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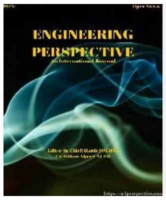

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Research Paper

Fatigue and Dynamic Behavior of Prestressed Concrete Sleepers

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ABSTRACT

In ballasted railway tracks, one of the important components that supports the rails and distributes wheel/rail loading onto the ballast supporting formation is a railway sleeper. In this paper, the dynamic and fatigue response of prestressed concrete sleepers used along the Ethiopian National Railway lines (Chinese Type II sleeper) is presented. For simulation, a finite element modelling package, ANSYS was employed. Concrete was modelled using a three-dimensional solid element (SOLID 65) and the behavior of prestressing wires was simulated using truss elements (LINK 180). Validation of simulation results was done using existing experimental data of Rikard's model. To obtain resonance conditions; the harmonic response of the sleeper for the excitation in the range of 0-2000Hz and variation of stress and displacement amplitudes with respect to frequency were studied. It's observed that the most resonant frequency corresponds to the third bending mode shape. From fatigue life assessment in this study, it is observed that the sleeper fails before attaining its design life of 40 years (11,300,400 cycles). This is due to the development of cracks which are likely to limit the sleeper's ability to hold the geometry of the line. As a result, the sleeper cannot attain the main technical standards of speed of 120 km/h and axle load of 25 tons. The minimum life of the sleeper is equivalent to about 31.8% of its design life. Moreover, it was observed that at a speed of 80km/h and an axle load of 25 tons, the life of the sleeper was found to be 85%. Thus, to attain the design life of the sleeper, during operational phase, it is recommended to limit the speed of the train to 80km/h.

Keywords: ballasted track, fatigue, frequency response, prestressed concrete sleeper, speed.

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1. Introduction

The railway sleeper is a vital railway component that lies between the rail and the ballast whose functions include; uniform transfer and distribution of loads from the rail foot to ballast bed, provision of an anchorage for the fastening system, and the restraining of lateral, longitudinal, and vertical movement of the rails [1], [2]. In addition, sleepers provide a cant to the rails to help develop proper rail-wheel contact by matching the inclination of the conical wheel shape [2]. The sleepers can be manufactured using timber, concrete, steel, or other engineering materials and concrete is commonly used around the world [3]. Prestressed concrete sleepers (PCSs) are the most commonly used type of sleepers. They play an essential role in track performance, behaviour and safety [4]. Besides, the large weight, PCSs provide stability for heavy haul and are more sustainable than timber counterparts [5].

Throughout their life cycles, sleepers experience static, dynamic and often impact loading conditions whose levels depend on the type and speed of the train, the track geometry, the wheel-rail interactions associated with abnormalities in either the wheel or the rail and the ballast reaction on the sleepers [6]. Usually, a few hundred-wheel axles act sequentially on each sleeper during the passage of a single train producing two dynamic effects; the resonance phenomenon caused by the build-up of the response induced by a wheel impact on the sleeper; and creep or fatigue caused by the repetitively acting loads [7]. Fatigue failure can therefore be defined as the failure that occurs below the stress limit of a material when it has been exposed to repeated loadings [8]. Fatigue failure involves progressive process of micro-crack initiation and propagation that leads to macro-cracks that grow to the point at which failure occurs [9]. Fatigue damage of prestressed concrete sleepers is mainly due to the accumulation of defects caused by the repeated load from trains [10]. Fatigue failure in prestressed concrete members can occur due to failure of concrete from flexural compression, diagonal tension or shear, failure of strands or failure of bond [11].

In this paper, the dynamic and fatigue behaviour of sleepers is investigated. Besides, the minimum lifetime of the sleeper and optimal speed of the train is estimated.

2. Model Validation

A simple static sleeper model with fixed support condition was modelled, analysed and compared with Rikard model [12].

The model was created using the design modeller of ANSYS workbench. The concrete was modelled using a three-dimensional solid element, SOLID65, which has the material model to predict the failure of brittle materials. To simulate the behaviour of prestressing wires, truss elements, LINK180, were used to withstand the initial strain attributed to prestressing forces, by assuming a perfect bond between these elements and concrete. Pre-tensioning was modelled using an initial strain of 5mm/m in the tendons corresponding to the prestressing forces at final stage (sustained prestressing force after all losses) as shown in Figure 1. At the validation step, a sleeper was subjected to the same hydraulic jack loading as the Rikard model [12]. Figure 2 shows the load applied to the rail seat area varied from 0 to 237.5 kN.

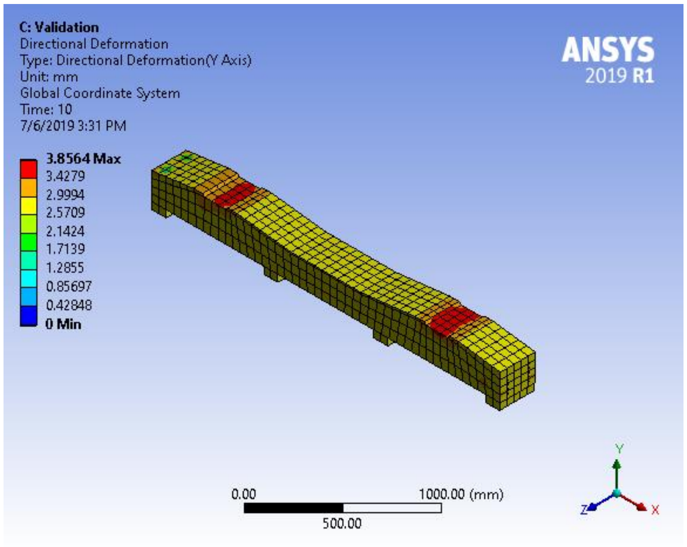

Figure 1. Deformation at 237.5 kN load

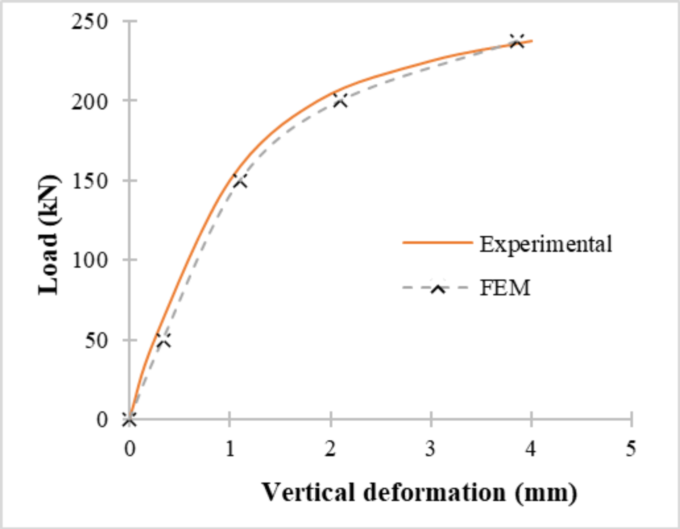

Figure 2. Force - Deformation graph

The resulting force-deformation diagram matches very well to the Rikard model [12] which proves that the quality of the FE results is good and thus, further modelling and analysis using FEM follows in the next sections of the paper.

3. Numerical model

The sleeper used for modelling is the Chinese type II sleeper which is currently in use on the Ethiopian National lines. The detailed drawing and dimensions are shown in Figure 3;

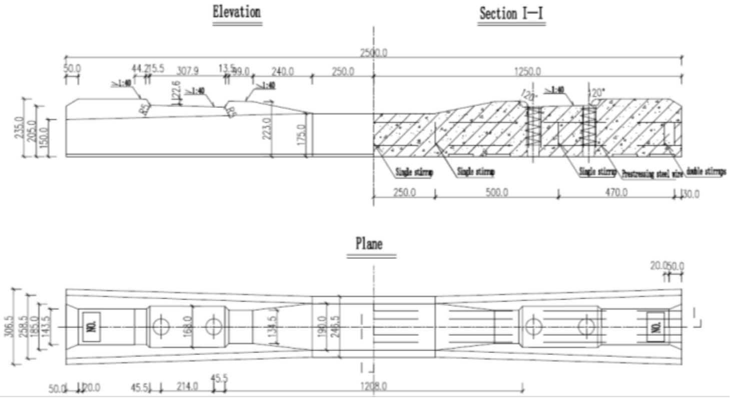

Figure 3. Type II sleeper drawing

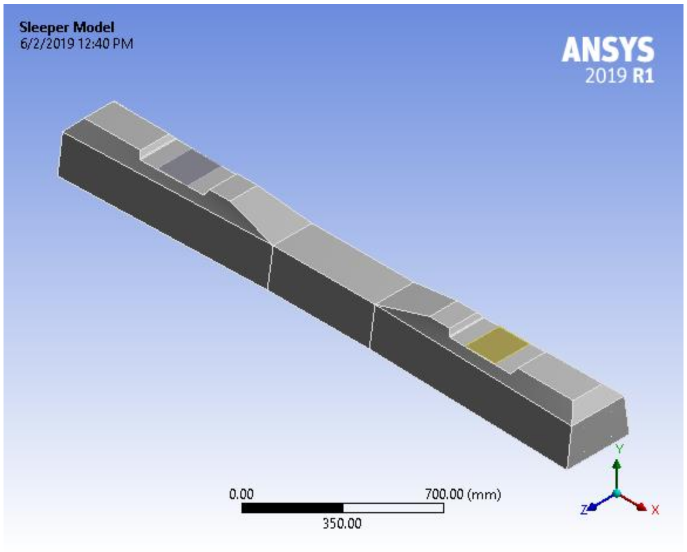

Figure 4. Sleeper geometry in ANSYS

3.1 Material property of the sleeper

For concrete grade C60 and prestressing steel, the material properties are listed in Table 1 and Table 2 respectively;

Table 1. Material property of concrete [13], [14], [12]

Density ρ_s (kg/m^3)	2400
Young's modulus, E_c (MPa)	37720
Poisson's ration, v_c	0.2
Compressive strength, σ_{cc} (MPa)	60
Tensile strength, σ_{ct} (MPa)	2.85
Fracture energy, GF (N/m)	154

Table 2. Material property of prestressing steel [13], [14], [12]

Density, ρ_s (g/cm^3)	7.8
Young's modulus, E_c (GPa)	200
Poisson's ratio, υ_c	0.3
Characteristic strength for prestressed steel wire, f_{ptk} (MPa)	1750
Diameter, θ (mm)	5

3.2 Dynamic modelling of the sleeper

Since railway track is always subjected to a variety of time-dependent loads, understanding the dynamic track behaviour is essential in order to evaluate the structural safety and service life of the railway track components [15]. Sleepers are subjected to extremely high forces and strains under dynamic loading and also play an essential role in the dynamic response of global railway track, vibration damping and energy dissipating into the ballast [16]. It is known that sleeper damage can in some cases arise from the sleeper's resonant behaviour, such damage being cracking of sleepers in the vicinity of the fastening, with this damage mostly occurring at resonant frequencies of the sleepers [15].

The sleeper is modelled as a solid element as in the previous static model. But most importantly, the sleeper model is supported by a viscously damped, massless elastic foundation with certain stiffness that simulates the underlying ballast supports which allows the sleeper to move up and down.

4. Results and discussions

4.1 Natural frequency extraction

To examine the vibration characteristics of concrete sleepers, modal analysis is used. In this model, 20 mode shapes are extracted, some of which are shown in Figure 6. To obtain resonance conditions; harmonic response of the sleeper for the excitation in the range of 0-2000Hz and variation of stress and displacement amplitudes with respect to frequency were studied.

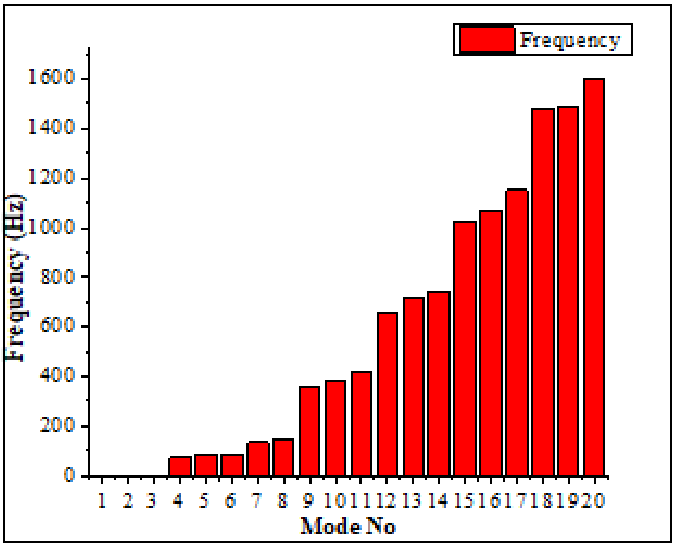

Figure 5. Mode No vs Frequency

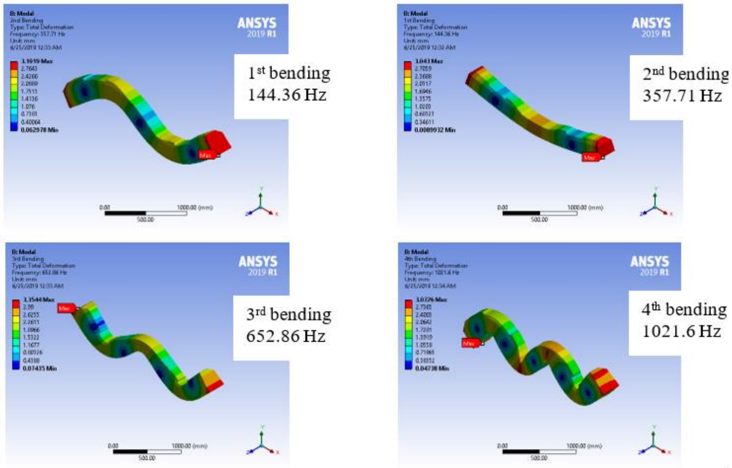

Figure 6. Mode shapes No 8, 9, 12 and 15 corresponding to 1st, 2nd, 3rd and 4th bending respectively.

Table 3. Frequencies and mode types

Frequency (Hz)	Type of mode
144.36	1st Bending
357.71	2nd bending
652.86	3rd Bending
1021.6	4th Bending

4.2 Vertical displacement and stress

The numerical results of dynamic structural response are considered as vertical displacement at rail seat and the stresses in the sleeper as shown in Figure 7 and Figure 8 respectively.

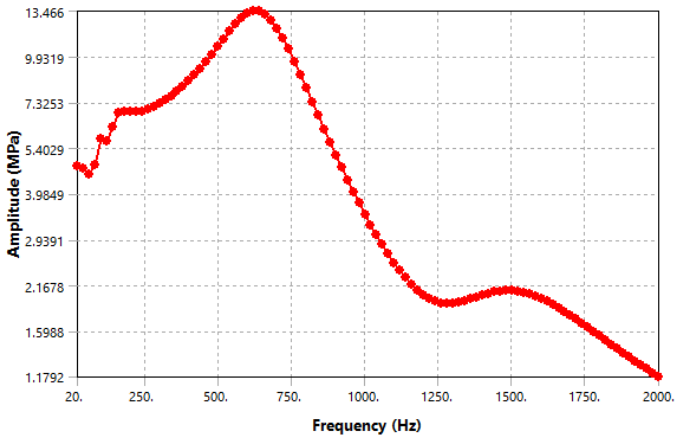

Figure 7. Stress amplitude at rail-seat

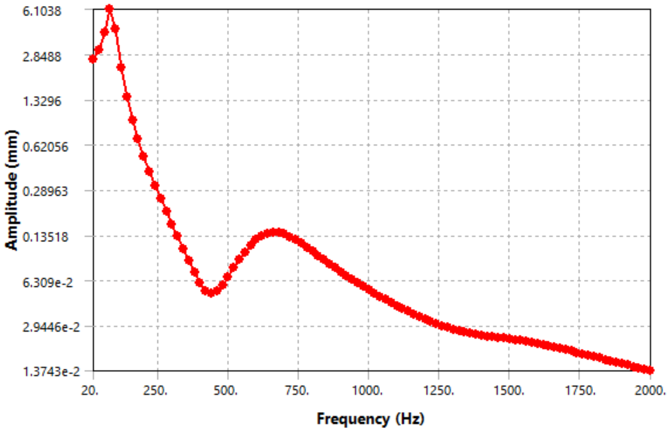

Figure 8. Vertical displacement at rail-seat

Knothe and Grassie [17] propose a frequency range of 0-1500Hz for damage to track components, such as the sleepers. Since the resonant behaviour up to 2kHz is discussed for the sleeper, the work is accordingly relevant to the entire frequency range in which the dynamic behaviour of the sleepers is of any significance to loading on the sleepers themselves or indeed to loads on the track more generally.

4.3. Static Analysis

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

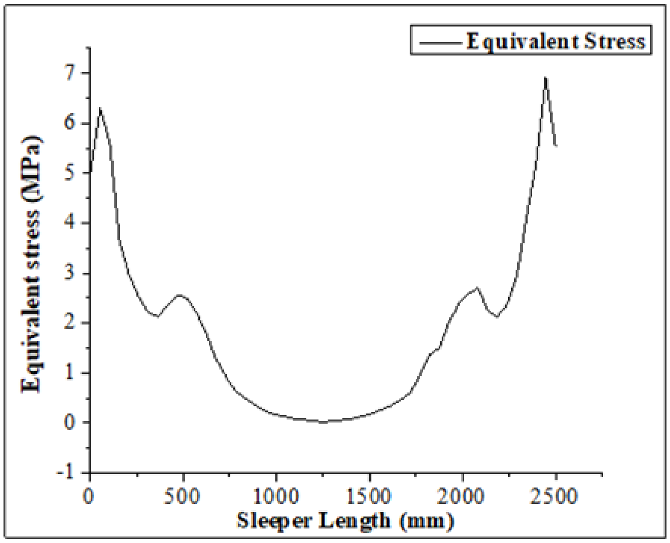

Figure 9. Variation of Equivalent stress along the sleeper

4.4 Fatigue Analysis (cyclic loading)

The mechanical properties of the material will change under repeated cyclic loading, such as permanently increasing strain on the member, causing the stiffness to decrease. Cyclic loading may also cause a concentration of stress at the pre-stressed wires' surface, which can lead to sudden fracture [18], [19].

In terms of the deformations, the FE model captured the general trend of increasing deformations with the number of cycles. The FE results show almost similar deformation between 10^3 and 10^6 cycles, and a large increase in deformations after 10^6 cycles until when the sleeper fails due to fatigue at 3.6 x 10^6 cycles. Most cracks are found under the rail seat areas where the loads are applied and at the bottom edges of the sleeper. The location of cracks and crushes correspond with the location of failure of the sleeper.

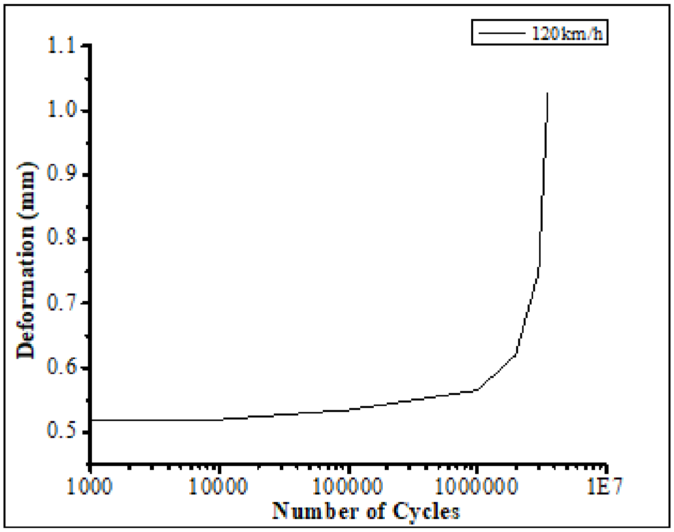

Figure 10. Deformation at rail-seat

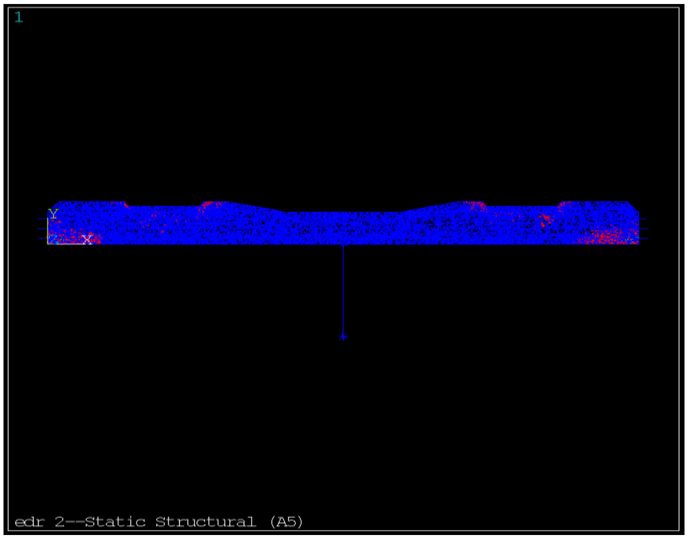

Figure 11. Crack pattern along the sleeper

To determine the ability to hold the geometry of a railway line, most railway organizations use a criterion to judge whether the sleeper is valid or not. Therefore, any cracking that leads to a sleeper's inability to keep the geometry of a railway line has to be considered as failing this criterion.

Table 4. Summary of FE results.

Analysis type	**Results**	**Value**
Static analysis	Vertical deflection (mm)	0.039
	Maximum equivalent stress (MPa)	7.3686
Fatigue results (cyclic loading)	Life	3,590,822
	Damage	3.147
	Safety Factor	0.972

The stresses induced in the sleeper are far below the allowable stress levels that the sleeper should be subjected to. However, due to the impact of repeated loadings, the sleeper as it is cannot attain the main technical standards of speed and axle load set by The Ethiopian Railways Corporations. The target speed used for analysis is 120km/h and 25tons for the axle load with an approximation of $1.13x10^7$ load cycles on each rail seat of the sleeper. To achieve the required loading cycles, a reduction in target speed and axle load or both is necessary to reduce the stresses induced in the sleeper and consequently increase the life span of the sleeper.

Table 5. Variation of fatigue life with speed.

Speed (km/h)	**Stresses (MPa)**	**Fatigue Life (cycles)**	**Fraction of total life**	**Damage**	**Safety Factor**
120	7.3686	3,590,822	31.8%	3.147	0.971
100	7.3105	5,294,990	46.9%	2.134	0.985
80	7.2236	9,694,696	85.8%	1.166	0.997

At a speed of 120km/h and an axle load of 25tons, the sleeper life is 31.8% of the total design life of the sleeper. A reduction of the speed to 100km/h increases the life of the sleeper to 46.9% of the total design life while a speed of 80km/h would increase the lifespan of the sleeper to 85.8% of the total design life.

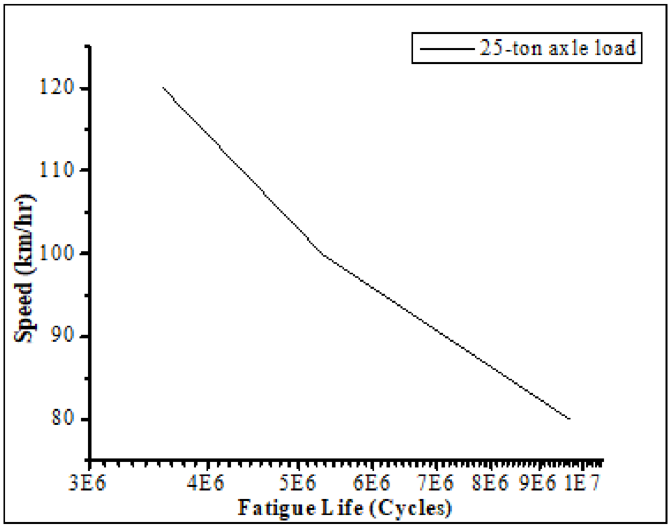

Figure 12. Variation of fatigue life with Speed

Figure 12 shows a clear relationship between speed and fatigue life. The fatigue life of the sleeper reduces as the line speed increases. An increase in line speed increases the rail seat load on the sleeper thus inducing more stresses into the sleeper which in turn reduces the life of the sleeper. The optimum speed to achieve above 80% of the life of the sleeper should be 80km/h with an axle load of 25-tons.

5. Conclusions

In this paper, the dynamic and fatigue response of the Chinese type II sleepers is assessed. Dynamic analysis of the sleeper obtained natural frequencies and mode shapes. It's observed that the most resonant frequency corresponds to the third bending mode shape. For the constant amplitude load considered in this simplistic model, the sleeper fails after 3,590,822 load cycles. Moreover, it is observed that at a speed of 80km/h and an axle load of 25 tons, the life of the sleeper was found to be 85%. Thus, to attain the design life of the sleeper, during the operational phase, it is recommended to limit the speed of the train to 80km/h.

It can be seen from the study that the Chinese type II sleeper is not adequate in fatigue. The sleeper develops cracks which are likely to limit the sleeper's ability to hold the geometry of the line and therefore failing in that criterion. Future studies on fatigue life optimisation of the Chinese type II sleeper are recommended to be carried out to increase the life of the sleeper to be able to serve its intended design life.

Since literature data on fatigue of concrete is scattered, it's also recommended for the sleeper to be tested in the laboratory for fatigue to validate the numerical results obtained in ANSYS.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Tarekegn, Abrham Gebre: Supervision, article editing and revision.

Wantono Francis: Conceptualization, writing original draft, article editing and writing final paper.

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