

# On the residual energy toughness of prestressed concrete sleepers in railway track structures subjected to repeated impact loads

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**ABSTRACT:** Installed as the cross-tie beam support in railway track systems, the prestressed concrete sleepers (or railroad ties) are designed in order to carry and transfer the wheel loads from the rails to the ground. It is nowadays best known that railway tracks are subject to the impact loading conditions, which are attributable to the train operations with either wheel or rail abnormalities such as flat wheels, dipped rails, etc. These loads are of very high magnitude but short duration, as well as there exists the potential of repeated load experience during the design life of the prestressed concrete sleepers. These have led to two main limit states for the design consideration: ultimate limit states under extreme impact and fatigue limit states under repeated impact loads. Prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, their impact responses and behaviours under the repetitions of severe impact loads are not deeply appreciated nor taken into the design consideration. This experimental investigation was aimed at understanding the residual capacity of prestressed concrete sleepers in railway track structures under repeated impact loading, in order to form the state of the art of limit states design concept for prestressed concrete sleepers. A high-capacity drop weight impact testing machine was constructed at the University of Wollongong as to achieve the purpose. Series of repeated impact tests for the in-situ prestressed concrete sleepers were carried out, ranging from low to high impact magnitudes. The impact forces have been correlated against the probabilistic track force distribution obtained from a Queensland heavy haul rail network. The impact-damaged sleepers were re-tested under static conditions in order to evaluate the residual energy toughness in accordance with the Australian Standard. It is found that a concrete sleeper damaged by an impact load could possess significant reserve capacity sufficient for resisting the axle load of about 1.05 to 1.10 times of the design axle loads. The accumulative impact damage and residual energy toughness under different magnitudes of probabilistic impacts are highlighted in this paper. The effects of track environment including soft and hard tracks are also presented as to implement design guidance related to the serviceability or fatigue limit states design.

*Keywords: Prestressed concrete sleeper; Repeated impact behaviour; Impact fatigue; Accumulative damage; Residual energy toughness; Ballasted railway track*

## 1 INTRODUCTION

Railway prestressed concrete sleepers have been utilized in railway industry for over 50 years. The railway sleepers (called 'railroad ties') are a main part of railway track structures. A major role is to distribute loads from the rail foot to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is considered around 50 years (Standards Australia, 2003). Figure 1 shows the typical ballasted railway tracks and their components. There are two main groups of track components: substructure and superstructure. The substructure includes ballast sometimes with

subballast, subgrade, and ground formation, while the superstructure consists of rails, rail pads, fastening systems, and railway concrete sleepers. Railway track structures are often subjected to the impact loading conditions due to wheel/rail interactions associated with the abnormalities in either a wheel or a rail (Remennikov & Kaewunruen, 2008). The magnitude of the dynamic impact loads per railseat is varying from 200 kN to sometimes more than 750 kN, whilst the design static wheel load per railseat for a 40-tonne axle load could be only as much as 110 kN (Kaewunruen & Remennikov, 2008a).

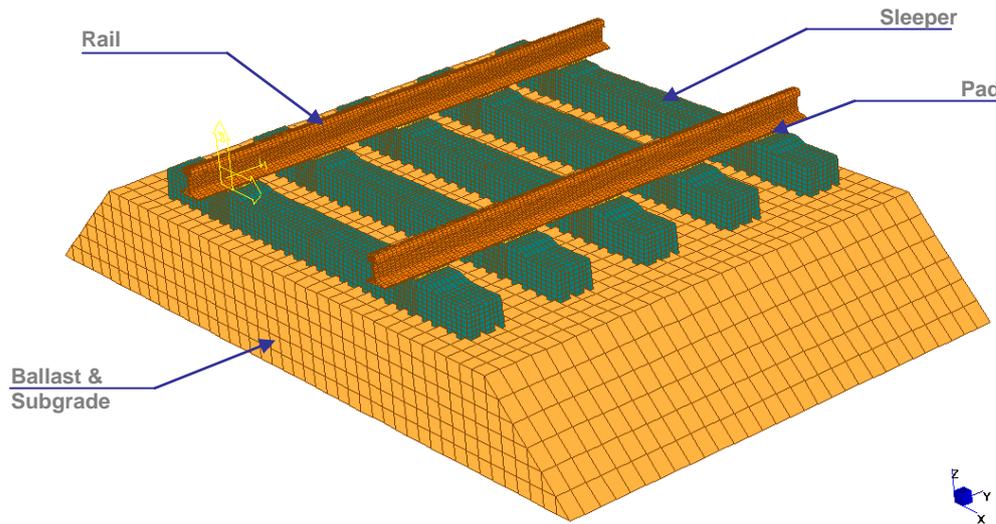


Figure 1. Typical components of railway tracks

All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. The typical dynamic load imposed by running wagons can be treated as a quasi-static load when no irregularity exists. However, when the irregularity appears, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles passing at any generic operational speed (Kaewunruen, 2007). The shape of impact loading varies depending on various possible sources of such loading, e.g. wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called “wheel fly”, will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse applied right after when the static wheel load is removed during the loss of contact (Kaewunruen, 2007). The typical magnitude of impact loads depends on the causes and the traveling speed of train. The durations of such loads are quite similar, varying between 1 and 10 msec. However, the representative values of the first peak ( $P_1$ ) of the forces caused by dipped joints should be about 400 kN magnitude with 1 to 5 msec time duration. For the second peak ( $P_2$ ), the average values are about 80 kN magnitude and 5 to 12 msec time duration. The effect of impact forces depends on the duration. It was found that the longer the duration, the significance the effect (Remennikov & Kaewunruen, 2008).

Therefore, it should be taken into account that the typical duration of impact wheel forces varies widely between 1 and 12 msec (Wakui & Okuda, 1999; Esveld, 2001; Kaewunruen & Remennikov, 2008b).

A recent study showed that it is highly possible that railway sleepers could be subjected to severe impact loads (Leong, 2007). In general, the dynamic load characteristics considered in design and analysis include the magnitudes of impact loading and the variety of pulse durations. In general, although the loading and strain rate effects may increase the strength of materials, the high loading magnitude could devastate the structural members. In structural design and analysis, the public safety must not be compromised so the design loads must be appropriate and associated with the long return periods, which would optimally provide the low probability of occurrence on structures during their design life. For further explanation, a design load that is associated with 50 year return period has the likelihood of occurrence that the design load might happen only once in 50 years regardless of the structural life span.

Wheel load is an important factor in design and analysis of railway track and its components. The design load ( $F^*$ ) for the limit states design concept takes into account both the static ( $F_s$ ) and dynamic ( $F_i$ ) wheel loads. There are three main steps in designing the concrete sleepers. First, the design actions or loads are to be determined based on the importance level of the track (e.g.  $F^* = 1.2 F_s + 1.5 F_i$ ). Then, the design shear and moment envelopes can be achieved by converting the design load to sleeper responses using advanced railtrack dynamic analysis or the design formulation (Kaewunruen and Remennikov, 2007). Last, the strength and serviceability of the prestressed concrete sleepers can be optimized in

accordance with AS3600 Concrete structures (Standards Australia, 2012). An initially proposed limit states design methodology and procedure can be found in details in Remennikov et al. (2007).

The building code of Australia (BCA) in conjunction with Standards Australia indicates the importance levels of structures for determining the probabilistic wheel loads for track design at ultimate limit states, upon the consequences of failure of the structures (Australian Building Codes Board, 1994). As the design criteria for railway sleepers (with 50 to 100 years design life), loading with 100 years return period should be considered for the Category 1 tracks (infrequent traffic, interstates); 500 years return period for Category 2 tracks (regular, freight); and 2,000 years return period for Category 3 tracks (inner city suburban, heavy haul). For design and analysis of prestressed concrete sleepers, certain design loads associated with probabilistic return periods (related to the importance level of the structure) must be considered. The dynamic responses of prestressed concrete sleepers in railway track structures under repeated impact loads associated with the design probability of occurrence (and return period) have not yet been adequately addressed, although they are the key indicator for determining the reserved strength mechanism and performance-based optimisation (Murray and Cai, 1998).

Leong (2007) showed the statistical data of wheel loading obtained from railway networks in Queensland, Australia. Using probabilistic analysis, the possibility of occurrence related to the magnitude of impact loading on railway sleepers can be predicted. Figure 2 shows a statistical data of actual wheel loading applied on top of the rail obtained from a railway network in North Queensland (Murray and Leong, 2006; Leong et al., 2007).

From Figure 2, the relationships between the impact forces  $I$  (kN) and the return periods  $R$  (year) can be written as follows:

$$\text{For Braeside, } \frac{1}{R} = 10^{-0.019I+5.92} \quad (1)$$

$$\text{For Raglan, } \frac{1}{R} = 10^{-0.010I+4.1} \quad (2)$$

These formulae can be used to determine the impact force factor ( $k_r$ ), which is based on the return periods and consequences of changing operations, such as speeds or wheel/rail defects (Leong et al., 2007).

Limit states concept is a more logical entity for use as the design approach for prestressed concrete sleepers, in a similar manner of Australian Standard AS3600 (Standards Australia, 2012). It considers

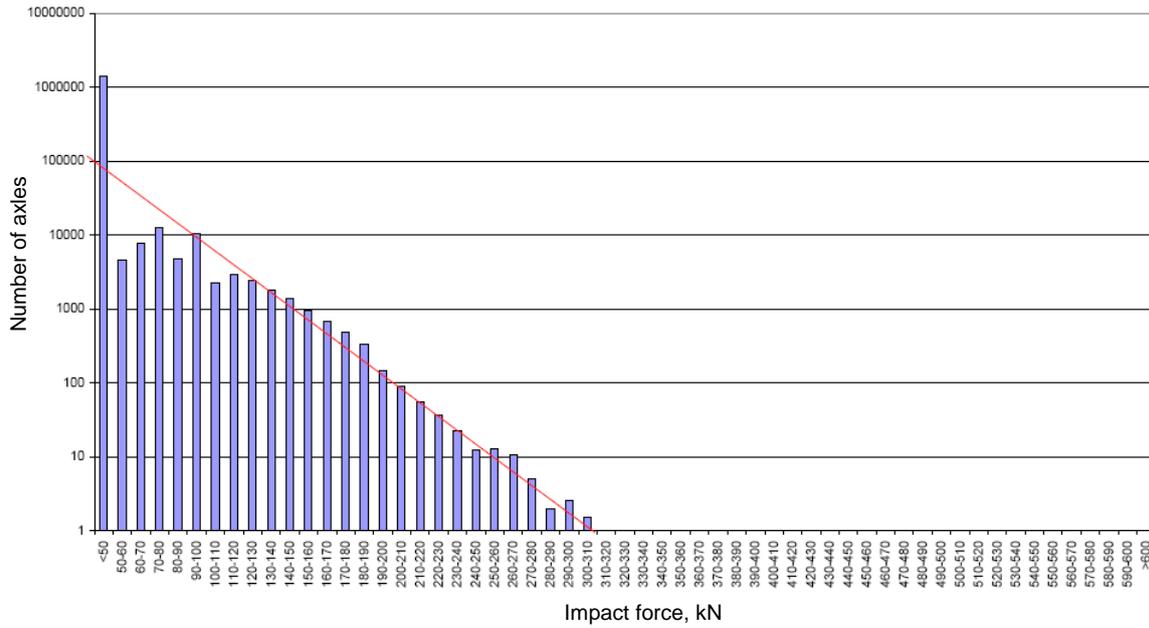
both strength and serviceability (Warner et al., 1998). In order to devise a new limit states design concept, research efforts are required to perform comprehensive studies of the loading conditions, the static behaviour, the dynamic response, and the impact resistance of the prestressed concrete sleepers (Kaewunruen, 2007). A major research task is to evaluate the impact responses and behaviours of concrete sleepers under impact loading, including the damage under accumulative condition and the damage under repeated impact events. It is noted that the failure of a cluster of railway sleepers is more likely due to the cumulative damage rather than due to only a once-off extreme event, which might occur due to derailment or terrorist attack. However, it was found that, for prestressed concrete sleepers, the low magnitude but high cycle impact fatigue tend to be insignificant in comparison with the high magnitude but low cycle impact fatigue (Stevens and Dux, 2004; Steenbergen et al., 2007). This paper focuses on the repeated severe impact behaviour of the prestressed concrete sleepers.

According to the literature review, 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. The key hindrance was about how rail pad and support condition really affect the system impact responses and the significance of such factors. Wakui and Okuda (1999) have later proposed a simplified technique to predict the ultimate capacity of concrete sleepers. The strain rate and loading rate are taken into account in moment capacity calculation on the basis of sectional analysis and only steel tendons' failure mechanisms. Kaewunruen and Remennikov (2007b) found that the Wakui and Okuda technique is more suitable to the members failing in a bending or a shear-bending mode. In addition, they performed the experimental studies to evaluate the energy absorption capacity of prestressed concrete sleepers under impact loading (Remennikov and Kaewunruen, 2005; 2007b; Kaewunruen and Remennikov, 2007c).

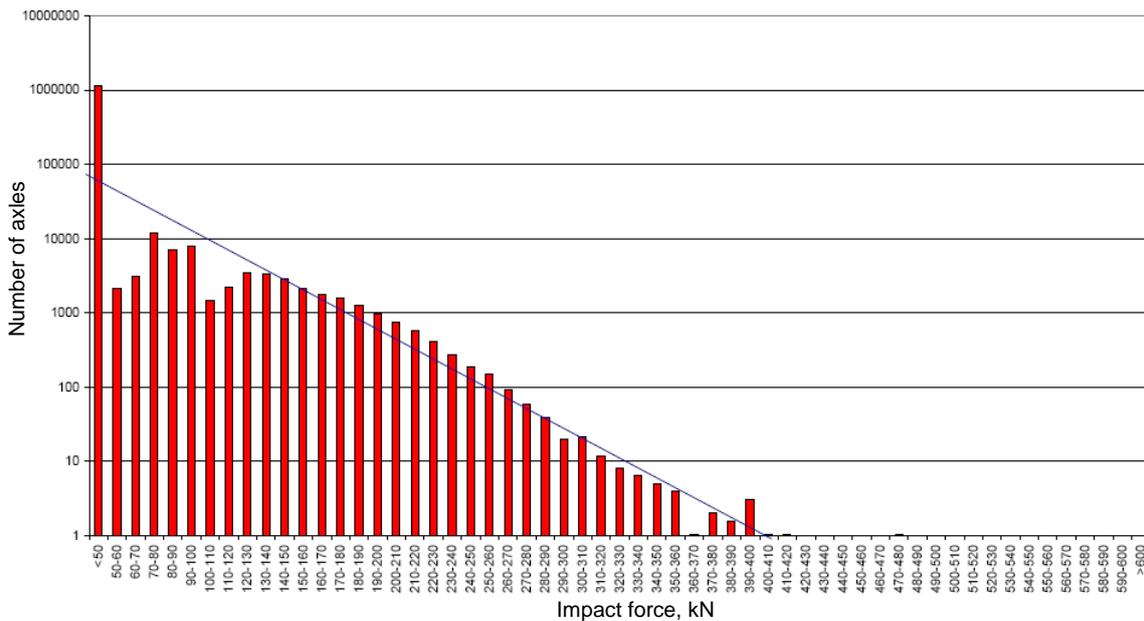
This study investigates the repeated impact responses and behaviour of railway prestressed concrete sleepers subjected to a variety of repeated impact loads. The prestressed concrete sleepers used were designed complied with Australian Standard: AS1085.14 (2003). Drop-weight impact hammer was used to apply multiple impacts directly to the railseat at identical drop heights in order to repeat the pulse characteristics at each return period. The

impact pulses were captured using the high capacity load cell connected to the National Instrument data acquisition system. The dynamic measurements also include dynamic strains and accelerations. Softening media placed on top to the railhead to reduce the contact stress was used. Neoprene rubber pads with thickness of 1.5mm were used to control the duration of load pulses. Impact damage and crack propagation at each drop test were recorded. After each

repeated impact test, a static test was carried out to identify the residual capacity of a damaged prestressed concrete sleeper in accordance with AS1085.14 (2003). This paper presents the reserve capacity of the impact-damaged prestressed concrete sleepers. Also demonstrated are the effects of track environment including soft and hard tracks on the repeated impact behaviour and residual capacity of the prestressed concrete sleepers.



(a) at Braeside



(b) at Raglan

Figure 2. A typical statistical data of loading on tracks (Leong, 2007)

## 2 EXPERIMENTAL OVERVIEW

### 2.1 Test specimens

In this investigation, the test specimens are typical full-scale prestressed concrete sleepers commonly used in Australia. They were supported by an Australian manufacturer, under a collaborative research project of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC). The prestressed concrete sleepers are often the main part of the broad gauge rail tracks. The dimensions of the prestressed concrete sleeper are given in Table 1. The cross-sections of the prestressed concrete sleeper were optimized for specific load carrying capacities at different functional performances for rail seat and mid span. The prestressing tendons are the chevron-patterned indented wires of about 5mm diameter. High strength concrete material was used to cast the prestressed concrete sleepers, with design compressive strength at 28 days of 55 MPa, and the prestressing steels used were of high strength quality with rupture strength of 1860 MPa. The cored samples (50mm diameter), drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard AS1012.14 (Standards Australia, 1991), as shown in Figure 3. Although the common concrete strength adopted for design is 50 MPa, it is found that the average characteristic compressive strength at the test age of about two years is  $80 \pm 3.5$  MPa and the control of concrete quality could be considered as very high. It is believed that the high strength prestressing wires are of high quality and the strength will not rapidly change during time.

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



Figure 3. Cored concrete samples

### 2.2 Alternative materials for support conditions

The materials used in the impact testing include the supporting rubber (acting as ballast), steel rails, and the fastening system. Summary of the material properties is given in Table 2. The conveying belt rubber using in the mining processes has been adopted as the supporting condition. A validation of the support condition was conducted earlier in accordance with AS1085.19 (Kaewunruen and Remennikov, 2008c; Standards Australia, 2001). Standard rigid 60kg rails were used to distribute impact loading and to provide restraint at the railseats. It is assumed that the rails would be relatively rigid and would transfer all dynamic load onto the sleepers, so that rail pad has been omitted in these tests in order to investigate the behaviour of the concrete sleepers under the measurable impact applied at the rail heads. The rails were clamped to the strong base using the high strength steel rods (Standards Australia, 2001).

Table 2. Mechanical properties of materials used

Materials	Elastic modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete	38,000	80	7.6
Prestressing tendon	190,000	-	1,860
Rubber mat (one layer)	26	-	-
Steel rails	205,000	-	-

### 2.3 Impact testings

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 (Kaewunruen, 2007). The weight of the projectile was set at 5.81 kN (592 kg), and therefore, the drop height becomes the only variable (Kaewunruen and Remennikov, 2007c-e, 2008c-d). Experimental investigations were previously carried out to relate specific energy absorption capacity to a particular type of sleeper, in order to back calculating for the optimum drop height. The drop height was adjusted from a series of pre-test numerical and experimental studies to cause complete collapse under multiple blows (Kaewunruen, 2007). To eliminate surrounding noise and ground motion in laboratory, the concrete sleepers were set up in accordance with AS1085.19 (Standards Australia, 2001) and placed on a strong isolated floor in the laboratory (Kaewunruen and Remennikov, 2007e). The strong floor is very stiff and owns significantly higher fun-

damental frequency than the experimental equipment. It is installed on shock absorber to reduce the stress wave reflection. At the rail seat was installed the rigid rail piece 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 (at difference performance of the sleeper) and released by an electronic quick release system.

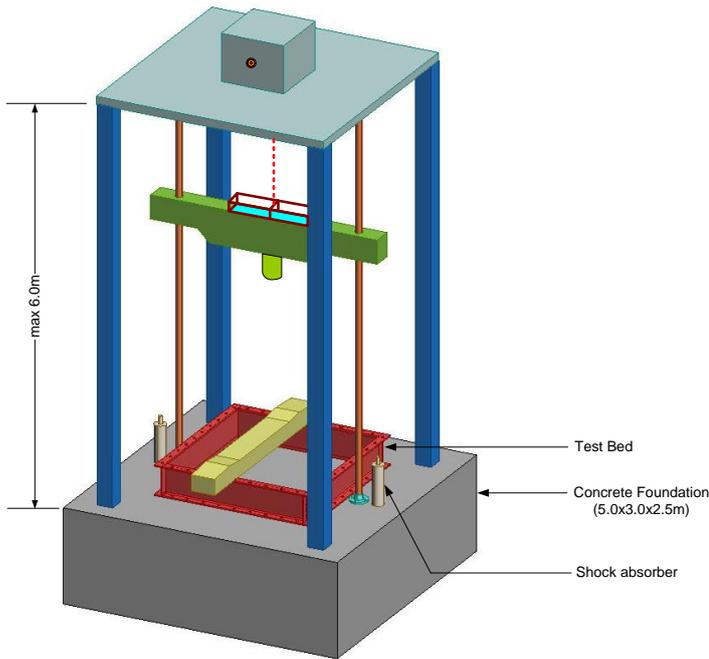


Figure 4. Schematic layout of the drop-weight impact test rig

The sketch of impact testing setup is illustrated in Figure 4. 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 10.8 m/s. The impact load was monitored and recorded by the dynamic load cell connected to the impact hammer. 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

$$h = h_T / 0.98^2 \quad (3)$$

#### 2.4 Static testings

Schematic diagram for the experimental setup of rail-seat positive moment test is shown in Figure 5.

The test setup is similar to the benchmark prescribed in AS1085.14 (Standards Australia, 2003) as to identify the reserve strength of the damaged concrete sleepers against the undamaged concrete sleepers currently designed using the permissible stress concept. The location of measurements was at the centre line of rail seat. In this test, inclinometers were also installed at the simply supported edges.

Strain gauges were installed 10 mm from the top and bottom surfaces at the centre of sleeper as to avoid stress concentration from loading. Linear variable displacement transformer (LVDT) was used to measure deflection at the load point. The rotations at supports that represent the gauge rotations were measured using inclinometers. Static tests were carried out at the same loading rate (about 10 kN/min). The equipment required in these tests included

- LVDT for sleeper deflections at loading line,
- Strain gages and wires installed at loading line and at middle span for obtaining both top- and bottom-fibre strains,
- Load cell,
- Laser deformation measurement of loading steel column,
- Inclinometers at supports,
- DataLogger, and
- Electronic load control.

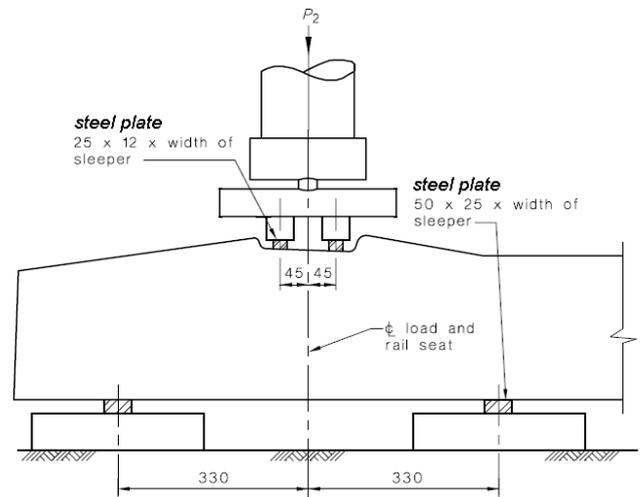


Figure 5. Rail Seat-positive moment test (Standards Australia, 2003)

Figure 6 shows the actual setup and instrument for the maximum positive moment test at rail seat section. A vertical seat was used to keep the loading path in vertical plane. The maximum experimental load was found to be 585 kN, which is equivalent to bending moment of about 83 kNm. Shear strength deficiency governed the observed failure mode. It

was found that the predicted design ultimate load from Response-2000 (Bentz, 2000) was 410 kN (or bending moment of 58 kNm).



Figure 6. Experimental setup for rail seat- positive moment test

### 2.5 Test programme

In this study, the prestressed concrete sleepers are subjected to certain identical impact magnitudes. There are two phases of the experiments. The first phase is to evaluate the behaviours under 50 identically repeated impacts. The rationale for the 50 identical drop tests was that the sleepers are generally designed for 50 years and the potential of the concrete sleepers subject to increased wheel loads (associated with annual return period) was sought by the industry. The reference life of 50 years has then been adopted for the likelihood of 50 times that a sleeper might be practically exposed to the increased demand of wheel load. The later phase is to identify the once-off impact behaviours (single drop) of the sleepers under the same sets of pulse magnitudes. Those impact tests have the same set of the impact force magnitudes, including 500 kN (associated with 50 years return period), 740kN (associated with 2,000 years return period), and 810 kN (associated with 10,000 years return period). These probabilities, which were obtained from the field data, can be calculated using equations (8), as shown in Figure 2 (Leong, 2007).

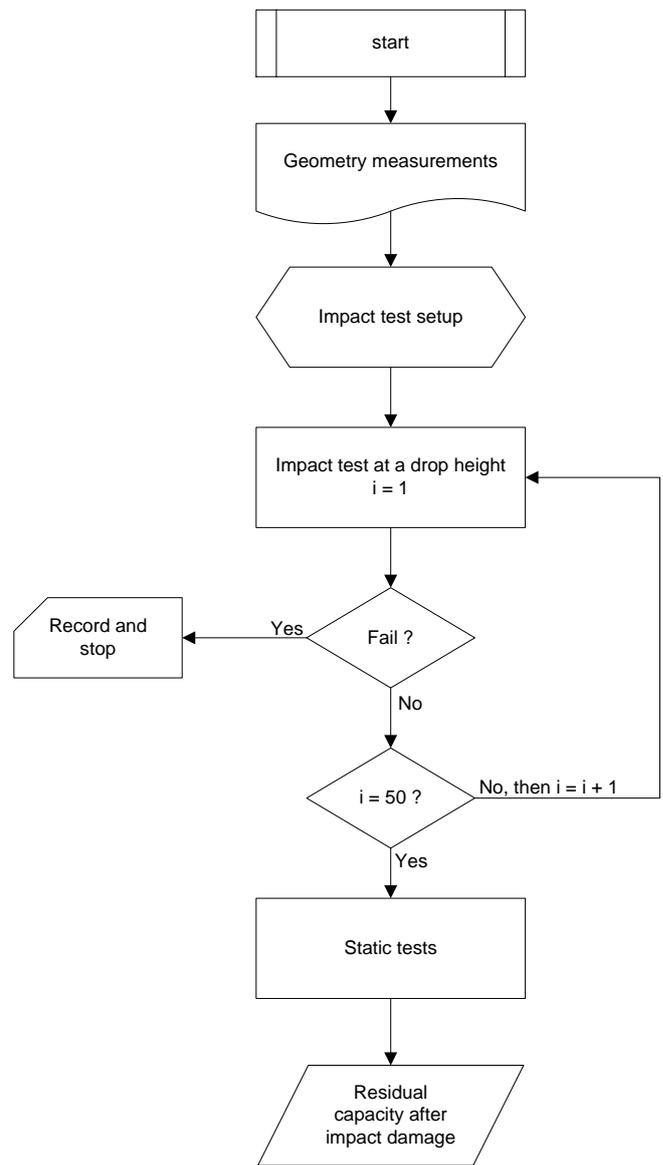


Figure 7. Flow chart of the repeated impact and residual capacity toughness tests

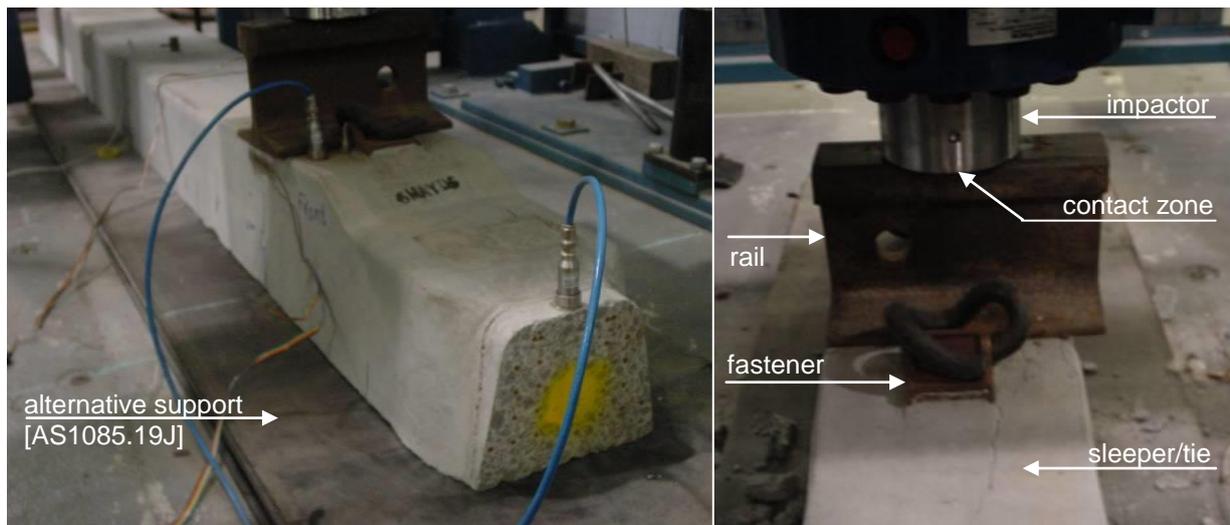
Figure 7 presents schematic flowchart of the investigations of concrete sleepers under impact and static loadings to evaluate the responses to repeated impacts and the consequent fracture toughness of the prestressed concrete sleepers. Table 3 shows a series of test program with the particular emphasis on the different target levels of impact force acting on the prestressed concrete sleepers. It is important to note that low-frequency pass signal threshold (<1,000 Hz) had been used to filter out the noise of impact signals. The peak of impact force in Table 3 corresponds to the flexural behaviour of the concrete sleeper, varying in a frequency range between 160 and 200 Hz. The series of impact test program were conducted using the test setup shown in Figure 8. Special attention was paid to the identical drop height on the prestressed concrete sleepers to achieve the structural conditions under 50 repeated

impact loads. In addition to impact, acceleration, and dynamic strain signals, the data measurements include the crack propagations and the crack widths at each drop test. This paper experimentally investigates the influence of ballast supports on the residual load-carrying capacity, repeated impact responses, and dynamic crack propagation. For comparison, two support conditions termed ‘soft track’ and ‘hard track’ were calibrated against the vibration modal parameters of the ballast support in actual tracks (Kaewunruen, 2007). In practice (Cai, 1992), the soft track can be considered as thin ballast bed (about 100-150 mm in depth on a compacted soil), while the hard track represents the thick layer of the ballast bed (more than 250mm in depth). The experimental setups for track support conditions (static track spring rates: about 60 kN/mm for soft track; and 135 kN/mm for hard track) were in accordance with AS1085.19 (Standards Australia, 2001), as illustrated in Figure 8. The tests followed the schemat-

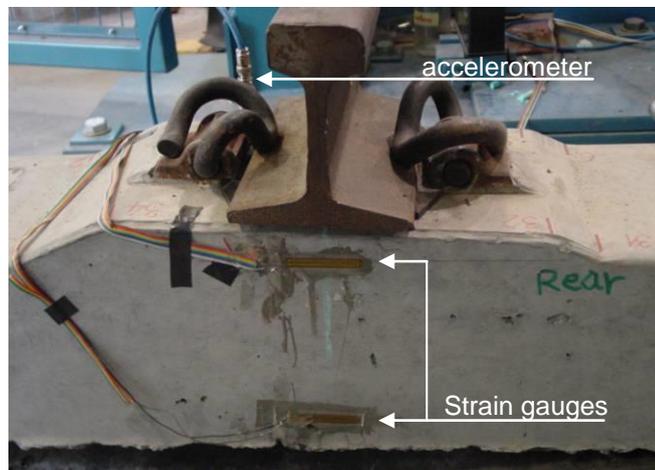
ic flowchart in Figure 7 but the magnitudes of impacts varied as follows: 500 kN, 740 kN, and 810 kN, as tabulated in Table 3 (Kaewunruen, 2007).

Table 3. Summary of impact and static testing programs

Support conditions	Impact force (kN)	Related return period (years)	Number of drops	Subjecting static test
Soft track	500	50	1	Yes
			50	Yes
	740	2000	1	Yes
			50	Yes
810	10,000	1	Yes	
		50	Yes	
Hard track	500	50	1	Yes
			50	Yes
	740	2000	1	Yes
			50	Yes
810	10,000	1	Yes	
		50	Yes	



(a) in-situ condition setup



(b) instrumentation

Figure 8. A setup of the in-situ prestressed concrete sleeper

### 3 STATIC CAPACITY OF NEW PRESTRESSED CONCRETE SLEEPERS

#### 3.1 Load-deflection relationships

The load-deflection relation for the railseat cross-section of the tested concrete sleeper is presented in Figure 9, whereas the moment-deflection curve can be seen in Figure 10.

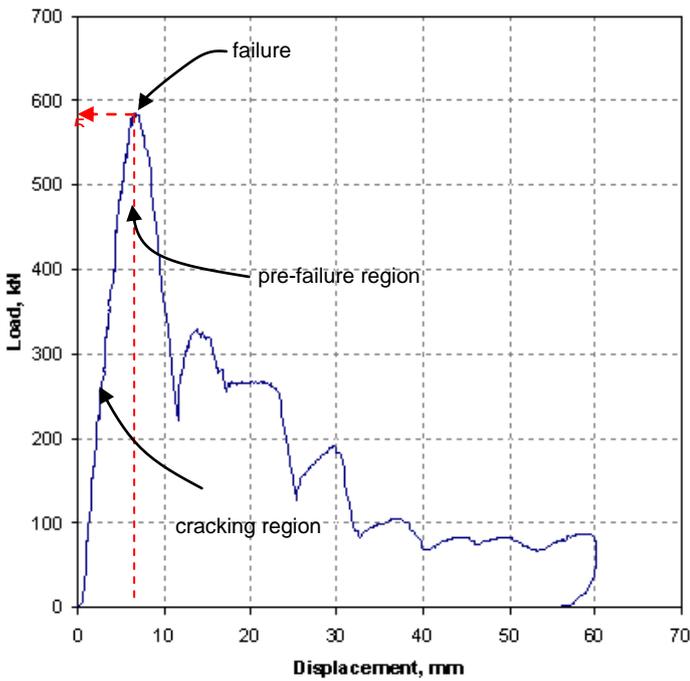


Figure 9. Load-deflection curve of rail seat positive moment test of uncracked sleeper

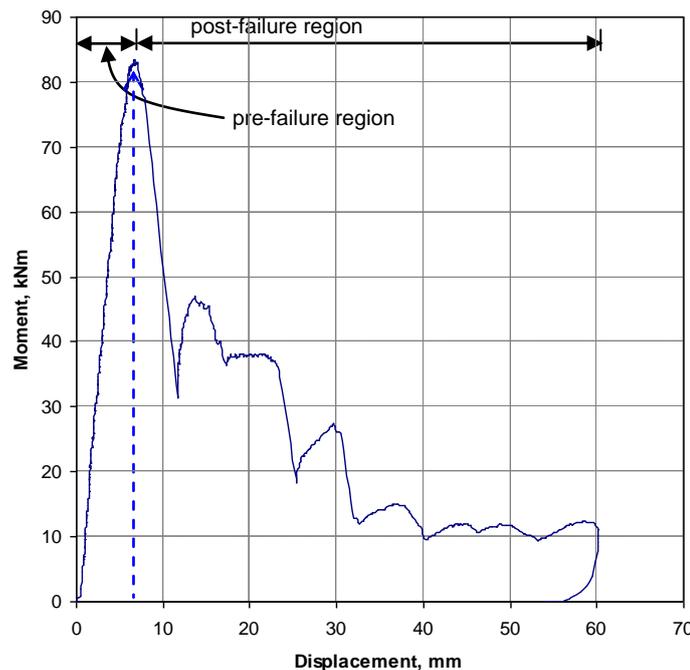


Figure 10. Moment-deflection curve of rail seat positive moment test

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 load-deflection relations of the average data in stages I and II (Gustavson, 2002) as shown in Figure 11. Comparisons of measured and visualized crack initiation loads showed quite good agreement. The crack initiation load determined by visual observation was about 240 kN, while the measured one was about 235 kN.

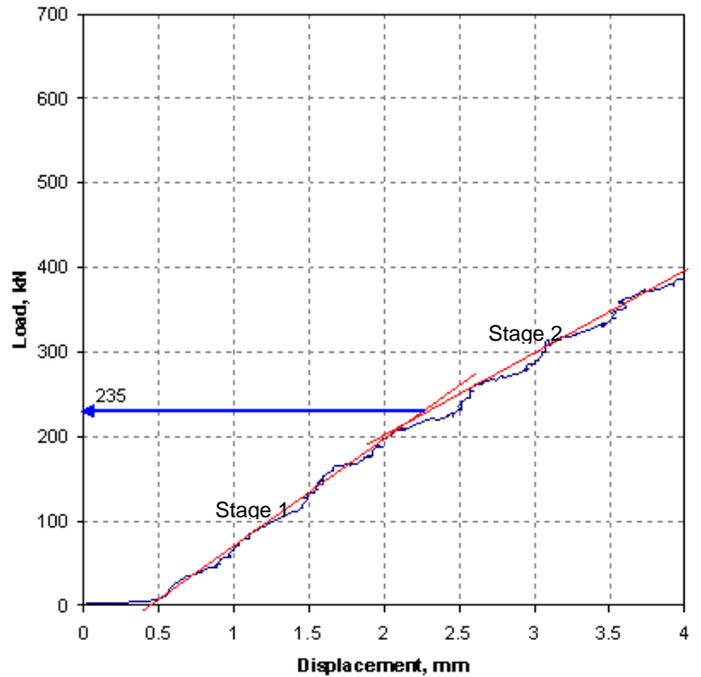


Figure 11. Measured cracking load of rail seat positive moment test

At the very beginning stage when the load was applied at railseat, the vertical displacement of the railseat was linearly proportional to the applied load and bending moment up until the tensile strains at the bottom fibre almost reach the ultimate tensile strength. Once the strain reached the tensile strength, the concrete started cracking and the nonlinear relation between load and deflection appeared. When the top-fibre strain of concrete approached the ultimate compressive strength, the crushing of concrete occurred.

#### 3.2 Energy toughness characteristics

As aforementioned, the energy toughness capacity reflects how much the structure can dissipate the work done by external forces. The energy absorption characteristics determined from the rail seat positive moment test are shown found in Figure 12. It should be noted that the failure is indicated when the major

fracture of concrete occurs at the top fibre of railseat. At fracture, energy given to deform sleeper railseat vertically to about 6.5mm was about 2,000J, which is slightly higher than the energy absorbed at mid-span cross-section. On the other hand, an amount of 250J of energy is required to cause cracking in the railseat of the tested concrete sleeper.

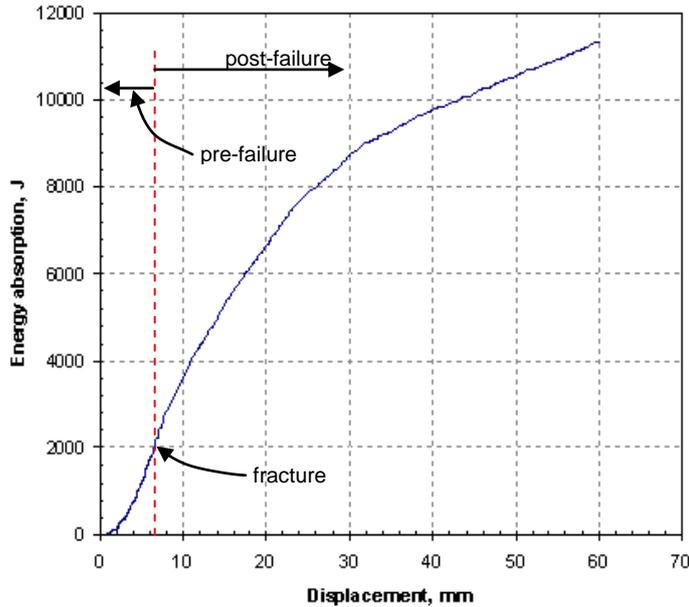


Figure 12. Energy absorption characteristic due to rail seat positive moment test

### 3.3 Rotational capacity

In this railseat test, the inclinometers were mounted coincident with both supports. Although the rotations at these setup supports play an insignificant role on the rail gauge, they provide important information in relation to the curvature at the inflection point between positive bending moment at railseat and negative bending moment at mid span. The rotational capacity under applied load and moment is presented in Figures 13 and 14, respectively. It is found that the left and right hand side rotations were fairly similar before the sleeper fails. The angle of rotation that is associated with the fracture of railseat section is about 0.8 degree. The allowable angle of rotation that causes cracking at the railseat is found to be about 0.1 degree. It should be noted that the rotations of angle, which cause cracking and failure at rail seat of the tested concrete sleeper, are less than those at mid-span of the tested concrete sleeper. This is because the shear span ratio of the railseat test setup is much less than that of the mid-span test setup. It can also be observed that at each progressive collapse of tendons, the fluctuation of signals (loops) is

due to the sudden rupture of concrete, creating the instability motions of inclinometers.

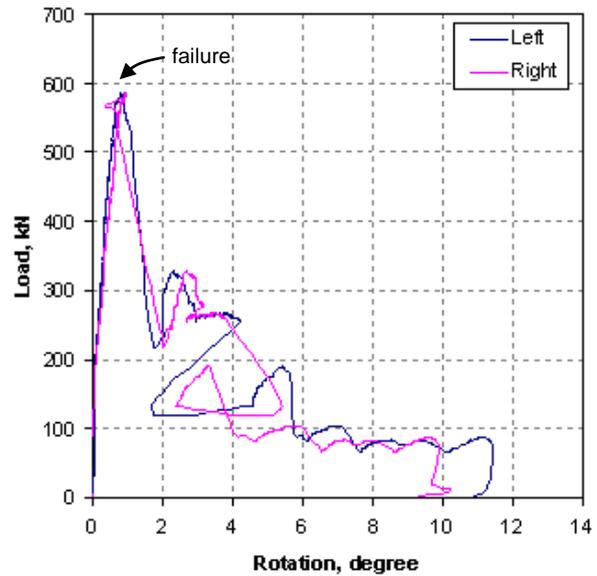


Figure 13. Load-rotation relation from the centre negative moment test

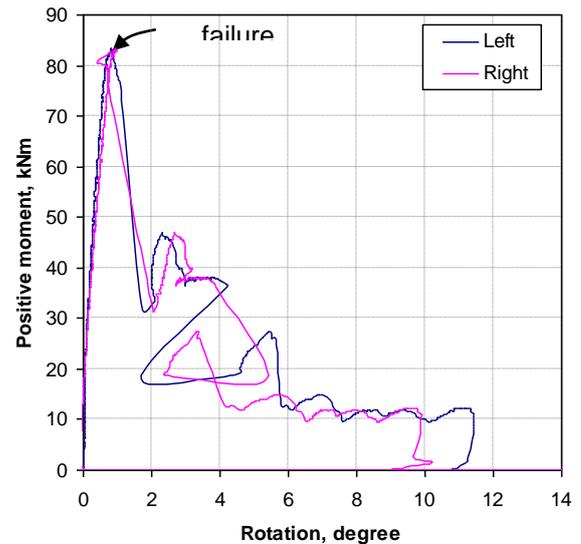


Figure 14. Moment-rotation relation from the centre negative moment test

## 4 EVOLUTION OF IMPACT CRACK GROWTHS OF PRESTRESSED CONCRETE SLEEPERS

Cracks in the prestressed concrete sleepers were visually observed after each drop test. This type of crack is referred to as the residual crack since the cracks were closed in the unloaded conditions by the prestress (Kaewunruen and Remennikov, 2007a-e). Measurements of crack widths and lengths were carried out after each impact using the magnifying glass. The length of the residual cracks is the main indicator for the durability and serviceability of the prestressed concrete sleeper in practice (Wakui and Okuda, 1999). It should also be noted that the

lengths of the residual crack and the maximum opened crack due to dynamic impact are fairly close (Kaewunruen, 2007). From previous studies (Kaewunruen, 2007), it was found that the cracks in the concrete sleepers can form due to a range of impact forces. Table 4 shows the crack initiation thresholds of the prestressed concrete sleepers in different track support conditions. It implies that the cracks of sleepers in stiffer track support could be detected more often under dynamic loading condi-

tions.

Table 4. Impact crack identification of railway prestressed concrete sleepers

Support condition	Drop height (m)	Impact force (kN)	Return period of loading*	Crack type
Soft track	0.2	500 - 560	50 years	bending
Hard track	0.1	400 - 480	9 months	bending

\*based on a field data from a site in Central Queensland (Leong, 2007).



(a) soft track



(b) hard track

Figure 15. Cracks in a sleeper after a single impact of 500 kN



(a) soft track



(b) hard track

Figure 16. Cracks in a sleeper after a single impact of 740 kN



(a) soft track

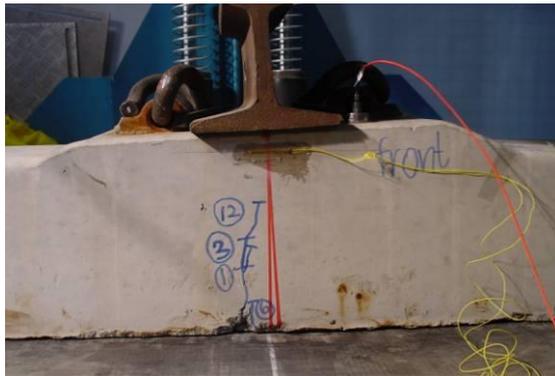


(b) hard track

Figure 17. Cracks in a sleeper after a single impact of 810 kN

Figures 15-17 show the impact crack growths in the prestressed concrete sleepers under different impact force magnitudes and different track support conditions. It is evident that under the same impact force the cracks in the hard track sleepers tend to be more severe than those in the soft track sleepers. Figures 18-20 show the impact crack propagations in the prestressed concrete sleepers under 50 repetitions of different impact magnitudes and different track support conditions. Clearly, it was noticeable that the

cracks of the hard track sleepers propagated more than those of the soft track sleepers. However, it reveals that the structural conditions of the impact-damaged sleepers in both track support conditions were still functional. The impact-damaged sleepers' gauge was in acceptable tolerances. The damaged rail seat areas were flat and good enough to be installed by a rail pad. Although there were small concrete spillings due to compression at around rail seats, the rail shoulders were tightly embedded in the



(a) soft track



(b) hard track

Figure 18. Cracks in a sleeper after 50 repeated impacts of 500 kN



(a) soft track



(b) hard track

Figure 19. Cracks in a sleeper after 50 repeated impacts of 740 kN



(a) soft track



(b) hard track

Figure 20. Cracks in a sleeper after 50 repeated impacts of 810 kN

sleepers. There were some shear crack propagations but their sizes are not substantial (Kishi et al., 2002).

## 5 RESIDUAL CAPACITY OF IMPACT-DAMAGED PRESTRESSED CONCRETE SLEEPERS

The impact damaged sleepers were retested under the prescribed static testing condition in order to identify the comparable and repeatable residual energy toughness (Kaewunruen, 2007). After completing 50 drop tests, it is clear that the sleepers have a great potential that they could withstand further loading. As a result, the damaged sleepers were subjected to the static testing as described in Section 2.4, as to evaluate residual load carrying capacity and residual fracture toughness of the prestressed concrete sleepers. Through the static tests, the residual load carrying capacity is plotted against railseat deflection. The fracture toughness can subsequently be identified by the integration (area under the curve) of load-deflection relationship (Fryba, 1996). The comparative index is a ratio between the toughness before and after impact damage (Kaewunruen and Remennikov, 2010; 2011). There are two sets of damaged sleepers, including those under single impacts and those under repeated impacts. The single impact tests and the repeated impact tests are associated with the pulse magnitudes of 500 kN, 740 kN, and 810 kN. The effect of support conditions (soft and hard tracks) on the residual capacity is to be determined. The comparison between residual capacities of those cases is the highlight in this section.

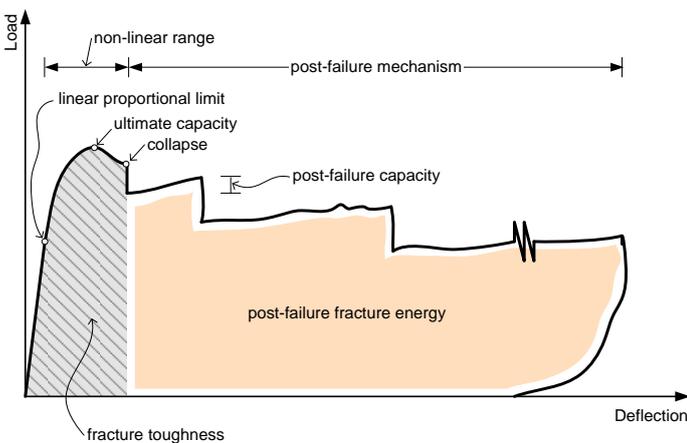


Figure 21. Schematic full load-deflection curve of structural member

In general, full load deflection curve can be found in Figure 21. The first stage of the curve is elastic stage when materials behave linearly in elastic range.

Then, the nonlinear behaviour takes place when the principal stress reaches the proportional yield stress and the materials make use of the nonlinear portion of the strength. Until the structural member reaches ultimate capacity or stability failure, the nonlinear portion dominates. At the ultimate point, the load deflection curve drops at certain extent due to the yielding of high strength strands and the spalling of concrete. The strength beyond this ultimate capacity, if the member is further loaded, is referred to as the residual fracture toughness in the post failure mechanism. The post failure mechanism can be clearly seen in Figure 21. It exhibits that the strands still provide the strength hardening effects to the residual load carrying capacity and the energy absorption mechanism until they reach the rupture capacity. The hardening effect is significant when more tendons remain and the effect decreases as the remaining number of tendons diminishes.

### 5.1 Residual capacity under single impacts

#### 5.1.1 After subjecting the impact load of 500 kN

Figures 22 and 23 show the residual load-deflection curve and the energy absorption mechanism of the prestressed concrete sleeper after subjecting to the single impact load of 500 kN, respectively. It clearly shows from the residual load-deflection curve that the soft-track sleeper can yield larger deflection before collapsing at ultimate failure point. The failure load of the hard-track sleeper is slightly lesser than that of the soft-track one. However, the post-failure fracture toughness energy of the hard-track sleeper seems to be significantly higher.

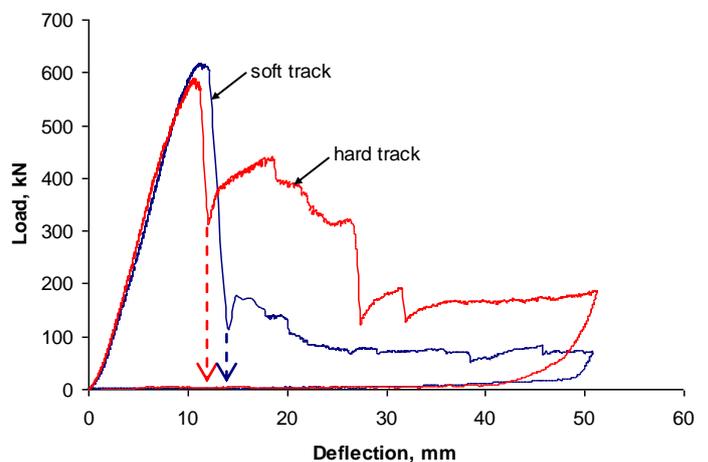


Figure 22. Residual load-deflection relation for sleepers subjected to a 500 kN impact

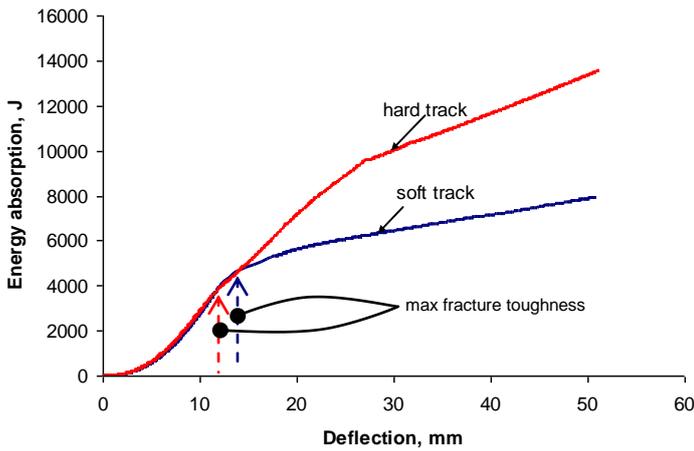


Figure 23. Residual energy absorption for sleepers subjected to a 500 kN impact

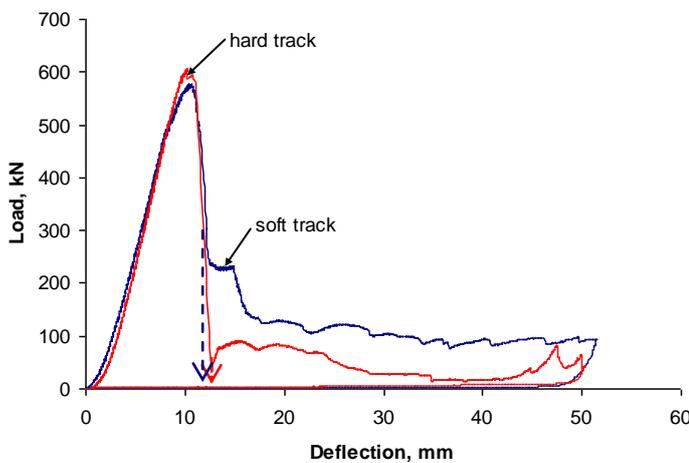


Figure 24. Residual load-deflection relation for sleepers subjected to a 740 kN impact

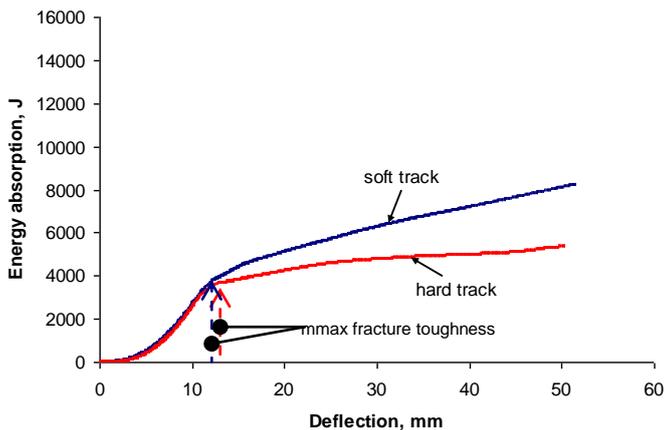


Figure 25. Residual energy absorption for sleepers subjected to a 740 kN impact

### 5.1.2 After subjecting the impact load of 740 kN

Figures 24 and 25 show the residual load-deflection curve and the energy absorption mechanism of the prestressed concrete sleeper after subjecting to the single impact load of 740 kN, respectively. The residual load-deflection curve shows that

although the failure load of the hard-track sleeper is similar to the soft-track one, the residual fracture toughness energy of the hard-track sleeper seems to be slightly lesser. This is because the sleepers carried more internal damage in terms of local bonding and internal cracks.

### 5.1.3 After subjecting the impact load of 810 kN

Figures 26 and 27 show that under the single high impact load of 810 kN, the sleeper in either soft or hard track can still yield certain deflection before collapsing at ultimate failure point. However, the effect of the track conditions is regardless since the failure loads as well as the residual fracture toughness energy are fairly similar. It should be noted that at higher impact loading more cracks are occurred in the hard-track sleeper. These cracks allow the sleepers to behave and fail in a more ductile mode. On the other hand, the sleeper with few hair cracks (in soft track) tends to fail in a shear brittle mode and consequently provides poor residual fracture toughness energy.

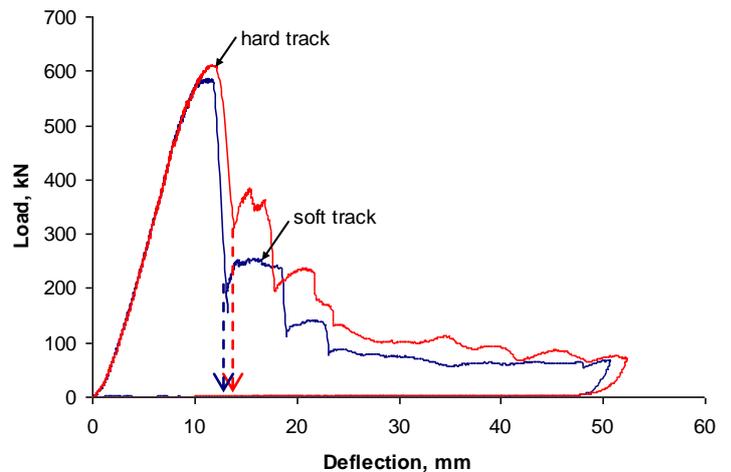


Figure 26. Residual load-deflection relation for sleepers subjected to a 810 kN impact

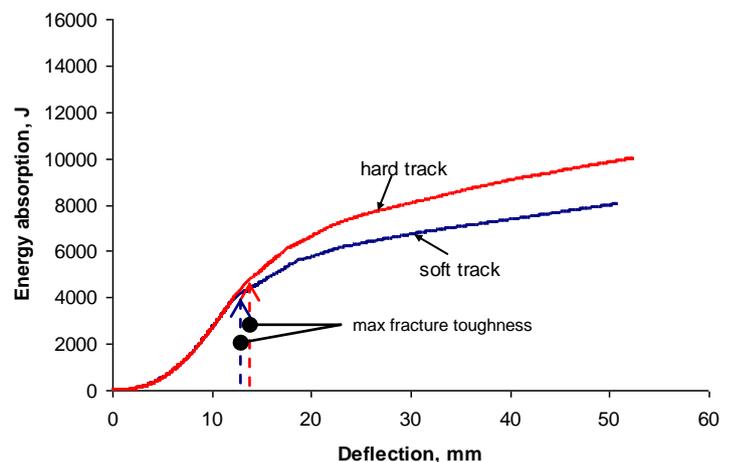


Figure 27. Residual energy absorption for sleepers subjected to a 810 kN impact

Overall, the impact magnitude tends to have little influence on the prestressed concrete sleepers in soft track environment. In contrast, the sleepers in hard track environment are sensible to the impact magnitudes. When the dynamic bending moment is larger and more major cracks occur, they are likely to absorb more fracture toughness energy. When considering the ultimate failure, it seems that there is no remarkably influential factor, which considerably degrades the sleepers under these single impact events.

### 5.2 Residual capacity under repeated impacts

#### 5.2.1 After subjecting the impact load of 500 kN

Figures 28 and 29 show the residual load-deflection curve and the energy absorption mechanism of the prestressed concrete sleeper after subjecting to 50 repeated impact loads of 500 kN, respectively. It is evident that although the sleepers can absorb more energy with a large deflection before collapsing at ultimate failure point, the post failure behaviours are poor in performance. The effect of the soft and hard track environments seems insignificant to the residual fracture toughness energies. This is because the repeated impacts substantially degrade the bonding between the concrete and the prestressing steels. As a result, the weak surface can be located along the tendon alignments. The failure mode of the prestressed concrete sleepers becomes the splitting mode along the tendon alignments, as shown in Figure 30. Once the sleeper loses its bonding strength between the tendons and concrete, the residual fracture energy mechanism is remarkably poor.

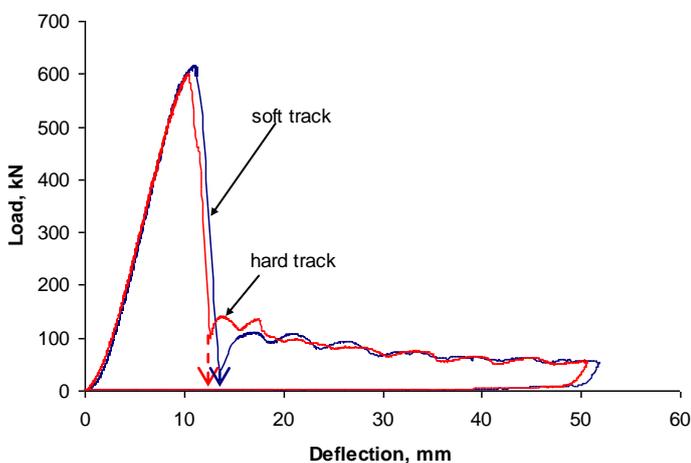


Figure 28. Residual load-deflection relation for sleepers subjected to 50 repeated impact loads of 500 kN impact

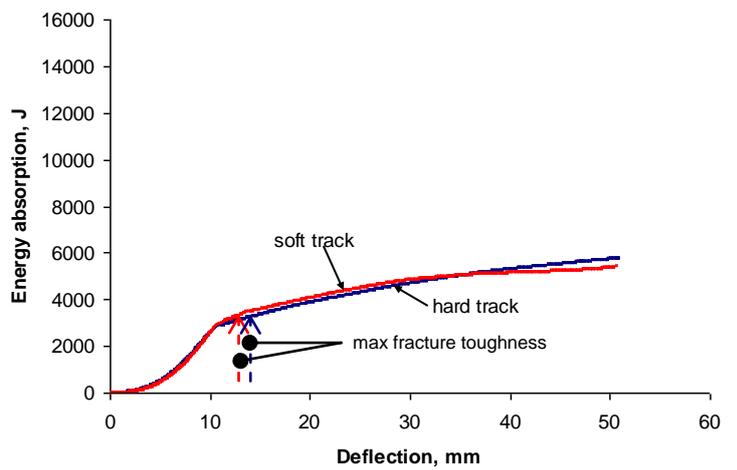
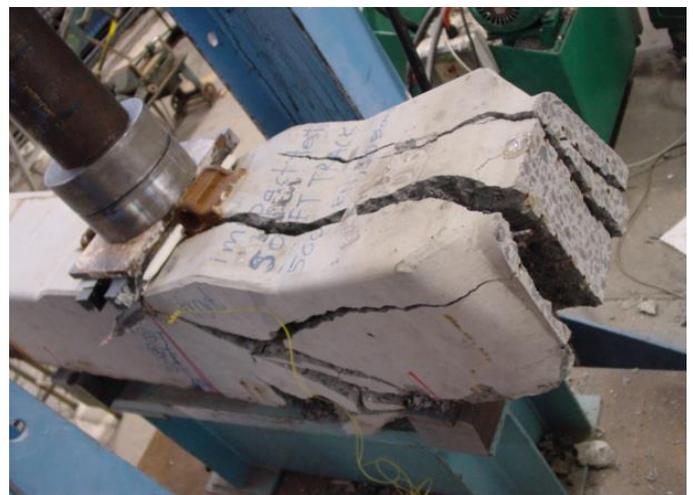
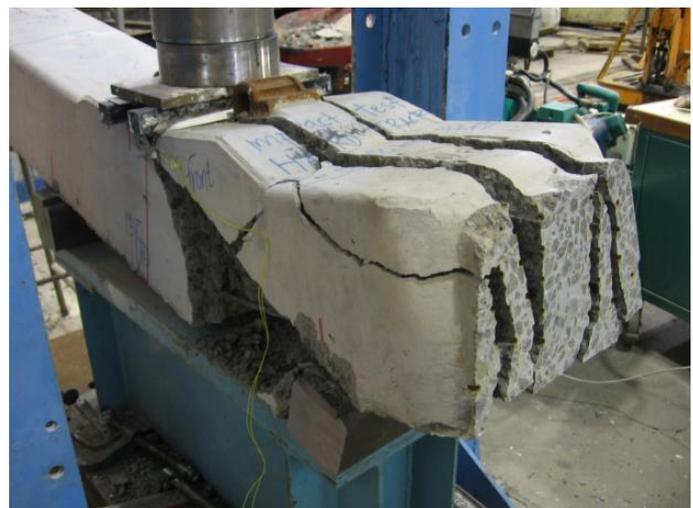


Figure 29. Residual energy absorption for sleepers subjected to 50 repeated impact loads of 500 kN impact



(a) soft track environment



(b) hard track environment

Figure 30. Residual static failure mode of the sleepers subjected to 50 repeated impact loads of 500 kN impact

#### 5.2.2 After subjecting the impact load of 740 kN

Figures 31 and 32 show the residual load-deflection curve and the energy absorption mecha-

nism after subjecting to 50 repeated impact loads of 740 kN, respectively. The residual load-deflection curves exhibit that the sleepers can still provide a reasonable deflection before reaching at ultimate failure point. However, they show poor performance for the post failure energy absorption mechanism. The effect of the soft and hard track environments tends to be insignificant for the residual fracture toughness energy. At failure, the prestressed concrete sleepers also show the splitting mode along the tendon alignments, as shown in Figure 33.

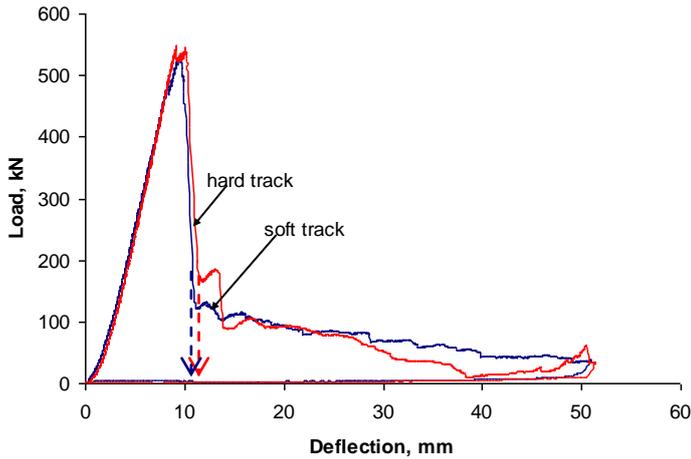


Figure 31. Residual load-deflection relation for sleepers subjected to 50 repeated impact loads of 740 kN impact

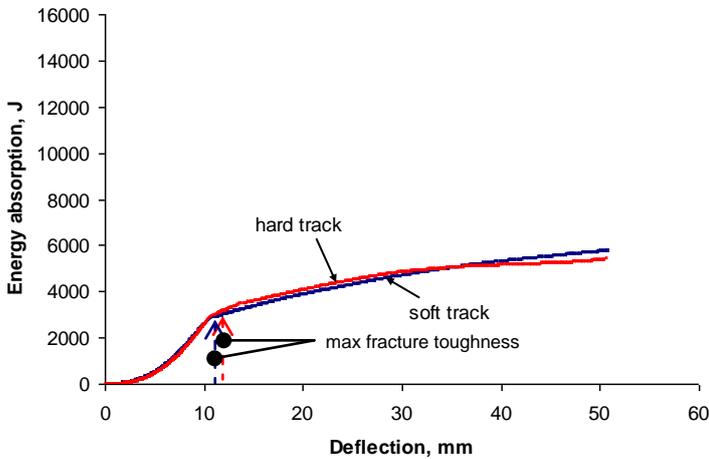


Figure 32. Residual energy absorption for sleepers subjected to 50 repeated impact loads of 740 kN impact

### 5.2.3 After subjecting the impact load of 810 kN

Figures 34 and 35 show the residual load-deflection curve and the energy absorption mechanism after subjecting to 50 repeated impact loads of 810 kN, respectively. They exhibit that the residual fracture toughness energy is independent to support conditions. Splitting mode along the tendon alignments due to tendon debonding shown in Figure 36 becomes the common failure mode under repeated impacts.



(a) soft track environment



(b) hard track environment

Figure 33. Residual static failure mode of the sleepers subjected to 50 repeated impact loads of 740 kN impact

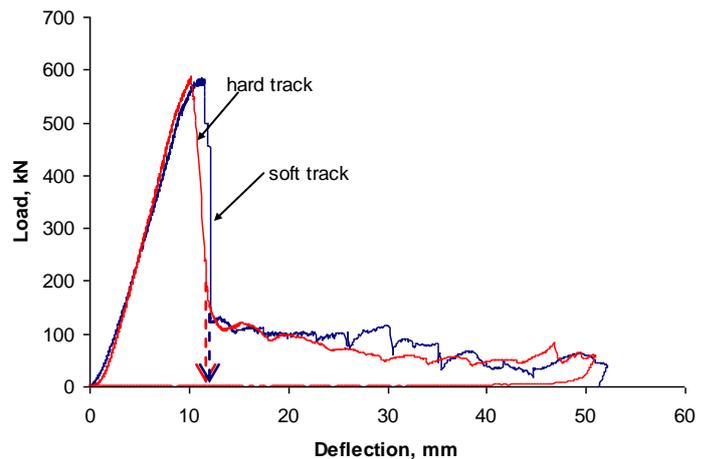


Figure 34. Residual load-deflection relation for sleepers subjected to 50 repeated impact loads of 810 kN impact

Overall, under repeated impact loading, the sleepers are considered as having a large amount of reserved strength that is untapped. The results of follow-up static tests suggest that the sleepers under the certain impacts can further withstand the ultimate failure

load comfortably, regardless of different support conditions. The ultimate failure modes of concrete sleepers damaged from repeated impacts are rather the splitting mode along the debonded tendons resulting in an insignificant amount of residual fracture toughness energy.

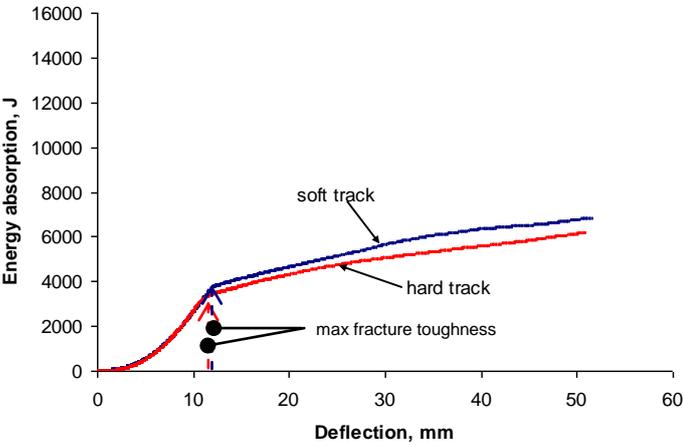


Figure 35. Residual energy absorption for sleepers subjected to 50 repeated impact loads of 810 kN impact



(a) soft track environment

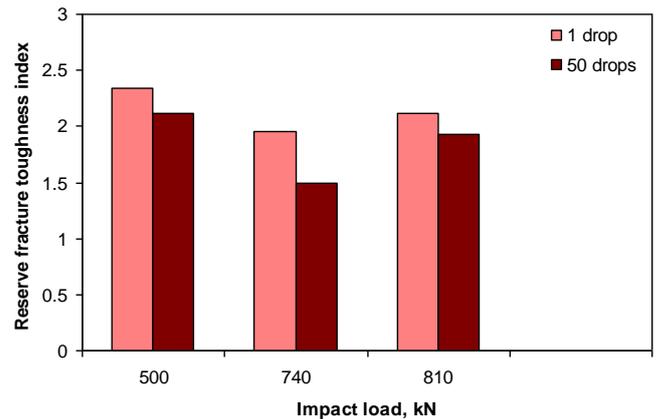


(b) hard track environment

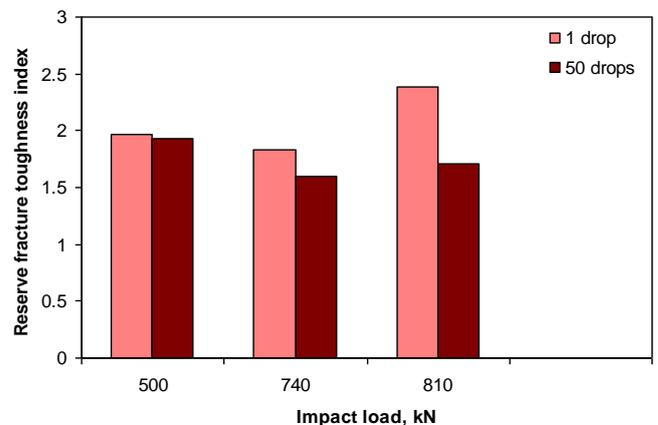
Figure 36. Residual static failure mode of the sleepers subjected to 50 repeated impact loads of 810 kN impact

## 6 RESERVED STRENGTH OF PRESTRESSED CONCRETE SLEEPERS

The residual energy absorption mechanisms imply the reserve strengths of the prestressed concrete sleepers. Figure 37 shows the reserve fracture toughness indices of the concrete sleepers under different conditions. The reserve fracture toughness index here is the ratio between fracture toughness of dynamically damaged concrete sleeper and that of the undamaged, uncracked concrete sleeper, obtained earlier in Section 3.



(a) soft track environment

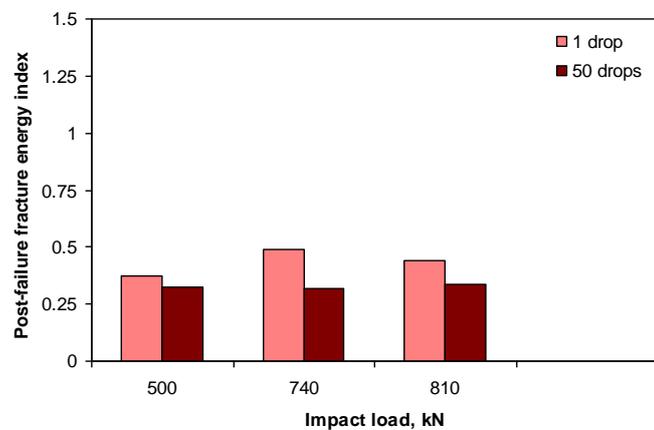


(b) hard track environment

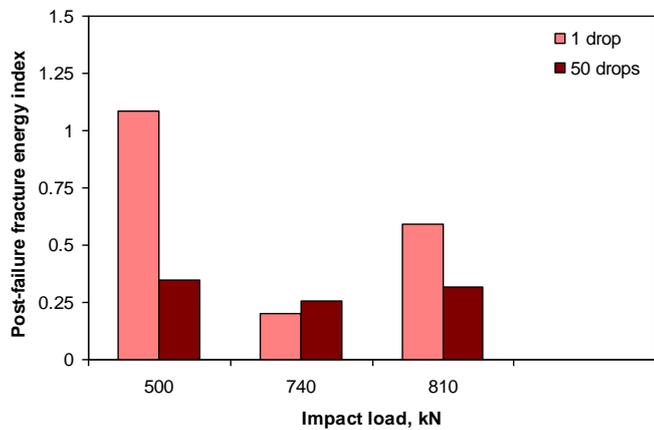
Figure 37. Reserve fracture toughness of the concrete sleepers

It is found that in general the concrete sleepers potentially have the large amounts of reserve fracture toughness. Overall, the reserve fracture toughness indices are more than 1.5. This is because the fractures and cracks in concrete sleepers, caused by the impact loads, attenuate the stress concentration around the tensile region of the concrete sleepers. As the tensile regions play a vital role on fracture formation and failure mode, those cracks allow more flexibility and add more damping to the flexural toughness of the concrete sleepers. The test results show that the reserve fracture toughness indices are averagely 2.10 and 1.85 for the soft-track sleepers

under 1 and 50 impact drops, respectively. Also, they are about 2.04 and 1.75 for the hard-track sleepers under 1 and 50 impact drops. The mean differences between the in-service experiences (1 and 50 impact drops) were found to be 14 and 17 percent for soft- and hard-track sleepers. The more experienced concrete sleepers tend to provide lesser reserve fracture toughness because the repetitive impact stress wave deteriorates the bonding along the prestressing wires, especially in the hard track environment where the support condition imparts significant flexural moments. As a result, the splitting failure mode would occur in a faster manner relative to those sleepers with lesser in-service experiences.



(a) soft track environment



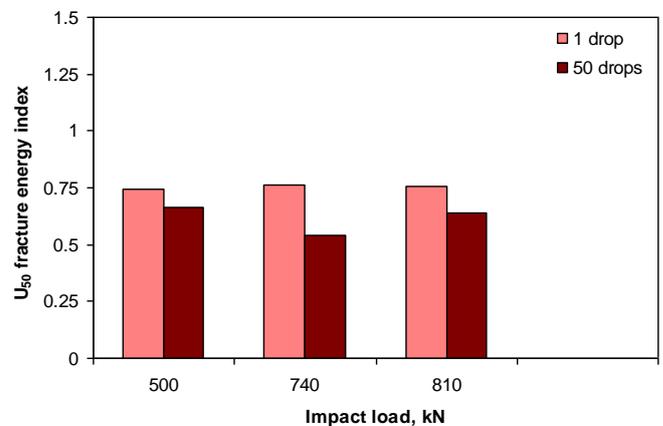
(b) hard track environment

Figure 38. Post-failure fracture energy of the concrete sleepers

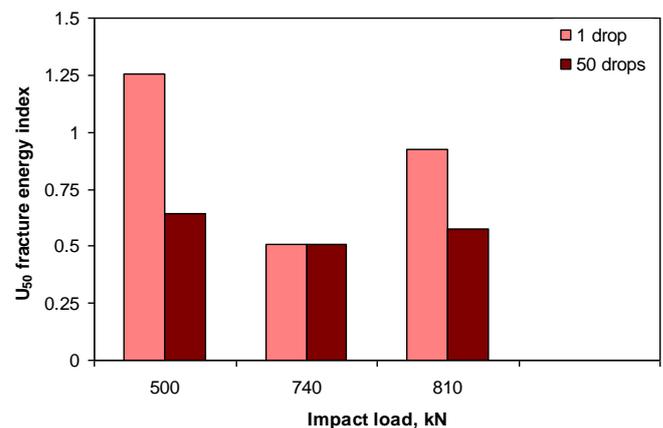
The post-failure fracture energy is the energy absorbed by a concrete sleeper after the failure was identified up until the sleeper is completely devastated or the load-carrying capacity become very low and negligible. Figure 38 shows the post-failure fracture energy indices of the concrete sleepers. The post-failure fracture energy index represents the ratio between the post-failure fracture energy of damaged concrete sleeper and that of undamaged concrete

sleeper obtained earlier in Section 3. In general, the post-failure fracture energy of the damaged concrete sleepers is most likely to be lower than that of the undamaged sleeper. The average post-failure fracture energy indices of the soft-track sleepers under an impact drop and under 50 impact drops are about 0.42 and 0.32, respectively. Those of the hard-track sleepers are 0.73 and 0.30, respectively.

The overall post-failure fracture energy absorptions are relatively low because the internal concrete cracking and prestressing wire debonding were developed during impact repetitions. As a result, less energy would be demanded for forming internal cracks, stretching steel reinforcements, or developing sectional strength.



(a) soft track environment



(b) hard track environment

Figure 39. Post-failure fracture energy of the concrete sleepers

Figure 39 illustrates the total fracture energy absorbed by the concrete sleepers to vertically deform about 50mm (where the sleeper disintegrates completely), so-called  $U_{50}$ . The total fracture energy is the summation of the reserve fracture toughness and the post-failure fracture energy. The actions and causes are resulted from the combination of cracks in concrete and deterioration of bonds between the

wires and concrete as described above. The  $U_{50}$  fracture energy index is computed from the ratio between the total fracture energy of damaged sleeper and that of undamaged sleeper.

Interestingly, it is found that the damaged sleepers tend to possess the lower total fracture energy absorptions than the new sleeper. The average  $U_{50}$  fracture energy indices are about 0.74 and 0.61 for the soft-track sleepers under a single and 50 impact drops, respectively. They are also found to be around 0.98 and 0.57 for the hard-track sleepers under a single and 50 impact drops, respectively. From the experimental results, it is clear that the sleepers with more impact loaded experience would have less residual total fracture energy absorption.

The residual energy absorption mechanisms show that the indicator to predict the residual capacity and reserve strength includes the concrete cracking severity and the debonding level of the prestressing wires in the concrete sleepers due to the severe impact loads. Although there were cracks in concrete sleepers, the remaining prestressing force has kept the cross-section closed after impact loading and the sleeper could provide further load resistance with increased flexibility. The residual failure consequences of the damaged concrete sleeper are found to be fairly different to the failure mode of the new concrete sleeper. However, it is noteworthy that only the fracture toughness portion in the total energy absorption region is useful for railway track design purpose. The post-failure mechanism provides the insight into the residual behaviour and the prospective strategy for mitigation of the concrete sleepers under severe impact loading conditions.

## 7 CONCLUSIONS

The imperfections on either wheel or rail provide a potential for railway sleepers to subject to large extent of impact loading with the various pulse magnitudes and durations. For analysis and design taking into account the extreme action, the behaviour and capacity of the prestressed concrete sleepers are required. In general, those impact loads are of very high magnitude and they are of low-possibility occurrence during the design life of the prestressed concrete sleepers. For example, a 50 year-return-period load has the likelihood of occurrence that the extreme load might happen only once in 50 years regardless of the structural life span. The building code of Australia (BCA) in conjunction with Standards Australia indicates the importance levels of structures for determining the probabilistic loads for track

design at ultimate limit states, upon the consequences of failure of the structures. In a capacity design consideration (50 to 100 years design life), it is important to note that the loading with 100 years return period should be considered for the Category 1 tracks (less importance); 500 years return period for Category 2 tracks (medium importance); and 2,000 years return period for Category 3 tracks (very high importance) (Remennikov et al., 2012). Note that other mode of failure, e.g. rail seat abrasion, will not be discussed here but can be found in Pfeil's study (1997).

This paper thus identifies the dynamic behaviours and responses of prestressed concrete sleepers in railway track systems under either single or repeated impact loads associated with the design probability of occurrence (and return period). The residual capacities of the damaged prestressed concrete sleepers due to those impact actions are discussed in this paper. The residual capacity implies the reserved strength of the prestressed concrete sleepers, which is untapped and believed of its existence by railway industry. Effects of track environment including soft and hard tracks on the impact responses and residual capacity of the prestressed concrete sleepers are also presented. The test specimens were the prestressed concrete sleepers designed complied with Australian Standard: AS1085.14. Drop-weight impact hammer was used to apply multiple impacts directly to the railseat at identical drop heights as to repeat the pulse characteristics at each return period. After each repeated impact test, the static tests were carried out as to identify the residual capacity of the damaged prestressed concrete sleepers.

Based on the dynamic crack propagations, it is found that the initial cracks could occur in the hard track more rapid than in the soft track. The first cracks due to impacts in the prestressed concrete sleepers either in the soft or the hard tracks are always due to flexures. The testing results reveal that the larger impact, the larger and wider are the cracks. Under a single impact load testing, it is found that the track environments (soft and hard tracks) play a sensible role on the crack propagation of the prestressed concrete sleepers. The dynamic crack propagation of the prestressed concrete sleeper in hard track environment grows faster and higher than that in soft track environment. After either single or 50 impact drop tests, the damage in the sleepers was not significant. As a result, the damaged sleepers were later determined for the residual capacity under static testing.

After the sleepers were subjected to static testing, it is found that the failure modes of the sleepers under repeated impact loading are associated with both flexural and longitudinal splitting actions. The splitting fractures are aligned along the prestressing tendons due to the combined bursting and debonding effects. Due to the repetition of compression and tension in the bonding between concrete and tendon, the tendon surface alignments are weakened from the repeated impact tests. Consequently, the residual fracture toughness energy after the ultimate static failure of prestressed concrete sleepers remains minimal, regardless of the track support conditions. On the other hand, under a single impact event, the impact magnitude tends to have little influence on the residual fracture toughness of prestressed concrete sleepers in soft track environment, whilst the sleepers in hard track environment are sensible to the impact magnitudes and are likely to absorb more fracture toughness energy when the dynamic bending moment is larger and more major cracks occur. However, to consider only the energy absorption at the ultimate failure, it seems that there is no remarkably influential factor, which considerably degrades the sleepers under these single impact events.

Reserve capacity of the concrete sleepers can be extracted from the fracture toughness portion in the residual energy absorption diagrams. The experimental results clearly exhibit that overall the damaged concrete sleepers tend to possess large amounts of reserve strength, which is about 50 percent of the fracture toughness of the new concrete sleeper. The reserve capacity would depend on the prestressing steel and concrete interaction under remaining prestressing force at the cross-section and the increased flexibility due to concrete cracks formed by the impact loads.

## 8 ACKNOWLEDGEMENT

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