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Limit states design of railway concrete sleepers

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Abstract. The recently updated information has raised a concern in not only the existing cost-ineffective design method but also the unrealistic analysis mode of railroad prestressed concrete sleepers. Because of the deficient knowledge in the past, railway civil engineers have been mostly aware of the over conservative design methods for structural components in any railway track, which rely on allowable stresses and material strength reductions. Based on a number of proven experiments and field data, it is believed that the concrete sleepers complied with the allowable stress concept possess the unduly untapped fracture toughness. A collaborative research run by the Australian Cooperative Research Centre for Railway Engineering and Technologies (RailCRC) was initiated to ascertain the reserved capacity of Australian railway prestressed concrete sleepers designed using the existing design code. The findings have led to the development of a new limit states design concept. This article highlights the conventional and the new limit states design philosophies and their implication to both railway and public community.

Keywords: Railway concrete tie or sleeper; Structural safety; Limit states; Permissible stress

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1. GENERAL

Railway is commonly believed as the world's safest transportation system for either passengers or merchandise across distant areas. It has been estimated that investment in railway infrastructure by 2013 possesses one third of total investment in rail market of over 200 billion US dollars. Accordingly, research and development becomes a strong momentum to railroad asset management. Track structures guide and facilitate the safe, cost-effective, and comfort ride of trains. Figure 1 illustrates the typical ballasted railway track. Remennikov and Kaewunruen[1] reviewed the typical load conditions on railway track structures as well as common design procedures for ballasted railway tracks. It has been found that the design method for railway sleepers in most countries, e.g. Australia, Asia, New Zealand, and the US, is based on permissible stress design concept.

Figure 1 Typical ballasted railway tracks

2. DESIGN DEFICIENCY

Codes of practice including Australian Standard[2] and AREMA[3] prescribe a primitive design methodology for PC sleepers. The design process relies on the permissible or allowable stress of materials. A load factor is used to increase the static axle load 'as if' to incorporate dynamic effects. The design load is then termed '*combined quasi-static and dynamic load*', which has a specified lower limit as much as 2.5 times static wheel load[2,3]. In reality, impact forces due to wheel/rail interactions may subject the sleepers to dynamic loads that are much larger than the code-specified design forces. A recent finding shows that there is a high chance that the impact forces could be up to four to six times of wheel load[4]. The current design method prohibits any structural cracks in a concrete sleeper. As a result, any cracked concrete sleepers due to irregular forces must be removed without any retentive classification, resulting in the excessive maintenance. As a result, there is a need to develop a new design concept for concrete sleepers in which it permits controllable cracks to occur so that the true capacity of the sleepers could be exploited. To develop the limit states design approach, studies of the response of concrete sleepers to high-magnitude short-duration loading were carried out at: UBC Canada[5]; RTRI Japan[6]; CHARMEC Sweden[7]; and recently UOW Australia[8]. In general, the current design methods are very conservative. However, there is often a special case that a rail organization could take risk of high maintenance cost by introducing its own fit-for-purpose dynamic impact factor but still exercising the existing design concept. It is important to note that this practice is not commonly standardized and has not been adequately calibrated to ensure the public safety. Although there has been an attempt to develop a low-profile concrete sleeper for a specific use as timber-replacement sleepers, the in-field performance of such product is very poor and its design method could be either unsafe or doubtful[9-14].

3. LIMIT STATES OF CONCRETE SLEEPERS

Most railway organisations would condemn a sleeper when its ability to hold top of line or gauge is lost. 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. Leong[10] noted that for railway concrete sleepers the limit state categories could be different from the traditional structural approach and the designer should take into consideration the track’s ability to continue operating in an event of exceedance of a limit state (fail-safe design), as follows:

Ultimate Limit State

The ultimate limit state is caused by 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 midspan. 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 operational conditions). The load magnitude for ultimate limit state design of sleepers depends on the significance or importance level of the railway track and statistical operational service data[8].

Damageability (or Fatigue) Limit State

This is 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 impact forces over its lifetime. In sleeper design perspective, the lifetime can be specified by the design service life of the sleepers or from the expected train/track tonnage. The loading ranges for the fatigue life prediction vary on the load frequency distribution as shown in Figure 2. Using the data in Figure 2 for fatigue life prediction of sleepers is applicable whereas the actual life must be longer than the design life. From the statistical loading range, the cumulative fatigue damage should not result in any failure condition described earlier.

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.

Figure 2 Frequency of occurrence of impact forces

Engineering Design

In general, the key detrimental factor for the prestressed concrete sleepers relies on the ultimate limit state. This is because the decompression moment due to prestressing of the sleepers minimises the fatigue damage and the dimension and topology of the sleepers provide the compliments to serviceability limit states. Wheel load is the main factor in design and analysis of railway track and its components. The proposed methodology for the calculation of the design wheel load and the design approach of the limit states concept for strength and serviceability are in concurrence with generic design standards for concrete structures. There are three main steps in designing the concrete sleepers on the basis of the new limit states design concept: first, the determination of design loads (F^*)[10]; second, the dynamic analysis of design moment or actions ($M^* = 0.8F^*$ or using the Dynamic Analysis of Rail Track Package, D-TRACK)[8]; and third, the structural design and optimisation of concrete sleepers ($M^* \leq \phi M_u$)[8].

The design wheel load (F^*) for the limit states design concept takes into account both the static (F_s) and dynamic (F_i) wheel loads[10], as presented below. It should be noted that the factors 1.2 and 1.5 are derived from the statistical data and probability analysis of loading actions in general. It is not the permission to overload any type of structures[11-12].

$$F^* = 1.2\, k_{tf} F_s + 1.5\, F_i \quad (1)$$

$$F_i = k_r\, k_t\, k_{vf}\, P_{axle} \quad (2)$$

where

F^* = ultimate limit state wheel/rail design force applied to rail head, kN

F_i = design wheel/rail impact force, kN

F_s = design static wheel load, kN

k_t = factor allowing for type of track (track importance factor)

k_{tf} = factor allowing for quality of maintenance on rail track

k_r = factor associated with the basic return period of loading, R_b

k_{vf} = factor allowing for quality of maintenance on vehicle wheels

P_{axle} = nominal axle load, kN

R_b = basic return period of load occurrence in years

Table 1 shows the dynamic force factors related to the reliability confidence. It should be noted that the impact load factor k_r, which is the factor associated with the basic return period of loading (R_b), can be obtained from the statistical data of loading. Leong[8] carried out the probabilistic analysis of the impact loads (excluding static axle force) measured by the wheel impact load detector (WILD). Based on the statistical traffic data, the impact load factor k_r can be written as follows:

$$k_r = 11.6 + 2\log_{10}\left[\frac{1}{5}\frac{R_b V_t}{P_{axle}}\right] \tag{3}$$

where V_t is the estimated traffic volume in million gross tonnes (MGT) per annum; and P_{axle} is in tonnes for Equation (3)[8].

Once the dynamic load and responses of the sleepers can be obtained, the reliability analysis of the sleeper capacity designed by limit states design can be performed. The reliability or safety index derived from the analysis will be correlated with the target safety index[12]. The reliability-based design of the sleepers can thus be achieved as illustrated by Figure 3[13]. It is important to note that the factors for both strength and load action should be re-evaluated in order to attain the target safety indices, which are specifically suitable for a particular track operation[14].

Figure 3 Reliability-based design schematic diagram for prestressed concrete sleepers[13]

4. SUMMARY

The current design of railroad prestressed concrete sleepers, stated in many countries, including the US and Australia, is based on the permissible stress concept. Such design process is based on the quasi-static wheel loads and the static response of concrete sleepers. The research finding shows that the current concept of design and analysis is very conservative as well as unrealistic. This negative gearing deters the greener and leaner values of such permanent way component. This research project has investigated all important facets such as the spectrum and amplitudes of dynamic forces on railway tracks, evaluation of the reserve capacity of typical concrete sleepers designed to the current design concept, and the development of a new limit states design concept. It is noteworthy that using the new limit state design concept, one could save material cost of railroad sleepers up to 15 %[8,14]. The new concept permits a sleeper design with a reduced depth and weight that is beneficial to any low-clearance corridor. In addition to cost saving, the use of the new design method has a positive, potential gearing to environment and sustainability in a railway corridor over its life cycle.

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Table 1 Importance factors

Track Importance Category	Track Importance factor (k_t)	Basic Return Period of Loading (R_b)	Track Maintenance Group	Track Maintenance factor (k_{tf})	Wheel Maintenance Group	Wheel Maintenance factor (k_{vf})
Category I	1.0	100	Excellent	1.0	Excellent	1.0
Category II	1.1	500	Very Good	1.2	Very Good	1.2
Category III	> 1.2*	2,000	Good	> 1.2*	Good	> 1.2*

*required for reliability based correlation as illustrated in Figure 3[13]

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Photo 2 Alex M Remennikov**,** BE Hons (Civil), PhD, MIEAust, CPEng, Associate Professor of Structural Engineering at University of Wollongong Wollongong, NSW Australia

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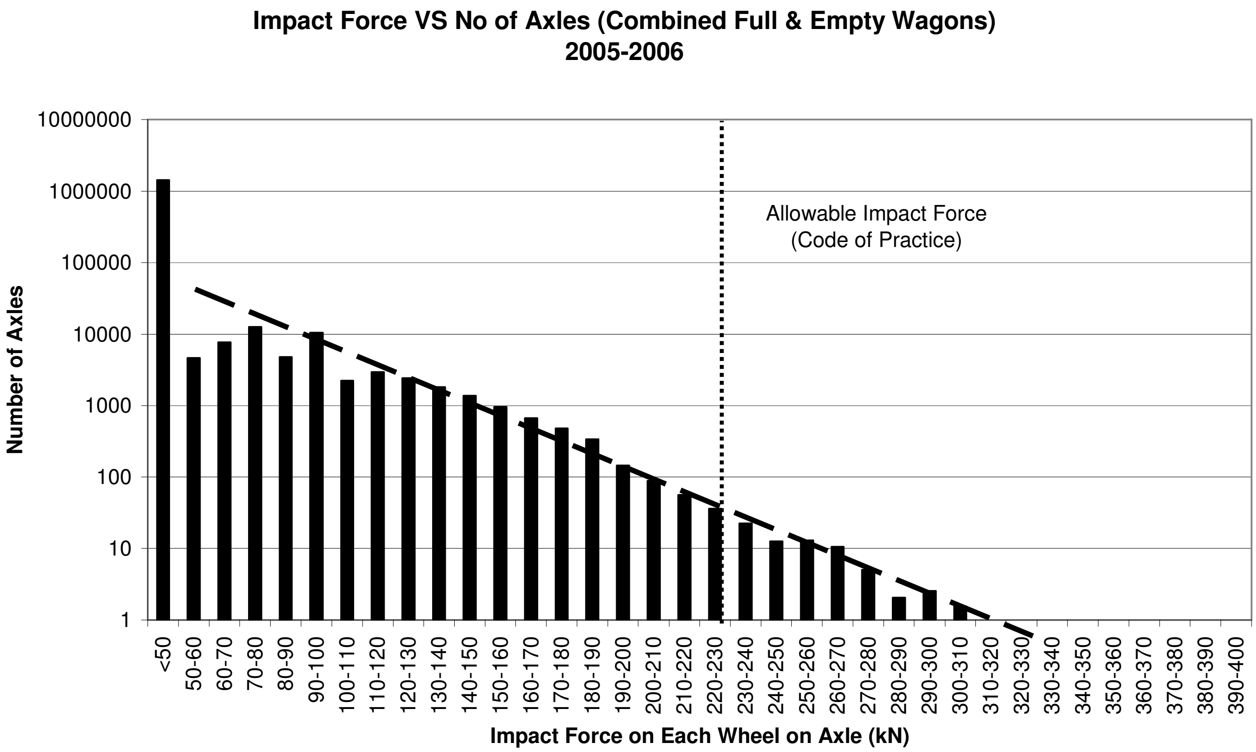

Figure 2 Frequency of occurrence of impact forces

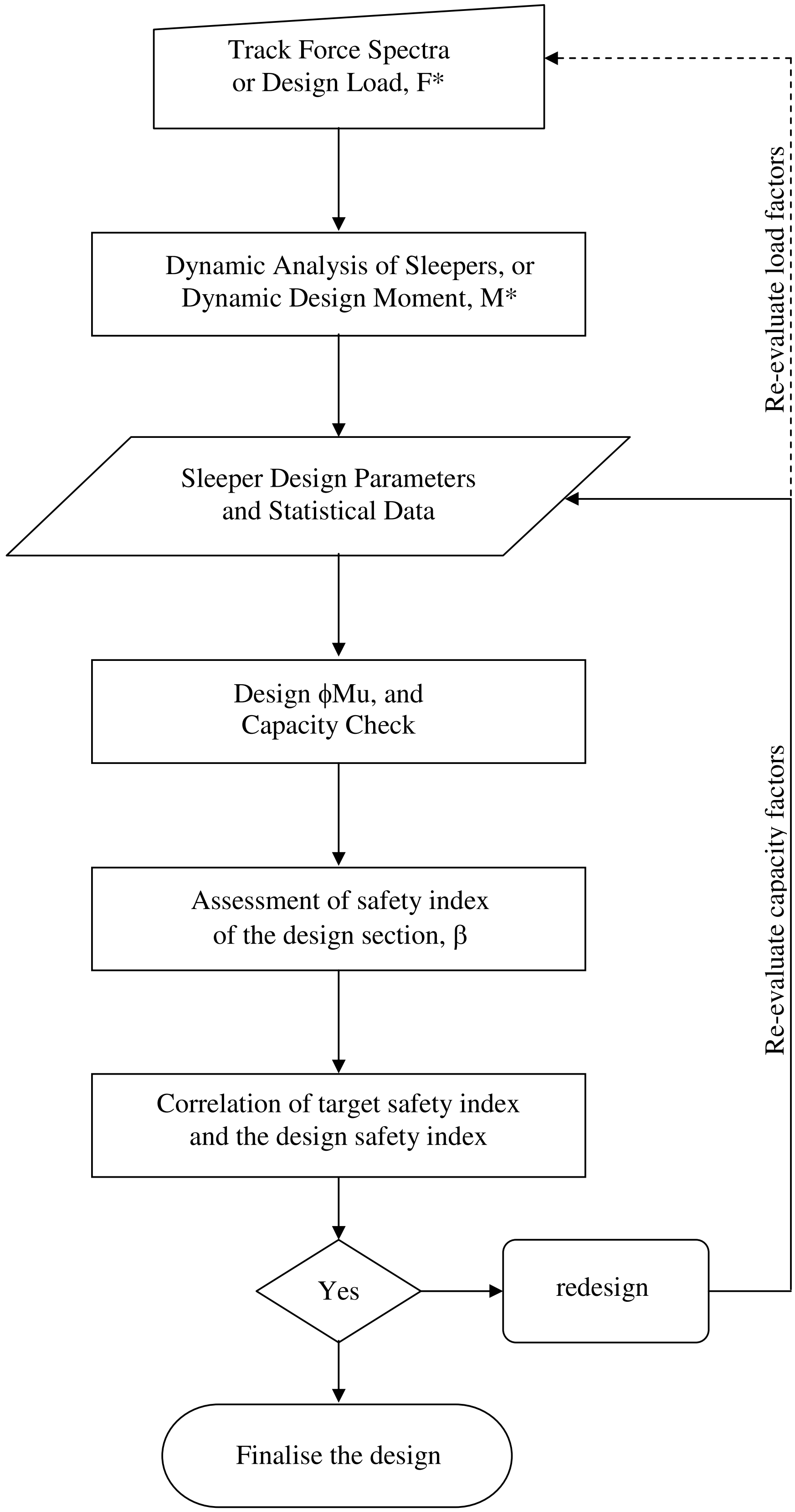

Figure 3 Reliability-based design schematic diagram for prestressed concrete sleepers