

Greener and Leaner—Unleashing Capacity of Railroad Concrete Ties via Limit States Concept

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Abstract: New knowledge has raised a concern about the cost-ineffective design methods and the true performance of railroad prestressed concrete ties. Because of previous knowledge deficiencies, railway civil and track engineers have been aware of the conservative design methods for structural components in any railway track that rely on allowable stresses and material strength reductions. In particular, railway sleeper (or railroad tie) is an important component of railway tracks and is commonly made of prestressed concrete. The existing code for designing such components makes use of the permissible stress design concept, whereas the fiber stresses over cross sections at initial and final stages are limited by some empirical values. It is believed that the concrete ties complying with the permissible stress concept possess unduly untapped fracture toughness, based on a number of proven experiments and field data. Collaborative research run by the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC) was initiated to ascertain the reserved capacity of Australian railway prestressed concrete ties that were designed using the existing design code. The findings have led to the development of a new limit-states design concept. This paper highlights the conventional and the new limit-states design philosophies and their implication to both the railway community and the public. DOI: 10.1061/(ASCE)TE.1943-5436.0000215. © 2011 American Society of Civil Engineers.

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Introduction

Railway is commonly believed to be the world's safest transportation system for passengers or merchandise across distant areas. It has been estimated that investments in railway infrastructure will comprise one-third of the total investment in the rail market, of more than US\$200 billion by 2013. Accordingly, research and development becomes a strong momentum to railroad asset management. Track structures guide and facilitate the safe, cost-effective, and comfortable ride of trains. There are two main types of modern railway tracks. The most common one is the ballasted railway track, whereas the other is the slab track. The ballasted railway track requires less capital investment for construction but more maintenance regime. It is cost-effective and preferable for long-distance transportation, as well as heavy haul and mixed-traffic operations. The slab track is costly but requires less maintenance. It is suitable for urban transports, metro, and high-speed rail systems where noise and vibration can be controlled. The drawbacks of slab track systems include their low maintainability and adjustability as well as the requirement of very high accuracy in construction. Fig. 1 illustrates the typical ballasted railway track on which

this study focuses. 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, prestressed concrete (PC) ties, under sleeper pads, and fastening systems form a group that is referred to as the superstructure. The substructure is associated with a geotechnical system consisting of ballast, subballast and subgrade (formation) (Esveld 2001; Indraratna and Salim 2005).

In Australia, the 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 United States and Canada. The main duties of ties are to (1) transfer and distribute loads from the rail foot to the 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 (Esveld 2001). Remennikov and Kaewunruen (2008) reviewed the typical loading conditions acting on railway track structures, as well as the common design procedures for ballasted railway tracks. The existing design method for railway ties in most countries, e.g., Australia, Asia, New Zealand, and the United States, is based on permissible fiber stresses.

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. 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 (Remennikov and Kaewunruen 2007, 2008). Murray and Leong (2005, 2006) proposed a limit-states design concept and load factors for a revamped Australian standard AS1085.14 (Kaewunruen and Remennikov 2006). The expressions for predicting the impact loads at different return periods (based on long-term field data from

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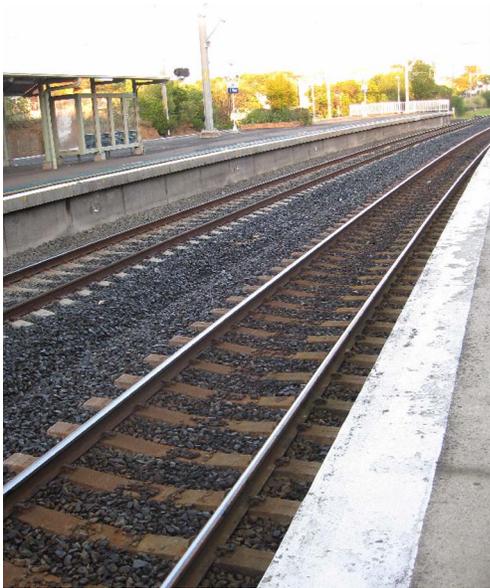


Fig. 1. Typical ballasted railway tracks

impact detectors at two sites) were proposed. It was suggested that a simple pseudostatic (using factored load) approach can be used in the design procedures of concrete ties under routine traffic. For concrete ties under nonroutine traffic, a dynamic analysis was suggested as part of a design process (Leong 2007; Kaewunruen and Remennikov 2005a, b). The new limit-states design provides the benefit of optimal use of cement materials, contributing to the greener and leaner products. Part of the sleeper is made of cement whose manufacture produces carbon dioxide, a key factor in global warming (Kaewunruen and Remennikov 2009a, b, c, d, e, 2010a, b; Remennikov and Kaewunruen 2009). This paper is aimed at relating the new design concept to transport asset planners and rail track authorities, who make key decisions of asset performance and selection of modern railway tracks.

Conventional Design Concept

Codes of practice including Standards Australia (2003) and American Railway Engineering and Maintenance-of-Way Association (AREMA) Manuals (2006) prescribe a primitive design methodology for PC ties. The design process relies on the permissible or allowable stress of materials. The design life of the ties based on this method is 50 years. 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,” and has a specified lower limit of 2.5 times static wheel load. Load distribution to a single tie, rail seat load, and moments at rail seat and center can be interpolated using tables provided in the standards (Standards Australia 2003; AREMA 2006). Generally, the ballast pressure underneath a tie (effective zones) is not permitted to exceed 750 kPa (Remennikov and Kaewunruen 2008).

Factors to be used for strength reduction of concrete and steel tendons at transfer and after losses can be found in the standards, ranging between 40 and 60% reduction. However, the minimum preamber compressive stress at any cross section through the rail seat area is set at about 1 MPa after all losses (loaded only from prestress). A 25% loss of prestress is to be assumed for preliminary design or when there are no test data. A lower level of 22% loss has been generally found in final design of certain types of ties

[see details in Standards Australia (2003)]. The standard testing procedures prescribed in either AS1085.14 (2005) or the AREMA Manual (2006) have been recommended for strength evaluation of PC ties.

Past practice has shown that uses of this standard are adequate for flexural strength design and that there is no need for any other consideration to checking stresses other than flexural stresses, because the permissible stress design concept limits the strengths of materials to relatively low values compared with their true capacity. Despite under the design loads, the material is kept in the elastic zone so there is no permanent deformation. In general, the cross ties that comply with the permissible stress design concept have all cross sections fully in compression, under either preamber or design service loads. This approach ensures that an infinite fatigue life is achieved and no cracking occurs. Ties designed in this manner therefore have an unduly significant reserve of strength within their 50-year life cycle under normal service loads. In fact, the relatively low allowable stresses imply that a deeper or bigger cross-section of tie is required. The conventional design method has been the obstruction for performance-based, special purpose crossties (e.g., replacement sleepers, transoms, turnout/crossing bearers) that are used in existing structures (tunnels, aged bridges, viaducts, etc.) where space and structural capacity are tightly limited.

In reality, impact forces caused by wheel/rail interactions may subject the ties 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 4 to 6 times more than those of wheel load (Remennikov and Kaewunruen 2008). This means that the conventional design does not consider a realistic design load action for the tie. Large dynamic impact forces may initiate cracking in the concrete ties; indeed, static type testing at the University of Wollongong has shown that shear failure can also occur at or near the ultimate flexural limit (Kaewunruen 2007). However, concrete sleeper flexural failures have rarely been observed in railway tracks, showing the conservative nature of the existing design process. Allowing cracks in ties could also be considered in a limit-states design approach. To develop the limit-states design approach, studies of the response of concrete ties to high-magnitude short-duration loading were carried out at the University of British Columbia Canada (Wang 1996); Railway Technical Research Institute Japan (Wakui and Okuda 1999); Chalmers University of Technology Sweden (Gustavson 2002); and recently at the University of Wollongong Australia (Kaewunruen 2007).

Dynamic Load Characteristics

In Australia, a maximum allowed impact force of 230 kN to be applied to the rail head by passing train wheels has been prescribed in *The Code of Practice for the Defined Interstate Network* (Australasian Railway Association 2002). That impact force may come about from a variety of effects, including flats worn on the wheel tread, out-of-round wheels, and defects in the wheel tread or in the rail head. Leong (2007) showed that the largest impact forces are most likely from wheel flats; because such flats strike the rail head every revolution of the wheel, severe flats have the potential to cause damage to track over many kilometers. Despite the *Code of Practice* requirement, little published data show 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 230 kN is therefore a desired upper limit rather than a measure of real maximum forces encountered on track, although it may not be safe or suitable for operations of the other different track structure systems.

A comprehensive investigation of actual impact forces was undertaken by Leong (2007) as part of the Rail CRC project at Queensland University of Technology (QUT). Over a 12-month period, track force data have been gathered from two Teknis wheel condition monitoring stations located on different heavy haul mineral lines. The forces from a total of nearly 6 million passing wheels were measured, primarily from unit trains with 255 to 275 kN axle loads (26 to 28 t), in both the full and empty states. An analysis of Leong's data from one of those sites is shown as a histogram in Fig. 2. The vertical axis shows the number of axles on a log scale, while on the horizontal axis is the measured impact force from the Teknis station. The impact force in Fig. 2 is the dynamic increment above the static force exerted by the dynamic mass of the wagon on a wheel (about 60–140 kN). More than 96% of the wheels created impact forces less than 50 kN. However, that small percentage still comprised more than 100,000 wheels throughout the year of the study, and they caused impact forces as high as 310 kN. The sloping dashed line in the

graph represents a line of best fit to the data for these 100,000 wheel forces (Remennikov et al. 2007).

The horizontal dotted line in Fig. 2 represents the Australasian Railway Association's *Code of Practice* maximum impact force of 230 kN, even though the heavy haul lines from which the data came are not part of the defined interstate network, it is clear that in normal operation very large impact forces can occur that greatly exceed the *Code of Practice* specification (2002). The vertical axis in Fig. 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 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 310 kN. On that basis, one could predict that an impact force of 380 kN would occur at the rate of 0.1 axles per year, or once in every 10 years; an impact of 450 kN would occur on average once in every 100 years. To determine the impact force applied to components further down the track structure, such as the cross tie or ballast, appropriate measures

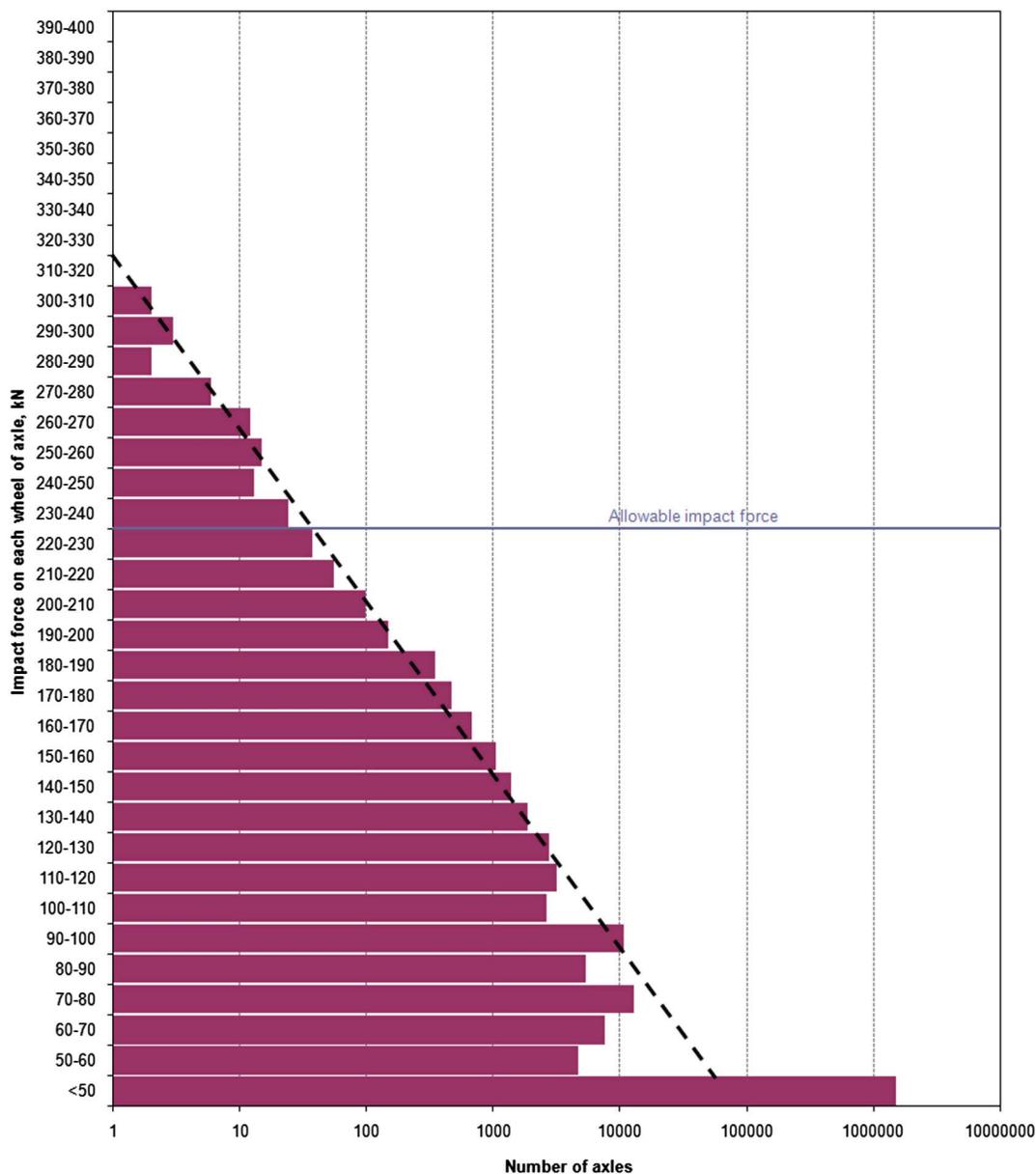


Fig. 2. Frequency of occurrence of impact forces, derived from Murray and Leong (2005)

should be applied that allow for force sharing among support elements and allow for the dynamic behavior of the track. A Monte Carlo model was developed to evaluate the potential damage of track components considering the design return period of loading (Leong and Murray 2008). Using the return period of 200–500 years could provide a safe and reliable rail infrastructure (Kaewunruen and Remennikov 2006).

Limit-State Design of Prestressed Concrete Sleepers

According to Leong (2007), Australian railway organizations would condemn a tie when its ability to hold top of line or gauge is lost, depending on the defect limit acceptance or base operating condition of such organizations. 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 tie causing a 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 tie causing the tie to flex and spread the gauge; and
- Severe degradation of the concrete tie because of 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 ties’ inability to hold top of line and gauge will be considered as the failure criterion 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 ties is the acceptance levels of the structural performances under design load conditions. Infinite fatigue life of ties 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 (Standards Australia 2005) prescribes the general principles for reliability for structures, and indicates that limit states can be divided into the following two categories:

1. Ultimate limit state, which corresponds 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 (2007) and Murray and Leong (2006a, b) noted that for railway concrete ties, the limit-state categories could be different from the traditional structural approach and should consider the track’s ability to continue operating in an event of exceedance of a limit state. Therefore, the following three limiting conditions (Leong 2007) have been proposed that would be relevant to the design of railway concrete tie.

Ultimate Limit State

The ultimate limit state defines a condition in which a single once-off event such as a severe wheel flat that generates an impulsive load capable of failing a single concrete tie. 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 spectra recorded over several years or for a suitable period (generally at least a year to obtain a good representation of track forces over its lifetime under various train/track conditions). The load magnitude of the ultimate event for ultimate limit-state design of

ties depends on the significance or importance level of the railway track (Kaewunruen 2007; Leong 2007). For example, the building code of Australia (BCA 1994) in conjunction with Standards Australia indicates the importance levels of structures for determining the probabilistic wheel loads for track design at ultimate limit states on the consequences of failure of the structures. As the design criteria for railway ties (with 50 to 100 years design life), the Australian Building Codes Board (1994) suggests that loading with a 100-year return period be considered for Category 1 tracks (infrequent traffic, interstates); 500-year return period for Category 2 tracks (regular, freight); and 2,000-year return period for Category 3 tracks (inner city suburban, heavy haul). 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% fractiles and hence have a 5% probability of being exceeded (Standards Australia 2001a, b; Warner et al. 1998).

Damageability (or Fatigue) Limit State

The damageability (or fatigue) limit state defines a time-dependent limit state where a single concrete tie 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 ties (e.g., 30, 50, or 100 years) or from the expected train/track tonnage (or how many load cycles are 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 Fig. 2 (the load frequency data recorded for a year). Using the data in Fig. 2 for fatigue-life prediction of ties is applicable, whereas the actual life must be longer than the design life. Alternatively, if the tie is to be designed for a 50-year service life under 28 t axle load, the loading range for the fatigue life consideration can be obtained from Eq. (2) plus the wheel load of 140 kN, which is up to 540 kN (Leong and Murray 2008). Using a statistical analysis, the number of axles or cycles of each loading range can be achieved for the cumulative fatigue damage. Based on the previous example, it shows a likelihood that there is only one time that the tie experiences the dynamic load of 540 kN over the tie 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, Concrete model code by European Committee for Concrete—CEB). Such damage should not result in any failure condition described earlier.

Serviceability Limit State

This limit state defines a condition in which tie failure is beginning to impose some restrictions or tolerances on the operational capacity of the track, for example, prestressing losses, tie deformations (shortening and camber), track stiffness, back canting, and rail seat abrasion. The failure of a single tie (in a 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 ties, 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 ties 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 ties through a suitable spacing arrangement to provide a track modulus or stiffness similar to the existing one.

In general, the key, governing detrimental factor for the prestressed concrete ties relies on the ultimate limit state because decompression moment due to prestressing of the ties minimizes the fatigue damage, and the dimension and topology of the ties provide the complements to serviceability limit states. Leong and Murray (2008) investigated that if the ties are designed for the 100- or 200-year return periods, fewer than 5% of the ties in the clustered track system will have a probability of failure.

As described previously, Murray and Leong (2006a, b) proposed a method by which the ultimate limit-state wheel/rail impact design forces may be calculated on the basis of data drawn from a Queensland Rail wheel impact load detector (WILD) on a heavy haul coal line. But the problem with converting the design wheel/rail force to the design sleeper moment is still open for discussion (Kaewunruen 2007). Murray and Leong (2006a, b) emphasized the need for computer dynamic track analysis using such packages, as dynamic analysis of rail track (DTRACK) to compute the design sleeper moment. While in principle this approach could be viable, it could lead to a complication with formulating statistical ultimate limit-state models of concrete ties for their reliability assessment and for model calibration in the conversion process to a new limit-states design code format. The impact tests to establish the relationship between the impact load and the railseat bending moment have been carried out using a new drop hammer machine at the University of Wollongong (UoW). In the impact tests, the fall height of an anvil was increased step-by-step up to the maximum height from which the resulting bending moments would not exceed the cracking moment capacity. The duration of impact loads was kept almost constant at about 4–5 msec regardless of the fall height (by varying the suitable softening media placed between the impactor and the railhead). To provide support in interpreting the data from the tests, finite-element modeling of crossties subjected to impact loads and DTRACK simulations were also used. The findings from these studies showed that the results of UoW experiments were very close to those obtained from DTRACK (Kaewunruen 2007; Kaewunruen and Remennikov 2007a, b, 2008a, b, c).

Wheel load is the main factor in the 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 ties on the basis of the new limit-states design concept:

First, the determination of design loads (F^*);

Second, the analysis of design moment (M^*) or actions

$$M^* = 0.8 F^* \quad (\text{or D-TRACK Analysis}) \quad (1)$$

Third, the structural design and optimization of concrete ties

$$M^* \leq \phi M_u \quad (2)$$

where M_u = ultimate moment capacity of the tie; and ϕ = capacity reduction factor (Kaewunruen 2007).

Limit-State Design: Experience and Benefits

The limit-states design concept for railroad concrete ties has been recently adopted in European countries, e.g., Germany, Sweden, and Switzerland (European Committee for Standardization 2002). Since 2002, concrete railroad ties in the European countries have been designed for railroad construction, mainly for the green field projects (new railroads) whereas the rail-track components are rather new and any track imperfection (e.g., rail defects, poor

welds, or wet foundation) is hardly detected. So far, there has not been any report in relation to the structural integrity and failure of those concrete ties under service (Freudenstein and Haban 2006). It has been investigated that the limit state design could help save on the material cost of each railroad tie by as much as 15%. In addition to the cost saving, the new methodology helps reduce the amount of cement used for manufacturing concrete ties with respect to the omission of carbon dioxide during the cement production process which is a factor contributing to global warming (Murray and Leong 2006a, b; Kaewunruen 2007). The new concept also allows rail engineers to predict accurately the actual failure mode of tracks while the tie dimension can be optimized. Based on the recent life-cycle evaluation of railroads (for green field projects with a service life of 60 years), concrete ties have superior environmentally friendly benefits and are a low contributor toward carbon emission in comparison with timber, steel, and polymer (fiber composite) crossties over their service lives. In contrast, the timber tie seems to be the last option, as its life is relatively short, requiring very expensive maintenance and renewal programs; and more important, the timber tie decays over time as well as emitting substantial amounts of carbon dioxide to the environment (Petersen and Solberg 2005; Owens 2006; Kaewunruen and Remennikov 2009a, b, c, d, e, 2010a, b). Alternatively, the new design concept can unleash the true capacity of the existing concrete ties previously rolled out in tracks, to provide either a heavier or a faster operational service.

For any brown field railroad project (e.g., track upgrading, reconditioning, or refurbishment), the design and use of concrete ties must be carefully considered on a case-by-case basis. For example, in a track upgrading where the formation and all components are rebuilt, the transition between the old track sections and the reconditioning track should be smoothed by adjusting the transitional track stiffness. In some refurbishment projects (e.g., in tunnels or in tracks with permanent overhead structures), the transit space (horizontal and vertical clearances) is the key priority, so the concrete ties have to be thin enough to fit within the limited space. In a reconditioning project, the capacity of existing support structures or formation has to be investigated to minimize the weight of track components. On this ground, the specific purposes indicate the performance and durability-based design of the concrete ties. Then, the limit states concept is much more suitable and applicable to the fit-for-purpose, innovative design of railroad crossties because the structural performance under more realistic conditions can be accurately established (Remennikov and Kaewunruen 2009). Such a design concept unleashes the capacity of materials and the flexibility for design fit (so-called like-for-like design). To date, the fit-for-purpose concrete ties used in many steel bridges or in many reconditioned tracks have not shown any critical problem in services. Nevertheless, the quality control from the design process by professional engineer to manufacturing, to handling and transportation, and to installation of concrete ties must be reinforced since some problems related to minor structural cracks, excessive precamber (deflection), creep and shrinkage, and bursting ends were found (Kaewunruen and Remennikov 2010a, b).

Conclusion

The current design of railroad prestressed concrete ties, stated in many codes of practice (e.g., Australian Standards, American Railway Engineering, and Maintenance-of-Way Association Manuals) is based on the permissible stress concept. Design process is based on the quasi-static wheel loads and the static response

of concrete ties. The research finding shows that the current design concept is very conservative as well as unrealistic. This negative value deters the greener and leaner designs of permanent way components. To shift to a more rational design method involves significant research effort within the framework of the CRC for Railway Engineering and Technologies. The collaborative research between the University of Wollongong and Queensland University of Technology has involved all important facets, such as the spectrum and amplitudes of dynamic forces applied to the railway track, evaluation of the reserve capacity of typical prestressed concrete ties designed to the current design concept, and the development of a new limit-states design concept. This paper presents the background, concepts and research outcomes of the Rail CRC research project aimed at developing the new limit-states design concept for prestressed concrete ties. Importantly, it is also aimed at relating the new design concept that contributes to a greener and leaner product to transport asset planners and a railway authority. The current and new design methods have been discussed and it is found from parallel studies that using the new limit-state design concept, one can save up to 15% on the material cost of railroad ties. The optimum use of materials, that are key factors toward global warming altogether makes the concept leaner and greener. In sum, improved knowledge has led to a greener, safer, and more cost-effective design method for concrete ties. It is the time for rail track owners and asset operators to make a change.

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