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Document Version
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Citation for published version (Harvard):
Kaewunruen, S, Li, D, Remennikov, A & Ishida, T 2019, Dynamic resistance and rational design of railway prestressed concrete sleepers. in W Derkowski, P Krajewski, P Gwozdziewicz, M Pantak & L Hojdys (eds), *Proceedings of the fib Symposium 2019: Concrete - Innovations in Materials, Design and Structures.* Proceedings of the fib Symposium 2019: Concrete - Innovations in Materials, Design and Structures, The International Federation for Structural Concrete: FIB, pp. 1477-1484, fib SYMPOSIUM 2019: CONCRETE - INNOVATIONS IN MATERIALS,
DESIGN AND STRUCTURES, Krakow, Poland, 27/05/19.

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 01/05/2019

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DYNAMIC RESISTANCE AND RATIONAL DESIGN OF RAILWAY PRESTRESSED CONCRETE SLEEPERS

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Abstract

Current design philosophy for railway concrete sleepers is based on the analysis of static and quasi-static stresses resulting from quasi-static wheel loads and essentially the static response of concrete sleepers. In general, cracking can incur when the bottom fibre stress is larger than tensile strength of concrete. Premature cracking of prestressed concrete sleepers has been detected in railway tracks. The major cause of cracking is the infrequent but high-magnitude wheel loads produced by a small percentage of "out-of-round" wheels or railhead surface defects, which are crudely accounted for in any design and test standards (including EN 13230) by a single load factor in design (or *k* factors for test criteria). These prescribed factors in either design or testing have very little to none of relationship with real behaviours of railway prestressed concrete sleepers, especially considering their entire service life. In fact, its scientific origin is somewhat questionable. Based on the current design methods (either by European EN 13230 or other international standards, e.g. Australia AS 1085.14 or American AREMA Manual Chapter 30), the cracked sleepers must be theoretically replaced by new ones, resulting in a costly maintenance budget each year. In reality, concrete sleepers are embedded in ballast or in mass concrete slabs. Crack detection is neither normally carried out by visual inspection nor any NDT&E approach. This has raised a paradox political game between manufacturers and asset managers about the shared responsibility and risk. Such the critical issue is hidden under other more pressing demands by other highly-publicised rail problems. On this ground, it is important to address such important issues as the realistic spectrum and amplitudes of dynamic forces applied to the railway track, and the rational limit states design concept that is taking care of the realistic loading conditions and the true behaviour and dynamic capacity of the sleepers. This paper presents a rational limit states design concept for prestressed concrete sleepers. The paper highlights the dynamic design guideline and the necessity to shift from static to dynamic consideration for railway concrete sleepers. The numerical investigations and case scenarios have been performed using dynamic analyses of railway tracks calibrated by dynamic testing data of materials and structures. The dynamic design guideline embraces uncertainties on railway tracks in which a simple measurement on railway sleepers might be inadequate to ascertain thorough understanding into their behaviours, and unable to design or manufacture the sleepers safely, efficiently and effectively.

Keywords: Dynamic resistance, rational design, dynamic limit states, prestressed concrete sleepers, ballasted railway tracks.

1. Introduction

1.1. Background

Ballasted railway tracks have been utilised as a modern type of railway systems for urban, suburban, metro and freight rail networks. Their railway track structures guide and facilitate the safe, cost-effective, and smooth ride of trains. Fig. 1 shows the main components of a typical ballasted railway track, consisting superstructure and substructure (Steffens, 2005). 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, fastening systems, under sleeper pads and ballast form a group that is referred to as the superstructure. The substructure is associated with a geotechnical system consisting of sub-ballast, ballast mat, and subgrade (formation) (Esveld, 2001; Indraratna and Salim, 2005). The main duties of sleepers are to transfer and distribute loads from the rail foot to underlying ballast bed; to hold and secure the rails at the proper gauge through the rail fastening system; to maintain rail inclination; and to r-strain longitudinal, lateral and vertical movements of the rails (Remennikov and Kaewunruen, 2008a).

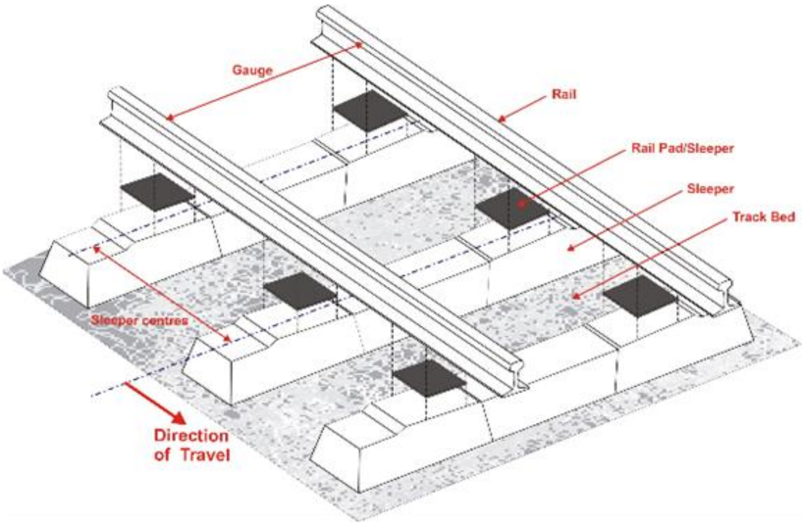


Figure 1. Typical ballasted railway tracks and their components (Steffens, 2005).

The recently improved knowledge raises a concern in the design and manufacturing of prestressed concrete structures. Civil engineers are mostly aware of the static design codes for structural prestressed concrete members, which rely on allowable static stresses, material strength reductions, or partial limit state factors (Standards Australia, 2003; AREMA, 2006; EN 13230). In particular, railway sleeper (or railroad tie), which is a safety-critical component of railway tracks, is commonly made of the prestressed concrete. The existing code for designing or manufacturing railway concrete sleepers makes use of the static stress design concepts (either allowable stresses or limit states) whereas the fibre stresses over cross sections at initial (at transfer) and final stages (under services) are limited. Based on a number of experiments and field data (Kaewunruen, 2007), it is believed that the concrete sleepers complied with the permissible stress concept possess the unduly untapped fracture toughness. A collaborative research run by the Australian Cooperative Research Centre for Railway Engineering and Technologies was initiated to ascertain the reserved capacity of Australian railway prestressed concrete sleepers designed using the existing design code as to develop a new limit states design concept. Since 2007, the collaborative research between the University of Wollongong and Queensland University of Technology had previously addressed such important issues as the spectrum and amplitudes of dynamic forces applied to the railway track, evaluation of the ultimate and serviceability performances, and reserve capacity of typical prestressed concrete sleepers designed to the current code, and the reliability based design concept (Remennikov and Kaewunruen, 2008b). This paper focuses on the new dynamic design method as the replacement of the existing static design approach for prestressed concrete sleepers. A real-life example of the step change from this novel approach is the industrial adoption of new concrete sleeper design concept using dynamic design guideline for heavy haul rail track construction in the world largest iron ore mine in Pilbara, Australia (Kaewunruen et al., 2014).

The limit states design concept and load factors have been proposed by Murray and Leong (2005a, 2005b). The expressions for predicting the more realistic impact loads at different return periods (based on field data from impact detectors at two sites over 3 years) were proposed as a practical guideline (Remennikov et al., 2012). It was suggested that a simple pseudo-static (using factored load) approach can be used in the design procedures of PC sleepers under routine traffic. For concrete sleepers under non-routine traffic, a dynamic analysis (using dynamic properties of railway track, its components, and materials) was recommended as an essential part of the design process. The collaborative research has undertaken statistical, probabilistic and experimental studies to investigate the dynamic resistance of the PC sleepers (i.e. serviceability, dynamic toughness and endurance, and impact strength) required by limit states design approach (Leong, 2007; Kaewunruen, 2007). Without systems-thinking consideration of dynamic effects, the sleepers can lead to poor track serviceability and differential track settlements as shown in Fig. 2. To effectively improve track systems performance, it is essential to accrue the state-of-the-art knowledge of dynamic behaviour and dynamic resistance of railway sleepers. It is well known that the performance of structural systems depends on the weakest element with lowest reliability e.g. a weak bolt supporting the beam-column connection (Melchers, 1987). Conversion of the existing design standard into new limit states design format requires comparative examination and benchmarking of the safety margin, structural reliability and probability of failure of PC sleepers. The dynamic design guideline covers the various uncertainties on railway tracks due to a wide range of track occupancies, support conditions, vehicle types, rail gauges, and wheel/rail irregularities. The present paper proposes the use of dynamic design method for prestressed concrete sleepers using dynamic resistance derived from dynamic testings on the basis of limit states design concept. The dynamic design and analysis of railway sleepers has been demonstrated using dynamic analyses. The numerical examples and case scenarios have been demonstrated using a package for dynamic analysis of railway tracks, D-Track. Note that the package was an achievement of the collaboration within the framework of the Australian CRC for Railway Engineering and Technologies, and is available from Rail Innovation Australia.

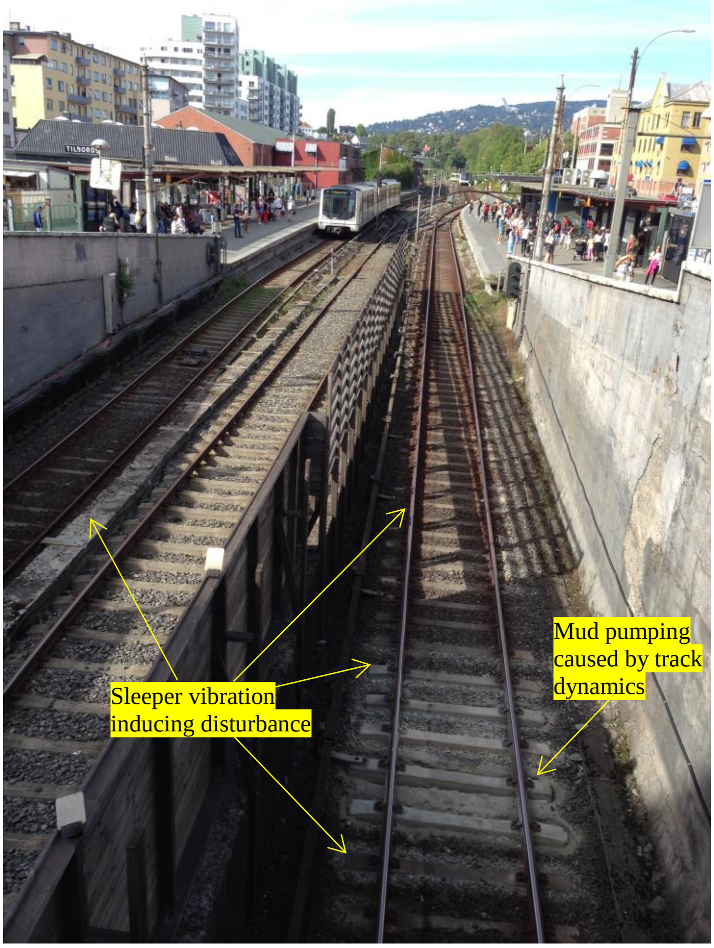


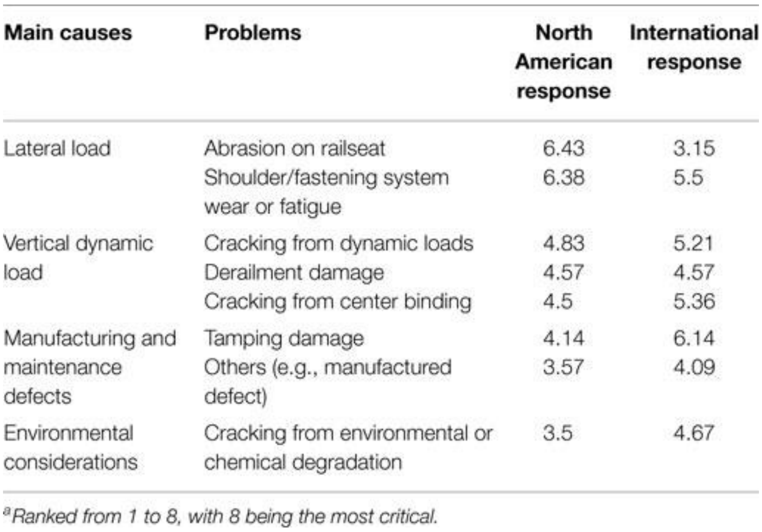
Figure 2. Track problems due to the lack of systems thinking into dynamic effects of railway sleepers, resulting in poor track conditions (Kaewunruen, 2014; Kaewunruen and Remennikov, 2016). This fact signifies the importance of dynamic damping of materials and components in minimising localised damages. Track decay rate does not play a key role in structural vibration damaging track components.

2. Current state of practice

2.1. Europe

A general manufacturing guidance for prestressed concrete sleepers was reviewed and recommended by *fib* (1987). However, the guidance was mainly focused on the manufacturing of concrete sleepers with little evidences related to the design and realistic behaviours of sleepers throughout their entire service life. European Standard EN 13230 (2016) merely represents manufacturing and testing criteria for railway sleepers for quality control and benchmarking purpose (only test methods). All test methods (for static, cyclic and high-cycle fatigue) have been described based on a 3-point-load test system over on a simple roller-roller support condition. It has very recently introduced a design guideline on a pilot stage (prEN13230-6) based on UIC approach using quasi-static factors to represent dynamic loading, and uncertainties of support conditions, track maintenance level and so on. However, the new design guideline for dynamic loading and action calculations (prEN13230-6) has never been scientifically proven nor validated by structural reliability and safety margin in accordance with ISO 2394:2015. In practice, the static resistance of concrete is rather used for structural design in accordance with EuroCode2 (for concrete structures). In addition, high-cycle fatigue failure of sleepers is rarely observed in the field if ever any. The contribution of sleepers towards track system dynamics has never been established through EN 13230, resulting in the ineffective and perhaps inefficient design of such the component. This very obvious inconsistency and drawback is due to the lack of full knowledge and collective data for the track systems and the realistic behaviours of sleepers in track systems. Clear evidences are recent European research about railway sleepers, which are literally based on the standardised test methods and the test results cannot relate to on-track performance (Zanuy and Albajar, 2018). Hopefully, European Commission's *Plan S*, where open data shall be established by 2020, will alleviate the situation of non-existence of the pertinent scientific data for track systems interconnected with their components.

Table 1. Critical problems related to concrete sleepers based on international survey outcomes from railway networks globally (You et al., 2018).



Main causes	Problems	North American response	International response
Lateral load	Abrasion on railseat	6.43	3.15
	Shoulder/fastening system wear or fatigue	6.38	5.5
Vertical dynamic load	Cracking from dynamic loads	4.83	5.21
	Derailment damage	4.57	4.57
	Cracking from center binding	4.5	5.36
Manufacturing and maintenance defects	Tamping damage	4.14	6.14
	Others (e.g., manufactured defect)	3.57	4.09
Environmental considerations	Cracking from environmental or chemical degradation	3.5	4.67

[a] *Ranked from 1 to 8, with 8 being the most critical.*

2.2. International

Unlike Europe, most countries around the world (e.g. Australia, Canada, China, Japan, USA, and South Americas) have already prescribed both design methodology and test methods for PC sleepers for decades (Standards Australia, 2003; AREMA, 2016). With the design method, the life cycle of the sleepers can be targeted for 50 years. The service life is scientifically unknown in EN 13230 (in Europe) but national specifications (e.g. in the UK) often refer to 70 years (for low axle-load trains). In many countries (except Japan), the design process relies on the permissible or allowable stress of materials. A load factor is used to increase the static axle load to incorporate dynamic effects. The design load (serviceability limit state) is termed 'combined quasi-static and dynamic load' which has a specified lower limit of 2.0 to 2.5 times static wheel load. Load distribution to a single sleeper, rail seat load, and moments at rail seat and centre can be obtained using empirical formulas. Under the design loads, the material is kept in the elastic zone so there is no permanent set. In particular, sleepers that comply with allowable stress design method have all cross sections of the sleepers fully in compression, under either pre-camber or design service loads. This approach ensures that an infinite fatigue life is obtained and no cracking occurs (Warner et al., 1998; *fib*, 2016). On the other hand, Japan has adopted limit state design concept considering both stiffness (serviceability limit state) and strength (ultimate limit state). A dynamic load factor of 2.0 to 2.5 is used to represent service loads (the actions are then obtained from dynamic analyses) and to assure the full compression across the cross sections of sleepers. A factor to 3.0 to 4.0 is adopted for ultimate strength (static resistance of sleepers). Goto et al. (2018) indicated that high-cycle fatigue failure of sleepers has never been observed in Japan rail networks, which is in agreement with many other countries. Federal Railroad Administration (You et al., 2018) carried out an international survey and found that the main cause of sleeper failure tends to be due to wear (soffit or rail seats), dynamic loads (derailment, tamping, irregularities), and poor fastening integrity as shown in Table 1. It is very clear that these critical problems are mainly caused by either dynamic lateral force or dynamic vertical load.

3. Dynamic loads and actions

If dynamics is neglected, the design load will be the same as the static axle load (Newton's first law of *statics:* $F = mg$). In reality, the design load for serviceability is multiplied by a dynamic impact factor to represent the service load and uncertainties from common wheel/rail irregularity and maintenance level. The ultimate capacity is often associated with the probability of failure (or in the form of a return period) and various uncertainties. Basically, the sleepers are designed for 50 year life, so that they could reach their ultimate moment capacity when the 1-in-50-year dynamic impact force of 400 kN (or total force of 140+400 = 540 kN) would occur. However, such damage would be of high percentage when considering the clustered sleeper track. A cumulative damage model has been developed by Leong and Murray (2008) to investigate the time-dependent accumulation of damage in sleepers in track. It is found that less than 2 percent of the sleepers in track would fail if such sleepers are designed using the impact load associated with 1-in-200-year return period. Interestingly, the sleeper failure rate over its life span remarkably increases if the design return period is lower than 100 years. For practical design purpose, the design wheel load (F*) for the limit states design concept taken into account both the static (Fs) and dynamic (Fi) wheel loads (Leong, 2007; Kaewunruen, 2007) can be presented as follows. 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 (as a partial limit state factor). It is ***not*** the permission to overload any type of structures.

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

$$F_i = k_r\, k_t\, k_{vf}\, P_{axle} \tag{2}$$

where:

F^*	is the ultimate limit state wheel/rail design force applied to rail head, kN
F_i	is the design wheel/rail impact force, kN
F_s	is the design static wheel load, kN
k_t	is the factor allowing for type of track (track importance factor)
k_{tf}	is the factor allowing for quality of maintenance on rail track
k_r	is the factor associated with the basic return period of loading, R_b
k_{vf}	is the factor allowing for quality of maintenance on vehicle wheels
P_{axle}	is the nominal axle load in tonnes
R_b	is the basic return period of load occurrence in years (100 years for freights, 500 years for light rails, 2000 years for passenger traffics)

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. These factors can be identified by using dynamic analyses of railway tracks together with appropriate track measurements.

Practically, the dynamic load action on the railway sleepers can be achieved using the Beam on Elastic Foundation theory or Zimmerman method (considering five sleeper panels on elastic foundation). Using these theories, the bending moment at railseat and mid-span can be conservatively obtained and correlated (Standards Australia, 2003; UIC, 2004; Kaewunruen and Remennikov, 2008). Note that these analytical methods yield static responses since dynamic effects ($m\ddot{x} + c\dot{x}$) are ignored and only static stiffness is utilised in calculations. In order to identify the dynamic effects and actions on the sleepers considering both magnitude and duration of impact load conditions, dynamic testing should be conducted to obtain dynamic properties of materials and structures. These are the important inputs for the dynamic analyses resulting in more rational dynamic amplification factor (due to resonances, which are directly correlated to dynamic properties of materials), dynamic load redistribution (i.e. dynamic railseat load, which are directly correlated to dynamic properties of structures), and resultant dynamic actions (i.e. dynamic bending moment, dynamic sleeper/ballast pressure) on the sleepers in a clustered track system. A few case scenarios have been complied using a dynamic finite element analysis of railway track software, DTRACK, as a demonstration. The case studies include the various data inputs as to represent uncertainties such as the different operational functions, the variety of dynamic material properties and realistic support conditions of railway tracks. An example of analytical results have been illustrated in Fig. 3 to obtain the dynamic relationships between impact loads transferring onto a railseat and the resultant bending moment at the railseat. These dynamic analyses underpin the Shift2Rail objective (S2R-OC-IPX-01-2019) in the way that '*rail is a network, is a system, and is predictable*'.

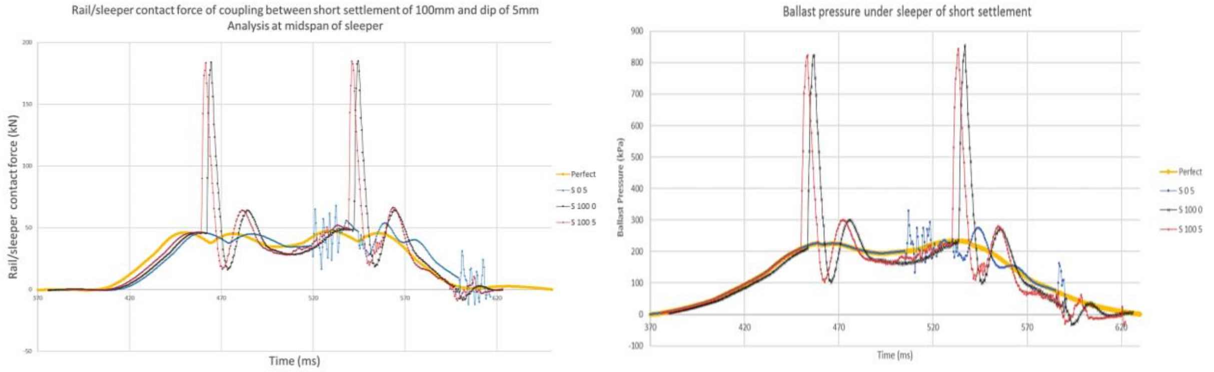


Figure 3. Dynamic actions derived from dynamic analyses (Kaewunruen and Cheingson, 2018)

4. Dynamic resistance

The dynamic wheel load and dynamic actions are the main factors in design and analysis of railway track and its components. The rational method for the calculations of the design wheel load and the design performance criteria using the limit states concept for strength and serviceability shall adopt the dynamic analyses of a track system interconnected with clustered components (sleepers, ballast, etc.). The dynamic properties of materials (and perhaps of the component) should be utilised in order to improve sciences and accuracy of the dynamic analysis. In summary, there are three main steps in designing the concrete sleepers on the basis of the rational limit states design concept: first, the determination of design loads (F*); second, the dynamic analysis for design moment or actions (M*); and third, the structural design and optimisation of concrete sleepers (using dynamic resistance). In general, flexural design is sufficient for railway concrete sleepers.

Although limit states design concept has been adopted for structural concrete worldwide, its use in compliant structures (e.g. bridge dynamics, offshore structures, or prestressed concrete sleepers) is limited. Currently, the EuroCode prEN 13230-6 (prestressed concrete sleeper design) has adopted the concept using a partial factor method. However, the method makes use of static analysis, static response and static resistance (or static strength/capacity). Using European Code and based on static tests, the ratios between the design ultimate wheel load and the static wheel load can be as much as 4.37 for train speeds > 200 km/h; and 3.75 for train speeds < 200 km/h. These values imply an over-conservative design (due to crude estimation and analysis, a higher factor of safety is adopted).

However, since there is no design validation or prediction available in EN 13230, it is unclear and difficult to obtain the life span of sleepers. In contrast, using the proposed design method, the dynamic resistance (derived from more realistic dynamic tests e.g. impact tests) can indicate true performance for rational design of the sleepers (Ngamkhanong et al., 2019). By using the dynamic resistance, the ratios between the design ultimate wheel load and the static wheel load can vary from 3.00 to 4.50 depending on the track and wheel conditions, as well as the confidence level regarding the return period of impact loading. In addition, the dynamic strength can further reduce the required safety margin and enable a more cost-effective design of the sleepers (Kaewunruen et al., 2018a; 2018b). The use of dynamic design method will allow track designers to produce rational performance-based design of the prestressed concrete sleepers integrated in a track system.

5. Conclusion

In Europe, there is no unified design method for railway prestressed concrete sleepers. Current European standard (EN 13230) simply defines test methods (static, cyclic and high-cycle fatigue) based on static three-point load test of specimens over a simple support condition (roller-roller). A recent development of the design method is in pilot stage. Unlike Europe, international communities have experienced and embraced both design and test methods of railway concrete sleepers over decades. However, current design philosophy for railway concrete sleepers is still based on the analysis of static and quasi-static stresses resulting from quasi-static wheel loads and essentially the static response of concrete sleepers. Such the design philosophy cannot address the issue of premature cracking of prestressed concrete sleepers, which were detected in railway tracks. This is because only a single load factor in design (or *k* factors for test criteria) crudely accounted for various effects is generally used in any design and test standards (including EN 13230). These prescribed factors in either design or testing have very little to none of relationship with real behaviours of railway prestressed concrete sleepers, especially considering their entire service life. In fact, its scientific origin is somewhat questionable. Accordingly, this paper addresses such important issues as the realistic spectra and load characteristics of actual dynamic forces applied to the railway track, and the rational limit states design concept that is taking care of the realistic loading conditions and the true behaviour and dynamic capacity of the sleepers. This paper highlights the incorporation of dynamic resistance (derived from dynamic behaviors of materials and component) as the essential part of a rational limit states design concept for prestressed concrete sleepers. The paper demonstrates the dynamic design guideline and the necessity to shift from static to dynamic consideration for railway concrete sleepers. It is clear that by using dynamic design method, more rational, cost-effective railway sleepers can be appropriately designed and manufactured. Many may not know but saving 15% to 20% of material waste in 1 million sleepers (or just 600-650 km of railway track length) implies the reduction of over 1,200 ton of CO_2 emission.

Acknowledgements

This article is based on work from COST Action DENORMS CA15125 and TU1404, supported by COST (European Cooperation in Science and Technology). The first author wishes to gratefully acknowledge the Japan Society for Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The JSPS financially supports this work as part of the research project, entitled “Smart and reliable railway infrastructure”. We would like to sincerely thank European Commission for H2020-MSCA-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network,” which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing under extreme conditions (www.risen2rail.eu) (Kaewunruen et al., 2016).

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