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DOI:

[10.5592/CO/CETRA.2018.668](https://doi.org/10.5592/CO/CETRA.2018.668)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

You, R, Li, D & Kaewunruen, S 2018, Fatigue life losses of railway concrete sleepers due to surface abrasions. in *The 5th International Conference on Road and Rail Infrastructure*. University of Zagreb, pp. 757-763, The 5th International Conference on Road and Rail Infrastructure , Zadar, Croatia, 17/05/18. <https://doi.org/10.5592/CO/CETRA.2018.668>

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Checked for eligibility: 24/05/2018

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FATIGUE LIFE LOSSES OF RAILWAY CONCRETE SLEEPERS DUE TO SURFACE ABRASIONS

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Abstract

Railway concrete sleepers are one of the most significant components of ballasted track. The failure of a concrete sleeper is considered to be the process of accumulated damage due to repeated loads over a long period of time. The fatigue life of concrete sleepers is a concerned question of operation and maintenance departments of railway line. Despite the importance of the effects of wheel-rail interaction loads in the reduction of the life cycle and operation time of concrete sleepers has been realized, at present, there is no systematic procedure for the service life analysis of concrete sleepers under repeated loads. Based on the damage accumulation method, this paper presents a fatigue life assessment method for a prestressed concrete sleeper, and researches the fatigue life losses caused from surface abrasions. Surface abrasion is one of the most common problems of the concrete sleepers will reduce its resistance capability, and then influence its fatigue life. The outcome of this study can be used to evaluate the service performance of the abrasive concrete sleeper and improve the rail track maintenance and inspection criteria.

Keywords: railway infrastructure, prestressed concrete sleeper, surface abrasion, fatigue, time-dependence

1 Introduction

Development of railway transportation system is significant and continuously around world. Railway transportation plays a vital role for economy. Railway is also the safest transportation which gives highly enjoyable ride for both of passengers or freights. Conventional ballasted railway structure consists of superstructure and substructure. The superstructure includes rails, rail pads, fastening system and sleepers. The substructure consists of ballast, sub-ballast and formation. Railway sleeper (also called rail tie in North America) is very important component in rail track structure. The main functions of sleeper are [1]:

- 1) Support the rails and maintain the track gauge.
- 2) Transfer and distribute vertical loads from superstructure to substructure.
- 3) Withstand vertical and longitudinal movement of rails.

Railway sleepers can be manufactured by timber, steel, concrete and any other engineered materials. Nowadays, prestressed concrete is the most common type used in sleepers around the world, which it has good structural performance and low cost in maintenance. However, railway sleepers experience millions repeated loading in service life and the progress of cracking depends on cyclic behaviour which caused by the wheel-rail interaction force. Nowadays, the permissible stress (also called ‘allowable stress’) method is utilised for concrete sleeper design which the dynamic load is not considered in design accurately [2, 3]. For example, in Japan

concrete sleepers cracks happen frequently have been found in high quality track under severe loading environments [4]. Therefore, the fatigue limit state should be considered in design process. Amount of experiments about dynamic influence on prestressed concrete sleepers has been conducted in University of Wollongong, the crack damage due to fatigue were investigated [5-8]. This research aims at providing a principle understanding of cyclic behaviour of railway concrete sleepers. This study also presents prediction method of cyclic behaviour on railway concrete sleepers. The outcome of this research will provide appropriate design principle for the concrete sleepers and it will help improve track maintenance and inspection system.

2 Fatigue life and predict method

2.1 Structural performance

Fatigue is a time-dependent behaviour where the damage due to repeat load will be accumulated. The fatigue damage in railway sleeper generated from wheel-rail interaction and it is determined by wheel-rail stress. The damage is random but the performance of railway concrete sleeper will decrease due to material degradation. The service life of railway concrete is usually more than 50 years. The life cycle performance of railway concrete sleeper is shown in Figure 1. $R(t)$ is the resistance of concrete sleeper and $S(t)$ is the effect of cyclic roads. The performance graph is presented by probability distribution function. It can be considered as probability of sleeper failure when $R(t) < S(t)$ in risk measurement. From the curve, the probability of sleeper failure keeps increasing with time.

2.2 Fatigue life time prediction

The Miner's Rule is usually used in predicting accumulated damage in many design codes [9, 10]. The damage accumulation method will be used to predict fatigue life of railway concrete sleeper in this research.

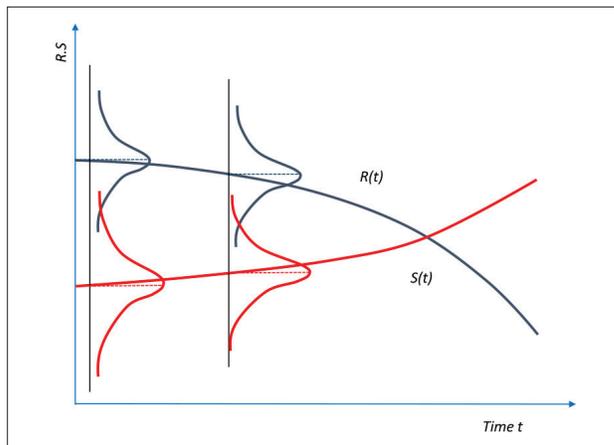


Figure 1 Life cycle performance of concrete sleeper

The cumulative damage index $\sum Di$ in multi-cycles with variable amplitudes can be calculated by:

$$\sum Di = \sum_i \frac{n(\Delta\sigma_i)}{N(\Delta\sigma_i)} \quad (1)$$

Where $n(\Delta\sigma_i)$ is the applied number of cycles for a stress range $\Delta\sigma_i$; $N(\Delta\sigma_i)$ is the resisting number of cycles for a stress range $\Delta\sigma_i$.

This method is used to predict fatigue life under constant amplitude cycle loads and it is based on damage accumulation method. The corresponding S-N curve shown Figure 2 is utilised to determine the maximum applied number of cycles for single stress amplitude.

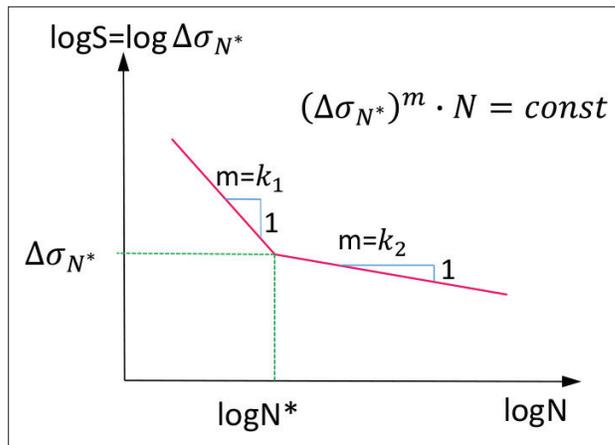


Figure 2 the corresponding S-N curve

Therefore, the failure cycles of the prestressing steel under a constant amplitude cyclic load can be given by:

$$\text{If } \Delta\sigma > \Delta\sigma_{N^*}, \log N_f = \log N^* - k_1 [\log(\Delta\sigma) - \log(\Delta\sigma_{N^*})] \quad (2)$$

$$\text{If } \Delta\sigma \leq \Delta\sigma_{N^*}, \log N_f = \log N^* + k_2 [\log(\Delta\sigma_{N^*}) - \log(\Delta\sigma)] \quad (3)$$

Where:

$\Delta\sigma$ is the stress range in the prestressing steel;

$\Delta\sigma_{N^*}$ 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	Stress exponent			$\Delta\sigma_{N^*}$ [MPa] at N^* cycles
	N^*	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.

2.3 Fatigue load

To determine the fatigue load is the first step to investigate the cyclic behaviour of railway concrete sleepers. The fatigue loads are generated from wheel-rail interaction which influenced by train speed, axle loads, curve radius of track, track quality and environments etc. wheel-rail interaction force is various even in same rail line. Therefore, it's hardly to obtain accurate fatigue load of railway sleeper through whole service life. Some researchers use the wheel dynamic load detector to obtain the wheel-rail interaction force in the railway (at least 1 year in period). The data obtained from site which can be used to generate numerical

modelling and predict the fatigue load. In 2004, the impact force was tested by Queensland University of Technology in two different sites. The dynamic wheel-rail interaction force statistical data is shown in Figure 3.

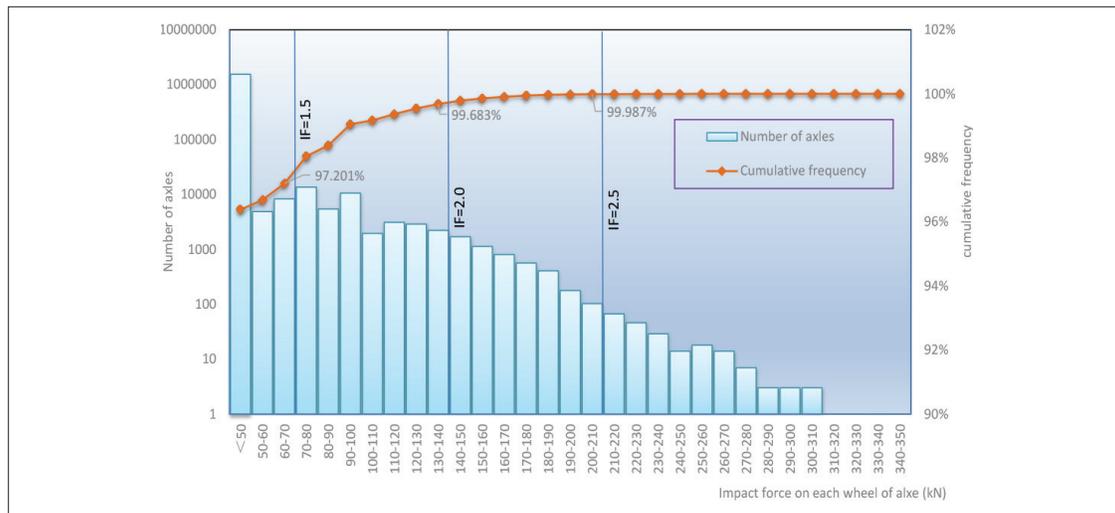


Figure 3 Typical impact force statistical data on track

Most of impact forces are not more than 70 kN and the cumulative frequency of these data are 97.201%. Impact loads more than 210 kN, the frequency of these extremely large impact load is less than 0.0013 %, which could be led by imperfection of geometry of wheel or rail.

2.4 Bending moment

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:

$$R = P \times DF \times IF \quad (4)$$

Where: P is the static load, DF is distribution factor, IF is impact factor. Maximum positive bending moment at railseat:

$$M_{RS+} = \frac{R}{8}(L - g) \quad (5)$$

Maximum negative bending moment at railseat:

$$M_{RS-} = 0.67M_{RS+} \quad (6)$$

Maximum negative bending moment at centre:

$$M_{C-} = \frac{R}{4}(2g - L) \quad (7)$$

Maximum positive bending moment at centre:

$$M_{C+} = 0.05R(L - g) \quad (8)$$

3 Section and material properties

The detail of railway sleeper is shown on Figure 4. The material properties of railway sleeper is shown in Table 2.

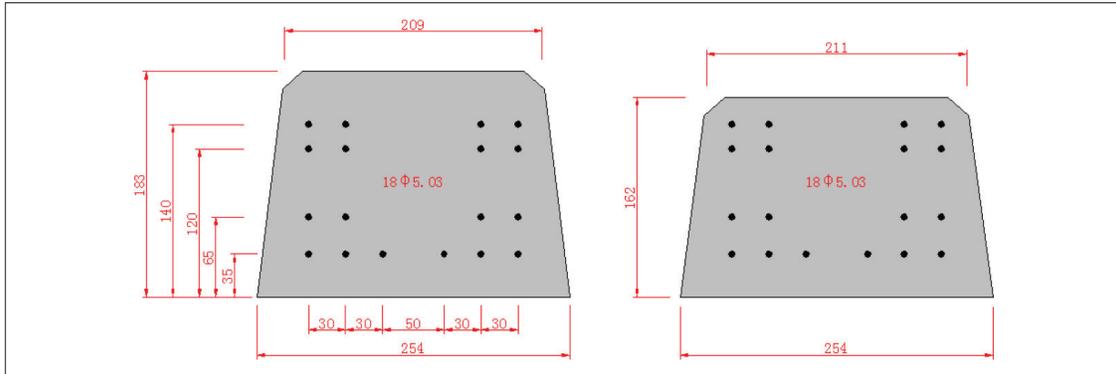


Figure 4 Railseat and centre section of sleeper

Table 2 Material properties of railway sleeper

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

4 Remaining fatigue life calculation

The failure analysis of fatigue of concrete sleeper can be divided into two stages. In first stage, there is no crack appeared in this stage. The relationship between stress and stain is assumed as linear for both of concrete and steel. The critical cracking moment can be calculated:

$$M_{cr} = I_t \cdot \frac{\sigma_{cf}^b + f_{cf}}{y_t} \quad (9)$$

$$\sigma_{cf}^b = \frac{nA_{ps}\sigma_{se}}{A_t} + \frac{nA_{ps}\sigma_{se}e}{I_t} y_t \quad (10)$$

In second stage, the crack happens and the neutral axis of cross-section will change. When the section is fully cracked, the prosperity of the section can be calculated. The distance from the center gravity of the effective transformed area to the top of the compressed area y_{cg} can be calculated by:

$$y_{cg} = \text{root} \left[\left[\begin{array}{l} S_{pcli} - n_e A'_{p4} (h - y_{cg} - d_4) - n_e A'_{p3} (h - y_{cg} - d_3) \\ - n_e A'_{p2} (h - y_{cg} - d_2) - n_e A'_{p1} (h - y_{cg} - d_1) \end{array} \right], y_{cg} \right] \quad (11)$$

Where the S_{pcII} is the first moment about the bottom fibre after cracking, the A'_{pi} is area of the prestress steel in layer i , and d_i is the distance from prestress steel in layer i to the bottom of tension area.

Using transformed area of concrete section A_{cII} , the effective transformed section can be calculated:

$$A_{tII} = A_{cII} + n_e A_p \quad (12)$$

The moment of inertia of the fully cracked section:

$$I_{cr} = I_{crr} + n_e A'_{p4} (h - y_{cg} - d_4)^2 + n_e A'_{p3} (h - y_{cg} - d_3)^2 + n_e A'_{p2} (h - y_{cg} - d_2)^2 + n_e A'_{p1} (h - y_{cg} - d_1)^2 \quad (13)$$

Effective moment of inertia in the life time:

$$I_{ef} = I_{cr} + (I_t - I_{cr}) \left(\frac{M_{cr}}{M_{max}} \right)^3 \quad (14)$$

Where the I_t is the moment of inertia of transformed section before cracking, M_{cr} is the cracking moment, M_{max} is the maximum bending moment at section under cyclic load.

And then, the tension stresses range in the first layer prestress steel at tension area:

$$\Delta\sigma_{pt1} = n_e \frac{M_{max} - M_{min}}{I_{ef}} (h - y_{cg} - d_1) \quad (15)$$

Where M_{min} is the minimum bending moment at the section under cyclical loads.

5 Results

The damage index of each year (D_i) and accumulated damage (ΣD_i) are calculated and shown in Figure 6. The total cyclic impact between wheel and rail through a sleeper is assumed 1609712 times for a year.

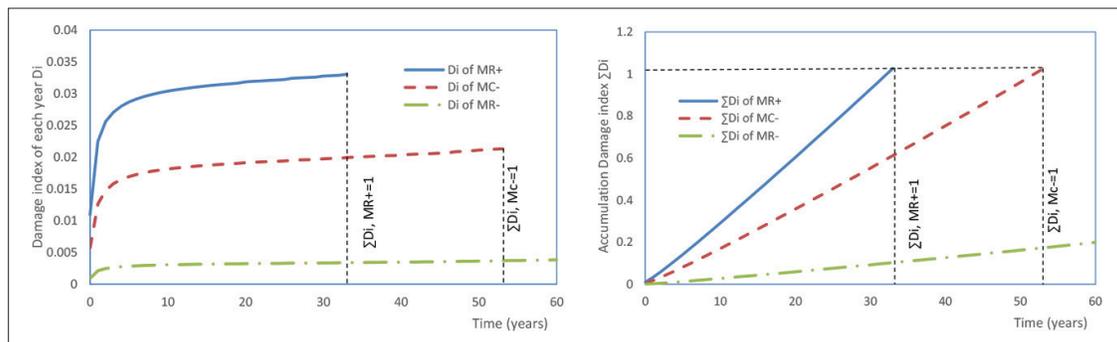


Figure 5 The damage index of each year and accumulated damage with time

From the graph, in early age the damage increases sharply which could be led by loss of prestress. After 2 years in service, the the loss of prestress due to material properties become steady then the damage increases slow. The accumulated damage index shows that the positive bedding moment is about 33 years, which means the fatigue life is 33 years.

6 Conclusion

In this paper, the fatigue life of railway concrete sleepers has been assessed by damage accumulation method. In fatigue life analysis, the fatigue load and material properties are the most important parts to calculate fatigue life of railway sleepers. During the service life, the material properties will be influenced by impact loading and degradation. In long-term, degradation of concrete sleepers become significantly. This research also found more than 99.5% impact loads can't result in positive flexure cracking. The results show that the fatigue failure of railway sleepers at railseat area is determined by the positive bending moment and the fatigue life is around 33 years. At centre area, the fatigue failure is determined by negative bending moment which has 53 years fatigue life.

In different rail lines, the fatigue life can be influence by several factors like material properties, maintenance and manufacture quality etc. This report will improve the concrete sleeper design, maintenance and inspection system.

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