DYNAMIC RESPONSES OF ASYMMETRICAL TURNOUT BEARERS TO COUPLING VERTICAL AND LATERAL WHEEL FORCES IN RAILWAY SWITCHES AND CROSSINGS

7TH EUROPEAN CONFERENCE ON COMPUTATIONAL FLUID DYNAMICS (ECFD 7)

(ECCM –ECFD 2018 CONFERENCE)

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Key words: Dynamic responses, FEM, turnout bearers, coupling force, switches and crossings, asymmetry.

Abstract. In modern days, railway systems are a critical catalyst for growth of cities and regions. Railway infrastructure is under pressure to provide higher capacity to the complex rail system. Railway capacity is governed not only by a number of trains over a time window, but is also by its infrastructure's geometry and alignment, structural components, and track conditions. Railway urban turnout is a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that consists of steel rails, points (or called 'switches'), crossings (special track components), steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation. It is often found that most train-turnout interaction induces coupling dynamic transient loading on the track components, especially on curves. In many cases, trains divert from one tangent track to another curved turnout road. 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 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. This study is the world first to highlight asymmetric topology of railway concrete bearers and identify dynamic influences of topologic asymmetry on their coupling vertical and lateral behaviours.

1 INTRODUCTION

Most highly dense urban systems rely on railway systems to efficiently and effectively provide mass transportation and mobility to their residences. The railway networks can be built either on surface or underground. A railway network can be comprised of many types of railway tracks and their components. In fact, even a railway line can be built using a combination of many key infrastructure components that form specific functional assets such as railway tracks, bridges, turnouts (switches and crossings), overhead line structure, etc. A most common type of railway infrastructure (especially for metro, urban, suburban and freight networks) is ballasted railway tracks [1]. Railway sleepers or bearers (also called 'railroad tie' in North America) are a vital structural element in the railway track systems. Railway sleepers are different to bearers in terms of topology, location, utilization, steel rail components they support, and the dynamic load condition they are subjected to. The key role of railway bearers is quite similar to sleepers in the way that they serve to redistribute loads from the rails to the underlying ballast bed, as well as to secure rails and crossings under live operations. The design and testing approaches for both sleepers and bearers are similar. Based on the current design approach, the design life span of the concrete sleepers and bearers is targeted at around 50 years in Australia [2] and around 70 years in Europe [3-6], whilst actually turnout bearers tend to last just about half lives of sleepers in the field [7-10].

Railway 'switches and crossings' or called 'railway turnouts' in Australia, Asia and North America are a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that consists of steel rails, points (or called 'switches'), crossings, steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation (see Figure 1). This complex system requires the track support to have structural integrity; and a broken bearer can significantly impair operational safety [11-15].
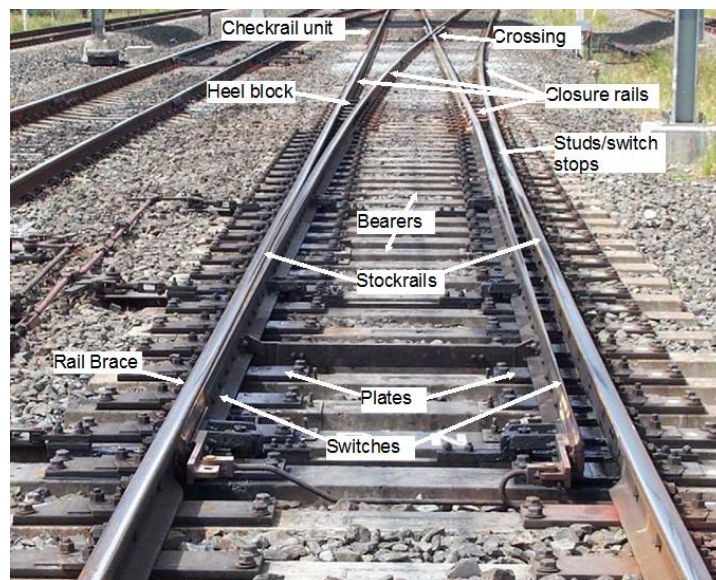

Figure 1: A typical turnout structure with concrete bearers [5]

Based on various researches on railway turnout systems, there have been a number of previous investigations on the railway sleeper and bearer models [16-20]. 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 [21-24]. 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 [25]. In fact, field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the realistic loading conditions and the support condition induced by ballast packing and tamping [26-30]. However, it is still questionable at large whether modern ballast tamping process is effective and it could enable realistic 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 binding. 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).
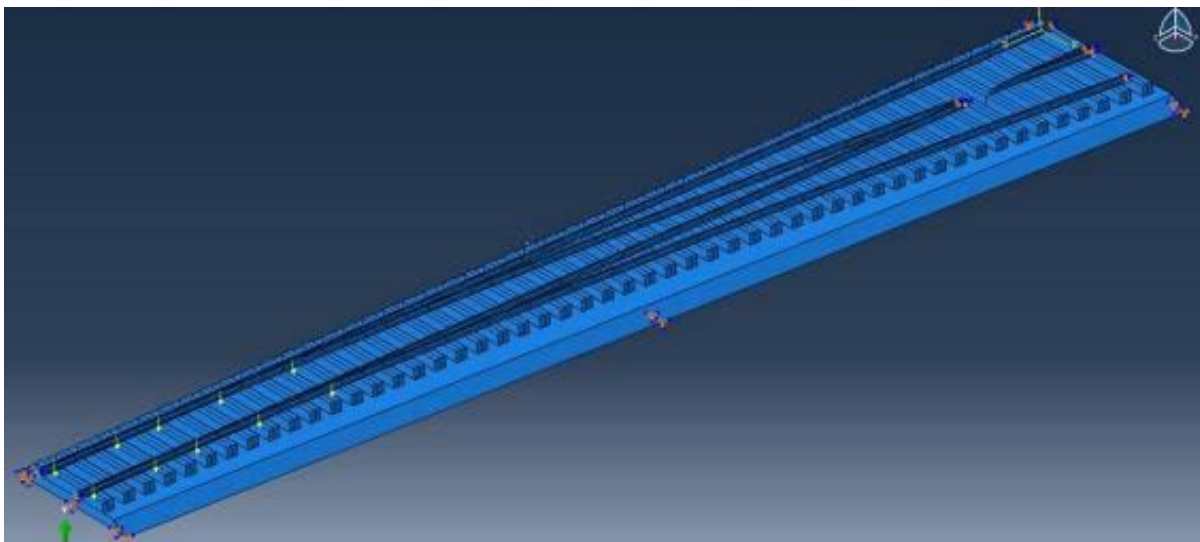

Figure 2: A typical turnout system layout [23, 24]

Over 150 of open literatures on modeling railway turnout systems have been critically reviewed [5]. The review reveals that the dynamic behavior of turnout bearers has not been fully investigated. The design parameters of the bearers in Europe are indeed estimated from a small scale empirical study by a specific rail network. The maximum envelop for bending moment design is then just an approximate of crude behavior of the bearers in the field. This has led to either over or under conservative design of the safety-critical components, resulting in structural uncertainty of the components that are exposed to inter-operations. As shown in Figure 2, a railway turnout system can generally be analysed the using a grillage beam method [27]. Although the simplification is very 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 [23]. A number of researches have been conducted to locate the critical section within a turnout, and many of which conclude that the critical section is located specifically at the crossing panel at either v-crossing or k-crossing [24]. Although it is clear that the turnout bearers are topological asymmetry, the aspect of coupling vertical and lateral forces acting at the crossings has never been fully investigated. This paper thus highlights a turnout bearer modeling capable of nonlinear impact analysis, in order to evaluate the dynamic effect of topological asymmetry of railway turnout bearers 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 [31]. Since dynamic impact loads are over a quarter of annual track load spectra, the dynamic behaviour is crucial to track maintenance criteria [32-33]. Therefore, the effect of coupling vertical and lateral wheelset dynamics over crossing nose will be focused in this study.

2 FINITE ELEMENT MODELLING

A finite element model has been used extensively in railway industry as a vertification tool. Some railway networks (e.g. in Germany, France, and the UK) have adopted the outcome of the model for product approvals. In this study, a nonlinear finite element model of full-scale railway concrete bearer has been previously developed and calibrated against the numerical and experimental modal parameters [22]. The realistic model is in very good agreement with previous extensive studies (less than 8% deviation between numerical and experimental data), which established that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads [16-18]. Figure 3 shows the two-dimensional finite element model for *in-situ* railway turnout bearers. Using STRAND7 [34], the numerical model included the beam elements, which take into account shear and flexural deformations. 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 bearer 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. The use of elastic foundation in the current standards in Australia and North America does not well represent the real uplift behaviour of bearers in hogging moment region (or mid span zone of railway bearers). In this study, the support condition was simulated using the tensionless beam support feature in STRAND7 [34]. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. The tensionless support can correctly represent the 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 in Europe. These data have been validated and the verification results have been presented elsewhere [28]. Also, 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. 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 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 2.5m to 4.0m, which is practically common in the 2 and 3 rail-seats sections (see Figure 3). The impulse is stimulated only at the inner rail seat (as the inner wheel travels over crossing).
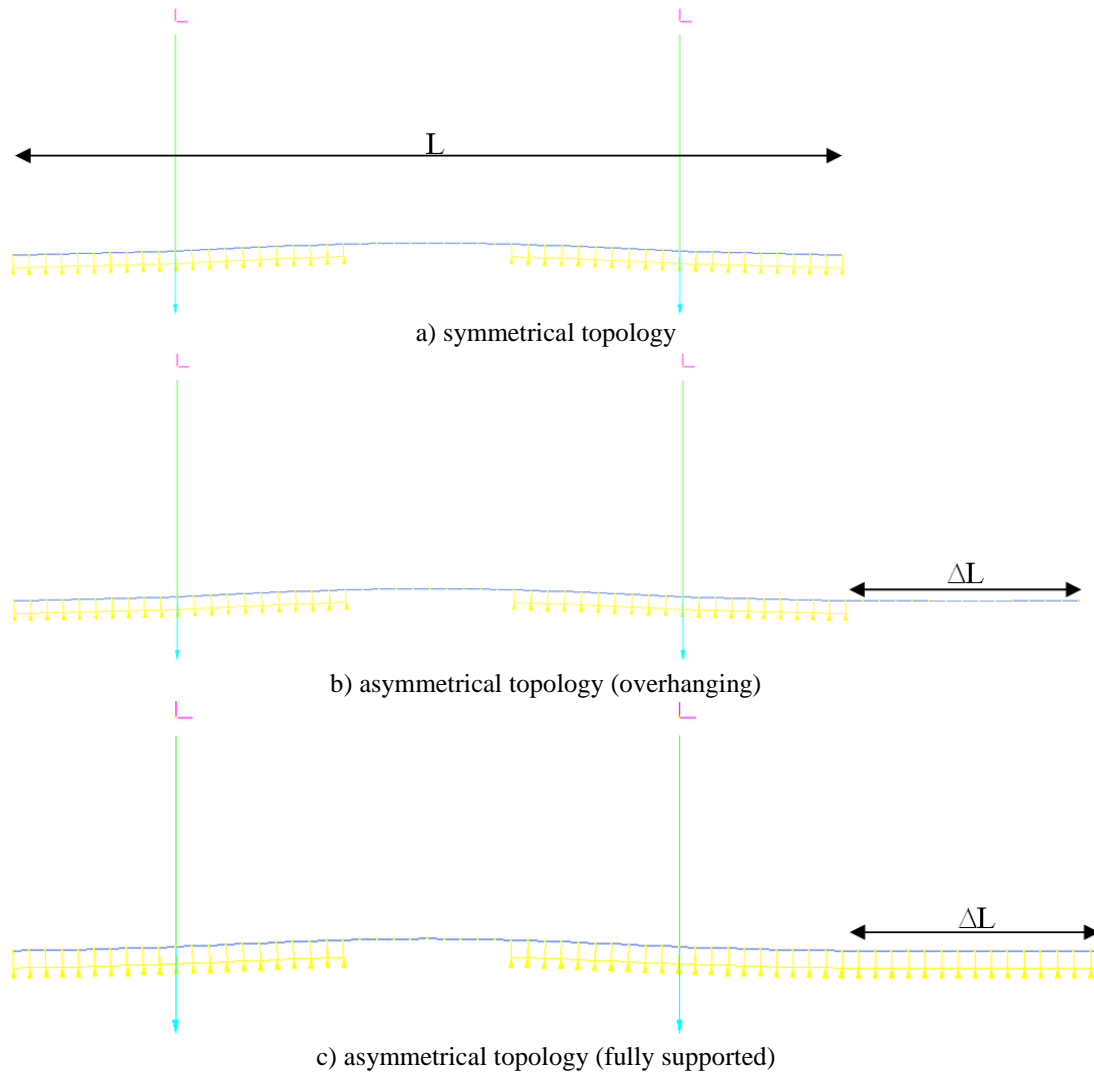

a) symmetrical topology

b) asymmetrical topology (overhanging)

c) asymmetrical topology (fully supported)

Figure 3: A typical turnout system layout [23, 24]

3   RESULTS AND DISCUSSION

Based on the verified data in Table 1, the finite element model can be used to predict dynamic bending moment envelops along the bearer when subjected to the wheel load impulse of 100kN (3 ms) at a railseats, as illustrated in Figure 4. Damping of concrete is

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relatively low and is neglected in this study. This is because the damping could not react quickly enough under impact loading and the analysis could attain design purpose when worst-case scenario is required. Based on AS1085.14 [2], the design maximum positive and negative bending moment at the rail seat is 12.50 kNm (if considered full support). To establish maximum envelop, the maximum lateral force acing at the wheel-crossing contact is taken as 0.2 of the vertical force.

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

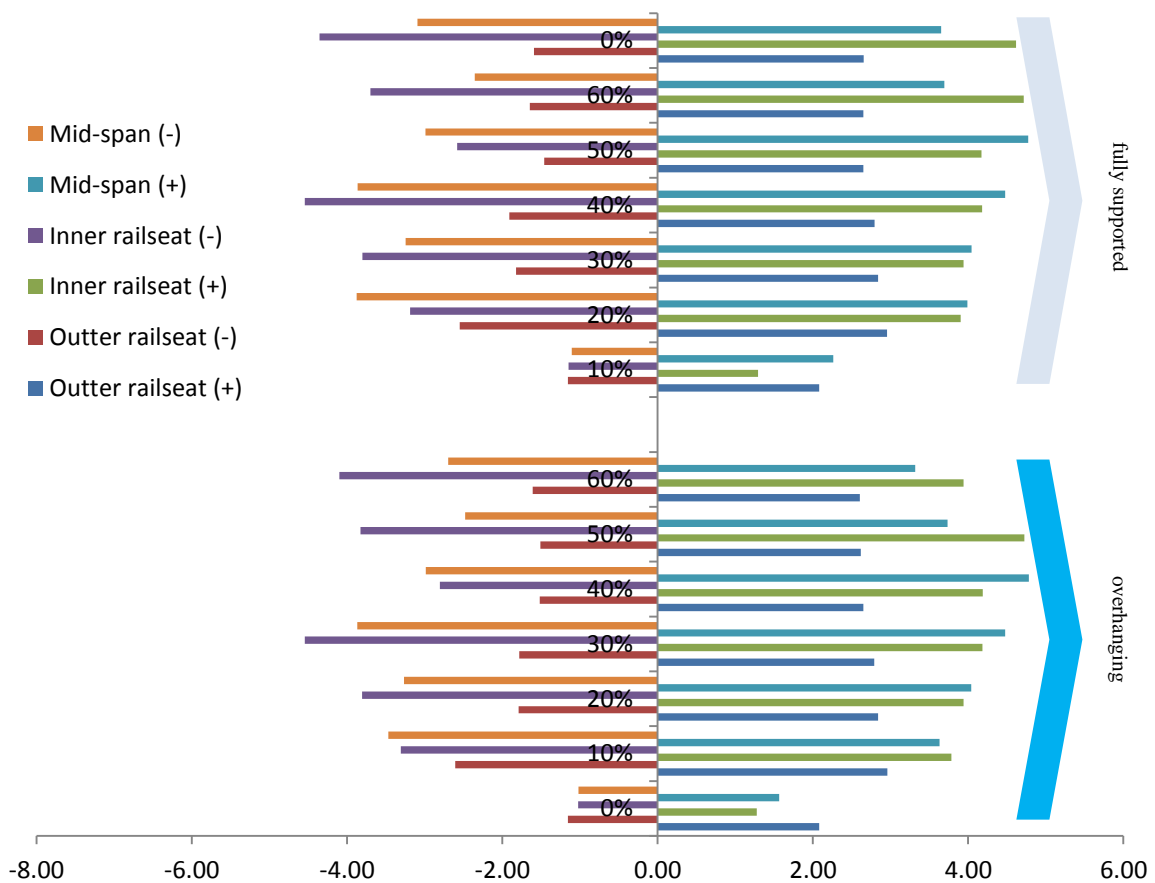| Parameter lists		
Flexural rigidity	$EI_c = 4.60$, $EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502$, $\kappa GA_r = 628$	MN
Ballast modulus	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	kg/m^3
Sleeper length	$L = 2.5$	m
Track load distance	$g = 1.5$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

Figure 4: Dynamic moment ratio ($M_{dynamic}/M_{design}$) vs. vertical axis $\Delta L/L$

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The results shows that the coupling vertical and lateral wheel impact loading can cause high impact factor over 2.5 (a general serviceability impact factor for design) and some cases can be over 4.0 (a general ultimate impact factor for design) in both conditions of overhanging and fully-support by ballast. These clearly exceed the design limits for fatigue serviceability and ultimate limit states, respectively. This implies that the coupling vertical and lateral forces can rapidly deteriorate the performance and shorten the life span of the concrete bearers in the field. Figure 5 demonstrates the movement of maximum bending curvature when the bearer is subjected to coupling vertical and lateral force. It is shown that the position of maximum bending moment has shifted from at rail seats to the edge of railseats. This result confirms the failure mode of turnout concrete bearers found in the field [35], as illustrated in Figure 6
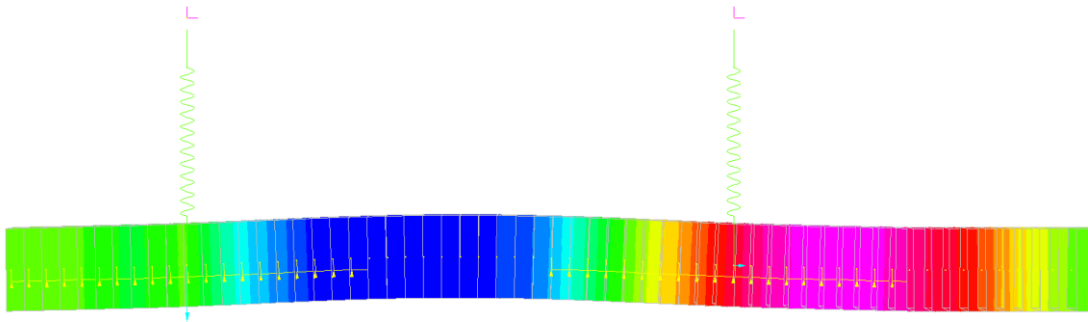

Figure 5: Dynamic moment contour due to coupling vertical and lateral force.

Figure 6: Evidence of a failure mode of concrete bearer found in the field [35].

4 CONCLUSION

Railway infrastructure is required to support higher train capacity (more frequency, faster speed and higher axle load) to drive the growth of the urbanisation. In reality, railway capacity is governed not only by a number of trains over a time window (with respect to train frequency), but is also by its infrastructure's geometry and alignment (with respect to train speed), structural components, and track conditions (with respect to train axle load). Railway urban turnout is a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. This structural grillage system is an inevitable asset since it enables operational flexibility. Notably, train-turnout interaction induces coupling dynamic transient loading on the track components, especially on curves. Not only does the complex train-track interaction generate high-intensity vertical impact loading, but the curving behavior of the train body also induce quasi-static lateral force (from wheel flanging) acting on the crossing nose. This paper has established a numerical simulation of a standard-gauge concrete bearer, taking into account the realistic tensionless nature of ballast support. The finite element model was calibrated using static and dynamic responses using past experiments. This paper highlights asymmetric topology of railway concrete bearers and identifies dynamic influences of topologic asymmetry on their coupling vertical and lateral behaviours. Apparently, the results exhibit that the impact load can amplify the bending moments in both conditions, resulting in potential damages under high-intensity impact loading, which could trigger and sweep through various resonant frequencies of the turnout bearers. It is also found that the lateral force can re-locate the maximum bending curvature and change the position experiencing the maximum bending moments. The understanding has raised the awareness of track engineers for better design and maintenance of turnout support structures to minimise transient effects.

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