Influence of Asymmetrical Topology on Structural Behaviours of Bearers and Sleepers in Turnout Switches and Crossings

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Abstract. Railway infrastructure is nonlinear by nature, scientifically proven by its behaviours, geometry and alignment, wheel-rail forces and operational parameters such as tractive efforts. It is often found that most train-turnout interaction models do not consider the time dependent ballast degradation. Such ballast degradation later causes differential settlement and aggravates impact forces acting on partial and unsupported sleepers and bearers. Furthermore, localised ballast breakages underneath any railseat increase the likelihood of centre-bound cracks in railway sleepers and bearers due to the unbalanced support. This paper presents a numerical simulation of a standard-gauge concrete bearer at crossing panel, taking into account the tensionless nature of ballast support. The finite element model was calibrated using static and dynamic responses using past experiments. In this paper, the influences of topologic asymmetry on both sagging and hogging behaviours of crossing bearers are firstly investigated. In addition, it is the first to demonstrate the effects of sleeper length on the design consideration of turnout bearers in crossing panel. The outcome of this study will improve the railway turnout construction and maintenance criteria in order to improve train-turnout interaction and ride comfort.

1 Introduction

In ballasted railway tracks, railway sleepers (also called ‘railroad tie’ in North America) are a vital element of railway track structures. Their key role is to redistribute loads from the rails to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is targeted at around 50 years in Australia and around 70 years in Europe (Australian Standards 2003; Kaewunruen et al. 2015, 2016a,

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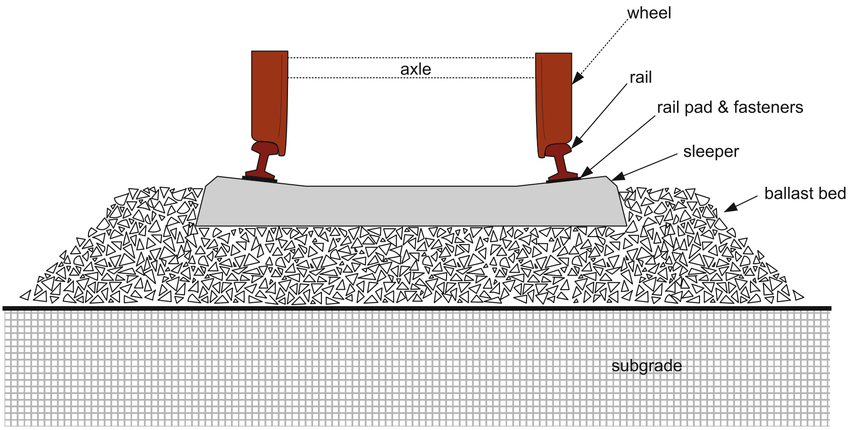


Fig. 1. Typical ballasted railway track components.

2016b). Figure 1 shows the typical ballasted railway tracks and their key components. There have been a number of previous investigations on the railway sleeper models (Neilsen 1991; Cai 1992; Grassie 1995). Most of the models 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 (Cai 1992; Kaewunruen and Remennikov 2006, 2007). In practice, the lateral force is less than 20% of vertical force and the anchorage of fastening has been designed to take care of lateral actions (Remennikov and Kaewunruen 2008). 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 (Wolf et al. 2015; Sae Siew et al. 2015; Vu et al. 2016). 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).

In contrast, the structural behavior of turnout bearers has not been fully investigated. Figure 2 shows the typical layout of a turnout system. A railway turnout system have generally been analysed the using a grillage beam method (Ferdous et al. 2015). Although the simplification is useful, such a method could not adequately assist in the failure analyses of turnout components. In some cases, the results using the grillage beam method seem to have discrepancies with the field observations where the maximum bending and shear forces were evident within the crossing panel (Kaewunruen 2012). A number of research has been conducted to locate the critical section within a

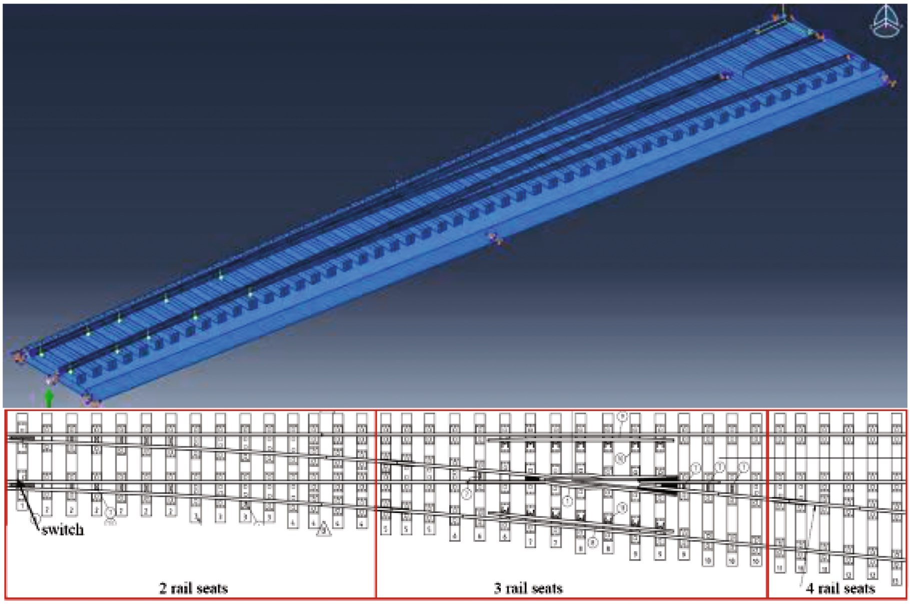


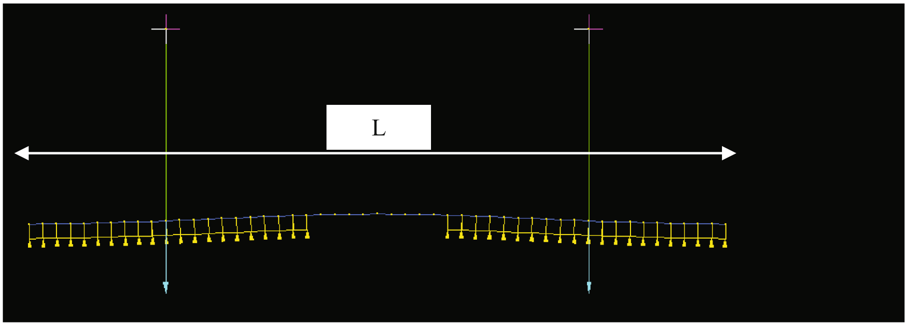
Fig. 2. Typical turnout system layout (Sae Siew et al. 2016).

turnout, and many of which conclude that the critical section is located specifically at the crossing panel at either v-crossing or k-crossing (Kassa and Nielsen 2009; Wiest et al. 2008; Xiao et al. 2011).

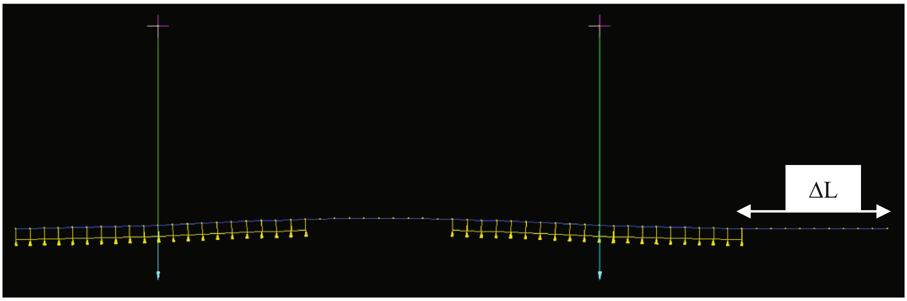
Although it is clear that the turnout bearers are topological asymmetry, such the aspect has never been fully investigated. This paper presents an advanced railway concrete sleeper modeling capable of analysis into the effect of topological asymmetry on the positive and negative flexural responses of railway sleepers. It focuses on the nonlinear static flexural response 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.

2 Finite Element Model

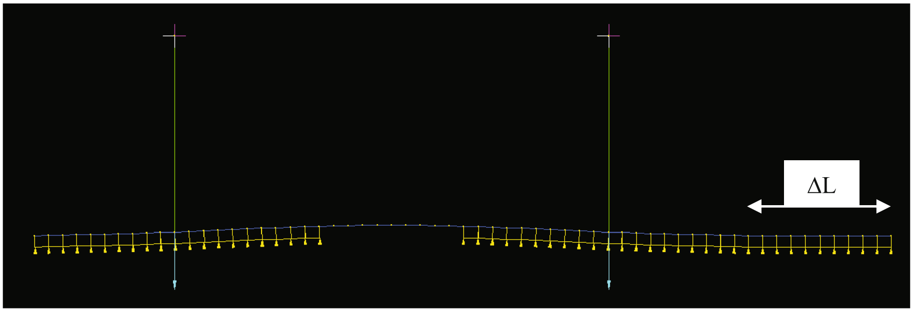
Previous extensive studies established that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads (Nielsen 1991; Grassie 1995). In this investigation, the finite element model of concrete sleeper (optimal length) has been previously developed and calibrated against the numerical and experimental modal parameters (Kaewunruen and Remennikov 2006a). Figure 3 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 (G+D Computing 2001), the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the concrete sleeper. The trapezoidal



a) symmetrical topology



b) asymmetrical topology (overhanging)



c) asymmetrical topology (fully supported)

Fig. 3. STRAND7 finite element model of a concrete bearer

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.

As a result, the use of elastic foundation in the current standards in Australia and North America (Standards Australia 2003; Wolf et al. 2015) 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 tensionless beam support feature in Strand7 (G+D Computing 2001). This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks (G+D Computing 2001). 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 (Kaewunruen et al. 2015).

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	$g = 1.5$	m

Based on our critical literature review, the flexural influences on railway concrete bearers in a turnout system (switch and crossing) due to the variations of ballast support conditions together with the asymmetric topology of sleeper has not yet addressed by the past researchers (Manalo et al. 2012). Especially when the uplift behaviour due to ballast tensionless support in hogging region of sleepers is considered, a finite element analysis is thus required to supersede the simple manual calculation. For this study, the numerical simulations have been extended to conduct the analyses using the nonlinear solver in STRAND7. The effects of asymmetric topology of concrete bearers on their flexural responses in a turnout system can be evaluated. The length of bearer varies from 2.5 m to 4.0 m, which is practically common in the 2 and 3 rail-seats sections (see Fig. 2).

3 Results and Discussion

Using the design data in Tables 1, 2 and 3 present the static bending moment envelops along the bearer when subjected to the equal wheel loads of 100 kN at both railseats, in comparison with the standard design moments. Based on AS1085.14 (Standards Australia 2003), 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

Table 2. Maximum bending moment of overhanging bearer

ΔL/L (overhanging)	At railseat (kNm)		At mid span (kNm)	
	M*	M^*/M_{Design}	M*	M^*/M_{Design}
0	+11.93	0.95	−0.95	0.14
10%	+11.93	0.95	−0.95	0.14
20%	+11.93	0.95	−0.96	0.14
30%	+11.93	0.95	−0.96	0.14
40%	+11.93	0.95	−0.96	0.14
50%	+11.93	0.95	−0.96	0.14
60%	+11.93	0.95	−0.96	0.14

Table 3. Maximum bending moment of fully-supported bearer

ΔL/L (full support)	At railseat (kNm)		At mid span (kNm)	
	M*	M^*/M_{Design}	M*	M^*/M_{Design}
0	+11.93	0.95	−0.95	0.14
10%	+15.16	1.21	+2.22	0.32
20%	+16.50	1.32	+3.15	0.45
30%	+16.74	1.34	+3.29	0.47
40%	+16.74	1.34	+3.29	0.47
50%	+16.74	1.34	+3.29	0.47
60%	+16.74	1.34	+3.30	0.47

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 Fig. 3).

Based on the static results in Tables 2 and 3, it is clear that the influence of the asymmetrical topology is pronounced when there is a contact between bearer and ballast layer. Considering field investigation, such the contact could occur when there is a differential settlement on the mainline track (or run-through turnout road). Once the ballast-bearer contact establishes, the bearer will take additional bending moment at the inner railseat.

The natural frequencies of the bearers can be observed in Tables 4 and 5. It can be seen that the topology of bearer plays a key role in dynamic natural frequencies and corresponding mode shapes of the bearers. Overhanging bearers tend to be relatively much affected by the topology aspect in comparison with the dynamic behavior of fully supported bearers. Figure 4 shows the dynamic softening behavior of the turnout bearers with asymmetrical topology. It is clear that the dynamic softening is more pronounced at a higher frequency range.

Table 4. Natural frequencies of overhanging bearer

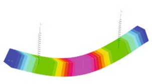
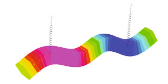
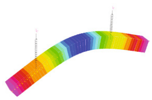
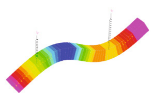
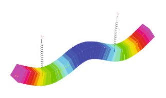
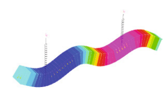
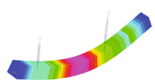
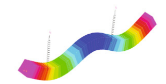
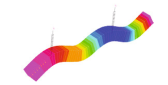
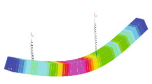
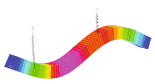
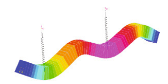
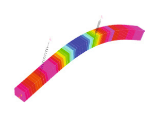
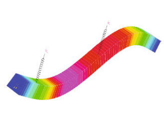
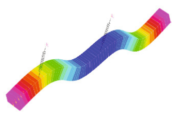
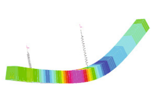
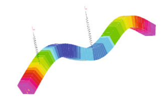
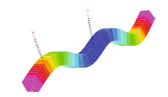
ΔL/L (overhanging)	Resonances (Hz)			
	Mode 1	Mode 2	Mode 3	Mode 4
0	143 	370 	714 	1155 
10%	118 	308 	594 	957 
20%	102 	261 	498 	818 
30%	89 	224 	426 	702 
40%	80 	194 	369 	601 
50%	73 	170 	322 	524 
60%	67 	150 	284 	470 

Table 5. Natural frequencies of fully-supported bearer

ΔL/L (full support)	Resonances (Hz)			
	Mode 1	Mode 2	Mode 3	Mode 4
0	143	370	714	1155
10%	121	309	599	970
20%	105	263	504	830
30%	93	227	431	716
40%	84	197	374	620
50%	77	173	328	542
60%	71	154	290	480

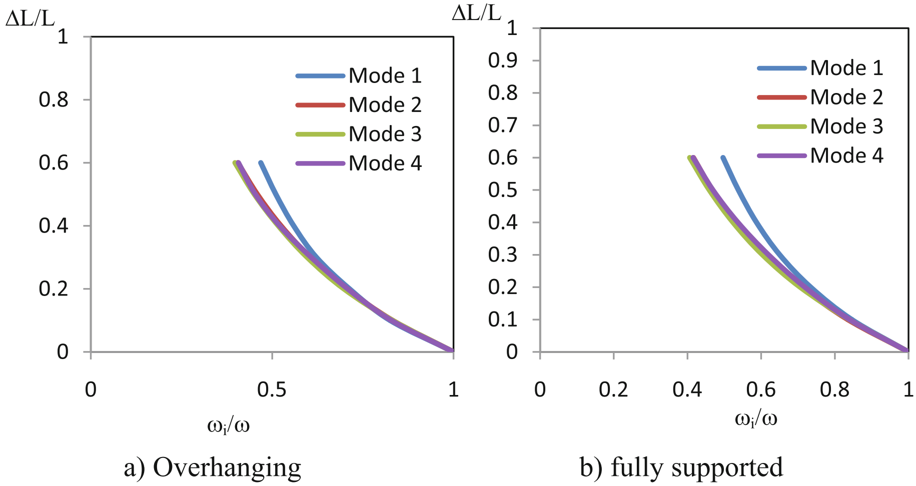


Fig. 4. Frequency ratios of turnout bearer

4 Conclusions

This paper numerically investigates the critical structural effects of a variety of ballast conditions and asymmetric topology on the flexural responses and free vibration behaviors of the railway sleepers and bearers in a turnout system (switches and crossings). The finite element model of bearers, which was established and calibrated earlier, is utilised in this study. The influences of the variation of ballast support conditions at bearer end together with the asymmetric length of sleepers on the bending of the railway sleeper were highlighted in comparison with the standard design. The nonlinear solver in STRAND7 was employed to handle sleeper/ballast contact mechanics. Under static and free vibration conditions for overhanging and supported bearers, the numerical results exhibit that the bending moment resultants are barely affected by topological aspects when the ballast-sleeper contact is not established. The standard design bending moments tend to be overestimated for the overhanging bearer, whilst they can be highly underestimated when bearer end is laid on ballast. Generally, positive bending moments at inner railseat of bearer have generally high sensitivity to the spectrum of ballast support conditions in comparison with the more pronounced influence of sleeper length. In such case, the nominal bending moment at inner railseat could be larger than the structural capacity of sleeper and resulted in structural cracks and failure. In contrast, such behavior is insignificant and tolerable for overhanging bearers. By understanding the free vibration behavior of bearers, it is clear that the asymmetrical topology induces dynamic softening in the turnout bearers. This implies that the asymmetrical bearers are prone to damage under high-intensity impact loading, which could trigger and sweep through various resonant frequencies of the turnout bearers. The insight in this structural behavior of bearer has raised the awareness of track engineers for better design and maintenance of switch and crossing support structures.

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