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Static and dynamic behaviours of railway prestressed concrete sleepers with longitudinal through hole

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Abstract

As the crosstie beam in railway track systems, the prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground. Their design takes into account static and dynamic loading conditions. It is evident that prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, there have always been many demands from rail engineers to improve serviceability and functionality of concrete sleepers. For example, signalling, fibre optic, equipment cables are often damaged either by ballast corners or by tamping machine. There has been a need to re-design concrete sleeper to cater cables internally so that they would not experience detrimental or harsh environments. Accordingly, this study will investigate the effects of through hole or longitudinal hole on static and dynamic behaviours of concrete sleepers under rail shock loading. The modified compression field theory for ultimate strength design of concrete sleepers will be highlighted in this study. The outcome of this study will enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

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Static and dynamic behaviours of railway prestressed concrete sleepers with longitudinal through hole

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Abstract. As the crosstie beam in railway track systems, the prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground. Their design takes into account static and dynamic loading conditions. It is evident that prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, there have always been many demands from rail engineers to improve serviceability and functionality of concrete sleepers. For example, signalling, fibre optic, equipment cables are often damaged either by ballast corners or by tamping machine. There has been a need to re-design concrete sleeper to cater cables internally so that they would not experience detrimental or harsh environments. Accordingly, this study will investigate the effects of through hole or longitudinal hole on static and dynamic behaviours of concrete sleepers under rail shock loading. The modified compression field theory for ultimate strength design of concrete sleepers will be highlighted in this study. The outcome of this study will enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

1. Introduction

Railway is one of the most efficient and effective modes of transportation, conveying cargo, passengers, minerals, grains, and so forth. In general, railway sleepers (also called 'railroad tie' in North America) embedded in ballasted railway tracks are laid to support the rails. 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. 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.

Currently, railway track components are often being modified at construction sites to fit with signaling gears, cables, and additional train derailment protections, such as guard rails, check rails, earthquake protection rails, etc. [19-21]. The practical guideline for crosstie retrofit has not been well established and many attempts were carried out based on trials and errors. Despite a common task in construction site, the behaviour of holes and web openings on concrete crossties has not been well documented in open literature. In this manner, it is important to ensure that concrete crossties can be retrofitted and modified for add-on fixture in practice. This paper presents an advanced railway concrete sleeper modelling capable of parametric analysis into the effect of longitudinal holes on the dynamic behaviours of railway sleepers. 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 existing prestressed concrete sleepers. The moment capacities are predicted by the modified compression field theory using Response-2000 [22]. 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 [23].

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 [24].

Concrete:

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

Prestreesing wires:

$$\frac{f_{y,dyn}}{f_{y,st}} = 10^{0.38 \log_{10} \dot{\varepsilon}^{-0.258}} + 0.993 \tag{2}$$

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 $\dot{\varepsilon}$ is the strain rate in tendon.

3. Material properties

In this study, there are 2 positions of existing prestressed concrete sleepers. As shown in figure 1, the prestressed concrete sleepers in normal position and inverse position with and without longitudinal hole are considered to evaluate the positive and negative ultimate moment capacities, respectively. The position of the longitudinal hole is at the middle. The diameter of the longitudinal hole is varied from 10mm to 50mm.
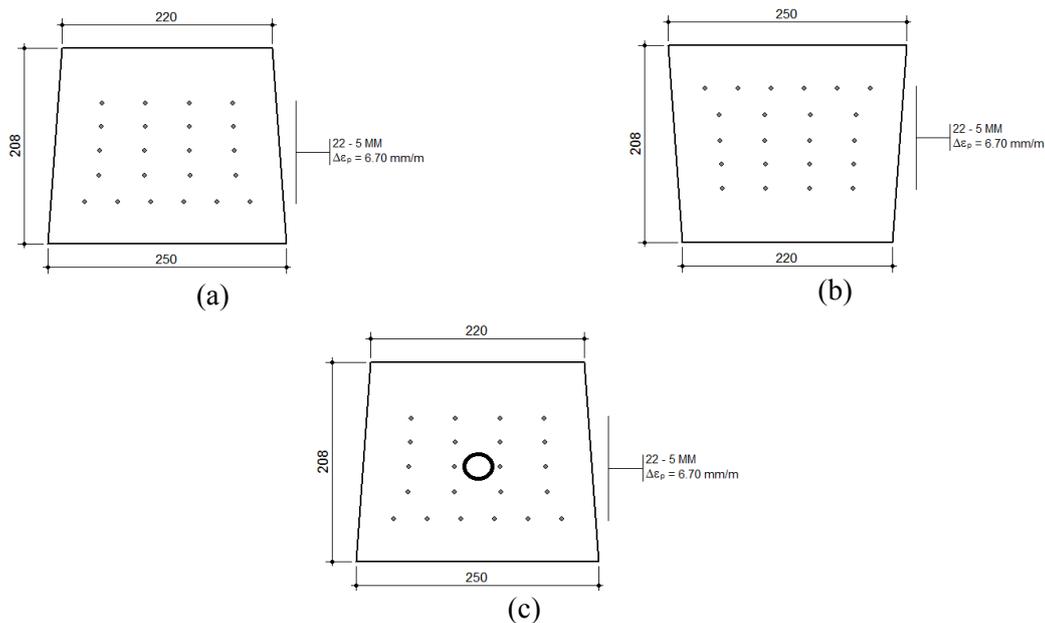
Figure 1. Prestressed concrete sleepers in (a) normal position for positive capacity computation. (b) inverse position for negative capacity computation. (c) normal position with longitudinal hole.

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 [23] 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.
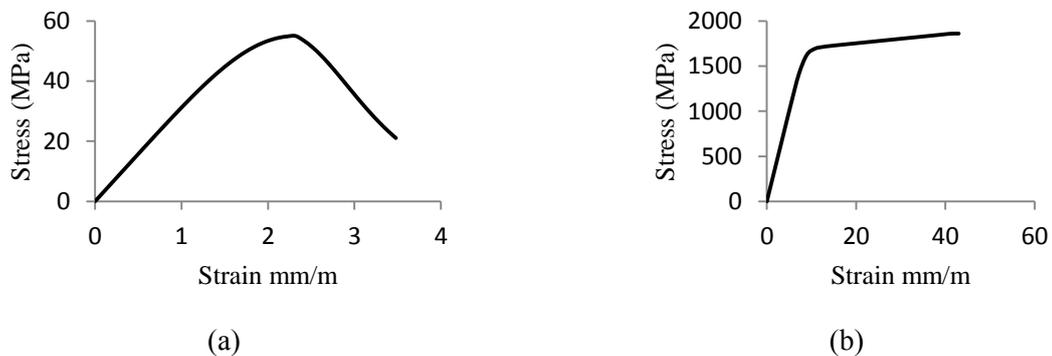
Figure 2. Stress-strain curve of (a) concrete (b) steel.

3.2 Dynamic

The prediction of moment capacity has been carried out using the data obtained from the previous experiments [25]. 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 s^{-1}. 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 s^{-1}. This is because the impact stress wave delays during the stress propagation and will be impeded through concrete [24]. 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 longitudinal hole in the prestressed concrete sleepers is evaluated by the moment capacity. Using the material properties from section 3, the ultimate moment capacities of prestressed concrete sleepers under static loading and impact loading can be illustrated.

In general, longitudinal hole can affect the prestressing steels because when the hole dimension is larger, the concrete covering (effective anchorage zone) reduces and can induce the significant losses in prestressing steels. It is assumed that pre-strain of prestressing steel, which can be affected by a longitudinal holes, could be lost by 80% due to the losses of steel [26-27] . Table 1 shows the number of steel affected by longitudinal hole.

Table 1. Number of steel affected by longitudinal hole.

Hole Diameter	Effect on prestressing steel
10 mm	-
20 mm	-
30 mm	Layer 2 - 2 steels
40 mm	Layer 2 - 2 steels and Layer 3 - 2 steels
50 mm	Layer 2 - 2 steels, Layer 3 - 2 steels and Layer 4- 2 steels

4.1 Static Analysis

The effect of longitudinal hole in the prestressed concrete sleepers is evaluated by the moment capacity. The obtained results indicate that the longitudinal hole in prestressed concrete sleepers can affect the moment capacity due to the reduction in cross sectional area and loss in prestressing steels. Figure 3 and table 2 illustrate the moment curvature of prestressed concrete sleepers under static loading. It can be clearly seen that the ultimate positive moment capacity of prestressed concrete sleepers without a longitudinal hole is about 60 kNm which is more than the moment capacity of all sleepers with a longitudinal hole. In case of inverse position, it also exhibits that trend of negative moment capacity are similar to positive case but the magnitude is lower. Nevertheless, for 10 and 20 mm holes, it is interesting to note that the moment capacities are reduced by less than 1%. This is because the reduction in cross sectional areas is very small (less than 1%) and there are no losses in prestressing steel caused by longitudinal hole.
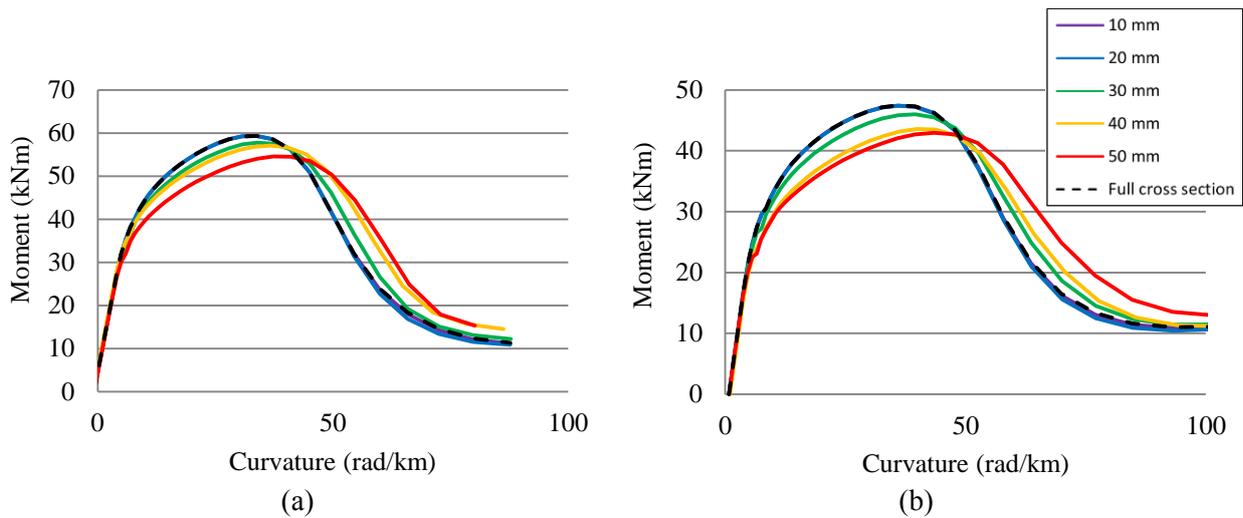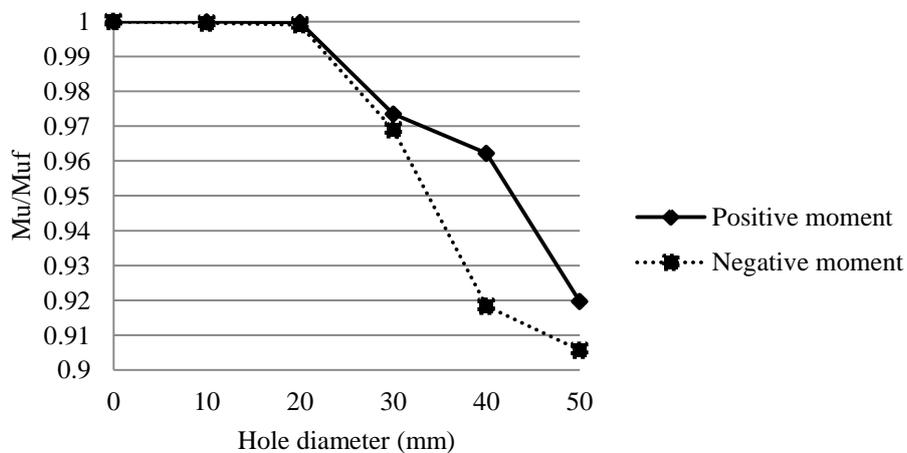
Figure 3. (a) Positive moment-curvature of prestressed concrete sleepers under static loading.
(b) Negative moment-curvature of prestressed concrete sleepers under static loading.

Table 2. Moment capacities of prestressed concrete sleepers under static loading.

| Section	Moment capacity (kNm)	
	Positive	Negative
Full	59.34	47.45
10 mm hole	59.33	47.43
20 mm hole	59.32	47.41
30 mm hole	57.77	45.98
40 mm hole	57.10	43.58
50 mm hole	54.58	42.98

Figure 4 illustrates the relationship between M_u/M_{uf} ratio and holes diameter under static loading. It can be seen that the ultimate moment capacities ratio reduce when the hole diameter is more than 20 mm. This is because the hole affects the loss in prestressing steels. It is note that when 6-prestressing steels are affected by longitudinal hole, about 8-9% reduction in moment capacities are observed.

Figure 4. M_u/M_{uf} -hole diameter relationship under static loading.

4.2 Dynamic Analysis
Figure 5 and Table 3 illustrate the moment curvature of the prestressed concrete sleepers under impact loading. It can be clearly seen that the trend of moment-curvature relationship under impact loading are similar to static loading but it is interesting that the ultimate moment capacity is higher. This is because the material strengths are higher than static case due to the effect of strain and loading rates.
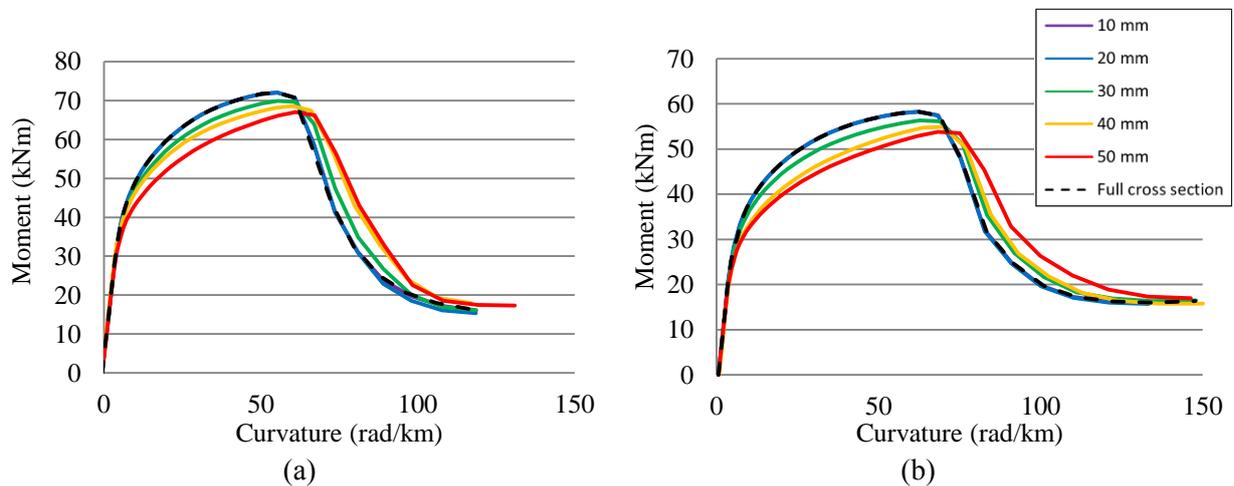

Figure 5. a) Positive moment-curvature of prestressed concrete sleepers under impact loading.
b) Negative moment-curvature of prestressed concrete sleepers under impact loading.

Table 3. Moment capacities of prestressed concrete sleepers under impact loading.

Section	Moment capacity (kNm)	
	Positive	Negative
Full	72.02	58.25
10 mm hole	72.01	58.24
20 mm hole	72.00	58.22
30 mm hole	69.92	56.31
40 mm hole	68.59	54.91
50 mm hole	67.05	53.80

Figure 6 illustrates the relationship between M_u/M_{uf} ratio and holes diameter under impact loading. It is clear that the result of impact loading follows the trend of static loading. It is note that when 6-prestressing steels are affected by longitudinal hole, about 7-8% reduction in moment capacities are observed. From the obtained result, it should be note that prestressing steels play an important role in the ultimate moment capacity. Nonetheless, for 10 and 20 mm holes, it is note that the moment capacities are reduced by less than 1% because there are no effects of losses in prestressing steels and the reduction in cross sectional areas are very small. It can be concluded that when the diameter is less than 20 mm, longitudinal holes play a very little role in moment capacity of concrete sleepers.
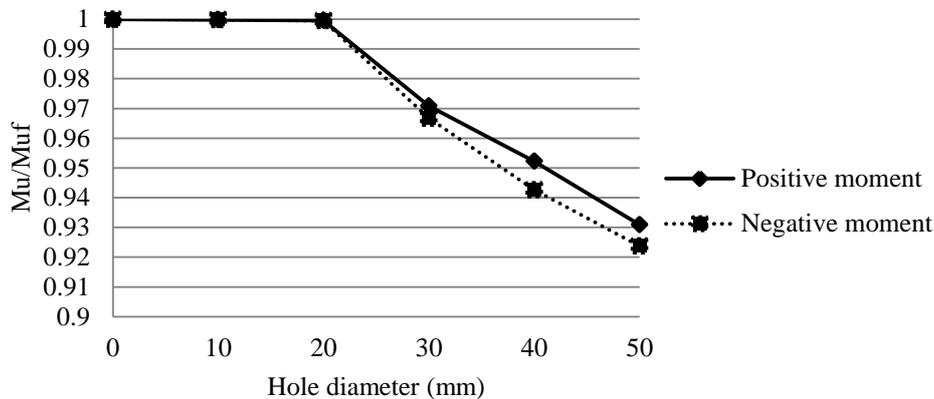
Figure 6. M_u/M_{uf}-hole diameter relationship under impact loading.

5. Conclusions

This study is the world first to investigate the effect of longitudinal holes on the static and dynamic capacity of railway prestressed concrete sleepers. It exhibits that the longitudinal holes undermine strength and impact capacity of railway concrete sleepers when the hole is large enough to affect the bond between concrete and presstressing steels. Therefore, it is essentially important for track and rail engineers to assure that the modification or retrofitting of existing concrete sleepers at construction sites is carried out in a proper manner. By the results obtained from these unprecedented studies, the longitudinal holes play a significant role in moment capacity only when the losses in prestressing steel are present. The longitudinal hole can reduce almost 10% and 8% of static and dynamic load bearing capacity of the sleepers, respectively. The insight into the impact behaviour of the concrete sleepers with longitudinal holes will enable safer built environments in railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice.

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