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INFLUENCES OF SURFACE ABRASIONS ON DYNAMIC BEHAVIOURS OF RAILWAY CONCRETE SLEEPERS

Sakdirat Kaewunruen

The University of Birmingham, School of Engineering, Edgbaston, Birmingham, UK
email: s.kaewunruen@bham.ac.uk

Chayut Ngamkhanong

The University of Birmingham, School of Engineering, Edgbaston, Birmingham, UK,

Rims Janeliukstis

Riga Technical University, Institute of Materials and Structures, Riga, Latvia,

Ruilin You

China Academy of Railway Sciences, Railway Engineering Institute, Beijing, P.R. China,

By nature, railway infrastructure is nonlinear, evidenced by its behaviors, geometry and alignment, wheel-rail contact and operational parameters such as tractive efforts. Based on our critical review, there exists no previous work that considers the degradation of railway concrete sleepers over time. In fact, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. This paper presents a nonlinear 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 influences of surface abrasions, including surface abrasion and soffit abrasion, on the dynamic behaviours of sleepers are firstly highlighted. The outcome of this study will improve the rail maintenance and inspection criteria in order to establish appropriate and sensible remote track condition monitoring network in practice.

Keywords: Surface abrasion, railseat abrasion, soffit abrasion, railway sleepers, crossties, dynamic behaviour

1. Introduction

Railway sleepers (also called ‘railroad tie’ in North America) embedded in ballasted railway tracks are a vital element to support the track structures. Their key duty is to redistribute loads from the rails to the underlying ballast bed and to secure rail gauge and enable safe passages of rolling stocks. 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 [1-8]. Figure 1 shows a typical ballasted railway track and their key components. There are two groups of track components: superstructure and substructure. Superstructure consists of rails, rail pads, fastening systems, sleeper, under sleeper pad and ballast bed. Substructure includes subballast (or called ‘capping layer’), formation, and foundation (e.g. structural fills). A number of previous investigations have been conducted in order to establish rational railway sleeper models [9-15].

Previous work revealed that most of the numerical and analytical 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 [16-20]. About 5-15% difference was found for vertical responses between 3D solid and 2D beam simulations depending on various track and environmental factors [21]. 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 [22-23]. 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 [24-28]. 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, ballast densification at railseats is induced by dynamic broadband behaviours 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) [29-30]. At railseat, the dynamic loading condition gives a high change that the bottom of sleeper (or called 'soffit') may experience aggressive abrasive force, wearing out the materials in the region. Also, excessive mid-span contacts soffit abrasion and then often cause 'centre-bound' problem when the sleeper cracks at mid-span.

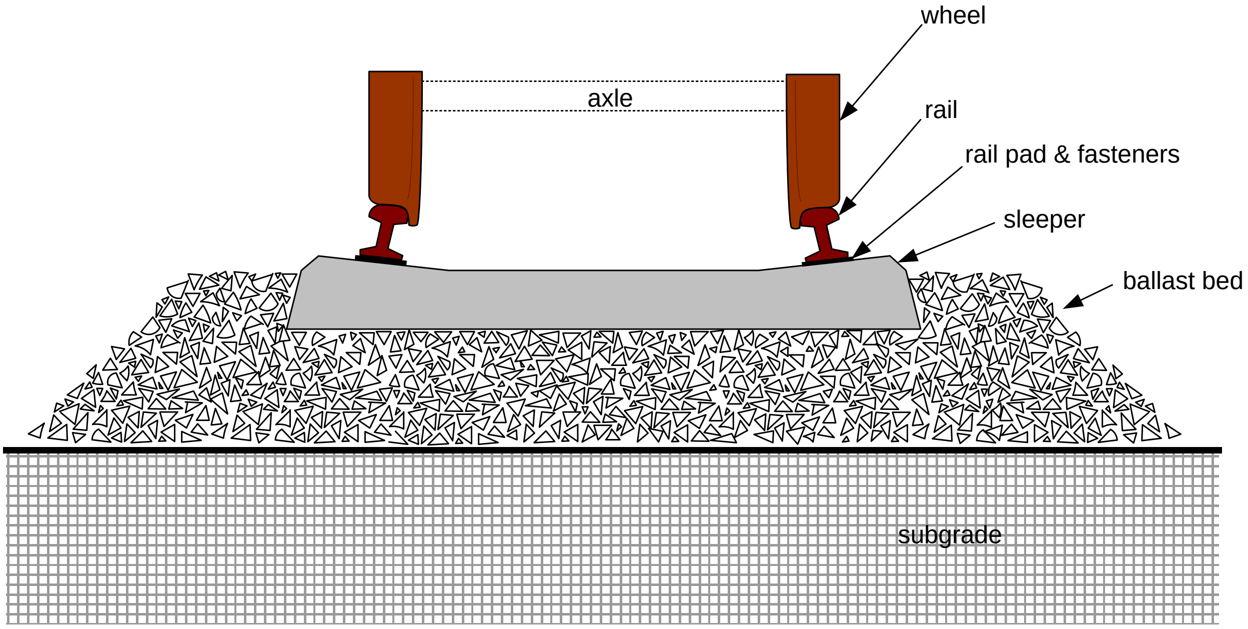
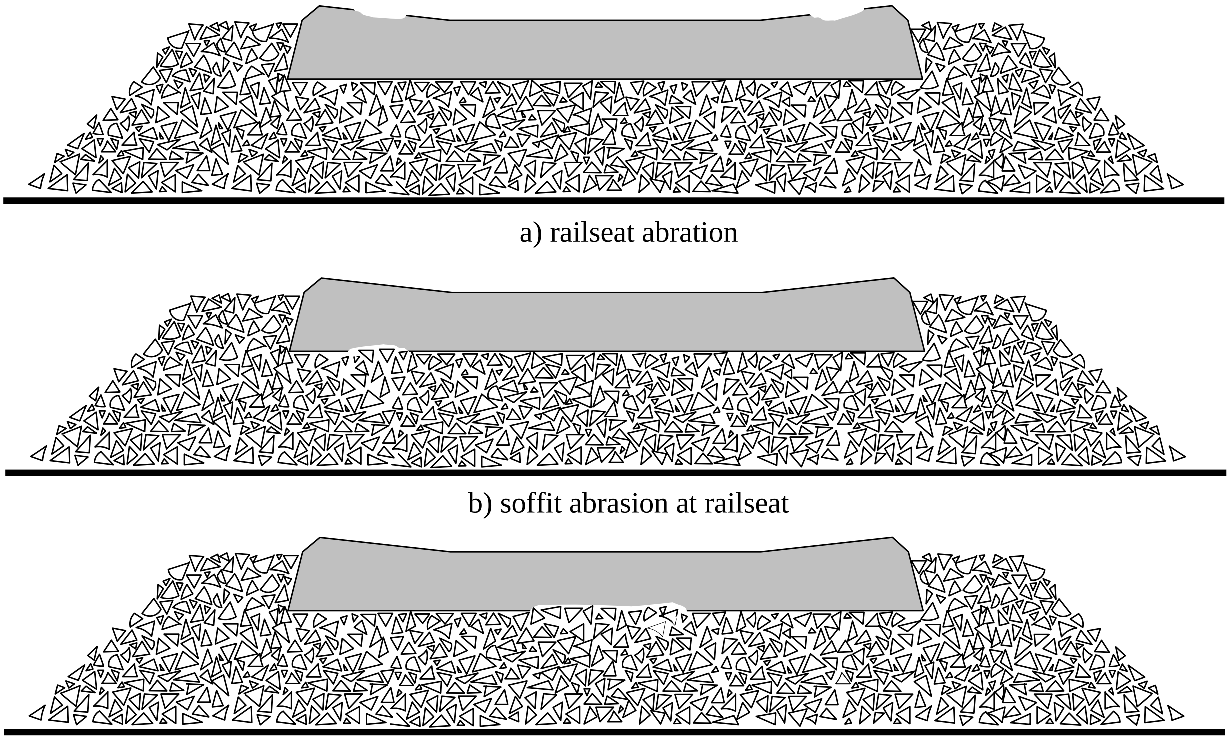


Figure 1: Typical ballasted railway track components.

The critical literature review reveals that the dynamic behavior of railway sleepers has not been fully investigated, especially when the sleepers are deteriorated by excessive wears. Figure 2 shows the typical wears of a railway sleeper [30-33]. Most common wears are railseat abrasion, soffit abrasion at railseat and soffit abrasion at mid span. These deterioration mechanisms can be observed in the fields. Although it is clear that the railway sleepers can experience dynamic lateral wears, such the aspect has never been fully investigated. This paper is the world first to investigate and present an advanced railway concrete sleeper modelling capable of parametric analysis into the effect of surface abrasion on the dynamic behaviours of railway sleepers. The emphasis is placed on the nonlinear free vibrations of the deteriorated railway concrete sleepers subjected to a spectrum of wear or abrasion at the mid span and at the railseats, in comparison with the intact railway sleepers. The findings will help improve the understanding into fundamental dynamics of damaged sleepers and pave the pathway to identify appropriate damage detection technology for railway sleepers.



a) railseat abration

b) soffit abrasion at railseat

c) soffit abrasion at midspan

Figure 2: Typical surface abrasions of railway sleepers.

2. Finite Element Simulations

Previous extensive studies established that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads [2-5]. In this study, the finite element model of concrete sleeper has been previously developed and calibrated against the numerical and experimental modal parameters [25-30]. Figure 3 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 [31], the numerical model of an in-situ sleeper included the beam elements, which take into account shear and flexural deformations, for evaluating the vertical responses. 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.

As a result, the use of elastic foundation in the current standards in Australia and North America [1, 18] 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 [31]. 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 [31-34]. Using Timoshenko beam stiffness algorithm, this nonlinear boundary condition is solved using Newton Raphson iteration to quantify suitable contact region. 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 [25-30]. Parametric study has been carried out considering the possible cases of railseat abrasion, soffit abrasion at railseat zone and soffit abrasion at mid-sleeper region.

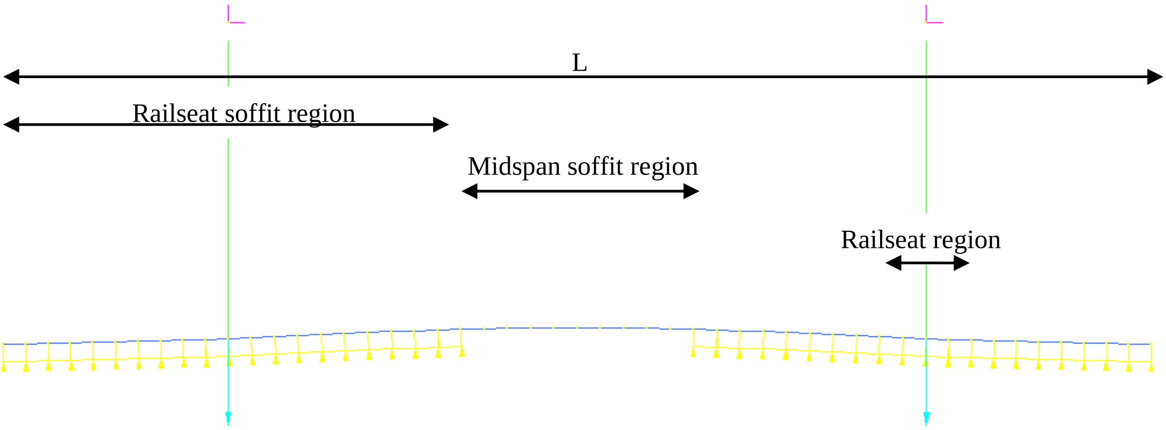


Figure 3: STRAND7 finite element model of worn concrete sleepers.

Table 1: Engineering properties of the reference sleeper used in the modelling validation

Parameter List	Characteristic value	Unit
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-centre distance	$G = 1.5$	m
Rail gauge	$g = 1.435$	m

3. Results and Discussion

Using the design data in Table 1, the natural frequencies and corresponding mode shapes of the worn concrete sleepers can be illustrated in Tables 2, 3, and 4 for railseat abrasion, soffit abrasion at railseat, and soffit abrasion at mid span, respectively.

3.1 Railseats Abrasion

As illustrated in Table 2, it exhibits that railseats abrasions play a little role on fundamental or lowest natural frequency of the worn sleepers. However, at higher frequency range, the dynamic effect of railseats abrasion can be slightly clearer. It is found that the railseats abrasion induces dynamic softening phenomena of the worn sleepers.

3.2 Soffit Abrasion at a Railseat region

It is quite clear in Table 3 that the soffit abrasion at a railseat region can play a dominant role in dynamic behaviour of worn sleepers at all frequency bands. Especially at higher order modes, the soffit abrasion at railseat can influence not only the natural frequencies but also the corresponding mode shapes. The analysis of mode shapes will be carried out in the future. However, this implies that using mode shapes for damage detection is feasible and more suitable that merely using the natural frequency alone. Interestingly, the soffit abrasion at a railseat enhances the dynamic softening nonlinearity of the worn sleepers.

3.3 Soffit Abrasion at Mid-span region

The dynamic influence of soffit abrasion at mid-span region can be demonstrated in Table 4. The dynamic softening phenomena can be clearly observed. However, it is important to note that the nonlinear dynamics are considerably enhanced by the abrasion in the low frequency range, whilst higher order modes do not have similar effects. This implies that the abrasion at mid-span responds significantly to low frequency excitations (e.g. from train speed change). The damage of worn sleepers can then be extended quicker than other wear types. This rapid rate of deterioration should be identified early in order to prioritise predictive and preventative track maintenance.

Table 2: Dynamic behaviours of worn sleepers due to railseat abrasion

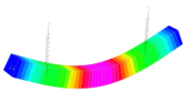
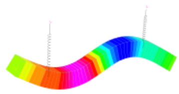
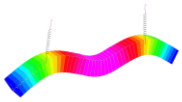
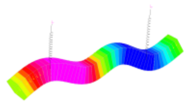
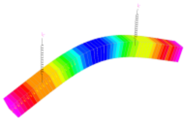
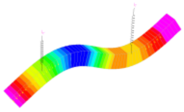
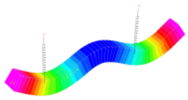
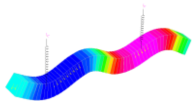
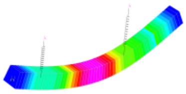
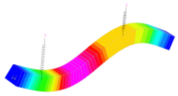
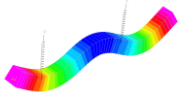
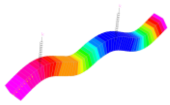
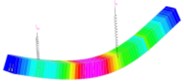
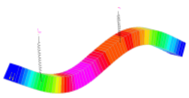
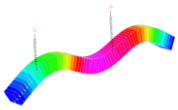
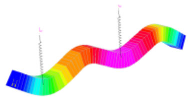
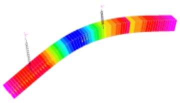
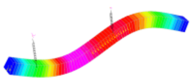
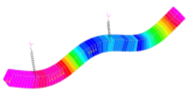
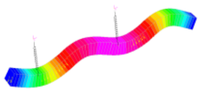
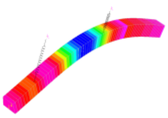
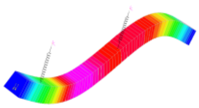
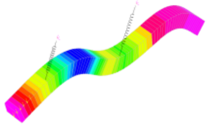
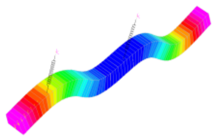
ΔD/D	**Resonances (Hz)**			
(%worn depth)	Mode 1	Mode 2	Mode 3	Mode 4
0	143 	370 	714 	1155 
5%	143 	368 	709 	1145 
10%	142 	365 	702 	1134 
15%	142 	360 	692 	1119 
20%	141 	355 	680 	1103 
25%	141 	348 	665 	1084 

Table 3: Dynamic behaviours of worn sleepers due to soffit abrasion at a railseat region

ΔD/D	**Resonances (Hz)**			
(%worn depth)	Mode 1	Mode 2	Mode 3	Mode 4
0	143	370	714	1155
5%	142	362	705	1134
10%	140	354	694	1110
15%	138	346	682	1085
20%	135	338	668	1060
25%	132	329	651	1030

Table 4: Dynamic behaviours of worn sleepers due to soffit abrasion at mid-span region

ΔD/D (%worn depth)	Resonances (Hz)			
	Mode 1	Mode 2	Mode 3	Mode 4
0	143	370	714	1155
5%	140	368	706	1145
10%	134	365	696	1131
15%	130	362	688	1117
20%	124	358	679	1100
25%	118	353	671	1080

4. Conclusion

In real life, railway infrastructure experiences harsh environments and aggressive loading conditions from increased traffics and load demands. As evidenced by its behaviors, geometry and alignment, wheel-rail contact and operational parameters have influenced the rate of deterioration of track components. Based on a critical literature review, it is found that previous research work in open literatures has never considered the degradation of railway concrete sleepers in dynamic analysis. In fact, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. This paper presents a nonlinear finite element model of a standard-gauge concrete sleeper in a track system, capable of capturing the tensionless nature of ballast support and evaluating the dynamic behaviour of the worn sleepers. The finite element model was calibrated using static and dynamic responses in the past. This paper is the world first to highlight the influences of surface abrasions, including surface abrasion and soffit abrasion, on the dynamic behaviours of sleepers.

The dynamic analysis results reveal that all surface abrasion types induce dynamic softening phenomena of the concrete sleepers. Also, it is found that the softening nonlinearity is highly influenced by soffit abrasion at railseat region. Importantly, it is found that the soffit abrasion at midspan play a critical role in increasing damage rate of sleepers especially at low frequency loading conditions (e.g. derived at a normal speed trains). The outcome of this study will improve the rail maintenance and inspection criteria in order to establish appropriate and sensible remote track condition monitoring network in practice.

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REFERENCES

1 Standards Australia, Australian Standard: AS1085.14-2003 Railway track material - Part 14: Prestressed concrete sleepers, Sydney, Australia (2003).

2 Neilsen JCO., Eigenfrequencies and eigenmodes of beam structures on an elastic foundation, Journal of Sound and Vibration, 145 (1991), 479-487.

3 Cai Z. Modelling of rail track dynamics and wheel/rail interaction, Ph.D. Thesis, Department of Civil Engineering, Queen’s University, Ontario, Canada, (1992).

4 Grassie, S.L. Dynamic modelling of concrete railway sleepers. Journal of Sound Vibration, 187, 799-813, (1995).

5 Kassa, E. & Nielsen, J. C. O. Dynamic train–turnout interaction in an extended frequency range using a detailed model of track dynamics. Journal of Sound and Vibration, 320, 893-914, (2009).

6 Kaewunruen S, Remennikov AM. Sensitivity analysis of free vibration characteristics of an in-situ railway concrete sleeper to variations of rail pad parameters, Journal of Sound and Vibration 298(1): 453-461, (2006a).

7 Kaewunruen S, Remennikov AM. Rotational capacity of railway prestressed concrete sleeper under static hogging moment, the 10th East Asia-Pacific Conference on Structural Engineering and Construction, Bangkok, Thailand, (2006b).

8 Kaewunruen S, Remennikov AM. Investigation of free vibrations of voided concrete sleepers in railway track system, Journal of Rail and Rapid Transit – Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit, 221(4): 495-507, (2007).

9 Kaewunruen, S., Ishida, T., Remennikov, A.M., “Numerical simulations of negative flexural responses (hogging) in railway prestressed concrete sleepers”, RILEM International Conference on Strategies for Sustainable Concrete, Rio de Janeiro, Brazil, December 14-16, (2015).

10 Kaewunruen, S., Ishida, T., Remennikov, A.M., “Impact analyses for negative flexural responses (hogging) in railway prestressed concrete sleepers”, International Conference on Recent Advances in Structural Dynamics, Southampton, UK, July 3-6, 2016. (2016a).

11 Kaewunruen, S., Minoura, S., Watanabe, T., Remennikov, A.M., “Remaining service life of railway prestressed concrete sleepers”, Proceedings of International RILEM Conference on Materials, Systems and Structures in Civil Engineering, 22-24 August 2016, Technical University of Denmark, Lyngby, Denmark, (2016b).

12 Kaewunruen, S. and Chamniprasart, K. “Damage analysis of spot replacement sleepers interspersed in ballasted railway tracks”, Proceedings of the 29th Nordic Conference on Computational Mechanics, Chalmers University of Technology, Gotenburg, Sweden, (2016).

13 Remennikov, A.M. and Kaewunruen, S., A review on loading conditions for railway track structures due to wheel and rail vertical interactions, Structural Control and Health Monitoring, 15(2): 207-234, (2008).

14 Sae Siew, J., Mirza, O., Kaewunruen, S., Nonlinear finite element modelling of railway turnout system considering bearer/sleeper-ballast interaction, Journal of Structures, (2015), http://dx.doi.org/10.1155/2015/598562

15 Sae Siew, J., Mirza, O., Kaewunruen, S., Torsional effect on track support structures of rail turnouts crossing impact, ASCE Journal of Transportation Engineering, (2016), in press.

16 Vu, M., Kaewunruen, S., Attard, M., Chapter 6 – Nonlinear 3D finite-element modeling for structural failure analysis of concrete sleepers/bearers at an urban turnout diamond, in Handbook of Materials Failure Analysis with Case Studies from the Chemicals, Concrete and Power Industries, p.123-160, Elsevier, the Netherlands. (2016) http://dx.doi.org/10.1016/B978-0-08-100116-5.00006-5.

17 Wiest, M., Kassa, E., Daves, W., Nielsen, J. C. O. & Ossberger, H. Assessment of methods for calculating contact pressure in wheel-rail/switch contact. Wear, 265, 1439-1445, (2008).

18 Wolf, H.E., J.R. Edwards, M.S. Dersch and C.P.L. Barkan. Flexural Analysis of Prestressed Concrete Monoblock Sleepers for Heavy-haul Applications: Methodologies and Sensitivity to Support Conditions. In: Proceedings of the 11th International Heavy Haul Association Conference, Perth, Australia, June, (2015).

19 Kaewunruen S, Ishida, T and Remennikov, AM. Impact analyses for negative flexural responses (hogging) in railway prestressed concrete sleepers. J. Phys.: Conf. Ser. 744(1): 012101. (2016). http://dx.doi.org/10.1088/1742-6596/744/1/012101.

20 Gamage EK, Kaewunruen S, Remennikov AM, Ishida T. Toughness of Railroad Concrete Crossties with Holes and Web Openings. Infrastructures. 2, 3. (2017), doi:10.3390/infrastructures2010003.

21 Kaewunruen S, Remennikov AM. Dynamic properties of railway track and its components: Recent findings and future research direction. Insight: Non-Destructive Testing and Condition Monitoring. 52, 1, 20-22. (2010), doi: 10.1784/insi.2010.52.1.20.

22 British Standards Institute, EN BS 13230 Railway applications. Track. Concrete Sleepers and Bearers. Prestressed Monoblock Sleepers; British Standards Institution: London, UK, (2009).

23 Rahrovani S. Structural Reliability and Identification with Stochastic Simulation: Application to Railway Mechanics. Ph.D. Thesis, Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden, (2016).

24 Gustavson R. Structural behaviour of concrete railway sleepers, PhD Thesis, Department of Structural Engineering, Chalmers University of Technology, Sweden, (2002).

25 Kaewunruen S, Remennikov AM. Effect of improper ballast packing/tamping on dynamic behaviours of on-track railway concrete sleeper, International Journal of Structural Stability and Dynamics,(2007), 7(1): 167-177.

26 Kaewunruen S, Remennikov AM. Nonlinear transient analysis of a railway concrete sleeper in a track system, International Journal of Structural Stability and Dynamics, (2008), 8(3): 505-520.

27 Kaewunruen S, Remennikov AM. Dynamic flexural influence on a railway concrete sleeper in track system due to a single wheel impact, Engineering Failure Analysis, (2009), 16(3): 705-712.

28 Kaewunruen S, Remennikov AM. Nonlinear finite element modeling of railway prestressed concrete sleeper, in Proceedings of the 10th East Asia-Pacific Conference on Structural Engineering and Construction; Bangkok; Thailand; 3-5 August, (2006), 4: 323-328.

29 Kaewunruen S, Remennikov AM, Aikawa A. A numerical study to evaluate dynamic responses of voided concrete railway sleepers to impact loading, Acoustics 2011: Breaking New Ground, Gold Coast, Australia, 2-4 November 2011, (pp. 1-8). [URL http://ro.uow.edu.au/engpapers/628/]

30 Kaewunruen S, Remennikov AM. An alternative rail pad tester for measuring dynamic properties of rail pads under large preloads, Experimental Mechanics, (2008), 65: 55-64.

31 G+D Computing, Using Strand7: Introduction to the Strand7 finite element analysis system, Sydney, Australia, (2001).

32 Kaewunruen S, Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction, Case Studies in Nondestructive Testing and Evaluation, (2014), 1(1): 19-24.

33 Kaewunruen S, Minoura, S., Remennikov, AM., Asymetry influences on nonlinear dynamics of railway turnout bearers, 24^{th} International Congress on Sound and Vibration, 24-27 July 2017, London, UK.

34 Connolly D.P., Kouroussis G., Laghrouche O., Ho CL, Forde M.C., Benchmarking railway vibrations - track, vehicle, ground and building effects, Construction and Building Materials, 2015, 92, 64-81