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Experimental load rating of aged railway concrete sleepers

Alex M. Remennikov¹ and Sakdirat Kaewunruen²

Abstract: Prestressed concrete sleepers (or railroad ties) are structural members that distribute the 56 wheel loads from the rails to the track support system. Over a period of time, the concrete sleepers 57 age and deteriorate in addition to experiencing various types of static and dynamic loading 58 conditions, which are attributable to train operations. Recent studies have established two main limit 59 states for the design consideration of concrete sleepers: ultimate limit states under extreme impact 60 and fatigue limit states under repeated probabilistic impact loads. It was noted that the prestress 61 level has a significant role in maintaining the high endurance of the sleepers under low to moderate 62 repeated impact loads. This experimental investigation was aimed at static and dynamic load rating 63 of aged railway concrete sleepers after service. Fifteen sleepers were extracted from a heavy haul 64 rail network for testing using experimental facilities at the University of Wollongong (UoW), 65 Australia. The structural evaluation program included quasi-static bending tests, dynamic impact 66 tests, and tests to establish the current level of prestress in the steel wires using the dynamic 67 relaxation technique. Two of the sleepers were evaluated for the level of prestressing forces in 68 accordance with Australian Standards. Through diagnostic tests, the results of quasi-static bending 69 tests produced the in-track bending capacities of sleepers that can be combined with the moments 70 and forces anticipated over the next ten years to predict performance of the sleepers on a heavy haul 71 coal line. The dynamic tests simulating the ability of concrete sleepers to resist extreme loading 72 events due to heavy impact loads demonstrated that the sleepers in-track are likely to be able to 73 resist the planned increased traffic without catastrophic failure over the next decade. Final 74 75 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. 76

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Failure mode; Ballasted railway track; Transport infrastructure.

79

80 1. Introduction

Over the past 50 years, railway prestressed concrete sleepers have been used in rail networks around 81 the world, especially in Europe and Japan. In Australia, concrete sleepers have been designed to 82 withstand up to 40 tonne axle loads and used for nearly 35 years [1-3]. The railway sleepers (called 83 'railroad tie' in the US) are a key structural element of railway track structures. The sleepers 84 redistribute dynamic pressures from the rail foot to the underlying ballast bed. Based on the current 85 design approach, the design life span of the concrete sleepers is also considered to be around 50 86 years [3-6]. Figure 1 demonstrates a typical ballasted railway track and its components. During their 87 life cycles, railway track structures experience static, dynamic and often impact loading conditions 88 due to wheel/rail interactions associated with the abnormalities in either a wheel or a rail [7]. Based 89 on this investigation, the magnitude of the dynamic impact loads per railseat varies from 200 kN to 90 600 kN, whilst the design static wheel load per railseat for a 40-tone axle load could be only as 91 much as 110 kN nominally. The dynamic wheel load forms the basis for design and analysis of 92 railway track and its components in an operational environment with uncertainties [8-10]. In 93 principle, the impact capacity relates to design load (F^*) for the limit states design concept [11], 94 taking into account both the static (F_s) and dynamic (F_i) wheel loads. There are three main steps in 95 designing the concrete sleepers. First, the design actions or loads are to be determined based on the 96 importance level of the track (e.g. $F^* = 1.2 F_s + 1.5 F_i$). Then, the design moment can be achieved 97 by converting the design load to sleeper bending moment envelopes using an advanced dynamic 98 analysis of railway tracks or an empirical design formulation [11-13]. Finally, the strength and 99 serviceability of the prestressed concrete sleepers can be optimized in accordance with the 100 Australian Standard AS3600 [6] and other design guidelines for concrete structures [14, 15]. 101

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Recent investigations showed that a railway sleeper could have experienced multiple high-102 intensity impact loads, causing a rapid degradation of its structural integrity and durability [16, 17]. 103 In-field, experimental and numerical data recorded by the University of Wollongong has revealed 104 that the failure of a railway sleeper is more likely be due to cumulative damage rather than due to a 105 once-off extreme event, which might occur due to the derailment [2, 3]. It is important to note that, 106 for prestressed concrete sleepers, the low magnitude but high cycle impact fatigue tends to be 107 insignificant in comparison with the high magnitude but low cycle impact fatigue [14, 17-20]. In 108 contrast, it was found from a critical literature review that there is no research investigation into 109 load rating or remaining life prediction of concrete sleepers. As a result, many assumptions have 110 been made in practice that may lead to either incorrect or inefficient asset management under 111 constantly changing operations. This practical issue has resulted in an initiative to investigate the 112 existing condition of railway concrete sleepers and to develop a standard guidance for predicting the 113 remaining life of such components. The strength and capacity of concrete sleepers depends largely 114 on the residual material strengths (concrete and strands), the prestressing force and the bond 115 between steel strands and concrete [17-18]. Over time, the concrete sleepers experience diverse 116 traffic loads from operational activities, and may have damage and cracks, also resulting in an 117 118 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 119 120 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

University of Wollongong (UoW), Australia. Visual inspections and laboratory material testings 127 were conducted at the initial stage of the project. Eight of the sleepers were evaluated for the static 128 bending capacities in accordance with Australian Standards. Three of the sleepers were subjected to 129 multiple high-intensity impact loads associated with the risk and the probabilistic loads on the track. 130 This paper presents experimental studies into the load rating of *in situ* prestressed concrete sleepers 131 and engineering characteristics of construction materials used for manufacturing concrete sleepers. 132 In addition, dynamic impact load rating of the concrete sleepers was carried out in order to underpin 133 the failure mode analyses associated with operational track forces' risk and probability. 134

135

136 **2. Experimental Programs**

137 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 142 sleepers from 1982. Design data detailing concrete strength, level of prestress, and design bending 143 moment capacities were not available for a direct comparison between the current design parameters 144 145 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 146 147 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 148 tabulated in Table 2 were thus adopted from AS1085.14 and AS3600, respectively [4, 5]. Before the 149 tests started, every sleeper was visually inspected and the major dimensions of the sleepers were 150 then measured. The measurements were taken at the rail seat and the centre of the sleepers. Since no 151 original drawings were provided, it was not possible to compare the *in-situ* dimensions to the 152

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 156 evaluation as displayed in Figure 2. The prestressed concrete sleepers are usually the main 157 component of the standard-gauge, heavy-haul rail tracks. High strength concrete material is used to 158 cast the prestressed concrete sleepers, with design compressive strength at 28 days of 50-55 MPa, 159 and the prestressing steels used are high strength with rupture strength of 1700 MPa. Cored samples, 160 drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard 161 AS1012.14 [22], as shown in Figure 3. Although the common concrete strength adopted for design 162 is 50 MPa, it was found that condition of the concrete at the test age of about 30 years (since 1982) 163 had deteriorated. The prestressing tendons are the chevron-patterned indented wires of about 5 mm 164 diameter. From visual inspection, it could be observed that the high strength prestressing wires were 165 of high quality and thus the strength would not rapidly change during time. 166

167

168 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

178 cores extracted from the freshly cut interior face. The concrete cores were extracted from between 179 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 180 overall smoothness, steps, ridges and grooves. The ends of the samples were trimmed and finished 181 to a smooth flat surface with the length-to-diameter ratio maintained at 2:1. An investigation into 182 the actual residual strength of concrete, using five concrete cylinders with a diameter of 55 mm, 183 suggested that the average compressive strength was 44 MPa (+ 4 MPa) [21]. Compared with the 184 design data in Table 2, the deviation of concrete strength (about 10%) could be attribute to poor 185 quality during manufacturing and construction, internal micro cracking due to sudden transfer of 186 pre-stressing and dynamic impact loads, and material deterioration in an aggressive environment. 187

188

189 **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 coalline 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.

205 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].

213

214 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 221 determine their 'impact resistance'. Extensive studies of impact resistance of concrete sleepers were 222 initiated by Kaewunruen and Remennikov [1-2] and Kaewunruen [3] as part of research activities 223 within the framework of the Cooperative Research Centre for Railway Engineering in Australia. 224 The methodology for impact testing of sleepers developed by Kaewunruen [3] was utilised in this 225 project to test three concrete sleepers for impact strength at the rail seat. In this study, three sleepers 226 were tested for impact strengths at the rail seat for the prescribed values of track moduli 8, 30 and 227 120 MPa (soft, moderate and hard track conditions). It is well known that defining track stiffness by 228 track modulus is quite crude when considering sleeper's response. This is because track modulus is 229

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.

233

234 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 244 stiffness of the track with moderate stiffness. The rail was placed on the rail seat and the rail pad 245 was not included. This is because field observations suggested that deteriorated and worn rail pads 246 may not provide any resilience [23-26]. The effect of rail pads on impact attenuation were presented 247 248 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 249 10, the extreme cases of track moduli were replicated by using ballast (200 mm) over a thick layer 250 of sand-rubber mix (50% by volume of rubber crumbs) for the very soft track, and a thin ballast 251 layer (150 mm) on a shock mat placed directly on the concrete strong floor for the very stiff track. 252

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.

261

262 **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 263 Leong [29] where the likely maximum impact forces that would be applied to the rail above an 264 individual sleeper were determined. Using the methodology presented in [29], the maximum likely 265 incremental impact force for a 1:400 year return period is 430 kN. The total wheel-rail force that 266 would occur at 1:400 year event would be the incremental impact force of 430 kN plus the upper 267 5th percentile of the static load distribution, which would be 168 kN. The dynamism of static loads 268 is theoretically and practically negligible. The static load was correlated to a factored load case (i.e. 269 $1.2F_s$) developed for limit states design principle [29]. Thus, the total impact force has some 270 reasonable probability of occuring over the next 10 years based on 'big data' recorded over few 271 years, obtained from wayside systems. It should later be used for dynamic testing of the sleepers at 272 rail seat, which is 168 + 430 = 598 kN [29]. 273

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].

296

3. Experimental results of static tests

298 **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.

301 **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 306 subjected to the rail seat positive moment test. The load-displacement relationships for both sleepers 307 were similar up to the maximum load capacity. The sleeper UOW5 shows slightly higher 308 displacement than the sleeper UOW6 before they failed. For the sleeper UOW5, fine cracks started 309 to appear at the loading points after the applied load exceeded 350 kN. The cracks propagated 310 upwards as the loading increased. For sleeper UOW6, the existing crack propagated upward as the 311 applied load exceeded 350 kN. At about 550 kN, the load resistance of both sleepers dropped due to 312 the formation of diagonal shear crack between the loading point and the support, as shown in Figure 313 13. After that, the load resistance of the sleepers increased again and reached maximum load 314 capacity of about 580 kN before the sleepers failed due to crushing of concrete in compression and 315 splitting at the end of sleeper as illustrated in Figure 14. 316

317

3.1.2 Rail seat negative moment test

Rail seat negative moment tests were performed on the sleeper UOW7 and sleeper UOW8. 318 The sleeper UOW7 suffered severe abrasion of the concrete cover at the bottom surface and 319 concrete was damaged at the end of the sleeper causing one of the prestressing wires to be exposed. 320 The sleeper UOW8 suffered very severe abrasion on the concrete cover at the bottom surface. 321

Figure 15 shows the load-displacement relationships for sleepers UOW7 and UOW8. For 322 both sleepers, a crack started when the load reached approximately 150 kN. The crack propagated 323 324 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 325 drop slightly. The sleeper UOW7 reached maximum load of 420 kN where it failed by splitting at 326 the end of the sleeper similar to sleeper UOW5 (Figure 13). Sleeper UOW8 showed lower 327 maximum load compared to sleeper UOW7 due to different failure mode. The flexural crack in 328 sleeper UOW8 developed into a wide crack when the applied load increased as shown in Figure 16 329 (b). The sleeper reached maximum load of 350 kN before it failed by crushing of concrete in 330 compression as shown in Figure 17. 331

332 **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.

335 **3.2.1** Centre positive moment tests

Figure 18 shows the load-displacement relationships for sleepers UOW1 and UOW2 336 subjected to the centre positive moment test. Both sleepers had suffered severe abrasion of concrete 337 cover at the bottom surface. The load-displacement relationships for both sleepers were similar up 338 to 17 mm displacement. For both sleepers, fine cracks appeared underneath the loading points and 339 the mid-span at approximately 80 kN. The maximum flexural load for UOW1 and UOW2 was 99.5 340 KN and 99 kN, respectively. After that, the concrete in compression started to crush and then caused 341 the sleeper to exhibit softening behaviour where the resistance gradually decreased with increase in 342 displacement. Figure 19 shows the cracking and crushing of concrete for sleeper UOW1. 343

344 **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 350 shows that sleeper UOW4 has a higher flexural load capacity than sleeper UOW3. For sleeper 351 UOW3, flexural cracks started at mid-span when the load exceeded 85 kN (Figure 21a) and it 352 reached the maximum flexural load capacity of 104 kN. For sleeper UOW4, fine cracks were 353 observed at mid-span when the flexural load reached about 110 kN, as shown in Figure 21b. The 354 maximum flexural load for sleeper UOW4 was about 138 kN. After reaching the maximum flexural 355 load, the concrete in compression started to crush and the load resistance of the sleepers dropped as 356 the displacement increased. Sleeper UOW3 showed lower maximum flexural load compared to 357

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.

362 **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 heavyhaul 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].

370

4. Experimental results of impact tests

372 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.

398 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.

419 **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 438 visible damage to the concrete sleeper was observed. There was no visible damage in the sleeper rail 439 seat for the 1200 mm impact with the corresponding peak force of 840 kN. The final impact load in 440 excess of 1000 kN was generated by dropping the anvil from a 2 m height. This also did not cause 441 observable damage to the rail seat area of the sleepers. Based on the above observations, the 442 concrete sleeper resisted all impact events, including several extraordinary impact loadings, with no 443 cracking thus demonstrating the high load carrying capacity of the concrete sleepers for resisting 444 dynamic loads of high magnitude and short duration. 445

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447 **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 453 installed in the heavy haul rail network were removed from the rail track (coal lines) 454 and transported to the structures laboratory at the UoW, Australia. Visual inspections 455 and laboratory material testings were conducted. The sleepers were evaluated for the 456 static and dynamic impact performances and the data was benchmarked in 457 accordance with Australian Standards for prestressed concrete sleepers. Based on the 458 critical literature review, it was found that the research investigation into residual 459 condition or remaining life prediction of concrete sleepers is inadequate. This paper 460

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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 465 with durability of the sleepers. Concrete spalling of sleepers due to tamping damage, poor 466 construction, and loss of concrete section due to abrasions were among the problems that could 467 cause the rapid deterioration of strength and serviceability. Through diagnostic static tests, eight 468 aged concrete sleepers were subjected to bending tests according to the procedures prescribed [4]. 469 Through a series of bending tests, the strength of sleepers was determined at the rail seat and the 470 sleeper centre. The experimental results of quasi-static bending tests produced the in-track bending 471 capacities of sleepers that can be combined with the moments and forces anticipated from the 472 standard design concept over the next 10 years to predict performance of the sleepers on a heavy 473 haul coal line. 474

Three concrete sleepers were tested for impact strength at the rail seat for three values of the 475 track moduli (8, 30, and 120 MPa) representing soft track, moderate and hard track supporting 476 477 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 478 479 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 480 resisting extreme loads generated by wheel and rail abnormalities without catastrophic failure under 481 current traffic and even with increased traffic due to planned expansion on this line over the next 482 decade. It is also recommended from a risk management framework (considering dynamisms of rail 483 operations and track maintenance regimes) that the rail infrastructure operator exercise a routine test 484 program every five years to ascertain the load rating of clustered sleepers and its fastening system in 485 486 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 |

620 Table 2. Design properties of materials

| Materials | Elastic modulus | Compressive strength (MPa) | Tensile strength (MPa) |
|---------------------|-----------------|----------------------------|------------------------|
| | (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 | Remaining prestress in wires | SRA2 |
| | tendons [21] | | |
| 9* | Material testing [21] | Concrete compressive strength | SRA1 |
| *test data | and results are available in [21]. | | |

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

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 imp | act testing (mediu | um 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 |



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



Figure 2 Physical condition of concrete sleepers

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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

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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).



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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

- 0.11



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 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