Determination of Prestressing Force in Railway Concrete Sleepers Using Dynamic Relaxation Technique

Remennikov, Alex; Kaewunruen, Sakdirat

DOI:

[10.1061/\(ASCE\)CF.1943-5509.0000634](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000634)

License:

None: All rights reserved

Document Version

Peer reviewed version

Citation for published version (Harvard):

Remennikov, A & Kaewunruen, S 2015, 'Determination of Prestressing Force in Railway Concrete Sleepers Using Dynamic Relaxation Technique', *Journal of Performance of Constructed Facilities*, vol. 29, no. 5, pp. 04014134-1 - 04014134-7. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000634](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000634)

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

Final published version available at: [http://dx.doi.org/10.1061/\(ASCE\)CF.1943-5509.0000634](http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0000634)

Remennikov, Alex M., and Sakdirat Kaewunruen. "Determination of prestressing force in railway concrete sleepers using dynamic relaxation technique." *Journal of Performance of Constructed Facilities* (2014): 04014134. © 2014 American Society of Civil Engineers

Checked December 2015

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

1 REVISION OF TECHNICAL PAPER

2
3 “Determination of prestressing force in railway concrete sleepers using dynamic
4 relaxation technique”

5
6 (Title contains 11 words)

7
8
9 by

10
11 **Alex M. Remennikov**

12 School of Civil, Mining, and Environmental Engineering, Faculty of Engineering
13 University of Wollongong, Wollongong, NSW, Australia

14
15 and

16
17 **Sakdirat Kaewunruen**

18 Department of Civil and Environmental Engineering
19 Massachusetts Institute of Technology
20 Cambridge MA USA

21
22
23 Submitted to
24 ASCE Journal of Performance of Constructed Facilities

25
26
27 Corresponding Author:

28
29 Sakdirat Kaewunruen
30 Technical Specialist
31 RailCorp – Track Engineering
32 Level 13, 477 Pitt St
33 Sydney NSW 2000 Australia
34 Tel: 02 89221151
35 E-mail: sakdirat@mit.edu

36
37
38
39 Manuscript Summary:

Total pages	24 (including 1-page cover)
Number of figures	10
Number of tables	3

Determination of prestressing force in railway concrete sleepers using dynamic relaxation technique

Alex M. Remennikov¹ and Sakdirat Kaewunruen²

Abstract: Prestressed concrete sleepers (or railroad ties) are designed in order to carry and transfer the wheel loads from the rails to the track foundation. Over a period of time, a railway track could experience various types of static and dynamic loading conditions, which are attributable to commercial train operations. Previous studies have established two main limit states for the design consideration of concrete sleepers: ultimate limit states under extreme impact and fatigue limit states under repeated probabilistic impact loads. Prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, their remaining lives are not deeply appreciated nor taken into account for track maintenance and renewal. This experimental investigation was aimed at determining the residual prestressing force of railway concrete sleepers after revenue services using the dynamic relaxation technique. Fifteen sleepers were extracted from a heavy haul rail network for testing using experimental facilities at the University of Wollongong Australia. Structural evaluation program included quasi-static bending tests, dynamic impact tests, and tests to establish the current level of prestress in the steel wires using the dynamic relaxation technique. Two of the sleepers were evaluated for the level of prestressing forces in accordance with Australian Standards. It is found that the level of prestress determined using the dynamic relaxation technique turned out to be significantly lower than that expected from the theoretical analysis of time-dependent prestressing losses for the concrete sleepers.

Keywords: Prestressed concrete sleeper; Remaining prestressing force; Accumulative damage; Dynamic relaxation technique; Ballasted railway track.

¹ Associate Professor of Structural Engineering, School of Civil, Mining, and Environmental Engineering, Faculty of Engineering, University of Wollongong, Wollongong, NSW 2522 Australia; e-mail: alexrem@uow.edu.au

² Corresponding author; Technical Specialist, RailCorp, Sydney NSW 2000 Australia; currently a visiting executive fellow at Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge MA 02139-4307 USA; e-mail: sakdiat@mit.edu

Introduction

In Australia, railway prestressed concrete sleepers have been used in a rail network for nearly 35 years in comparison with those experiencing about 50 years in European and Japanese rail networks. The railway sleepers (or called ‘railroad tie’ in the US) are a main part of railway track structures. Its main duty is to distribute loads from the rail foot to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is also considered around 50 years (Standards Australia, 2003). Typical ballasted railway tracks and their components are shown in Figure 1. During their life cycles, railway track structures experience static, dynamic and often impact loading conditions due to wheel/rail interactions associated with the abnormalities in either a wheel or a rail (Remennikov and Kaewunruen, 2008). It was found that the magnitude of the dynamic impact loads per railseat is varying from 200 kN and sometimes can be more than 600 kN, whilst the design static wheel load per railseat for a 40-tonne axle load could be only as much as 110 kN. In principle, wheel load is an important factor in design and analysis of railway track and its components. The design load (F^*) for the limit states design concept takes into account both the static (F_s) and dynamic (F_i) wheel loads. There are three main steps in designing the concrete sleepers. First, the design actions or loads are to be determined based on the importance level of the track (e.g. $F^* = 1.2 F_s + 1.5 F_i$). Then, the design moment can be achieved by converting the design load to sleeper bending moment envelopes using advanced railtrack dynamic analysis or the design formulation (Kaewunruen and Remennikov, 2008; 2009). Last, the strength and serviceability of the prestressed concrete sleepers can be optimized in accordance with AS3600 Concrete structures (Standards Australia, 2001).

Recent studies showed that it is very likely that a railway sleeper could be subjected to severe impact loads, resulting in a rapid deterioration of its structural integrity and durability (Esvelt, 2001; Kaewunruen, 2007; Leong, 2007; Kaewunruen et al., 2014). A major research effort at the University of Wollongong (UOW) has revealed that the failure of a railway sleeper is more likely due to the cumulative damage rather than due to only a once-off extreme event, which might

104 occur due to the derailment or the terrorist attack. However, it was found that, for prestressed
105 concrete sleepers, the low magnitude but high cycle impact fatigue tend to be insignificant in
106 comparison with the high magnitude but low cycle impact fatigue (Ye et al., 1994; Wang, 1996;
107 Wakui et al., 1999; Gustavson 2002; Stevens and Dux, 2004; and Kaewunruen, 2007). According to
108 the literature review, it appears that there exists no research investigation into residual condition or
109 remaining life prediction of concrete sleepers. These have caused either incorrect or inefficient asset
110 management under constantly changing operations in the real world. This practical issue has
111 resulted in an initiative to investigate the existing condition of railway concrete sleepers and to
112 develop a standard guidance for predicting the remaining life of such component. The strength and
113 capacity of concrete sleepers depend largely on the prestressing force and bonds between steel
114 strands and concrete (Warner et al., 1998). Loss of prestress can generally be classified into two
115 stages: initial loss and time-dependent loss. Initial loss of prestress in concrete sleepers (due to
116 elastic shortening, bond and friction, and anchorage set) at the release of prestress was measured to
117 be between 20 and 27 percent - depending on the type of strands, bond characteristics, concrete
118 materials and the workmanship during the processes of prestress release (Kaewunruen, 2007). Over
119 the time, the concrete sleepers experience various traffic loads and may incur any damages and
120 cracks, resulting in a further time-dependent loss in prestress level (due to shrinkage and creep of
121 concrete, and relaxation of steel). [The phenomena also incur even without external loading.](#) This
122 paper addresses a part of the main initiative with respect to the determination of remaining
123 prestressing force in concrete sleepers after a period of service life using dynamic relaxation
124 method.

125 This investigation arose from planned expansion of the traffic on the heavy haul coal line in
126 New South Wales (NSW), Australia. The company planned to double the traffic on that coal line
127 and was concerned about the ability of its railway concrete sleepers (SRA types 1 and 2 concrete
128 sleepers on the coal line) to carry the increased traffic loads. The sleepers on that coal line were
129 manufactured and installed in 1982-84. A cluster of fifteen in-service concrete sleepers that were

130 installed in a heavy haul rail network were pulled out from the rail track and shipped to the
131 structures laboratory at UoW, Australia. Visual inspections and laboratory material testings were
132 conducted at the initial stage of the project. Two of the sleepers were evaluated for the level of
133 prestressing forces [based on the design method](#) in accordance with Australian Standards. This paper
134 presents the experimental study into the remaining prestressing force of existing aged prestressed
135 concrete sleepers. Also demonstrated are the engineering characteristics of materials used for
136 manufacturing concrete sleepers.

137

138 **Experimental Overview**

139 ***Test specimens***

140 Fifteen sleepers were retrieved from the heavy-haul coal line and delivered to UOW in July
141 2011 for testings in accordance with Australian Standards AS1085.14 (2003). The railway operator
142 and maintainer confirmed that the sleepers were typical heavy-duty sleepers manufactured around
143 1982. Design parameters detailing concrete strength, level of prestress, design moment capacities
144 were not available and therefore could not be used in this project for the direct comparison of the
145 current design parameters to the original design parameters at the time of sleeper manufacture.
146 However, it was reported from industry practices that the permissible stresses and design
147 restrictions of the concrete sleepers back in 1980s are very similar to those in existing standards
148 (Standards Australia, 2003). There was not much change in the standard design methodology and
149 inputs over the past decades. The design characteristics as tabulated in Table 2 were thus adopted
150 from AS1085.14 and AS3600, respectively (Standards Australia, 2003; 2001)

151 In this investigation, two test specimens are typical full-scale prestressed concrete sleepers
152 commonly used in Australia, as shown in Figure 2. [Two test specimens were selected to](#)
153 [demonstrate the variation and importance of detecting prestressing loss in currently used aged](#)
154 [concrete sleepers.](#) The prestressed concrete sleepers are often the main part of the standard-gauge,
155 heavy-haul rail tracks. The measured dimensions of the prestressed concrete sleeper are given in

156 Table 1. The cross-sections of the prestressed concrete sleeper were optimized for specific load
157 carrying capacities at different functional performances for rail seat and mid span. The prestressing
158 tendons are the chevron-patterned indented wires of about 5mm diameter (Standards Australia,
159 2003). The high strength concrete material was used to cast the prestressed concrete sleepers, with
160 design compressive strength at 28 days of 50-55 MPa, and the prestressing steels used were the high
161 strength with rupture strength of 1700 MPa (or 0.2% proof stress of 1530 MPa). The cored samples,
162 drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard
163 AS1012.14 (Standards Australia, 1991), as shown in Figure 3. Although the common concrete
164 strength adopted for design is 50 MPa, it was found that condition of the concrete at the test age of
165 about 30 years (since 1982) was deteriorated. From visual inspection, it could be observed that the
166 high strength prestressing wires were of high quality and the strength would not rapidly change
167 during time.

168

169 ***Material testing***

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

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

181 Once the cylindrical cores were extracted from the sleeper ends, they were checked for
182 overall smoothness, steps, ridges and grooves. The ends of the samples were trimmed and finished
183 to a smooth flat surface with the length-to-diameter ratio maintained at 2:1.

184

185 *Dynamic relaxation technique*

186 Experimental verification of prestressing force in the prestressing wires was conducted using
187 a dynamic relaxation technique. Dynamic relaxation is a process whereby 100 percent relaxation of
188 the steel wire is induced in an instant, relieving all remaining prestress (Otter et al., 1966; Saiidi et
189 al., 1994; Nawy, 1996; Lundqvist, 2012). Using the technique of dynamic relaxation, the
190 prestressing force in the prestressed wires was determined. With the knowledge of the final state of
191 strain in the wires after relaxation and Hooke's law for the prestressing steel, the prestressing force
192 was calculated for the individually tested wires. To perform the test, three specimens were prepared.
193 Two sleepers extracted from the coal line under investigation were prepared in accordance with
194 Australian Standards (1991, 2001, 2003) while an additional concrete sleeper (similar type)
195 removed from another mixed-traffics railway track in NSW was used for comparison and validation
196 of the results.

197 The top 30 mm of concrete cover was removed from the specimens to expose the top row of
198 the reinforcing wires near the centre of the sleepers. The mid-span position was chosen to ensure
199 adequate anchorage zone of prestressing tendons surrounding the test zone. A small area of concrete
200 was removed from underneath the wires to eliminate the steel-concrete bond and ensure complete
201 freedom of the wires for longitudinal displacement during the test as shown in Figure 5. In total, less
202 than 5 percent of concrete was removed axially along the sleepers in order to ascertain that the
203 concrete cover removal did not critically affect the prestress level and eccentricity according to
204 AS3600 (Standards Australia, 2001). The wires were polished and cleaned and had strain gauges
205 with a 2 mm gauge length attached by using dynamic strain gauge epoxy resin as shown Figure 6.
206 The strain gauges were attached to symmetrical wires on each specimen. The strain gauges were

207 connected to the high-speed data acquisition system. The data logger was calibrated to process and
208 capture changes in axial strains at the rate of 10,000 data points per second, anticipating a very
209 sudden relaxation of the wires.

210 After attaching the strain gauges to the wires, the strain gauged wires were cut one at a time
211 using bolt cutters, as seen in Figure 7. The cutting process was swift and very minimal disturbance
212 on the dynamic strains can be observed in Figure 8. Cutting the wires released the tensile stress that
213 the wires were subjected to during prestressing. Rapid removal of this stress provoked axial
214 vibration of the steel wire that was recorded as a time history of strains by the high-speed data
215 logger. Note that the residual effect of strain relaxation on the condition of strain gauges is
216 negligible as shown in the final state of strains in Figure 8. It was observed that the dynamic strains
217 could be acquired reliably using dynamic strain gauges and there was no slip nor delamination of
218 strain gauges after the tests.

219

220 **Material Properties**

221 Five compressive tests were conducted using compression testing apparatus in the High Bay
222 laboratory at the University of Wollongong. The tests were performed in accordance with concrete
223 compressive testing procedures outlined in AS 1012.9-1999 (Standards Australia, 1999). Table 3
224 presents the results of concrete compressive tests. The average compressive strength of the tested
225 core samples was found to be 44.2 MPa.

226 The typical characteristic concrete compressive strength (after 28 days) in prestressed
227 concrete sleepers is 50 MPa. It was expected that the 30-year old concrete sleepers would develop
228 compressive strength around 65-80 MPa (Kaewunruen and Remennikov, 2010; 2014), thus the
229 experimentally determined concrete strength of 44.2 MPa (± 4 MPa) was much lower than that
230 expected. There was no known reason for such significant degradation of the concrete compression
231 strength over the service life period, unless the sleepers were originally manufactured with very low
232 strength of concrete of around 25-30 MPa.

Experimental results and discussion of dynamic relaxation tests

Figures 8 (a) and (b) present the time histories of axial strain from the dynamic relaxation of the wires for the two sleepers tested. The graphs demonstrate how the strain relaxed over a very short period of time before settling on a final constant value representing the actual prestressing force. Upon cutting, the sudden release of prestressing force causes the exposed portion of wire to undergo a rapid shortening along its length, expressed as a sudden drop in strain on the graphs. Due to the inertial effects, the wire segment vibrates with rapidly decreasing amplitudes due to damping and friction effects generated by the steel-concrete interface. The calculated differential strain from the initial prestressed state to the final relaxed state is approximately 2000 microstrain for both sleepers tested, as seen in Figures 8 (a) and (b).

Adopting a modulus of elasticity of 200 GPa for the steel tendons and using the experimentally determined axial strain of 2000 microstrain, the steel wire stress can be calculated as

$$\sigma_{s,1} = E_s \times \epsilon_{s,1} = (200 \times 10^3) (MPa) (0.002) = 400 MPa \quad (1)$$

With the 0.2% proof stress of 1530 MPa, the theoretical design value of prestressing stress should be about $0.85 \times 1530 = 1300$ MPa. Allowing for 20% initial loss of prestress at the sleeper centre, the design stress in the steel wires should have been 1040 MPa in the top row of wires. This shows that the experimentally determined level of prestress is just about 40 percent of the expected stresses in the prestressing tendons in the coal-line sleepers tested herein.

The experimentally determined values of the prestressing force were validated by utilising the same experimental procedure to determine the level of prestress in a heavy-duty sleeper (similar type) extracted from the mixed-traffic track near Wollongong, NSW. It is estimated that the heavy-duty sleeper has been in service for about 10 years and subjected predominately to suburban train loads.

Figure 9 demonstrates the time histories for the axial strains from the dynamic relaxation of the top row wires at the centre of heavy-duty sleeper. One can notice that the average measured

strain from relaxation for the two wires was approximately 5200 microstrain. Adopting a modulus of elasticity of 200 GPa for the steel and using the experimentally determined axial strain of 5200 microstrain, the steel wire stress can be calculated as

$$\sigma_{s,2} = E_s \times \epsilon_{s,2} = (200 \times 10^3) (MPa) (0.0052) = 1040 MPa \quad (2)$$

which is reasonably close to the theoretical design stress of 1040 MPa in the top row of wires at the sleeper centre, or about 23% loss from the initial design prestress, which is justifiable. According to AS1085.14 (Standards Australia, 2003), the prestress level at transfer only (or without any applied wheel load) should remain approximately consistent. Note that the overall cross-section relationship between fibre stresses (σ), prestressing forces (P_s) and eccentricity (e) can be correlated as:

$$\sigma = -\frac{P_s}{A_g} \pm \frac{P_s \cdot e \cdot y}{I_g} \quad (3)$$

where y is the moment-arm distance from neutral axis, A_g and I_g are the gross area and moment of inertia of cross section, respectively.

Based on the validating results for the heavy-duty sleeper, it is believed that the experimentally determined value of prestress is justified, and it indicates significant loss of prestress in some existing coal-line sleepers tested in this programme. One possible explanation of the above phenomenon is illustrated in Figure 10, showing one of the tested sleepers with a significantly damaged end. This type of concrete damage may have resulted in the loss of bond between the steel wire and the concrete and reduction in the level of prestress in the steel wire. But, the second sleeper tested did not have significant concrete damage and also showed a very low level of the prestress. It is therefore recommended that the proposed experimental technique for determining the level of prestress in the existing concrete sleepers is adopted as part of assessment of remaining life of sleepers in the existing heavy haul train lines.

Conclusions

This paper presents a part of the investigation arose from the planned expansion of the

283 traffic on the heavy-haul coal lines by a rail operator and maintainer. There was a concern whether
284 the railway concrete sleepers would be capable of carrying the increased traffic loads. Note that the
285 concrete sleepers on that coal line were manufactured and installed in 1982-84.

286 Accordingly, fifteen aged concrete sleepers that were installed in the heavy haul rail network
287 were extracted from the rail track and shipped to the structures laboratory at the [University of](#)
288 [Wollongong \(UOW\), Australia](#). Visual inspections and laboratory material testings were conducted.
289 The sleepers were evaluated for their current positive and negative bending capacities, fatigue
290 resistance, and resistance to impact loading. Several sleepers were evaluated for the current level of
291 prestressing forces in accordance with Australian Standards.

292 The visual inspection of the concrete sleepers revealed that there were potential problems
293 with durability of the sleepers. Concrete spalling of sleepers due to tamping damage, poor
294 construction, and loss of concrete section due to abrasions were among the problems that could
295 cause the rapid deterioration of strength and serviceability.

296 It is found that the dynamic relaxation technique is a suitable procedure for the
297 determination of the level of prestress in existing aged concrete sleepers. [Using this technique, it](#)
298 [was possible to detect the existing sleepers in which the current level of prestress in the steel wires](#)
299 [was only 40 percent of the design value](#). The experimental results demonstrated that loss of
300 prestress could be linked to the integrity of the concrete material, which could be used for initial
301 screening of the existing concrete sleepers with a view of detecting defective sleepers. This
302 information is also critical for predicting remaining life of concrete sleepers in existing railway
303 tracks and their ability to sustain higher wheel loads or higher train speeds when expansion of the
304 traffic is planned.

305 It is important to note that loss of prestress affects serviceability (rail gauge widening, cant
306 dynamics, rotational capacity at rail seats, dynamic geometry and deflection, etc.) and durability (i.e.
307 fatigue life, crack propagation, etc.) of sleepers. The future investigations will include the material
308 strengths, structural capacity, spectrum of impact loads from the wheel impact detectors, and

309 responses of the concrete sleepers to impact and fatigue loading conditions, in order to predict their
310 remaining capacity of concrete sleepers to cater for the current or planned increased traffic loads.

311

312 **Acknowledgement**

313 The authors are grateful to Australian Rail Track Corporation (ARTC), Sydney Trains
314 (Wollongong Maintenance Depot), and sleeper manufacturer, ROCLA, for the support
315 throughout this study. Valuable comments and support from Drs M.H. Murray and R. Blomsvik
316 are acknowledged. The authors would like to thank the Structural Lab Manager Alan Grant for
317 his assistance during the experiments. Also, the second author wishes to thank Australian
318 Government's Department of Innovation for supporting his Endeavour Executive Fellowships at
319 Department of Civil and Environmental Engineering, Massachusetts Institute of Technology,
320 Cambridge MA, USA, at John F Kennedy School of Government, Harvard University,
321 Cambridge MA, USA, and at Railway Mechanics Centre, Chalmers University of Technology,
322 Gothenburg, Sweden.

323

324 **References**

325

326 Esveld, C., 2001. *Modern Railway Track*, The Netherlands MRT Press.

327 Gustavson, R., 2002. Structural behaviour of concrete railway sleepers. *PhD Thesis*, Department of
328 Structural Engineering, Chalmers University of Technology, Sweden.

329 Kaewunruen, S. 2007. Experimental and numerical studies for evaluating dynamic behaviour of
330 prestressed concrete sleepers subject to severe impact loading. *PhD Thesis*, School of Civil,
331 Mining, and Environmental Engineering, University of Wollongong, Australia.

332 Kaewunruen, S. and Remennikov, A.M., 2008, Nonlinear transient analysis of railway concrete
333 sleepers in track systems. *International Journal of Structural Stability and Dynamics*, 8(3):
334 505-520.

335 Kaewunruen, S. and Remennikov, A.M., 2009, "Progressive impact behaviours of prestressed
336 concrete sleepers in railway track environments." *Engineering Structures*, 31(10):2460-2473.

337 Kaewunruen, S. and Remennikov, A.M., 2010, "Dynamic crack propagations of prestressed
338 concrete sleepers in railway track systems subjected to severe impact loads." *ASCE Journal of*
339 *Structural Engineering*, 136(6): 749-754.

340 Kaewunruen, S. and Remennikov, A.M., 2014, "On the residual energy toughness of prestressed
341 concrete sleepers in railway track structures subjected to repeated impact loads." *Electronic*
342 *Journal of Structural Engineering*, in press.

343 Kaewunruen, S., Remennikov, A.M., Aikawa, A., and Sakai, H., 2014, "Free vibrations of
344 interspersed railway track systems in three-dimensional space." *Acoustics Australia*, 42(1): 14-
345 20.

346 Leong, J., 2007. Development of a limit state design methodology for railway track. Master of
347 Engineering Thesis, Queensland University of Technology, QLD, Australia.

348 Lundqvist, P., 2012. Assessment of long-term losses in prestressed concrete structures, PhD Thesis,
349 Lund University, Lund, Sweden.

350 Nawy, E.G., 1996, *Prestressed concrete: a fundamental*, Prentice Hall Inc., New Jersey, USA.

351 Otter, J.R.H, Cassell, A.C., Hobbs, R.E., 1966, "Dynamic relaxation", *ICE Proceedings*, 35(4): 633-
352 656.

353 Remennikov, A.M. and Kaewunruen, S., 2008. A review on loading conditions for railway track
354 structures due to wheel and rail vertical interactions. *Progress in Structural Engineering and*
355 *Materials*, incorporated in *Structural Control and Health Monitoring*, 15(1):207-234.

356 Saiidi, M., Douglas, B., and Feng, S., 1994, "Prestress force effect on vibration frequency of
357 concrete bridges." *ASCE Journal of Structural Engineering*, 120(7): 2233-2241.

358 Standards Australia, 1991. Method of testing concrete – Method for securing and testing cores from
359 hardened concrete for compressive strength. *Australian Standard: AS1012.14-1991*, Sydney
360 Australia

361 Standards Australia, 1999. Method of testing concrete – Determination of the compressive strength
362 of concrete specimens. *Australian Standard: AS1012.9-1999*, Sydney Australia

363 Standards Australia, 2001. Design of Concrete Structures. *Australian Standards: AS3600-2001*,
364 Sydney Australia

365 Standards Australia, 2001. Railway track material - Part 19: Resilient fastening systems. *Australian*
366 *Standard: AS1085.19-2001*, Sydney Australia

367 Standards Australia, 2003. Railway track material - Part 14: Prestressed concrete sleepers.
368 *Australian Standard: AS1085.14-2003*, Sydney Australia

369 Stevens, N.J. and Dux, P.F., 2004. A method of designing a concrete railway sleeper, *International*
370 *Patent No WO 2004/019772 A1*, Publication Date 4 March 2004, World Intellectual Property
371 Organisation, International Bureau.

372 Wakui, H. and Okuda, H., 1999. A study on limit-state design for prestressed concrete sleepers.
373 *Concrete Library of JSCE*, **33**: 1-25.

374 Wang, N., 1996. Resistance of concrete railroad ties to impact loading, *PhD Thesis*, University of
375 British Columbia, Canada.

376 Warner, R.F., Rangan, B.V., Hall, A.S., and Faulkes, K.A., 1998. *Concrete Structures*, Addison
377 Wesley Longman, Melbourne, Australia.

378 Ye, X., Wang, N., and Mindess, S., 1994. Effect of loading rate and support conditions on the mode
379 of failure of prestressed concrete railroad ties subjected to impact loading, *Cement & Concrete*
380 *Research*, **24**(7): 1386-1298.

381

382

383

384 **Table 1.** Dimensions and masses of the test sleepers

Mass (kg)	Gauge length (m)	Total length (m)	At railseat (m)		At centre (m)	
			width	depth	width	depth
206.0	1.60	2.50	0.20	0.23	0.21	0.18

385

386

387

388

389

390 **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	-	-

391

392

393

394

395 **Table 3.** Tested compressive strength of concrete

Core No	Mean diameter (mm)	Ultimate load (kN)	Compressive strength (MPa)
1	54.20	114	49.4
2	54.39	100	43.1
3	54.18	90	39.1
4	54.24	102	44.1
5	54.26	105	45.4
Average			44.2

396

397

Figure 1. Typical components of railway tracks.

436
437
438

439
440

441
442
443
444
445
446
447
448
449
450

Figure 2. Condition of concrete sleepers

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

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

478
479

480
481

Figure 5. Preparation of specimens for dynamic relaxation tests

482
483
484
485

486
487

Figure 6. Two-millimetre strain gauges attached to prestressing wire

488
489
490
491
492
493

494
495
496

497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522

Figure 7. Cutting of prestressing wires

523
524

525
526
527

a) Coal-line Sleeper #1

528 Figure 8. Dynamic relaxation of prestressing force in prestress tendons for coal-line sleepers

529
530
531
532
533
534
535
536
537

b) Coal-line Sleeper #2

Figure 8. Dynamic relaxation of prestressing force in prestress tendons for coal-line sleepers

553
554

555
556
557
558
559
560
561
562
563
564
565
566
567

Figure 9. Dynamic relaxation of prestressing force in prestress tendons for ROCLA sleepers (validating test)

568
569
570
571

572
573
574
575

Figure 10. Sleeper end damage possibly resulting in considerable loss of prestress