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Damping Effects on Vibrations of Railway Prestressed Concrete Sleepers

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Abstract. Railway concrete sleepers have been generally used in ballasted railway track around the world for over 50 years. They are commonly used to redistribute wheel forces onto track structure and to assure stable track gauge for safe passages of rolling stocks. The dynamic behaviours of railway sleepers are commonly well known; however, its damping characteristic is often neglected. With the increased demand for heavier and faster trains, the nature of track forces applying onto each track components is no longer static or quasi-static. Statistically, almost a quarter to track load spectra is typically of transience and high intensity. The ignorance of damping can no longer be persisted as pre-mature damage or failure of track components can take place at a faster rate. A single sleeper failure may not affect open, plain track operations but it can give rise to the risks of rail breaks at rail joints, welds, bridge ends, switches and crossings, curved track, etc. Such the risks can later result in detrimental train derailments. This is thus very important to consider the failure of sleepers in a case by case basis that is suitable for the track type, track condition and level of maintenance and operations. This paper will highlight the effects of damping on the vibrations of railway concrete sleepers in a track system. An established and validated finite element model of sleeper has been adopted for further studies. The model has been validated by experimental results. This study aims to quantify the potential to improve damping in concrete in order to suppress vibrations in a track system. The insight into the vibration suppression of railway sleepers will help track engineers to decide the better choice of advanced materials for manufacturing railway concrete sleepers.

1. Introduction

Railway sleepers (also called ‘railroad tie’ in North America) are a vital safety-critical element of railway track structures. The experience of design and application of railway concrete sleepers have been over 60 years around the world. Their key functions are to redistribute loads from the rails onto the underlying ballast bed, and to secure rail gauge for safe and smooth train passages. Based on the current design approach using static and quasi-static theory of solid mechanics, the design life span of the concrete sleepers is targeted at around 50 years in Australia and around 70 years in Europe [1-4]. In design practice, dynamic problems have not fully been taken into account, giving rise to the lack of new innovation for concrete sleepers. Current industry practice is still based on topological

optimisation and selection of tailored or bespoke dynamic factors for design [5-8]. This is due to the fact that the current design and testing standards are somewhat primitive and overly simplified.

Figure 1 shows the typical ballasted railway tracks and their key components [9]. There have been a number of previous investigations on the railway sleeper modelling methods [10-13]. Most of the models have employed the concept of beam on elastic foundation where a sleeper is fully laid on the elastic support, acting like a series of continuous 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 [14-16]. In practice, the rail cant is often less than 1 in 20, and the lateral force from curving effects tends to be less than 20% of vertical force and the anchorage of fastening has been designed to take care of lateral actions [2, 17]. In fact, field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the support condition induced by ballast packing and tamping [1, 14, 18-20]. 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. 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 study thus takes a realistic approach in modelling *in-situ* concrete sleepers.

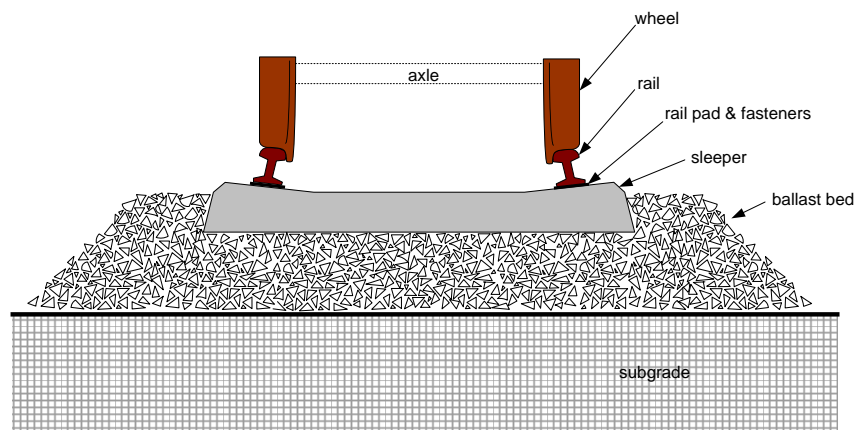


Figure 1 Typical ballasted railway track

Under dynamic loading conditions, the structural behavior of concrete sleepers has not been fully investigated. The insight into dynamic behaviours is imperative to improve dynamic design guideline and field performance of track components [21-25]. Importantly, it is noted that damping coefficient has not been taken into design analysis of railway concrete sleepers. This is because design practice often needs the worst-case scenario analysis when damping is absent. This has resulted in the lack of innovation in material research. A number of research has been conducted to identify advanced concrete technology that can also suppress vibration in railway environments [22-25]. It is found that higher damping can be developed for high-strength concrete that can also satisfy complex systems requirements by railway industry. This damping effect is known to help suppress vibration damage in track components. However, the research into such the effect is very little.

Although it is clear that the railway sleepers are exposed to dynamic loading conditions, the damping aspect has never been fully investigated. This paper presents an advanced railway concrete sleeper modeling capable of analysis into the damped effects of transient loading on the positive and negative flexural responses of railway sleepers. This study focuses on the nonlinear dynamic flexural response of railway concrete sleepers subjected to effective viscous damping of concrete material [26].

It is the first time that the damped responses of concrete sleepers have been investigated. The insight into the damped behaviour will help track engineers making a better choice in material design and selection. It will also inspire materials engineers to further improve the dynamic material capabilities.

2. Finite Element Modelling

There have been several extensive studies showing that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads [10-12]. 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 [16]. Figure 2 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 [27], the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the concrete sleeper. 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 [17].

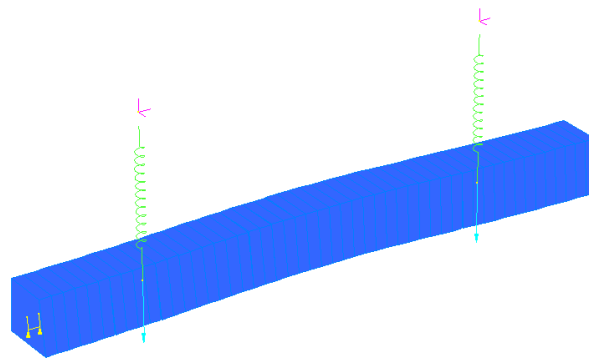


Figure 2 STRAND7 finite element model of a concrete sleeper

Table 1 Engineering properties of the standard sleeper used in the modeling validation

Parameter lists		
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
Rail gauge	$g = 1.435$	m

In this study, the support condition is simulated using the tensionless beam support feature in Strand7 [27]. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. This attribute creates nonlinear boundary conditions to the sleeper model, requiring Newton Raphson's numerical iterations to resolve the sleeper-ballast contact

perimeter. The tensionless support option can correctly represent the ballast characteristics in real tracks. 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. These data have been validated and the verification results have been presented elsewhere [17].

It is common practice in structural design to assume that concrete material has negligible viscous damping ratio [26]. However, it is often found that the effective damping of high-strength concrete can be varied from 0.1% to 2% [24]. The equation of forced motion for multi-degree-of-freedom (MDOF) system can be written as [26]:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \quad (1)$$

where m is the mass of structure; c is equivalent viscous damping; $f(t)$ is force function; $x(t)$ is the displacement; $\dot{x}(t)$ is the velocity; and $\ddot{x}(t)$ is the acceleration. Taking a mass-normalized formulation approach, the acceleration measured on the structure becomes the mass-normalized inertial force. The mass-normalized velocity proportional equivalent viscous damping ratio can be written in terms of the damping coefficient and the natural period of a sub-critically structure as [26]:

$$\beta = \frac{c T_n}{m 4\pi} \quad (2)$$

where β is the equivalent viscous damping ratio and T_n is the natural period of the structure (i.e. period of the dominate mode of response). In this study, the first bending mode of sleeper vibration has been used to calculate the damping ratio. The equivalent viscous damping (c) has been used in the FE modelling for transient dynamic integration in order to avoid matrix errors for explicit finite solution calculations.

3. Results and discussion

The static bending moment envelops along the bearer when subjected to the equal wheel loads of 100kN at both railseats can be quantified as the standard design moments using the design data in Table 1. Based on AS1085.14 [6], the design maximum positive bending moment at the rail seat = 12.50 kNm, while the centre negative design bending moment = 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. By eigenvalue analysis, Figure 3 shows the dominant bending modes of vibration of the sleepers. As a result, T_n is 7 msec and the mass of sleeper (m) is 354 kg.

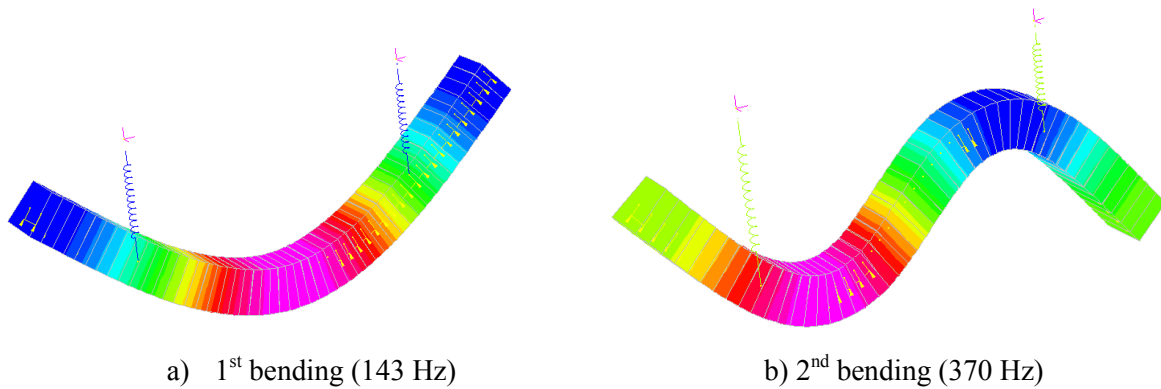
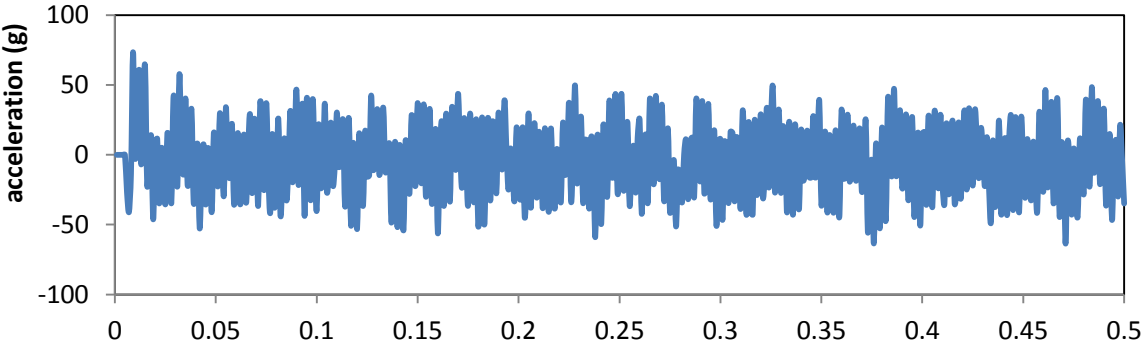
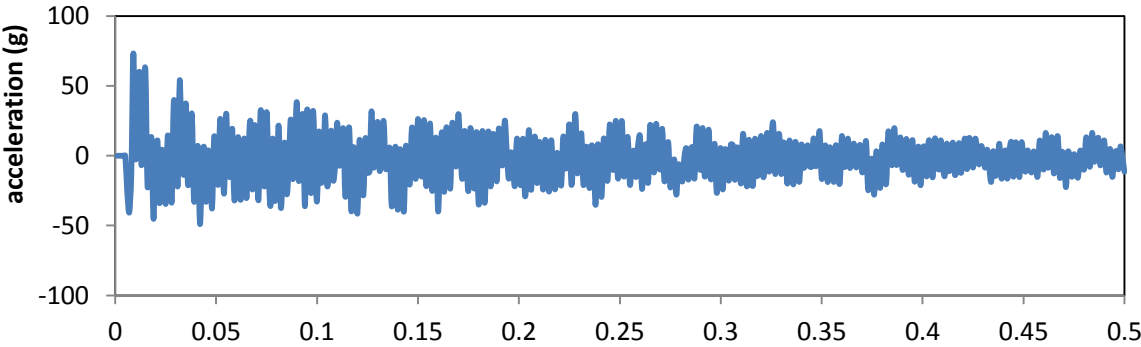


Figure 3 Natural frequencies and corresponding mode shapes of railway concrete sleeper

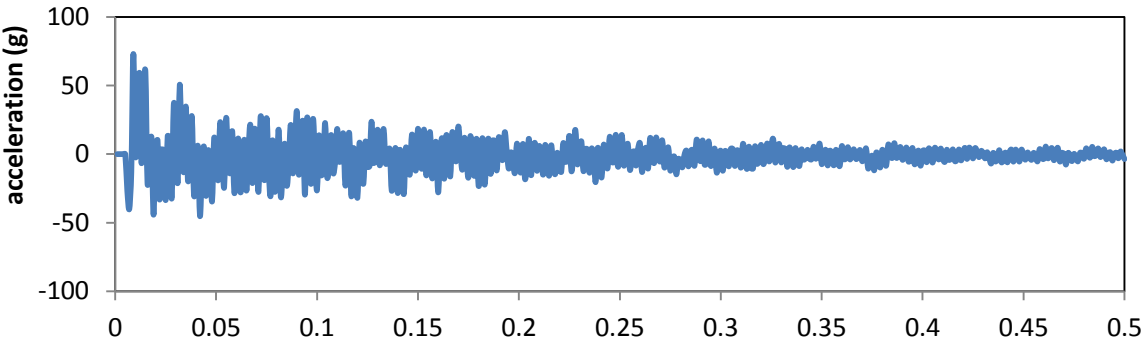
Dual impact loads of 100 kN and 3 msec are applied at both railseats. This impulse is equivalent to the effect of common wheel burns on railway tracks. The effects of damping on the transient responses of railway concrete sleeper at railseats can be illustrated in Figure 4. It can be seen that damping effect plays significant role in suppressing vibrations at railseats of the concrete sleeper. This can be implied that the improvement in material damping can help suppress vibrations that can cause breakage of underlying ballast [28-29].



a) 0% damping ratio

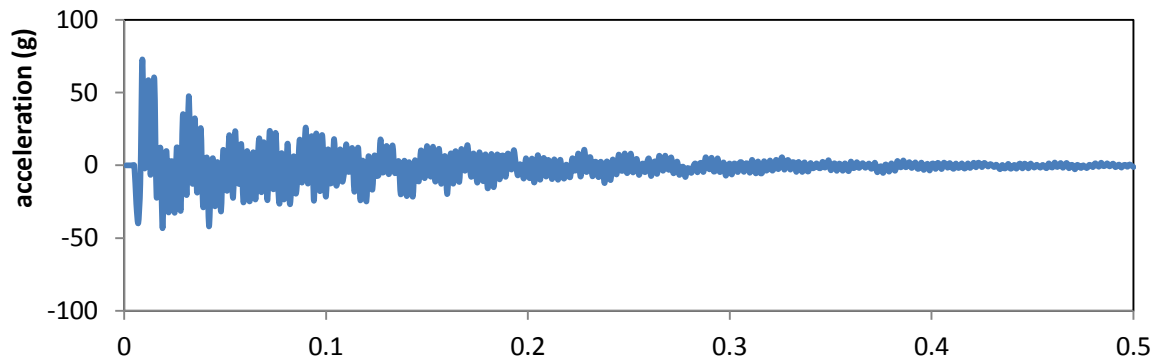


b) 2% damping ratio

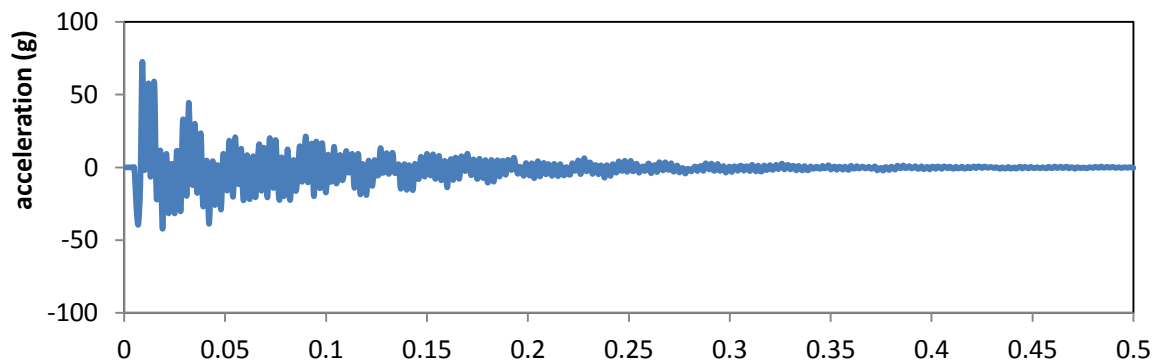


c) 4% damping ratio

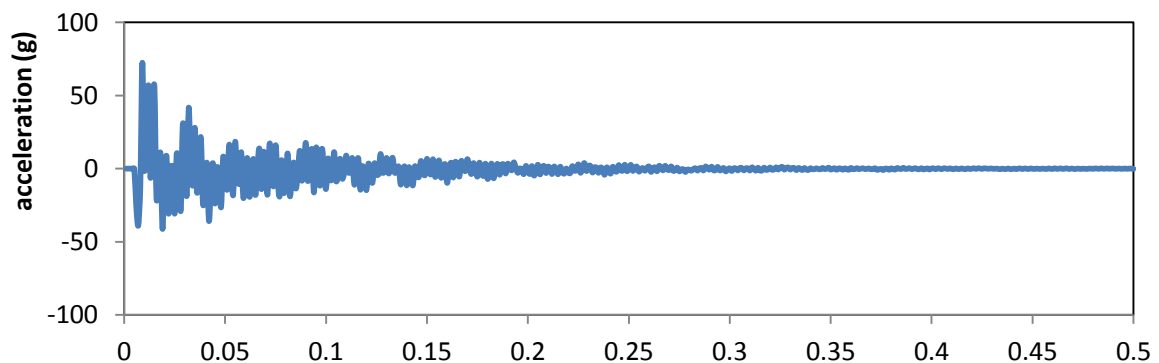
Figure 4 Transient responses of railway concrete sleeper at railseats (time domain)



d) 6% damping ratio



e) 8% damping ratio



f) 10% damping ratio

Figure 4 Transient responses of railway concrete sleeper at railseats (time domain)

4. Conclusion

Globally, railway networks have exploited concrete sleepers in cost-effective ballasted tracks for over five decades. Concrete sleepers redistribute wheel forces onto track structure and secure track gauge for safe passages of rolling stocks. Railway tracks of any kind experience dynamic loading condition due to wheel-rail interaction. For design purpose, concrete material's damping characteristic is often neglected. As such, the understanding into damped vibrations of the concrete sleepers is rather limited. The ignorance of damping has resulted in little research into advanced concrete technology for railway applications. This study is the world first to incorporate advanced insight of novel concrete with high damping with dynamic design of concrete sleepers. This paper highlights the effects of damping on the

vibrations of railway concrete sleepers in a track system. Using an established and validated finite element model of concrete sleepers, realistic sleeper-ballast contact conditions have been adopted for nonlinear transient analysis. This study is the first to reveal the potential to improve damping in concrete in order to suppress vibrations of concrete sleepers in a track system. The insight into the vibration suppression of railway sleepers will help track engineers to decide the better choice of advanced materials for manufacturing railway concrete sleepers.

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