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Relationship between impact energy and fracture toughness of prestressed concrete railway sleepers

Sakdirat Kaewunruen
RailCorp, sakdirat@hotmail.com

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

Relationship between Impact Energy and Fracture Toughness of Prestressed Concrete Railway Sleepers

Sakdirat Kaewunruen[1] and Alex M Remennikov[2]
[1]RailCorp – Track Engineering, Level 13, 477 Pitt St, Sydney NSW 2000
[2]University of Wollongong, Northfield Ave, Wollongong, NSW 2522

Synopsis: The prestressed concrete sleepers (or railroad ties), which are installed in railway track systems as the crosstie beam support, are designed to carry and transfer the wheel loads from the rails to the ground. It is well known that railway tracks are subject to 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. In addition, there exists the potential of repeated load experience during the design life of prestressed concrete sleepers. Prestressed concrete has played a significant role in maintaining the high endurance of sleepers subjected to low to moderate repeated impact loads. In spite of the common use of prestressed concrete sleepers in railway tracks, their impact response and behaviour under repetitions of severe impact loads are not deeply appreciated nor taken into consideration in design. This experimental investigation was aimed at understanding the residual capacity of prestressed concrete sleepers in railway track structures under ultimate impact loading, in order to develop state of the art limit states design concepts for prestressed concrete sleepers. A high-capacity drop weight impact testing machine was constructed at the University of Wollongong to achieve this purpose. A series of severe impact tests on in-situ prestressed concrete sleepers was carried out, ranging from low to high impact magnitudes. The impact energy was evaluated in relation to the drop heights. The impact-damaged sleepers were re-tested under static conditions in order to evaluate the residual fracture toughness in accordance with the Australian Standard. It was found that a concrete sleeper damaged by an impact load could possess significant reserve capacity sufficient for resisting about 1.05 to 1.10 times the design axle loads. The applied impact energy and residual fracture toughness under different magnitudes of impacts are highlighted in this paper. The effects of track environment including soft and hard tracks are also presented together with a design guidance related to the serviceability and ultimate limit states design.

Keywords: prestressed concrete railway sleepers; impact energy; fracture toughness; ultimate limit states; permissible stress.

1. Introduction

Prestressed concrete railway sleepers have been utilized in the railway industry for over 50 years. The railway sleepers (or called 'railroad tie') are a main part of railway track structures. Their 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 concrete sleepers is also considered to be around 50 years [1]. 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 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 [2]. The magnitude of the dynamic impact loads per railseat varies from 200 kN to more than 600 kN, whilst the design static wheel load per railseat for a 40-tone axle load could be only as much as 110 kN [3]. All static, quasi-static, and impact loads are very important in design and analysis of railway tracks and their components. Generally, dynamic shock loading from modern track vehicles corresponds to the frequency range of 0 to 2000 Hz. 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 acting after the static wheel load is removed. The typical magnitude of impact loads from the reviewed cases [4] varies roughly between 200 kN to 750 kN, depending on the causes and the traveling speed of the 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 in magnitude with 1 to 5 msec time duration. For the second peak (P_2), the average values are about 80 kN and 5 to 12 msec time duration. Therefore, it should be taken into account that the typical duration of impact wheel forces varies widely between 1 and 12 msec [5-7].

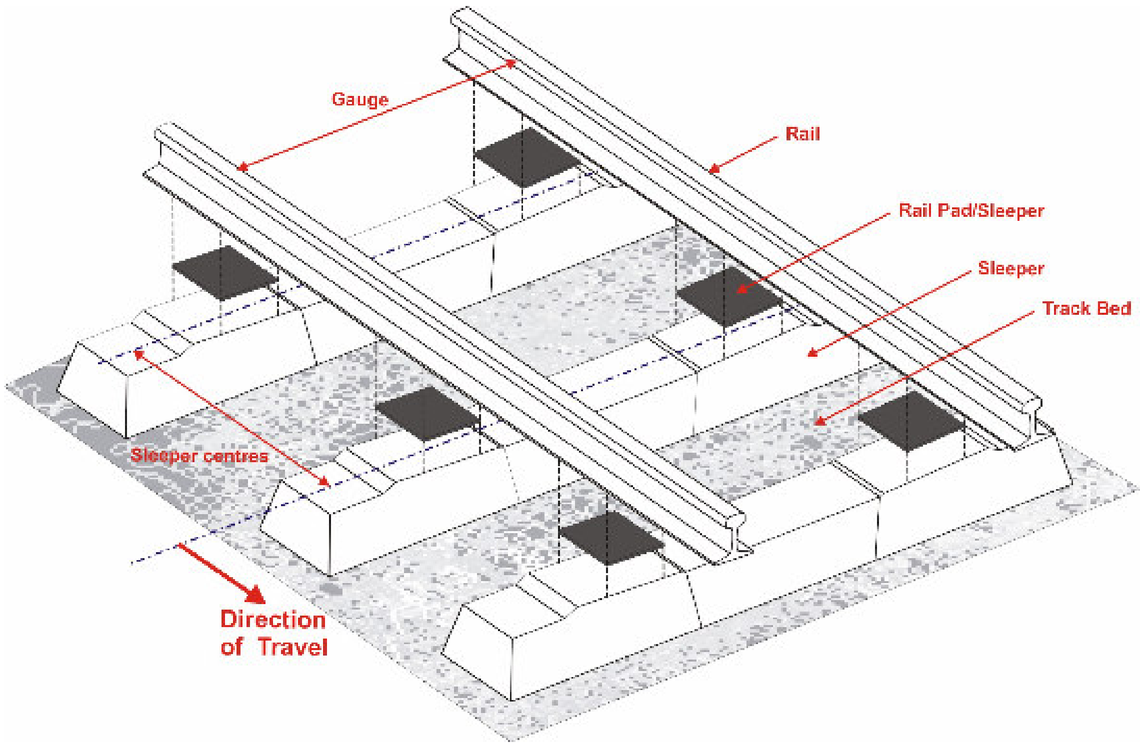

Figure 1. Typical ballasted railway track [8, 9]

A recent study showed that there is a potential possibility of failure for railway sleepers subjected to severe impact loads [10-11]. In general, the dynamic load characteristics considered in design and analysis include the magnitudes of impact loading and the variety of pulse durations. The loading and strain rate effects tend to affect the strength of materials, whilst the high loading magnitude devastates the structural members. In structural design and analysis, 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 a likelihood of occurring 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 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 moment can be achieved by converting the design load to sleeper moment using advanced railtrack dynamic analysis or the design formulation [8]. Last, the strength and serviceability of the prestressed concrete sleepers can be optimized in accordance with AS3600 Concrete structures [12]. The proposed limit states design methodology and procedure can be found in details in ref [13].

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, based upon the consequences of failure [14]. As the design criteria for railway sleepers (with 50 to 100 years design life), loading with 100 years return period should be considered for 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 [8]. Leong [15] 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 loading obtained from a railway network in North Queensland [15]. It should be noted that alternatively the ultimate load action can be correlated to those at 95 percentile of the load spectra [16].

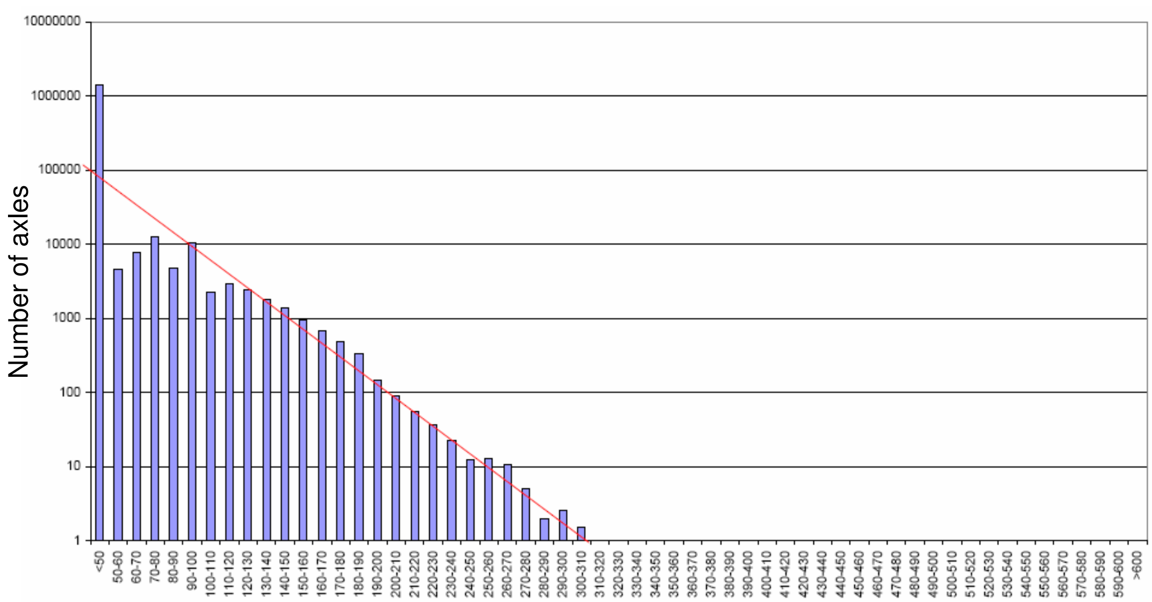

Figure 2. A typical statistical data of loading on tracks [16]

This paper focuses only on the ultimate impact responses and behaviour of prestressed concrete railway sleepers subjected to a variety of severe impact loads. The serviceability and fatigue performance of the prestressed concrete sleepers is presented elsewhere [4]. The prestressed concrete sleepers used were designed in accordance with Australian Standard: AS1085.14 [1]. The test specimens were supplied by an Australian manufacturer. 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 a high capacity load cell connected to a National Instrument data acquisition system. The dynamic measurements also include dynamic strains and accelerations. A softening media placed on top of the railhead to reduce the contact stress was used. Neoprene rubber pads with thickness of 1.5mm ware used to control the duration of load pulses. Impact damage and crack propagation at each drop test were recorded. After each impact test, the static test was carried out to identify the residual capacity of the damaged prestressed concrete sleeper in accordance with AS1085.14 [1]. 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 impact behaviour and residual capacity of prestressed concrete sleepers.

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

2. Experimental Methodology

In this investigation, the test specimens are typical full-scale prestressed concrete sleepers commonly used in Australia. They were provided by Australian manufacturers, under a collaborative research project of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC). Prestressed concrete sleepers are often the main part of the broad gauge rail tracks. The dimensions of the sleeper are given in Table 1. The typical profile and cross section of the prestressed concrete sleepers at railseat is shown in Figure 3. The prestressing tendons are the chevron-patterned wires of 5mm diameter. High strength concrete was used to cast the prestressed concrete sleepers, with design compressive strength at 28 days of 55 MPa, and the prestressing steel used had a rupture strength of 1860 MPa. The cored samples, drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard AS1012.14. 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 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 over time.

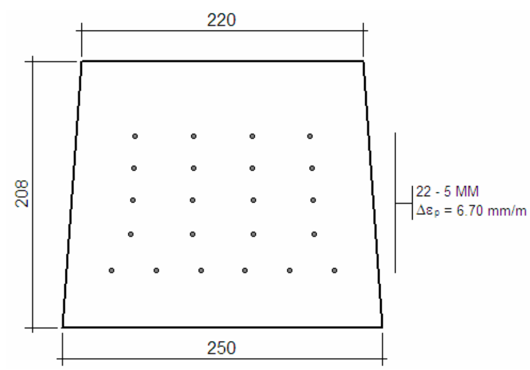

Figure 3. Rail seat cross section of sleeper specimens

2.1 Materials used

The materials used in the experimental setup include the supporting rubber (acting as ballast), steel rails, and the fastening system. Conveyor belt rubber used in mining processes has been adopted as the supporting condition. Validation of the alternative supporting condition was conducted earlier [17] in accordance with AS1085.19 [18]. 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 loads onto the sleepers, so that the 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 high strength steel rods.

2.2 Impact testing

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 [2]. The weight of the projectile was set at 5.81 kN, and therefore, the drop height becomes the only variable. The experimental setup was thus required for specific energy absorption capacity for a particular sleeper, in order to back calculate 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 [19]. To eliminate surrounding noise and ground motion, the concrete sleepers were set up and placed on a strong isolated floor in the laboratory. The strong floor is very stiff and has significantly higher fundamental frequency than the experimental equipment. The drop hammer used has the weight of 5.81kN (592kg). A rigid rail piece was installed at the railseat 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 and released by an electronic quick release system. The impact testing setup is illustrated in Figure 4.

Table 2 Summary of impact and static testing programs [4]

Support condition	Impact force (kN)	Associated Related return period (years)	Number of impact drop	Potential Energy Input (J)
Soft track (track modulus ≤10 MPa)	500	50	1	1510
	740	2000	1	2264
	810	10,000	1	2627
	1500	1,000,000	1	6969
Hard track (track modulus ≥20 MPa)	500	50	1	1220
	740	2000	1	1916
	810	10,000	1	2091
	1500	1,000,000	1	6098

Figure 4. High-capacity impact testing machine at University of Wollongong

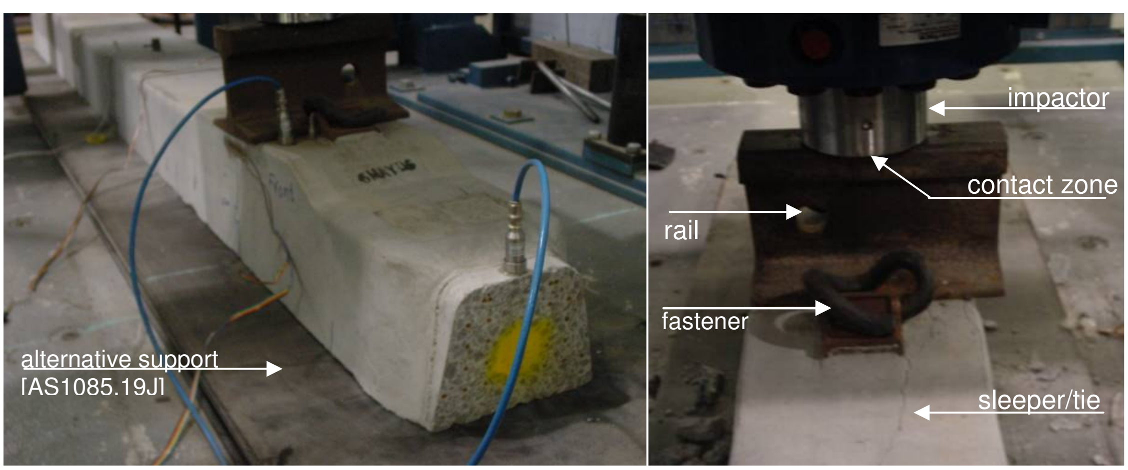

Figure 5 Instrumentation after AS1085.19 [18]

Table 2 shows details of the test programs with particular emphasis on the different target levels of ultimate impact force acting on the prestressed concrete sleepers. The static test program was conducted after the impact test as prescribed in AS1085.14 [1]. Two different support conditions, including ‘soft track’ and ‘hard track’, have been calibrated against the vibration modal parameters of the ballast support in the actual tracks [18-22]. The soft track can be considered as thin ballast bed (about 100-150 mm in depth or track modulus about 5-10 MPa), while the hard track represents the thick layer of the ballast bed (more than 250mm in depth or track modulus about >20 MPa). The experimental setups for support conditions were in accordance with AS1085.19 [18], as illustrated in Figure 5. This setup was verified to be sufficient for investigating the sleepers’ behaviour at railseat [5]. The method of superposition can also be utilized to understand the behaviour of the prestressed concrete sleepers at mid span. As a result, many railway companies have simplified by using simply a half sleeper for their tests.

3.0 Experimental Results

Cracks in the prestressed concrete sleepers were visually observed after each drop test. This type of crack is referred to as the residual crack, as the cracks were closed in the unloaded conditions. Measurements of crack widths and lengths were carried out after each impact using a magnifying glass telescope. The length of the residual cracks is the main indicator for the durability and serviceability of the prestressed concrete sleeper in practice. It should also be noted that the lengths of the residual crack and the maximum opened crack due to dynamic impact are fairly close [4]. The test result shows that the cracks in the concrete sleepers can form due to a range of impact forces, depending on the track support condition.

Figures 6-9 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. Clearly, it is noticeable that the cracks of the hard track sleepers propagate more than those of the soft track sleepers. However, it reveals that the impact-damaged sleepers in both track support conditions are still functional and structurally sound. The impact-damaged sleepers still have the sleeper gauge in acceptable tolerances. The damaged rail seat areas are still good enough to be installed by the rail pads. Although there are some small concrete spallings due to compression at around rail seats, the rail shoulders are tightly embedded in the sleepers. There are some shear crack propagations but their sizes are not substantial [4]. With these observations, the impact damaged sleepers were retested under the prescribed static testing condition in order to identify the comparable and repeatable residual energy toughness [4]. Note that the detailed static testing method is prescribed in AS1085.14 [1].

a) soft track b) hard track

Figure 6. Cracks in a sleeper after a single impact of 500 kN

a) soft track b) hard track

Figure 7. Cracks in a sleeper after a single impact of 740 kN

a) soft track b) hard track

Figure 8. Cracks in a sleeper after a single impact of 810 kN

a) soft track b) hard track

Figure 9. Cracks in a sleeper after a single impact of 1500 kN

Figures 10 and 11 show the reserve fracture toughness indices and the relation between the impact energy and fracture toughness indices of the prestressed concrete sleepers after being subjected to a single impact load. The reserve fracture toughness index here is the ratio between the fracture toughness of a dynamically damaged concrete sleeper and that of an undamaged, uncracked concrete sleeper. It is found that in general the concrete sleepers potentially have 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 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 unleash the flexural toughness of the concrete sleepers.

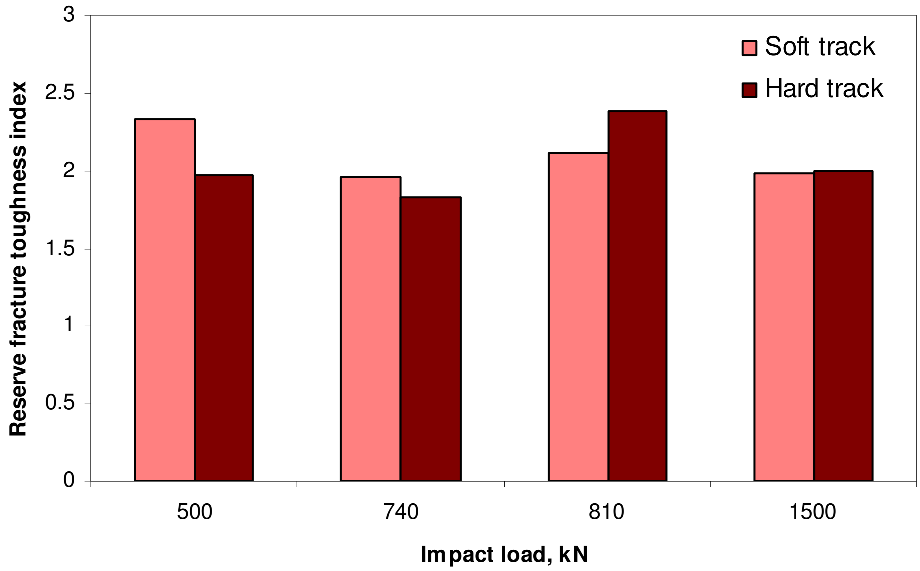

Figure 10. Reserve fracture toughness indices

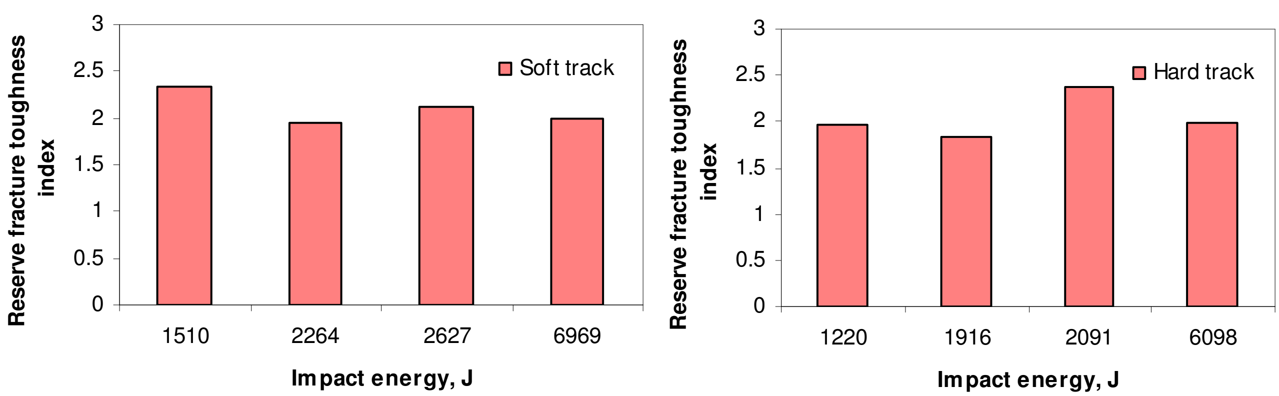

Figure 11. Reserve fracture toughness and impact energy

4. Conclusions

This paper identifies the dynamic behaviour and response of prestressed concrete sleepers in railway track systems under single ultimate 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 demonstrates the reserve strength of prestressed concrete sleepers, which is untapped and believed of to exist by the railway industry. Effects of track environment including soft and hard tracks on the probabilistic impact responses and residual capacity of the prestressed concrete sleepers are also highlighted. The test specimens were the prestressed concrete sleepers complying with Australian Standard: AS1085.14. They were kindly supplied by Australian manufacturers (Rocla and AUSTRAK). Drop-weight impact hammer was used to apply multiple impacts directly to the railseat at identical drop heights so as to repeat the pulse characteristics at each return period. Measurements included the dynamic impact load history, dynamic strains, and acceleration responses. In these investigations, to reduce the contact stress between railhead and impactor, neoprene rubber with the thicknesses of 1.5mm was used as the softening media placed on top of the railhead. After each impact test, static tests were carried out so 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 more rapidly with the hard track than with 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 flexure. The testing results reveal that the larger the impact, the larger and wider are the cracks. Under a single impact load test, it is found that the track environments (soft and hard tracks) play a significant role on the crack propagation of the prestressed concrete sleepers.

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

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