University of Wollongong
Research Online

Faculty of Engineering - Papers (Archive)

Faculty of Engineering and Information Sciences

2007

Investigations of static and dynamic performance of railway prestressed concrete sleepers

S. Kaewunruen
University of Wollongong, sakdirat@hotmail.com

A. M. Remennikov
University of Wollongong, alexrem@uow.edu.au

Publication Details

This peer-reviewed paper was originally published as: Kaewunruen, S & Remennikov, A, Investigation on static and dynamic performance of prestressed concrete sleepers, in Proceedings of 2007 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, 4-6 June 2007, Springfield, Massachusetts, [CD-Rom]. Copyright 2007 The Society of Experimental Mechanics (SEM). Original conference proceedings are available here.

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Investigations of static and dynamic performance of railway prestressed concrete sleepers

Sakdirat Kaewunruen[1] and **Alex M Remennikov**[2]
[1]PhD Candidate, [2]Senior Lecturer
School of Civil, Mining, and Environmental Engineering, Faculty of Engineering
University of Wollongong, Wollongong, NSW 2522 Australia

ABSTRACT: Ever increasing axle loads and train speeds are pressing track owners to extract as much performance as possible from their asset without wholesale or catastrophic failure. Unfortunately, there is insufficient knowledge of the static and dynamic loadings that a track may be subjected to in its lifetime, and there is widespread suspicion that track components have reserves of strength that are untapped, especially concrete sleepers. Addressing these issues has the potential for substantial savings for track owners. It's important therefore to ascertain the spectrum and amplitudes of forces applied to tracks, to understand more clearly the manner in which track components respond to those forces, and to clarify the processes whereby concrete sleepers in particular carry those actions.

In this paper the load-carrying capacity of the selected Australian prestressed concrete sleepers is investigated under static and dynamic loading conditions. The sleepers are subjected to impact loading using a large capacity drop hammer to simulate the repeated impacts due to wheel flats or engine burns. These repeated impacts could eventually lead to cracking and failure of the sleepers, and hence are important in the context of developing the limit state design approach for the concrete sleepers. Using the impact loading technique, such phenomena as impact damage and residual strain, as well as the fracture energy as a performance indicator of damage for the selected limit states, are also quantitatively evaluated.

1. INTRODUCTION

Transportation structures are very important as a significant drive for the growth of both economy and society of any country around the world. It is commonly understood that railway system provides the best and safest solution for transportation of either passenger or freight nowadays. Among the modern types of railway tracks, ballasted railway track is often used for accessing to remote and rural area. The financial viability of the ballasted track relies on its cost-effectiveness in construction, maintenance, and renewal. Esveld [1] stresses that ballasted railway track has many advantages; for example, the construction costs are comparatively low, the maintenance and repair of track and its components are convenient, it has high damping characteristics and very good drainage properties, and noise and ground-borne vibrations can be controlled. Since railway track is always subjected to a variety of dynamic loads, understanding the dynamic track behaviour is essential in order to evaluate the structural safety and service life of the railway track components. In general, there are two major parts of ballasted railway track, including the super-structure and the sub-structure. The super-structure is made up of steel rails, the fastening systems and railway sleepers (or so-called 'railroad ties' in the US); whilst the ballast, sub-ballast, sub-grade and formation, form the sub-structure. Figure 1 illustrates the ballasted track components.

Railway prestressed concrete sleepers have been developed and utilized in railway industry for over 50 years. Current design approach is based on permissible stress design whereas the structural behaviours or deformations are kept within the elastic range. The design load for structural design is taken from static or quasi-static loads, ascribed to a dynamic impact factor multiplying with the wheel load. Interestingly, the design life span of the concrete sleepers is also considered around 50 years [2]. In reality, the nature of loading conditions on railway track structures is somewhat time dependent. Major research attention has been focussed on vertical static and dynamic forces as they are the main source of railway track problems when trains are operated at different speeds and static axle loads. It has been found that wheel/rail interactions result in much higher-frequency and much higher-magnitude forces than simple quasi-static loads. These forces are often called as '*dynamic wheel/rail*' or '*impact*' forces. The typical impact loadings due to train and track vertical interaction has been presented in ref [3] with particular reference to the shapes of the typical waveforms of impact loads generally found in railway track structures.

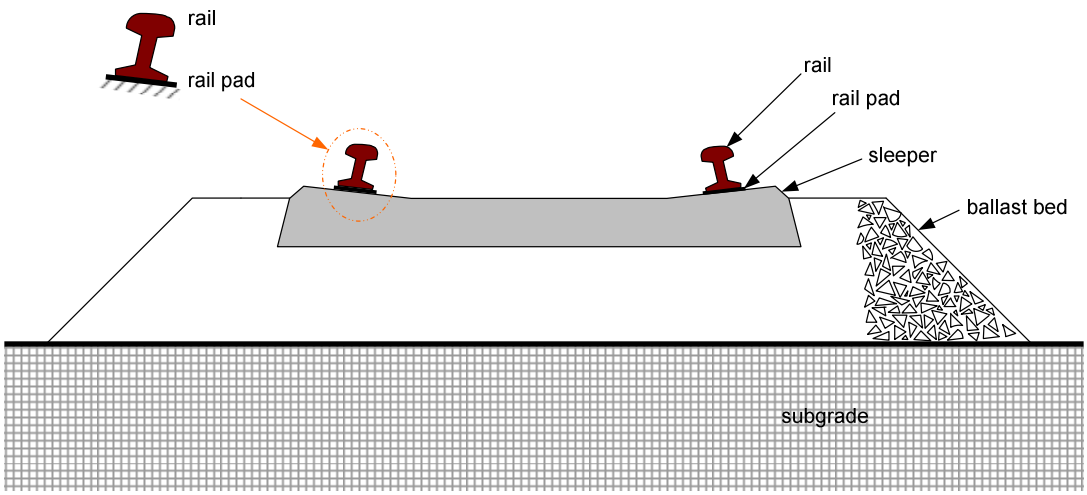


Figure 1 Typical ballasted track structure

It is believed based on the industry experience that railway concrete sleepers have reserves of strength that are untapped. It is thus important to ascertain the spectrum and amplitudes of forces applied to the railway track, to understand more clearly the manner in which track components respond to those forces, and to clarify the processes whereby concrete sleepers in particular carry those actions. In addition, cracks in concrete sleepers have been visually observed by many railway organizations. As noted in the review [4], the principal cause of cracking is the infrequent but high-magnitude wheel loads produced by a small percentage of "bad" wheels or railhead surface defects. Those loads are of short duration but of very high magnitude. For instance, the typical loading duration produced by wheel flats is about 1-10 msec, while the force magnitude can be over 600 kN per rail seat. As mentioned, existing design philosophy for prestressed concrete sleepers is based on allowable stress principle taking into account only the static and quasi-static loads, which are unrealistic to the actual dynamic loads on tracks. In order to devise a new limit states design concept, the research efforts are required to perform comprehensive studies of the loading conditions, the static behaviour, the dynamic response, and the impact resistance of the prestressed concrete sleepers [5-8]. A major research effort at the University of Wollongong is to evaluate and compare the resistance capacities of concrete sleepers under static and impact loads.

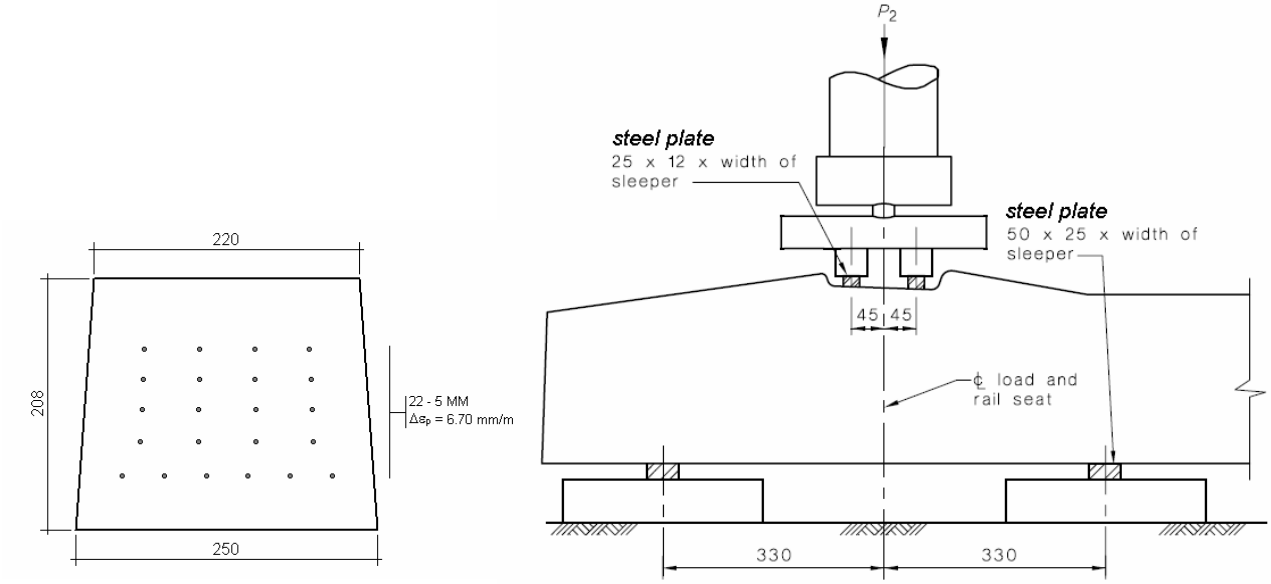
From the literature review, Sukontasukkul et al. [9,10] found that concrete strength under impact loading shows different behavior from that under static loading. Considerably, the concrete material behaves in a more brittle manner, and increases in strength, toughness, and modulus of elasticity were found as the rate of loading increased. This is because the impact cracks tend to propagate through rather than around aggregate granular, resulting in an increase in strength and toughness, and a decrease in the nonlinear portion of stress-strain curve. Then, the failure mode is affected through that process. Under static loading, mixed shear-flexure failure modes can be observed, whilst under impact loading the identical specimens failed only in shear failure type. Apart from the impact material property testing, the studies of impact behaviors of concrete members mostly dealt with flexural members. The failure of such experiments was simply represented by the flexural toughness of such specimens [11-13]. It is discovered that the response of a structure to impact loading depends on an interaction between impacting body and structure by many factors, including relative masses, velocities, contact zone stiffness, frequency of loading, precision of impact, and locally energy-absorbed area [14-15]. Regarding to railway sleepers, Ye, et al. [16] and Wang [17] investigated the resistance of concrete railroad ties to impact loading. Their study focused on the effect of material uses on the ultimate capacity of prestressed concrete sleepers. However, it was unclear whether strain rate has an effect on the behaviors of concrete sleepers or not, and whether there could be a simplified prediction for the ultimate capacity of concrete sleepers. The key hindrance was about how rail pad really affect the system impact responses and how much of that effect. Wakui and Okuda [18] have later proposed a simplified technique to predict the ultimate capacity of concrete sleepers but they failed to prove it. The strain rate and loading rate have been taken into account on the basis of sectional analysis considering only steel tendons' failures. Recently, the impact behaviors as well as the method to predict the energy absorption of railway sleepers under impacts have been presented, but only based on the partial support [19-21].

The emphasis of this paper is placed on the static and dynamic performance of railway prestressed concrete sleepers subjected to static and impact loadings. The prestressed concrete sleepers were designed complied with the Australian Standard: AS1085.14 [2]. The test specimens were kindly supplied by an Australian manufacturer, AUSTRAK Ltd. Load carrying capacity can be obtained from the static tests. Drop-weight impact hammer was used to apply impact loading to the specimens at varied drop heights on the basis of the test arrangement. The drop height is increased step by step until the cracks on sleepers can be visually observed. The impact pulse signals were recorded using the high-capacity dynamic load cell connected to the National Instrument data acquisition system. The relationships between contact impact force and bending moment at railseat of the concrete sleepers are presented in the companion paper [22]. After applying the impact loads, the energy absorptions and impact responses can be achieved. The comparative study of both static and impact energy absorption of prestressed concrete sleepers was carried out. The crack propagations were also identified in this paper.

2. EXPERIMENTAL OVERVIEW

The prestressed concrete sleepers were supplied by an Australian manufacturer, under a collaborative research project of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC). The total length of the sleeper is 2.15m with the gauge length of 1.69m. The details can be found in another companion paper [23]. The broad gauge sleepers obtained are commonly used in the heavy haul coal lines of Australian railway network, especially in the state of Queensland railway system. Figure 2a shows the cross section of the test sleepers.

A series of static tests on the concrete sleepers was performed in accordance with the Australian Standards. The positive four-point bending moment test was conducted based on the assumption that the sleepers would behave as close as those on in-situ tracks [2]. It should be noted that the initial strain of wires due to prestressing is about 6.70 mm/m, and each prestressing wire has a proof stress of 1860 MPa. It is believed that the high strength prestressing wires are of high quality and the strength will not change during time. The tested average compressive strength of cored concrete is 88.5MPa. This value has been corrected according to AS1012.14 [24]. The details of static responses, rotational capacity, post-failure mechanisms, and residual load-carrying capacity of the prestressed concrete sleepers under static loading can be found in ref: [25-26]. Figure 2b depicts the setup for static testing. An electronic load cell was used to measure the applied load in order to keep load accurate and consistent, while LDVT was mounted at the mid-span to obtain the corresponding deflection. Strain gauges were mounted at the top and bottom surfaces of the test sleeper in both sides. The device was connected to computer for recording. The applied loading rate was 0.5mm per minute.



a) cross-section of test sleeper

b) static test setup [2]

Figure 2 Geometry and static testing of concrete ties

A new high-capacity drop-weight impact testing machine has been developed at the University of Wollongong, as depicted in Figure 3. It is currently the largest in Australia. To eliminate surrounding noise and ground motion, the concrete sleepers were set up and placed on a strong isolated floor in the laboratory. The thick rubber mat was used to replicate the ballast support. It is found that the test setup represents the concrete sleepers in general soft track systems [21]. To apply impact loads, the drop hammer used has the weight of 5.81kN. At the railseat was installed the rail with fastening system to transfer the load to the specimens. The roller was attached to the steel drop mass through runners guiding the descent of the drop weight hammer. The hammer was hoisted mechanically to the required drop heights and released by an electronic quick release system. The core of the test rig is the free-fall hammer that can be dropped from a maximum height of 6m, or equivalent to the maximum drop velocity of 10 m/s. The impact load was monitored and recorded by the dynamic load cell connected to the computer. Efficiency of drop weight hammer has been obtained through the calibration tests done using high speed camera. It is found that due to friction of guiding runner the hammer's experimental velocity averagely reduces to 98% of theoretical velocity. Experimental setup and impact tests were arranged in accordance with the Australian Standards. The in-situ conditions of railway concrete sleeper were replicated as shown in Figure 3. Attempts to simulate impact loading actually occurred in tracks were succeeded experimentally and numerically [21].

Figure 3 New high-capacity drop-weight impact testing machine at the University of Wollongong

Table 1 Efficiency of high capacity impact testing machine

Drop height (m)	Measured free falling velocity (m/s)	Theoretical free falling velocity (m/s)	Efficiency (%)
1	4.33	4.43	97.76
2	6.12	6.26	97.70
5	9.65	9.90	97.43
average			97.62

Table 1 presents the efficiency of the impact test rig evaluated using the high speed camera. The theoretical free falling velocity is computed from the conservation of energy. The measured free falling velocity is calculated from the moving time frames corresponding with movement of the object. It is found that the efficiency is gently decreased as the drop height increases.

3. STATIC PERFORMANCE

Cross section of the test concrete sleeper is presented in Figure 2a. Ultimate moment capacity was predicted by sectional analysis of prestressed concrete section, which was calculated from a computer package, Response-2000. This package relied upon the modified compression field theory for concrete structures [25]. The input data include: the measured initial strain of wires due to prestressing is about 6.70 mm/m, and each prestressing wire has a proof stress of 1860 MPa. The tested compressive strength of concrete is 88.5 MPa. It is found that the ultimate positive moment is 58 kNm, while the decompression moment is about 24 kNm.

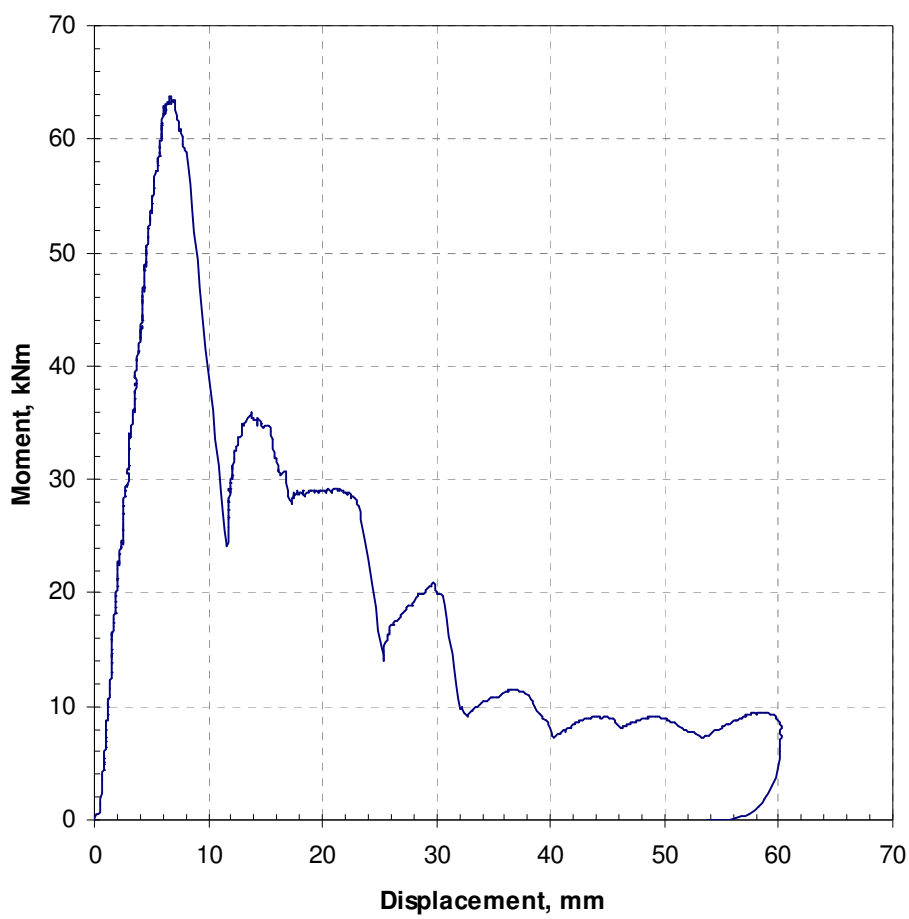


Figure 4 Static moment-displacement relationship

The moment-deflection relationships are presented in Figure 4. The crack initiation load was detected visually during each test as well as determined by the use of the load-deflection relation. Crack initiation was defined as the intersection between the moment-deflection relations in the first and second linear stages [25-26]. This method provides a slightly higher cracking load that from the first deviation point from the linear elastic part of load-deflection relationship. It should be noted that the first cracks are in flexure. The visualized crack initiation moment is about 26 kNm while the measured cracking moment is about 29 kNm. The maximum load experimentally found is 583 kN, equivalent to bending moment about 64 kNm. Comparisons of measured and predicted collapse loads showed good agreement. Figure 5 shows the energy absorption capacity of the sleepers at railseat. The energy absorption characteristic reflects how much the structure can dissipate the work done by external forces. It indicates how much energy given to make sleeper deform at different displacements.

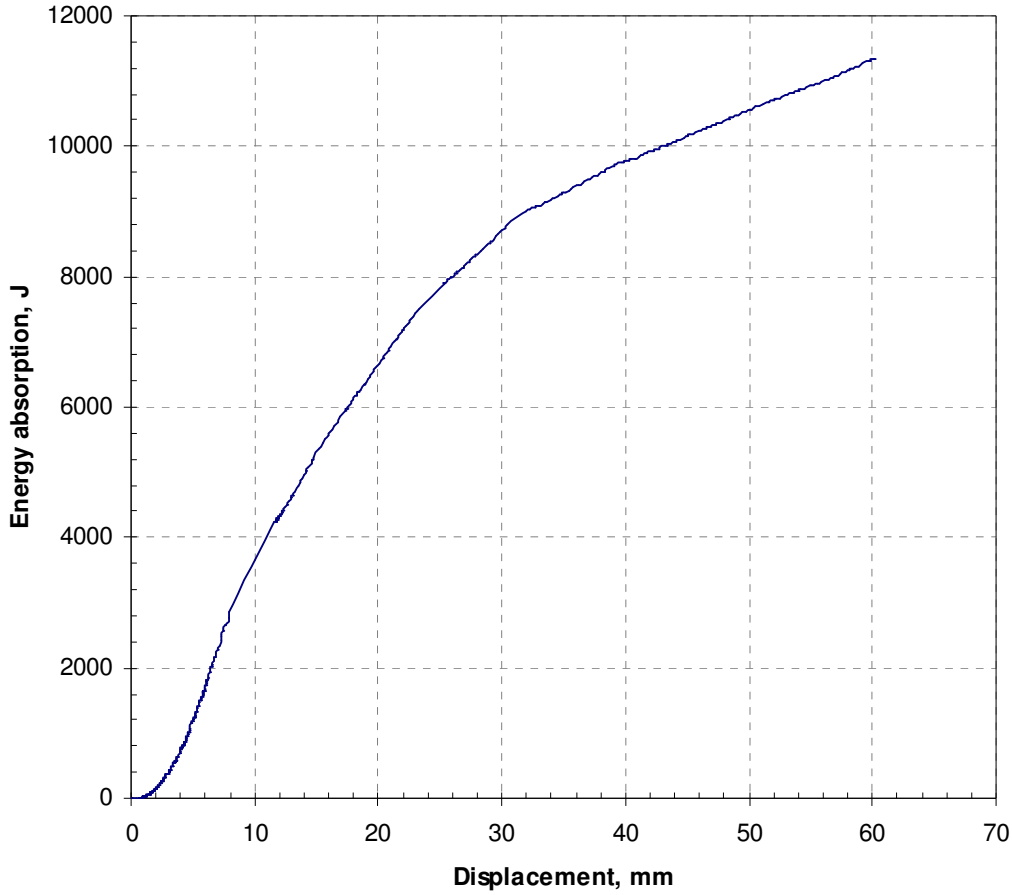


Figure 5 Static energy absorption of the test concrete sleeper

The first crack during the test was a flexure crack appearing in the line of loading, see Figure 6. As the load was increased, the flexure-shear cracks formed at each side after the bending cracks stopped at a distance of about one third of the sleeper depth. All cracks were initiated at the base of the sleeper and propagated towards the compressive zone beneath the applied load. When the load reached the maximum, the concrete crushed and spalled. At this stage, the applied load decreased while the deformation continued from that about 12mm. The prestressing wire seemed to govern the sleeper strength and slightly yield. Combined flexure and shear failure seems to be suitable to explain the crack behaviors. The behaviours of the sleeper after failure can be explained based on its moment-deflection curve. At certain deflections, the prestressing wires started to damage one by one, resulting in a sudden significant vertical drop of load carrying capacity in moment-defection curve. It is discovered that the wire damage started from the lowest layer of such prestressing wires. Each sudden drop releases the breaking noise and loses the residue carrying moment about 10 kNm. It also shows that the concrete sleeper tends to have small ductility, especially smaller after the wires begin to tear off.

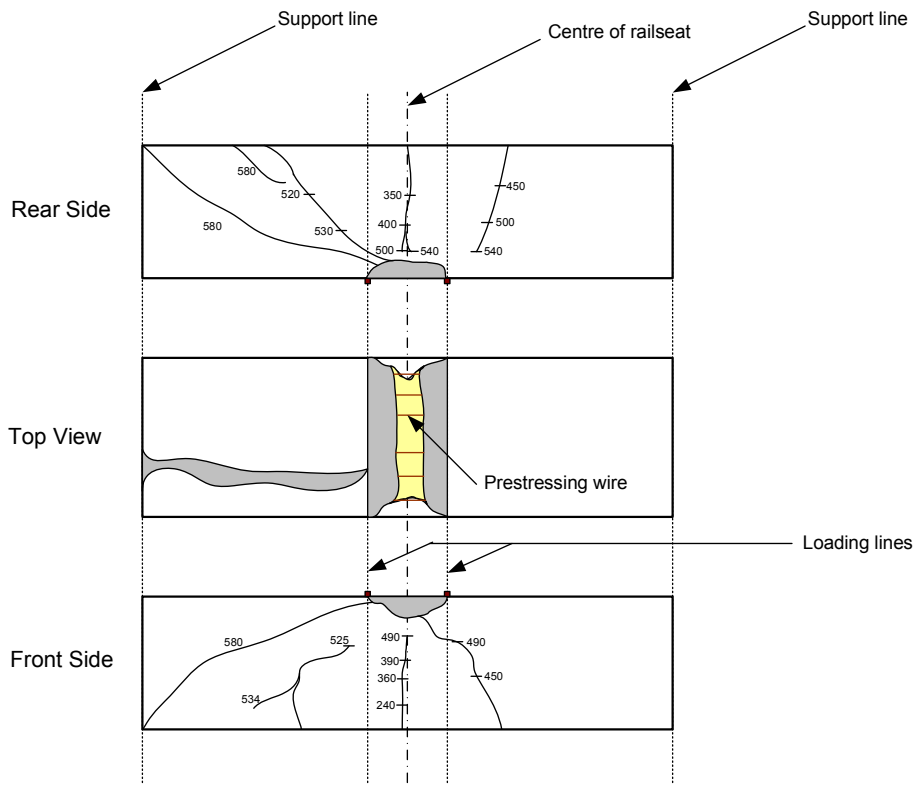


Figure 6 Static crack propagation of the test concrete sleeper

4. DYNAMIC PERFORMANCE

Impact loading is given to the concrete sleeper by dropping the mass of 5.81 kN at varied drop heights step by step. The impact forces measured from the dynamic load cell from direct contact between rail and impactor are presented in Figure 7. Very small bending crack was firstly detected at the drop height of 600mm but the small shear cracks were also found after few blows at the drop height of 800mm. However, no major failure can be observed. Figure 8 shows the cracks due to impact loads.

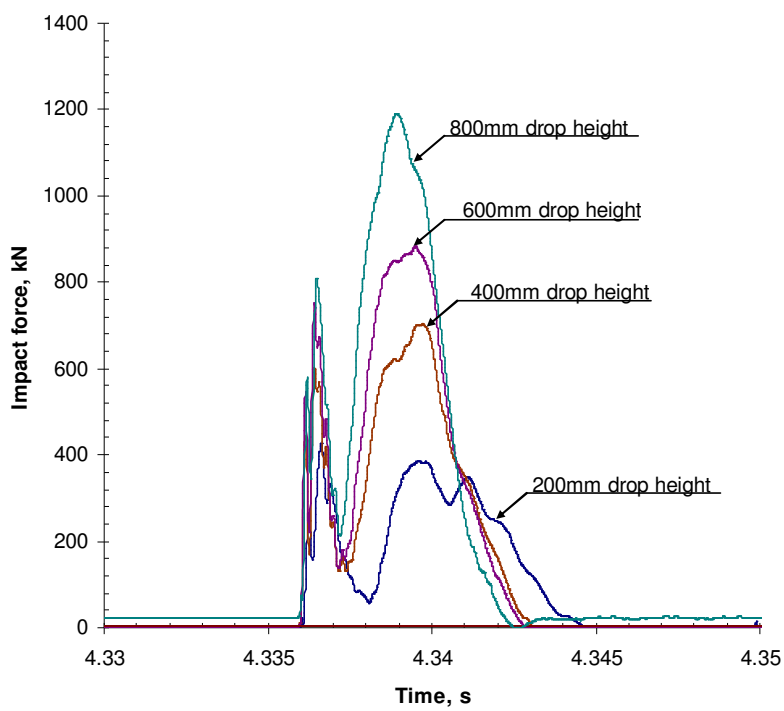


Figure 7 Impact forces at different drop heights

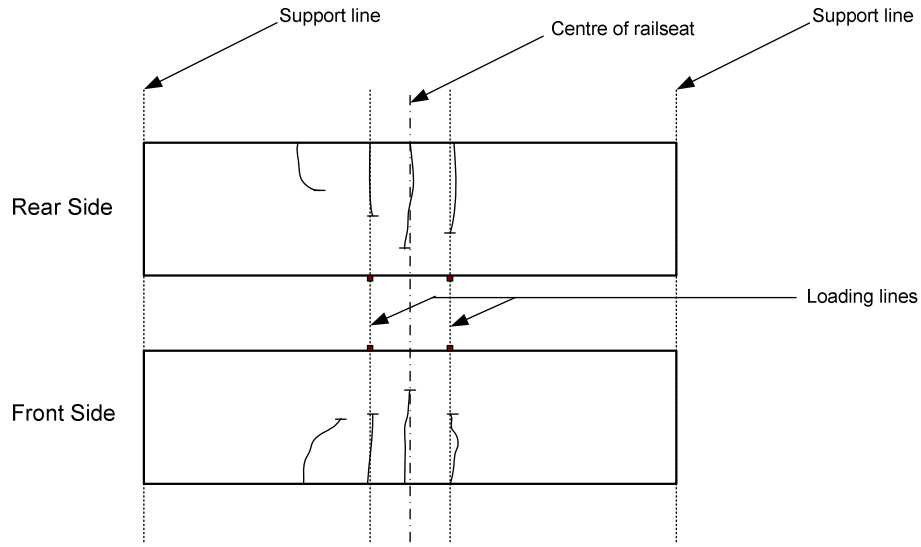


Figure 8 Impact crack propagation of the test concrete sleeper

According to Wang [17], the energy loss in impactor (ΔE) due to frictions in contact zones can be calculated from the integration of impact force signal as follows.

$$\Delta E = \frac{1}{2}M\left(\left[\frac{1}{M}\int p(t)dt - 0.98\sqrt{2gh}\right]^2 - 2gh(0.98)^2\right) \quad (1)$$

The factor 0.98 is the efficiency of the test rig. *M* is the drop mass (5.81kN); *p(t)* is the impulse load history; *g* is 9.81 m/s^2; and *h* is the drop height.

The energy losses in the impactor at each drop height are tabulated in Table 2. The potential energy (E_p) is computed from the equation E_p = Mgh. It is found that the higher drops loss lesser energy in the impactor due to contact frictions. The average percent loss in the impactor is about 30% so that only about 70% of the total energy transfers to the track components.

Table 2 Energy losses in the impactor at different drop heights

Drop height (m)	Energy loss (J)	Total Potential Energy (J)	Percent loss (%)
0.2	421.9	1161.5	36.3
0.4	678.9	2323.0	29.2
0.6	991.5	3484.5	28.5
0.8	1267.1	4646.0	27.3
average			30.3

Figure 9 shows the example of acceleration responses at mid-span and at railseat of the railway concrete sleepers. The displacement responses can subsequently obtained from the integration of acceleration responses. Based on Birch et al. [27], the actual energy absorbed by the sleepers can be approximately computed from the multiplication between maximum impact load and the maximum displacement spectra integrated from the acceleration responses. Table 3 gives the results of energy absorption by the test sleeper under different drop heights. Note that the energy input is derived from the remaining energy applied to the track components. Calculated from Table 2, it is the results when the total potential energy is subtracted by the energy loss. Table 4 summarizes the energy distribution to each particular part in the test setup while Figure 10 presents the energy distribution percentage. Averagely, the impact energy will be absorbed by the sleepers in this particular track (simulated as general soft tracks) about 45%. It should be noted that this value is based on the simplification that uses the maximum displacement response and maximum impact load. This value is the upper bound of the actual dynamic performance of the sleeper and track system.

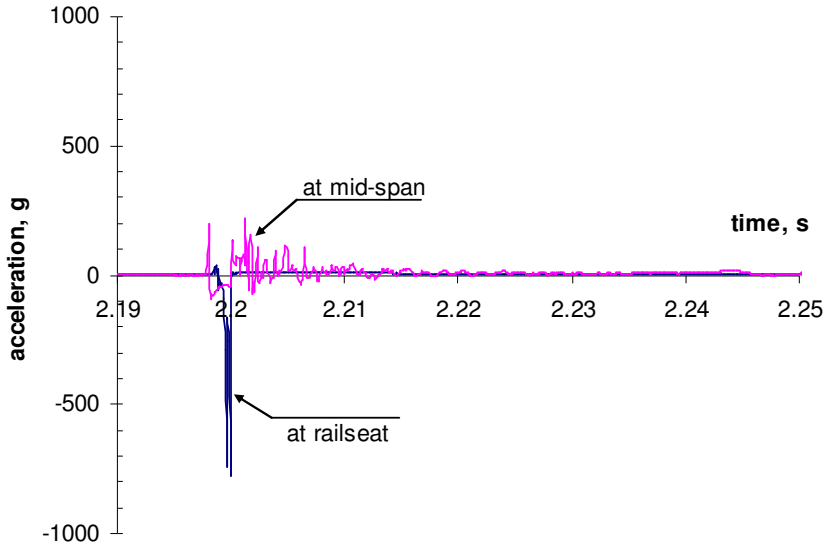


Figure 9 Acceleration responses of the concrete sleeper to impact loading (0.2m drop height)

Table 3 Energy losses to the ballast support at different drop heights

Drop height (m)	Max displacement (mm)	Max impact load (kN)	Energy absorbed by sleeper (J)	Energy Input (J)	Energy loss to ballast support (J)
0.2	1.3	426	554	740	186
0.4	1.5	700	1050	1644	594
0.6	1.6	883	1413	2494	1081
0.8	1.9	1160	2204	3379	1175

Table 4 Summary of energy losses

Drop height (m)	Total Potential Energy (J)	Energy loss in the impactor (J)	Energy loss to ballast support (J)	Total energy loss (J)	Energy absorbed by sleeper (J)
0.2	1162	422	186	608	554
0.4	2323	679	594	1273	1050
0.6	3485	992	1081	2073	1413
0.8	4646	1267	1175	2342	2204

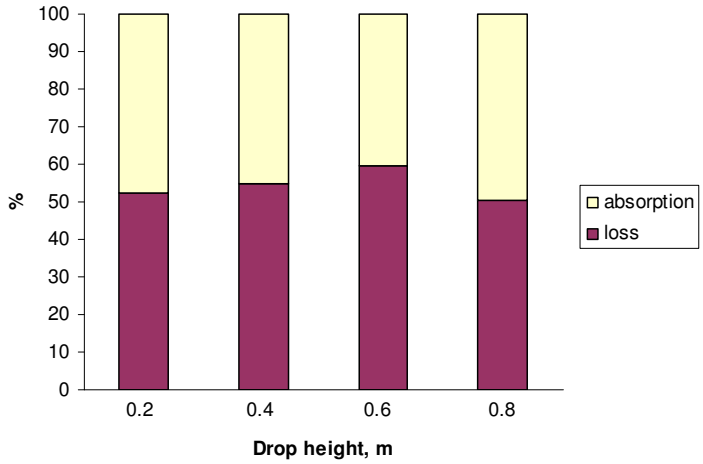


Figure 10 Energy distribution

Based on the energy balance theory, it is also discovered that the cracking moment of about 29 kNm is associated with the energy absorbed by the sleeper of roughly 1000J. It can be seen from the impact testing that the required drop height to create cracks in the sleeper is at 0.6m. At this drop height, the impact energy absorbed by sleeper is 1413J, which is slightly higher than the static energy absorption. This phenomenon is ascribed to the effect of strain rate, as when the strain rate is high the concrete material becomes stronger but brittle [9,10,20].

5. CONCLUSIONS

The nature of loading on tracks is of impact loading. Current design manner omits those actions since the existing knowledge is insufficient. The main aim of this study is to develop the rational design method for prestressed concrete sleepers on the basis of limit states design concept. This study includes comprehensive investigations in loading conditions, static and dynamic performance, and impact resistance of prestressed concrete sleepers. This paper presents the performance of the selected Australian prestressed concrete sleepers under static and dynamic loading conditions. The ultimate capacity of the prestressed concrete sleeper has been carried out in accordance with the Australian Standards. The fracture energy and energy losses under static and dynamic conditions of the prestressed concrete sleepers as a performance indicator of damage for the selected limit states, are also quantitatively evaluated.

The static results are found in good agreement with those sampling tests done by the manufacturer itself. It can be seen that the prestressed concrete sleeper has relatively low ductility. Also, it is found that the modified compression field theory can be used to predict the static responses of prestressed concrete sleepers. The predicted result is about 10% different from the experimental one. The energy absorption capacities of prestressed concrete sleepers under static and dynamic loading are highlighted in this paper. It can be concluded that the energy balance theory is applicable to the railway sleepers and track system. This paper investigate the energy loss in either the impactor (or equivalent to wheels) and in rubber mat (equivalent to ballast support). For this particular test setup, representing soft railway tracks in general, it is found that the impact energy can be lost up to 55%. This energy will damage the wheel and break the ballast gravel. The remaining of around 45% will be absorbed by the railway sleeper. Energy absorption capacity can clearly indicate the damage severity of the tested specimens. It is also discovered that, due to the effect of high strain rate, concrete material plays a dominant role in the dynamic failure mode of prestressed concrete sleepers.

6. ACKNOWLEDGEMENT

The authors are grateful to the Australian CRC for Railway Engineering and Technologies (Rail-CRC) for the financial support throughout the Project No 5/23. The prestressed concrete sleepers were kindly provided by Austrak Ltd and ROCLA Ltd. The authors would also like to thank Alan Grant, Ian Bridge, Bob Roland, and Jason Knurst, for their assistance during the course of this project.

7. REFERENCES

1. Esveld C, Modern Railway Track, The Netherlands MRT Press, 2001.
2. Standards Australia, “Railway track material - Part 14: Prestressed concrete sleepers” Australian Standard: AS1085.14-2003, 2003
3. Remennikov AM and Kaewunruen S, A review on loading conditions for railway track structures due to wheel and rail vertical interactions. Progress in Structural Engineering and Materials, invited, 2006.
4. Murray M and Cai Z, Literature review on the design of railway prestressed concrete sleeper. RSTA Research Report, Australia, 1998.
5. Gustavson R, Static and dynamic finite element analyses of concrete sleepers. Licentiate Eng. Thesis, Dept of Struct Eng, Chalmers University of Technology, Göteborg, Sweden, 2000.
6. Remennikov, AM and Kaewunruen, S, Experimental investigation on dynamic railway sleeper/ballast interaction. Experimental Mechanics, 46(1), 57-66, 2006.
7. Kaewunruen, S and Remennikov, AM, Sensitivity analysis of free vibration characteristics of an in-situ railway concrete sleeper to variations of rail pad parameters. Journal of Sound and Vibration, 298(1-2), 453-461, 2006.

8. Kaewunruen, S and Remennikov, AM, Effect of improper ballast tamping/packing on dynamic behaviors of on-track railway concrete sleeper. International Journal of Structural Stability and Dynamics, 7(1), 1-11, 2007.
9. Sukontasukkul P, Mindess S. The shear fracture of concrete under impact loading using end confined beams. Materials and Structures 36: 372-378, 2003.
10. Sukontasukkul P, Mindess S, Banthia NP. Effect of loading rate on damage of concrete. Cement and Concrete Research 34: 2127-2134, 2004.
11. Banthia NP, Mindess S, Bentur A. Impact behaviour of concrete beams. Materials and Structures 20: 293-302, 1987.
12. Kishi N, Mikami H, Matsouka KG, Ando T. Impact behaviour of shear-failure-type RC beams without shear rebar. International Journal of Impact Engineering 27: 955-968, 2002.
13. Kishi N, Mikami H, Ando T. Impact-resistant behaviour of shear-failure-type RC beams under falling-weight impact loading. In: Proceedings of the 7th International Conference on Structures under Shock and Impact, p. 499-508, 2002.
14. Adachi T, Tanaka T, Sastranegara A, Yamaji A, Kim S-K, Yang I-Y. Effect of transverse impact on buckling behavior of a column under static axial compressive force. International Journal of Impact Engineering 30: 465-475, 2004.
15. Remennikov AM and Kaewunruen S, Impact resistance of reinforced concrete columns: experimental studies and design considerations. Procs of the 19th Australasian Conference on the Mechanics of Structures and Materials, Nov 29 - Dec 1, Christchurch, New Zealand, 817-824, 2006.
16. Ye X, Wang, N, Mindess, S.Effect of loading rate and support conditions on the mode of failure of prestressed concrete railroad ties subjected to impact loading, Cement & Concrete Research 24(7): 1386-1298, 1994
17. Wang, N. Resistance of concrete railroad ties to impact loading, PhD Thesis, University of British Columbia, Canada, 1996.
18. Wakui H and Okuda H. A study on limit-state design for prestressed concrete sleepers. Concrete Library of JSCE 33: 1-25, 1999.
19. Kaewunruen S and Remennikov AM. Low-velocity impact analysis of railway prestressed concrete sleepers. Proceedings of the 23rd Biennual Conference of Concrete Institute of Australia - Concrete 2007, October 18-20, Adelaide, Australia, 2007.
20. Remennikov AM and Kaewunruen S. Experimental determination of energy absorption capacity for railway prestressed concrete sleepers under ultimate impact loading. Proceedings of International Conference on Structural Engineering and Construction - ISEC2007, Sep 26-28, Melbourne, Australia, 2007.
21. Kaewunruen S and Remennikov AM. Experimental and numerical studies of railway prestressed concrete sleepers under static and impact loads. Civil Computing; Special Issue on Computer Application in Civil Engineering, AIT-ACECOMS, (invited), 2007.
22. Kaewunruen S and Remennikov AM. Relationship between interface impact force and railseat moment of railway prestressed concrete sleepers. Proceedings of the SEM Annual Conference and Exposition 2007, June, MA, USA.
23. Kaewunruen S and Remennikov AM. Influence of voids and pockets on vibration characteristics of railway concrete sleepers. Proceedings of the SEM Annual Conference and Exposition 2007, June, MA, USA.
24. Standards Australia, Method of testing concrete – Method for securing and testing cores from hardened concrete for compressive strength, Australian Standard: AS1012.14-1991, 1991.
25. Kaewunruen S and Remennikov AM, Rotational capacity of railway prestressed concrete sleeper under static hogging moment, Proceedings of the tenth East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-10), Bangkok, Thailand, August 3-5, 2006.
26. Kaewunruen S and Remennikov AM, Post-failure mechanism and residual load-carrying capacity of railway prestressed concrete sleeper under hogging moment. Proceedings of the International Conference on Structural Integrity and Failure - SIF2006, Sep 27 - 29, Sydney, Australia, 2006.
27. Birch RS, Jones N, Jouri WS, Performance assessment of an impact test rig, Proceedings of the Institution of Mechanical Engineers, Part C. 202(4): 275-285, 1988.

Note: The authors' work can be electronically found via the University of Wollongong's Research Online at URL **http://ro.uow.edu.au**