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DOI:

[10.1016/j.engstruct.2014.06.032](https://doi.org/10.1016/j.engstruct.2014.06.032)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Remennikov, A & Kaewunruen, S 2014, 'Experimental load rating of aged railway concrete sleepers', *Engineering Structures*, vol. 76, no. 10, pp. 147-162. <https://doi.org/10.1016/j.engstruct.2014.06.032>

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Checked December 2015

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1 REVISION OF TECHNICAL PAPER

2
3 “Experimental load rating of aged railway concrete sleepers”

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5 (Title contains 8 words)

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8 by

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36
37
38 Manuscript Summary:

39 Total pages 48 (including 1-page cover)
40 Number of figures 36
41 Number of tables 8

Experimental load rating of aged railway concrete sleepers

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

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77 **Keywords:** Prestressed concrete sleeper; Load rating; Remaining life; Experimental impact testing;
78 Failure mode; Ballasted railway track; Transport infrastructure.

79

80 **1. Introduction**

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

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

121 This investigation arose from a planned expansion of the traffic on a heavy haul coal line in
122 New South Wales, Australia. [The rail infrastructure operator planned to double the traffic on that](#)
123 [particular coal line and was concerned about the ability of its existing railway concrete sleepers to](#)
124 cater for the increased traffic loads. The sleepers [on the coal line](#) were manufactured and installed in
125 1982-1984. A cluster of fifteen in-service concrete sleepers that were installed in [the](#) heavy haul rail
126 network were extracted from the rail track and transported to the structures laboratory at the

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

135

136 **2. Experimental Programs**

137 **2.1 Test specimens**

138 Fifteen sleepers were extracted from the coal line and transported to UoW for testing in accordance
139 with Australian Standard AS1085.14 [4]. Table 1 shows the measured dimension of the sleeper
140 specimens. It was found that cross-sections of the prestressed concrete sleeper were optimized for
141 specific load carrying capacities at different functional performances for rail seat and mid span.

142 The rail infrastructure operator confirmed that the sleepers were typical prestressed concrete
143 sleepers from 1982. Design data detailing concrete strength, level of prestress, and design bending
144 moment capacities were not available for a direct comparison between the current design parameters
145 and the original design parameters at the time of sleeper manufacture. However, reportedly from
146 industry practices, the permissible stresses and design restrictions of the concrete sleepers back in
147 1980s were very similar to those in existing standards [4, 5]. There was not much change in the
148 standard design methodology and inputs over the past decades. The design characteristics as
149 tabulated in Table 2 were thus adopted from AS1085.14 and AS3600, respectively [4, 5]. Before the
150 tests started, every sleeper was visually inspected and the major dimensions of the sleepers were
151 then measured. The measurements were taken at the rail seat and the centre of the sleepers. Since no
152 original drawings were provided, it was not possible to compare the *in-situ* dimensions to the

153 nominal dimensions. From the visual inspection, most of the sleepers suffered severe abrasion of the
154 soffit surface. Some of the sleepers showed concrete spalling near the centre, adjacent to the rail seat
155 and at the sleeper ends. [Table 3 summarises](#) the physical conditions of the aged concrete sleepers.

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

167

168 **2.2 Material testing**

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

176 The ends of the two sleeper specimens were cut clean from the rest of the sleeper at the
177 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.

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

188

189 ***2.3 Experimental Load Rating Tests***

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

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

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

204

205 **2.3.1 Static Tests**

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

213

214 **2.3.2 Impact Tests**

215 The UoW structures laboratory contains the largest drop hammer facility for structural impact
216 testing in Australia. The facility has the ability to generate an impact load by a free-falling mass of
217 600 kg from the height of up to 6 metres. Monitoring equipment includes high-capacity load cells
218 for measuring impact loads up to 2000 kN, high speed laser displacement sensors, accelerometers,
219 strain gauges and high-speed camera. Figure 9 presents a general view of the drop hammer facility
220 at UoW.

221 Generally, there are no standards for undertaking impact testing of concrete sleepers to
222 determine their ‘*impact resistance*’. Extensive studies of impact resistance of concrete sleepers were
223 initiated by Kaewunruen and Remennikov [1-2] and Kaewunruen [3] as part of research activities
224 within the framework of the Cooperative Research Centre for Railway Engineering in Australia.
225 [The methodology](#) for impact testing of [sleepers](#) developed by Kaewunruen [3] was utilised in this
226 project to test three concrete sleepers for impact strength at the rail seat. In this study, three sleepers
227 were tested for impact [strengths](#) at the rail seat for the prescribed values of track moduli 8, 30 and
228 120 MPa (soft, moderate and hard track conditions). It is well known that defining track stiffness by
229 track modulus is quite crude when considering sleeper's response. This is because track modulus is

230 calculated based on rail support deflection in a cluster of components. This means that the change of
231 rail type, sleeper spacing, sleeper type, [fastening system, rail pad, and](#) formation will change track
232 modulus.

233

234 ***2.3.2.1 Track Moduli and Laboratory Support Setup***

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

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

244 For this project, it was found that six layers of conveyor belts would be equivalent to the
245 stiffness of the track with moderate stiffness. The rail was placed on the rail seat and the rail pad
246 was not included. [This is because field observations suggested that deteriorated and worn rail pads](#)
247 [may not provide any resilience \[23-26\]. The effect of rail pads on impact attenuation were presented](#)
248 [elsewhere \[27-28\].](#) This study simulated the worst case scenario with an ineffective worn rail pad
249 where all the impact energy [is totally absorbed by strain energy of the sleepers](#). As shown in Figure
250 10, the extreme cases of track moduli were replicated by using ballast (200 mm) over a thick layer
251 of sand-rubber mix (50% by volume of rubber crumbs) for the very soft track, and a thin ballast
252 layer (150 mm) on a shock mat placed directly on the concrete strong floor for the very stiff track.

253 Three concrete sleepers available for impact testing were investigated for their response in
254 hard, moderate and soft track situations. The impact load generated by a falling 600-kg anvil was
255 applied directly to the top of the rail. Since the direct impact of the steel impactor on the steel rail

256 generates very short duration load impulses (1-2 msec), a softening media (3-mm thick neoprene
257 pads) were placed on the rail top to control the duration of loading pulses. It is known from the
258 previous studies [1-3, 7-13] that the typical duration of impact load caused by wheel/rail
259 abnormalities is about 5-10 msec. The load duration close to 10 msec was [therefore](#) achieved in all
260 the tests in [this investigation](#).

261

262 ***2.3.2.2 Load actions associated with risk and probability***

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

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

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

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

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

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

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

296

297 **3. Experimental results of static tests**

298 **3.1 Rail Seat Bending Strength**

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

301 ***3.1.1 Rail seat positive moment tests***

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

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

317 **3.1.2 Rail seat negative moment test**

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

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

332 **3.2 Centre Bending Strength**

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

335 **3.2.1 Centre positive moment tests**

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

344 **3.2.2 Centre negative moment tests**

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

350 Figure 20 shows the load-displacement relationships for sleepers UOW3 and UOW4. It
351 shows that sleeper UOW4 has a higher flexural load capacity than sleeper UOW3. For sleeper
352 UOW3, flexural cracks started at mid-span when the load exceeded 85 kN (Figure 21a) and it
353 reached the maximum flexural load capacity of 104 kN. For sleeper UOW4, fine cracks were
354 observed at mid-span when the flexural load reached about 110 kN, as shown in Figure 21b. The
355 maximum flexural load for sleeper UOW4 was about 138 kN. After reaching the maximum flexural
356 load, the concrete in compression started to crush and the load resistance of the sleepers dropped as
357 the displacement increased. Sleeper UOW3 showed lower maximum flexural load compared to

358 sleeper UOW4 which could be attributed to the very severe abrasion of concrete cover at the bottom
359 surface and existing wide cracks on the top surface of the sleeper prior to the testing. It also shows
360 that severe damage of concrete between the mid-span and the rail seat in sleeper UOW4 had no
361 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**

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

370

371 **4. Experimental results of impact tests**

372 **4.1 Rail Seat Impact Strength, Hard Track Support Conditions**

373 One heavy-haul sleeper was investigated for the rail seat ultimate impact resistance in the
374 hard track support conditions, as shown in Figure 22. High-speed camera was used to record the
375 impact event as shown in Figure 23. New calibration of the parameters of impact testing was
376 required since the track stiffness influences the dynamic response of sleepers. It was found that a
377 915 mm drop height would be required to generate impact forces with a magnitude of 600 kN. The
378 load duration was controlled by the neoprene pads placed on the top of the rail and replaced for each
379 loading event.

380 The dynamic loading programme included 10 consecutive impact load applications by the
381 anvil dropped from the height of 910-915 mm. Following 10 repeated applications of the load with
382 a return period of 400 years ([representing a 1:400 load magnitude that is probabilistically designed](#)

383 to occur once a year [2, 32]), the sleeper was later subjected to the impact force of 700 kN by
384 dropping the anvil from a 1025 mm height. Table 6 presents the achieved load magnitudes and
385 durations for every test and observed damage.

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

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

398 **4.2 Rail Seat Impact Strength, Moderate Track Support Conditions**

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

405 The dynamic loading programme included 10 consecutive impact load applications by the
406 anvil dropped from the height of 350 mm. Following 10 repeated applications of the load resulting
407 in the impact load of about 600 kN (1:400 return period), the sleeper was subjected to the impact
408 load of 900 kN by dropping the anvil from a 750 mm height. The last two impacts, from the drop

409 heights of 950 mm and 1050 mm, induced impact forces of 1020 kN and 1200 kN, respectively.
410 Table 7 presents the achieved load magnitude, load durations for every test and the observed
411 damage.

412 The impact load-time histories for selected impact events are shown in Figure 30. No sleeper
413 cracking was observed for all ten impact load applications (see Figures 31-33). Some concrete
414 scabbing was observed under the rail after the impact load with a magnitude of 900 kN. Additional
415 concrete damage developed under the rail after subjecting the sleeper to the impact force of 1020 kN
416 by dropping the anvil from a height of 950 mm. Figure 31 shows the cracking pattern in the sleeper
417 at the end of the testing programme. It can be noticed that the final damage is minor and would not
418 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**

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

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

433 For the next stage of testing, the sleeper was subjected to a series of extremely high impact
434 loads simulating extraordinary loading events. The sleeper was initially subjected to a 1200 mm

435 drop of the anvil that generated an impact force with a magnitude of 840 kN. For the last impact, the
436 sleeper was subjected to an impact from a 2000 mm height and the impact load developed was
437 about 1070 kN. The impact load-time histories for selected impact events are shown in Figure 34.

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

446

447 **5. Conclusions**

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

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

461 firstly presents the experimental studies into the load rating of *in situ* prestressed
462 concrete sleepers using static and dynamic impact test regimes. This investigation is
463 an essential and inevitable contribution to the framework for estimation of the
464 remaining life of concrete sleepers, which is firstly presented in the open literature.

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

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

488 **Acknowledgement**

489 The authors are grateful to Australian Rail Track Corporation (ARTC), Sydney Trains
490 (Wollongong Maintenance Depot), and ROCLA for the support throughout this study. Valuable
491 comments and support from Drs M. H. Murray (KCPM, Australia) and R. Blomsvik (Abetong
492 AB, Sweden) are acknowledged. The authors would like to thank the Structural Lab Manager
493 Alan Grant for his assistance during the experiments. Also, the second author wishes to thank
494 Australian Government's Department of Innovation for supporting his Endeavour Executive
495 Fellowships at Department of Civil and Environmental Engineering, Massachusetts Institute of
496 Technology, Cambridge MA, USA, and at Railway Mechanics Centre, Chalmers University of
497 Technology, Gothenburg, Sweden.

498

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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

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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	-	-

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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.

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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].

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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	

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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

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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

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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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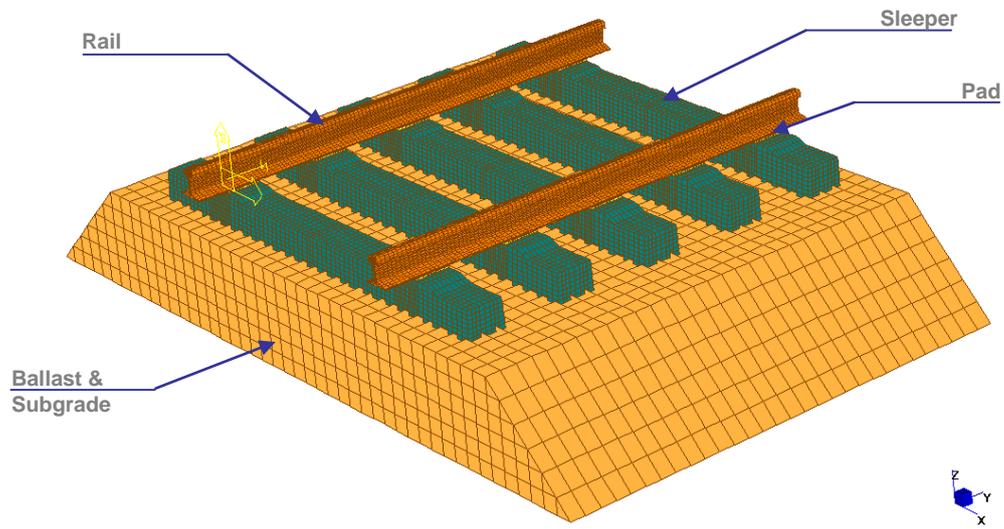


Figure 1. Typical components of railway tracks.

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



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b) concrete damage at the end of the sleeper UOW2

Figure 2 Physical condition of concrete sleepers

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723 c) severe abrasion of the concrete cover at the bottom surface of sleeper UOW3, causing one of prestressing wires was
724 exposed
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727 d) severe damage of concrete between the mid-span and the support for the sleeper UOW4

728 **Figure 2 Physical condition of concrete sleepers**

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

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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



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

Figure 2 Physical condition of concrete sleepers

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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)

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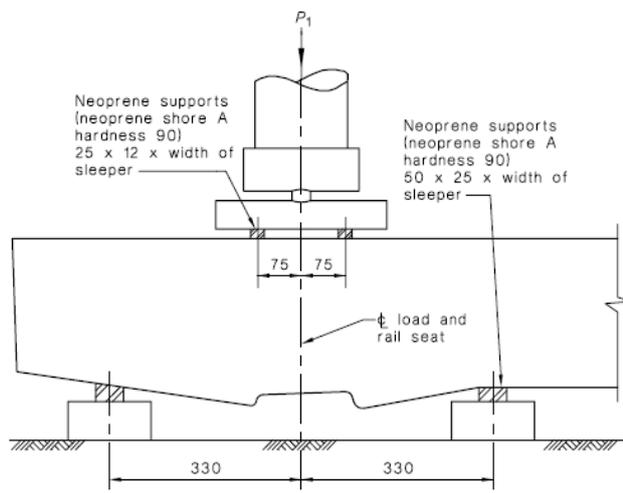


Figure 5 (a) and (b) - Rail seat vertical load static test for negative bending moment

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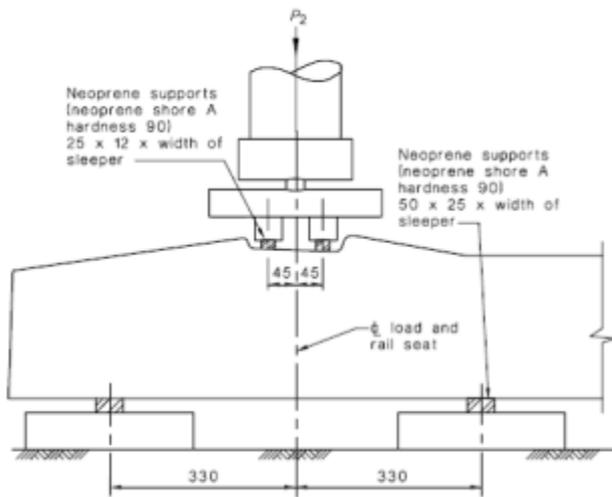


Figure 6 (a) and (b) - Rail seat vertical load static test for positive bending moment

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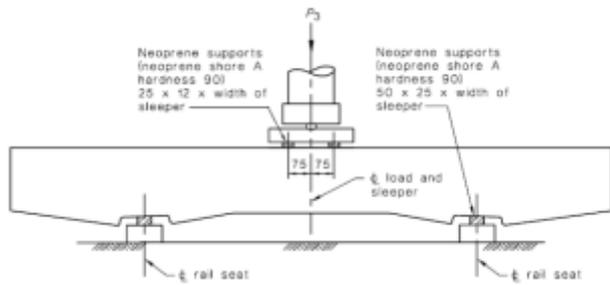
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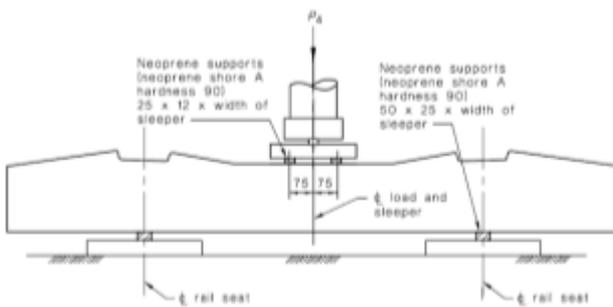
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Figure 7 (a) and (b) - Sleeper centre vertical load test for negative bending moment

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

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Figure 9 Drop hammer facility at UoW

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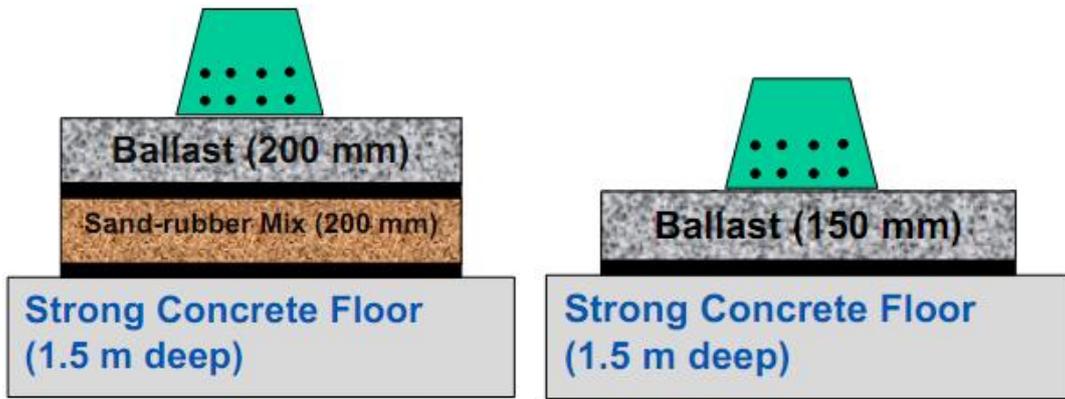


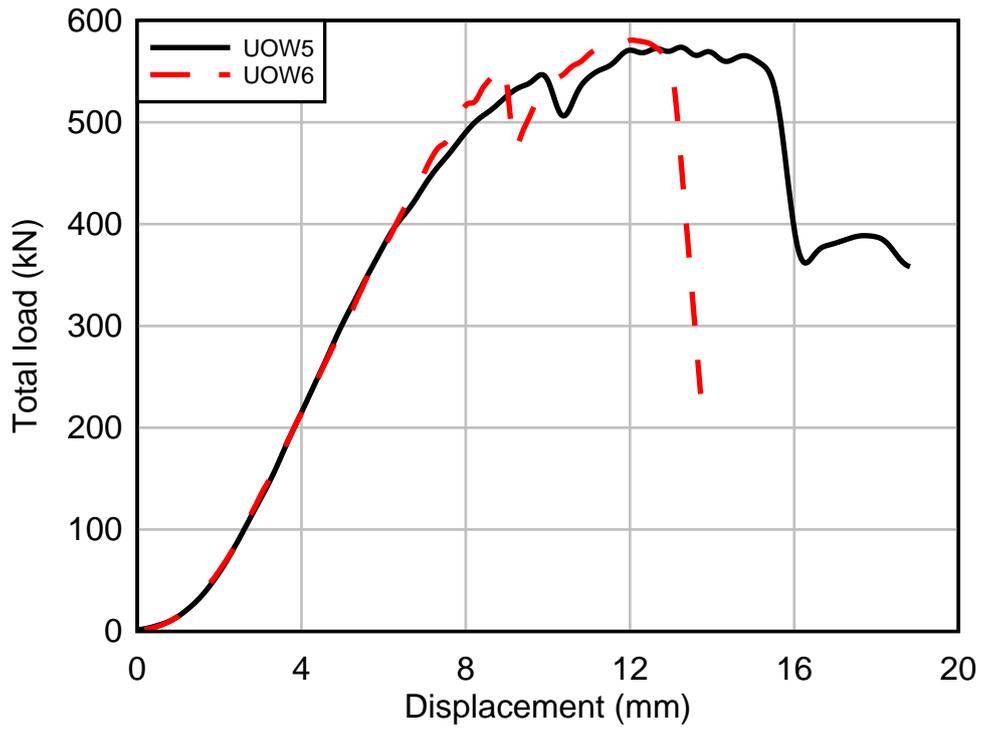
Figure 10 Modelling extreme cases of track support conditions: (a) very soft using sand-rubber mix; and (b) very hard.



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

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



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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.

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

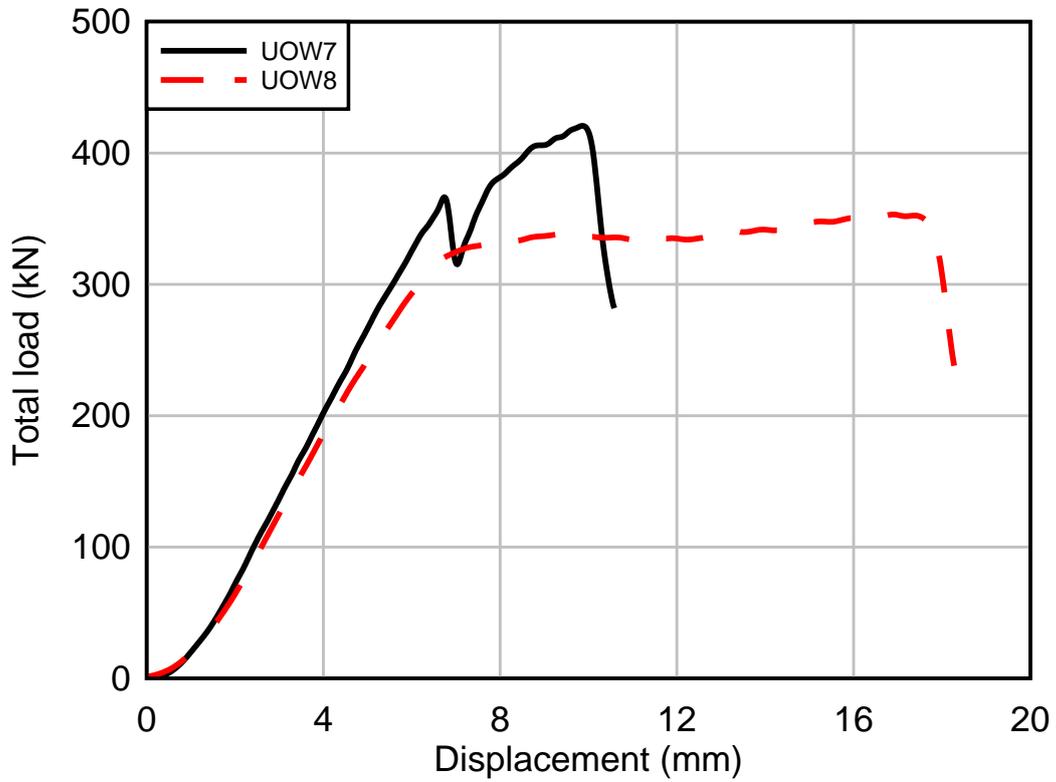


Figure 15 Load-displacement relationships for sleeper rail seat negative moment capacity.



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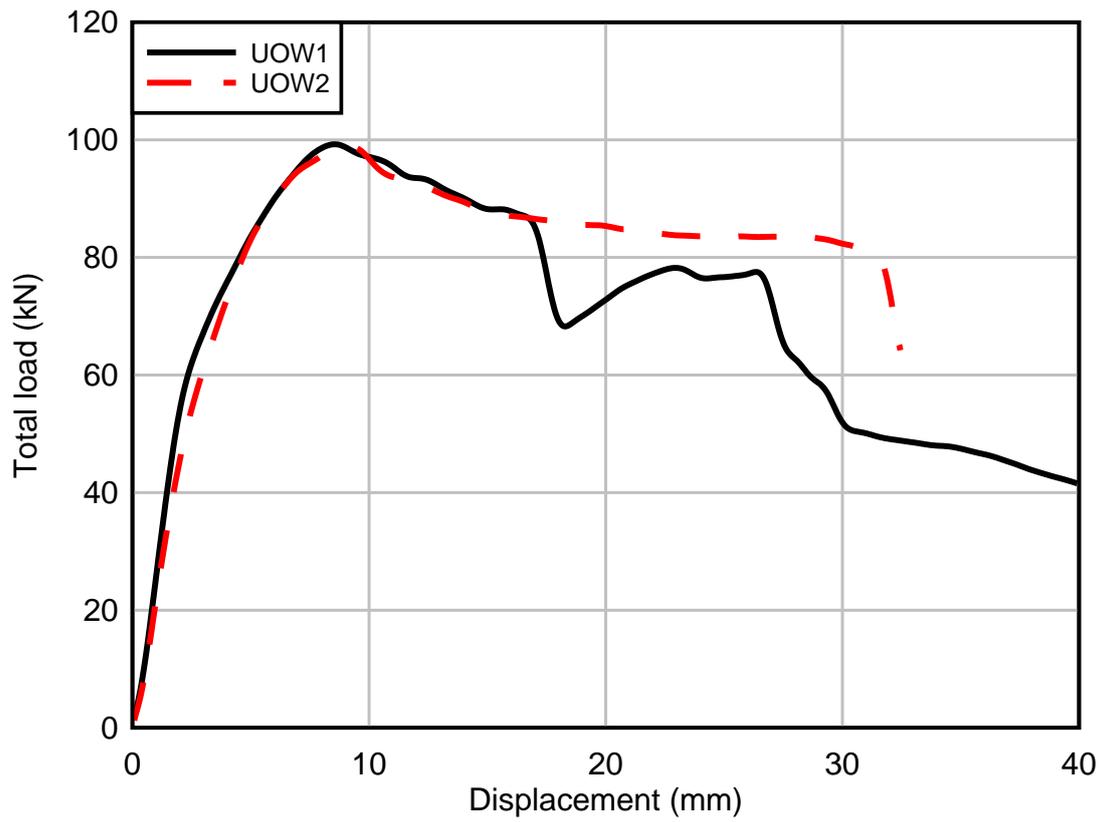
Figure 16 Damage on the sleepers (a) a flexural crack and a diagonal crack on the sleeper UOW7, (b) a wide flexural crack on the sleeper UOW8.

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



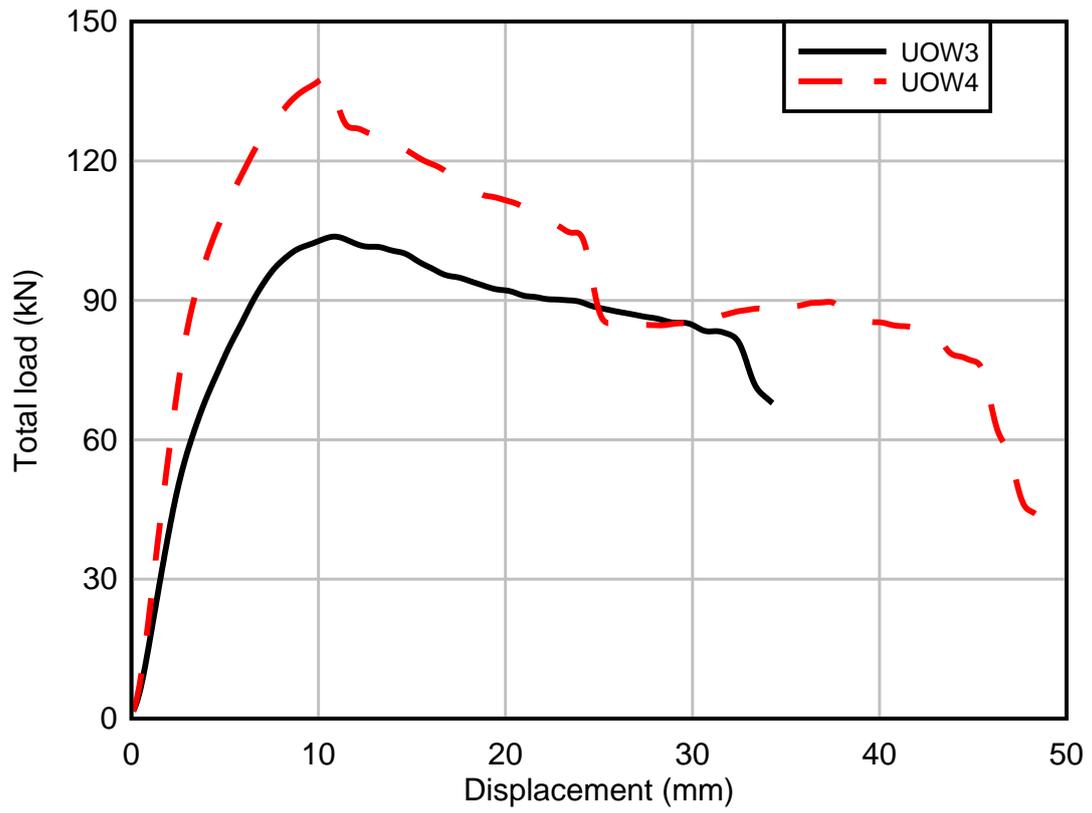
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Figure 18 Load-displacement relationships for sleeper centre positive moment capacity.



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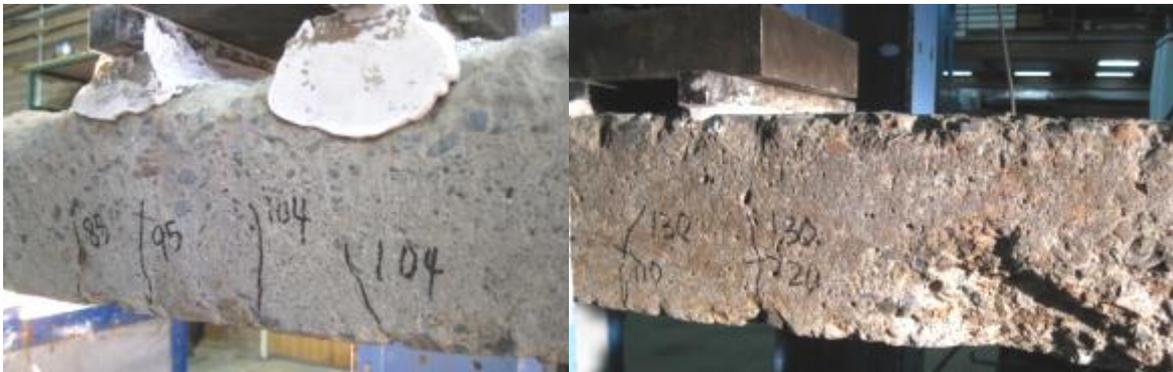
Figure 19 (a) Cracking of sleeper at mid-span for UOW1, and (b) crushing of concrete at the top for UOW1.



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

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



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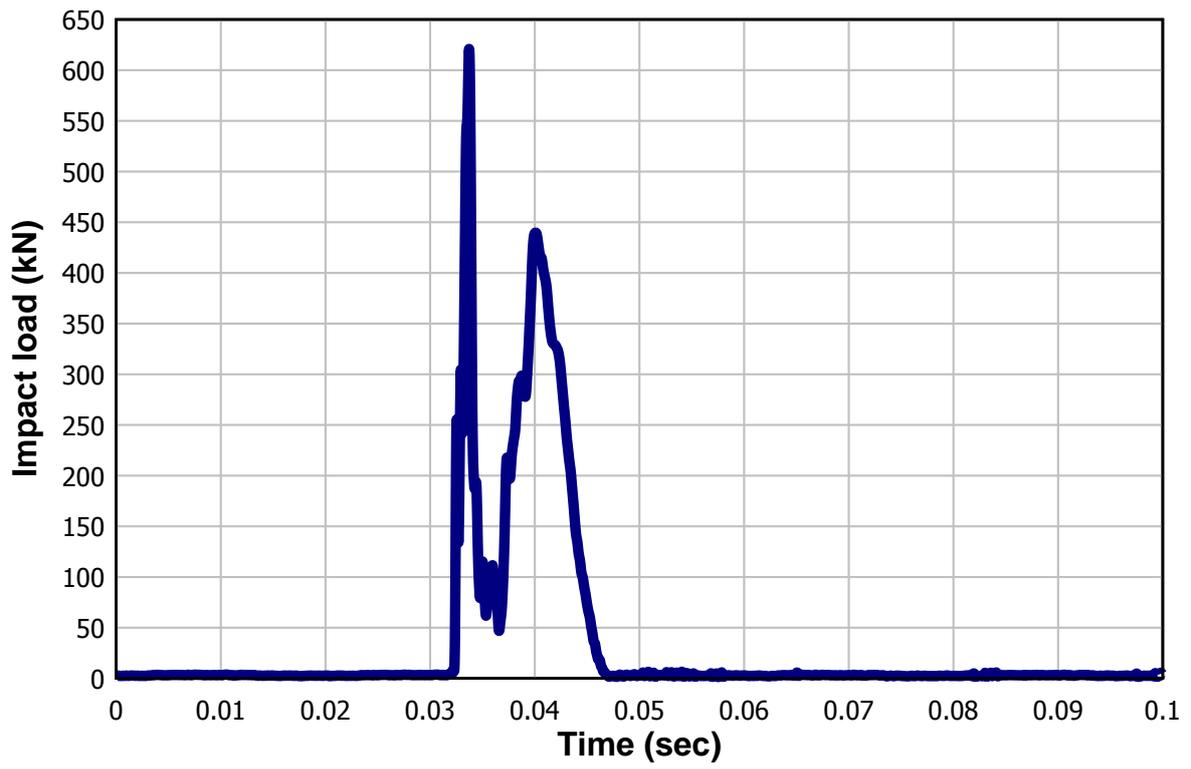
Figure 22 Experimental modelling of hard track support condition



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

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Figure 24 Typical impact load time history for hard track condition

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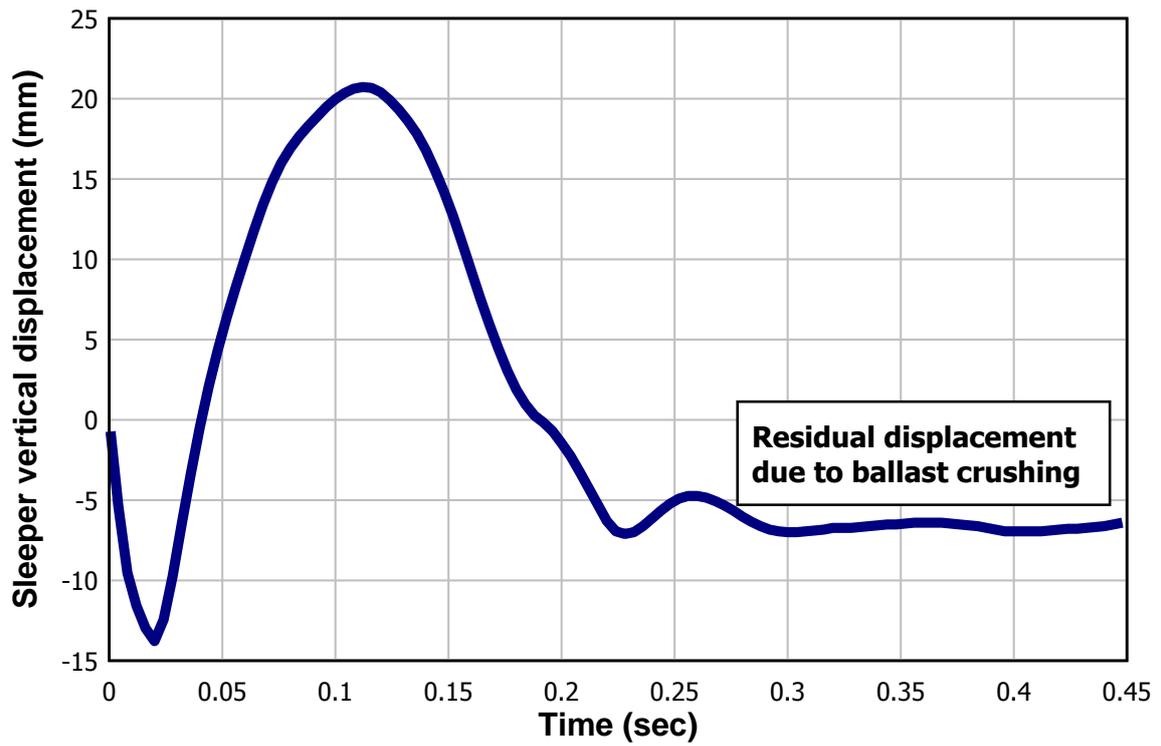


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Figure 25 High speed recording of dynamic response of sleeper in hard track condition

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



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Figure 27 Minor cracking at rail seat starting from soffit surface

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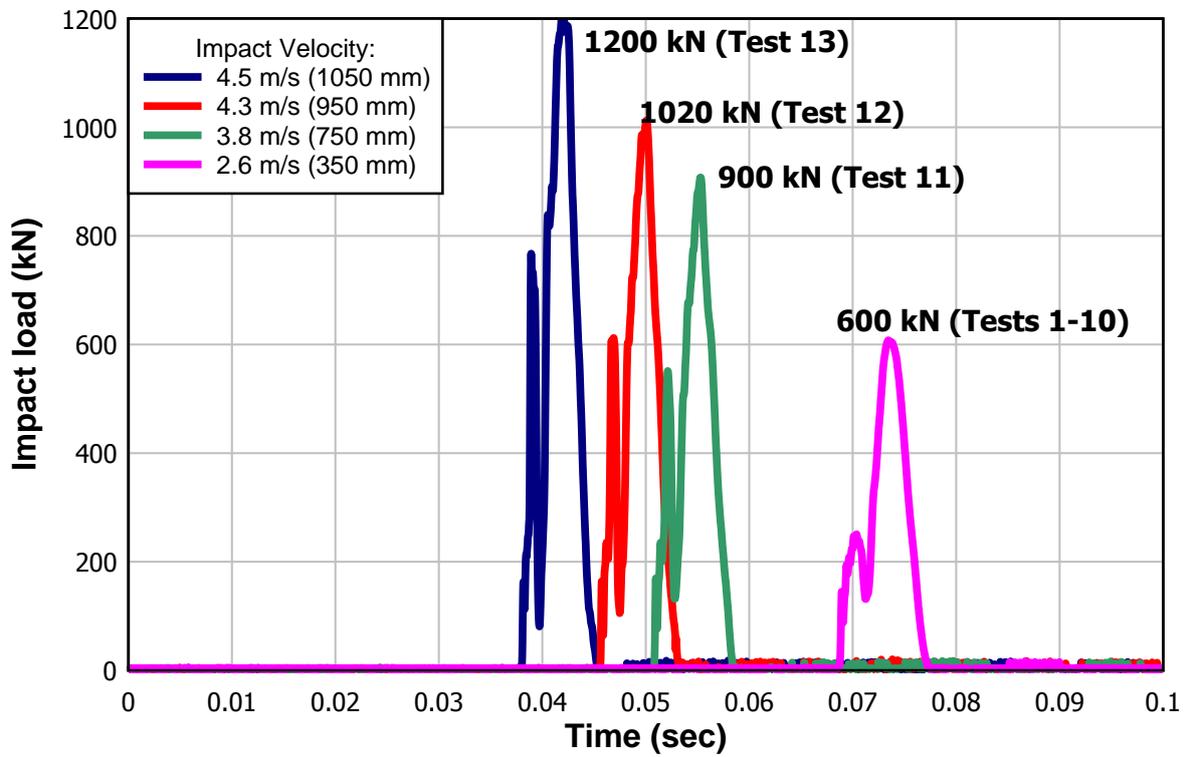
Figure 28 Crushing of ballast underneath concrete sleeper due to impact loads



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Figure 29 Experimental modelling of medium track support condition

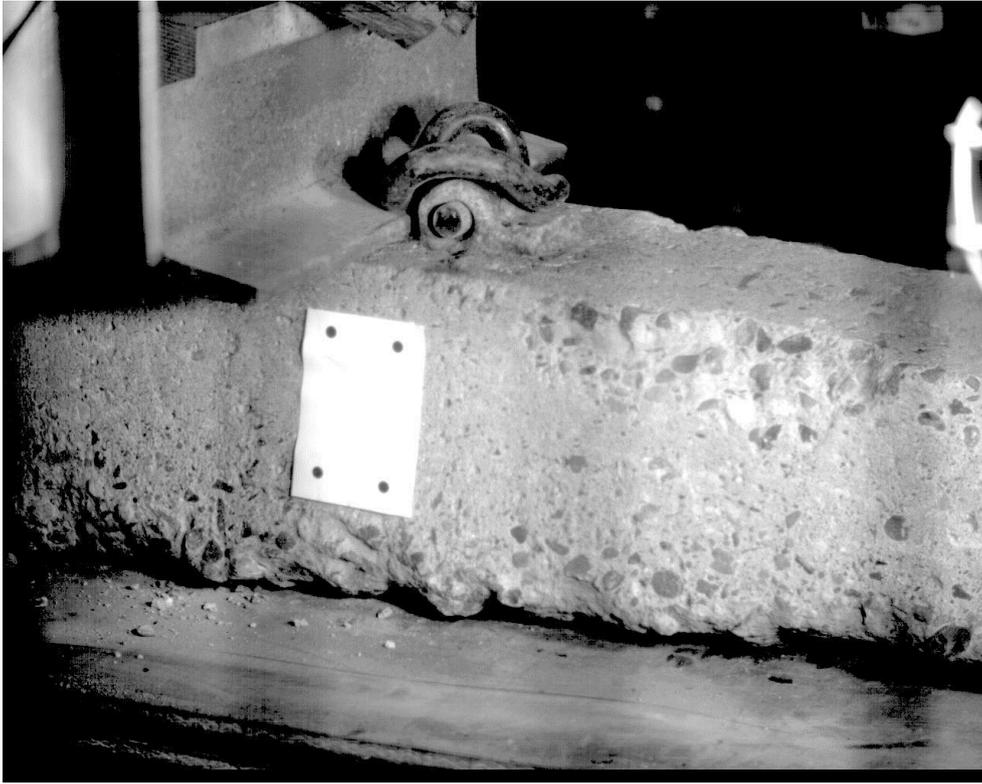
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Figure 30 Range of impact loads applied to sleeper for moderate track condition

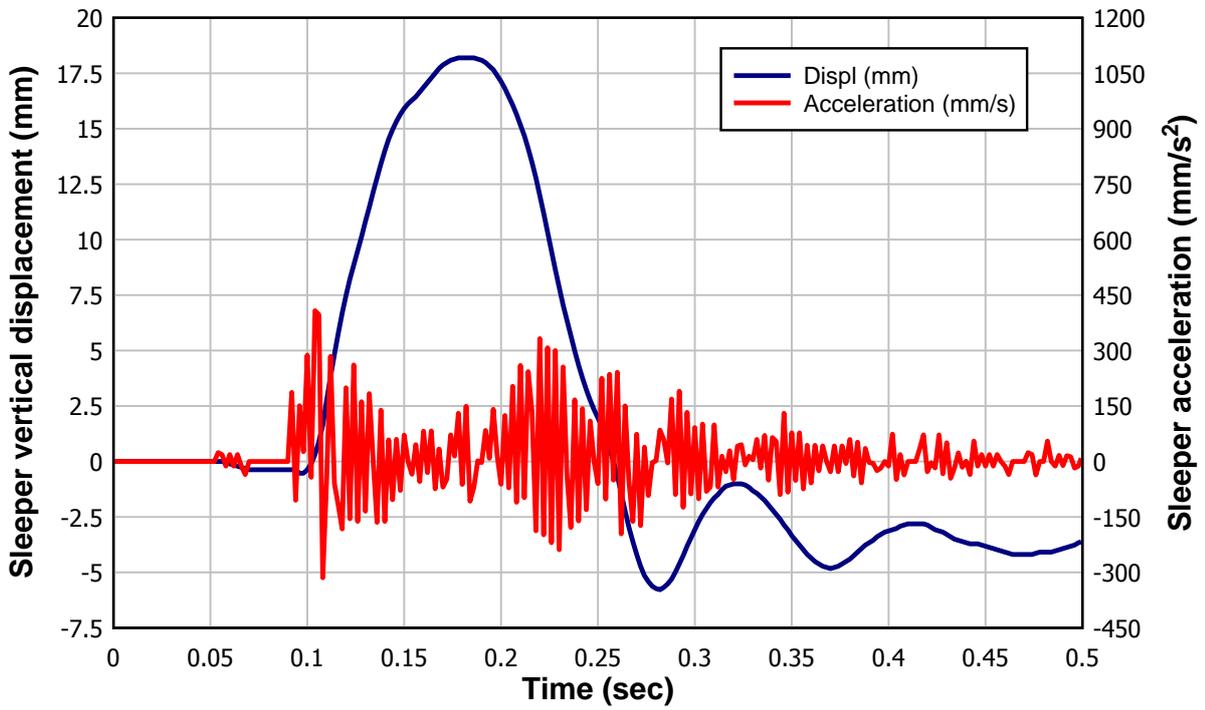
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Figure 31 High speed recording of dynamic response of sleeper in medium track condition

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

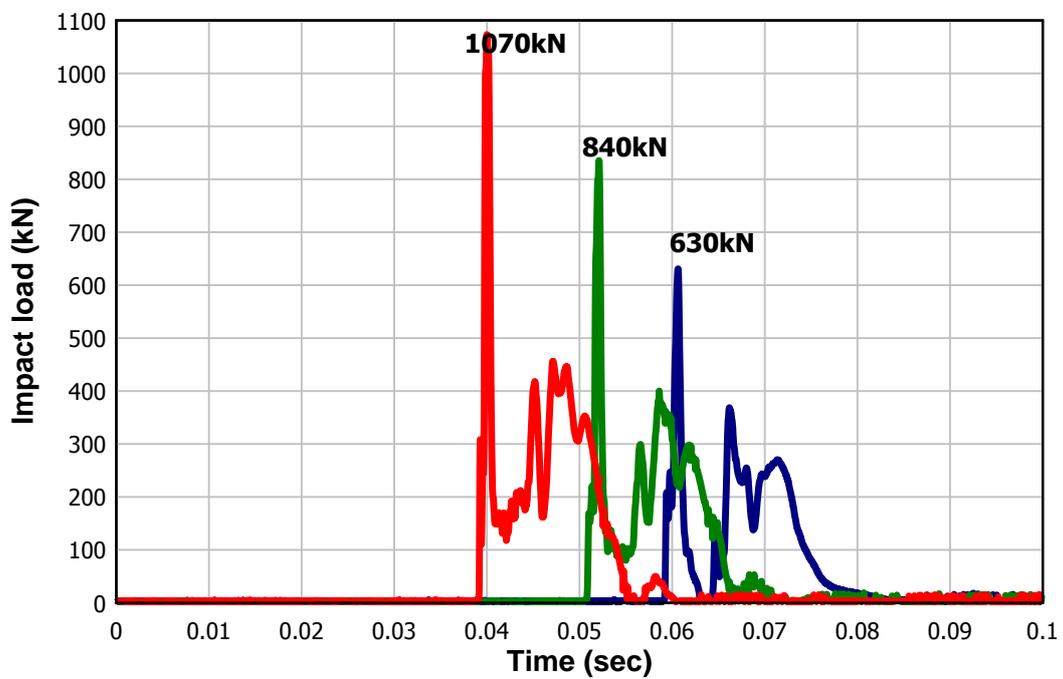


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Figure 33 Rail seat area – concrete scabbing under the rail – at the end of impact testing in medium track condition

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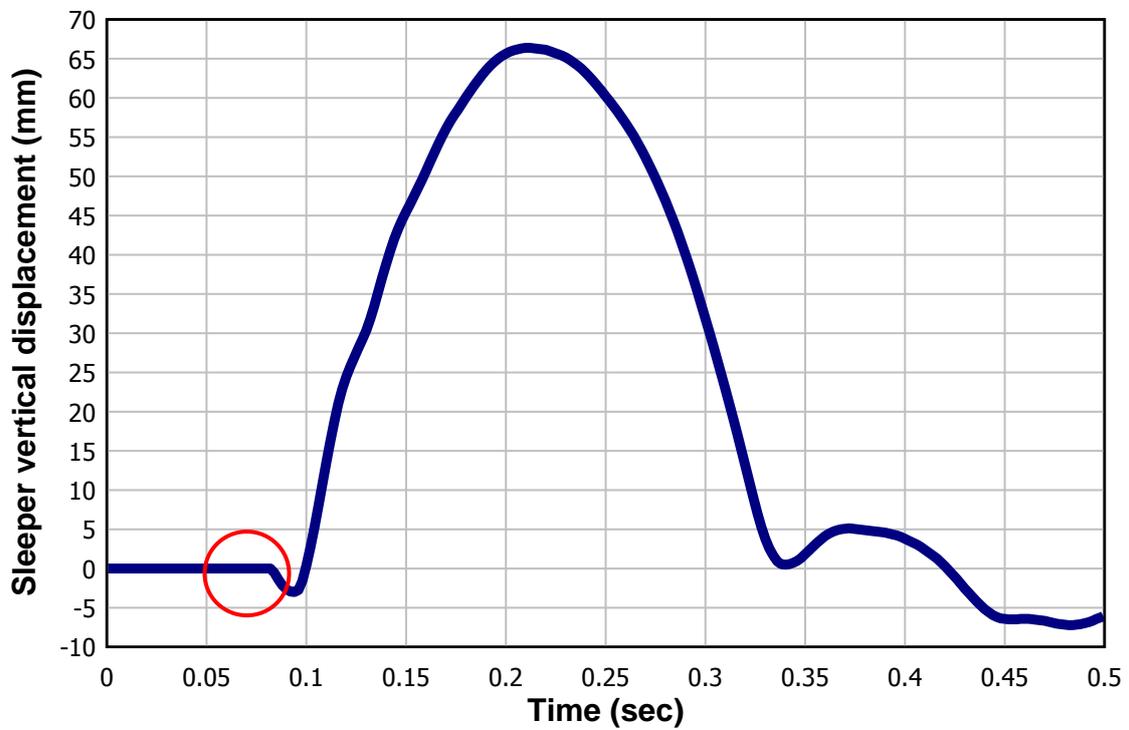
Figure 34 Soft track impact load time histories

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



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

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