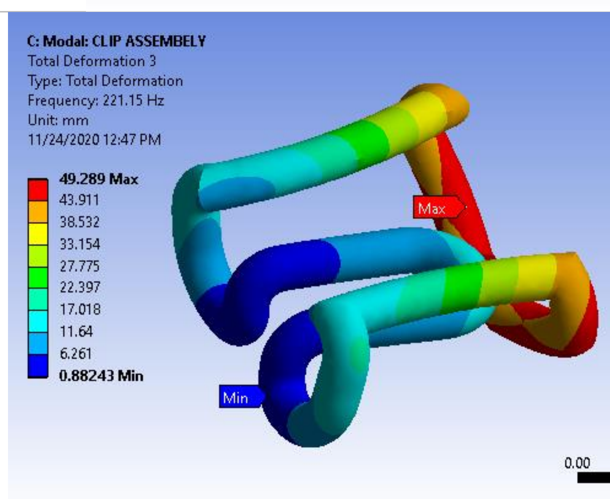
5 with frequency of 653.87 Hz, two low arches of the clip move vertically, while the two front toes remain in their position. For the mode 6 with frequency of 671.88 Hz, two high and low arches move longitudinally, but in different direction. It is seen that these frequencies exhibit high deformations, which can cause the cracks of the clips. During the manufacturing and design process, it is important to pay close attention to these areas to prevent rapid cracking.

Table.3. Frequency mode

Mode	(Hz)	Nephogram	Description of the vibration mode
1.	114.78		Two low arches of the clip and the two front toes move vertically in the same direction.
2.	221.15		Two heels of the clip and the front toes move longitudinally in the same direction.

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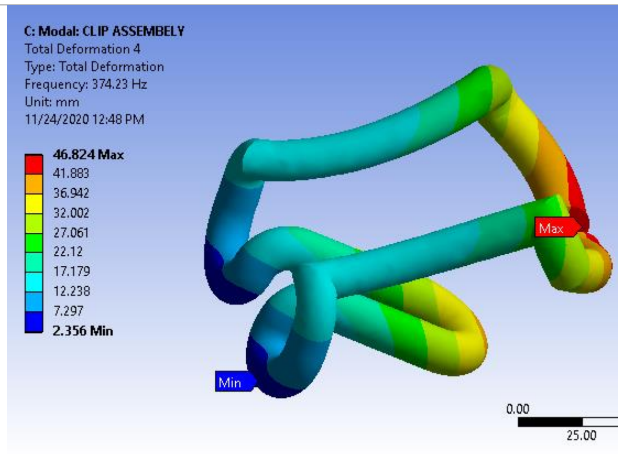
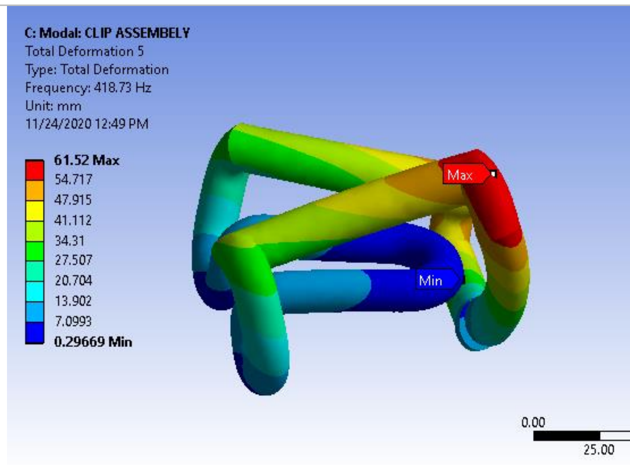
3.	374.23		Low arch of the clip and the two front toes move vertically, but in different direction.
4.	418.73		One high arch move vertically in different direction with the other high arch and one front toe move vertically in different direction with the other front toe.

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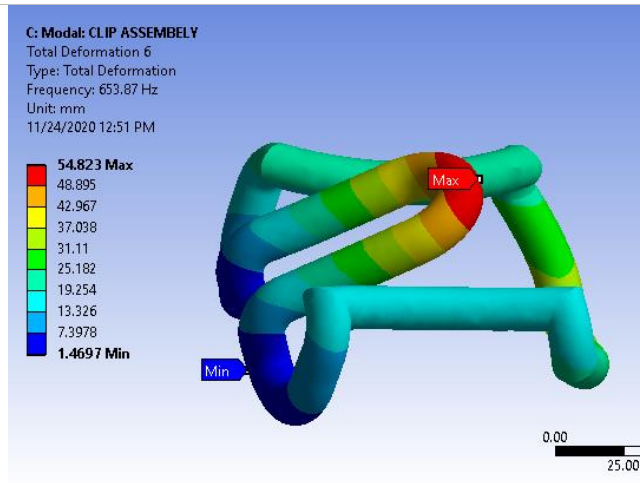
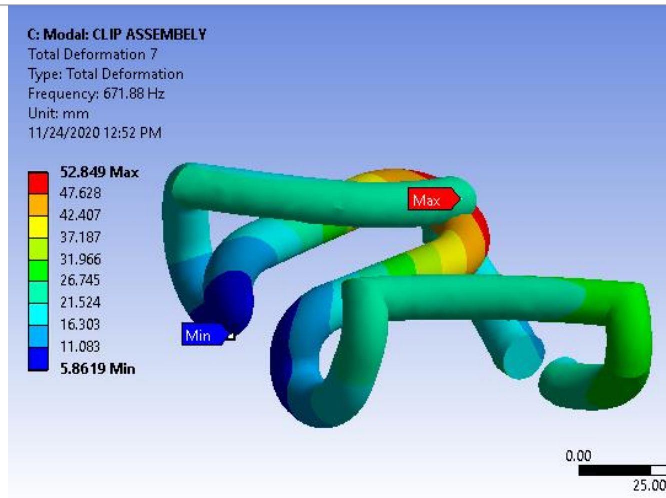
5.	653.87	 	Two low arches of the clip move vertically, while the two front toes remain in their position
6.	671.88	 	Two high and low arches move longitudinally, but in different direction.

Frequency response analysis has been conducted, and the results are presented in Figure 2 and 3, which shows frequency response by changing mechanical properties of rail clip a) Frequency response for 25t axle load, b) Frequency response for 40t axle load. As shown in the results, the analysis was performed for different speeds and axle loads. It can be observed that with an increase in speed, the amplitude also increases, but the corresponding frequency remains unchanged. This indicates that increasing speed does not affect the frequency excitation but leads to an increase in

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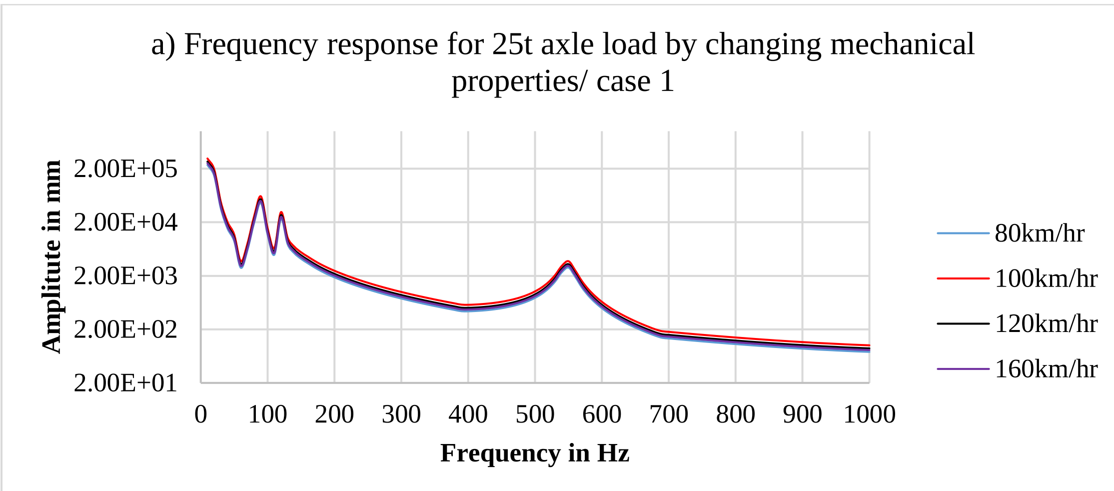
amplitude. When the axle load is increased from 25t to 40t, the amplitude increases, and the frequency increases at a low rate.

Furthermore, the analysis was also conducted by varying the mechanical properties (density, Young's modulus, and Poisson's ratio) as presented in Table 2. The results demonstrate that increasing the values of the mechanical properties leads to an increase in both the amplitude and corresponding frequencies. The amplitude is particularly high at low frequencies. It is worth noting that increasing the speed does not alter the amplitude or frequency shifts.



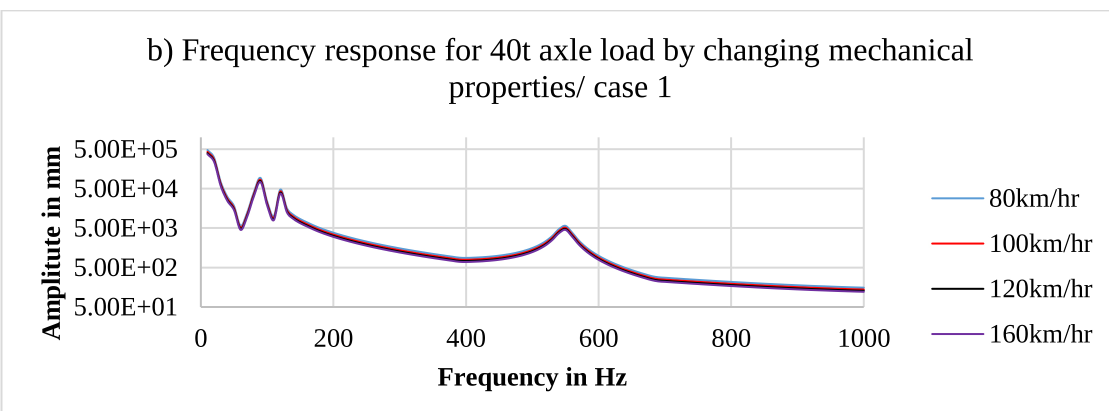


Figure.2. Frequency response by changing mechanical properties of rail clip a) Frequency response for 25t axle load (Case 1), b) Frequency response for 40t axle load (Case 1)

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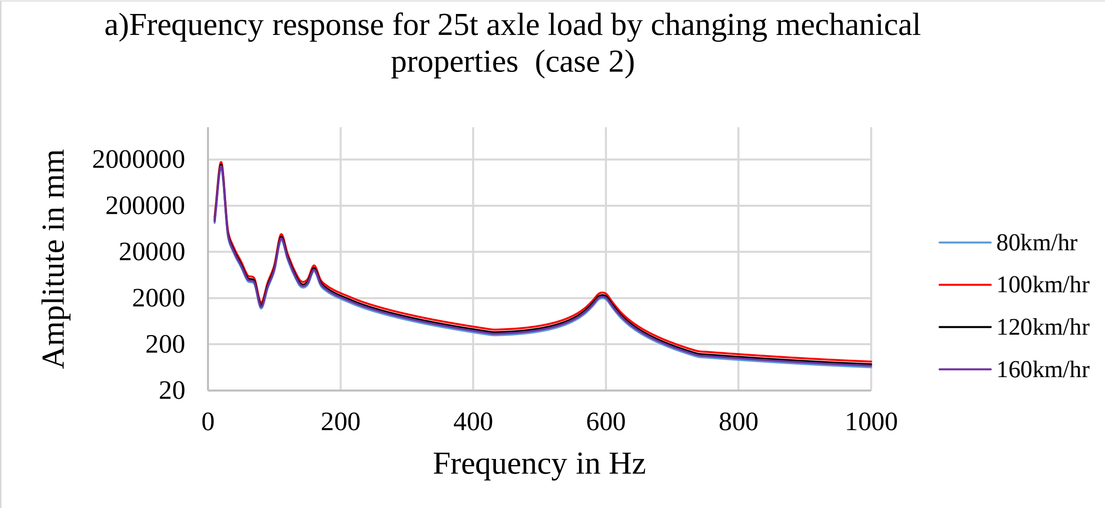

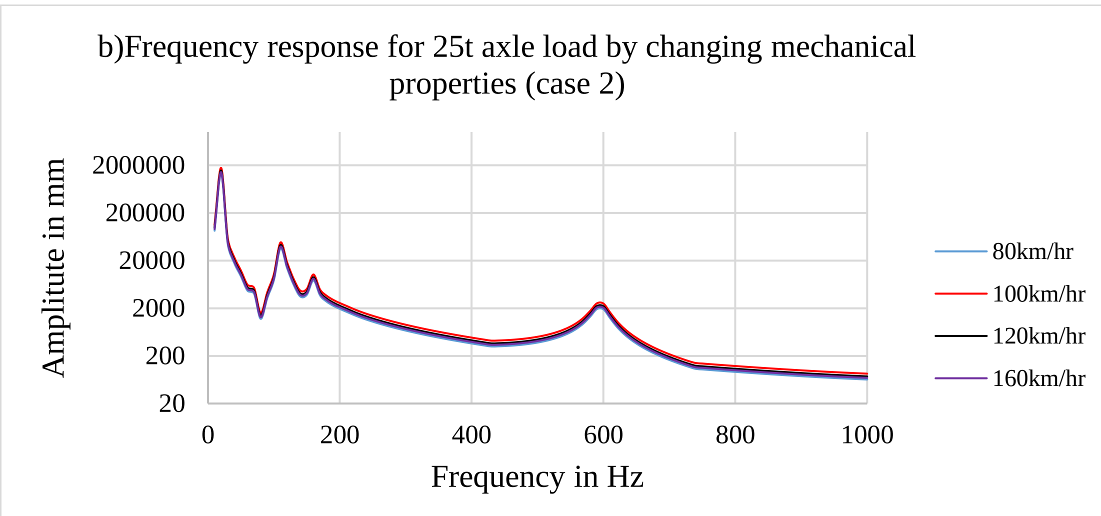

Figure.3. Frequency response by changing mechanical properties of rail clip a) Frequency response for 25t axle load (Case 2), b) Frequency response for 40t axle load (Case 2)

3.1. Optimization

In order to analyse the best design dimension for the clip, the optimization was done. During the optimization process, three parameters were considered: diameter, clip toe length, and clip low arch length. From the results, it can be observed that increasing the diameter of the clip leads to a reduction in deformation and stress, albeit at a low rate (Figure 4). A similar trend is observed

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when increasing the toe length of the clip (Figure 5). Conversely, increasing the clip low arch length results in increased deformation and stress (Figure 6). To achieve the best optimization for a clip, it is recommended to increase the diameter and clip toe length, while reducing the low arch length.

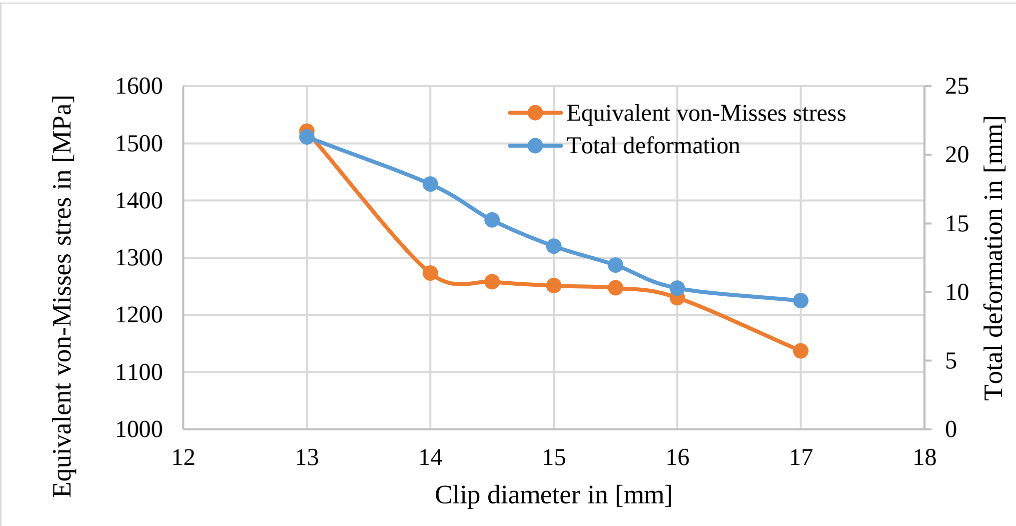

Figure.4. Stress/Deformation versus Clip Diameter

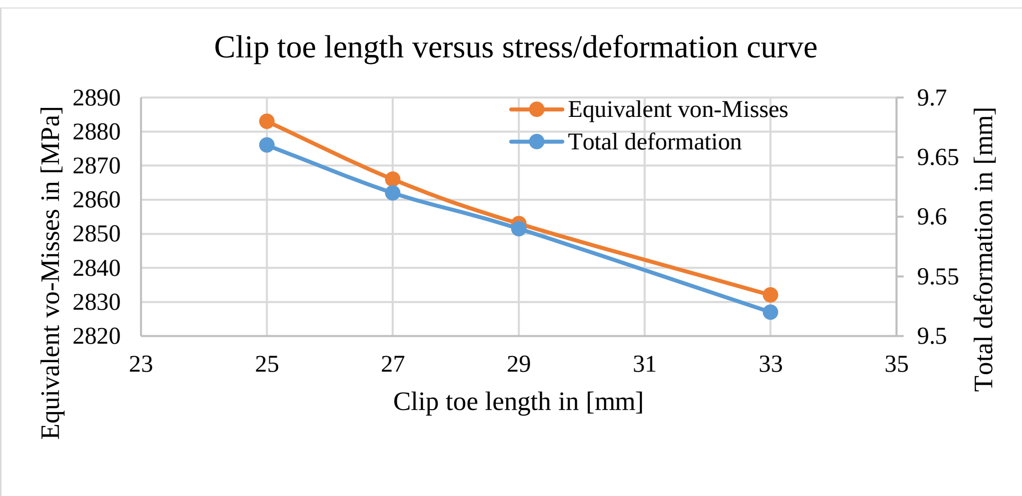

Figure.5. Stress/deformation versus clip toe length

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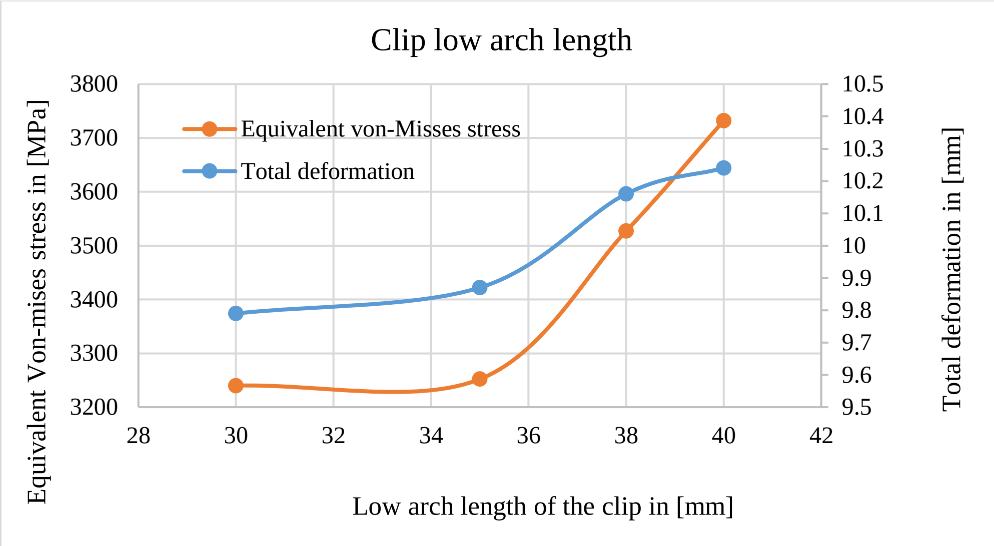

Figure.6. Stress- deformation versus low arch length of the clip

Fatigue analysis

The fatigue analysis for the rail clip has been performed for different diameters. The diameters considered range from 14mm to 17mm, as indicated in the results presented in Figures 7 to 16, with an increment of 1mm. From the results, it can be observed that the section in contact with the shoulder has the smallest safety factor, and there is not much difference in safety factors among the considered diameters. The S-N curves used in modeling were extracted from literature (Ping et al.,2020; Bruce et al.,1990; Vitaliy,2009; Wantono, 2019).

Figure 7 indicates that the life results of rail clip with diameter of 17mm. It is indicated that apart from low part that cannot last longer, other part have long life span.

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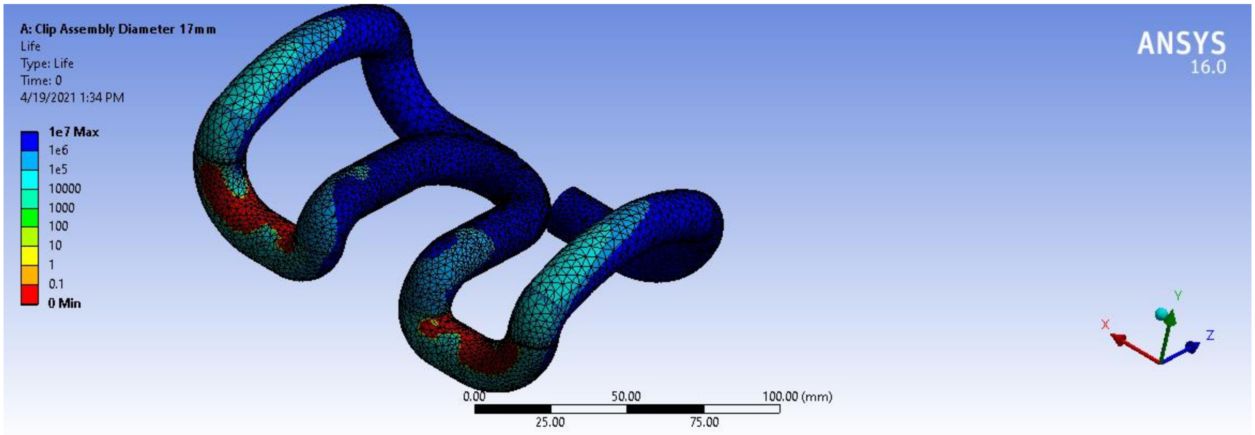

Figure.7. Life of a 17mm diameter rail clip

Figure 8 indicates that the safety results of rail clip with diameter of 17mm. It is indicated that many points exhibit low safety factor, which implied that cannot sustain the applied loads.

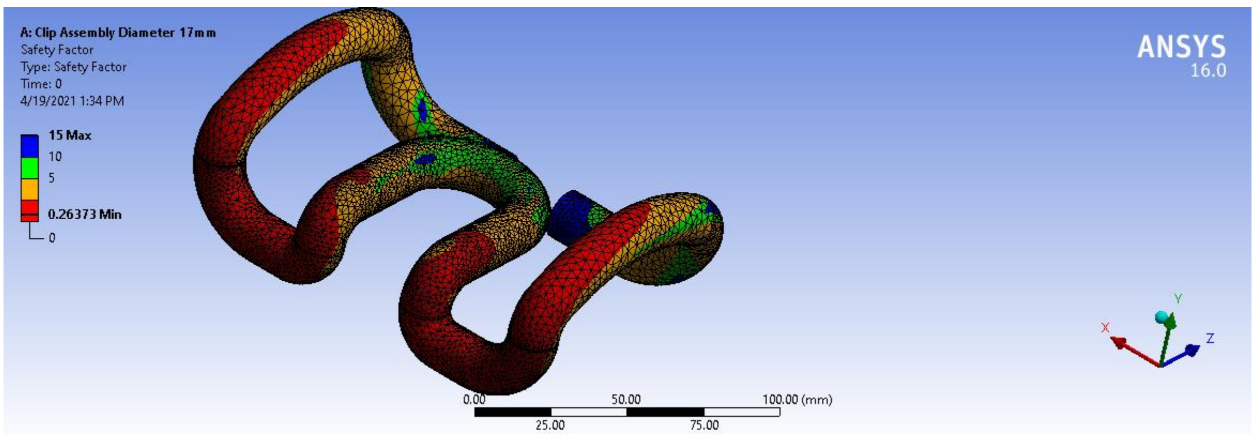

Figure.8. Safety factor of a 17mm diameter rail clip

Figure 9 indicates the life results of rail clip with diameter of 16mm. It is indicated that apart from low part that cannot last longer, other part have long life span. Compared to rail clip with 17mm diameter, it is shown that the one with 16mm diameter has many points with low life.

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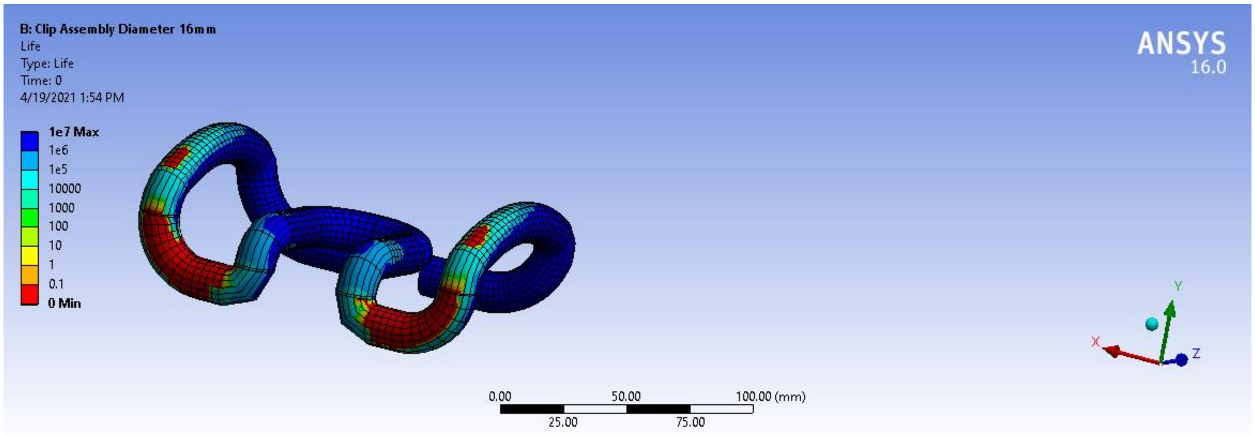

Figure.9. Life of a 16mm diameter rail clip

Figure 10 indicates the safety results of rail clip with diameter of 16mm. It is indicated that many points exhibit low safety factors, which implied that cannot sustain the applied loads. . Compared to rail clip with 17mm diameter, it is shown that the one with 16mm diameter has many points with low safety factors.

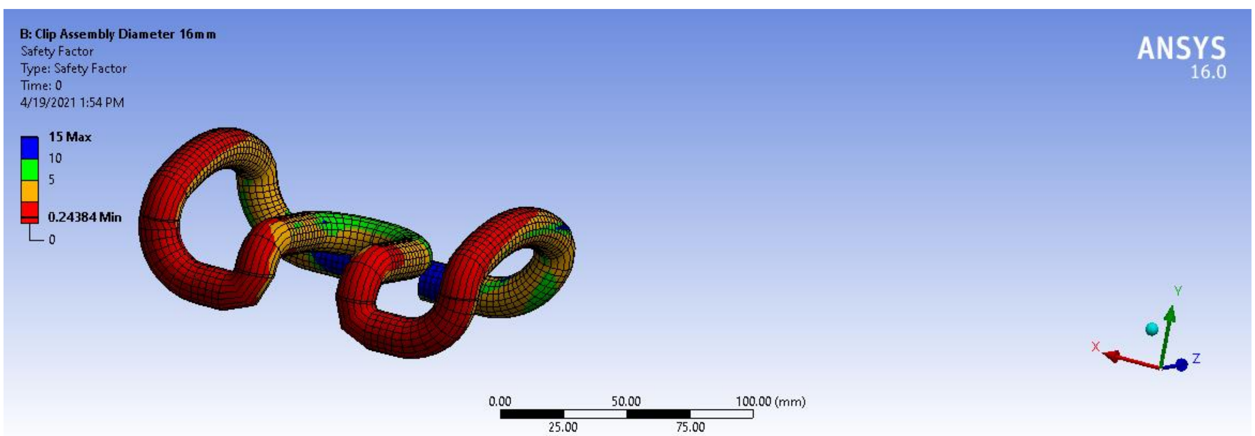

Figure.10 Safety factor of a 16mm diameter rail clip

Figure 11 indicates the life results of rail clip with diameter of 15mm. It is indicated that apart from low part that cannot last longer, other part has long life span. Compared to rail clip with 16mm diameter, it is shown that the one with 15mm diameter has many points with low life.

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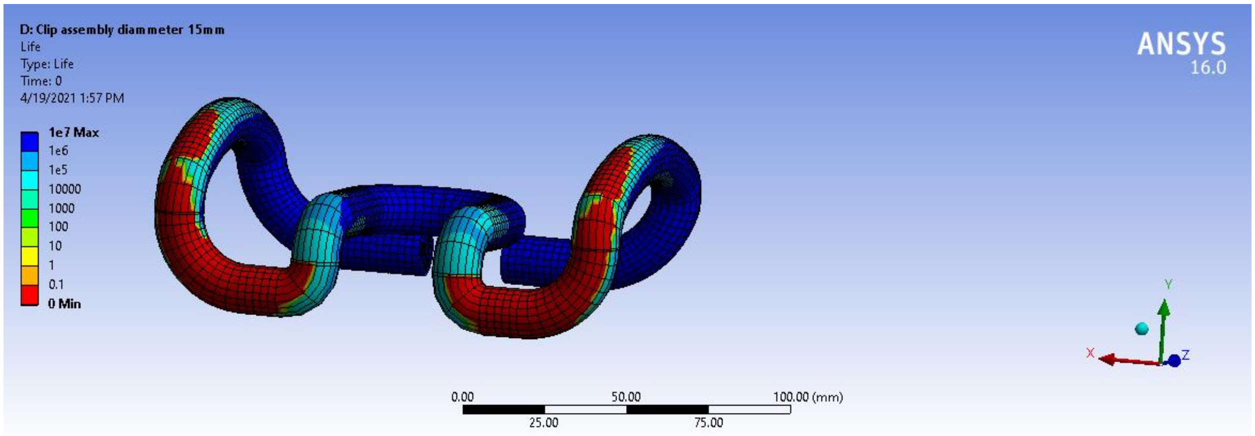

Figure.11. Life a15 mm diameter rail clip

Figure 12. indicates the safety results of rail clip with diameter of 15mm. It is indicated that many points exhibit low safety factors, which implied that cannot sustain the applied loads. . Compared to rail clip with 16mm diameter, it is shown that the one with 15mm diameter has many points with low safety factors.

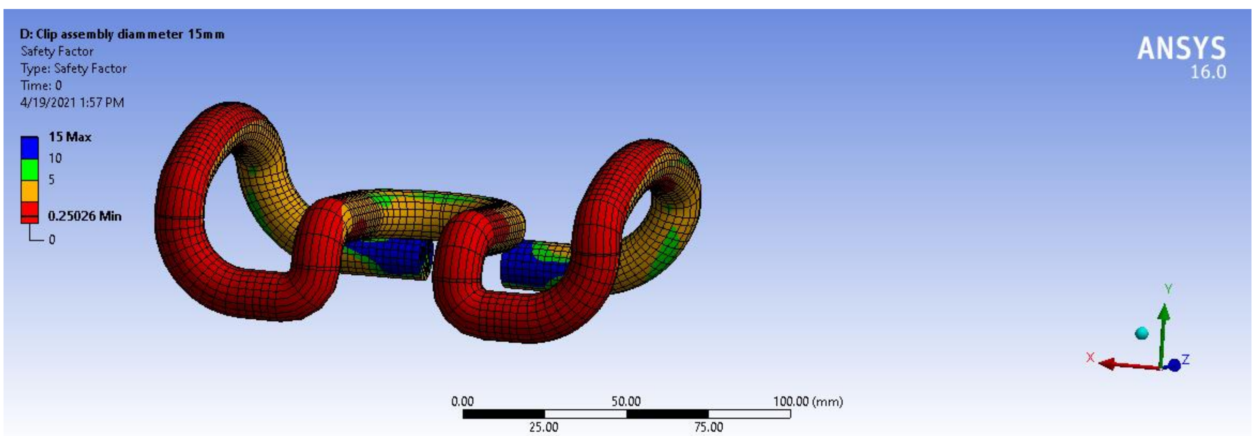

Figure.12. Safety factor of a15mm diameter rail clip

Figure 13. indicates the life results of rail clip with diameter of 14mm. It is indicated that apart from low part that cannot last longer, other part has long life span. Compared to rail clip with 15mm diameter, it is shown that the one with 14mm diameter has many points with low life.

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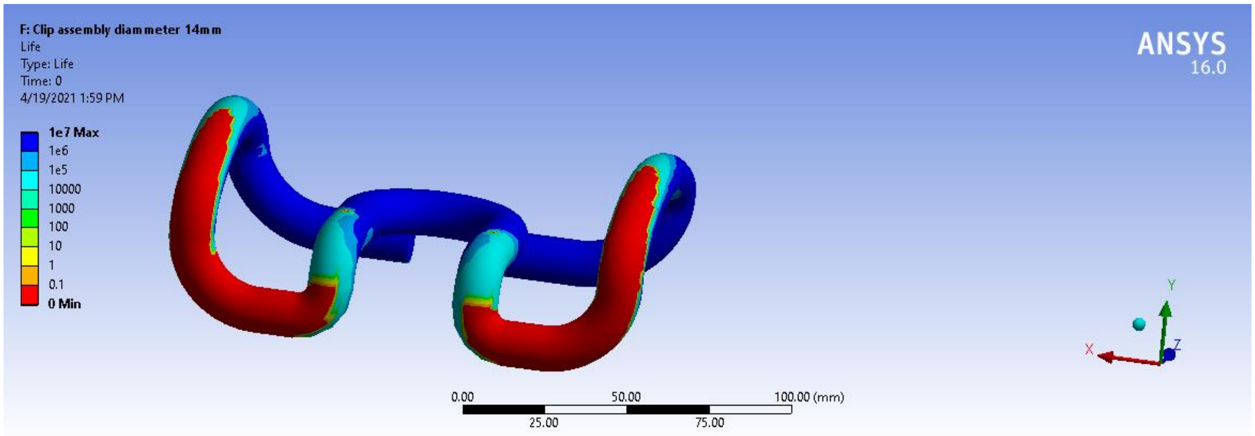

Figure.13. Life of a14mm diameter rail clip

Figure 12. indicates the safety results of rail clip with diameter of 14mm. It is indicated that many points exhibit low safety factors, which implied that cannot sustain the applied loads. . Compared to rail clip with 15mm diameter, it is shown that the one with 14mm diameter has many points with low safety factors.

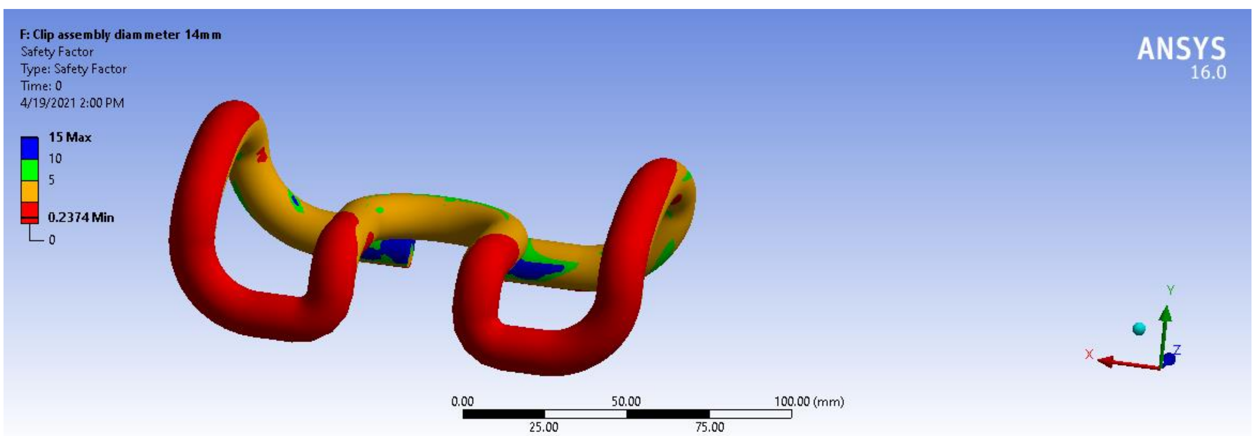

Figure.14. Safety factor of a 14mm diameter rail clip

Figure 15. indicates the life results of rail clip with diameter of 13mm. It is indicated that apart from the low part that cannot last longer, other part has long life span. Compared to rail clip with 14mm diameter, it is shown that the one with 13mm diameter has many points with low life.

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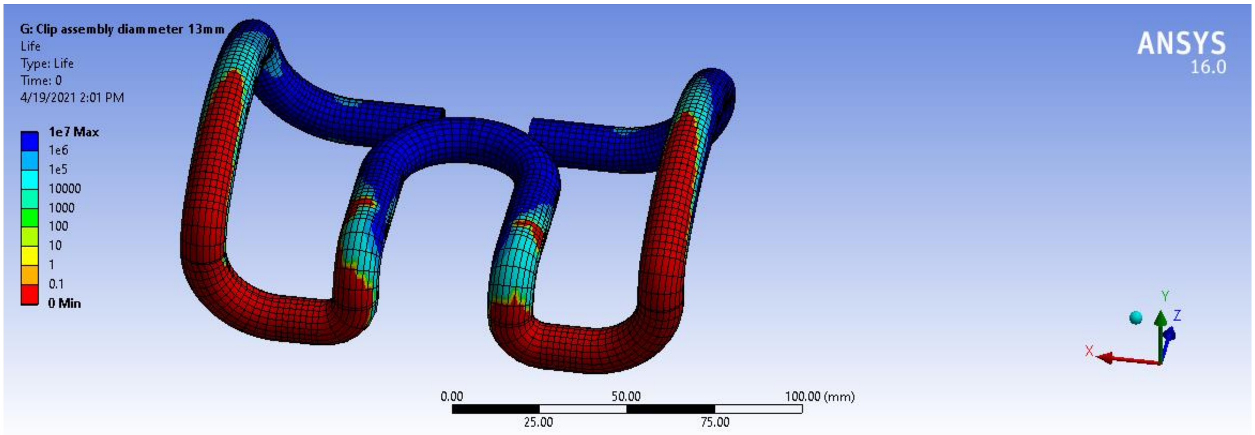

Figure.15. Life a 13 mm diameter rail clip

Figure 16. indicates the safety results of rail clip with diameter of 13mm. It is indicated that many points exhibit low safety factors, which implied that cannot sustain the applied loads. . Compared to rail clip with 14mm diameter, it is shown that the one with 13mm diameter has many points with low safety factors.

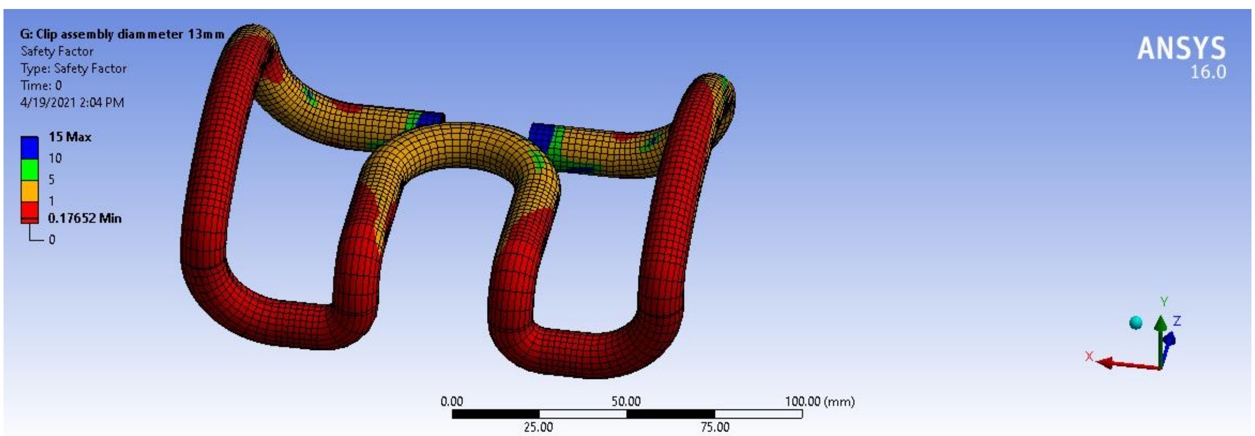

Figure.16. Safety factor of a 13 mm diameter rail clip

The results indicate that the studied clip cannot withstand up to 10E6 cycles. Both the life and safety factor from the fatigue analysis indicate that the point of contact with the shoulder cannot withstand up to 10E6 cycles, and its safety factor falls below the required minimum. While increasing the diameter results in higher safety factors and longer life, the point of contact with the shoulder still falls below the required minimum safety factor. However, the safety factors for rail

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clip diameters of 15-17mm are above 0.25, although this only applies to a small part of the clip. Increasing the material on that part would increase its safety factor.

4. Conclusion and Recommendations

After the analysis it was conclude that increasing speed results in a gradual increase in amplitude, while the corresponding frequency remains unchanged. It was also observed that increasing the axle load from 25t to 40t leads to an increase in both amplitude and frequency, although the increase in frequency is at a low rate. On the other hand, increasing the mechanical properties values results in higher amplitudes and corresponding frequencies. It was also shown that increasing the diameter of the clip reduces deformation and stress at a low rate. Similarly, increasing the toe length of the clip shows the same observation. Conversely, increasing the clip low arch length leads to an increase in deformation and stress. From the analysis of rail clip, it has been seen that the vulnerable part of the clip is the section in contact with the shoulder, and the results indicate that the studied clip cannot withstand up to 10E6 cycles. The fatigue analysis, considering both life and safety factors, reveals that the point of contact with the shoulder cannot withstand 10E6 cycles, and the safety factor is below the required minimum.

Furthermore, to achieve the best optimization for a clip, it is recommended to increase the diameter and clip toe length, while reducing the low arch length.

5. References

Bartos D, Lakusic S and Vinski T., Numerical Analysis of the Rail Fastening Spring Clip Type SKL-1, European Modelling Symposium, London, UK, September 11-12, pp. 27-31, 2006.

Bruce Boardman, Deere and Company, Technical Center 1990. ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys ASM Handbook Committee, p 673-688.

F.Doyle 1980, *Railway Track Design: A Review of Current Practice*, BHP Melbourne Research Laboratori, AUSTRALIAN GOVERNMENT PUBLISHING SERVICE CANBERRA.

https://dx.doi.org/10.4314/rjeste.v7i1.14

Ferreño D., Casado J. A., Carrascal I. A. et al., “Experimental and finite element fatigue assessment of the spring clip of the SKL-1 railway fastening system,” *Engineering Structures*, vol. 188, pp. 553–563, 2019.

Hasap A., Paitekul P., Noraphaiphipaksa N., and Kanchanomai C., “Analysis of the fatigue performance of elastic rail clip,” *Engineering Failure Analysis*, vol. 92, pp. 195–204, 2018.

Hasap A., Paitekul P., Noraphaiphipaksa N., and Kanchanomai C., “Influence of toe load on the fatigue resistance of elastic rail clips,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 232, no. 4, pp. 1078–1087, 2018.

Hu L., Yang J., Li Z. et al., “Optimization study of geometric parameters of type W1 elastic rail clip for high speed railway,” *Journal of Railway Engineering Society*, vol. 34, no. 12, pp. 24–29, 2017.

Li Z., Lin H., Yan H. et al., “An investigation on effects on mechanical properties and optimization methods of parameters of ω shape tension clamp,” in *Proceedings of the 95th Annual Meeting Transportation Research Board*, Washington, DC, USA, January 2016.

Liang L., Wei L., Hongxia S., Xinbiao X, Zefeng W and Xuesong J., Experimental and numerical investigation of the effect of rail corrugation on the behaviour of rail fastenings, *Vehicle System Dynamics*, vol. 52, no. 9, pp. 1211–1231, 2014.

Mohammadzadeh S., Ahadi S., and Keshavarzian H., “Assessment of fracture reliability analysis of crack growth in spring clip type Vossloh SKL14,” *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 228, no. 5, pp. 460–468, 2014.

Mohammadzadeh S., Ahadi S., and Nouri M., “Stress-based fatigue reliability analysis of the rail fastening spring clip under traffic loads,” *Latin American Journal of Solids and Structures*, vol. 11, no. 6, pp. 993–1011, 2014.

Ping Wang, Jun Lu, Caiyou Zhao, Li Yao, and Xuanhui Ming. Analysis on the Effects of Material Parameters on the Fatigue Performance of Novel Anti-corrugation Elastic Rail Clips. Hindawi, Shock and Vibration Volume 2020.

Ping.W., Jun L. ,Caiyou Z. , Li Y., and Xuanhui M., Analysis on the Effects of Material Parameters on the Fatigue Performance of Novel Anti-corrugation Elastic Rail Clips. Hindawi, Shock and Vibration Volume 2020.

https://dx.doi.org/10.4314/rjeste.v7i1.14

Ryan G Kernes, Amogh A Shurpali, Riley Edwards J, Marcus Dersch S, David Lange A and Christopher Barkan P L (2014). Investigation of the mechanics of rail seat deterioration and methods to improve the abrasion resistance of concrete sleeper rail seats ProcIMechE Part F: J Rail and Rapid Transit 2014, Vol. 228(6) 581–589).

Sadeghi, J. &Barati, P. 2010., Evaluation of conventional methods in Analysis and Design of Railway Track System, *International Journal of Civil Engineering*, Vol. 8, No.1.

Sadeghi, J.2007, Investigation on the Fatigue Phenomena in the Railway Track Fastening Systems and Design of Fatigue Testing Machine, Research Program Report 348F15, Iranian Railway Research Center.

Van Dyk B.J., Edwards J.R., Ruppert C.J., Barkan C.P.L. (2012). Considerations for Mechanistic Design of Concrete Sleepers and Elastic Fastening Systems in North America Rail Transportation & Engineering Center (RailTEC), University of Illinois at Urbana-Champaign (UIUC), Urbana, IL, USA

Vitaliy Kazymyrovych. Very high cycle fatigue of engineering materials - A literature review Research Report Karlstad University Studies 2009:22.

Wantono Francis 2019, Fatigue Life Assessment of Prestressed Concrete Sleepers: A Case Study of Ethio-Djibouti Line, A MastersThesis in Railway Engineering (Civil Infrastructure) Addis Ababa University, unpublished).

Xiao H., Wang J.-B., and Zhang Y.-R., "The fractures of e-type fastening clips used in the subway: theory and experiment," Engineering Failure Analysis, vol. 81, pp. 57–68, 2017.

Xiao J. and Zhao R., "Optimization design and study of elastic rail clip fastening," *China Railway Science*, vol. 16, no. 4, pp. 42–47, 1995.

Yang J. and Pan Z. T. C., "Analysis on influence of elastic rail clip material on fastening performance parameters," High Speed Railway Technology, vol. 4, pp. 15–18, 2012.

Yung C. C. , Chen M. K., Cheng K.L. and Min S. X., Optimization design of rail clip in Vossloh fastening system by uniform design and grey relation analysis Proc IMechE Part C: J Mechanical Engineering Science 0(0) 1–14, 2021.

https://dx.doi.org/10.4314/rjeste.v7i1.14