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Damage and failure modes of railway prestressed concrete sleepers with holes/web openings subject to impact loading conditions

Sakdirat Kaewunruen[a,b], Chayut Ngamkhanong[a,b], Chie Hong Lim[a]

[a] Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham B152TT, United Kingdom
[b] Birmingham Centre for Railway Research and Education, School of Engineering, University of Birmingham, Birmingham B152TT, United Kingdom

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ABSTRACT

Prestressed concrete sleepers are essential to the structural integrity of railway track structures, redistributing wheel loads from the rails to underlying ballast bed while securing rail gauges for safe train traffics. In practice, drilled holes or web openings are usually generated ad hoc in sleepers to enable signalling equipment and cables at a construction site. These holes and web openings could however affect the structural integrity of sleepers, especially when they are exposed to impact loading. In fact, statistically, 15–25% of dynamic loading conditions are of transience and high-intensity by the nature of wheel-rail interaction over irregularities. This study is thus the world first to rigorously investigate the impact behaviours of railway sleepers with hole and web openings, which is critical to railway safety and reliability. In this study, three-dimensional finite element modelling using ABAQUS Explicit is used to comprehensively design and analyse the behaviour of prestressed concrete sleepers with various types of holes and web openings upon impact loading. Two different modelling techniques including concrete damaged plasticity model and brittle cracking model are also exercised to aid in this study. The results obtained show that the brittle cracking model provides better damage results as it can illustrate crack propagation very well until reaching the failure mode under impact loading. The findings illustrate a pathway to use brittle cracking model instead of concrete damaged plasticity model for dynamic impact analysis. Moreover, the outcome of this study will provide a better and new insight into the influences of holes and web openings on sleepers' failure modes under impact loading so that appropriate guidance can be proposed to rail and track engineers in order to generate holes and web openings ad hoc in prestressed concrete sleepers without compromising their structural performance.

1. Introduction

The railway sleeper plays a significant role in a railway track system, where it is responsible for transferring and distributing vehicle loads from rail foot to the underlying ballast bed. It also helps maintain track gauge and insulate the rails against electricity. It should be noted that railway sleepers are a structural and safety-critical component in railway track systems experiencing aggressive dynamic conditions [1–15]. Railway sleepers can be constructed of various materials such as timber, concrete, steel, and other engineered materials [16–18]. It is important to note that an individual failure of a sleeper will generally not cause disruption to rail operations but it will increase periodic track maintenance costs, increase costs and effort for safety-related track inspection and monitoring, and impair ride comfort of train passengers depending on the severity. For various exceptional cases, the failure of a sleeper will significantly increase the risk of rail breaks at welds, joints, rail surface defects, rail foot defects, turnouts (or called 'switches and crossings') [17,18], and will inevitably create asymmetrical load balancing and redistribution [11]. These exceptional risks can lead to detrimental train derailments causing not only financial penalties but also losses of lives [14,15].

Notably, prestressed concrete sleepers have been widely used for more than 50 years [19–23]. Prestressed concrete sleepers would have an improved structural capacity and/or serviceability as compared to conventional reinforced concrete. Given their importance, it is crucial to ensure that concrete sleepers are always in excellent condition before and during operation. However, they are prone to deterioration issues as cracks may occur and expand. This may incur extra costs as concrete cannot be repaired and has to be replaced should it suffer considerable damage and fail over time. All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. Railway sleepers are often subjected to impact loading, which is a shock load applied over a short period. Impact loading is a possible source of damage which may induce cracking in sleepers. Impact

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E-mail address: s.kaewunruen@bham.ac.uk (S. Kaewunruen).

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loading is caused by the interaction with abnormalities in either wheel or rail, as well as the resonance produced among the track components [24]. Impact load, which varies roughly from 200 kN to 750 kN, would imply severe damage to the sleepers. In fact, many studies over a number of years show that statistically, up to 25% or more of dynamic loading conditions are of transience and high-intensity by the nature of wheel-rail interaction over irregularities [3–9,15,24]. This issue is further compounded considering that holes are often drilled into sleepers for signalling gears, cables, and additional train derailment protection, such as guard rails, check rails, earthquake protection rails, etc. [25–27]. With the introduction of these holes into sleepers, the structural integrity of the sleeper may be weakened and thus, more vulnerable to the adverse effects under impact loading. Not only will that mean a replacement of the sleeper is in order, there is likelihood that the signalling equipment may get affected as well. If that happens, signalling faults may result and cause disruption to the entire track operation. Based on the literature, although the effects of holes on the capacity reduction of concrete sleepers have been studied via compression field theory and experiments [28–31], performance and crack propagation prediction under impact loading corresponding to dynamic wheel load has not been fully investigated.

Hence, these evidences highlight the importance of studying the performance of these railway sleepers under impact loading. Finite element analysis (FEA), which is a common approach for solving engineering problems, is a numerical technique and used through a finite element software ABAQUS. Numerical modelling is an ideal tool to enable complex structural scenarios to be replicated and analysed, providing insights that would be beneficial for solving issues without using a huge amount of resources as traditional experimental methods would. Two different methods, the concrete damaged plasticity (CDP) model [32–35] and the brittle cracking model [36,37] are used to compare the results. The CDP model is designed based on two failure mechanisms, tensile cracking and compressive crushing. The brittle cracking model contains a failure criterion and allows the removal of elements during the analyses. The aim of this study is to investigate the failure modes of prestressed concrete sleepers with holes/web openings under impact loading considering two different finite element models: concrete damaged plasticity (CDP) and brittle cracking model, in order to compare the different from both models. The condition recommended by European Standard [10] to identify common failure modes of concrete sleepers is emphasised. The results show that the brittle cracking model demonstrates better results by illustrating crack propagation and removed elements until failure. The findings of this study can provide information to rail and track engineers in determining the best way to generate holes into sleepers without compromising the sleeper performance during operation. Consequently, this study will enhance structural safety and reliability of railway infrastructure.

2. Methodology

2.1. Finite element modelling

The finite element software ABAQUS was used to establish the models for this study. Different type of holes and web opening were demonstrated. It should be noted that the hole diameters considered (32 mm and 42 mm) are practical options for drilling sleepers and have been cored in a similar manner as in an actual construction. Two different types of models will be adopted, namely the Concrete Damaged Plasticity (CDP) models and the Brittle Cracking models.

The CDP model is designed as a continuum and plasticity-based model, with the assumption of two main failure mechanisms being tensile cracking and compressive crushing of concrete. The strain hardening during compression, the stiffness recovery, and the sensitivity to the straining rate may be controlled to allow the resemblance of the behaviour of concrete. However, it is impossible to conduct a crack propagation analysis with the CDP models as the CDP concept does not employ a failure criterion. The CDP is one of the most popular concrete models and has been used for concrete behaviour simulation in ABAQUS as seen in the literature [32–35]. This model was theoretically described by Lubliner et al. [32] and developed by Lee and Fenves [33]. The main assumptions of this model are listed as follows.

- There are two damage mechanisms: tensile cracking and compressive crushing of concrete,
- Material stiffness is reduced by two damage parameters, separately for tension and compression,
- The yield function is specified according to Lubliner et al. [32] and the flow potential is a hyperbolic function,
- Non-associated potential plastic flow is assumed.

To enable the study of crack propagation of the sleeper models under impact loading, an alternative, the brittle cracking model, has been suggested [36,37]. The brittle cracking model contains a failure criterion and allows the removal of elements during the analyses. This method provides the capability for modelling brittle materials and is designed for structures which are dominated by tensile cracking such as concrete. It should be noted that the linear elastic is assumed in this method. This implies that the crack propagation of the sleeper can be thoroughly examined when it undergoes impact loading. It is noted that a vertical velocity of 1.94 m/s is applied at the centre of the wheel to generate the impact loading equivalent to the 600 kg falling mass with the drop height of 0.2 m which has been developed in previous experiments [38]. This velocity can generate the impact load associated with actual train load.

2.1.1. Element and mesh size

The four components used for the models are the concrete sleeper, the prestressed tendons, the wheel, and the rail. Their element sizes are 15 mm, 35 mm, 12 mm and 10 mm respectively. All components except the prestressed tendons are of C3D8R element type, while the prestressed tendons are of the C3D6 element type [39]. The C3D8R element is eight-node brick element with reduced integration whereas the C3D6 is a six-node wedge element. These element types and sizes were selected to reduce the computational time for contact analysis, without compromising the realism and accuracy of the results. It is important to note that these element size have reflected the accuracy results since the results started to converge to a particular value. Fig. 1 shows the constructed mesh of the model setup. The number of element and mesh density are shown in Table 1.

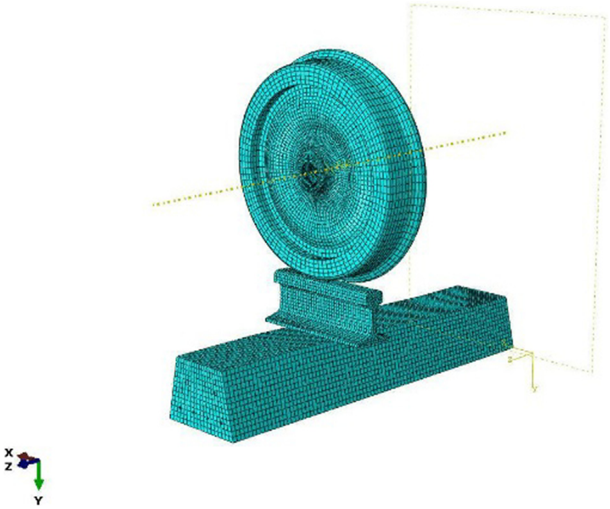

Fig. 1. Constructed mesh of sample model.