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DOI:

[10.1088/1757-899X/245/3/032048](https://doi.org/10.1088/1757-899X/245/3/032048)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Ngamkhanong, C, Li, D & Kaewunruen, S 2017, Impact Capacity Reduction in Railway Prestressed Concrete Sleepers with Surface Abrasions. in *World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium.*, 032048, IOP Conf. Ser.: Mater. Sci. Eng. , vol. 245, IOP Publishing Ltd., pp. 1-10, World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium, Prague, Czech Republic, 12/06/17. <https://doi.org/10.1088/1757-899X/245/3/032048>

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Impact Capacity Reduction in Railway Prestressed Concrete Sleepers with Surface Abrasions

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Abstract. Railway sleepers (also called ‘railroad tie’ in North America) embedded in ballasted railway tracks are a main part of railway track structures. Its important role is to transfer the loads evenly from the rails to a wider area of ballast bed and to secure rail gauge and enable safe passages of rolling stocks. By nature, railway infrastructure is nonlinear, evidenced by its behaviours, geometry and alignment, wheel-rail contact and operational parameters such as tractive efforts. Based on our critical review, the dynamic behaviour of railway sleepers has not been fully investigated, especially when the sleepers are deteriorated by excessive wears. 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 structural capacity of concrete sleepers under dynamic transient loading. The modified compression field theory for ultimate strength design of concrete sleepers under impact loading will be highlighted in this study. The influences of surface abrasions, including surface abrasion and soffit abrasion, on the dynamic behaviour of prestressed concrete 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. Moreover, this study will also improve the understanding of the fundamental dynamic behaviour of prestressed concrete sleepers with surface abrasions. The insight into these behaviours will not only improve safety and reliability of railway infrastructure but will enhance the structural safety of other concrete structures.

1. Introduction

Railway sleepers (also called ‘railroad tie’ in North America) embedded in ballasted railway tracks are laid to support the rails. Notably, railway prestressed concrete sleepers have been used in railway industry for over 50 years [1-5]. The sleepers can be typically made of timber, concrete, steel or other engineered materials [6]. They have been systemically introduced to railway industry for many decades ago and currently are introduced in almost every railway network in the world. The main duties of sleepers are: (a) to transmit the wheel load from the rail foot to the underlying ballast bed, (b) to hold the rails at the proper gauge and alignment through the rail fastening system, (c) to maintain rail inclination, and (d) to restrain longitudinal, lateral, and vertical movements of the rails and the rail

gauge for safe passages of rolling stocks. It is important to note that railway sleepers are a structural and safety-critical component in railway track systems [7-17].

Railway track structures often experience impact loading conditions due to wheel/rail interactions associated with abnormalities in either a wheel or a rail [18]. All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. Generally, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles. The shape of impact loading varies depending on various possible sources of such loading, e.g. wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called “wheel fly”, will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse acting after the static wheel load is removed. For instance, the typical loading duration is about 1-10 msec, while the force magnitude varies between 200 kN and up to 750 kN, depending on the causes and the traveling speed of train [4]. Note that these actual loading conditions are different to the loading conditions specified in type testing methods of sleeper standards [1, 10]. This is because the type testing methods are commonly used for benchmarking purpose.

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. 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 [10, 19]. 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 [20-27]. 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. 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) [28-30]. 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.

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 [29-33]. Most common wears are railseat and soffit abrasion at railseat. 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 of this study has been placed on the impact capacity of the cross-ties with abrasion. The insight into these behaviours will not only improve safety and reliability of railway infrastructure but will enhance the structural safety of other concrete structures.

2. Prediction for ultimate moment capacity

2.1 Modified compression field theory

In this study, the moment-curvature has been used to represent the capacity of prestressed concrete sleepers. The moment capacities are predicted by the modified compression field theory using Response-2000 [37]. This theory is capable of predicting the behaviour of reinforced concrete subjected to in-plane shear and normal stresses. The concrete stresses in principal directions along with prestressing steel are considered in only axial direction and the uncracked portion will carry on to sustain a load in the analysis [38].

2.2 Effect of strain and loading rates

Based on the assumption of perfect bond between prestressing wires and concrete, the dynamic material properties of concrete and prestressing wires can be determined as follows [39].

Concrete:

$$\frac{f'_{c,dyn}}{f'_{c,st}} = 1.49 + 0.268 \log_{10} \dot{\epsilon} + 0.035 [\log_{10} \dot{\epsilon}]^2 \quad (1)$$

Prestressing wires:

$$\frac{f_{y,dyn}}{f_{y,st}} = 10^{0.38 \log_{10} \dot{\epsilon} - 0.258} + 0.993 \quad (2)$$

Where $f_{y,dyn}$ is the dynamic upper yield point stress, $f'_{c,st}$ is the static upper yield point stress of prestressing wires (about 0.84 times proof stress), and $\dot{\epsilon}$ is the strain rate in tendon.

3. Material properties

In this study, there are 2 positions of prestressed concrete sleepers. As shown in figure 1, the prestressed concrete sleepers in normal position and inverse position are considered to evaluate the positive and negative ultimate moment capacities, respectively.

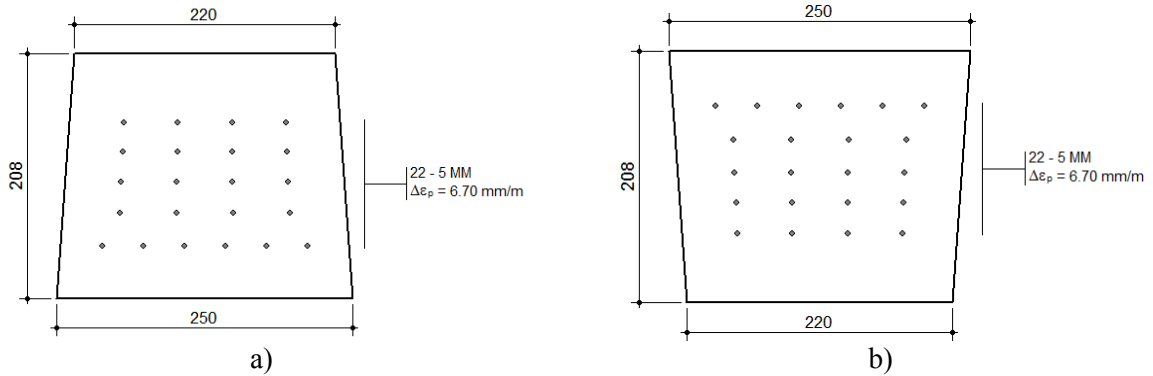


Figure 1. Prestressed concrete sleepers in a) Normal position b) Inverse position

3.1 Static

The dimension and shape of prestressed concrete sleepers are shown in figure 1. The high strength concrete was used with the design cylinder compressive strength of 55 MPa. The stress-strain curve of concrete derived by Vechio and Collin [38] was used in this study, as shown in figure 2. The 22-prestressing steels used were the high ultimate strength with rupture ultimate strength of 1860 MPa. The initial elastic modulus of prestressing steel was 20000MPa.

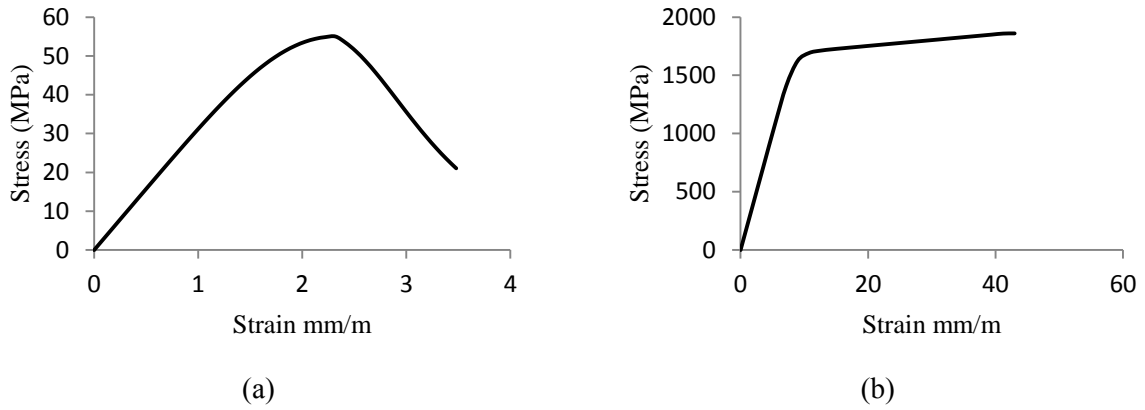


Figure 2. Stress-strain curve of a) concrete b) steel

3.2 Dynamic

The prediction of moment capacity has been carried out using the data obtained from the previous experiments [40]. It should be noted that the average total duration of impact forces is about 4 ms. In this study, the strain rate of concrete is approximately about 2. It is well known that the dynamic ultimate strain of prestressing steel is about 20×10^{-3} , and the total duration of impact force influencing the steel fibre is roughly about $4 + 2 = 6$. This is because the impact stress wave delays during the stress propagation and will be impeded through concrete [39]. Using Equation (1) and (2), the dynamic strength of materials can be obtained as the input for the sectional analysis.

4. Results and discussions

In general, the first stage of the behaviour of the material is elastic range when there is no damage in the material and the applied external force is less than the proportional limit. Then, when the moment reaches the proportional yield point, the nonlinear behaviour takes place till the member reaches the ultimate capacity. After that, the curve drops rapidly due to the crushing and spalling of concrete.

The effect of abrasion in the prestressed concrete sleepers is evaluated by the moment capacity. The obtained results indicate that the abrasion in prestressed concrete sleepers can affect the moment capacity due to the reduction in cross-sectional area.

Using the material properties from section 3, the ultimate moment capacities of worn prestressed concrete sleepers under static loading and impact loading can be illustrated in figure 3 and 4 for railseat abrasion and soffit abrasion, respectively.

4.1 Railseat Abrasion

In this study, the depth of prestressed concrete sleepers is reduced by 10 cm, 20 cm, and 30 cm, respectively, at the top surface. As illustrated in figure 3, it exhibits that railseats abrasions play a dominant role on positive moment capacity of the worn sleepers, whilst negative moment capacity does not have similar effects. This indicates moment capacities of worn sleepers are about 65% of positive moment capacities of a full cross-sectional area by 30 cm increasing in worn depth of concrete sleepers, as shown in figure 5a.

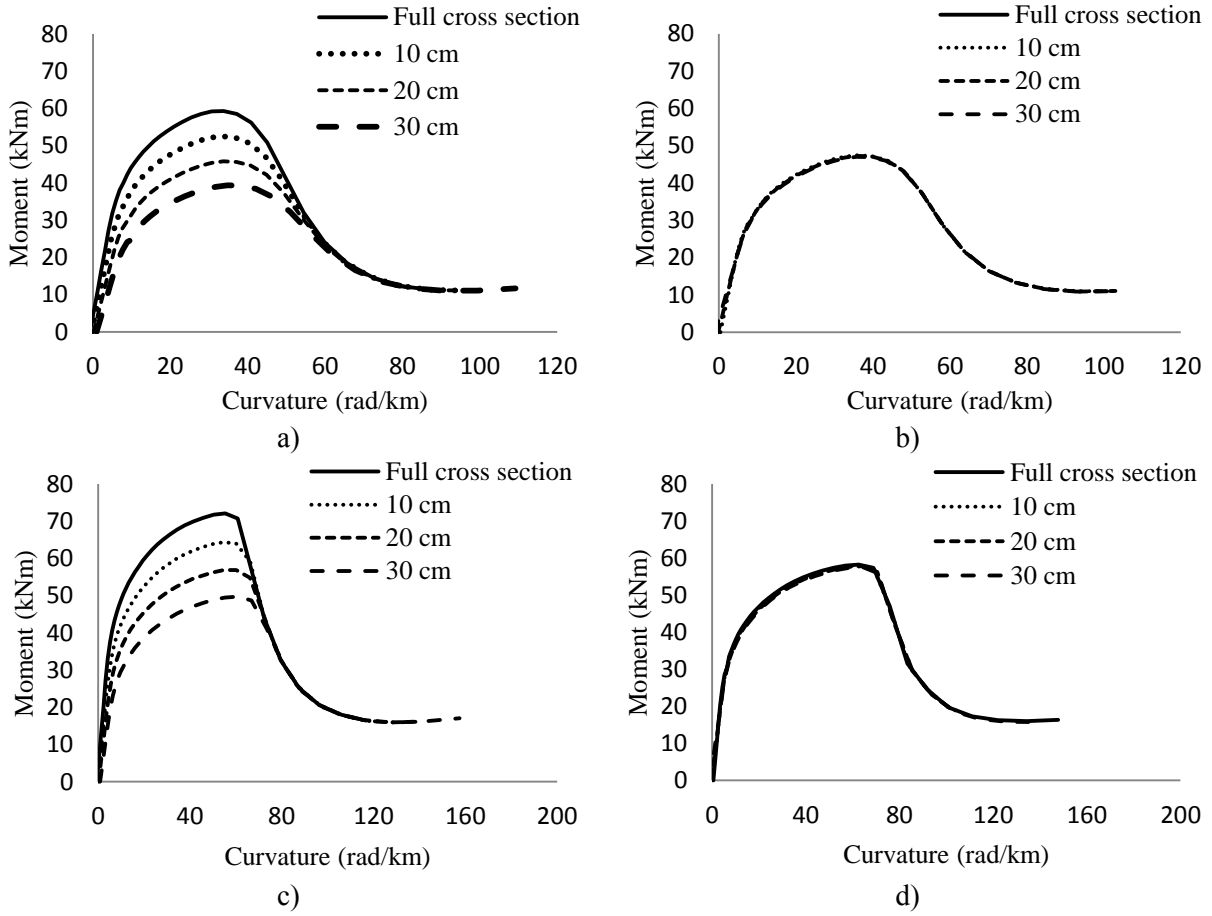


Figure 3. a) Positive moment curvature of worn sleepers due to railseat abrasion under static loading
 b) Negative moment curvature of worn sleepers due to railseat abrasion under static loading
 c) Positive moment curvature of worn sleepers due to railseat abrasion under impact loading
 d) Negative moment curvature of worn sleepers due to railseat abrasion under impact loading

4.2 Soffit Abrasion

The depth of prestressed concrete sleepers is reduced by 15 cm, 30 cm, and 45 cm, respectively, at the bottom surface. It is observed that the depth is reduced until the position of lowest layer of prestressing steel. It is assumed that the steel still locate in the bottom position.

The moment capacities of soffit abrasion can be demonstrated in figure 4. It exhibits that soffit abrasion play a little role on positive moment capacities of the worn sleepers. However, sleepers in inverse position, the negative moment capacities of sleepers can be slightly clearer. It should be noted that about moment capacities of worn sleepers are 42% and 47% for static and impact loading, respectively, of negative moment capacities of full cross-sectional area by 45 cm increasing in worn depth of concrete sleepers, as illustrated in figure 5b.

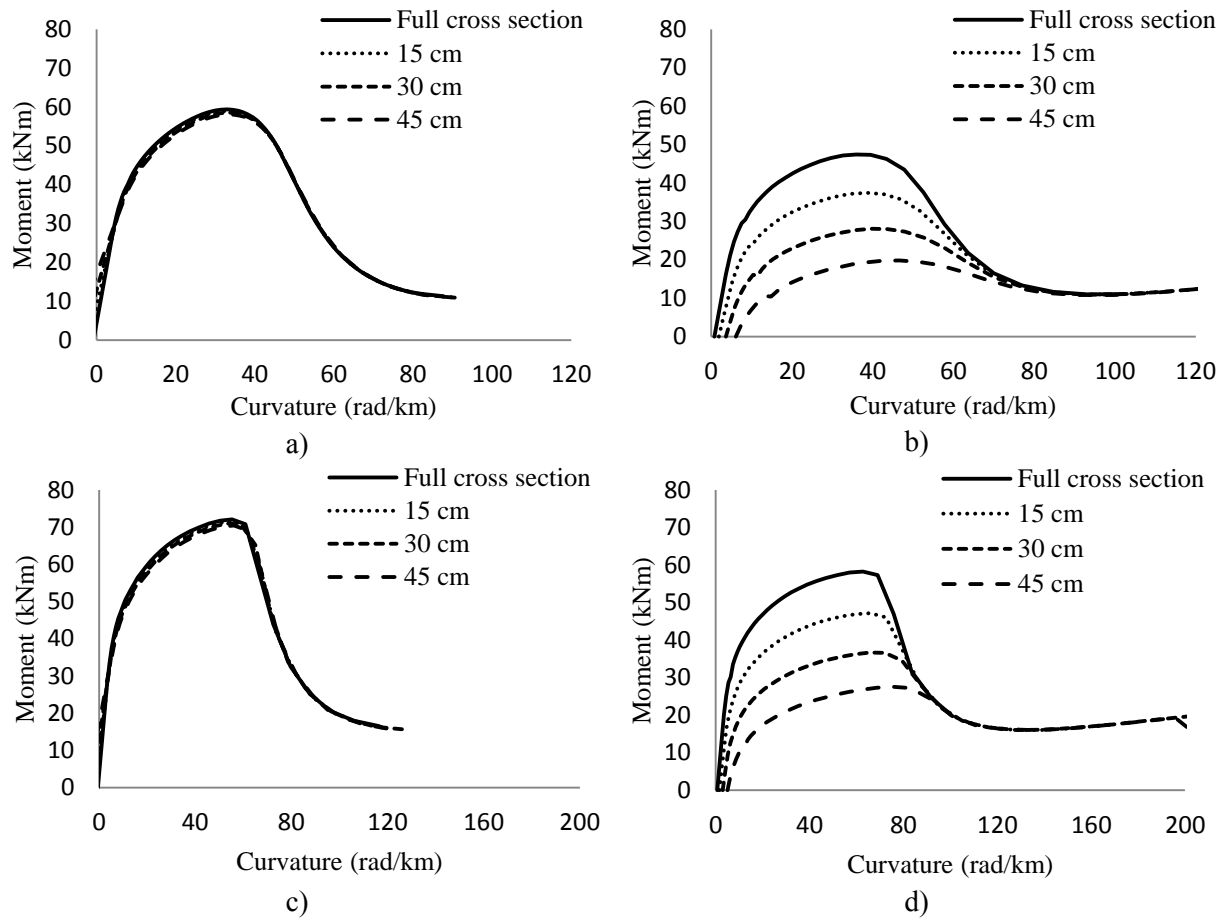
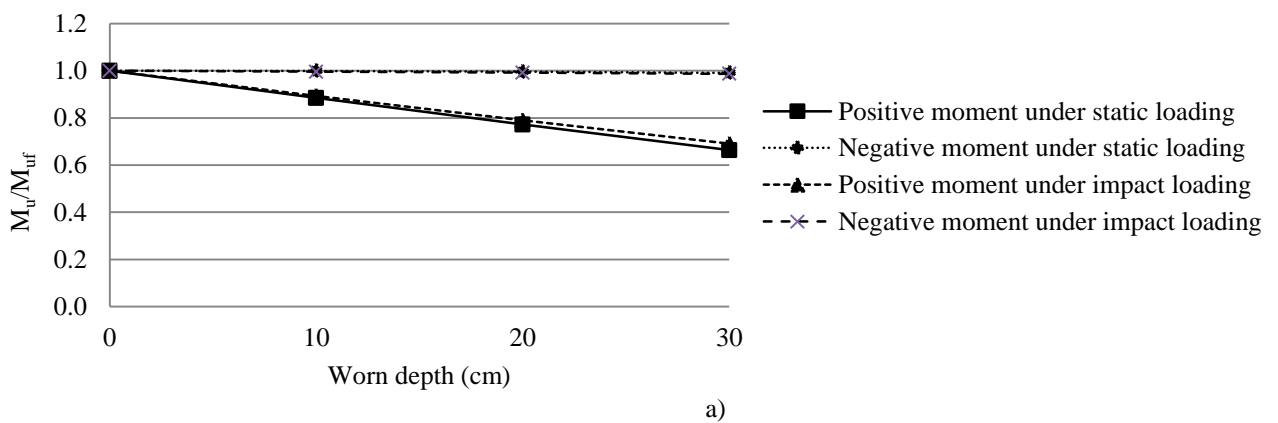


Figure 4. a) Positive moment curvature of worn sleepers due to soffit abrasion under static loading
b) Negative moment curvature of worn sleepers due to soffit abrasion under static loading
c) Positive moment curvature of worn sleepers due to soffit abrasion under impact loading
d) Negative moment curvature of worn sleepers due to soffit abrasion under impact loading



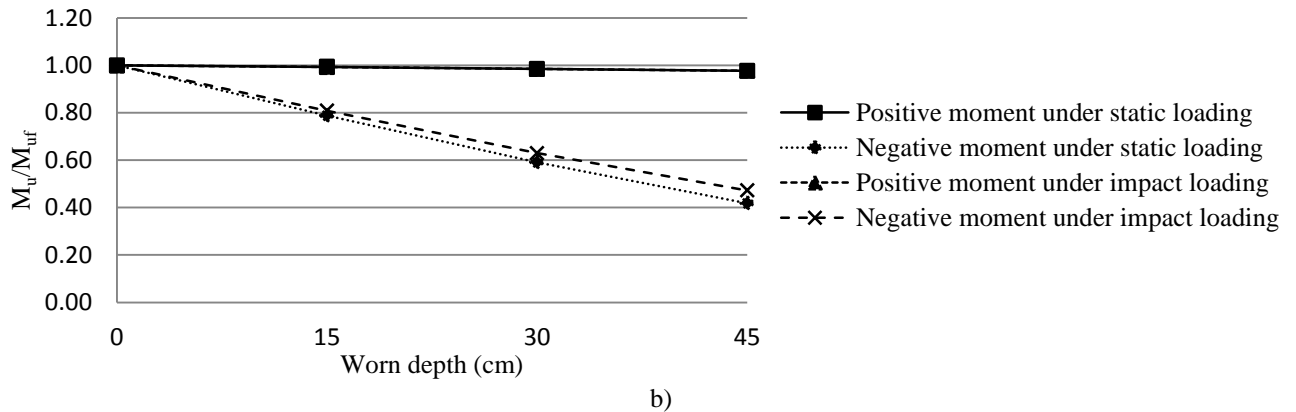


Figure 5. M_u/M_{uf} worn depth relationship under static and impact loading due to a) Railseat abrasion b) Soffit abrasion

In addition, the combination of railseat and soffit abrasion is also considered. As shown in Table 1. It can be clearly seen that railseat abrasion does not affect the positive moment capacity of prestressed concrete sleepers. Also, in term of negative moment capacity, It is clear that the sleepers are not effected by soffit abrasion, although, the railway sleepers can experience both surface abrasions.

Table 1. Ultimate moment capacities of prestressed concrete sleepers due to surface abrasion

No	Worn depth (cm)		Static loading		Impact loading	
	Railseat	Soffit	Positive	Negative	Positive	Negative
1	0	0	59.3	47.5	72.0	58.2
2	10	0	52.5	47.4	64.4	58.0
3	20	0	45.8	47.3	56.9	57.8
4	30	0	39.4	47.0	49.7	57.5
5	0	15	59.0	37.4	71.5	47.1
6	0	30	58.5	28.1	71.0	36.7
7	0	45	58.0	19.8	70.4	27.5
8	10	15	52.1	37.3	63.9	46.8
9	10	30	51.7	28.0	63.3	36.5
10	10	45	51.3	19.7	62.8	27.3
11	20	15	45.4	37.2	56.5	46.6
12	20	30	45.1	27.9	56.0	36.3
13	20	45	44.6	19.7	55.4	27.1
14	30	15	39.0	37.0	49.3	46.3
15	30	30	38.7	27.7	48.9	36.1
16	30	45	38.3	19.5	48.4	27.0

5. Conclusions

This study is the world first to investigate the effect of surface abrasion on the impact capacity of railway prestressed concrete sleepers. It exhibits that the surface abrasion undermines strength and impact capacity of railway concrete sleepers. Based on a critical literature review, it is found that previous research work in open literature 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. Therefore, it is essentially important for track and rail engineers to assure that the modification or retrofitting of concrete sleepers at construction sites is carried out in a proper manner. By the results obtained from these unprecedented studies, the railseat abrasion can reduce the positive moment capacity of the sleepers. Also, it is found that the soffit abrasion plays a critical role on negative moment capacity reduction. The insight into the impact behaviour of the concrete sleepers with surface abrasion will enable safer built environments in railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice.

6. Acknowledgements

The first author gratefully appreciates the School of Engineering and Birmingham Centre for Railway Research and Education of his PhD scholarship. The authors would also like to thank British Department of Transport (DfT) for Transport - Technology Research Innovations Grant Scheme, Project No. RCS15/0233; and the BRIDGE Grant (provided by University of Birmingham and the University of Illinois at Urbana Champaign). The last author is gratefully acknowledge the Japan Society for the Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network," which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu).

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