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DYNAMIC ANALYSIS AND BALANCING OF RAILWAY TRACKS SUPPORTED BY CONCRETE SLEEPERS

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ABSTRACT

Purpose: This study aims to improve the design to prevent vibration and improve railway performance by examining the behaviour of the railway track supported by a concrete sleeper.
Design/Methodology/Approach: The simulation for dynamic stresses has been carried out using Finite element modelling and analysis for the track-sleeper system's dynamic response. The frequencies and responses are obtained using modal and harmonic analysis with the help of ANSYS, a standard FEA software. In experimental validation, the finite element analysis results were compared to the actual track vibration behaviour at a train speed of 120 km/h.
Findings: The research shows that optimising the design and composition of concrete sleepers could greatly diminish vibrations and more evenly distribute loads. The results are improved structural performance, less maintenance required, and more stable tracks. The results emphasise the significance of concrete sleeper design in reducing track dynamic loads.
Research Limitation: This research is constrained because it considers only trains running at a maximum velocity of 120km/h.
Practical Implication: Improving the technology of the precast concrete sleeper can also reduce track vibrations, decrease maintenance costs, and increase the service life of railway infrastructure.
Social Implication: An efficient rail network helps switch to cleaner transportation systems, especially in densely populated urban areas.
Originality/Value: By integrating finite element modelling (FEM) with experimental validation, this study thoroughly evaluates the dynamic behaviour of rails supported by concrete sleepers. It sheds novel ways on the track-sleeper interaction, showing how design optimisation can improve performance while decreasing operating costs, which is suitable for railway engineering and sustainable infrastructure.

Keywords: *Concrete sleepers. dynamic analysis. railway tracks. track stability. vibration reduction*

INTRODUCTION

Train travel is a sustainable and effective way to move goods and people long distances, so the global economy depends on it. The structural integrity of the rails and their supporting components determines most of the dependability and efficiency of rail systems (Fang et al., 2023). Among these parts, concrete sleepers are most often employed because of their long-lasting character and capacity to distribute loads equally (Bezgin, 2017). Trains running on railway tracks can cause significant strain on them, resulting in vibrations that might limit their service life and maybe cause degradation of the tracks (Punetha et al., 2021). Maintaining track stability and guaranteeing passenger comfort depends on knowing about and acting to reduce these dynamic effects (Ouakka et al., 2022). Many research on the dynamic behaviour of railway rails (Siahkouhi et al., 2023) have underlined the necessity of efficient vibration-reducing measures (Shin et al., 2016).

In this sense, concrete sleepers are essential since they significantly influence the dynamic responsiveness of the track. Using finite element modelling helps one better to grasp the complicated interactions in the track-sleeper system since it enables thorough simulations of many loading conditions (Sayeed & Shahin, 2023). More accurate track performance forecasts made possible by recent modelling technique developments (Aggestam et al., 2022)(Liu et al., 2022) enable Sleeper Design Optimization.

Studies have shown that load distribution can be increased and vibrations can be lowered by maximising the form and material composition of concrete sleepers (Aktaş et al., 2022; Sol-Sánchez et al., 2021).These developments help to build better train systems that can manage growing traffic loads (Aktaş et al., 2022).

To optimise design parameters to lower vibrations and enhance structural integrity, this work intends to explore the dynamic behaviour and balance of railway tracks supported by concrete sleepers. This work aims to clarify how to effectively build and preserve railway tracks by use of finite element modelling and experimental validation

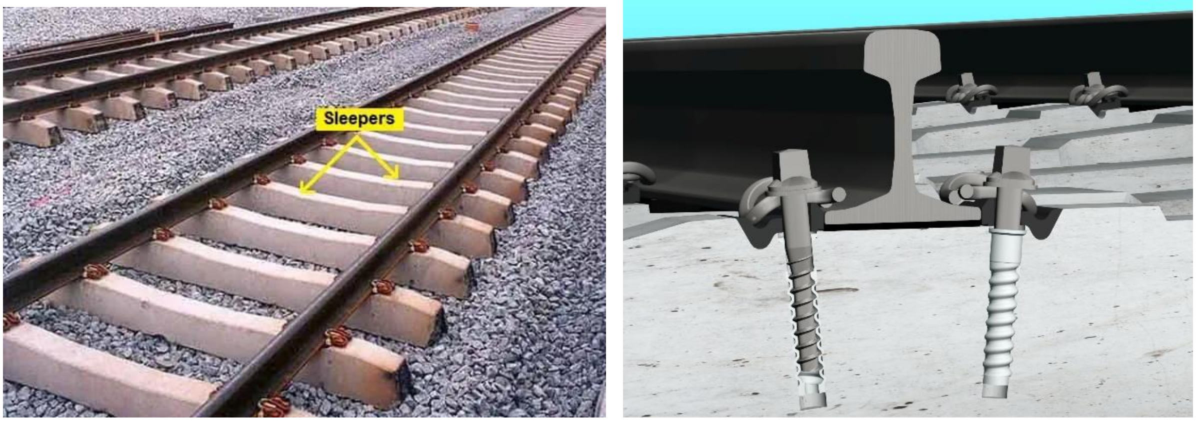

Figure 1: A railway track with rail on concrete sleepers and the rail fastened into the sleeper

LITERATURE REVIEW

Research into the dynamic behaviour of railway tracks has emerged as a key focus aimed at improving the efficiency and longevity of track components. Initial studies suggest that track construction is essential for effectively distributing dynamic loads and reducing vibrations (L. Xu, 2022). Sleepers are critical components that transfer loads from the rails to the ballast, ensuring track stability. Compared to timber sleepers, concrete sleepers significantly enhance load-bearing capacity and durability (Liu et al., 2021). This benefit stems primarily from concrete's inherent strength and rigidity, which provides excellent support under repeated dynamic loading. Furthermore, concrete sleepers' extended lifespan and lower maintenance needs make them preferable in contemporary railway track systems.

Recent progress in finite element modelling (FEM) has dramatically enhanced the precision of simulations concerning railway track dynamics. These innovations facilitate comprehensive assessments of the intricate relationships among rails, sleepers, and ballast under various loading scenarios (Xu & Lu, 2021). By elucidating the impact of different design elements and operational variables on track performance, finite element models are invaluable for advancing railway infrastructure.

FEM provides a detailed examination of essential factors such as sleeper spacing and material quality. The characteristics of sleepers, including their damping properties and rigidity, are pivotal in determining how loads are transmitted and absorbed within the track structure (Aggestam et al., 2022). Furthermore, the arrangement of sleepers is crucial for optimising load distribution and enabling track flexibility. By modifying these parameters within simulations, researchers can foresee and address potential challenges, such as increased stress on track components or diminished vibration dampening. Overall, these models have not only deepened theoretical insights into track dynamics but have also led to tangible enhancements in design, resulting in more resilient and effective railway systems.

Research indicates that the effectiveness of railway tracks can be greatly enhanced through careful design and material selection for sleepers. These improvements address key objectives such as minimising vibrations, evenly distributing loads, and ensuring the long-term integrity of the infrastructure. One significant development is the adoption of fibre-reinforced concrete sleepers, which offer better vibration reduction and durability than traditional concrete sleepers (Camille et al., 2022). By integrating fibres into the concrete mix, the sleepers exhibit improved tensile strength, crack resistance, and longevity, leading to extended service life and lower maintenance requirements. Beyond material advancements, innovative sleeper designs have shown considerable potential. For example, hollow-section sleepers decrease weight and uphold structural stability, achieving an optimal balance of efficiency and performance. Additionally, incorporating sensors within sleepers allows for monitoring track conditions, improving maintenance practices and promoting safety (Kaewunruen et al., 2014; Taherinezhad et al., 2013). These sensors collect data on various parameters such as stress, temperature, and vibration, yielding essential insights to prevent failures and enhance operational reliability. Collectively, these improvements illustrate the power of merging material science with creative engineering approaches to bolster railway systems' dynamic performance and monitoring capabilities.

Experimental research has been essential in validating the results of computational models related to railway track dynamics. Field trials using enhanced sleeper designs have shown their effectiveness in improving track performance, particularly by prolonging the track's lifespan and decreasing the need for maintenance (You & Kaewunruen, 2019). These practical studies provide vital evidence that reinforces the implementation of enhancements initially shown in theoretical and simulated environments.

A key finding from these investigations is the confirmation of modern materials in constructing sleeper systems. Using innovative materials, such as fibre-reinforced concrete or composite reinforcements, has improved durability and vibration-damping characteristics. These materials increase the track's ability to endure dynamic and environmental stresses, leading to extended operational periods with reduced maintenance disruptions. Furthermore, scientific experiments have illustrated the effectiveness and advantages of integrating monitoring systems into novice sleeper designs. Often equipped with embedded sensors, these systems provide real-time evaluations of track conditions and responses to dynamic loads (Jemmali et al., 2022).

Using this information, train operators can decide when maintenance needs to be carried out to maintain safety and minimise service delay. This proves the high potential of experimental validation and technology interplay in achieving even more sustainable railways by merging more substantial theoretical research with practical applicability. Analysis in real-time has become the sound of the day for railway modernisation in modern times.

Incorporating sensors into sleepers, these systems can also continuously monitor conditions and take safety measures to track the stress and vibrations experienced by the operating model (Sol-Sánchez et al., 2021b) . This method helps to determine the abnormal or anomalous condition, which yields decent operational and safety management solutions. The data transferred from these sensors is valuable for maintenance decision-making. Such an application enables you to spot the locations of stress or vibrations that are too high and may easily lead to a failure hazard to remediate it instantly. This stops them from suffering severe damage and allows a quicker maintenance time by providing data, which reduces downtime and costs (Innovations in Railway Track Maintenance Technology, n.d.).

Moreover, railway safety could be improved as problems can be tracked before they become big problems (Ozdemir et al., 2017). More sophisticated systems utilise Internet of Things (IoT) technology to enable remote data anywhere with analysis techniques, which provides a rapid and efficient response from train operators. (Kumbhalkar et al., 2020). As technology advances, its importance in maintaining railways' long-term reliability and safety will also increase.

The need for developing standards, new materials and best practices to enhance railway sleeper performance continues to be met by research. Some of the present modelling, especially real-time analysis, have shifted the operational understanding necessary to design sleeper products and measure their distribution and vibration reduction. Similarly, developments in materials like fibre composites and high-strength polymers have enhanced concrete's tensile strength and vibration-damping capability when applied to heavy objects. Along this line, effectively managing the operations will require the continuous provision of information via measuring instruments on the loading and track integrity. The latter assimilates all relevant data, allowing for preventive action takings, thus improving safety and minimising downtime through predictive maintenance (Ganzaroli et al., 2022).

MATERIALS AND METHODS

This work aims to maximise the design of railway tracks supported by concrete sleepers and investigate their dynamic behaviour for better performance. The study approach combines computational modelling and experimental validation.

Table 1: Materials Needed for the Research

Track Element	Variables	Limits/Constraints
Rail	Elastic Modulus	210 GPa
	Damping Ratio	0.01-0.03
Concrete Sleeper	Density	2400 kg/m³
	Elastic Modulus	30-40 GPa
Ballast	Density	1600-2000 kg/m³
	Particle Size Distribution	20-60 mm
Subgrade	Bearing Capacity	> 50 kPa
	Moisture Content	< 20%
Fastening System	Stiffness	50-100 kN/mm
	Clamping Force	10-20 kN

This study primarily uses concrete sleepers from an essential mix of Portland cement, aggregates, and water. Fibre reinforcement can be included into the concrete mix (Shakeri et al., 202) to improve the mechanical qualities of the sleepers. Furthermore, sensors were included inside the sleepers to track dynamic responses under different loads (Xu et al., 2019)).

Analytical Analysis

The single gauge provisions of AS1085.14 apply to the design of dual gauge sleepers that carry weights in the broader gauge rails (Bernal, n.d). Use the following ballast pressure distributions and design formulae for narrow gauge rails to support loads on dual gauge sleepers. For the

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concrete sleepers to better grip the railroads' lengthy sections of sharp curves and steep grades, sanding is an absolute must. Because of the high levels of wear and tear on soffits and rail seats in these harsh running conditions, concrete sleepers are engineered to minimise these risks. Every fastener, cast-in shoulder, pad, spacer, and insulator must also adhere to the relevant ARTC Standards. The track specifications call for 1435mm (Standard), 1067mm (Narrow), and 1600mm (Broad). Rails must be AS60 (according to AS 1085.1 or a comparable standard) with a cant of one in twenty. Heavy duty allows up to 30 tonnes at 80 km/h, 23 tonnes at 110 km/h, 23 tonnes at 115 km/h, and 19 tonnes at 160 km/h on the Standard Gauge, whereas medium duty allows 25 tonnes at 80 km/h.

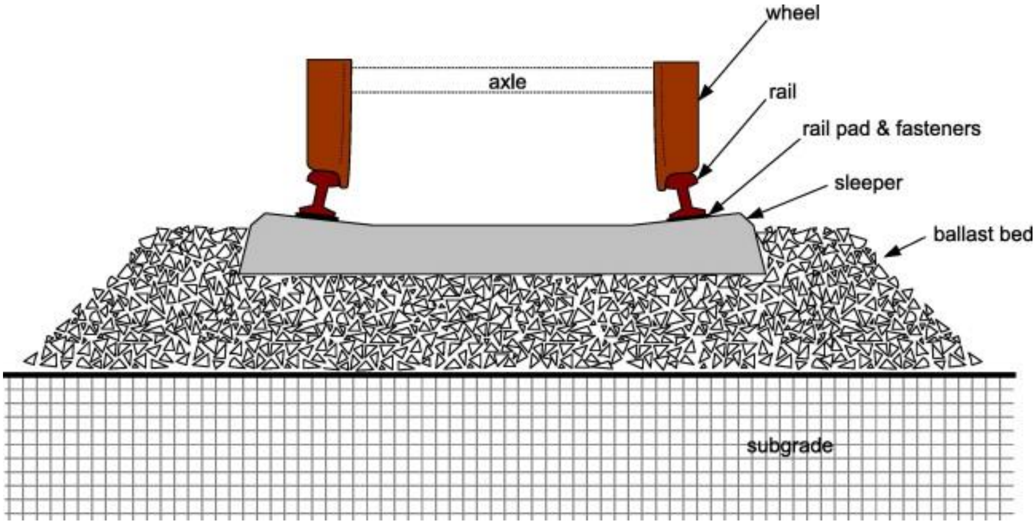


Figure 2: Structure of railway track

SG/BG sleeper, positive moments

Design ballast pressure (p_{ab})

$$p_{ab} = \frac{R\left(2 - \frac{g_{SG}}{g_{BG}}\right)}{w\left(L - g_{BG}\right)}$$

Design positive bending moment at rail seat (M_{R+})

$$M_{R+} = \frac{R \cdot g_{SG}\left(L + g_{BG} - 2 \cdot g_{SG}\right)^2}{8 \cdot g_{BG} \cdot \left(L - g_{BG}\right)}$$

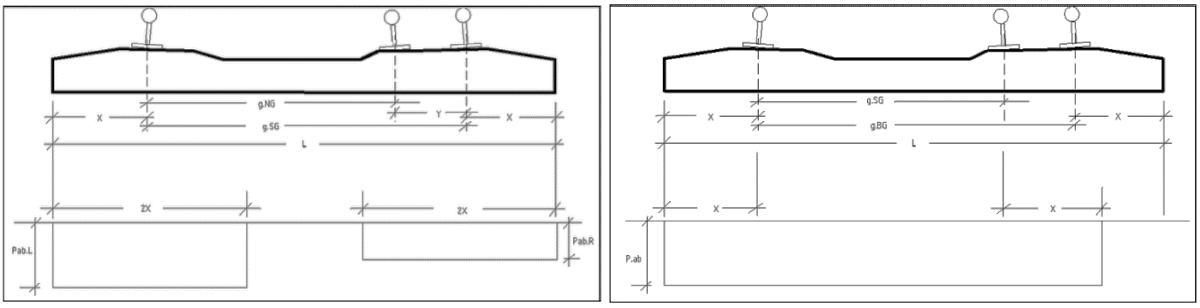
SG/BG sleeper, negative moments

Design ballast pressure (p_{ab})

$$p_{ab} = \frac{2R}{w\,(L - g_{BG} + g_{SG})}$$

Design positive bending moment at center (M_{C-})

$$M_{C-} = \frac{R\,(L - g_{BG} - g_{SG})}{4}$$



Rail seat moments Sleeper centre moments

Figure 2: Rail seat and sleeper centre moments

To calculate the design ballast pressure (pab) and positive bending moments at the rail seat (MR+) and the centre (MC−), the provided track specifications will be used. However, some variables, such as the load R, sleeper width w, and sleeper length L, must be determined or assumed based on typical values.

These calculations explain the forces and moments acting on the sleepers under the specified heavy-duty track conditions.

Table 2: Forces and moments acting on the sleepers during train running condition

Sr. No.	Weight (tonne)	Speed (km/hr)	p_{ab} (kN/m^2)		MR+	MC−
			Standard Gauge	Broad Gauge		
1	30	80	1202.41	840.26	55.46	−39.36
2	23	110	204.64	142.7	18.8	-13.38
3	23	115	470.9	328.3	43.1	−30.76
4	19	160	388.7	271.1	35.4	−25.41

Dynamic Response of Concrete Sleepers

This study examines the dynamic behaviour of a railway track system in detail, analysing how the track and its components react to real-world loading circumstances, especially at high train speeds, using finite element modelling and experimental observations.

An experimental setting with concrete sleepers was used to assess the vibration response of the track in order to validate the model. A train moving at a typical speed of about 120 km/h was used to conduct the experiment(Harris et al., 2016). The track underwent considerable distortion due to the system's flexibility, supported by a ballast layer. Crushed stone makes up the ballast, which provides a sturdy but pliable base for the track. Nevertheless, the track and sleepers undergo discernible deformation due to its pliability when subjected to weight.

The rails are fastened to every sleeper in the track system, making the track run like a beam. The stability of the track gauge, in this instance 1676 mm, over long distances depends on this continuous beam behaviour, which equalises the stresses operating on the track. Rail stability and safety are critically affected by the gauge, which is the distance between the inner sides of the rails. Maintaining this gauge, preventing derailments and maintaining smooth train operations is made possible by the continuous beam-like structure of the rail-sleeper system, even after extensive exposure to vibrations.

The research also included vertical, lateral, and longitudinal acceleration measurements. These measurements provide a comprehensive image of the track system's behaviour under dynamic loading situations, which is crucial. The longitudinal acceleration is associated with the forces acting forward and backwards as the train moves, the lateral acceleration with the swaying or side-to-side movement, and the vertical acceleration with the train's bouncing on the track (Kumbhalkar et al., 2017)). Twenty meters per second squared was the highest recorded acceleration for the rail-sleeper system, which is a considerable number that shows how powerful the dynamic forces are (He et al., 2022et al., 2022).

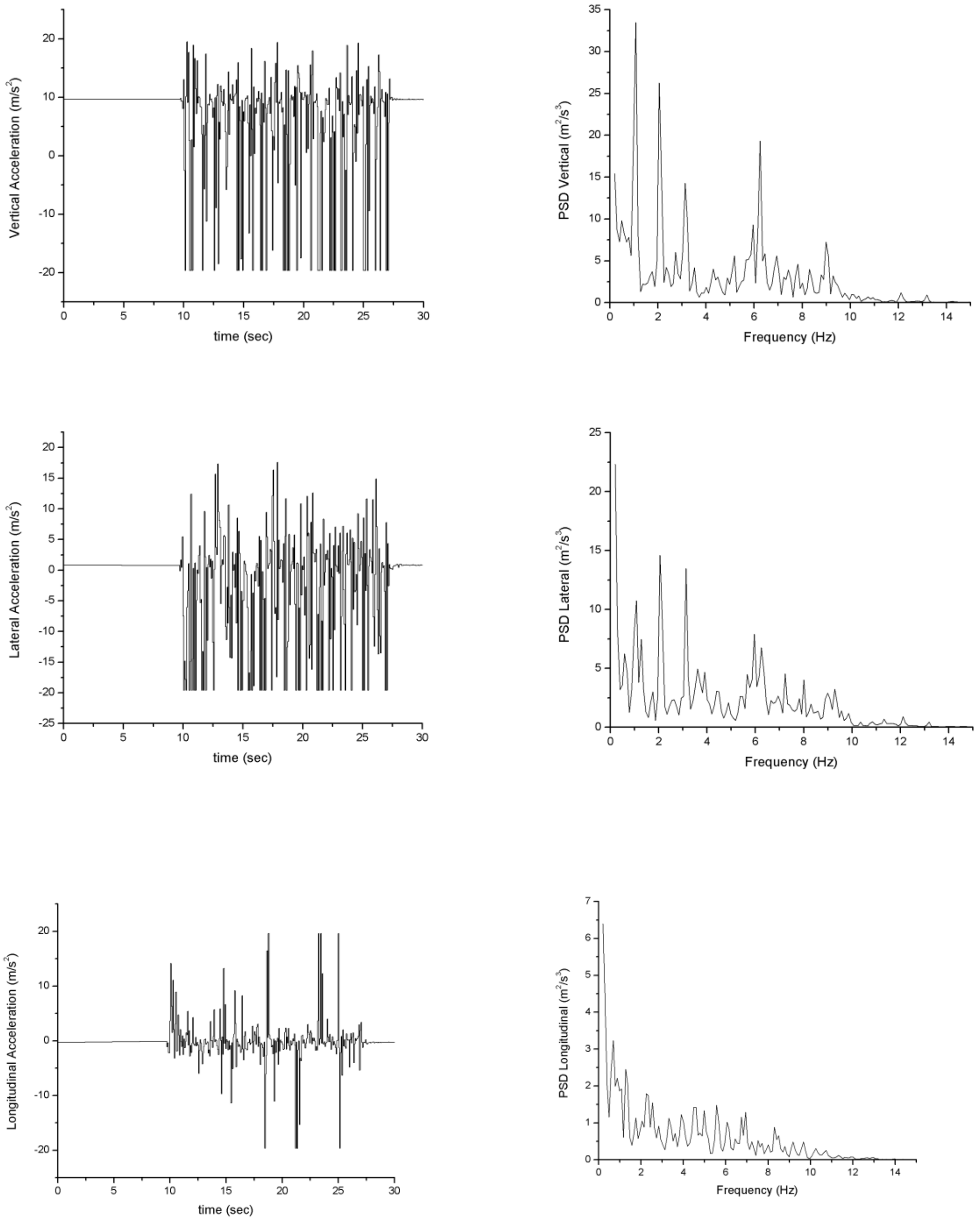


Figure 4: Vibration of the track with the concrete sleeper for the running train at approximately 120 km/hr

Finite Element Model and Dynamic Behaviour

The finite element model (FEM) was employed to simulate the track system's dynamic behaviour under varying loads. Dynamic interactions between railway rails and concrete sleepers were replicated using finite element modelling (FEM). ANSYS, which can manage complicated geometries and material behaviours Kumbhalkar et al., (2018) was the FEM program used in this work. With suitable boundary conditions, the model comprised the rail, sleepers, ballast, and subgrade, therefore mimicking real-world conditions (Costa et al., 2021). Standard engineering guidelines determined the material qualities of the concrete sleepers—Young's modulus, Poisson's ratio, density, and so on (Miri et al., 2021). To precisely depict its effect on the sleeper's dynamic performance (Ferro et al., 2020).

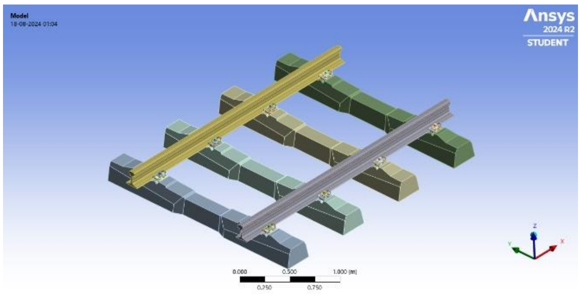


Figure 5: CAD Model of railway track

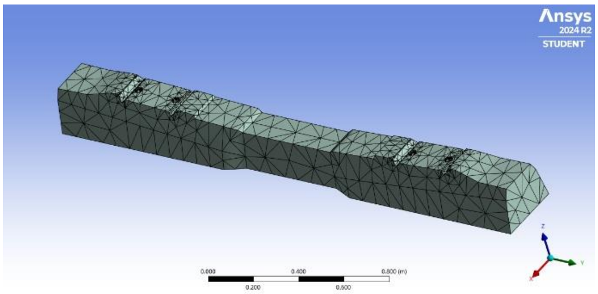
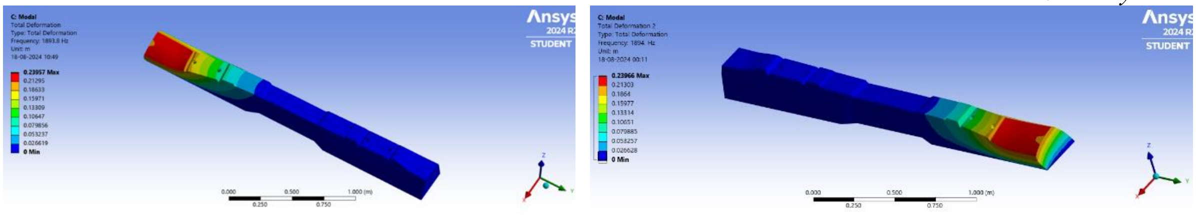


Figure 6: Mesh model of sleeper

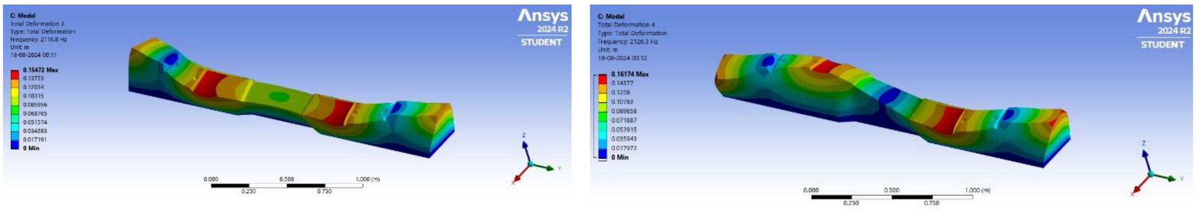
Modal and Harmonic analysis of sleeper:

Based on the results of the modal analysis, the sleeper's natural frequencies were as follows: 1893 Hz and 1894 Hz for the first two modes, 2116.8 Hz and 2126.3 Hz for the following two modes, and 2263.8 Hz and 2265.6 Hz for the last two modes. The obtained frequencies using modal analysis focus on the sleeper's vibrational properties when subjected to dynamic stresses. The harmonic analysis revealed a displacement amplitude of 1.9×10^{-7} m and an acceleration amplitude of 28.87 m/s^2 for the dynamic force at approximately 115 km/hr. These findings provide important implications for railway track system design and maintenance by demonstrating the efficacy of the FEM in anticipating the sleeper's behaviour under dynamic circumstances.



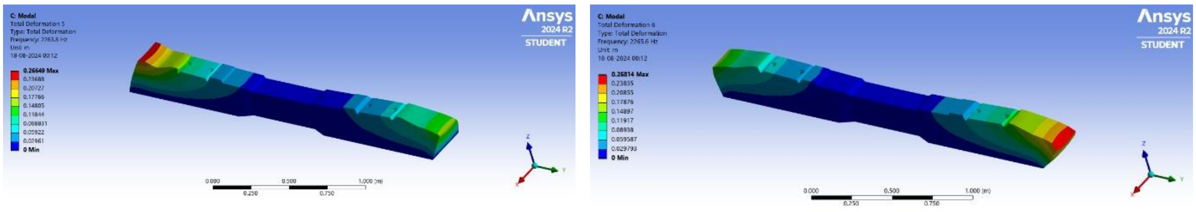
Mode 1: 1893 Hz frequency

Mode 2: 1894 Hz frequency



Mode 3: 2116.8 Hz frequency

Mode 4: 2126.3 Hz frequency



Mode 5: 2263.8 Hz frequency

Mode 6: 2265.6 Hz frequency

Figure 7: Natureal frequency of sleeper for six modes using Modal analysis

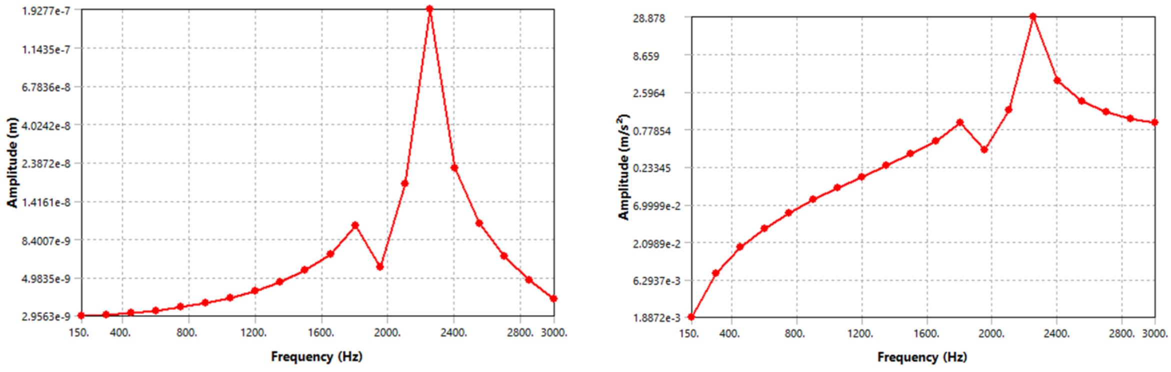


Figure 8: Displacement and acceleration amplitude for harmonic response of sleeper

Modal and Harmonic Analysis of Railway Track:

A railroad track's modal and harmonic structural examination provides valuable insights into its vibrational activity. The modal analysis determines the track's inherent frequencies in six

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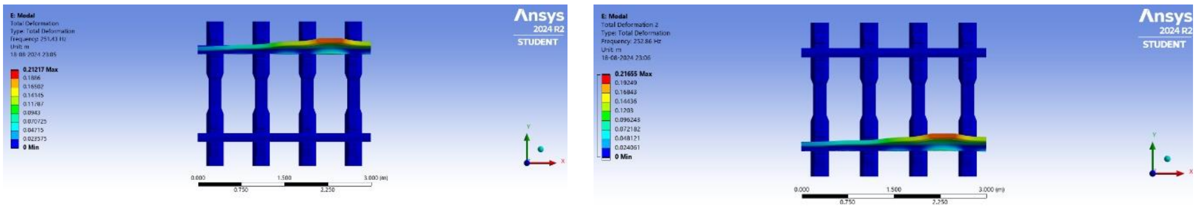
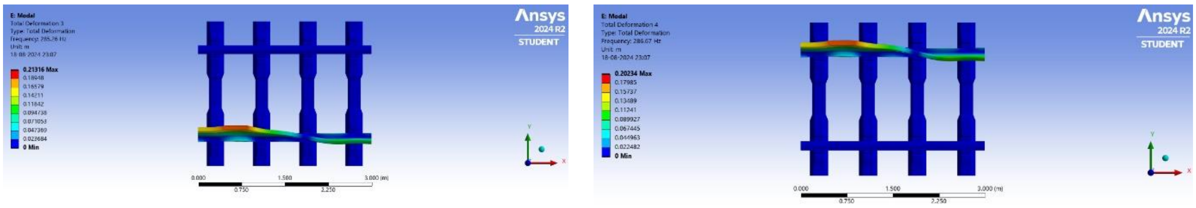
separate modes, ranging from 251.43 Hz to 337.92 Hz. These frequencies are crucial for ensuring the track's stability and endurance, as they indicate how the track will vibrate when subjected to external forces.

In contrast, the track's reaction to dynamic stresses is investigated in the harmonic analysis, particularly emphasising the acceleration amplitudes felt by independent parts. The sleepers react differently, with acceleration amplitudes ranging from 4.9 to 25.4 m/s², whilst the rails display more extreme values. The acceleration amplitude of 294.4 m/s² on Rail 1 is much greater than that of 13.4 m/s² on Rail 2, indicating that Rail 1 may provide a paramount problem regarding vibrational stress. To ensure the continued reliability and security of railway infrastructure, it is crucial to have a firm grasp of these dynamics, as they reveal any weak spots that vibrations could cause.



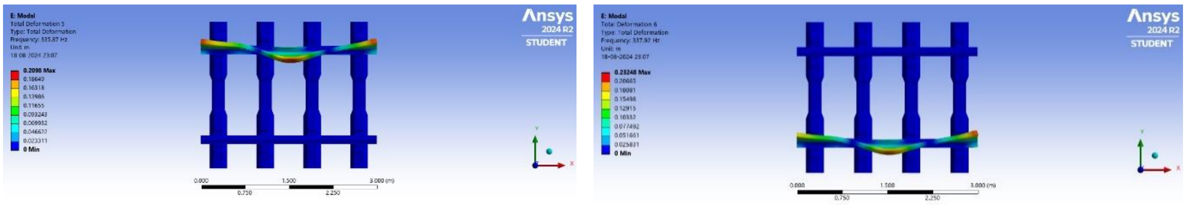
Mode 1: 251.43 Hz frequency

Mode 2: 252.86 Hz frequency



Mode 3: 285.26 Hz frequency

Mode 4: 286.67 Hz frequency



Mode 5: 335.87 Hz frequency

Mode 6: 337.92 Hz frequency

Figure 9: Natureal frequency of railway track for six modes using Modal analysis

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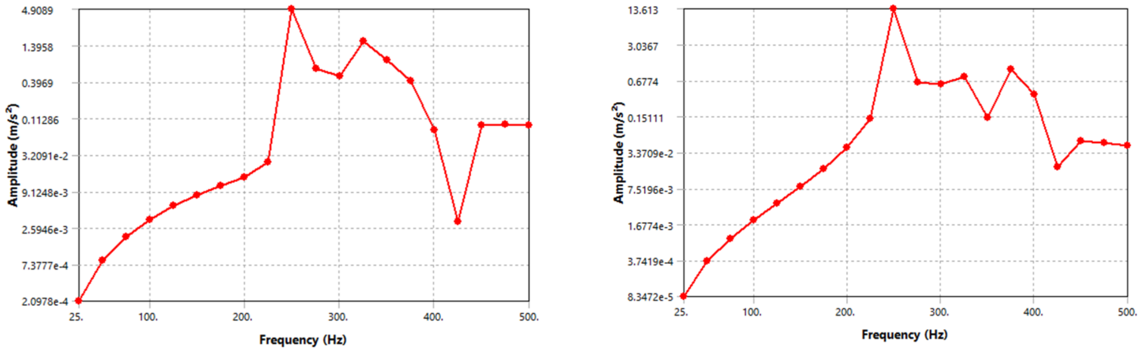
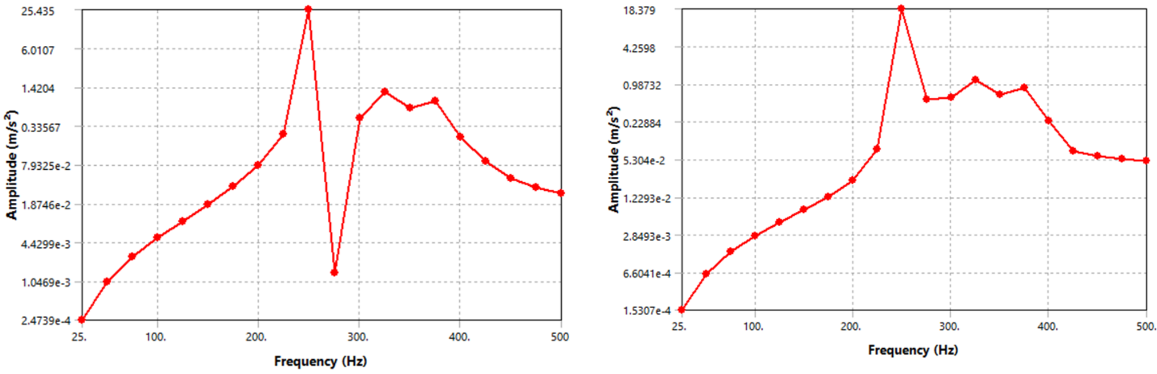


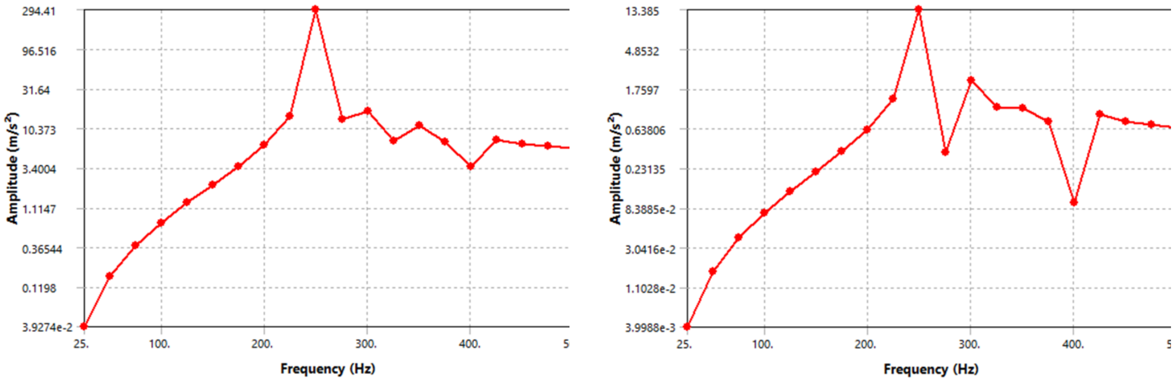
Harmonic response for Sleeper 1 with acceleration amplitude 4.9 m/s^2

Harmonic response for Sleeper 2 with acceleration amplitude 13.6 m/s^2



Harmonic response for Sleeper 3 with acceleration amplitude 25.4 m/s^2

Harmonic response for Sleeper 4 with acceleration amplitude 18.4 m/s^2



Harmonic response for Rail 1 with acceleration amplitude 294.4 m/s^2

Harmonic response for Rail 2 with acceleration amplitude 13.4 m/s^2

Figure 10: Harmonic analysis of railway track

RESULT AND DISCUSSION

The graph compares the harmonic response between the experimental and FEA results for different railway track components. The blue bars represent the experimental acceleration (assuming a constant value of 20 m/s²), while the red bars represent the FEA acceleration. This comparison highlights the differences in acceleration amplitudes for the sleepers and rails, with Rail 1 showing a particularly significant discrepancy.

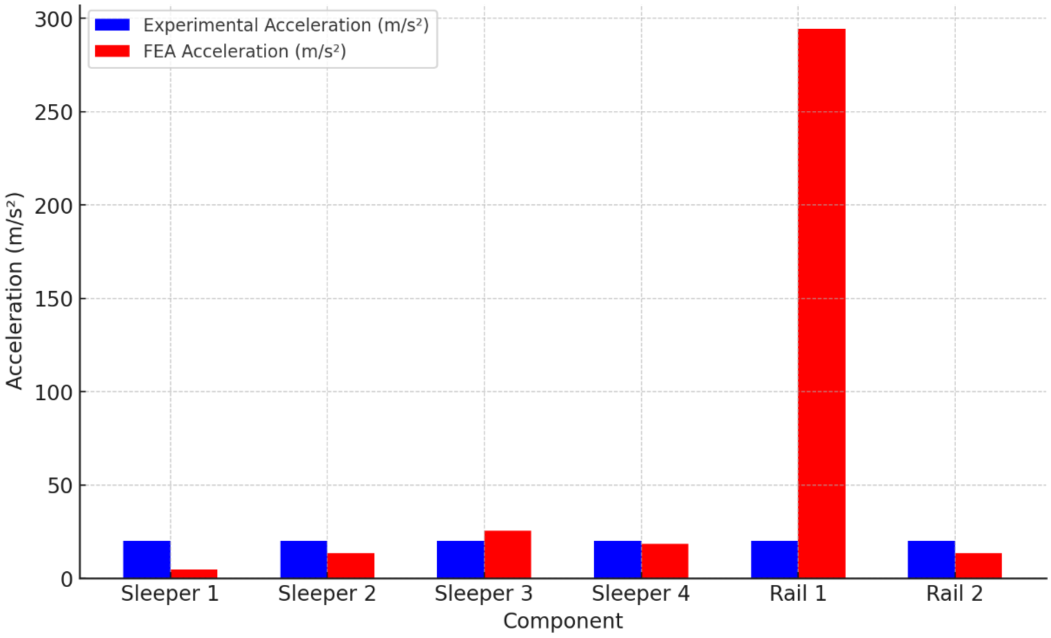


Figure 11: Comparison of harmonic response of railway track.

Modal and Harmonic Analysis of Sleeper

The modal analysis of the sleeper yielded natural frequencies for six modes. The first two modes were identified at 1893 Hz and 1894 Hz, followed by 2116.8 Hz and 2126.3 Hz for the next two modes, and 2263.8 Hz and 2265.6 Hz for the final two modes. These frequencies comprehensively understand the sleeper's vibrational characteristics under dynamic loading conditions. The results highlight the efficacy of the Finite Element Method (FEM) in accurately predicting the sleeper's dynamic behaviour. The results highlight the efficacy of the Finite Element Method (FEM) in accurately predicting the sleeper's dynamic behaviour, aligning with the findings of (Xu et al., 2019), who demonstrated the robustness of experimental and numerical methods in evaluating sleeper performance.

Harmonic analysis examined the sleeper's response to dynamic forces at an approximate train speed of 115 km/hr. The displacement amplitude was 1.9×10^{-7} m, while the acceleration amplitude reached 28.87 m/s². These results underscore the sleeper's dynamic resilience and its role in maintaining track stability under operational loads. The findings are consistent with the work of Xu et al. (2019), who emphasised the importance of understanding sleeper behaviour under dynamic conditions to enhance railway infrastructure performance.

Modal and Harmonic Analysis of Railway Track

The modal analysis of the railway track revealed six natural frequencies, ranging from 251.43 Hz for the first mode to 337.92 Hz for the sixth mode. These inherent frequencies are critical for understanding the track's vibrational behaviour and ensuring its stability under external excitations. Modes with lower frequencies typically indicate potential areas of concern for resonance with operational loads. This aligns with the findings of (Sayeed & Shahin, 2023), who emphasised the importance of dynamic response analysis in predicting track behaviour under moving loads.

The harmonic analysis provided further insights into the track's dynamic response. The acceleration amplitudes varied significantly between components, indicating differential vibrational stress distribution. Among the sleepers, acceleration amplitudes ranged from 4.9 m/s² (Sleeper 1) to 25.4 m/s² (Sleeper 3), demonstrating localised variations in dynamic response. The rails exhibited more pronounced acceleration amplitudes, with Rail 1 experiencing 294.4 m/s², substantially higher than the 13.4 m/s² observed on Rail 2. This suggests that Rail 1 is more susceptible to vibrational stress and may require additional reinforcement or maintenance to ensure system reliability. These observations are consistent with (Sayeed and Shahin's, 2023) analysis, which highlighted the critical role of 3D finite element modelling in understanding the dynamic responses of railway systems.

CONCLUSION

The sleeper and railway track show very different dynamic reactions in the comparison of their finite element analysis (FEA) results. The sleeper shows a controlled vibrational behaviour under dynamic loading circumstances, with a mild acceleration amplitude of 28.87 m/s². Unlike the sleeper, the railway track shows many acceleration amplitudes. On the track, the average acceleration is lower, yet some components, such as Rail, experience somewhat higher accelerations.

These results show that although the sleeper is designed to effectively control dynamic pressures, select areas of the rails could suffer more strong vibrating stresses. If this is not given enough thought during design and maintenance, structural issues or more wear and tear may result. Forecasting these behaviours and offering insights that can enhance design and maintenance strategies helps the FEA ensure the stability and safety of railway infrastructure over the long run.

This study highlights the necessity for ongoing surveillance and focused maintenance of railway components, particularly in high-stress regions such as Rail 1, to identify wear promptly and save expensive breakdowns. Enhancing rail design to manage dynamic loads more effectively can mitigate vibrations and improve performance. Socially, maintaining the soundness of railway infrastructure is essential for public safety, economic efficiency, and environmental sustainability. An adaptable railway system reduces interruptions, decreases maintenance expenses, and enhances safety and sustainability in transportation, hence cultivating public confidence in trains.

This study is distinctive in its comparative investigation of the dynamic behaviors of sleepers and tracks utilising Finite Element investigation (FEA). It elucidates the unique vibrational reactions of various components, providing novel insights into localised vibrational stresses. This dual-component methodology offers a more thorough comprehension of railway dynamics, facilitating more precise design and maintenance techniques.

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