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DYNAMIC RESPONSES OF RAILWAY SLEEPERS TO COUPLING VERTICAL AND LATERAL FORCES

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It is unquestionable that railway infrastructure is naturally a complex system. Its behaviours, geometry and alignment, wheel-rail forces and operational parameters such as tractive efforts are often found to be nonlinear and asymmetrical. Not only does the complex train-track interaction generate vertical impact loading, but the curving behavior of the train body also induce dynamic lateral force acting on the rail. This paper presents a numerical simulation of a standard-gauge concrete sleepers, taking into account the tensionless nature of ballast support. The finite element model was calibrated using static and dynamic responses using experimental data. Previous extensive studies revealed that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical and lateral loads. In this investigation, the finite element model of Timoshenko-like concrete sleeper has been developed and calibrated against the numerical and experimental modal parameters. The influences coupling loads on the dynamic behaviours of concrete sleepers are investigated. In addition, it is the first to demonstrate the effects of material damping on the dynamic spectra of railway sleepers. The dynamic properties of sleepers are critical to dynamic serviceability of both track systems and sleepers themselves. The insight from this study will improve the material design criteria in order to improve train-turnout interaction and ride comfort.
Keywords: Dynamic responses, FEM, concrete sleepers, coupling force, dynamic properties

1. Introduction

In reality, track loading conditions are rather dynamic and much more complex than simple static (or quasi-static as used in component design). Track systems are commonly designed to withstand those dynamic loads throughout the network. Although track load spectra have been identified, it is unlikely that the wayside system (to install load sensors) can really capture the train load throughout the network. As a result, track structures are often designed against the worst case scenarios to assure that no discontinuity could appear and derail the train services. Ballasted track systems consist of su-

perstructure and substructure. Superstructure includes rails, rail pads, fastening systems, sleepers or crossties, and ballast. Rails generally are supported by crossties, which are embedded in ballast over substructure (including subballast, formation and foundation). Railway sleepers, bearers and transoms are safety-critical and structural elements in ballasted railway track systems. Their main functions are not only to withstand static and dynamic loads imposed by the wheels and transfer them to the ballast and underlying formation, but also to secure the rail gauge to allow trains to travel safely [1-3]. The behaviours of sleepers and bearers in track systems are correlated to the loading and support conditions. Many evidences revealed that their structural failure, cracks, and poor serviceability (high deformation and rotation) are due to the resonances generated by the components excited by the dynamic train loads [4-7]. Therefore, the dynamic resistance (derived from dynamic properties of materials and structural component) is critical to enhance durability and endure service life of railway sleepers and bearers in track systems. However, many practitioners still neglect the dynamic testing due to the lack of under-standing into the realistic track performance. A clear example is the non-existence of realistic dynamic testing in design standards (e.g. European Standard EN 13230). On the other hands, a few countries have already developed dynamic resistance testing for sleepers and bearers (e.g. Australian Standard AS1085.14 and AS1085.19 – Impact attenuation tests; German DIN delivery guideline for Impact test for derailment resistance, etc.). These evidences show the inconsistency and different level of maturity of practices internationally.
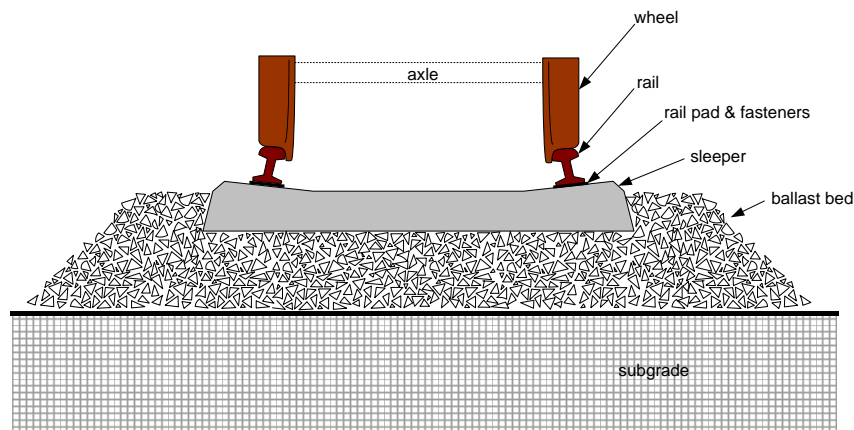

Figure 1: Typical ballasted track components.

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 [8-12]. Most of the models in practice employed the concept of beam on elastic foundation where a sleeper is laid on the elastic support, act-ing like a series of springs. It is reported 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 to the support condition induced by ballast packing and tamping [13-15]. It is im-portant to note that the designed cross sections and reinforcements deemed to comply with Design Standards (e.g. Australian AS1085.14, European EN 13230, etc.) shall provide adequate shear re-sistance. Even though the sleeper cross-section plays a vital role on its flexural strength, the responses of the railway sleepers are insignificantly dependent to either the bending rigidity or the modulus of elasticity of sleepers [16-18]. 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. It is thus very important to note that field measurements in a track system may not be able to appropriately inform a design of track components in another track system.

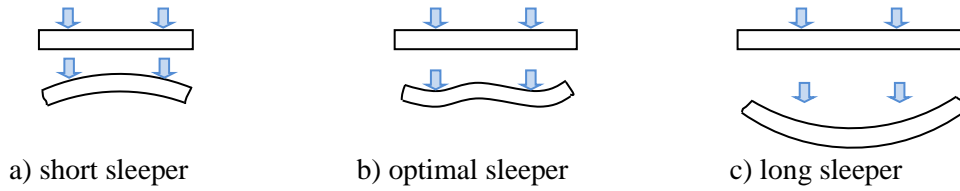a) short sleeper   b) optimal sleeper   c) long sleeper

Figure 2: Influences of sleeper length on flexural behaviour.

Although it is clear that the railway sleepers are topologically symmetrical, the aspect of coupling vertical and lateral forces acting at the crossings has never been fully investigated. This paper thus highlights a railway sleeper modeling capable of nonlinear impact analysis, in order to evaluate the dynamic effect of railway sleepers experiencing coupling vertical and lateral wheel forces. It focuses on the nonlinear dynamic flexural responses of railway concrete sleepers subjected to a spectrum of ballast stiffness at the mid span, in comparison with the current design method in accordance with the design standards. Since dynamic impact loads are over a quarter of annual track load spectra, the dynamic behaviour is crucial to track maintenance criteria [19-21]. Therefore, the effect of coupling vertical and lateral wheelset dynamics on curved tracks will be focused in this study.

2.   Finite element modelling

It is clear that many researches found that the two-dimensional Timoshenko beam model is the most suitable option for 2D modeling of concrete sleepers [2-5]. In this study, 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 for dynamic analyses. Using a general-purpose finite element package STRAND7 [22], 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 are 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. This study demonstrates the significant attempt to realistically model ballast behaviour in a track system.

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
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	$g_t = 1.5$	m
Rail gauge	$g = 1.435$	m

In practice, 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 is simulated using the nonlinear tensionless beam support feature in STRAND7 [22]. This special 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]. 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 using field measurements and the verification results have been presented elsewhere by the authors [5, 13-14]. Note that these data are the dynamic properties of the materials, which should be obtained by various appropriate dynamic testing methods (e.g. using a modal hammer or using a dynamic shaker) [23].
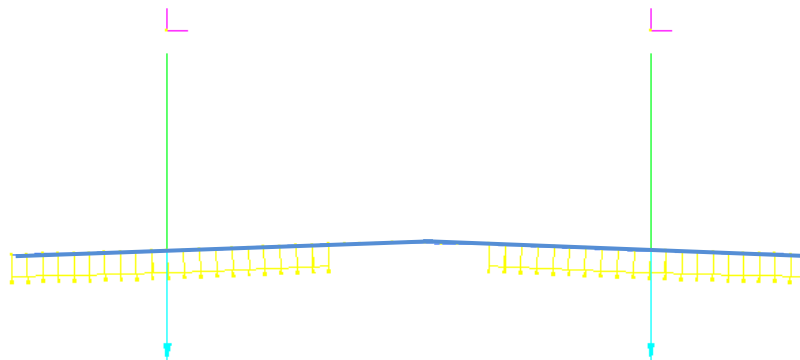

Figure 3. STRAND7 finite element model of a prestressed concrete sleeper - optimal length (2.5m).

To our knowledge, the nonlinear flexural analysis of railway concrete sleepers in a track system due to coupling vertical and lateral force has not yet fully addressed. 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, 24]. The impact simulations are conducted using the nonlinear solver in STRAND7 [22], to study the effect of lateral over vertical force ratios on the dynamic flexural response of the railway concrete sleeper in a track system.
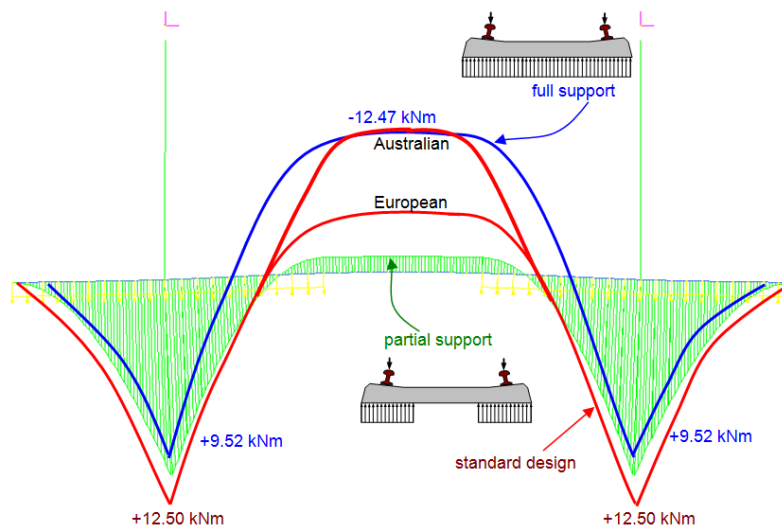

Figure 4: Quasi-static responses of the railway sleeper as per design.

3.   Quasi-static behaviour

Using the design data in Table 1, Figure 4 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. Based on Australian design standard, 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 4).

4.   Dynamic behaviours

The effect of lateral over vertical force (L/V) ratios on the dynamic moment resultants to impact loading is investigated. The nominal bending moments $M*$ at both rail seat and mid span are normalized by the maximum dynamic bending moments when L/V =0. Since the lateral force can be applied at both rails, two cases of the L/Vs have been investigated. The first case is when the lateral forces occur equally at both rails, and the other case is when the lateral force occurs only at the high rail.
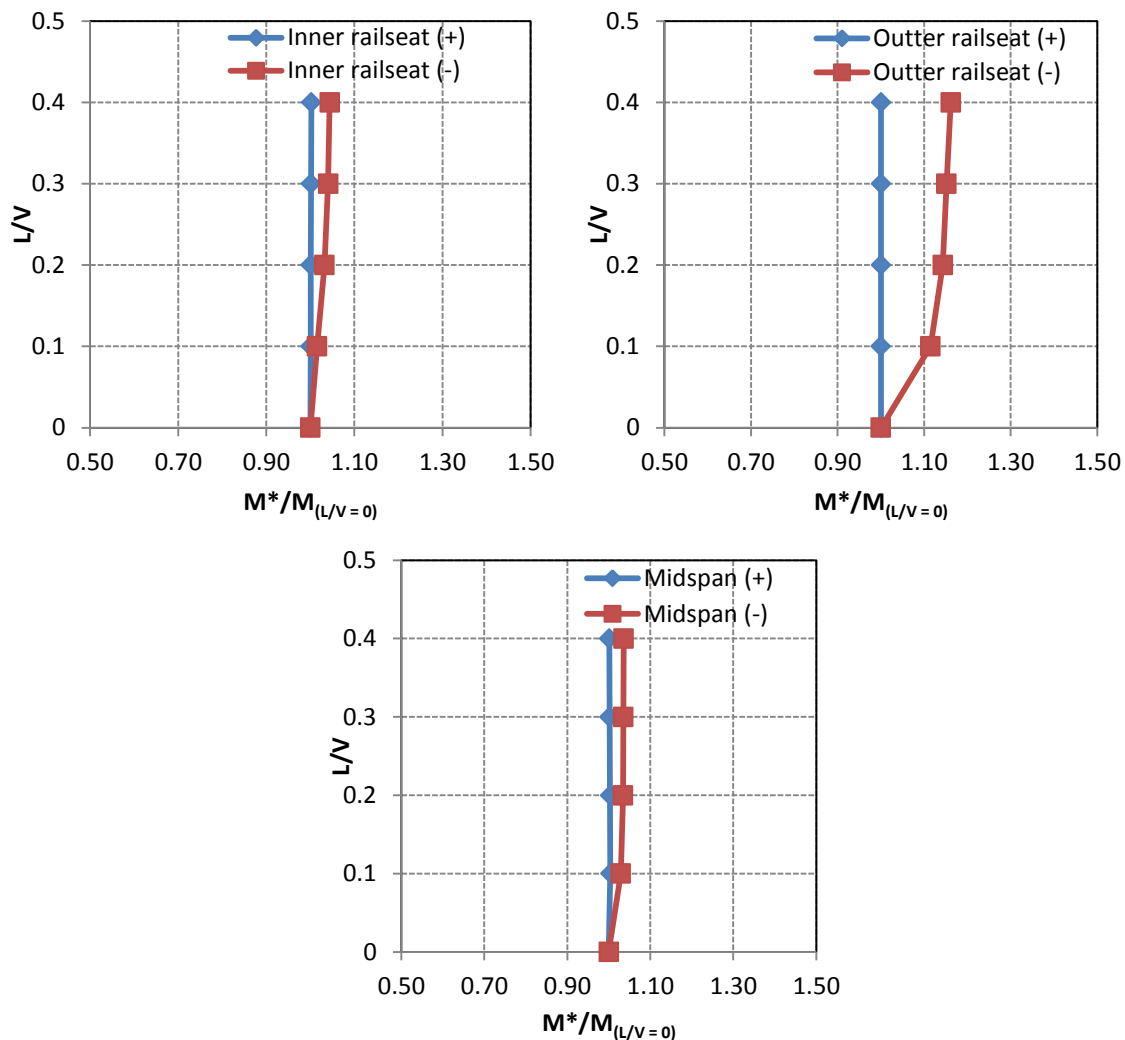

Figure 5: Effect of L/V ratios on the dynamics of railway sleepers (Case 1).

The results demonstrated in Figure 5 and 6 show that the effect of L/V is pronounced on the negative bending moments at all locations when the L/V is unsymmetrical (Case 2). In Case 1, it is found that the L/V can increase the dynamic negative bending moments up to 14% especially at the rail seats. On the other hand, unsymmetrical L/V can increase the dynamic negative bending moment at outer railseat up to 28%.
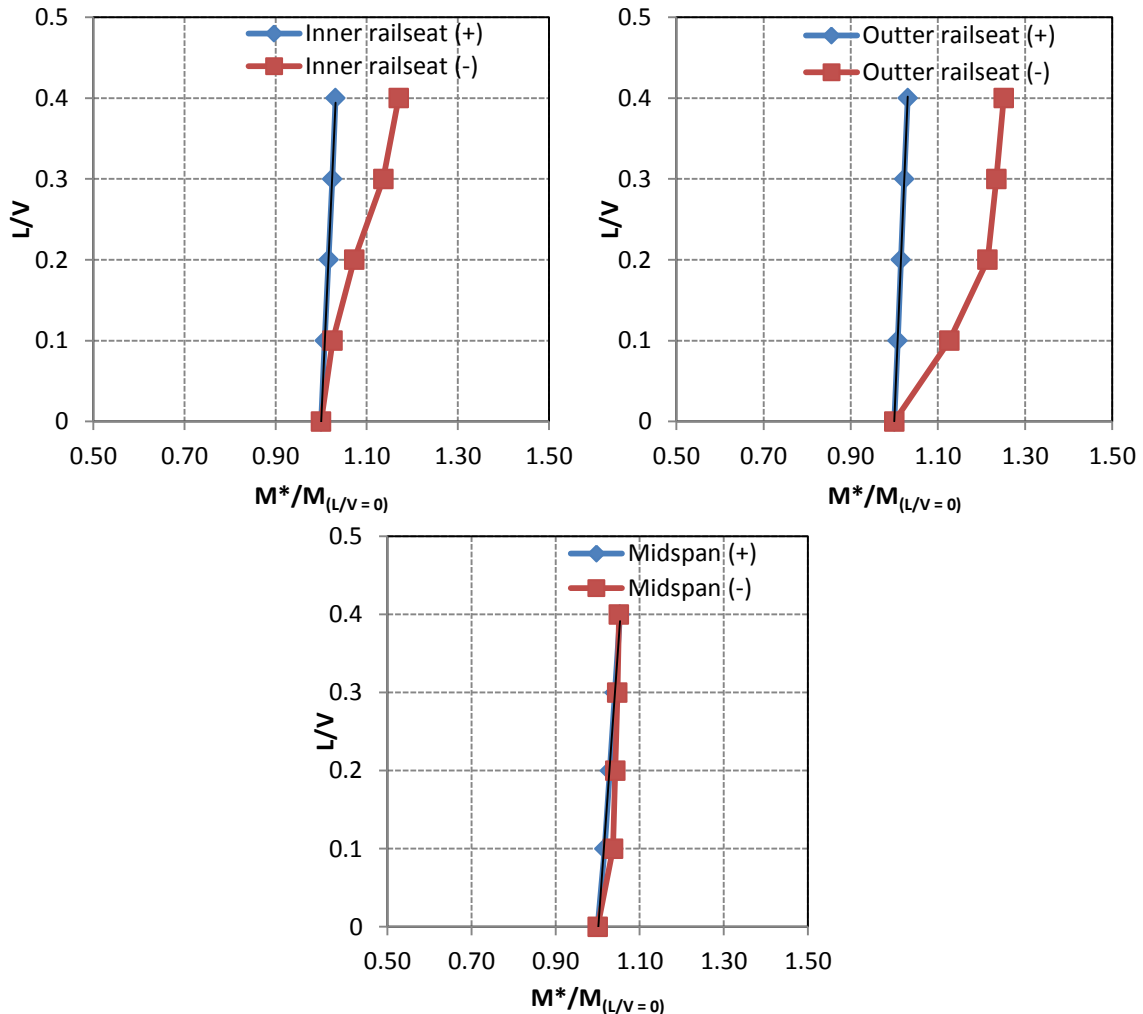

Figure 6: Effect of L/V ratios on the dynamics of railway sleepers (Case 2).

5. Conclusion

This investigation demonstrates the critical dynamic effects of a variety of lateral force conditions and lateral over vertical force (L/V) ratios 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 (using dynamic testing to obtain dynamic resistance and properties of the component), is utilised in this study. The nonlinear transient solver in STRAND7 was utilised to cope with nonlinear 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 force variation. The sleepers suffer from impact loading when there is an unsymmetrical lateral force at a rail. 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

L/V conditions in comparison with the more pronounced influence on the negative bending moment at outter railseat. In both symmetrical and unsymmetrical L/V cases, the dynamic negative bending moment at mid span is *insensitive* to the lateral forces.

Acknowledgement

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