REMAINING SERVICE LIFE OF RAILWAY PRESTRESSED CONCRETE SLEEPERS

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Abstract

Prestressed concrete sleepers (or railroad ties) are structural members that distribute the wheel loads from the rails to the track support system. Over a period of time, the concrete sleepers age and deteriorate in addition to fully experiencing various types of static and dynamic loading conditions, which are attributable to train operations. Recent studies have established two main limit states for the design consideration of concrete sleepers: ultimate limit states under extreme impact and fatigue limit states under repeated probabilistic impact loads (low and high cycles). It was noted that the prestress level has a significant role in maintaining the high endurance of the sleepers under low to moderate repeated impact loads. Based on extensive field investigations and experimental tests, this paper presents a variation of static and dynamic load condition of railway concrete sleepers in revenue services. It presents the limit states involving in testing and evaluating for the remaining service life of railway prestressed concrete sleepers. Experimental results are also highlighted to demonstrate the deterioration and toughness of the sleepers after services.

Keywords: Railway concrete sleepers, track environment, railway maintenance, structural condition, service life, remaining life, health monitoring.

1. Introduction

Railway prestressed concrete sleepers have been utilised in railway industry for over 50 years. The railway sleepers (called ‘railroad ties’) are a main part of railway track structures. A major role is to distribute loads from the rail foot to the underlying ballast bed. Based on the
Current design approach, the design life span of the concrete sleepers is considered around 50 years [1-3].

Figure 1 shows the typical ballasted railway tracks and its components. There are two main groups of track components: substructure and superstructure. The substructure includes subballast, subgrade, and ground formation, while the superstructure consists of rails, rail pads, fastening systems, railway sleepers (concrete or timber) and ballast (crushed aggregate). Railway track structures often experience the aggressive dynamic loading conditions due to wheel/rail interactions associated with the irregularities in either a wheel or a rail [4].

The magnitude of the dynamic impact loads per railseat is varying from 200 kN to sometimes more than 750 kN, whilst the design static wheel load per railseat for a 40-50 tonne axle load could be only as much as 110 kN [5-6].

All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. The typical dynamic load imposed by running wagons can be treated as a quasi-static load when no irregularity exists. However, when the irregularity appears, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles passing at any generic operational speed [7-8]. 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 applied right after when the static wheel load is removed during the loss of contact [8].

The typical magnitude of impact loads depends on the causes and the traveling speed of train. The durations of such loads are quite similar, varying between 1 and 10 msec. However, the representative values of the first peak ($P_1$) of the forces caused by dipped joints should be about 400 kN magnitude with 1 to 5 ms time duration. For the second peak ($P_2$), the average values are about 80 kN magnitude and 5 to 12 msec time duration. The effect of impact forces depends on the duration. It was found that the longer the duration, the greater the effect. Please contact sakdirat@hotmail.com for full paper.
Theref

therefore, it should be taken into account that the typi

cal duration of impact wheel forces varies widely between 1 and 12 msec

[4, 9, 10]. A recent study showed that it is highly

likely that railway sleepers could be

frequently subjected to severe impact loads

[11]. In general, the dynamic load characteristics considered

in design and analysis include the magnitudes of impact loading and the variety of pulse

durations. In general, although the loading and strain rate

effects may increase the strength of

materials, the high loading magnitude could devastate the structural members. In structural

design and analysis, the public safety must not be compromised so the design loads must be

appropriate and associated with the

long return periods, which would optimally provide the

low probability of occurrence on structures during their design life. For further explanation, a

design load that is associated with 50 year return period has the likelihood of occurrence that

the design load might happen only once in 50 years regardless of the structural life span

Wheel load is an important factor in design and analysis of railway track and its components.
The design load (F*) for the limit states design concept takes into account both the static (F_s)

and dynamic (F_i) wheel loads. There are three main steps in designing the concrete sleepers.

First, the design actions or loads are to be determined based on the importance level of the

track (e.g. F* = 1.2 F_s + 1.5 F_i). Then, the design

shear and moment envelopes can be

achieved by converting the design load to sleeper responses using advanced railtrack dynamic

analysis or the design formulation

[12]. Last, the strength and serviceability of the prestressed

cement sleepers can be optim

ized in accordance with AS3600 Concrete structures

(Standards Australia, 20

12).

An initially

proposed limit states design methodology and procedure can be

found in details in Remennikov

et al.

[13].

Figure 2

Example of statistical data of actual track loading

[15]. Leong

[15] showed the statistical data of wheel loading obtained from railway networks in

Queensland, Australia. Using probabilistic analysis, the possibility of occurrence related to

the magnitude

of impact loading on railway sleepers can be predicted. Figure 2 shows a

Impact force, kN

Number of axles

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Statistical data of actual wheel loading applied on top of the rail obtained from a railway network in North Queensland [15-16].

From Figure 2, the relationships between the impact forces $I$ (kN) and the return periods $R$ (year) can be written as follows:

$$I = 1.40 \times 10^{-10} R + 1.0$$

These formulae can be used to determine the impact force factor ($k_r$), which is based on the return periods and consequences of changing operations, such as speeds or wheel/rail defects [15].

Limit states concept is a more logical entity for use as the design and analysis approach for prestressed concrete sleepers, in a similar manner of Australian Standard AS3600 [3]. It considers both strength and serviceability.

Over time, the concrete sleepers experience diverse traffic loads from operational activities, and may have damage and cracks, also resulting in an additional time-dependent loss in prestress level [17-19]. However, previous studies have not thoroughly investigated the deterioration and residual strength of concrete sleepers [20]. This study thus investigates the remaining life of railway prestressed concrete sleepers after a period of service life through a variety of structural testing programs.

It experimentally investigates the remaining service life of railway prestressed concrete sleepers considering limit states design concept. The ageing railway concrete sleepers from various operational environments have been investigated. This paper presents the nominal reserve capacity of the old prestressed concrete sleepers from previous experimental investigations aimed at proposing a rational method for evaluating the remaining life of concrete sleepers.

2. Limit states of railway concrete sleepers

According to Leong [15], Australian railway organisations would condemn a sleeper when its ability to hold top of line or gauge is lost. It is also found that this practice is actually adopted in most of railway industries worldwide. Those two failure conditions can be reached by the following actions:

- Abrasion at the bottom of the sleeper causing loss of top;
- Abrasion at the rail seat location causing a loss of top;
- Severe cracks at the rail seat causing the ‘anchor’ of the fastening system to move and spread the gauge;
- Severe cracks at the midspan of the sleeper causing the sleeper to ‘flex’ and spread the gauge;
- Severe degradation of the concrete sleeper due to alkali aggregate reaction or some similar degradation of the concrete material.

Since abrasion and alkali aggregate reaction are not structural actions causing failure conditions, only severe cracking leading to sleeper’s inability to hold top of line and gauge will be considered as the failure criteria defining a limit state related to the operations of a railway system. A challenge in the development of a limit states design concept for prestressed concrete sleepers is the acceptance levels of the structural performances under...

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design load conditions. Infinite fatigue life of sleepers cannot be retained after allowing cracks under impact loads. Therefore, the general principles for reliability for structures, and indicates that limit states can be divided into the following two categories:

1. **ultimate limit states**, which correspond to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain or deformation;

2. **serviceability limit state**, which concerns the normal use and service life (fatigue and deformation).

Leong [15] suggested three limiting conditions would be relevant to the design of railway concrete sleeper:

**Ultimate Limit State**

A single once-off event such as a severe wheel flat that generates an impulsive load capable of failing a single concrete sleeper. Failure under such a severe event would fit within failure definitions causing severe cracking at the rail seat or at the mid-span. The single once-off event will be based on the probabilistic analysis of train load spectrums recorded over several years or for a suitable period (generally at least a year as to obtain the good representative of track forces over its lifetime under various train/track conditions). The load magnitude of the ultimate event for ultimate limit state design of sleepers depends on the significance or importance level of the railway track. It should be noted that in some cases when the load frequency distributions can only be obtained from the long-term track force measurements, the ultimate design loads are usually taken to be the 95 percent fractiles, and hence have a 5 percent probability of being exceeded [19].

**Damageability (or Fatigue) Limit State**

A time-dependent limit state where a single concrete sleeper accumulates damage progressively over a period of years to a point where it is considered to have reached failure. Such failure could come about from excessive accumulated abrasion or from cracking having grown progressively more severe under repeated loading impact forces over its lifetime. In sleeper design perspective, the lifetime can be specified by the design service life of the sleepers (e.g. 30, 50, or 100 years) or from the expected train/track tonnage (or how many load cycles expected for the track infrastructure, e.g. 10, 50, or 100 million cycles). The loading ranges for the fatigue life prediction vary on the load frequency distribution as shown in Figure 2 (the load frequency data recorded for a year). Using the data in Figure 2 for fatigue life prediction of sleepers is applicable whereas the actual life must be longer than design life. Alternatively, if the sleeper is to be designed for 50 year service life under 28ton axle load, the loading range for the fatigue life consideration can be obtained from Equation 1 plus the wheel load of 140kN, which is up to 540 kN [15]. Using a statistical analysis, the number of axles or cycles of each loading range can be achieved for the cumulative fatigue damage. Based on previous example, it shows likelihood that there is only 1 time that the sleeper experiences the dynamic load of 540 kN over the sleeper design life of 50 years. Once the numbers of cycle in each loading range (e.g. 105-115 kN, 535-545 kN range) are obtained, the cumulative fatigue damage can be calculated using the endurance limits of materials or generic fatigue design codes (e.g. European Code, CEB Model code, etc.). Such damage should not result in any failure condition described earlier.

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Serviceability Limit State

This limit state defines a condition where sleeper failure is beginning to impose some restrictions or tolerances on the operational capacity of the track, for example, prestressing losses, sleeper deformations (shortening and camber), track stiffness, etc. The failure of a single sleeper (in track system) is rarely if ever a cause of a speed restriction or a line closure. However, when there is failure of a cluster of sleepers, an operational restriction is usually applied until the problem is rectified. Recently, this serviceability limit state has extensively applied to the methodology for retrofit and replacement of sleepers made of different material properties in the existing aged track systems. For example, the deteriorated timber sleeper tracks have been replaced by new concrete/steel sleepers through a suitable spacing arrangement as to provide a similar track modulus or stiffness to the existing one. This method is sometimes called 'spot replacement' or 'intersperse method'.

It is important to note that a general recommendation (e.g. by Australian Office of Transport Safety Investigations) is to perform concrete sleeper installation only 'in-face' (i.e. the practice of installing the same sleeper type continuously rather than interspersed with other sleepers in between, also referred to as 'on-face' [21-22].

By nature, under operational services, the bottom face of prestressed concrete sleepers abrades by relative movement with ballast. The on-face method is likely to cause local differential stiffness and localised differential vertical smoothness ('top' surface geometry), resulting in a more aggressive dynamic wheel/rail interaction and causing higher level of sleeper's soffit abrasion.

3. Deterioration of concrete sleepers

This relative movement is occurred by dynamic action during train passage and impact force due to the wheel flat and rail irregularities. Abrasion of prestressed concrete sleeper can cause reduction of the loading capacity and the head of the PC steel. In this section, investigation into the abrasion of the bottom face (or called soffit) of aged prestressed concrete sleepers have been carried out in order to determine a relationship between amount of the abrasion and gross passing tonnage and aging of the prestressed concrete sleeper. In addition, effect of abrasion to loading capacity of prestressed concrete sleepers has been investigated by numerical analysis [22-23].

In this collaborative research project, more than 200 sleepers which is called "Type 3 sleeper" specified in Japanese industrial standard (JIS) have been monitored and tested under static and fatigue loading conditions in accordance with JIS standard benchmarking arrangements [24-25]. The amount of abrasion is investigated in two ways, detailed method and simple method. For the detail method, the abrasion of sleeper is measured at 20mm interval in longitudinal and rail directions. For the simple method, the abrasion is measured at 100mm intervals in only longitudinal direction.

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Figure 3 shows the results of the detailed and simple methods. For sleeper A, the amount of abrasion is approximately 30mm at the rail position and 10mm at the centre of the sleeper. For sleeper B, the amount of abrasion is over 30mm in some part of the sleeper. From these figures, simple method can generally trace the detailed method. Figure 4a shows the relationships between the maximum amount of abrasion and gross passing tonnage. Amount of abrasions were measured by the simple method. The power approximations curve that guides the envelope of maximum amount of abrasion in each aging and gross passing tonnage is also shown in the figure. From Figure 4, the maximum amount of abrasion is approximately 20mm when gross passing tonnage is 1 billion tons. Furthermore, amount of abrasion exceeds 30mm when gross passing tonnage is 1.2 billion tons. For this sleeper, PC steel bar was exposed and corrosion and fracture were observed. Figure 4b shows the relationships between the maximum amount of abrasion and aging of sleepers. From the figure, maximum amount of abrasions increased with aging and it exceeds 20mm when aging is approximately 30 years.

In comparison, a heavy haul track section (100m track length with sleeper spacing of 0.6m) had been inspected and about 20 sleepers were extracted for further load tests in accordance with AS1085.14 [11-12]. It is found that similar load effects can be observed in Australian heavy haul environment as shown in Figure 5. However, lesser soffit abrasion can be observed in general.
Figure 5: Abrasion of 30 years old heavy haul sleepers

4. Experimental load rating of concrete sleepers

Figure 6 shows the effect of the amount of abrasion to the loading capacity at rail position (positive bending) and the centre (negative bending) of the high speed rail sleeper. As showed in the figure, effect of abrasion to the loading capacity at the rail position was small. On the other hand, at the centre of the sleeper, loading capacity reduced with the increase of the amount of abrasion. In particular, loading capacity reduced approximately 10% with 10mm of abrasion at the rail position and loading capacity reduced 48% at the centre of the sleeper. At the rail position, even if the bottom surface of the sleeper was abraded, the distance from the compression edge of the concrete to the PC steel bar does not change. However, at the centre of the concrete, the distance from the compression edge of the concrete to the PC steel bar changes with the abrasion of the bottom face.

(a) Rail position (positive bending)
(b) Center of the sleeper (negative bending)

Figure 6: Effect of the amount of abrasion to the loading capacity of high speed rail sleepers

In comparison, aged sleepers have been tested under static loading to determine the positive and negative, cracking and ultimate moment capacities at the sleeper centre. The overall experimental program at the University of Wollongong indicated that heavy haul sleepers also suffer from severe abrasion of the concrete cover at the bottom surface and the concrete was damaged adjacent to the rail seat. The load-displacement relationships for both sleepers were similar up to the maximum load capacity. Figure 7 shows the load-displacement relationships.
Conclusions
This paper presents the field investigation of railway sleeper deterioration and the experimental load rating studies arose from the planned expansion of the traffics from both high speed and heavy haul rail operations. There was concern whether the railway concrete sleepers would be capable of sustaining existing operations after its design life, and whether they could be carrying the increased traffic loads. The visual inspection of the concrete sleepers revealed that there were potential problems with durability of the aged sleepers. Concrete spalling of sleepers due to tamping damage, poor construction, and loss of concrete section due to abrasions were among the problems that could cause the rapid deterioration of strength and serviceability. The results from field observations and static tests of Japanese and Australian concrete sleepers reveal that minor structural cracking was detected in the sleepers under the most adverse loading conditions for all three track supporting conditions. This implies that the in-track sleepers are likely to be capable of resisting extreme loads generated by wheel and rail abnormalities without catastrophic failure under current traffic and even with increased traffic. The confirmation derived from numerical evaluations of fatigue life based on fracture mechanics and cumulative energy absorption will be presented elsewhere in the near future.

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References