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การพัฒนาแนวทางการออกแบบหมอนรองรถไฟคอนกรีตอัดแรง โดยอ้างอิงความน่าเชื่อถือทางวิศวกรรม

DEVELOPMENT OF RELIABILITY-BASED DESIGN FOR RAILWAY PRESTRESSED CONCRETE SLEEPERS

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บทคัดย่อ : การเพิ่มน้ำหนักเพลาบรรทุกของรถไฟเป็นแนวทางหนึ่งในการบริหารระบบโลจิสติกส์ในการขนส่งวัสดุให้มีประสิทธิภาพ ซึ่งจะเพิ่มขีดความสามารถในการให้บริการทั้งทางด้านระบบขนส่งมวลชน ตลอดจนระบบขนส่งสินค้า วัสดุ และแร่ธาตุทางการค้า ในปัจจุบัน ระบบรางสมัยใหม่ได้มีการใช้หมอนรองรถไฟคอนกรีตสำหรับการขนส่ง ที่มีน้ำหนักบรรทุกสูง หมอนรองรถไฟเป็นชิ้นส่วนทางโครงสร้างที่สำคัญในการถ่ายเทน้ำหนักบรรทุก ของระบบราง อย่างไรก็ตาม รอยแตกของหมอนรองรถไฟคอนกรีตอัดแรงสามารถพบได้เสมอในระหว่าง การตรวจสอบโครงสร้างระบบรางเพื่อการบำรุงรักษา รอยแตกของคอนกรีตนี้มักเกิดขึ้นอันเป็นผลมาจากแรงกระแทกทางพลศาสตร์ ที่มีศักยภาพในการทำลายล้างสูง ซึ่งเป็นผลกระทบที่เกิดขึ้นจากความไม่สมบูรณ์ของระบบรางหรือความผิดปกติ ของระบบล้อและเพลารถไฟ ในปัจจุบันได้มีข้อโต้แย้งว่า หลักการออกแบบในปัจจุบันของหมอนรองรถไฟคอนกรีต อัดแรงด้วยวิธีหน่วยแรงใช้งานนั้น มีความไม่เหมาะสมเพียงพอ ทั้งทางด้านความปลอดภัยทางวิศวกรรมและ ทางด้านหลักเศรษฐศาสตร์ วิธีการดั้งเดิมได้ประยุกต์ใช้ความเค้นของวัสดุทางพลศาสตร์ในการออกแบบโครงสร้าง ระบบรางโดยปราศจากการพิจารณาถึงพฤติกรรมที่แท้จริงของวัสดุ ด้วยเหตุนี้ การออกแบบในปัจจุบันจึงมีการเผื่อค่าความเสี่ยงสูงและทำให้ระบบรางมีราคาที่สูงมากเกินความจำเป็นงานวิจัยนี้ได้ชี้ให้เห็นถึงข้อบกพร่องของทฤษฎีการออกแบบดังกล่าวในปัจจุบันด้วยการศึกษาวิเคราะห์พฤติกรรมทางพลศาสตร์ของหมอนรองรถไฟคอนกรีตอัดแรงทั้งด้วยการทดสอบในสภาวะจริงและวิเคราะห์เชิงตัวเลข ซึ่งผลของการศึกษาครั้งนี้ได้นำไปสู่การพัฒนานวัตกรรมในออกแบบทางวิศวกรรมโครงสร้างของระบบรางรถไฟเพื่อให้มีความปลอดภัยและมีประสิทธิภาพมากยิ่งขึ้นโดยแนวทางดังกล่าวได้พัฒนาจากทฤษฎีสภาวะขีดสุดและได้ผ่านการพิจารณาถึงความปลอดภัยทางวิศวกรรมจุดเด่นของนวัตกรรมการออกแบบนี้ได้ถูกทำการวิเคราะห์และพิสูจน์แล้วว่ามีความปลอดภัยสูงสามารถประหยัดค่าวัสดุก่อสร้างและที่สำคัญสามารถลดระดับการใช้ซีเมนต์ซึ่งมีกระบวนการผลิตที่เป็นตัวการสำคัญในการปลดปล่อยก๊าซคาร์บอนสู่ชั้นบรรยากาศที่จะนำไปสู่สภาวะโลกร้อน

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คำสำคัญ : การออกแบบโดยพิจารณาความน่าเชื่อถือทางวิศวกรรม, หมอนรองรถไฟ, คอนกรีตอัดแรง, ระบบรางแบบบาลลาส, ระบบโครงสร้างพื้นฐานของราง

Abstract : Faster and heavier train services are a driven improvement aspect for leaner and more profitable transport logistics of either passengers or freights. Ballasted rail track has been adopted for modern railways because of its many superior advantages in design, construction, short- and long-term maintenance, sustainability, financial capital and life cycle cost. An important element of the railway track system, which distributes the wheel load to the formation and holds the rail gauge, is the railway sleeper. Field data has raised concerns about design techniques for prestressed concrete (PC) sleepers. Most current design codes for these rely on allowable stresses and material strength reductions. In contrast, premature cracking of PC sleepers has been found in railway tracks. The major cause of cracking is the infrequent but high-magnitude wheel loads produced by the small percentage of irregular wheels or rail-head surface defects; both these are crudely accounted for in the allowable stress design method by an over-conservative single load factor. The current design philosophy, outlined in either Australian or American Standard, is based on the assessment of permissible stresses resulting from quasi-static wheel loads and essentially the static response of PC sleepers. To change the conventional methodology to a more rational and economical design method that involves a more realistic dynamic response of PC sleepers and performance-based design concept, comprehensive studies of the loading conditions, the dynamic response, and the dynamic resistance of PC sleepers have been conducted. This collaborative research has addressed such important issues as the dynamic load spectra applied to the railway track, evaluation of the reserve capacity of typical PC sleepers designed to Australian AS 1085.14, and the development of a new limit states design concept. This paper highlights the development of reliability-based design philosophy and rationales associated with structural limit states; also it presents a limit states design guideline. This approach has been proven to be sustainable by not only saving material costs, but also reducing the waste and the usage of cement, of which the production emits carbon towards global warming.

Keywords : Reliability based design, Prestressed concrete, Railway sleepers, Ballasted track, Rail infrastructure.

1. Introduction

Railway is commonly believed as the world's safest transportation system for either passengers or merchandise across distant areas. Track structures guide and facilitate the safe, cost-effective, and smooth ride of trains. Figure 1 illustrates the main components constituting typical ballasted railway track [1]. Its components can be subdivided into the two main groups: superstructure and substructure. The visible components of the track such as the rails, rail pads, concrete sleepers, and fastening systems form a group that is referred to as the superstructure. The substructure is associated with a geotechnical system consisting of ballast, sub-ballast and subgrade (formation) [1].

Both superstructure and substructure are mutually vital in ensuring the safety and comfort of passengers and a satisfactory quality of ride for passenger and freight trains. Note that in Australia, UK, and Europe, the common term for the structural element that distributes axle loads from rails to the substructure is 'railway sleeper', while 'railroad tie' is the usual term used in the US and Canada. The main duties of sleepers are to: (1) transfer and distribute loads from the rail foot to underlying ballast bed; (2) hold the rails at the proper gauge through the rail fastening system; (3) maintain rail inclination; and (4) restrain longitudinal, lateral and vertical movements of the rails. Remennikov and Kaewunruen [2] 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 is based on permissible fibre stresses [3]. The permissible stress design approach makes use of an empirical function taking into account the static wheel load (P_0) with a dynamic impact factor (ϕ) to account for dynamic vehicle/track interactions:

$$P_D = \phi P_0 \qquad (1)$$

where P_D is the design wheel load, P_0 is the quasi-static wheel load, and ϕ is the dynamic impact factor (>1.0).

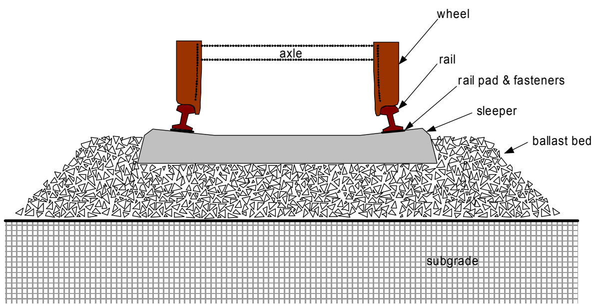


Figure 1 Typical ballasted rail tracks

Recently, significant research attention has been devoted to the forces arising from vertical interaction of train and track as these forces are the main cause of railway track problems when trains are operated at high speed and with heavy axle loads. It has been found that wheel/rail interactions induce much higher-frequency and much higher-magnitude forces than simple quasi-static loads. These forces are referred to as '*dynamic wheel/rail*' or '*impact*' forces. The summary of typical impact loadings due to train and track vertical interaction has been presented elsewhere with particular reference to the shape, magnitude and duration of impact loads found in railway track structures [3].

As aforementioned, current Australian and international design standards for prestressed concrete (PC) sleepers are based on the permissible stress concept where various limiting values or reduction factors are applied to material strengths and load effects [1, 3]. Empirical data collected by railway organisations suggests that railway tracks, especially railway PC sleepers, might have untapped strength that could bring potential economic advantage to track owners. The permissible stress design approach does not consider the ultimate strength of materials, probabilities of actual loads, risks associated with failure, and other short- and long-term factors which could lead to overdesigning the PC sleepers. A research programme to investigate the actual load carrying capacity of PC sleepers was initiated as a collaborative project between UoW, QUT and the industry partners (QR, RailCorp, Austrak, Rocla) within the framework of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail-CRC) Phase 1 (2001-2008). The main objective was the conversion of the existing Australian design code for PC sleepers into limit states design format, in order to account for the statistical nature, probability and risk of failure [4]. The by-product consequence is also the target safety index for the reliability-based design concept of such track components.

In addition to experimental investigations in this project, conversion of the existing design standard into new limit states design format required a comparative examination of the safety margin and probability of failure of PC sleepers designed in accordance with both permissible stress and limit states provisions [5]. To achieve uniform performance and reliability in structural designs for different design principles, the reliability-based approach is the most suitable, in order to either maintain consistent levels of desirable structural reliabilities or overcome the differences of such uncertainties [1, 5].

2. Deficiency of current design method

Codes of practice including Australian Standard [3] and AREMA [6] 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 [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 [2]. 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.

Accordingly, 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 [7]; RTRI Japan [8]; CHARMEC Sweden [9]; and recently UOW Australia [1]. 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 structural 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 doubtful [10].

3. Train-Track dynamic interaction

A maximum allowed impact force of 230kN to be applied to the rail head by passing train wheels is commonly accepted through the Defined Interstate Network Code of Practice (Volume 5, Part 2 - Section 8, 2002) [11]. In fact, impact loads may be caused by a variety of effects, including flats worn on the wheel tread, out-of-round wheels, defects in the wheel tread or in the rail head, and a derailment. The most severe impact forces are most likely from wheel flats [2]; because such flats strike the rail head every revolution of the wheel, and severe flats have the potential to cause damage to track over many kilometers before detection. Despite the Code of Practice requirement, there is little the Teknis station. The impact force in Figure 2 is the dynamic increment above the static wheel force (averagely 140 kN) exerted by the mass of the

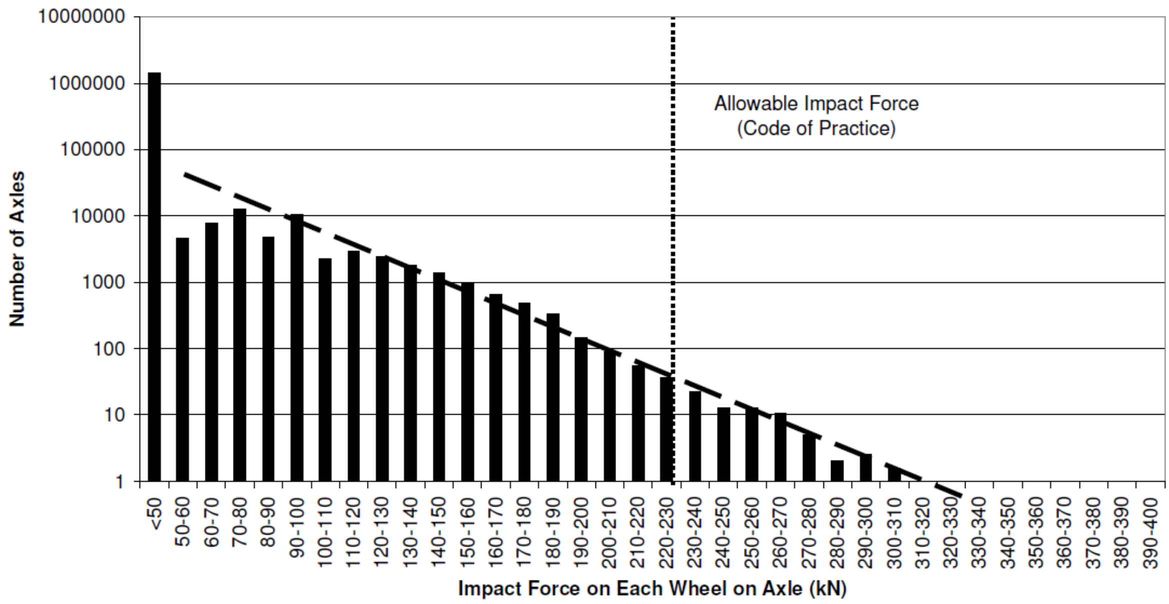


Figure 2 Typical wheel-rail dynamic loading

published data able to be found showing the actual range and peak values of impact for normal operation of trains, and certainly none were found for the defined interstate network. The value of 230kN is therefore a desired upper limit rather than a measure of real maximum forces encountered on track.

A comprehensive investigation of actual impact forces was undertaken as part of the Rail CRC project at QUT [4]. Over a year period data was gathered from two Teknis Wheel Condition Monitoring stations located on different heavy haul mineral lines. The loading data from a total of nearly 6 million passing wheels was measured, primarily from unit trains with 26 to 28 tonne axle loads, in both the full and empty states. An analysis of Leong's data from one of those sites is shown as a histogram Figure 2. The vertical axis shows the number of axles on a log scale, while on the horizontal axis is the measured impact force from wagon on a wheel. Over 96% of the wheels created impact forces less than 50kN. The bulk of the graph in Figure 2 therefore, is comprised of only the remaining 4% of wheels. However, that small percentage still comprised over 100,000 wheels throughout the year of the study, and they caused impact forces as high as 310kN. The sloping dashed line in the plot represents a line of best fit to the data for these 100,000 wheel forces.

In Figure 2, the vertical line represents the Code of Practice maximum wheel impact force of 230kN. Although the heavy haul rail networks from which the data came are not part of the defined interstate network, it's clear that in normal operation very large impact forces can occur and excessively exceed the Code of Practice specification (for rolling stock operation and testing) [11]. The frequency of high impact wheel forces in the histogram columns of Figure 2 lies along the sloping, dashed straight line, which means the distribution would appear as a logarithmic curve on a graph with a linear scale on the vertical axis. In this case, the vertical axis in Figure 2 is the number of impacting wheels per year, so if the rate of occurrence of such impacts over the year of the study is a representative of impacts over a longer period, then extrapolation of that sloping dashed line will provide the frequency of occurrence of impact forces greater than 310kN.

On that basis, it could be predicted that an impact force of 380kN would occur at the rate of 0.1 axles per year, or once in every 10 years; an impact of 450kN would occur on average once in every 100 years. This process naturally leads on to the concept of a return period for impact force, which Murray and Leong [12] developed to produce equation (2):

$$\text{Impact Force (kN)} = 53(5.8 + \log R) \qquad (2)$$

where R is the return period in years of a given level of impact.

4. Resistances of concrete sleepers

To evaluate the performance of prestressed concrete (PC) sleepers under static and impact loads, an experimental programme has been carried out at UoW [13-14]. As part of the collaborative research project supported by the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC), the PC sleepers were supplied by Australian manufacturers Rocla and Austrak.

A series of static tests on the concrete sleepers was performed in accordance with the Australian Standards. A positive four-point bending moment test was conducted for benchmarking. It should be noted that the initial strain of prestressing wires is about 6.70 mm/m, and each prestressing wire has a specified minimum proof stress of 1860 MPa. The average compressive strength of cored concrete was 88 MPa. Figure 3 shows a typical static moment-deflection relationship at the railseat for PC sleepers. The crack initiation load was observed visually during each test as well as determined by the use of the load-deflection relationships.

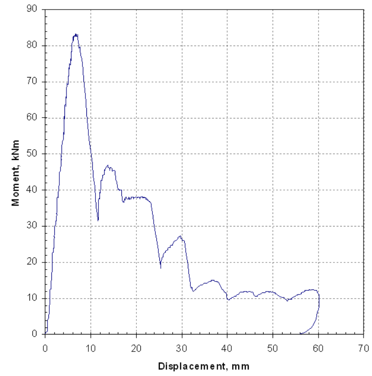
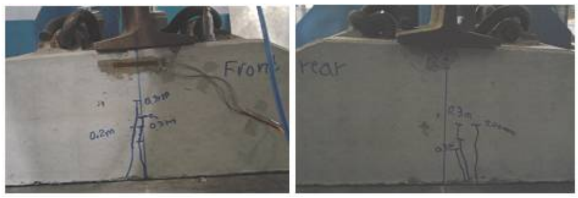
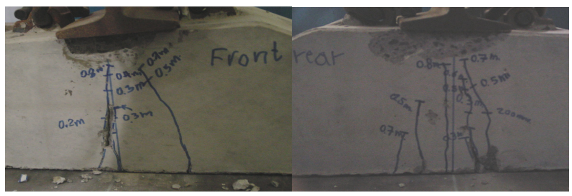


Figure 3 Static resistance of concrete sleeper

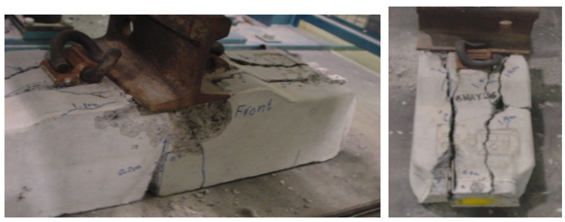


a) impact forces between 150 and 600kN

b) impact forces between 700 and 1,000 kN



c) impact forces between 1,000 and 1,500 kN



d) impact failure at 1,600 kN

Figure 4 Progressive impact response of a PC sleeper in soft track environment

For impact resistance evaluation, experimental setup and dynamic loading tests were arranged in accordance with the Australian Standards. The in-situ conditions of railway concrete sleepers were imitated [15]. A separate study was performed in order to simulate the impact loads recorded in tracks by means of the drop hammer machine and numerical impact simulations [1]. The progressive impact behaviour of a PC sleeper in the soft track environment (static track spring rates: about 60 kN/mm) is presented in Figure 4.

The failure mode was associated with both flexural and longitudinal splitting actions. The splitting fractures were aligned along the prestressing tendons as illustrated in Figure 4d. The probabilistic analysis of dynamic loading suggests that the magnitude of the ultimate impact load that caused failure of the PC sleeper would be equivalent to that with a return period of several million years [16].

5. Reliability concept

In principle, the errors and uncertainties involved in the estimation of the loads action and the capacity behaviour of a structure may be allowed for in strength design by using load factors to increase the nominal loads and using capacity factors to decrease the structural strength. The purpose of using any factors is to ensure that the probability of failure under the most adverse conditions of structural overload remains very small, which may be implicit or explicit in the rules written in a code. In outdated structural design codes that employed the traditional *working stress design* (e.g. AS 1250-1981 Steel Structures), and in the current AS1085.14 sleeper code, safe design was achieved by using *factors of safety* to reduce the failure stress to permissible working stress values, but ultimately the purpose was to limit the likelihood of failure under *normal* services [17].

In Australia all structural design codes except AS1085.14 have been converted and amended to a limit state design approach. Limit state deems that the strength of a structure is satisfactory if its calculated *nominal capacity (resistance)*, reduced by an appropriate capacity factor ϕ, exceeds the sum of the nominal load effects multiplied by various load factors γ, so that:

$$\sum (\gamma \times (\textit{Nominal load effects})) \leq \phi \times \textit{Nominal capacity} \qquad (3)$$

or

$$\textit{Design load effect} \leq \textit{Design capacity} \qquad (4)$$

where the nominal load effects are the appropriate bending moments, axial forces or shear forces, determined from the nominal applied loads by an appropriate method of structural analysis (static or dynamic). Even though the limit states are described in a deterministic form, the load and capacity factors involved are usually derived from *probabilistic models* based on statistical distributions of the loads and the capacities as depicted in Figure 5 [18].

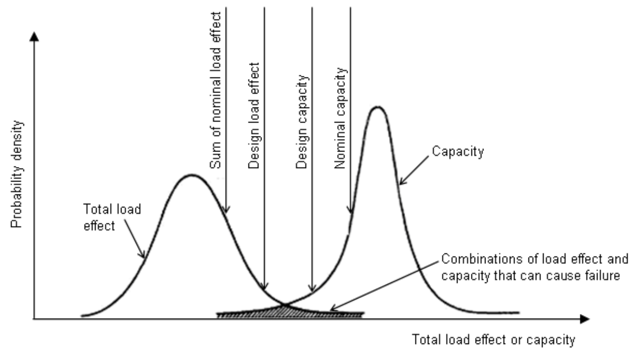


Figure 5 Probabilistic density functions for reliability

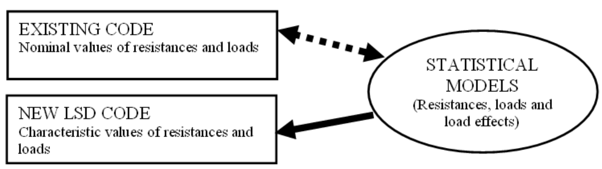


Figure 6 Reliability-based conversion of design code

It is recommended that the concept of a safety index be used to ensure that the use of the new code will lead to a satisfactory level of structural reliability and safety in the conversion of the existing design code AS1085.14 to a new limit states format. This could be attained by first selecting typical prestressed concrete sleepers that had already been designed according to the current working stress code. The safety indices of these sleepers would then be computed using idealised but realistic statistical models of their loads and structural capacities. These computed safety indices would be used to select target safety values for the limit state formulation. The load and capacity factors for the limit state design method would be varied until the target safety indices are achieved with reasonable precision. This generic procedure is called the *code calibration procedure*, as shown in Figure 6 [18].

6. Limit States Concept

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 [4]:

1. abrasion at the bottom of the sleeper causing loss of top;
2. abrasion at the rail seat location causing a loss of top/line integrity;
3. severe cracks at the rail seat causing the 'anchor' of the fastening system to move and spread the gauge;
4. severe cracks at the midspan of the sleeper causing the sleeper to 'flex' and spread the gauge;
5. 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. It is important to note that rail seat abrasion is a wear process of concrete that, if needed, could be considered as part of durability.

A challenge in the development of a limit states design concept for prestressed concrete sleepers is the acceptance levels of the structural performances under design load conditions. Infinite fatigue life of sleepers *cannot* be retained after allowing cracks under impact loads. Degree of reliability is also an important factor that needs to be taken into account. The Australian Standard AS 5104-2005 [19] prescribes the general principles for reliability for structures, and indicates that limit states can be divided into the following two categories [20]:

- **ultimate limit states**, which correspond to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain or deformation;
- **serviceability limit state**, which concerns the normal use and service life (fatigue and deformation).

7. Reliability Analysis

The limit state equation in *the partial factors format* is given by

$$S^* < \phi R_u \qquad (5)$$

where S^* is the design action effect due to the factored design loads, and ϕR_u is the factored resistance capacity of the actual member.

A reliability model for the ultimate limit states and the relationship between loading (*S*) and resistance (*R*) sides can be illustrated using the probability functions shown in Figure 5. The design values of resistance and load effect in the new limit states design code are calculated using the characteristic resistance R_k and the characteristic load effects (e.g. sleeper bending moment) S_k which should be determined from statistical analyses of wheel load distributions and the experimental results on impact resistance of concrete sleepers [17-18]. Table 1 gives an example of safety or reliability indices of a type of concrete sleeper [5] using the first order reliability method (FORM).

Table 1 Reliability indices of a concrete sleeper

Moment	Reliability Index	FORM
M_R^+	β_{tf} (top fibre stress at final stage)	3.829
	β_{bf} (bottom fibre stress at final stage)	1.872
M_R^-	β_{tf} (top fibre stress at final stage)	2.692
	β_{bf} (bottom fibre stress at final stage)	3.998

8. Reliability Based Design

In general, the key detrimental factor for the prestressed concrete sleepers relies on the ultimate limit state [16]. 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**= static (F_s) and dynamic (F_i)]; second, the dynamic analysis of design moment or actions ($M^* = 0.8F^*$ or using the Dynamic Analysis of Rail Track Package, D-TRACK); and third, the structural design and optimisation of sleepers ($M^* \le \phi M_u$) [16-18].

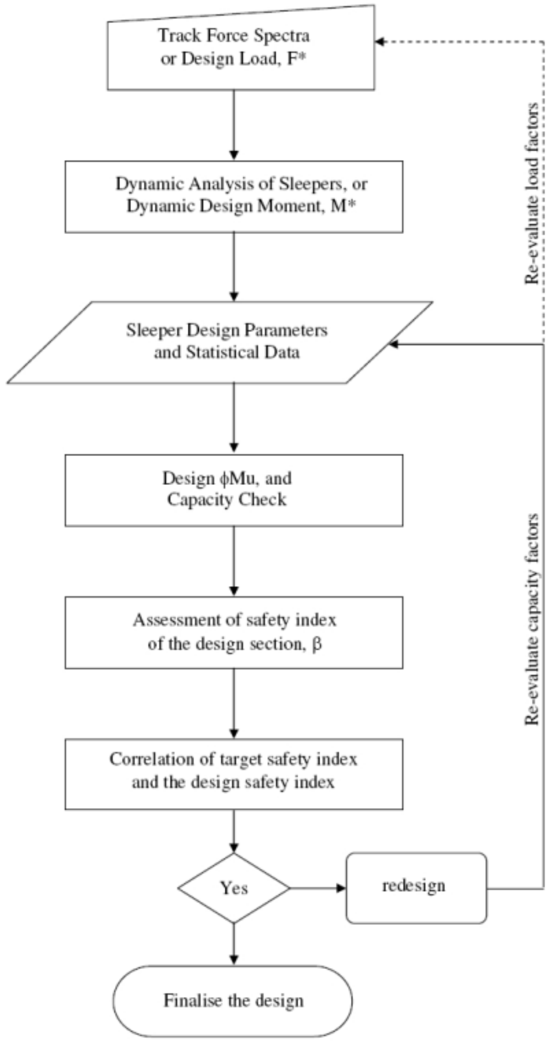


Figure 7 Reliability-based design process

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 [5]. The reliability-based design of the sleepers can thus be achieved as illustrated by Figure 7. 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 [16].

9. Conclusions

The current design of railway 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 paper presents the development of a new limit states principle and reliability-based design of concrete sleepers. It is noteworthy that using the reliability-based design concept, one could optimize and save material cost of railway sleepers up to 15%. 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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