Impact analyses for negative flexural responses (hogging) in railway prestressed concrete sleepers

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Abstract. By nature, ballast interacts with railway concrete sleepers in order to provide bearing support to track system. Most train-track dynamic models do not consider the degradation of ballast over time. In fact, the ballast degradation causes differential settlement and impact forces acting on partial and unsupported tracks. Furthermore, localised ballast breakages underneath railseat increase the likelihood of centrebound cracks in concrete sleepers due to the unbalanced support under sleepers. This paper presents a dynamic finite element model of a standard-gauge concrete sleeper in a track system, taking into account the tensionless nature of ballast support. The finite element model was calibrated using static and dynamic responses in the past. In this paper, the effects of centre-bound ballast support on the impact behaviours of sleepers are highlighted. In addition, it is the first to demonstrate the dynamic effects of sleeper length on the dynamic design deficiency in concrete sleepers. The outcome of this study will benefit the rail maintenance criteria of track resurfacing in order to restore ballast profile and appropriate sleeper/ballast interaction.

1. Introduction

Commonly, railway sleepers (also called 'railroad tie' in North America) are fundamental elements of railway track structures. Their major role is to redistribute train wheel loads from the rails to the underlying ballast bed and foundation. Based on present design practices, the design life span of the

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concrete sleepers is targeted at around 50 years in Australia, Asia and North America; and around 70 years in Europe [1]. Note that the exact design principle in Europe has not been fully addressed due to the recent development of Eurocode. Figure 1 shows the typical ballasted railway tracks and their key components. There have been a number of recent investigations on the railway sleeper models [2-5]. Most of the models in practice employed the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. It is found that only vertical stiffness is sufficient to simulate the ballast support condition because the lateral stiffness seems to play an insignificant role in sleeper's bending responses [6]. Field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the support condition induced by ballast packing and tamping [7-10].

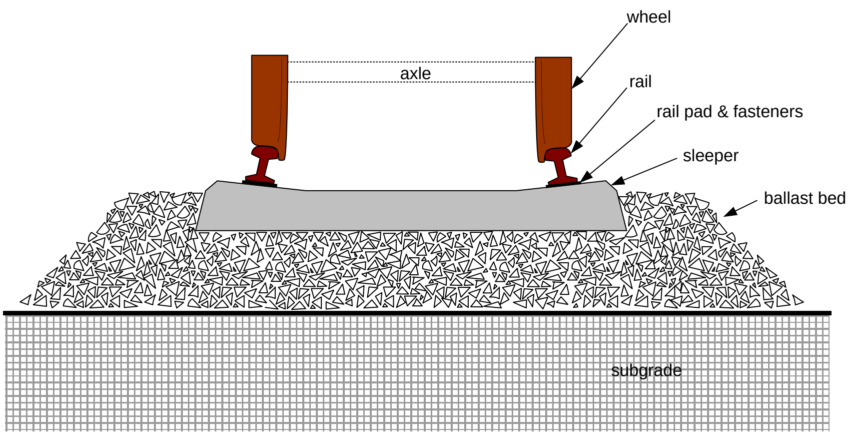


Figure 1. Typical ballasted railway track components.

For railway prestressed concrete sleepers, Australian Standard [1] clearly prescribes the method for assessing the bending moments for the design of railway concrete sleepers. Although the most critical loading conditions on the track systems are related to wheel impacts, the current design procedure takes the dynamic effects into account by using a dynamic load factor and treats the wheel burden as the quasi-static loading [7]. In practice, the wheel load generally imparts the positive bending moment at the railseat whilst provides the negative bending moment at mid span of the railway sleepers. For a standard or broad gauge sleeper, the design maximum positive bending moment at the rail seat, M_{R+}, can be evaluated by

$$M_{R+} = \frac{R(L-g)}{8} \tag{1}$$

where R is the rail seat load, L is the total length of sleeper, and g is the gauge length of the track. It should be noted that the length of ballast support beneath each railseat (a) can be calculated by $a = L - g$ [1]. Note that in the US, this (a) can be quantified from 1/3 of the sleeper length.

In Europe, the positive bending moment at the rail seat takes into account the rail base width (f) and sleeper depth (h), which can be calculated by

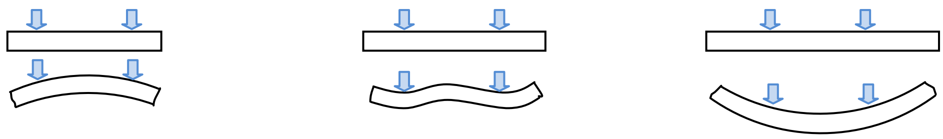
$$M_{R+} = \frac{R(L-g-f-h)}{8} \tag{2}$$

Analogously, the centre negative design bending moment M_{C-} for track gauge of 1,600mm and greater, for Australian rail networks, reads [1]:

$$M_{C-} = \frac{1}{2}\left[Rg - Wg(L-g) - \frac{1}{8}W(2g-L)^2\right] \tag{3}$$

where
$$W = \frac{4R}{3L - 2g} \tag{4}$$
For track gauge of 1,500mm or less, Australian standard suggests:
$$M_{C-} = \frac{1}{4}\left[R(2g - L)\right] \tag{5}$$
In European rail networks, the middle span area, b, (or $b = L - 2a$) will be considered by each rail authority whether to take into account half ballast support (partially consolidated support condition) or not. The centre negative design bending moment of constant width sleepers can thus be represented by (if $b = 0$, it will be equal to Equation 5):
$$M_{C-} = \frac{R}{2}\left[g - \frac{2L^2 - b^2}{4L - 2b}\right] \tag{6}$$

It is important to note that the designed cross sections and reinforcements deemed to comply with Australian Standard shall provide adequate shear resistance [1]. Even though the sleeper cross-section plays a vital role on its flexural strength, the responses of the railway sleepers are not significantly dependent to either the bending rigidity or the modulus of elasticity of sleepers [8]. By contrast, Figure 2 shows the effect of sleeper length on the flexural responses of sleepers. This is a root cause for variation in bending moment design calculation and field measurement resultants.



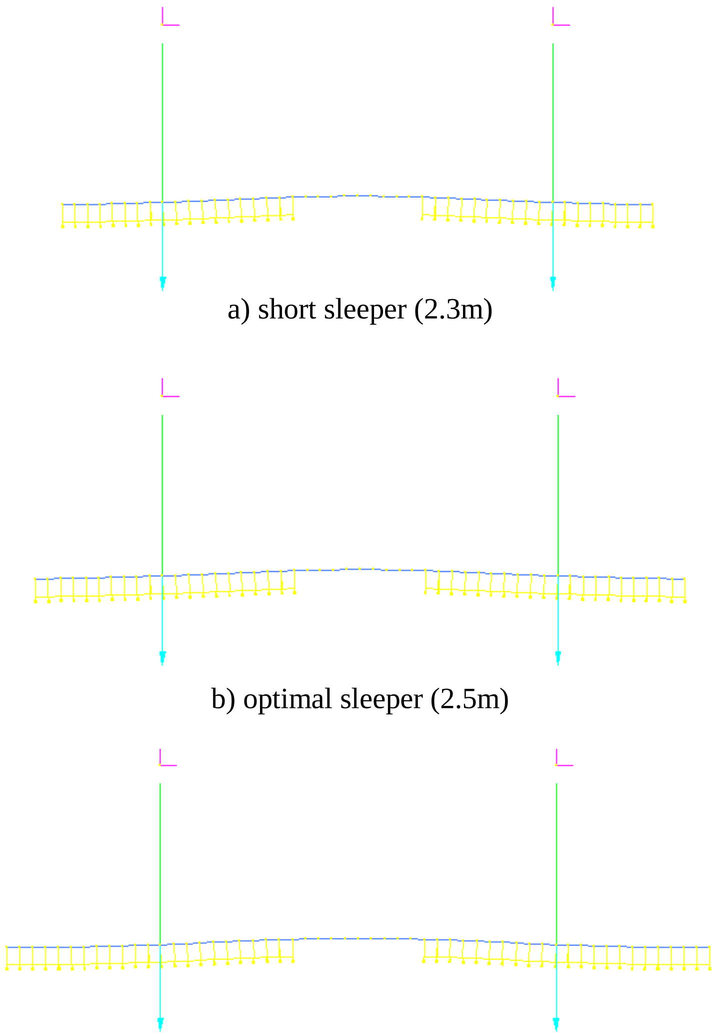
a) short sleeper b) optimal sleeper c) long sleeper

Figure 2. Flexural influences of sleeper length [9].

Based on previous researches [9-11], ballast support plays another key role in the bending moment resultants. However, it is still questionable at large whether modern ballast tamping process is effective and it could enable adequate symmetrical support for sleeper at railseat areas. In reality, the ballast is tamped only at the railseat areas. The ballast at the mid span is left loosening, with the intention to reduce negative bending moment effect on sleeper mid span, which is the cause of centre bound cracks. Over time, the dynamic track settlement induces ballast densification and the sleeper mid-span comes into contact or is fully supported by ballast until the track geometry is restored by resurfacing activity (i.e. re-tamping). This paper presents a dynamic railway concrete sleeper modelling capable of impact analysis into the effect of ballast conditions on the dynamic negative flexural responses of railway sleepers. It focuses on the nonlinear flexural response of railway concrete sleepers subjected to a spectrum of ballast stiffnesses at the mid span, in comparison with the current design method in accordance with the design standards.

2. Dynamic finite element modelling and its validation

Previous researches have established that the two-dimensional Timoshenko beam model is the most suitable option for modelling concrete sleepers [2-5]. In this investigation, the finite element model of concrete sleeper (optimal length) has been previously developed and calibrated against the numerical and experimental modal parameters [5, 9]. Figure 3 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 [12], the numerical model included the beam elements, which take into account shear and flexural deformations, is used for modelling the concrete sleeper. This full beam model has been established so that unbalanced load effects (such as impact loading from wheel flats [13-15]) can be evaluated in the future. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. In reality, the ballast support is made of loose, coarse, granular materials with high internal friction. It is often a mix of crushed stone, gravel, and crushed gravel through a specific particle size distribution. It should be noted that the ballast provides resistance to compression only.



a) short sleeper (2.3m)

b) optimal sleeper (2.5m)

c) long sleeper (2.7m)

Figure 3. STRAND7 finite element model of a concrete sleeper.

As a result, the use of elastic foundation in the current standard [1] does not well represent the real uplift behaviour of sleepers in hogging moment region (or mid span zone of railway sleeper). In this study, the support condition was simulated using the nonlinear tensionless beam support feature in Strand7 [12]. This special feature or attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted from the iterative numerical analysis. The tensionless support option can better represent the ballast characteristics in real tracks [12], especially subject to dynamic conditions. Table 1 shows the geometrical and material properties of the finite element model. It is important to note that the parameters in Table 1 give a representation of a specific rail track, particularly for common standard-gauge passenger train tracks. These data have been validated using field measurements and the verification results have been presented elsewhere by the authors [5, 13-14].

Table 1. Engineering properties of the standard sleeper used in the modelling validation.

	Parameter lists	Units
Flexural rigidity	$EI_c = 4.60,\ EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502,\ \kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	kg/m^3
Sleeper length	$L = 2.5$	m
Track loading gauge	$g = 1.5$	m

To our knowledge, the nonlinear flexural analysis of railway concrete sleepers in a track system due to the variations of ballast support conditions together with the length of sleeper has not yet been fully addressed by the research workers. Especially when the uplift behaviour due to ballast tensionless support in hogging region of sleepers is considered, a finite element analysis is required to supersede the simple manual calculation [15]. The impact simulations are conducted using the nonlinear solver in STRAND7 [12], to study the effects of ballast stiffness and the length of concrete sleeper on the flexural response of the railway concrete sleeper in a track system. The length of sleeper varies from 2.3m to 2.7m, which is practically acceptable [16-17]. Figure 4 displays an estimation of impact loading derived from wheel flats, wheel burns, out-of-round wheels, and wheel skids.

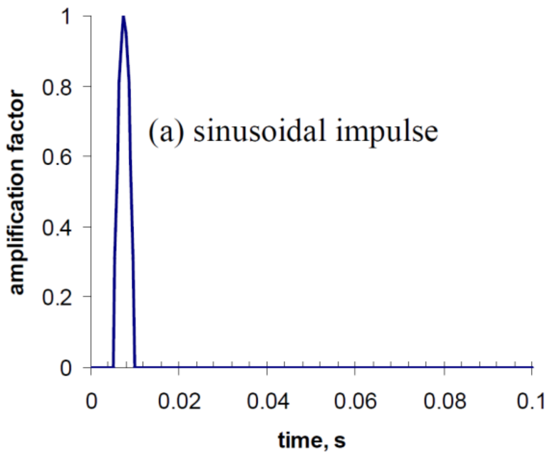


Figure 4. Estimations of transient loading [15].

3. Static Analysis

Using the design data in Table 1, Figure 5 shows the bending moment diagram along the sleeper when subjected to the equal wheel loads of 100kN at both railseats, in comparison with the standard design moments. This serviceability-based magnitude of railseat load can often be derived by merely suburban passenger trains running at a speed from 80 km/h to 120 km/h, operating on either Class 1 or Class 2 railway tracks. Based on Equations (1) and (2) in accordance with AS1085.14 [1], the design maximum positive bending moment at the rail seat M_{R+} = 12.50 kNm, while the centre negative design bending moment M_{C-} = 6.95 kNm (if considered half support) or =12.50 kNm (if considered full support). It is typical that the positive and negative moments are associated with the railseat and mid-span sections, respectively. It shows that the standard design moments provide the conservative results. The standard design moment at mid span is about half between the other two cases (see Figure 5 for more details).

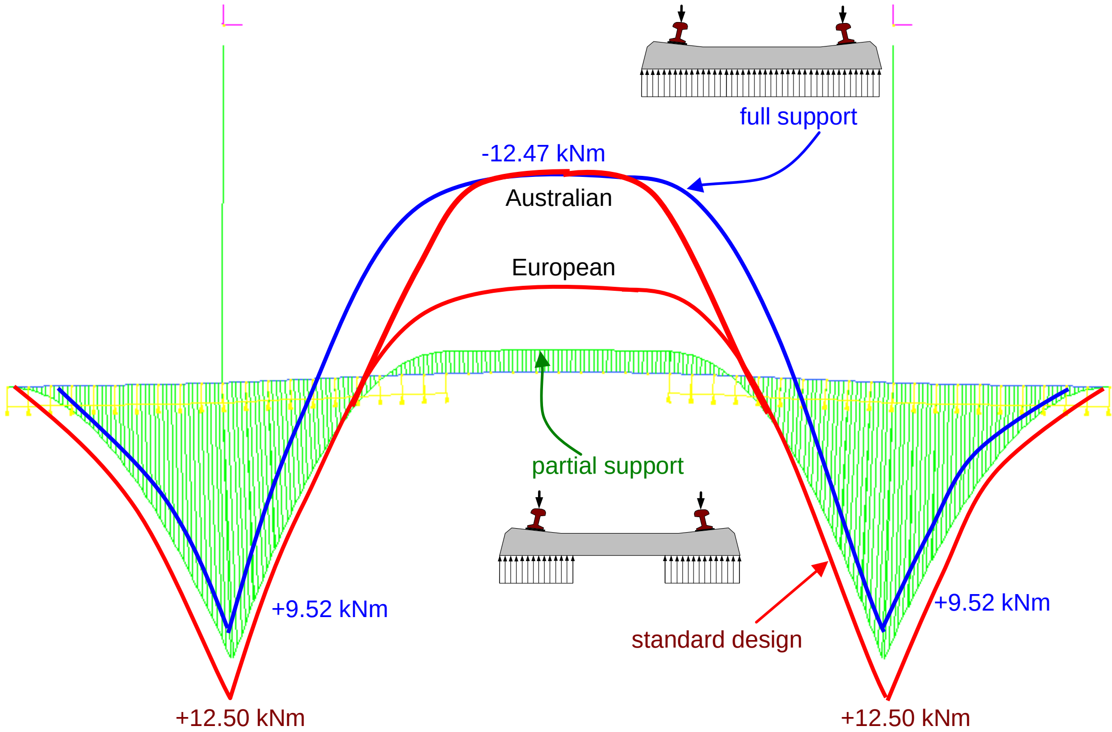


Figure 5. Flexural response of a railway sleeper in track system.

4. Impact Analysis

Impact simulations of standard length sleeper (2.5m) with no ballast support at midspan can be seen in Figure 6. The results resemble as dynamic flexural actions decaying, with reverse dynamic effects of tensionless support. This effect cannot be achieved by using a linear solver for responses under dynamic and impact load conditions. However, linear estimation may yield 3% to 5% differences in statically and linearly elastic range.

The effect of ballast stiffness on the dynamic moment resultants to impact loading is presented in Tables 2 to 4. The ballast support conditions have been justified from track settlement data when the support condition in the mid span of sleeper will be increased over time as the railseats deteriorate. The nominal bending moments M^* at both rail seat and mid span are normalized by the maximum standard design moments at rail seat (M_{R+}) and mid span (M_{C-}), respectively. Also, the ballast stiffness increment is presented in terms of the variation of percent changes from the initial ballast data in Table 1.

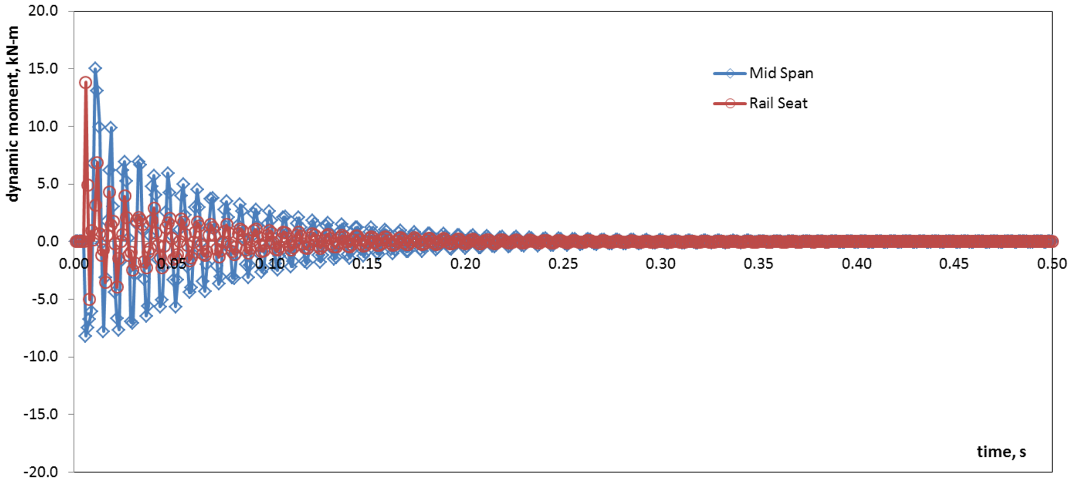


Figure 6. An example of impact responses of standard length sleepers with no ballast support at midspan.

Previous study [9] found that the static bending moments at rail seats of the railway sleeper are conservatively estimated by the design standard. For the dynamic bending moment at rail seats, the dynamic amplification between the static design moment and the dynamic moment can be noticed. For the short length sleeper, the variation can be from 32% (for no support) to 209% for deteriorated track (300% settled). Based on a comparison between dynamic load actions across the cases, it can be observed that the dynamic effects due to sleeper dimension are relatively greater than those due to the ballast conditions. When the mid span ballast contact increases, the positive dynamic moments at railseats increase whilst the positive dynamic moments at mid-span decrease in all cases. In contrast, the negative moments at mid span decrease in all cases when sleeper/ballast interaction at the mid span occurs.

Table 2 Dynamic flexural moment analysis of short-length sleeper (2.3m)

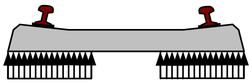
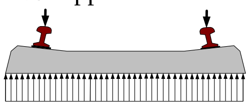
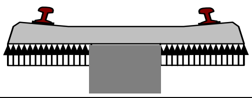
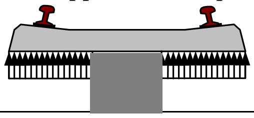
Ballast Support	At railseat (kNm)		At mid span (kNm)	
	$M+/ M_{static}$	$M-/ M_{static}$	$M+/ M_{static}$	$M-/ M_{static}$
No support in mid span 	1.32	-0.76	-4.34	3.09
100% support 	1.62	-0.93	-1.01	1.10
200% support at mid span 	1.88	-1.08	-0.72	0.80
300% support at mid span 	2.09	-1.21	-0.59	0.63

Table 3 Dynamic flexural moment analysis of optimal-length sleeper (2.5m)

Ballast Support	**At railseat (kNm)**		**At mid span (kNm)**	
	M+/ M_{static}	M-/ M_{static}	M+/ M_{static}	M-/ M_{static}
No support in mid span	1.16	-0.42	-15.0	8.18
100% support	1.39	-0.50	-0.77	0.81
200% support at mid span	1.59	-0.57	-0.43	0.54
300% support at mid span	1.77	-0.63	-0.29	0.51

Table 4 Dynamic flexural moment analysis of long-length sleeper (2.7m)

Ballast Support	**At railseat (kNm)**		**At mid span (kNm)**	
	M+/ M_{static}	M-/ M_{static}	M+/ M_{static}	M-/ M_{static}
No support in mid span	0.97	-0.06	2.38	-2.38
100% support	1.15	-0.07	-0.20	1.03
200% support at mid span	1.30	-0.08	-0.09	0.54
300% support at mid span	1.43	-0.18	-0.18	0.42

Interestingly, the negative moments at railseat increase when ballast stiffness at mid-span increase. It can be observed that the length of sleeper plays an influence role on the dynamic bending moments at both railseats and mid span of concrete sleepers.

At mid span, the negative dynamic moments can be significantly influenced by both sleeper length and support condition. In many cases, the sleeper can be cut shorten (by sawing) in order to accommodate ballast walls, signaling gears, turnout point motors, etc. From this study results, it can be found that, under impact loading, the short sleeper will benefit from sleeper/ballast contact at mid span. However, it is important to note that the impact loading can significantly damage all sleepers at the mid-span, especially when there is no ballast support. This implies that the centre-bound cracks of short sleepers could develop and become a serious problem for track maintenance if the wheel dynamic loads cannot be controlled. It also appears that the dynamic bending moments have generally low sensitivity to the spectrum of ballast stiffnesses in comparison with the dominant influence of sleeper length. These results demonstrate that the quality control of sleeper manufacture is very important as the additional length of sleeper is sometimes a defect as a result of poor quality control. Such defects modify the dynamic flexural behavior of sleepers on track. It is also important to note that the impact loading will have significant effects only on the sleepers without any ballast support in the mid span.

In terms of structural capacity of concrete sleeper, the design concept (in Australia and North America) often yields the large amount of prestressing tendons under the neutral axis of the sleeper cross section. This implies that dynamic hogging damage of sleepers could occur at mid span (under reinforced), especially when the train wheels are poorly maintained and imparts short-duration but high-magnitude loading on tracks [12-13], as shown in Figure 7. Note that it would generally take some years without any maintenance to facilitate 200-300% of ballast stiffness at mid-span of sleeper (provided that the condition after track construction is reasonably acceptable). In the dynamic impact analysis, it was found in previous studies [18-19] that the pulse duration due to wheel/rail irregularities is rather short and then the damping mechanism cannot react to the transient pulse velocity in time. As a result, damping effect becomes negligible and ignoring damping will be more beneficial for design purpose.

Figure 7. Broken concrete sleepers (taken from a vibration-sensitive track between Solihull and Birmingham).

5. Conclusions

This study highlights the critical dynamic effects of a variety of ballast conditions and sleeper length on the flexural responses of the railway concrete sleepers in a track system to impact loading. The dynamic finite element model of concrete sleepers, which was established and calibrated earlier, is utilised in this study. The dynamic influences of the variation of ballast support conditions at mid span of the sleeper together with the sleeper length on the bending of the railway sleeper were evaluated in comparison with the static analysis. The nonlinear transient solver in STRAND7 was employed to handle sleeper/ballast contact mechanics. Under static and dynamic conditions for equally supported sleepers, the numerical results exhibit that the bending moment resultants are affected by the ballast stiffness variation. The sleepers suffer from impact loading when there is no ballast support at the mid span. The standard design of sleepers tends to reinforce for the positive bending moment at both rail seats and mid span, resulting in an under-reinforced section for hogging moment at mid-span. Generally, negative bending moments at mid span of sleeper have generally low sensitivity to the spectrum of ballast support conditions in comparison with the more pronounced influence of sleeper length. However, under the impact loading, the negative bending moment resultants are affected significantly in the mid span of sleepers. In such case, the dynamic negative bending moment at mid span could be larger than the structural capacity of sleeper and resulted in structural cracks and failure due to impact loading over time. Such effects are lesser for short and long sleepers. This insight in dynamic bending moments will raise the awareness of track engineers for better quality assurance of sleeper manufacture and for better maintenance regime of train wheels. In addition, it is noted that such insight cannot be thoroughly evaluated using a linear spring solver.

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