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Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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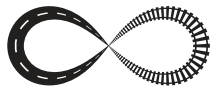
EFFECTS OF VERTICAL AND THROUGH HOLES ON CYCLIC BEHAVIOUR OF RAILWAY CONCRETE SLEEPERS

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Abstract

Railway sleeper is the very important element in rail track structure. Nowadays, prestressed concrete is the most common type used in railway sleeper because of its good structural performance. The main duties of sleeper are to distribute the wheel load to the formation and keep the rail gauge. Most of current design codes for sleepers design techniques rely on allowable stresses and material strength. However, railway sleepers also experience high frequent cyclic load due to wheel-rail interaction. The cracking could occur in prestressed concrete sleepers due to cyclic behaviour and accumulation of fatigue could finally result in prestressed concrete sleepers' failure. In addition, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. This paper presents the results of the extensive theoretical and analytical investigation aimed at predicted cyclic behaviour on prestressed concrete sleepers with holes. It highlights the effects on cyclic behaviours of railway concrete sleepers. The insight of this paper can be used to evaluate the service performance and predict the cyclic behaviours of the concrete sleeper, as well providing design flexibility and broadening the design principle. The outcome of this study may also improve the rail track maintenance and inspection criteria, in order to establish an appropriate track condition monitoring network in practice.

Keywords: railway infrastructure, prestressed concrete sleeper, cyclic behaviour, fatigue, time-dependence

1 Introduction

Nowadays railway transportation has been becoming the most popular transportation with its safe ride, high carry-capacity and high speed. Conventional track consists of rail, sleeper, rail pad, fastening system, ballast, sub-ballast, formation etc. railway sleeper is the very important component in track structure. The most important functions of railway sleeper are: a) Transfer and distribute vertical loads from superstructure to foundation, b) And restrain lateral, longitudinal and vertical movement of rails. The sleepers are usually manufactured by timber, steel, concrete, and any other engineered materials. Prestressed concrete are the most popular type used in sleeper around world [1-5].

In many countries, the permissible stress method is used in concrete sleeper design [6, 7]. The permissible stress of materials and load factor are used to consider dynamic effects. However, the permissible stress method can't take into account dynamic load accurately. Much research has been developed limit state method for concrete sleeper design [8-10]. Fatigue limit state is the time-dependent limit state which the damage of concrete sleepers will be accumulated over years when it reached to failure.

Fatigue first found in steel construction was in 1830. The concrete fatigue research started at the turn of 19 century [11]. Fatigue failure can be explained as the failure which occurs below the stress limit under cyclic load. The fatigue can be determined by: the magnitude of the stress range, the type and quality of the structure and the number of cycles. Cracking is considered ordinarily as the failure criterion to define fatigue state for concrete sleeper design. This paper reviews the main characteristics of cyclic behaviour and fatigue load of prestressed concrete sleepers. It also investigates the fatigue resistance. The outcome of this paper will improve prestressed concrete sleeper design and rail track maintenance system.

2   Fatigue load assessment

Cracks occur in concrete sleepers normally could cause by excessive flexural, shear or bond stresses [12]. However, many cracks depend on fatigue load and the material properties. The fatigue load in concrete sleepers is from the wheel-rail interaction. It can be divided into two parts: dynamic load and impact load. Dynamic load is normal wheel-rail interaction. Impact load is wheel-rail interaction with irregular wheel or rail.

2.1 Dynamic Load

Dynamic load is usually related to the train speed and it is used for permissible stress design. The dynamic wheel load can be expressed by:

$$P_d = \varnothing P_s \tag{1}$$

Where P_d is the dynamic wheel load, $\varnothing$ is the dynamic wheel load factor ($\varnothing > 1$), P_s is the static wheel load. The dynamic factor $\varnothing$ depends on train speed and it can be calculated:

$$\varnothing = 1.099 + 0.00621V \tag{2}$$

Where V is train speed.

2.2 Impact Load

The impact factor (k_i) can be determined by:

$$k_i = 0.00278R + 0.029V - 0.73 \tag{3}$$

Where R is the return period, V is train speed.
The relationship between return period and the impact force I can be expressed as:

$$\frac{1}{R} = 10^{-0.0191I + 5.92} \tag{4}$$

2.3 Concrete sleeper design

The concrete sleeper design procedures are shown below:
• Analysis of dynamic load coefficient;
• Calculating sleeper rail seatloads;
• Assuming the support conditions of the sleeper;
• Calculating the bend moment of the critical sections of the sleeper.

The bending moments of railway sleepers are caused by dynamic load on the railseat (railseat load) which affected by wheel load, impact factor and distribution factor. Railseat load can be determined by:

$$R = P \times DF \times IF \tag{5}$$

Where P is the static load, DF is distribution factor, IF is impact factor

3 Material properties

3.1 Concrete

Concete fatigue is a progressive process that microcracks occur intially then the crack will become larger forward to the failure point. The mechanical properties of concrete will change under repeated cyclic loading, such as permanently increasing strain on the concrete, causing the stiffness to decrease. Cyclic loading may also cause a concentration of stress at the prestressed wires' surface, which can lead to sudden fracture [13]. The fatigue reference compressive strength $f_{ck,fat}$ of cocnrete can be calculated based on the characteristic compressive strength f_{ck} as follow:

$$f_{ck,fat} = \beta_{cc}(t)\beta_{c,sus}(t,t_0)f_{ck}\left(1 - \frac{f_{ck}}{400}\right) \tag{6}$$

$$\beta_{cc}(t) = \exp\left\{s\left[1 - \left(\frac{28}{t}\right)^{0.5}\right]\right\} \tag{7}$$

Where $\beta_{c,sus}(t, t_0)$ is a coefficient which depends on the time under high sustained loads. Figure 1 shows the typical S-N curves of concrete under pure compresion. N is the number of cycles causing fatigue failure in plain concrete.

$$S_{c,max} = \left|\sigma_{c,max}\right|/f_{ck,fat} \tag{8}$$

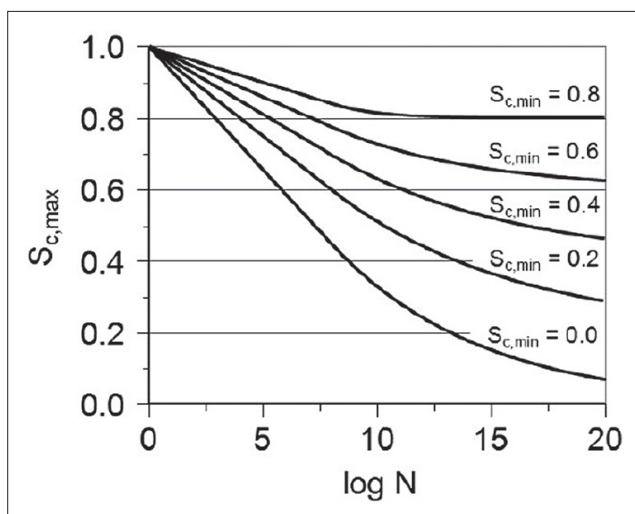$$S_{c,min} = \left|\sigma_{c,min}\right|/f_{ck,fat} \tag{9}$$

Figure 1   S-N curve for concrete under pure compression

3.2 Prestressing steel

The characteristic fatigue strength function for prestressed steel is shown in Figure 2. The parameters of prestressed steel are shown in Table 1. The failure cycles of the prestressing steel under a constant amplitude cyclic load can be given by:

$$\text{If} \quad \Delta\sigma > \Delta\sigma_{N^*}, \quad \log N_f = \log N^* - k_1\left[\log(\Delta\sigma) - \log(\Delta\sigma_{N^*})\right] \tag{10}$$

$$\text{If} \quad \Delta\sigma \leq \Delta\sigma_{N^*}, \quad \log N_f = \log N^* + k_2\left[\log(\Delta\sigma_{N^*}) - \log(\Delta\sigma)\right] \tag{11}$$

Where $\Delta\sigma$ is the stress range in the prestressing steel and $\Delta\sigma_{N^*}$ is the stress range at N* cycles which shown in Table 1.

Table 1   Parameters of S-N curves for prestressing steel

S-N curve of pre-stressing steel used for	N*	Stress exponent		$\Delta\sigma_{N^*}$ (MPa) at N* cycles
		k_1	k_2	
Pre-tensioning	10^6	5	9	185
$\Delta\sigma_{N^*}$ is the stress range obtained from a characteristic fatigue strength function.				

Loo et al. (2010) suggested that the mean value of $\Delta\sigma_{N^*}$ for reinforced steel is 290 MPa. Parvez and Foster (2015) stated the mean value of $\Delta\sigma_{N^*}$ is 300 MPa for prestressing steel. Therefore, in this study the $\Delta\sigma_{N^*}$ takes 300 MPa [14, 15].

4   Section and material properties

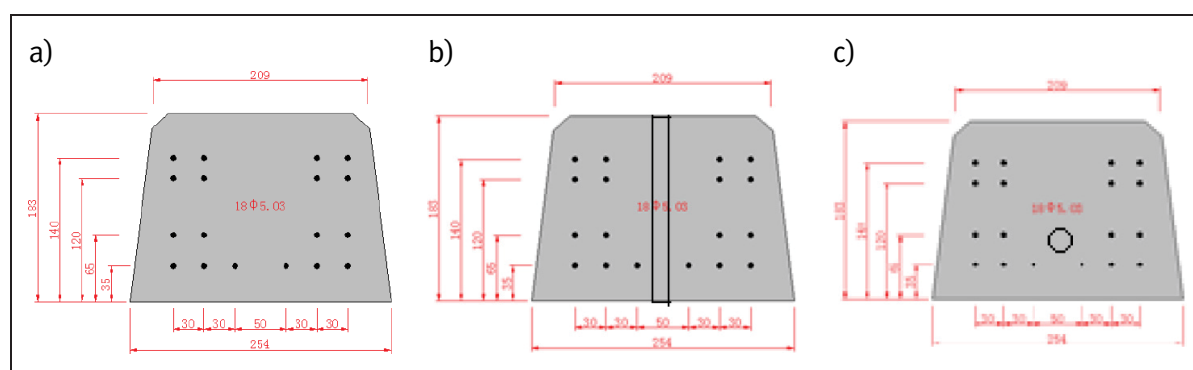The detail of railway sleeper is shown at Figure 2 and Table 2.

Figure 2   Cross section of sleeper: a) Full cross-section; b) cross-section with vertical hole; c) cross-section with horizontal hole

Table 2   Material properties of railway sleeper

Materials properties		Symbol	Value
Concrete	mean compressive strength	f_{cm}	58MPa
	Flexural tensile strength	f_{cf}	4.5MPa
	Modulus of elasticity	E_c	36.0GPa
Prestressed wire	Ultimate tensile strength	f_{pb}	1950MPa
	Yield strength	f_{py}	1620MPa
	Modulus of elasticity	E_s	200GPa

5 Results

To investigate effects of vertical and through holes on cyclic behaviour of railway concrete sleepers, 9 cases have been analysed including vertical holes with 10 mm, 15 mm, 20 mm diameter and horizontal holes with 10 mm, 15 mm, 20 mm, 25 mm, 30 mm diameters. The corresponding S-N curve is used to determine the maximum applied number of cycles for single stress amplitude as theoretical method (Figure 3). According to formula (10) and (11), the full cross-section failure cycles of the prestressing steel under constant amplitude cyclic load is 859055. Figure 4 shows the effects of vertical and through holes on cyclic behaviour of railway prestressed concrete sleepers. From the graph, the vertical holes have significant influence on cyclic behaviour which 10 mm dia with 34.0 % change, 15 mm dia with 56.6 % change and 20 mm dia with 84.0 % change. The horizontal holes have less influence than vertical holes which they are 10 mm dia with 1.2 % change, 15 mm dia with 2.8 % change, 20 mm dia with 5.0 % change, 25 mm dia with 7.9 % change and 30 mm dia with 11.6 % change. In theoretical calculation, both of vertical or horizontal holes impact concrete stress at bottom and first cracking moment, therefore the tension stress range can be influenced. In the other hand, holes in railway sleepers change the cross-section area which results in loss of prestress due to time-dependent behaviour like creep and shrinkage increase. It also influences the performance of cyclic behaviour of railway prestressed concrete sleepers [16].
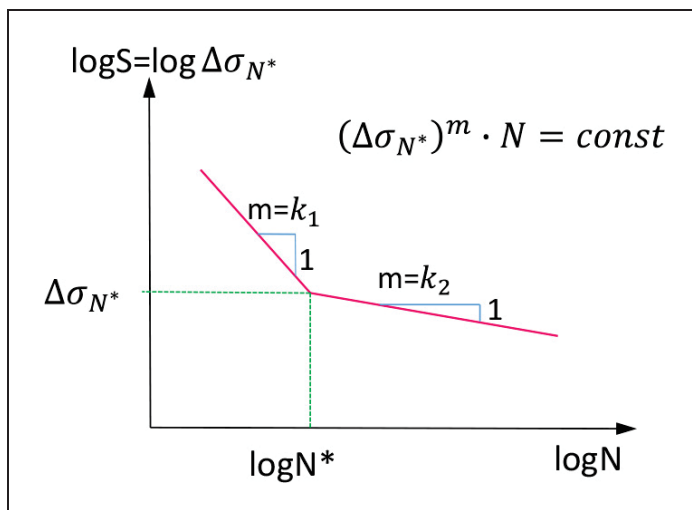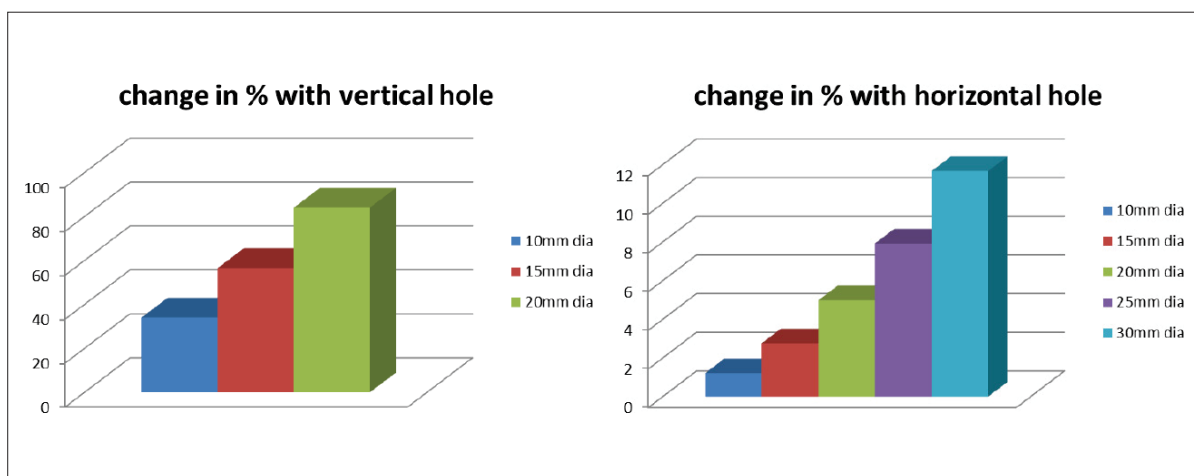

Figure 3   The S-N curve

Figure 4   Effects of holes on cyclic behaviour in percentage

6 Conclusion

This paper investigates effects of vertical and through holes on cyclic behaviour of prestressed concrete sleeper. The CEB-fip model and EN 1992-2 have been used as theoretical method to calculate the maximum applied number of cycles for constant stress. For concrete sleepers, the cracks are commonly considered as a failure criterion. The crack could occur due to excessive flexural, shear or bond stress. However, the progressive of crack depends on the cyclic behaviour. The cyclic damage of prestressed concrete sleepers is mainly due to the cumulative accumulation caused by wheel-rail interaction. In order to evaluate the fatigue life of prestressed concrete, the dynamic/impact load and bending moment needs to be analysed. The fatigue characteristics of prestressed concrete sleepers including S-N curve should be studied. The material properties are also very important to influence cyclic behaviour of prestressed concrete sleeper. According to material characteristics and the load moments, the reasonable cyclic behaviour criteria are developed. The concrete is not a homogenous material which means the material performance is very hard to define. Therefore, to obtain more accurate fatigue life prediction, the great deal of theoretical analysis, lab tests and field information are still required. This paper reviewed the previous research on the main characteristics of fatigue failure and fatigue load of prestressed concrete, in the presence of the fatigue resistance of prestressed concrete. This article also presents a convenient fatigue life assessment method for prestressed concrete sleepers. The outcome of this study can be used to evaluate the service performance and predict the fatigue life of concrete sleepers, as well as to help to engineer and improve concrete sleeper design and maintenance.

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