2007

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Publication Details

This peer-reviewed paper was originally published as Remennikov, AM and Kaewunruen, S, Experimental determination of energy absorption capacity of railway prestressed concrete sleepers under ultimate impact loading, Proceedings of the 4th International Conference on Structural Engineering and Construction (ISEC2007), Melbourne, Australia, 26-28 Sep 26-28 2007, 381-386. Copyright 2007 Taylor & Francis.

Experimental determination of energy absorption capacity for prestressed concrete sleepers under impact loads

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ABSTRACT: Extreme loading conditions on railway tracks may include dynamic impact loads with very high magnitude but short duration. These loading conditions are caused by wheel or rail abnormalities such as flat wheels, dipped rails, etc. A high-capacity drop weight impact testing machine was constructed at the University of Wollongong, in order to evaluate the ultimate capacity of prestressed concrete sleepers under impact loads. This paper presents the experimental investigations to evaluate failure modes, flexural toughness, and energy absorption mechanisms for railway prestressed concrete sleepers under static and impact loadings. Energy absorption capacity of the prestressed concrete sleepers was also evaluated to determine the amount of energy required to fail the sleeper under impact load. Static and impact tests were carried out on the Australian-manufactured prestressed concrete sleepers. The residual capacity of the prestressed concrete sleepers after impact has also been highlighted.

1 INTRODUCTION

Railway sleeper (or called 'railroad tie') is a main part of railway track structures. Its role is to distribute loads from the rail foot to the underlying ballast bed. Figure 1 shows the typical components of ballasted railway tracks. There is a widespread suspicion 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 (Murray and Cai, 1998), 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 400 kN per rail seat. Current design philosophy for prestressed concrete sleepers is based on permissible 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 (Kaewunruen and Remennikov, 2007). A major research effort at the University of Wollongong is to evaluate the ultimate capacities of concrete sleepers under static and impact loads.

In general, Sukontasukkul et al. (2003, 2004) 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 (Banthia et al., 1987; Kishi et al., 2002a, 2002b). 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, veloci-

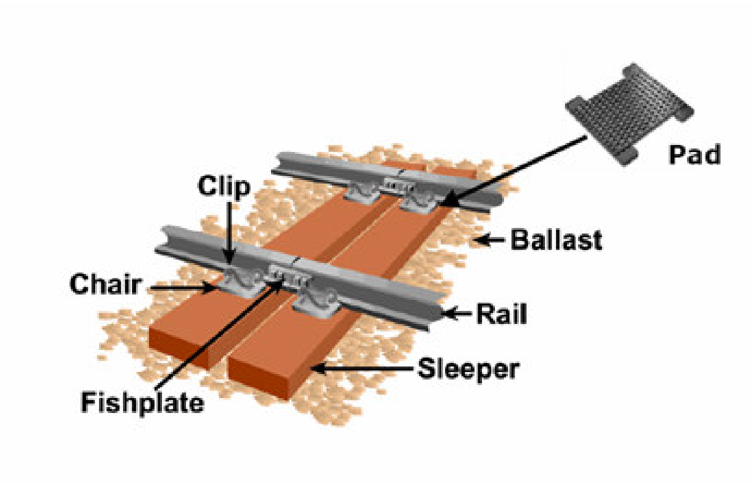


Figure 1. Typical components of railway tracks.

ties, contact zone stiffness, frequency of loading, precision of impact, and locally energy-absorbed area (Hughes and Al-Dafiry, 1995). Regarding to railway sleepers, Ye, et al. (1994) and Wang (1996) 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 (1999) have later proposed a simplified technique to predict the ultimate capacity of concrete sleepers but they failed to prove it. In the proposal, strain rate and loading rate have been taken into account in moment capacity calculation on the basis of sectional analysis and only steel tendons' failure mechanisms. So far, the ultimate behaviors of prestressed concrete sleepers under impacts are currently unclear and there is no method to predict the ultimate moment capacity under impact loading.

This paper examines the ultimate behaviour of railway prestressed concrete sleepers subjected to static and impact loading. The prestressed concrete sleepers were designed complied with Australian Standard: AS1085.14 (2003). The test specimens were kindly supplied by an Australian manufacturer, ROCLA. Static energy absorption capacity can be obtained from the static tests. Drop-weight impact hammer was used to apply extreme impact loading to the specimens at certain drop heights on the basis of the test arrangement. The impact pulses were recorded using the high capacity load cell connected to the National Instrument data acquisition system. After applying the ultimate impact load, the sleeper was re-tested for residual capacity and energy absorption. The comparative study of both static and impact energy absorption of prestressed concrete sleepers was carried out. The damage and failure modes were identified in this paper.

2 EXPERIMENTAL OVERVIEW

2.1 *Testing specimens*

The typical full-scale prestressed concrete sleeper, which is often used in broad gauge tracks, was selected for these tests. The dimensions and shape of the prestressed concrete sleeper are shown in Table 1. The high strength concrete material was used to construct the prestressed concrete sleepers, with design compressive strength at 28 days of 55 MPa, and the prestressing steels used were the high strength with rupture strength of 1860 MPa. The cored samples, drilled from the sleepers, were taken and tested, as per the Australian Standard AS1012.14, as shown in Figure 2. It was found that the average compressive strength at the test age of about two years was 80 MPa. It is believed that the high strength prestressing wires are of high quality and the strength will not change during time. Cross section of the prestressed concrete sleepers at railseat can be seen in Figure 3.

2.2 *Experimental program*

In the experiments, a steel plate was used to distribute impact load to concrete sleepers. The width of the plate is equivalent to railseat and effective zone described in AS1085.14 (2001). The supports were considered as a simple support with influential span due to elastic support. These supports provide restraints to the translational and rotational deformation. The weight of the projectile was set as 5.81 kN, and therefore, the drop height becomes the only variable.

The experimental setup thus required for specific energy absorption capacity for particular sleeper, in order to back calculating for the optimum drop height. A sleeper was performed the static tests in the conventional manner as shown in Figure 4. 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. The device was connected to computer for recording.

Figure 2. Cored concrete samples

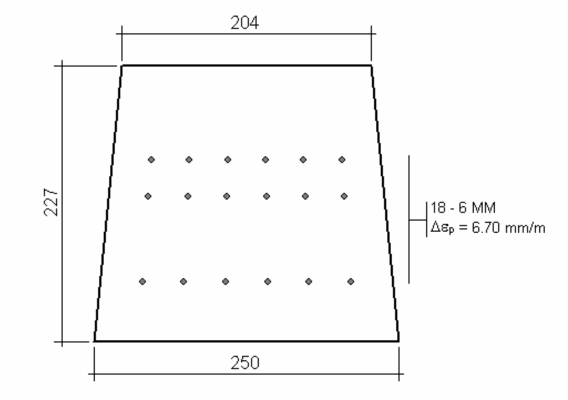


Figure 3. Cross section of sleepers at railseat

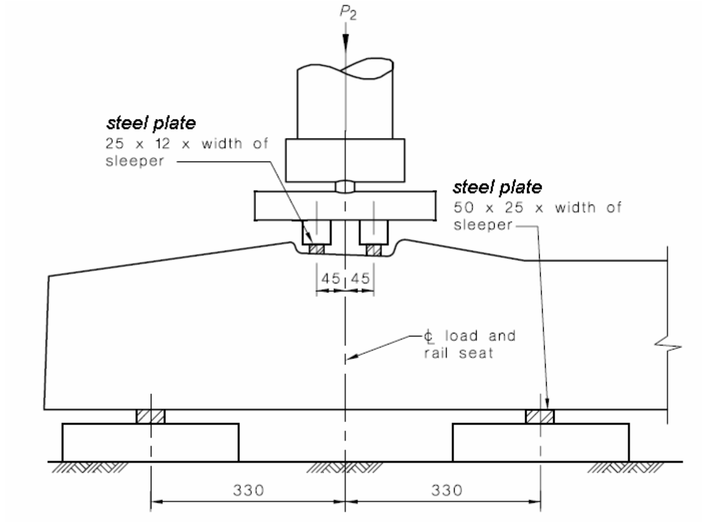


Figure 4. Static test setup.

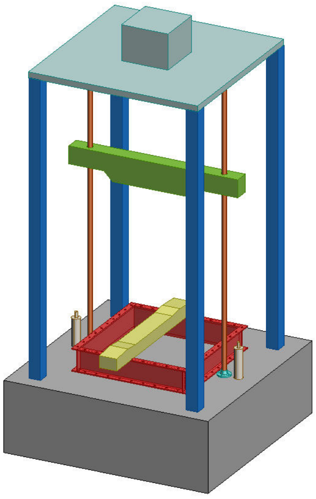


Figure 5. Impact test setup.

Table 1. Dimensions and masses of the test sleepers

Mass (kg)	Gauge length (m)	Total length (m)	At railseat (m)		At centre (m)	
			width	depth	width	depth
206.0	1.60	2.50	0.20	0.23	0.21	0.18

In this study, the drop height and drop mass were selected to simulate a typical impact load due to a wheel flat of 20-25mm, which could generate an impact of over 600kN. The drop height was determined from a series of pre-test experiments to cause complete collapse under one blow. To eliminate surrounding noise and ground motion, the concrete sleepers were set up and placed on a strong isolated floor in the laboratory. The drop hammer used has the weight of 5.81kN. At the railseat was installed the impact plate 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 height (ultimate resistance of the sleeper) and released by an electronic quick release system.

The sketch of impact testing setup is illustrated in Figure 5. 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 (h_T). Therefore, the required drop height based on energy conservation theory was revised taking the test rig efficiency into account. The new required drop height (h) read

$$h = h_T/0.96 \tag{1}$$

Table 2. Summary of the test series and specimens.

Experiment No.	Loading	Required Energy (J)	Drop Height Used (mm)	Imparted Energy (J)
A1-S	static	Failed at 2,700	-	
A2-I	single impact	574	100	580
A3-I	single impact	2,700	500	2,900

Table 3. Summary of experimental moment capacities of prestressed concrete sleepers.

Loading	Target Conditions	Tested moment capacity (kNm)	Type of damage
Static	crack	34	First crack is due to bending
	fail	84	Shear failure
Impact	crack	44	First crack is the bending crack
	fail	95	Bending-shear failure

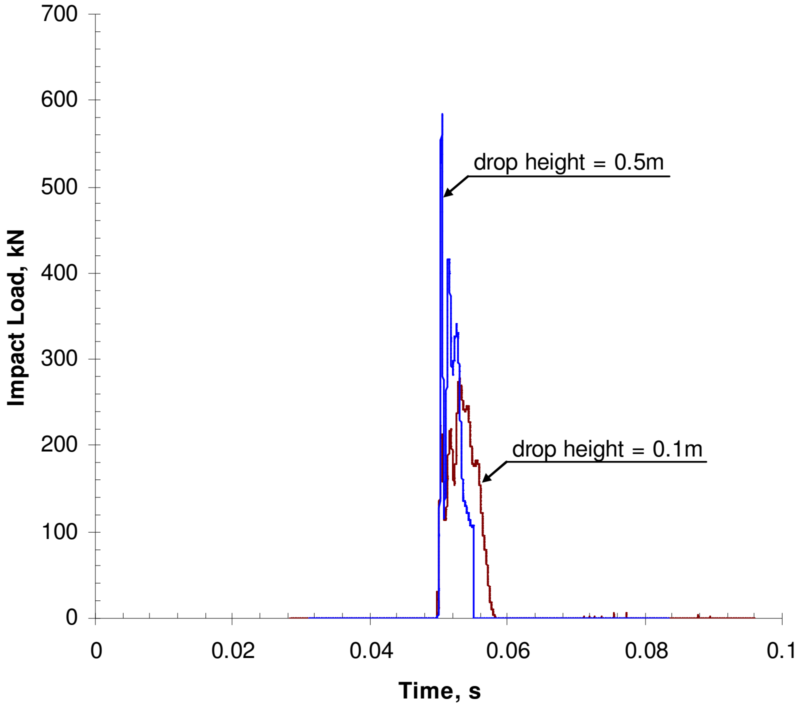
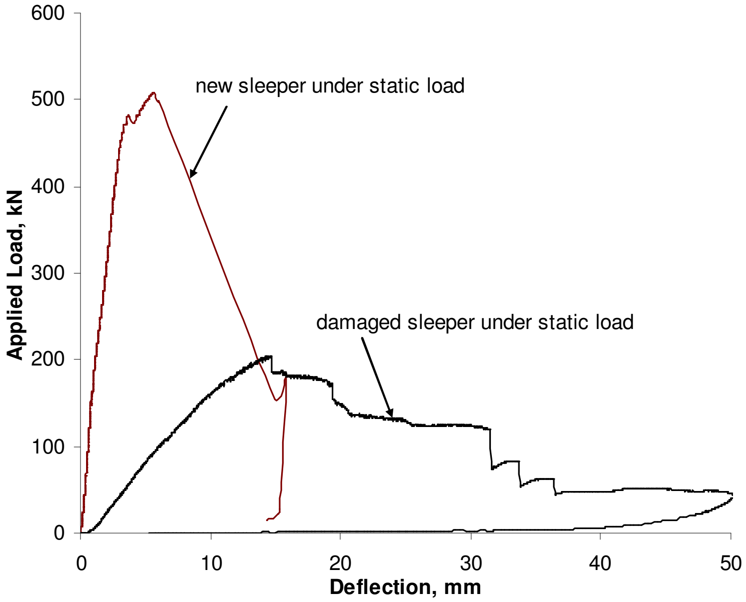


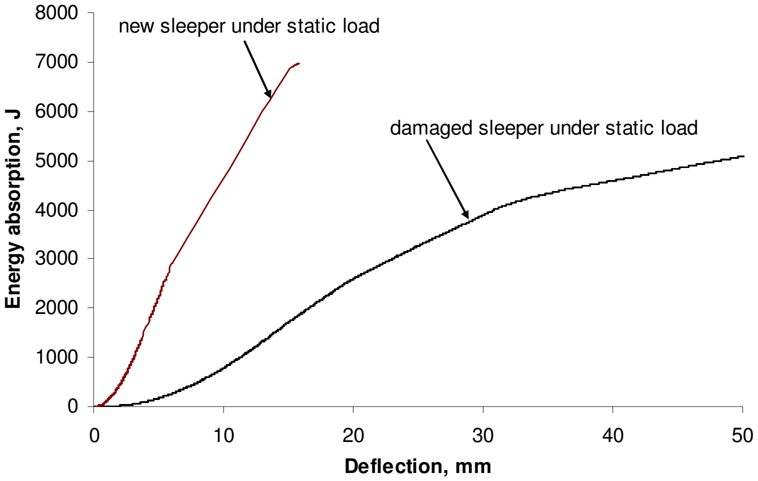
Figure 6. Impact force measurements.

Figure 7. Behavior of test concrete sleeper under static load.

Figure 8. Behavior of test concrete sleeper under ultimate impact load.



a) load-deflection curves



b) energy absorption

Figure 9. Comparison of residual strengths of fresh and damaged sleeper.

3 RESULTS AND DISCUSSIONS

Impact forces measured from the dynamic load cell are presented in Figure 6. The summary of static and impact experimental results is given in Table 3. Figure 7 presents the failure mode of the concrete sleeper under static loading. Bending crack was firstly detected but the significant cracks were associated with shear failure. Interestingly, it was found that the concrete sleeper under the ultimate impact (at drop height of 0.5m) has a major crack as shown in Figure 8, but the sleeper is likely to possess residual moment capacity as there is no visual indication of wire damage. The small visual cracks found include either bending and shear cracks. However, no major failure was observed. As a result, the damaged concrete sleeper was then re-tested under static loading to evaluate such residual capacity. Figure 9 shows the comparison of load-deflection curves between new and damaged sleepers. It is found that the residual load carrying capacity of damaged sleeper is much less than that of new sleeper. It is also found that the prestressing wires have already yielded after the impact test as at the beginning the slope of load-deflection curve is very low and negligible. Until a certain point, the concrete started to crush and the wires damaged one by one as can be seen from the significant drop of load curve.

Figure 9a shows the comparison of load-deflection curves between new and damaged sleepers. It is found that the residual load carrying capacity of the damaged sleeper is much less than that of the new sleeper. After a certain point, the concrete started to crush and the steel wires breaking one by one as can be seen from the significant drop of load curve. From Figure 9b, it is clear that the prestressing wires have yielded as there is no energy needed for the beginning range of displacements, up till 3mm. However, it is found that due to the reserve strength of the concrete and other wires, certain energy is required to further damage the sleepers until more crushing and damage of upper wires happen. This is the proof that the energy balance theory is applicable to this case as the total energy absorption for new ties is 7,200J, and after the impact energy of 2,900J is delivered with energy loss of about 400J, the residual capacity is found about 4,700J for the damaged sleeper (Wang, 1996).

4 CONCLUSIONS

This study investigates the energy absorption capacities of prestressed concrete sleepers under static and dynamic loadings, as well as the residual moment capacity after the ultimate impact. Based on the comparison of static behaviors of new and damaged sleepers, it can be concluded that the energy balance method can be used to indicate the ultimate impact behaviors of prestressed concrete sleepers. 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 and residual capacity of prestressed concrete sleepers.

ACKNOWLEDGEMENT

The authors are grateful to the Australian CRC for Railway Engineering and Technologies (Rail-CRC) for the financial support throughout this study. The authors would also like to thank Alan Grant and Ian Bridge, for their assistance in this project.

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