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Nonlinear finite element analysis for structural capacity of railway prestressed concrete sleepers with rail seat abrasion

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ABSTRACT

Prestressed concrete sleepers are the most commonly used type of railway sleepers in ballasted railway track. They have a strong influence on track performance, track stiffness and railway safety. Reportedly in many railway lines (especially in heavy-rail networks), many prestressed concrete sleepers have failed due to rail seat abrasion (RSA). RSA is a wear deterioration of the concrete underneath the rail that results in various problems such as loss of fastening toe load, gauge variation, improper rail cant, and eventually loss of rail fastening. In addition, the RSA will directly decrease the capacity of worn concrete sleepers. However, to the best of authors' knowledge, there were very few studies that quantitatively examined the effects of RSA on the structural capacity of the prestressed concrete sleepers. In this paper, a numerical study is executed to evaluate the load-carrying capacity of a prestressed concrete sleeper using LS-DYNA. The nonlinear model was validated firstly based on both theoretical analyses and experimental results in accordance with Australian Standard. Using the validated finite element model, the influences of different wear depth of RSA are investigated; and different compression strength and tensile strength of concrete and the prestress losses are highlighted. The outcomes of this study lead to better insight into the influences of RSA more clearly and improve track maintenance and inspection criteria.

1. Introduction

Prestressed concrete sleepers are one of the most important components in ballasted railway tracks [1–3]. Prestressed concrete sleepers lie between the rail and ballast, to transfer the train's loads from the wheel to the rail, and the rail to the ballast bed; and then to secure rail gauge and keep the geometry of railway line within a suitable range [4,5]. Fig. 1 shows the prestressed concrete sleepers in ballasted railway track.

Prestressed concrete sleepers play a major role in track performance, track stiffness and operational safety. The performance deterioration of concrete sleepers is a safety-concerned question of operation and maintenance departments within the railway organisations. A sleeper failure in critical locations such as switches and crossings, transom bridges, bridge ends, rail joints, and so on can lead progressively to significant incidents in railway operations (e.g. train derailments, operational downtime, broken signaling equipment, etc.). Because it is rather different to predict a particular location of long continuous tracks where the sleeper will fail, the performance of concrete sleepers is generally defined by structural reliability obtained from the stress generated from repeat loads (or

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Fig. 1. Prestressed concrete sleepers in ballasted railway track.

action) and sleepers' resistance (or capacity) [4]. In addition, the performance deterioration of concrete sleepers can be influenced by the lateral and vertical dynamic loads transferred from the rails, the manufacturing quality and maintenance defects, and the exposure to environmental conditions, etc. The most common problems related to concrete sleepers in North America and worldwide are surveyed and ranked in Table 1 [6,7].

From Table 1, we can see that abrasion and cracking are the main damages of prestressed concrete sleepers [8]. Rail seat abrasion (RSA) is the wear degradation underneath the rail on the surface of prestressed concrete sleepers (Fig. 2).

RSA of a prestressed concrete sleeper can be related to the climatic and traffic conditions and the location of the concrete sleepers in the track. In particular, axle load, traffic volume, curvature and grade of the rail line, the presence of abrasive fines (e.g. locomotive sand or metal shavings), the behaviour of the fastening system, and climate are the key factors that contribute to RSA [9,10]. Based on North American heavy railway network experiences and concrete sleeper tests results, heavy axle loads, abrasive fines, moisture, and rail movement appear to be the most important factors [11,12].

In 2009, Zeman and Bakke did some research work on the mechanisms of RSA; based on their results, abrasion, crushing, freeze-thaw cracking, hydraulic pressure cracking, hydro-abrasive erosion and cavitation erosion were the potential mechanisms [11–14]. In 2010, a laboratory test apparatus and procedure were devised by Zeman to investigate the influence of hydraulic pressure cracking, hydro-abrasive erosion, and cavitation erosion, and several suggestions to mitigating RSA were given [9,10]. Borg et al. performed large-scale abrasion tests in 2014 [15]; based on the results of the experiments, they concluded that the frictional characteristics between a rail pad and rail seat had an impact on the transfer of forces and relative movement and could influence RSA. Kaewunruen et al. [16] presented a nonlinear finite element model to evaluate influences of surface abrasions on dynamic behaviours of railway concrete sleepers. However, the initial work was focused on dynamic phenomena such as nonlinear frequencies and modeshapes [16].

RSA results in many problems of railway tracks such as loss of fastening toe load, gauge variation, improper rail cant, and eventually loss of rail fastening. There are many researches about RSA; from the literal review above, most of previous works focused on the mechanisms of RSA. However, there were very few studies that quantitatively examined the effects of RSA on the loading capacity of the prestressed concrete sleepers. This implies that the maintenance of sleepers cannot be properly scheduled or planned in advance. In fact, the sleepers are generally embedded in ballast, it is almost impossible to inspect structural damage such as cracks, which are the warning sign towards structural failure. One sleeper failure can definitely lead to another failure. Therefore, it is necessary to develop the engineering guideline to determine the structural integrity and capacity of the aging and worn railway sleepers with RSA. Without the insight into the structural capacity, the structural reliability of sleepers cannot be determined and

Table 1
Common damages of prestressed concrete sleepers (Ranked from 1 to 8, with 8 being the most critical) [6,7].

Main Causes	Damages	North American rank	International rank
Lateral load	Abrasion of concrete material on rail seat	**6.43**	3.15
	Shoulder/fastening system wear or fatigue	6.38	5.5
Vertical dynamic load	Cracking from dynamic loads	4.83	5.21
	Derailment damage	4.57	4.57
	Cracking from centre binding	4.5	5.36
Manufacturing and maintenance defects	Tamping damage (or impact forces)	4.14	**6.14**
	Other (e.g. manufactured defect)	3.57	4.09
Environmental considerations	Cracking from environmental or chemical degradation	3.5	4.67

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