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Experimental load rating of aged railway concrete sleepers

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Abstract: Prestressed concrete sleepers (or railroad ties) are structural members that distribute the wheel loads from the rails to the track support system. Over a period of time, the concrete sleepers age and deteriorate in addition to experiencing various types of static and dynamic loading conditions, which are attributable to train operations. Recent studies have established two main limit states for the design consideration of concrete sleepers: ultimate limit states under extreme impact and fatigue limit states under repeated probabilistic impact loads. It was noted that the prestress level has a significant role in maintaining the high endurance of the sleepers under low to moderate repeated impact loads. This experimental investigation was aimed at static and dynamic load rating of aged railway concrete sleepers after service. Fifteen sleepers were extracted from a heavy haul rail network for testing using experimental facilities at the University of Wollongong (UoW), Australia. The structural evaluation program included quasi-static bending tests, dynamic impact tests, and tests to establish the current level of prestress in the steel wires using the dynamic relaxation technique. Two of the sleepers were evaluated for the level of prestressing forces in accordance with Australian Standards. Through diagnostic tests, the results of quasi-static bending tests produced the in-track bending capacities of sleepers that can be combined with the moments and forces anticipated over the next ten years to predict performance of the sleepers on a heavy haul coal line. The dynamic tests simulating the ability of concrete sleepers to resist extreme loading events due to heavy impact loads demonstrated that the sleepers in-track are likely to be able to resist the planned increased traffic without catastrophic failure over the next decade. Final conclusions suggest that there should be a routine test program every five years to ascertain the load rating of clustered sleepers and their fastening system in the heavy haul track system.

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1. Introduction

Over the past 50 years, railway prestressed concrete sleepers have been used in rail networks around the world, especially in Europe and Japan. In Australia, concrete sleepers have been designed to withstand up to 40 tonne axle loads and used for nearly 35 years [1-3]. The railway sleepers (called 'railroad tie' in the US) are a key structural element of railway track structures. The sleepers redistribute dynamic pressures from the rail foot to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is also considered to be around 50 years [3-6]. Figure 1 demonstrates a typical ballasted railway track and its components. During their life cycles, railway track structures experience static, dynamic and often impact loading conditions due to wheel/rail interactions associated with the abnormalities in either a wheel or a rail [7]. Based on this investigation, the magnitude of the dynamic impact loads per railseat varies from 200 kN to 600 kN, whilst the design static wheel load per railseat for a 40-tone axle load could be only as much as 110 kN nominally. The dynamic wheel load forms the basis for design and analysis of railway track and its components in an operational environment with uncertainties [8-10]. In principle, the impact capacity relates to design load (F^*) for the limit states design concept [11], taking 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 moment can be achieved by converting the design load to sleeper bending moment envelopes using an advanced dynamic analysis of railway tracks or an empirical design formulation [11-13]. Finally, the strength and serviceability of the prestressed concrete sleepers can be optimized in accordance with the Australian Standard AS3600 [6] and other design guidelines for concrete structures [14, 15].

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Recent investigations showed that a railway sleeper could have experienced multiple high-intensity impact loads, causing a rapid degradation of its structural integrity and durability [16, 17]. In-field, experimental and numerical data recorded by the University of Wollongong has revealed that the failure of a railway sleeper is more likely be due to cumulative damage rather than due to a once-off extreme event, which might occur due to the derailment [2, 3]. It is important to note that, for prestressed concrete sleepers, the low magnitude but high cycle impact fatigue tends to be insignificant in comparison with the high magnitude but low cycle impact fatigue [14, 17-20]. In contrast, it was found from a critical literature review that there is no research investigation into load rating or remaining life prediction of concrete sleepers. As a result, many assumptions have been made in practice that may lead to either incorrect or inefficient asset management under constantly changing operations. This practical issue has resulted in an initiative to investigate the existing condition of railway concrete sleepers and to develop a standard guidance for predicting the remaining life of such components. The strength and capacity of concrete sleepers depends largely on the residual material strengths (concrete and strands), the prestressing force and the bond between steel strands and concrete [17-18]. Over time, the concrete sleepers experience diverse traffic loads from operational activities, and may have damage and cracks, also resulting in an additional time-dependent loss in prestress level [21]. This paper presents the experimental load rating results of railway prestressed concrete sleepers after a period of service life through a variety of structural testing programs.

This investigation arose from a planned expansion of the traffic on a heavy haul coal line in New South Wales, Australia. The rail infrastructure operator planned to double the traffic on that particular coal line and was concerned about the ability of its existing railway concrete sleepers to cater for the increased traffic loads. The sleepers on the coal line were manufactured and installed in 1982-1984. A cluster of fifteen in-service concrete sleepers that were installed in the heavy haul rail network were extracted from the rail track and transported to the structures laboratory at the

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University of Wollongong (UoW), Australia. Visual inspections and laboratory material testings were conducted at the initial stage of the project. Eight of the sleepers were evaluated for the static bending capacities in accordance with Australian Standards. Three of the sleepers were subjected to multiple high-intensity impact loads associated with the risk and the probabilistic loads on the track. This paper presents experimental studies into the load rating of *in situ* prestressed concrete sleepers and engineering characteristics of construction materials used for manufacturing concrete sleepers. In addition, dynamic impact load rating of the concrete sleepers was carried out in order to underpin the failure mode analyses associated with operational track forces' risk and probability.

2. Experimental Programs

2.1 Test specimens

Fifteen sleepers were extracted from the coal line and transported to UoW for testing in accordance with Australian Standard AS1085.14 [4]. Table 1 shows the measured dimension of the sleeper specimens. It was found that 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 rail infrastructure operator confirmed that the sleepers were typical prestressed concrete sleepers from 1982. Design data detailing concrete strength, level of prestress, and design bending moment capacities were not available for a direct comparison between the current design parameters and the original design parameters at the time of sleeper manufacture. However, reportedly from industry practices, the permissible stresses and design restrictions of the concrete sleepers back in 1980s were very similar to those in existing standards [4, 5]. There was not much change in the standard design methodology and inputs over the past decades. The design characteristics as tabulated in Table 2 were thus adopted from AS1085.14 and AS3600, respectively [4, 5]. Before the tests started, every sleeper was visually inspected and the major dimensions of the sleepers were then measured. The measurements were taken at the rail seat and the centre of the sleepers. Since no original drawings were provided, it was not possible to compare the *in-situ* dimensions to the nominal dimensions. From the visual inspection, most of the sleepers suffered severe abrasion of the soffit surface. Some of the sleepers showed concrete spalling near the centre, adjacent to the rail seat and at the sleeper ends. Table 3 summarises the physical conditions of the aged concrete sleepers.

In this experimental study, aged concrete sleepers were selected for the load rating evaluation as displayed in Figure 2. The prestressed concrete sleepers are usually the main component of the standard-gauge, heavy-haul rail tracks. High strength concrete material is used to cast the prestressed concrete sleepers, with design compressive strength at 28 days of 50-55 MPa, and the prestressing steels used are high strength with rupture strength of 1700 MPa. Cored samples, drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard AS1012.14 [22], as shown in Figure 3. Although the common concrete strength adopted for design is 50 MPa, it was found that condition of the concrete at the test age of about 30 years (since 1982) had deteriorated. The prestressing tendons are the chevron-patterned indented wires of about 5 mm diameter. From visual inspection, it could be observed that the high strength prestressing wires were of high quality and thus the strength would not rapidly change during time.

2.2 Material testing

Core samples were taken from two sleepers. The cored samples, drilled from the sleepers, were taken to confirm the material properties of the tested concrete sleepers, in accordance with the Australian Standard AS 1012.14 (1991) [22]. The standard recommends avoiding the top layer of a concrete member, as it may be of lower strength than the bulk of the concrete. There can be a strength gradient within the concrete, increasing with depth below the surface resulting from curing and consolidating effects. In their manufacture, the sleepers are cast upside down, therefore coring from the bottom was avoided in this study.

The ends of the two sleeper specimens were cut clean from the rest of the sleeper at the location of the rail seat, as shown in Figure 4. The sleeper ends were then placed upright and the cores extracted from the freshly cut interior face. The concrete cores were extracted from between the two rows of prestressing wires from each of the two specimens.

Once the cylindrical cores were extracted from the sleeper ends, they were checked for overall smoothness, steps, ridges and grooves. The ends of the samples were trimmed and finished to a smooth flat surface with the length-to-diameter ratio maintained at 2:1. An investigation into the actual residual strength of concrete, using five concrete cylinders with a diameter of 55 mm, suggested that the average compressive strength was 44 MPa (± 4 MPa) [21]. Compared with the design data in Table 2, the deviation of concrete strength (about 10%) could be attribute to poor quality during manufacturing and construction, internal micro cracking due to sudden transfer of pre-stressing and dynamic impact loads, and material deterioration in an aggressive environment.

2.3 Experimental Load Rating Tests

In accordance with the project task, eight concrete sleepers were tested to failure under monotonically increasing quasi-static loads and three concrete sleepers were tested for impact strengths under three different conditions of track moduli. Four concrete sleepers were tested for static bending strength at the rail seat to determine both the positive and negative cracking/ultimate rail seat moment capacities. Next four sleepers were tested under static loading to determine the positive and negative, cracking and ultimate moment capacities at the sleeper centre.

Resistance of the concrete sleepers to high-magnitude wheel impact loads was investigated using the drop hammer facility at UoW. The sleepers were tested for impact strengths at the rail seat for soft, moderate and hard track conditions to simulate on-track sleeper behaviours with different track moduli.

The overall experimental program at UoW is summarised in Table 4. Sleepers for static and dynamic tests were arbitrary selected from the fifteen sleepers removed from the heavy haul coal-line and shipped to UoW by the rail infrastructure operator. The details of the experimental setups developed for static, dynamic and prestressing tests are presented in Table 4.

2.3.1 Static Tests

A number of structural static tests were performed in order to rate the load performance of aged concrete sleepers in accordance with Australian Standards [4-5]. Figure 5 shows the test setup for rail seat vertical load tests – negative bending moment; Figure 6 shows the setup for rail seat vertical load tests – positive bending moment; Figure 7 shows the setup for centre negative bending moment test; and Figure 8 shows the test setup for centre positive bending moment test. These static tests are critical to the experimental load rating of the concrete sleepers to satisfy the requirements of relevant standards for concrete sleepers [4-5].

2.3.2 Impact Tests

The UoW structures laboratory contains the largest drop hammer facility for structural impact testing in Australia. The facility has the ability to generate an impact load by a free-falling mass of 600 kg from the height of up to 6 metres. Monitoring equipment includes high-capacity load cells for measuring impact loads up to 2000 kN, high speed laser displacement sensors, accelerometers, strain gauges and high-speed camera. Figure 9 presents a general view of the drop hammer facility at UoW.

Generally, there are no standards for undertaking impact testing of concrete sleepers to determine their '*impact resistance*'. Extensive studies of impact resistance of concrete sleepers were initiated by Kaewunruen and Remennikov [1-2] and Kaewunruen [3] as part of research activities within the framework of the Cooperative Research Centre for Railway Engineering in Australia. The methodology for impact testing of sleepers developed by Kaewunruen [3] was utilised in this project to test three concrete sleepers for impact strength at the rail seat. In this study, three sleepers were tested for impact strengths at the rail seat for the prescribed values of track moduli 8, 30 and 120 MPa (soft, moderate and hard track conditions). It is well known that defining track stiffness by track modulus is quite crude when considering sleeper's response. This is because track modulus is calculated based on rail support deflection in a cluster of components. This means that the change of rail type, sleeper spacing, sleeper type, fastening system, rail pad, and formation will change track modulus.

2.3.2.1 *Track Moduli and Laboratory Support Setup*

In light of the complexities involved in experimental modelling of prescribed values of track moduli, the experimental sleeper support conditions were grouped into Soft Track (< 20 MPa), Moderate Track (20-70 MPa) and Hard Track (100-120 MPa) for experimental simulation purposes.

Moderate track support condition was simulated following a detailed study of the sleeper support conditions in Kaewunruen [3] and the requirements of AS 1085.19 [5]. In this test, the track ballast bed was simulated by a series of rubber conveyor belts supporting the concrete sleepers and providing the support stiffness equivalent to that of the real ballast bed. Using the results of vibration analysis of the real track conditions, Kaewunruen [3] calibrated the experimental support conditions to closely match the dynamic characteristics for this type of track conditions.

For this project, it was found that six layers of conveyor belts would be equivalent to the stiffness of the track with moderate stiffness. The rail was placed on the rail seat and the rail pad was not included. This is because field observations suggested that deteriorated and worn rail pads may not provide any resilience [23-26]. The effect of rail pads on impact attenuation were presented elsewhere [27-28]. This study simulated the worst case scenario with an ineffective worn rail pad where all the impact energy is totally absorbed by strain energy of the sleepers. As shown in Figure 10, the extreme cases of track moduli were replicated by using ballast (200 mm) over a thick layer of sand-rubber mix (50% by volume of rubber crumbs) for the very soft track, and a thin ballast layer (150 mm) on a shock mat placed directly on the concrete strong floor for the very stiff track.

Three concrete sleepers available for impact testing were investigated for their response in hard, moderate and soft track situations. The impact load generated by a falling 600-kg anvil was applied directly to the top of the rail. Since the direct impact of the steel impactor on the steel rail generates very short duration load impulses (1-2 msec), a softening media (3-mm thick neoprene pads) were placed on the rail top to control the duration of loading pulses. It is known from the previous studies [1-3, 7-13] that the typical duration of impact load caused by wheel/rail abnormalities is about 5-10 msec. The load duration close to 10 msec was therefore achieved in all the tests in this investigation.

2.3.2.2 Load actions associated with risk and probability

The rationale for selecting a magnitude of the impact load was based on the outcomes of study by Leong [29] where the likely maximum impact forces that would be applied to the rail above an individual sleeper were determined. Using the methodology presented in [29], the maximum likely incremental impact force for a 1:400 year return period is 430 kN. The total wheel-rail force that would occur at 1:400 year event would be the incremental impact force of 430 kN plus the upper 5th percentile of the static load distribution, which would be 168 kN. The dynamism of static loads is theoretically and practically negligible. The static load was correlated to a factored load case (i.e. $1.2F_s$) developed for limit states design principle [29]. Thus, the total impact force has some reasonable probability of occuring over the next 10 years based on ‘big data’ recorded over few years, obtained from wayside systems. It should later be used for dynamic testing of the sleepers at rail seat, which is 168 + 430 = 598 kN [29].

It should be pointed out that in the above calculations the Distribution Factor (DF) for the dynamic force is taken as 1.0 due to very short duration of the loading pulses. It was assumed that due to high inertial characteristics of the rail track structure, the response time for bending of a substantial part of the track would be significantly longer than the applied load duration leading to the situation where only the sleeper directly under the impact would be resisting the effects of impact loading.

Assuming the most unlikely loading scenario, that the sleepers would experience, and even allowing for the greatly increased traffic planned for the heavy-haul coal line, the following testing regimes for the concrete sleepers were devised:

Step 1. Subject sleepers to impact load with a magnitude of approximately 600 kN and visually inspect the sleepers for cracking.

Step 2. Repeat loading the sleepers with the 600-kN impact load 10 times. This would effectively represent behaviour of the sleepers over a 4,000-year period. Inspect the sleepers for cracking after each impact event.

Step 3. Investigate behaviour of the sleepers under extreme loading conditions (with a return period of several million years) by applying loads with a magnitude in excess of 1000 kN.

For all dynamic tests in this investigation, the impact load time history was recorded by the high-capacity interface load cell connected to the high speed data acquisition system. The load time histories were recorded at the sampling rate of 50,000 samples per second (50 kHz) to capture all important features of the dynamic load waveforms. Figure 11 shows the experimental setup for the impact test. Note that the superposition principle was found applicable for analysis of sleeper's structural behaviour [30-38].

3. Experimental results of static tests

3.1 Rail Seat Bending Strength

The capacity of the heavy-haul, coal-line concrete sleepers was investigated for both positive and negative moments acting at the rail seat.

3.1.1 Rail seat positive moment tests

Two sleepers tested under rail seat positive moment test were the sleeper UOW5 and sleeper UOW6. The sleeper UOW5 suffered severe abrasion of the concrete cover at the bottom surface and the concrete was damaged adjacent to the rail seat. The concrete cover at the bottom surface of the sleeper UOW6 suffered moderate abrasion and there was a wide crack underneath the rail seat.

Figure 12 shows the load-displacement relationships for the sleeper UOW5 and sleeper UOW6 subjected to the rail seat positive moment test. The load-displacement relationships for both sleepers were similar up to the maximum load capacity. The sleeper UOW5 shows slightly higher displacement than the sleeper UOW6 before they failed. For the sleeper UOW5, fine cracks started to appear at the loading points after the applied load exceeded 350 kN. The cracks propagated upwards as the loading increased. For sleeper UOW6, the existing crack propagated upward as the applied load exceeded 350 kN. At about 550 kN, the load resistance of both sleepers dropped due to the formation of diagonal shear crack between the loading point and the support, as shown in Figure 13. After that, the load resistance of the sleepers increased again and reached maximum load capacity of about 580 kN before the sleepers failed due to crushing of concrete in compression and splitting at the end of sleeper as illustrated in Figure 14.

3.1.2 Rail seat negative moment test

Rail seat negative moment tests were performed on the sleeper UOW7 and sleeper UOW8. The sleeper UOW7 suffered severe abrasion of the concrete cover at the bottom surface and concrete was damaged at the end of the sleeper causing one of the prestressing wires to be exposed. The sleeper UOW8 suffered very severe abrasion on the concrete cover at the bottom surface.

Figure 15 shows the load-displacement relationships for sleepers UOW7 and UOW8. For both sleepers, a crack started when the load reached approximately 150 kN. The crack propagated upward when the loading increased. At about 370 kN, a diagonal crack appeared between the loading point and the support for the sleeper UOW7 (see Figure 16a), causing the load resistance to drop slightly. The sleeper UOW7 reached maximum load of 420 kN where it failed by splitting at the end of the sleeper similar to sleeper UOW5 (Figure 13). Sleeper UOW8 showed lower maximum load compared to sleeper UOW7 due to different failure mode. The flexural crack in sleeper UOW8 developed into a wide crack when the applied load increased as shown in Figure 16 (b). The sleeper reached maximum load of 350 kN before it failed by crushing of concrete in compression as shown in Figure 17.

3.2 Centre Bending Strength

The capacity of the heavy-haul concrete sleepers was investigated for both positive and negative moments acting at the centre.

3.2.1 Centre positive moment tests

Figure 18 shows the load-displacement relationships for sleepers UOW1 and UOW2 subjected to the centre positive moment test. Both sleepers had suffered severe abrasion of concrete cover at the bottom surface. The load-displacement relationships for both sleepers were similar up to 17 mm displacement. For both sleepers, fine cracks appeared underneath the loading points and the mid-span at approximately 80 kN. The maximum flexural load for UOW1 and UOW2 was 99.5 KN and 99 kN, respectively. After that, the concrete in compression started to crush and then caused the sleeper to exhibit softening behaviour where the resistance gradually decreased with increase in displacement. Figure 19 shows the cracking and crushing of concrete for sleeper UOW1.

3.2.2 Centre negative moment tests

Centre negative moment tests were performed on sleepers UOW3 and UOW4. Sleeper UOW3 showed severe abrasion of the concrete cover at the soffit surface, and there were three wide cracks at the top surface. Sleeper UOW4 showed moderate abrasion of the concrete cover at the soffit surface, and there was severe concrete damage at the top surface between the rail seat and the centre.

Figure 20 shows the load-displacement relationships for sleepers UOW3 and UOW4. It shows that sleeper UOW4 has a higher flexural load capacity than sleeper UOW3. For sleeper UOW3, flexural cracks started at mid-span when the load exceeded 85 kN (Figure 21a) and it reached the maximum flexural load capacity of 104 kN. For sleeper UOW4, fine cracks were observed at mid-span when the flexural load reached about 110 kN, as shown in Figure 21b. The maximum flexural load for sleeper UOW4 was about 138 kN. After reaching the maximum flexural load, the concrete in compression started to crush and the load resistance of the sleepers dropped as the displacement increased. Sleeper UOW3 showed lower maximum flexural load compared to sleeper UOW4 which could be attributed to the very severe abrasion of concrete cover at the bottom surface and existing wide cracks on the top surface of the sleeper prior to the testing. It also shows that severe damage of concrete between the mid-span and the rail seat in sleeper UOW4 had no significant effect on the load capacity of the sleeper as the flexural load was applied at the mid-span.

3.3 Summary of static load rating

The results from static tests on four concrete sleepers are summarised in Table 5, which presents the cracking moment and the ultimate moment capacities for the sleepers tested in this investigation. These results can be used for benchmarking assessments of the concrete sleepers on a future heavy-haul rail line (e.g. in Western Australia) when planning increased traffic on that line. It is important to note that sampling rate and number of sleepers is ample based on the consistency and reliability of statistical Track Condition Index (TCI) and Track Quality (TQ) history at the particular track section [39].

4. Experimental results of impact tests

4.1 Rail Seat Impact Strength, Hard Track Support Conditions

One heavy-haul sleeper was investigated for the rail seat ultimate impact resistance in the hard track support conditions, as shown in Figure 22. High-speed camera was used to record the impact event as shown in Figure 23. New calibration of the parameters of impact testing was required since the track stiffness influences the dynamic response of sleepers. It was found that a 915 mm drop height would be required to generate impact forces with a magnitude of 600 kN. The load duration was controlled by the neoprene pads placed on the top of the rail and replaced for each loading event.

The dynamic loading programme included 10 consecutive impact load applications by the anvil dropped from the height of 910-915 mm. Following 10 repeated applications of the load with a return period of 400 years (representing a 1:400 load magnitude that is probabilistically designed to occur once a year [2, 32]), the sleeper was later subjected to the impact force of 700 kN by dropping the anvil from a 1025 mm height. Table 6 presents the achieved load magnitudes and durations for every test and observed damage.

A typical impact load-time history is shown in Figure 24. Initial fine cracking was observed at the bottom surface of the rail seat after four impacts. New fine cracks were observed at the bottom surface of the rail seat after the 5th impact. These cracks did not propagate with repeated impact load applications. No additional cracking was observed at the sleeper rail seat after subjecting it to the impact force of 700 kN by dropping the anvil from a height of 1025 mm.

Using Image-Pro Plus software for image processing, the graph showing vertical displacements of the rail seat was produced, as seen in Figures 25 to 28 collectively. It shows that the ballast aggregates underneath the sleeper were crushed by heavy impact loads, causing significant vertical movement of the rail seat. This identified a limited bearing capacity of the ballast layer. Figure 27 shows a cracking pattern in the sleeper at the end of the testing programme. It can be noticed that the final damage is minor and would not affect the sleeper's ability to resist vertical rail seat loads.

4.2 Rail Seat Impact Strength, Moderate Track Support Conditions

One heavy-haul sleeper was investigated for the rail seat ultimate impact resistance in the moderate stiffnes track conditions, as shown in Figure 29. New calibration of the parameters of impact testing was required since the track stiffness influences the dynamic response of sleepers. It was found that a 350 to 380 mm drop height would be required to generate impact forces with a magnitude of 600 kN. The load duration was controlled by the neoprene pads placed on the top of the rail and replaced for each loading event.

The dynamic loading programme included 10 consecutive impact load applications by the anvil dropped from the height of 350 mm. Following 10 repeated applications of the load resulting in the impact load of about 600 kN (1:400 return period), the sleeper was subjected to the impact load of 900 kN by dropping the anvil from a 750 mm height. The last two impacts, from the drop heights of 950 mm and 1050 mm, induced impact forces of 1020 kN and 1200 kN, respectively. Table 7 presents the achieved load magnitude, load durations for every test and the observed damage.

The impact load-time histories for selected impact events are shown in Figure 30. No sleeper cracking was observed for all ten impact load applications (see Figures 31-33). Some concrete scabbing was observed under the rail after the impact load with a magnitude of 900 kN. Additional concrete damage developed under the rail after subjecting the sleeper to the impact force of 1020 kN by dropping the anvil from a height of 950 mm. Figure 31 shows the cracking pattern in the sleeper at the end of the testing programme. It can be noticed that the final damage is minor and would not affect the sleeper's ability to resist vertical rail seat loads as illustrated by Figures 32-33.

4.3 Rail Seat Impact Strength, Soft Track Support Conditions

One of the aged sleepers in this study was used to determine the rail seat ultimate impact resistance in the soft track conditions. As justified above, the impact force of 600 kN with a duration about 10 msec was chosen for impact testing of the concrete sleepers. The drop hammer machine was re-calibrated to achieve repeatability of the parameters of impact forces in each impact event. It was established that the 600 kg anvil is required to be dropped from a height of 800 mm to generate the impact force with a magnitude of about 600 kN. The load duration was controlled by the neoprene pads placed on the top of the rail.

The dynamic loading programme included 10 consecutive impact events applied to the rail seat through the rail. Table 8 presents the achieved load magnitude and duration for every test. It could be noticed that the dynamic load parameters showed very little variability for every test. After each loading event, the sleeper was carefully examined for the initiation of cracking. It was found that no cracking or other form of concrete damage occurred in the sleeper after 10 repeated load applications with a magnitude of about 600 kN.

For the next stage of testing, the sleeper was subjected to a series of extremely high impact loads simulating extraordinary loading events. The sleeper was initially subjected to a 1200 mm drop of the anvil that generated an impact force with a magnitude of 840 kN. For the last impact, the sleeper was subjected to an impact from a 2000 mm height and the impact load developed was about 1070 kN. The impact load-time histories for selected impact events are shown in Figure 34.

For the first 10 impact loading events, while the impact forces were kept at about 600 kN, no visible damage to the concrete sleeper was observed. There was no visible damage in the sleeper rail seat for the 1200 mm impact with the corresponding peak force of 840 kN. The final impact load in excess of 1000 kN was generated by dropping the anvil from a 2 m height. This also did not cause observable damage to the rail seat area of the sleepers. Based on the above observations, the concrete sleeper resisted all impact events, including several extraordinary impact loadings, with no cracking thus demonstrating the high load carrying capacity of the concrete sleepers for resisting dynamic loads of high magnitude and short duration.

5. Conclusions

This paper presents the experimental load rating studies arose from the planned expansion of the traffic on a heavy-haul coal line by a railway operator and maintainer. There was concern whether the railway concrete sleepers would be capable of carrying the increased traffic loads. Note that the concrete sleepers on that coal line were manufactured and installed in 1982-84.

For this investigation, fifteen actual railway concrete sleepers that were installed in the heavy haul rail network were removed from the rail track (coal lines) and transported to the structures laboratory at the UoW, Australia. Visual inspections and laboratory material testings were conducted. The sleepers were evaluated for the static and dynamic impact performances and the data was benchmarked in accordance with Australian Standards for prestressed concrete sleepers. Based on the critical literature review, it was found that the research investigation into residual condition or remaining life prediction of concrete sleepers is inadequate. This paper firstly presents the experimental studies into the load rating of *in situ* prestressed concrete sleepers using static and dynamic impact test regimes. This investigation is an essential and inevitable contribution to the framework for estimation of the remaining life of concrete sleepers, which is firstly presented in the open literature.

The visual inspection of the concrete sleepers revealed that there were potential problems with durability of the sleepers. Concrete spalling of sleepers due to tamping damage, poor construction, and loss of concrete section due to abrasions were among the problems that could cause the rapid deterioration of strength and serviceability. Through diagnostic static tests, eight aged concrete sleepers were subjected to bending tests according to the procedures prescribed [4]. Through a series of bending tests, the strength of sleepers was determined at the rail seat and the sleeper centre. The experimental results of quasi-static bending tests produced the in-track bending capacities of sleepers that can be combined with the moments and forces anticipated from the standard design concept over the next 10 years to predict performance of the sleepers on a heavy haul coal line.

Three concrete sleepers were tested for impact strength at the rail seat for three values of the track moduli (8, 30, and 120 MPa) representing soft track, moderate and hard track supporting conditions. The sleepers were subjected to a series of impact load applications with magnitudes corresponding to frequencies of occurrence ranging from 400 years to several million years. Very minor cracking was detected in the sleepers under the most adverse loading conditions for all three track supporting conditions. This implies that the in-track sleepers are likely to be capable of resisting extreme loads generated by wheel and rail abnormalities without catastrophic failure under current traffic and even with increased traffic due to planned expansion on this line over the next decade. It is also recommended from a risk management framework (considering dynamisms of rail operations and track maintenance regimes) that the rail infrastructure operator exercise a routine test program every five years to ascertain the load rating of clustered sleepers and its fastening system in the heavy haul track system.

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Table 1. Dimensions of the test sleepers

Sleeper mark	Rail Seat (mm)			Centre (mm)		
	Top Width	Depth	Soffit width	Top width	Depth	Soffit width
UOW1	205	210	240	210	165	245
UOW2	202	215	245	212	166	245
UOW3	204	195	242	212	152	240
UOW4	205	215	242	212	161	243
UOW5	203	215	241	211	164	245
UOW6	201	212	249	210	171	249
UOW7	201	208	240	210	165	244
UOW8	200	195	238	210	158	240

Table 2. Design properties of materials

Materials	Elastic modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete	38,000	55	6.30
Prestressing tendon	200,000	-	1,700
Steel rails	205,000	-	-

Table 3. Physical conditions of aged railway concrete sleeper specimens

Sleeper mark	Physical condition of the sleepers
UOW1	Severe abrasion of bottom concrete surface. Labelled with 3745083.
UOW2	Severe abrasion of bottom concrete surface and concrete was damaged adjacent to the rail seat.
UOW3	Very severe abrasion of bottom concrete surface. Three wide cracks at the top surface adjacent to the mid-span.
UOW4	Moderate abrasion of bottom concrete surface, and concrete between the mid-span and rail seat was damaged.
UOW5	Severe abrasion of bottom concrete surface and concrete was damaged adjacent to the rail seat.
UOW6	Moderate abrasion of bottom concrete surface and a wide crack underneath the rail seat.
UOW7	Severe abrasion of bottom concrete cover, damage of the concrete at the end of the sleeper causing one prestressing wire was exposed
UOW8	Very severe abrasion of bottom concrete surface.

Table 4 Description of sleeper testing program

Test #	Type of test	Parameters to be investigated	Sleeper Type
1	Static (monotonically increasing)	Rail seat – negative moment	SRA2 (UOW7, UOW8)
2	Static (monotonically increasing)	Rail seat – positive moment	SRA2 (UOW5, UOW6)
3	Static (monotonically increasing)	Centre – negative moment	SRA2 (UOW3, UOW4)
4	Static (monotonically increasing)	Centre – positive moment	SRA2 (UOW1, UOW2)
5	Dynamic (impact load)	Rail seat – soft track condition	SRA2 (UOW9)
6	Dynamic (impact load)	Rail seat – medium track condition	SRA2 (UOW10)
7	Dynamic (impact load)	Rail seat – hard track condition	SRA2 (UOW11)
8*	Determination of level of prestress in tendons [21]	Remaining prestress in wires	SRA2
9*	Material testing [21]	Concrete compressive strength	SRA1

*test data and results are available in [21].

Table 5 Summary of experimental load rating results (static testing)

	Type of test	Sleeper marks	Cracking load (kN)	Cracking moment (kN.m)	Ultimate load capacity (kN)	Ultimate moment capacity (kN.m)	Design moment capacity (kN.m)
1	Centre positive moment	UOW1	78	30.0	99	38	38
		UOW2	85	32.6	99	38	
2	Centre negative moment	UOW3	85	32.6	104	40	40
		UOW4	110	42.2	138	52	
3	Rail seat positive moment	UOW5	350	57.8	575	95	95
		UOW6	350	57.8	580	96	
4	Rail seat negative moment	UOW7	150	24.8	420	69	58
		UOW8	150	24.8	350	58	

Table 6 Summary of impact testing (hard track condition)

TestNo	Drop height (mm)	Maximum load (kN)	Loading duration (msec)	Observed damage
1	910	606	14	no damage
2	910	570	15	no damage
3	915	615	13	no damage
4	915	625	14	first minor crack
5	915	580	14	crack propagation
6	915	590	14	no additional damage
7	915	637	13	no additional damage
8	915	613	13	no additional damage
9	915	630	13	no additional damage
10	915	630	14	no additional damage
11	1025	700	13	no additional damage

Table 7 Summary of impact testing (medium track condition)

Test No	Drop height (mm)	Maximum load (kN)	Loading duration (msec)	Observed damage
1	350	580	9	no damage
2	350	628	9	no damage
3	350	630	8	no damage
4	350	628	8	no damage
5	350	580	9	no damage
6	350	560	9	no damage
7	370	613	9	no damage
8	370	625	10	no damage
9	380	630	9	no damage
10	380	608	9	no damage

11	750	900	8	concrete scabbing under rail
12	950	1020	7	more concrete damage under rail
13	1050	1200	7	no additional damage

Table 8 Summary of impact testing (soft track condition)

Test No	Drop height (mm)	Maximum load (kN)	Loading duration (msec)	Observed damage
1	800	625	22	no damage
2	800	620	20	no damage
3	800	600	21	no damage
4	800	585	22	no damage
5	800	590	22	no damage
6	800	580	23	no damage
7	800	570	23	no damage
8	800	540	21	no damage
9	850	505	23	no damage
10	900	630	21	no damage
11	1200	840	15	no damage
12	2000	1070	16	no damage

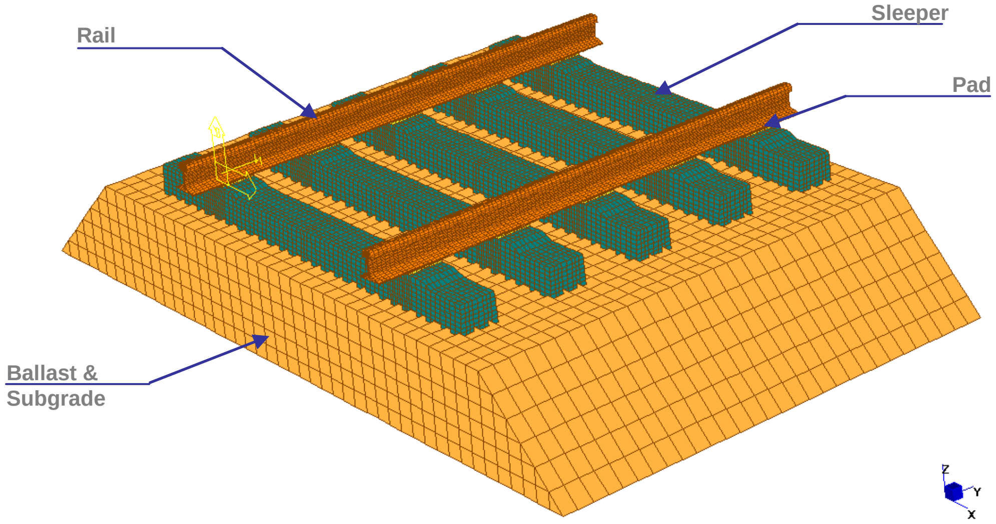

Figure 1. Typical components of railway tracks.

a) severe abrasion of concrete cover at the bottom surface of the sleeper UOW1

b) concrete damage at the end of the sleeper UOW2

Figure 2 Physical condition of concrete sleepers

c) severe abrasion of the concrete cover at the bottom surface of sleeper UOW3, causing one of prestressing wires was exposed

d) severe damage of concrete between the mid-span and the support for the sleeper UOW4

Figure 2 Physical condition of concrete sleepers

e) severe abrasion of the concrete cover at the bottom surface of sleeper UOW5

f) a wide crack underneath the rail seat of sleeper UOW6

Figure 2 Physical condition of concrete sleepers

g) damage of concrete at the end and one prestressing wire was exposed in sleeper UOW7

h) very severe abrasion on the concrete cover at the bottom surface of sleeper UOW8

Figure 2 Physical condition of concrete sleepers

Figure 3. Preparation of concrete samples (left: coring machine; and right: cored concrete samples prior to compression testing).

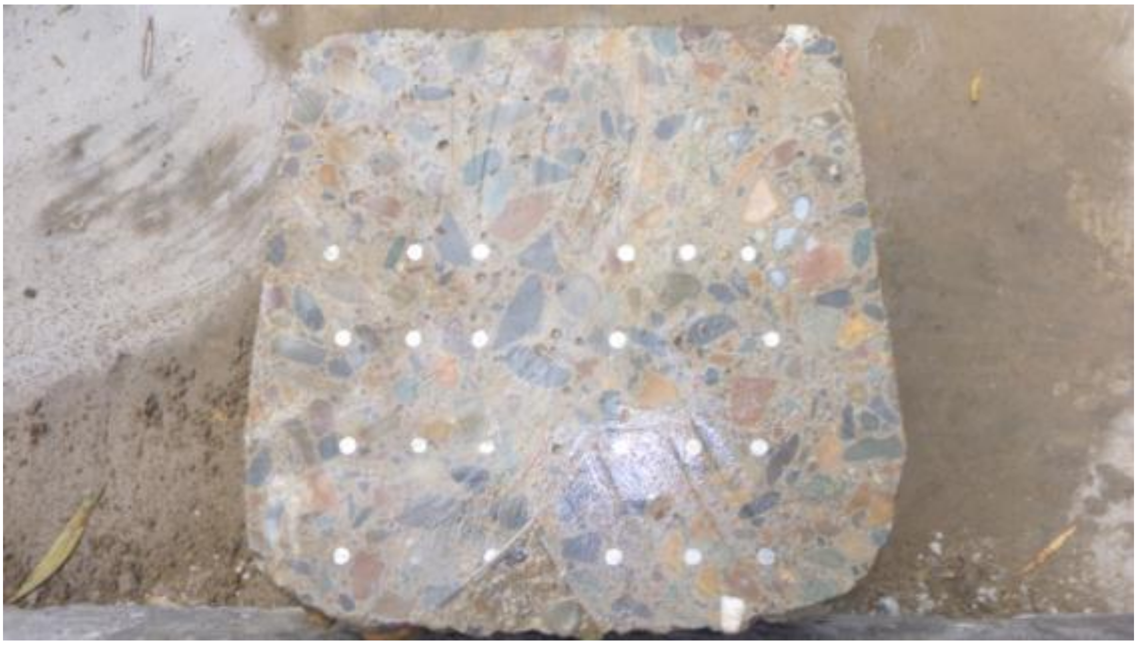

Figure 4. Freshly cut sleeper end ready for coring (SRA1)

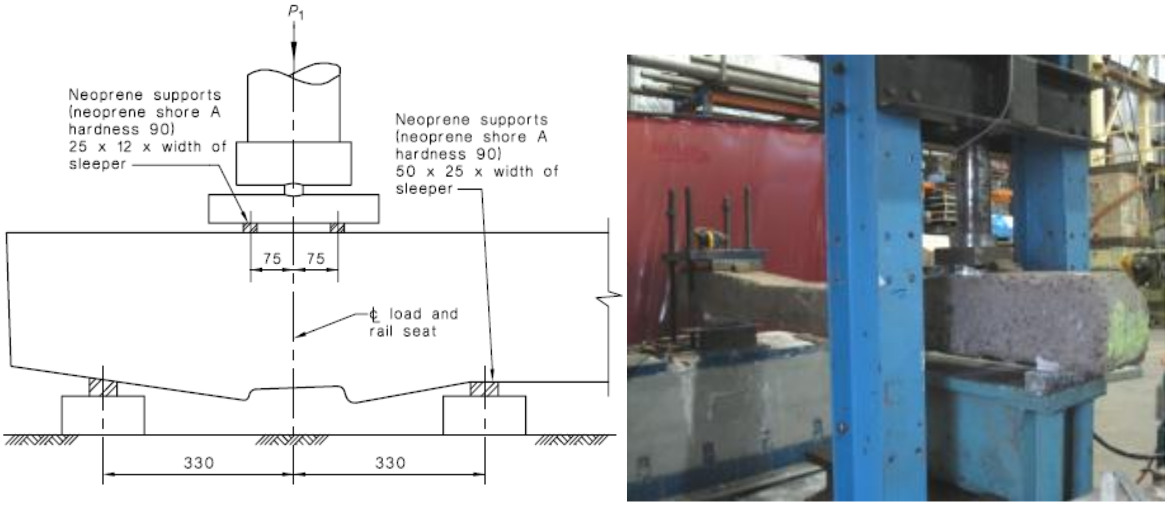

Figure 5 (a) and (b) - Rail seat vertical load static test for negative bending moment

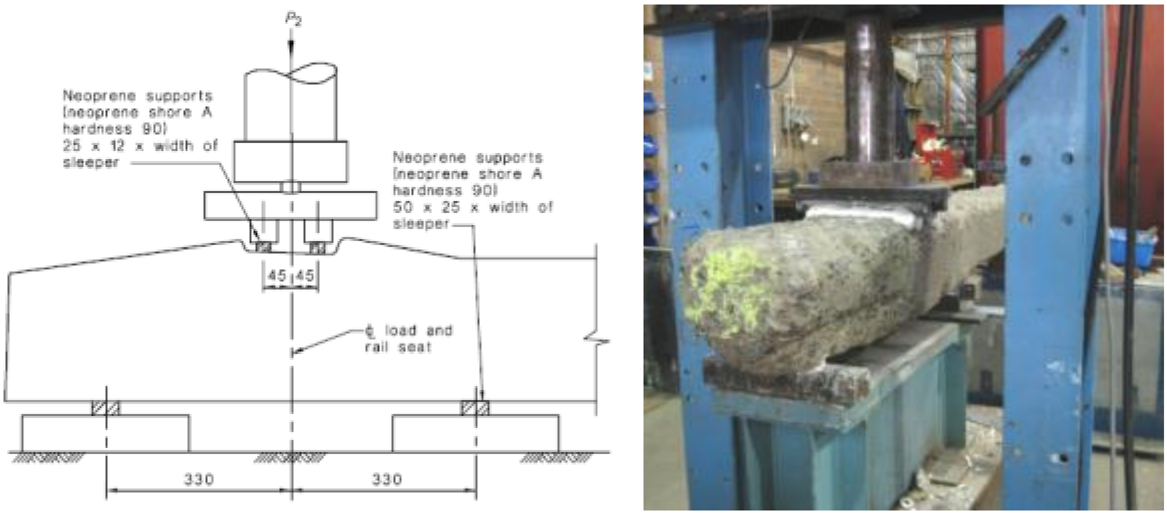

Figure 6 (a) and (b) - Rail seat vertical load static test for positive bending moment

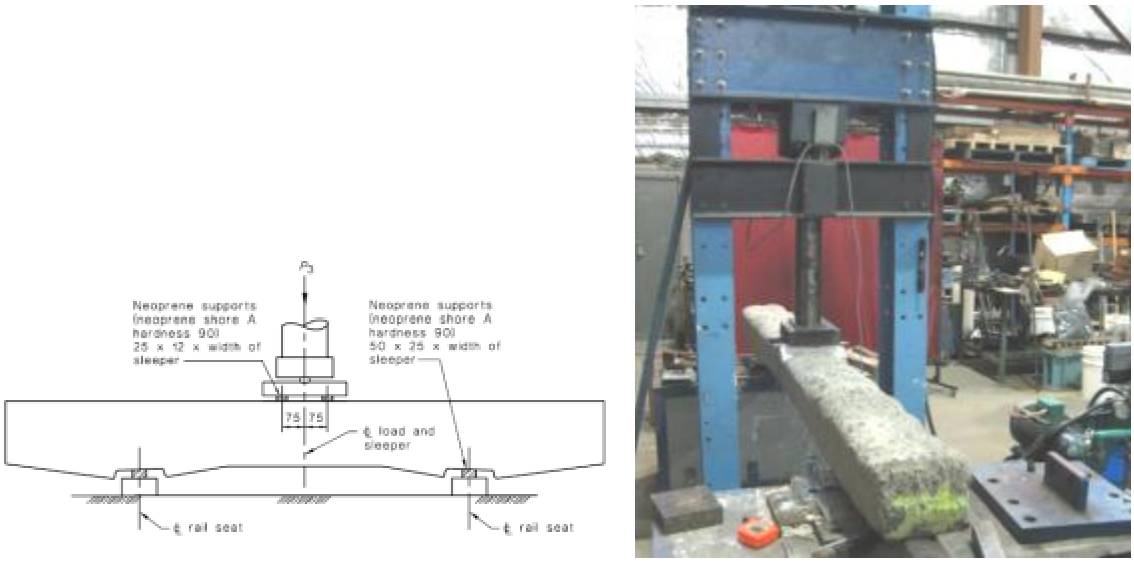

Figure 7 (a) and (b) - Sleeper centre vertical load test for negative bending moment

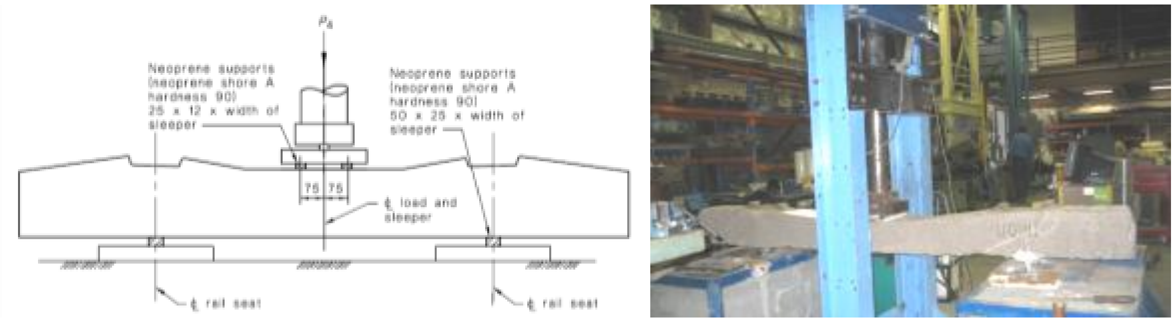

Figure 8 (a) and (b) - Sleeper centre vertical load test for positive bending moment

Figure 9 Drop hammer facility at UoW

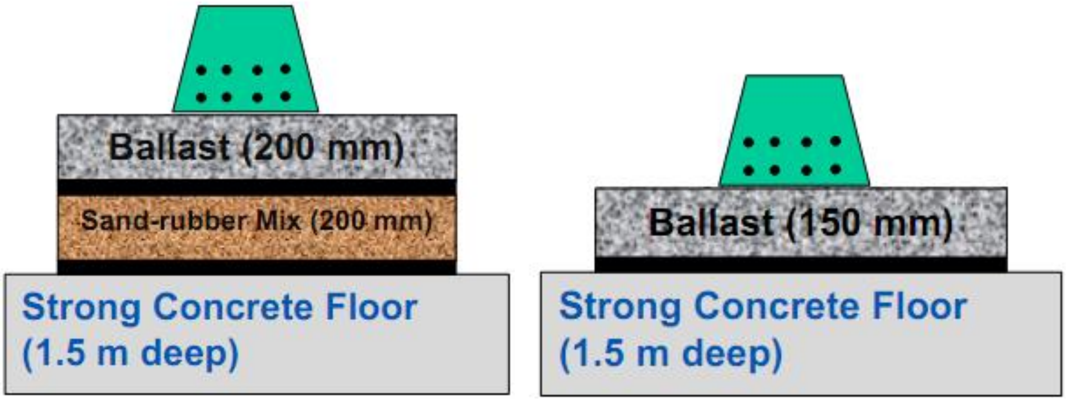

Figure 10 Modelling extreme cases of track support conditions: (a) very soft using sand-rubber mix; and (b) very hard.

Figure 11 Impact testing of coal-line concrete sleepers at rail seat

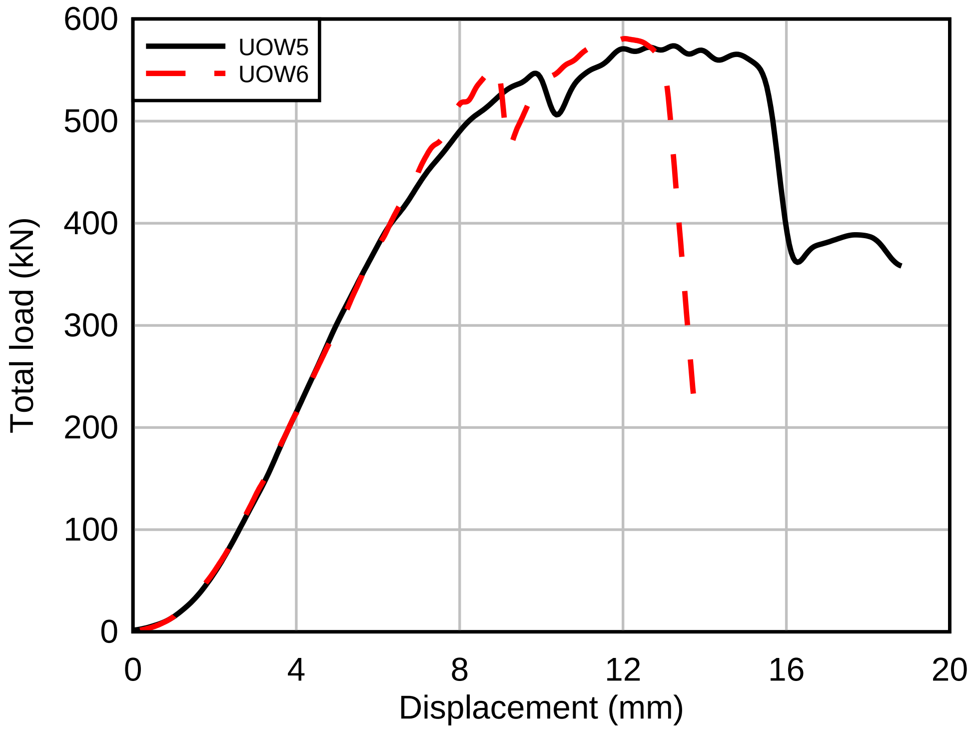

Figure 12 Load-displacement relationships for sleeper rail seat positive moment capacity.

Figure 13 Damage of sleepers under rail seat positive moment test (a) flexural cracks and diagonal crack for sleeper UOW5 and (b) flexural crack and diagonal crack for sleeper UOW6.

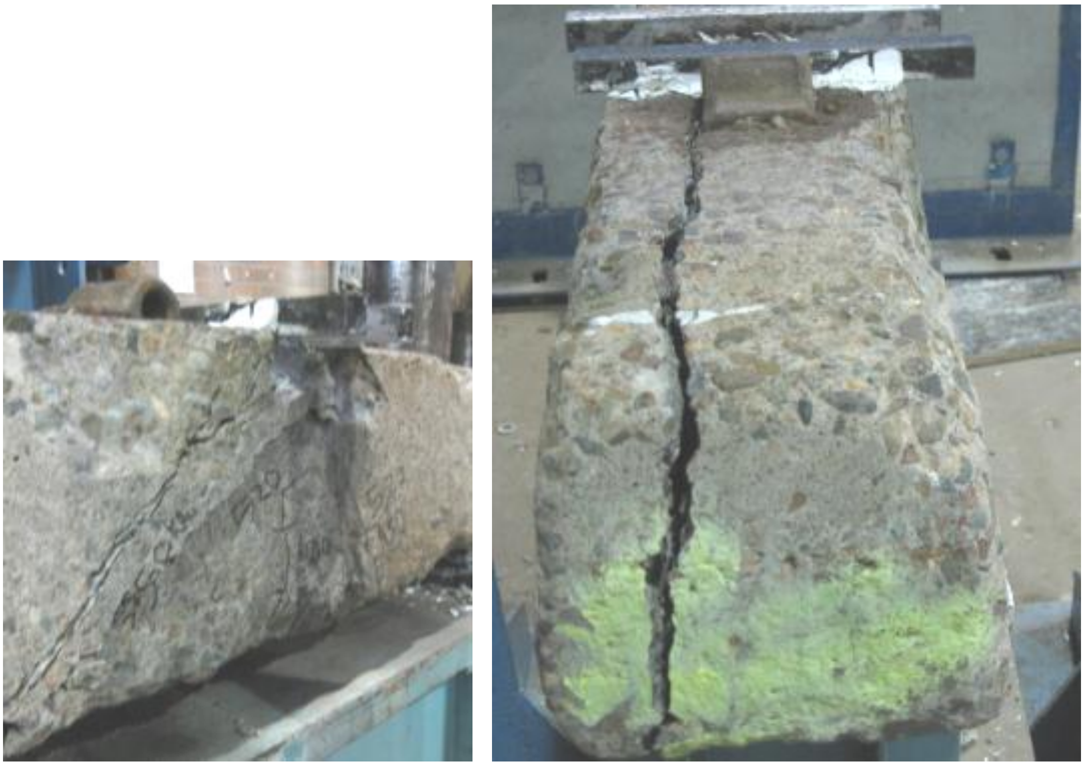

Figure 14 Failure modes of sleepers subjected to the rail seat positive moment test (a) crushing of concrete in compression, (b) end splitting failure.

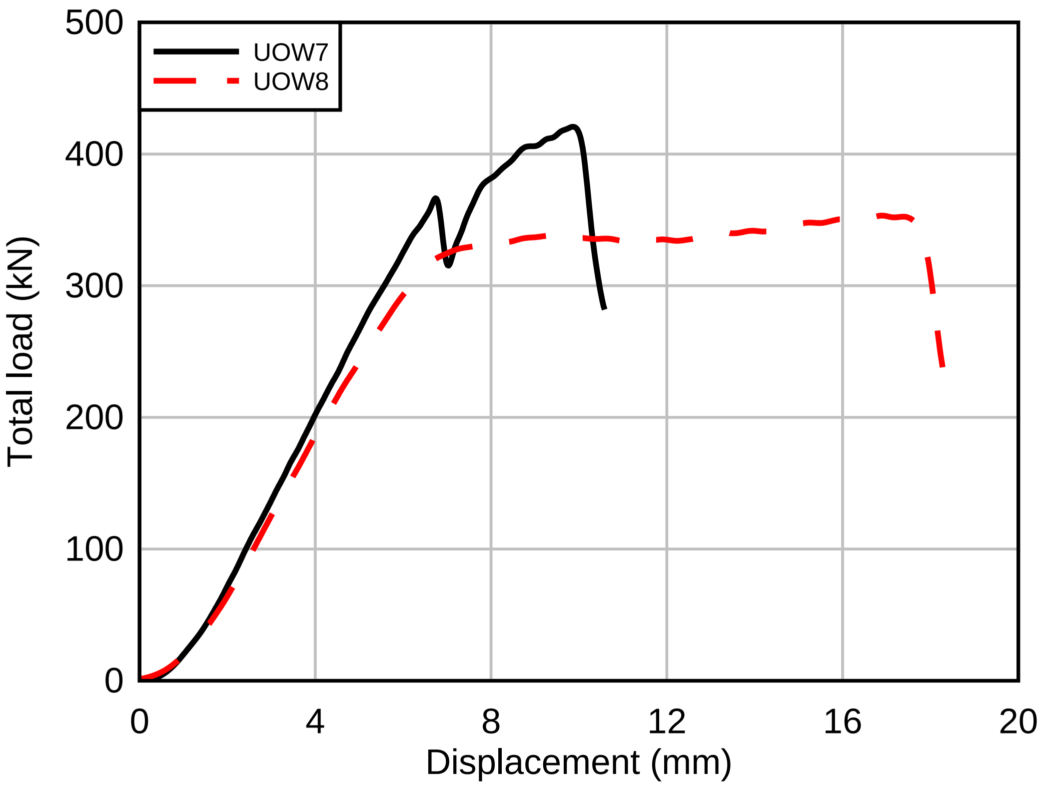

Figure 15 Load-displacement relationships for sleeper rail seat negative moment capacity.

Figure 16 Damage on the sleepers (a) a flexural crack and a diagonal crack on the sleeper UOW7, (b) a wide flexural crack on the sleeper UOW8.

Figure 17 Crushing of concrete in compression for the sleeper UOW8.

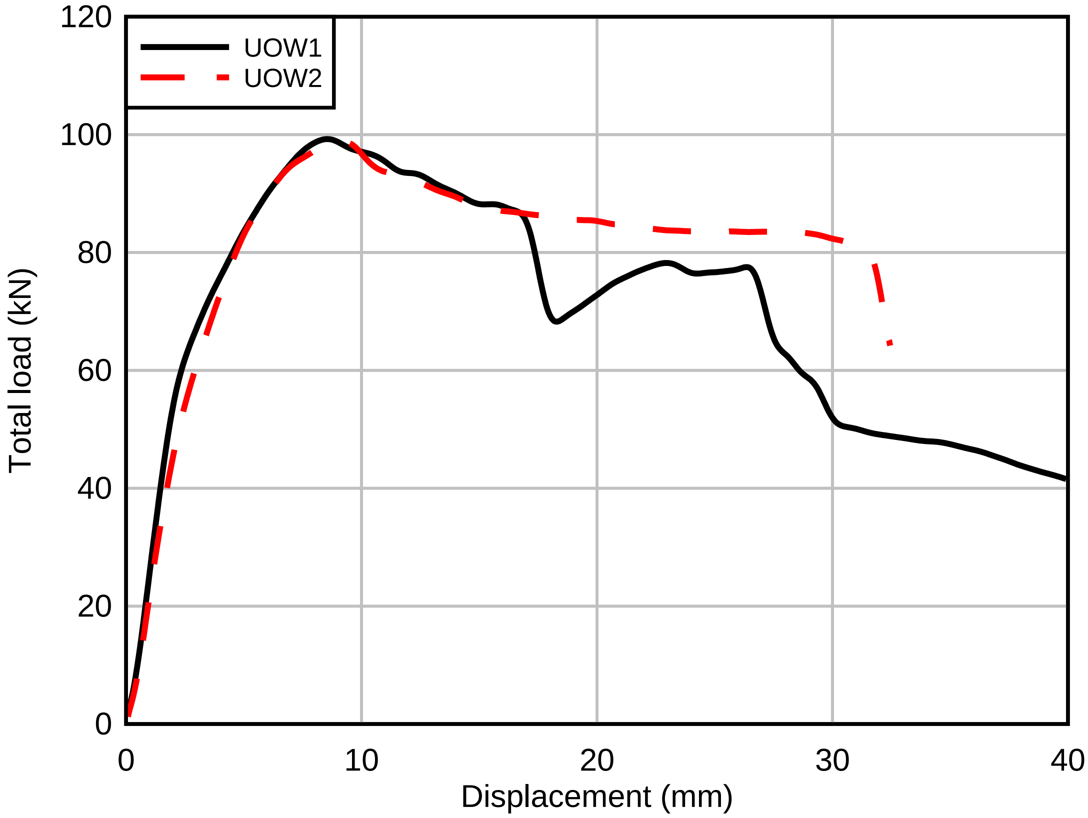

Figure 18 Load-displacement relationships for sleeper centre positive moment capacity.

Figure 19 (a) Cracking of sleeper at mid-span for UOW1, and (b) crushing of concrete at the top for UOW1.

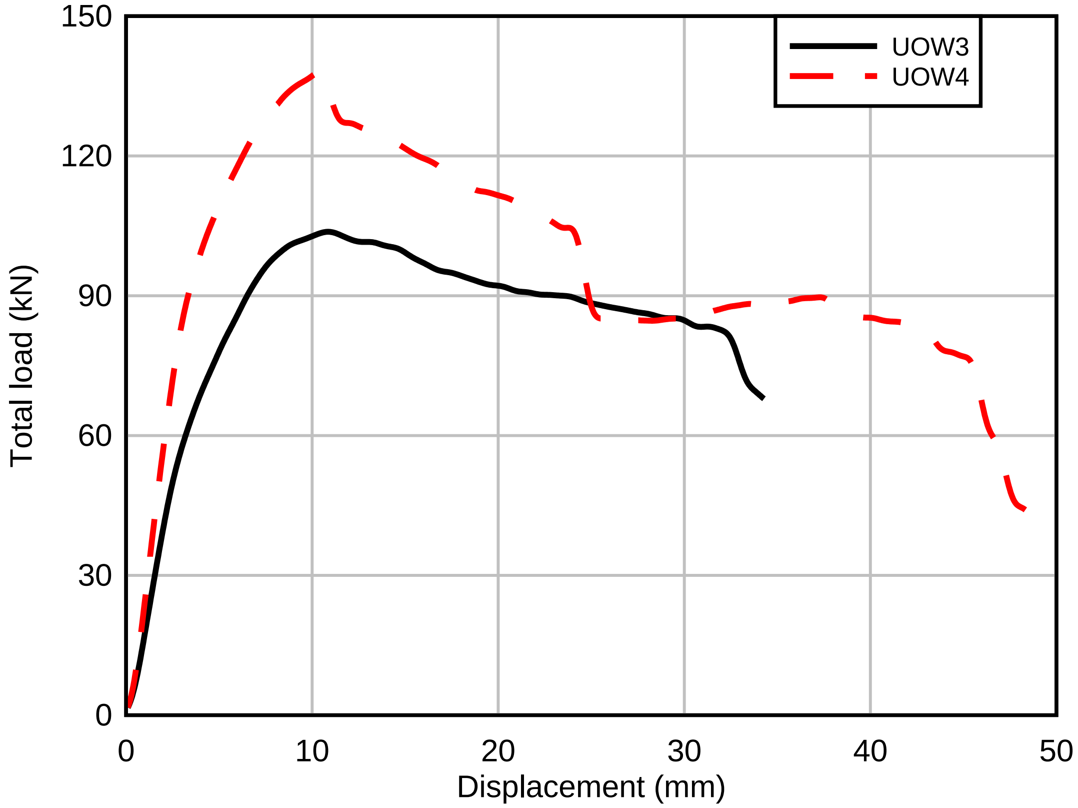

Figure 20 Load-displacement relationships for the sleepers subjected to negative moment test at sleeper centre.

Figure 21 (a) Cracking of sleeper at mid-span for UOW3, and (b) Cracking of sleeper at mid-span for UOW4.

Figure 22 Experimental modelling of hard track support condition

Figure 23 High speed camera for recording dynamic response of concrete sleeper

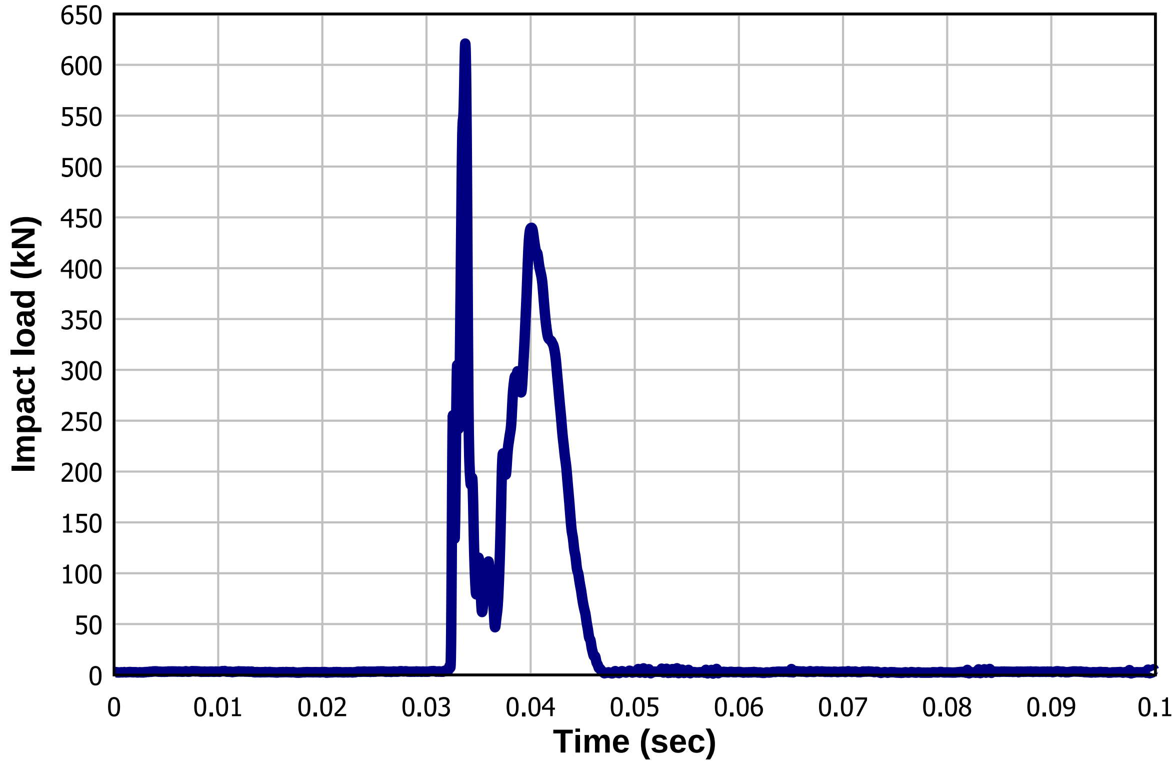

Figure 24 Typical impact load time history for hard track condition

Figure 25 High speed recording of dynamic response of sleeper in hard track condition

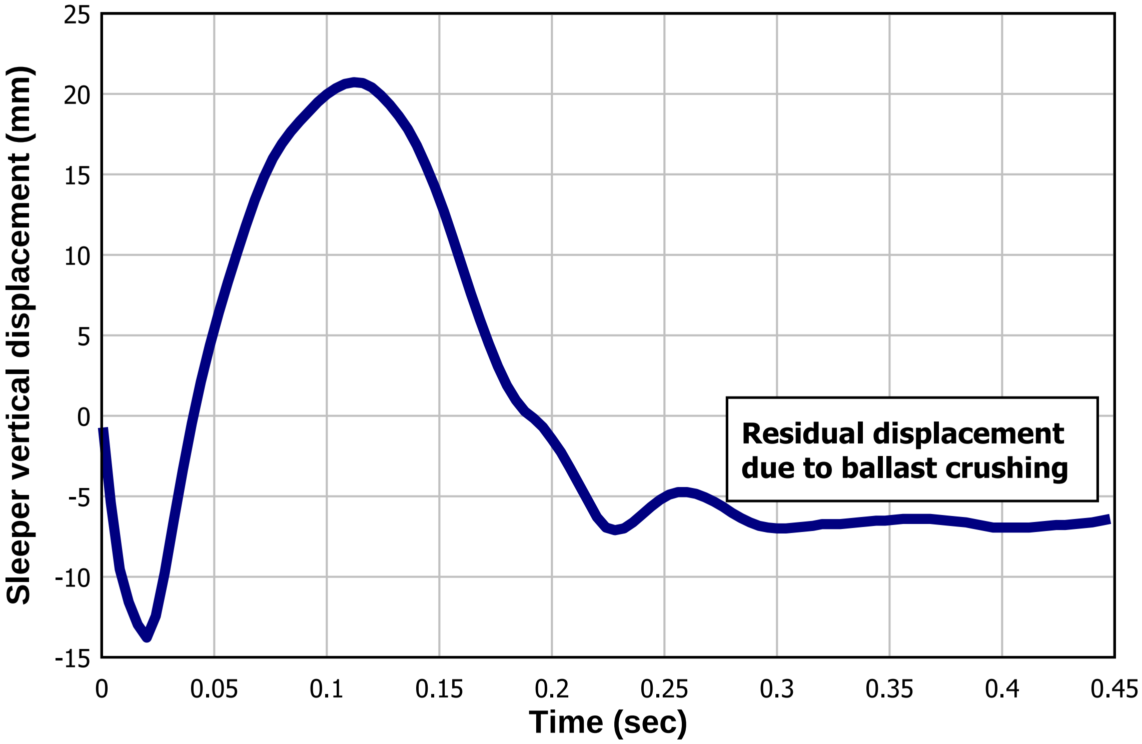

Figure 26 Dynamic response of sleeper to impact load from high-speed recording

Figure 27 Minor cracking at rail seat starting from soffit surface

Figure 28 Crushing of ballast underneath concrete sleeper due to impact loads

Figure 29 Experimental modelling of medium track support condition

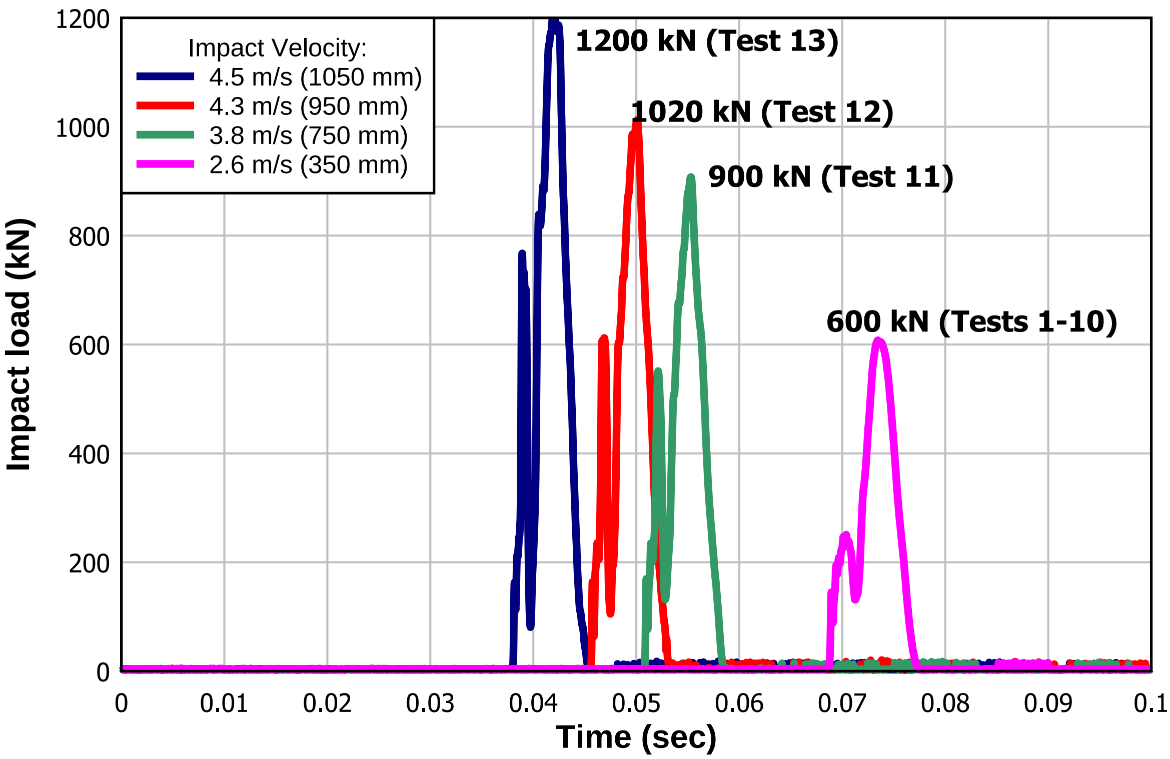

Figure 30 Range of impact loads applied to sleeper for moderate track condition

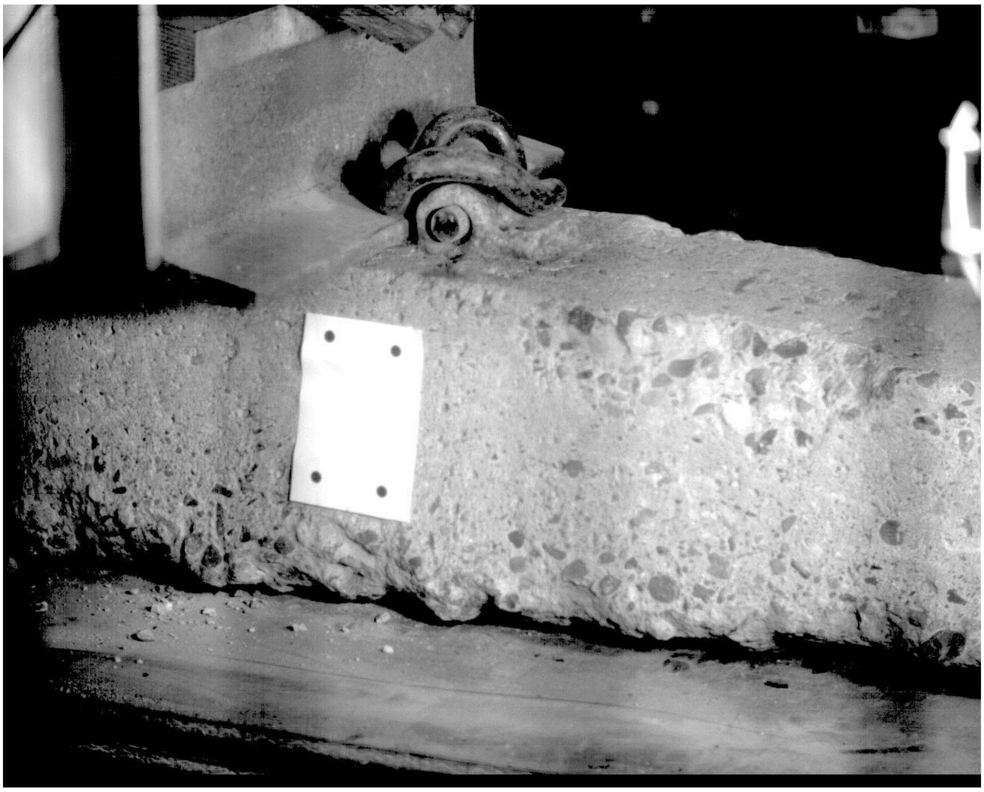

Figure 31 High speed recording of dynamic response of sleeper in medium track condition

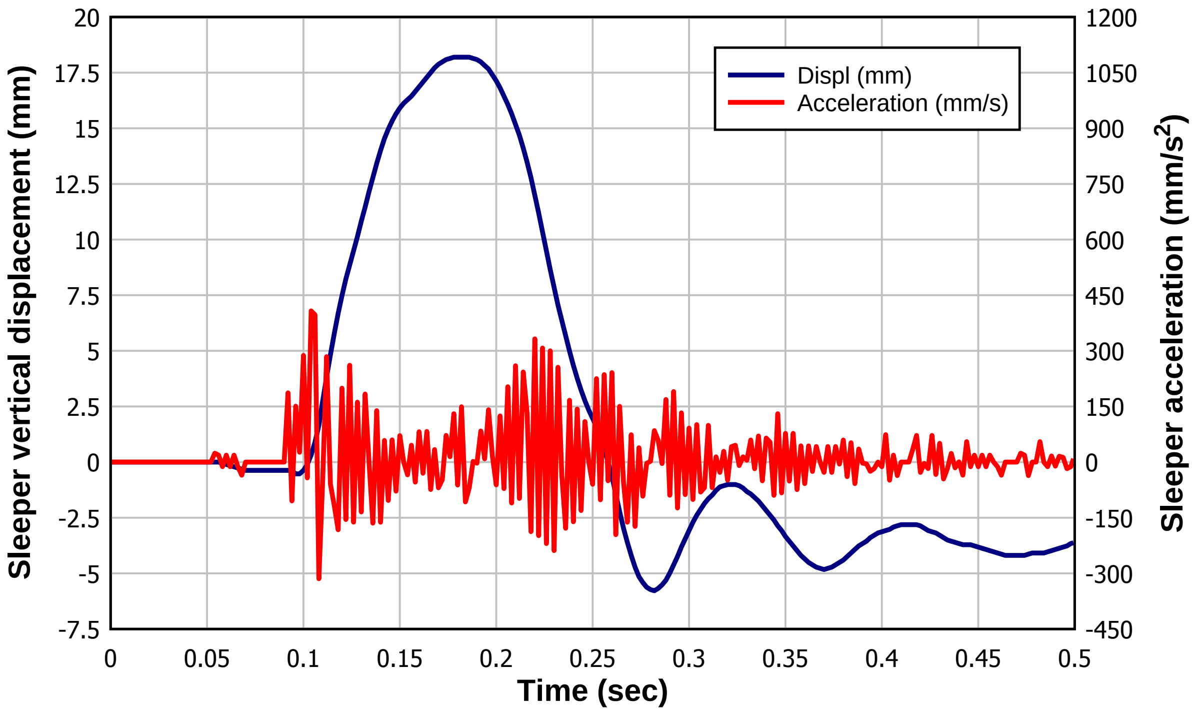

Figure 32 Dynamic response of sleeper to impact load from high-speed recording

Figure 33 Rail seat area – concrete scabbing under the rail – at the end of impact testing in medium track condition

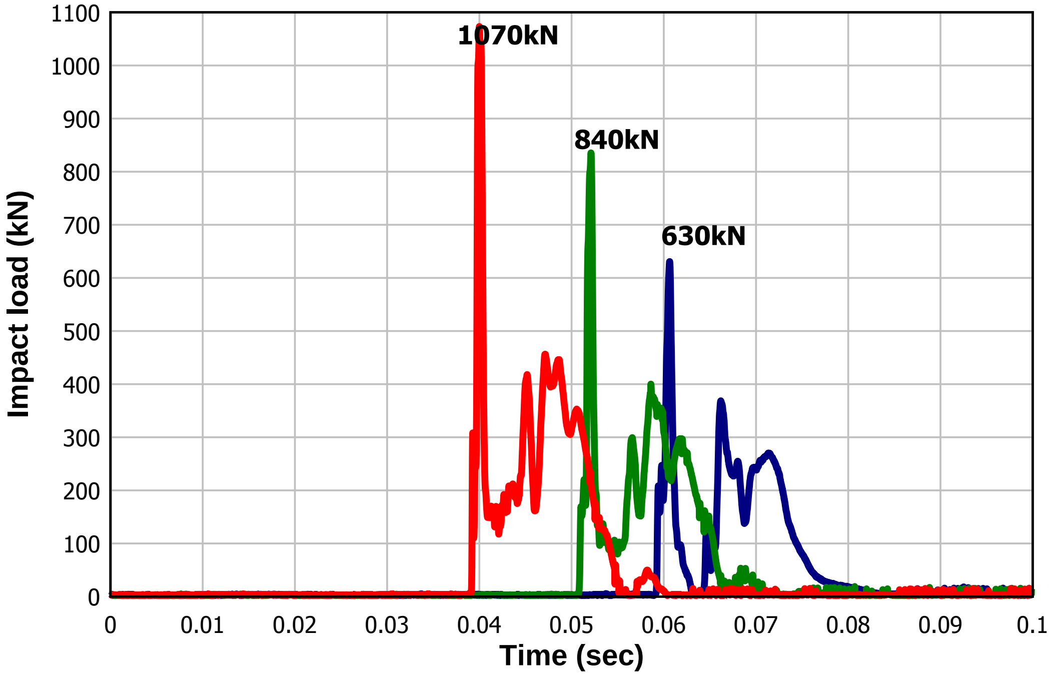

Figure 34 Soft track impact load time histories

Figure 35 High-speed recording of sleeper response in soft track condition

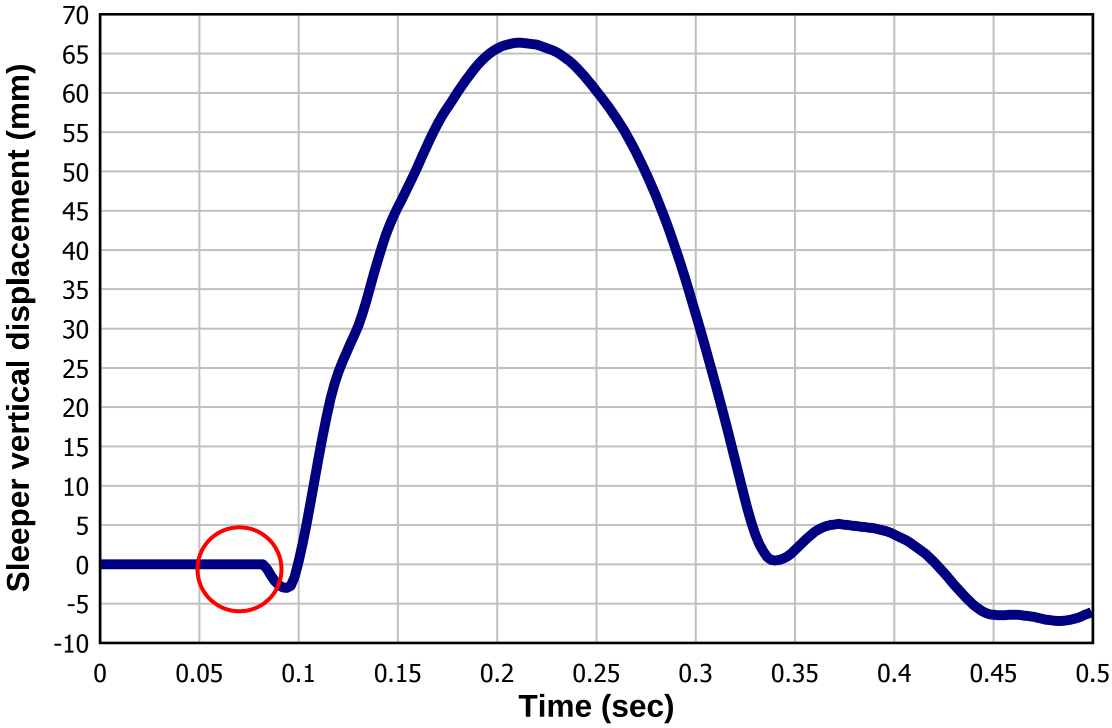

Figure 36 Dynamic response of sleeper to impact load from high-speed recording