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Alexander Remennikov
University of Wollongong, alexrem@uow.edu.au

Martin H. Murray
Queensland University of Technology

Sakdirat Kaewunruen
RailCorp, NSW, sakdirat@uow.edu.au

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Dynamic design guidelines for prestressed concrete sleepers

A.M. Remennikov
University of Wollongong, NSW, Australia

M.H. Murray
Queensland University of Technology, QLD, Australia

S. Kaewunruen
RailCorp, NSW, Australia

ABSTRACT: Current design philosophy, outlined in AS 1085.14, is based on the analysis of permissible 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 AS 1085.14 by a single load factor. Based on the current design method, the cracked sleepers must be replaced by new ones, resulting in a costly maintenance budget each year. The collaborative research between the University of Wollongong (UoW) and Queensland University of Technology (QUT) has addressed such important issues as the spectrum and amplitudes of dynamic forces applied to the railway track, evaluation of the reserve capacity of typical prestressed concrete sleepers designed to the current code AS 1085.14, in order to develop a new limit states design concept that is taking care of the realistic loading conditions and the true capacity of the sleepers.

This paper presents a new limit states design concept for prestressed concrete sleepers. The paper also describes the dynamic design guideline and unified design diagrams for railway concrete sleepers. The unified design diagrams have been developed for practical purpose in dynamic design and analysis of railway sleepers. The numerical investigations and case scenarios have been performed using a package for dynamic analysis of railway tracks, D-Track. The package was an achievement of the collaboration within the framework of the Australian CRC for Railway Engineering and Technologies. The dynamic design guideline covers the various effects on railway tracks due to a wide range of track occupancies, support conditions, vehicle types, rail gauges, and wheel/rail irregularities.

1 INTRODUCTION

Railway 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 (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, 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) (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 the rails at the proper gauge through the rail fastening system; to maintain rail inclination; and to restrain longitudinal, lateral and vertical movements of the rails (Remennikov and Kaewunruen, 2008a).

The recently improved knowledge raises a concern in the design manners of prestressed concrete structures. Civil engineers are mostly aware of the design codes for structural prestressed concrete members, which rely on allowable stresses and material strength reductions (Standards Australia, 2003; AREMA, 2006). In particular, railway sleeper (or railroad tie), which is an important component of railway tracks, is commonly made of the prestressed concrete. The existing code for designing such components makes use of the permissible stress design concept whereas the fibre stresses over cross sections at initial and final stages 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

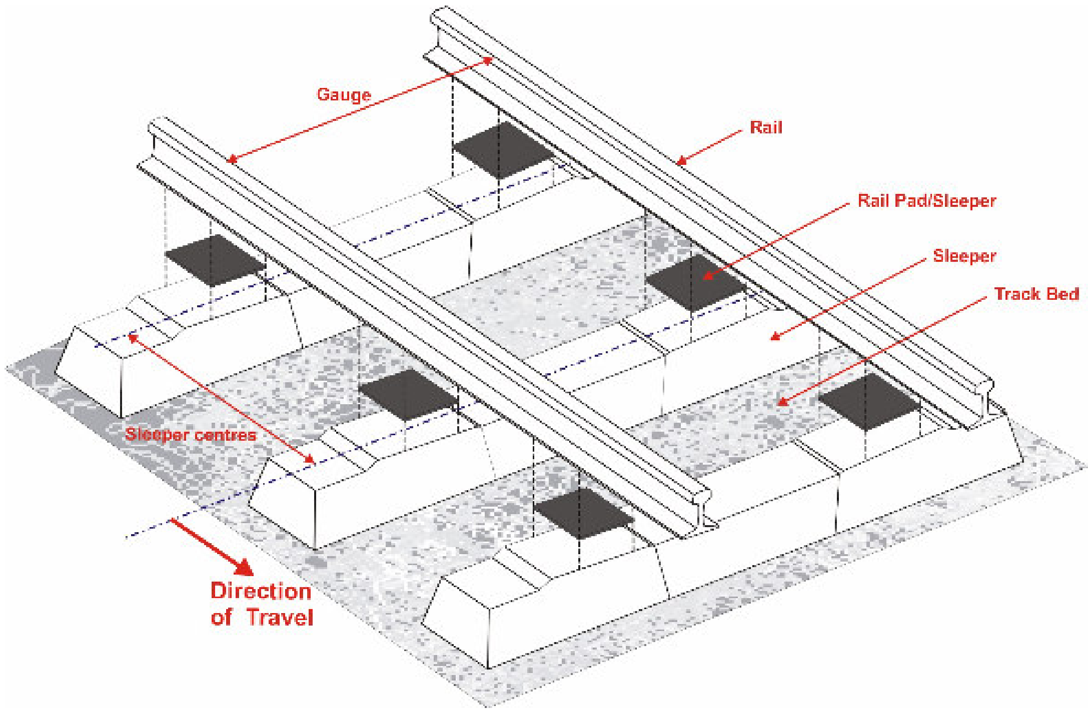

Figure 1 Typical ballasted railway tracks from D-Track (Steffens, 2005)

the unduly untapped fracture toughness. A collaborative research run by the Australian Cooperative Research Centre for Railway Engineering and Technologies has been 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. The collaborative research between the University of Wollongong and Queensland University of Technology has 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 code for prestressed concrete sleepers.

It is important to note that Murray and Leong (2005a, 2005b) proposed a limit states design concept and load factors for a revamped standard AS1085.14. The expressions for predicting the impact loads at different return periods (based on field data from impact detectors at two sites) were proposed. 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 was suggested as part of a design process. The research team of the Rail-CRC Project has undertaken statistical, probabilistic and experimental studies to investigate the ultimate resistance of the PC sleepers in a manner required by a limit states design approach (Leong, 2007; Kaewunruen, 2007). It is well known that the performance of structural systems depends on the weakest element with lowest reliability (Melchers, 1987). Conversion of the existing design standard into new limit states design format has been completed using 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. The new dynamic design guideline covers the various effects 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 on the basis of limit states design concept. The design diagrams have been developed for practical purpose in dynamic design and analysis of railway sleepers. The numerical examples and case scenarios have been demonstrated using a package for dynamic analysis of railway tracks, D-Track. 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.

2 CURRENT DESIGN PRACTICE

Australian Standard AS1085.14-2003 prescribes a design methodology for PC sleepers (Standards Australia, 2003). The *life cycle* of the sleepers based on this standard is 50 years. The design process relies on the permissible or allowable stress of materials. A

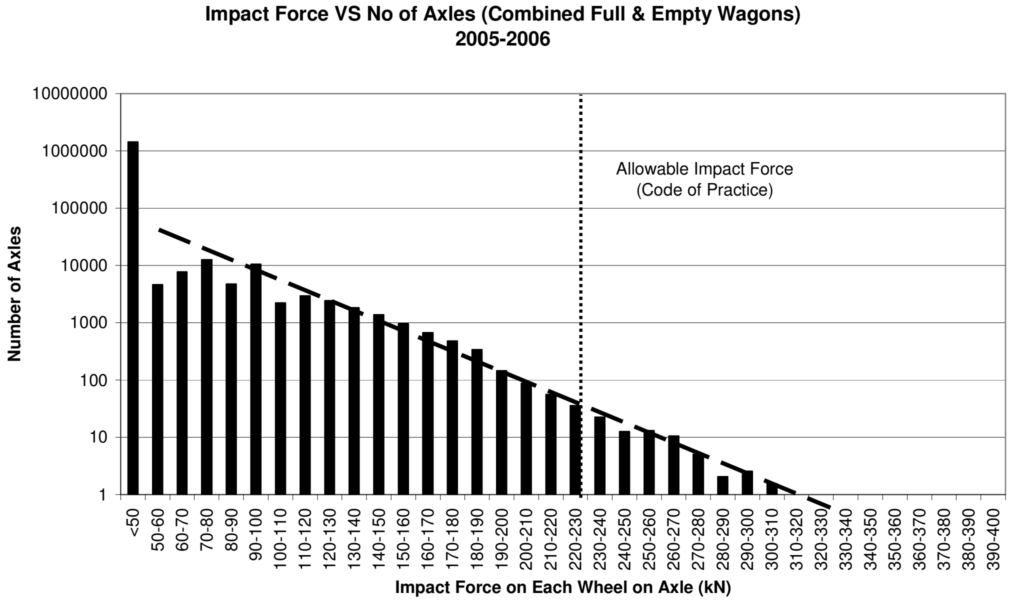

Figure 2 Frequency of occurrence of impact forces, derived from Leong (2007)

load factor is used to increase the static axle load to incorporate dynamic effects. The design load is termed '*combined quasi-static and dynamic load*' which has a specified lower limit of 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 tables provided in AS1085.14.

It should be noted that the ballast pressure underneath sleepers is not permitted to exceed 750 kPa for high-quality ballast as described by AS2758.7. Factors to be used for strength reduction of concrete and steel tendons at transfer and after losses can be found in the standard, ranging between 40% to 60% reduction. However, the minimum pre-camber compressive stress at any cross-section through the rail seat area is set at 1 MPa after all losses (loaded only from prestress). It should be noted that 25% loss of prestress is to be assumed for preliminary design or when there is no test data. A lower level of 22% loss has been generally found in final design of certain types of sleepers (see details in AS1085.14, Appendix E). The standard testing procedures in AS1085.14 have been recommended for strength evaluation of PC sleepers (Standards Australia, 2003).

Past practice has indicated that utilisation of this standard is adequate for flexural strength design. AS1085.14 states that if the design complies with AS1085.14, there is no need for consideration to checking stresses other than flexural stresses, because the permissible stress design concept limits the strengths of materials to comparatively low values compared to their true capacity. Under the design loads, the material is kept in the elastic zone so there is no permanent set. In particular, sleepers that comply with AS1085.14 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).

3 DYNAMIC LOADING ON TRACKS

3.1 *Industry Practice*

A maximum allowed impact force of 230 kN to be applied to the rail head by passing train wheels has been prescribed in The Defined Interstate Network Code of Practice in Volume 5, Part 2 - Section 8, 2002 (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 kilometres. Despite the Code of Practice requirement, there is little 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 230 kN is therefore a desired upper limit rather than a measure of real maximum forces encountered on track.

3.2 *Dynamic Load Measurements*

A comprehensive investigation of actual impact forces was undertaken by Leong (2007) as part of the Rail CRC project at QUT. Over a 12 month period, track force data have been gathered from two Teknis

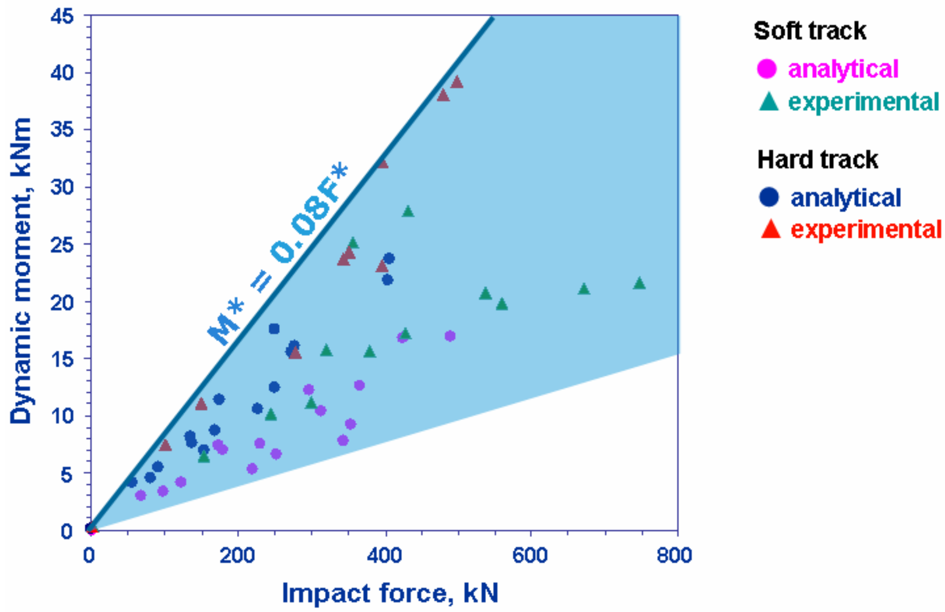

Figure 3 Dynamic actions, derived from Kaewunruen (2007)

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 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 the Teknis station. Note that the impact force in Figure 2 is the dynamic increment above the static force exerted by the mass of the wagon on a wheel (about 60-140 kN). Over 96% of the wheels created impact forces less than 50 kN. However, that small percentage still comprised over 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.

3.3 *Probabilistic Analysis*

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. This process naturally leads on to the concept of a return period for impact force, which Murray and Leong (2006) developed to produce equation (1):

$$\text{Impact Force (kN)} = 53(5.8 + \log R) \tag{1}$$

where R is the return period in years of a given level of impact. It should be emphasised that this impact force is that which is applied by a wheel to the rail head. To determine the impact force applied to components further down the track structure, such as the sleeper or ballast, appropriate measures should be applied which allow for force sharing amongst support elements and allow for the not insignificant dynamic behaviour of the track. Equation (1) can be used to help assess the probability of failure of concrete sleepers in the heavy haul lines which were monitored as part of this study. Alternatively, the number of impacts applied to the rails can be written in equation (2):

$$N_{Impact} = 10^{(5.81 - 0.0188Fi)} \tag{2}$$

where N_{Impact} is the number of impacts and Fi is the dynamic impact force magnitude, which does not include the static weight of the vehicle or about 140 kN (Leong and Murray, 2008).

3.4 *Design Load*

In general, 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 = 500 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 (F_s) and dynamic (F_i) 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. It is not the permission to overload any type of structures.

$$F^* = 1.2\, k_{tf} F_s + 1.5\, F_i \tag{3}$$

$$F_i = k_r\, k_t\, k_{vf}\, P_{axle} \tag{4}$$

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

Table 1 Track importance factor

Track Importance Category	**Track Importance factor (k_t)**	**Basic Return Period of Loading (R_b)**
Category I	1.0	100
Category II	1.1	500
Category III	1.2	2,000

Table 2 Track maintenance factor

Track Maintenance Group	**Track Maintenance factor (k_{tf})**
Group I	1.0
Group II	1.2
Group III	> 1.2

Table 3 Wheel maintenance factor

Wheel Maintenance Group	**Wheel Maintenance factor (k_{vf})**
Group I	1.0
Group II	1.2
Group III	> 1.2

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 (2007) carried out the probabilistic analysis of the impact loads (excluding static axle force) detected by WILD impact detector. Based on the statistical traffic data (Murray and Leong, 2006), the impact load factor k_r can be written as follows:

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

where V_t is the estimated traffic volume in MGT per annum. The details in Tables 1-3 can be found in Leong (2007) and Kaewunruen (2007).

4 DYNAMIC LOAD ACTION

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).

In order to identify the dynamic effects on the sleepers, both analytical and experimental studies have been carried out under the collaborative RailCRC project. Thirty-six case scenarios were complied using a dynamic finite element analysis of railway track software, DTRACK (Murray and Leong, 2006). The analytical studies were initially carried out in order to benchmark the analytical results and in order to evaluate the wheel/rail impact forces. The case studies include the various data inputs as to represent the different operational functions, and the variety of material properties and support conditions of railway tracks. The analytical results have been investigated to obtain the dynamic relationships between impact loads transferring onto a railseat and the resultant bending moment at the railseat.

To evaluate the experimental relationship between railseat bending moment and the associated impact force, a high-capacity drop-weight impact machine was built at the University of Wollongong. The drop heights were kept at low levels that would not create major cracks in the concrete. The drop heights were increased step by step until all strain gauges were broken due to the large dynamic tension at bottom fibre and compression at top fibre. The curvature at the railseat can be computed based on the assumption that strain plane is linear and remains plane after the deformation. The moment-curvature relationship for uncracked up till cracked sections is then employed for obtaining the resultant bending moment at the railseat of railway prestressed concrete sleeper. Figure 3 shows the relationships between the design impact load and the dynamic action on the sleepers. The practical moment envelope for the dynamic design guideline for prestressed concrete sleepers read

$$M^* = 0.08F^* \tag{6}$$

It should be noted that the impact force on sleeper railseat is roughly about 70 percent of the wheel/rail interaction force. It is also recommended that the more cost-effective design can be attained by determining the bending moment along the railway sleepers using the advanced dynamic analysis of railway tracks, e.g. DTRACK.

5 LIMIT STATES DESIGN

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 the current design standards: AS1170-2002 Loading on structures; and AS3600-2001 Concrete structures (the new amendment to appear in early 2008).

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^*); second, the analysis of design moment or actions ($M^* = 0.8F^*$ or D-TRACK); and third, the structural design and optimisation of concrete sleepers ($M^* \leq \phi M_u$, AS3600). In general, flexural design is sufficient for railway concrete sleepers.

6 DESIGN CODE COMPARISON

Although limit states design concept has been adopted for structural concrete worldwide, its use in prestressed concrete sleepers is limited. Currently, the EuroCode prEN 13230 (prestressed concrete sleeper design) has adopted the concept using the partial factor method. A comparison has been carried out to investigate the efficiency of the proposed method at ultimate limit state. Using European Code and based on static tests, the ratios between the design ultimate wheel load and the static wheel load are 4.37 for train speeds $\geq$ 200 km/h; and 3.75 for train speeds < 200 km/h.

In contrast, using the proposed design method, the ratios between the design ultimate wheel load and the static wheel load varies 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. It can be seen that the factors are in very good agreement. However, the proposed dynamic design method allows designers to produce performance-based design of the prestressed concrete sleepers.

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