September 2006

Post-failure mechanism and residual load-carrying capacity of railway prestressed concrete sleeper under hogging moment

Sakdirat Kaewunruen
University of Wollongong, sakdirat@hotmail.com

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

Structural Integrity and Failure - September 2006

POST-FAILURE MECHANISM AND RESIDUAL LOAD-CARRYING CAPACITY OF RAILWAY PRESTRESSED CONCRETE SLEEPER UNDER HOGGING MOMENT

S. Kaewunruen and A.M. Remennikov

School of Civil, Mining, and Environmental Engineering, University of Wollongong, Wollongong, 2522 NSW, Australia

ABSTRACT

Failure mechanisms of engineering structures to various loadings are the key indicators for structural engineers to design and predict the behaviours of such structures. However, the undetermined post-failure mechanisms are of major concern after the structural collapse, due to excessive loading. The residual load-carrying capacity yields the safety allowance to public domain, in order to escape from the incident. In railway practice, the concrete sleepers tend to be subjecting hogging or negative moment at the mid-span, resulting in the negative bending of the sleeper and associated gauge rail rotation. Although the concrete sleeper fails, it still tends to hold the rail gauges. Therefore, it is essential to understand into the behaviours after failure of the concrete sleeper. This paper elucidates the post-failure mechanism and the residual load-carrying capacity of railway concrete sleeper. To achieve this, Australian-manufacturer's concrete sleeper was employed for the negative bending test in accordance with AS1085. LDVT was employed in deflection measurement at the mid-span while the inclinometers were placed in line of the rail support. The post-failure load-deflection curves have been first presented here. The remaining part of the concrete sleeper was used to core for some samples. The concrete strength of 88.5MPa is found for the concrete material of this sleeper. Each prestressing wire has a proof stress of 1860 MPa. It is found that each prestressing wire restrains approximately 10kN residual load-carrying capacity of the concrete sleeper.

1 INTRODUCTION

1.1 Concrete Sleepers

Railway track has been constructed to overcome the challenges of excessive load-carrying capacity of the roads and trucks. It consists of rails, sleepers, formation, and fastening systems[1]. The railway sleepers are importantly functioned to:

- Uniformly transfer and distribute loads from the rail foot to underlying ballast bed;
- Sustain and retain the rails at the proper gauge by keeping anchorage for the rail fastening system; preserve rail inclination; and
- Provide support for rail; restrain longitudinal, lateral and vertical rail movements by embedding itself onto substructures.

It is clear that the sleeper has a major role in distributing axle loads to formation. The axle loads could be considered static or quasi-static when the speeds of trains are quite moderate[2]. However, in general, the axle loading tends to physically behave like the dynamic impact pulses due to the continual moving ride over track irregularities and faster speeds. These dynamic effects would then deteriorate the mechanical properties of the track components and undermine the load-carrying capacity of the concrete sleepers[3, 4].

1.2 Ultimate Behaviors

Although the dynamic effects seem to prevail over the failures of concrete sleepers, the limit states design concept still relies on the static sectional capacity of the sleepers. There have been many attempts to modify the dynamic influences into equivalent impact factors, in order to perform the design calculations on the static behavior basis[5, 6]. Interestingly, theoretical concepts of strength, ductility, stability, fracture mechanics, and so on, mostly refer to the static behaviors[7]. In particular, to have better understanding into static behaviors of concrete sleepers, the energy absorption phenomena of concrete sleeper specimens are required to evaluate the effectiveness of structural members, resulting to the better insight into dynamic and impact absorption. In addition, the future numerical modeling of prestressed concrete sleepers requires the static testing results to validate against each other. The convergence of the model over static behaviors and modal analysis results will certainly strengthen the confidence of using the numerical model in accurately predicting the impulsive responses of concrete sleepers under various boundary conditions. More details on experimental modal testing can be found in the previous state-of-the-art report[1].

In Australia, Standards Australia[5, 6] revised the conventional design of railway prestressed concrete sleepers and fastening assemblies. Also, the maximum design flexural moments in sleepers can be statically calculated from the pressure distribution as prescribed in the code. It is found that the maximum positive moment occurs at the rail seat, whilst the maximum negative moment remains at the middle of sleepers. Design concepts of concrete sleepers relied on permissible stresses has been governed in the 2003 Release[8, 9]. The Standard also gives consideration that need not to check sleeper section for stresses

other than flexural stresses, e.g. shear, if the design is complied with all clauses in the Standard. It is noteworthy that for prestressed concrete sleepers, the influence of the dead load can be ignored and the design load can be expressed by the wheel load alone[10].

1.3 Research Significance

Post-failure behaviors of prestressed concrete structures are the subtle area of knowledge for building structural concrete design nowadays. Most of static investigations on prestressed concrete members have focused on the peak or collapse loads and the related displacements. Understanding post-failure mechanism allows safety time of occupation and can lead to a new limit states design concept of such building components. In this paper, the static testing results are presented. Due to the high quality control and the limit number of concrete sleepers, a pilot test covers only the preliminary results on the post-failure behavior and residue load-carrying capacities of a railway concrete sleeper at the centre of the sleeper. At the centre section, the negative moment was applied through the four-point-load bending test. Normally, this hogging moment is notably attributed to the train axle load applying on both rail seats. Those tests were arranged in accordance with AS1085.14-2003 Prestressed concrete sleepers and AS1085.19-2003 Resilient fastening assemblies[5, 6]. A prestressed concrete sleeper, supplied by the Australian manufacturers, was employed in the ultimate negative moment test, see examples in Figure 1. All tests were performed using full-scale concrete sleeper without cutting, scaling, dividing, nor adjusting the sleeper. Elastic behaviors, cracking moments, and failure mode will be included in addition to the post-failure behavior and the residue capacity of concrete sleepers.

2 EXPERIMENTAL PROGRAMS

Experimental setups were carried out complying with Australian Standards: AS1085.14-2003 Prestressed concrete sleepers and AS1085.19-2003 Resilient fastening assemblies[5, 6]. AS1085.14-2003 indicates the boundary conditions, location of supports, and characteristics of loading. The strain measurements on top and bottom fibres at the surface of concrete sleepers are followed from AS1085.14-2003.

2.1 Specimen

The concrete sleeper specimen used in the ultimate test has been kindly supplied by an Australian manufacturer within the collaboration of the Cooperative Research Center for Railway Engineering and Technologies (Rail CRC). The total length is 2,700 mm and the rail gauge is 1,600 mm. Figure 2 shows the cross section at mid span of the tested sleeper.

2.2 Hogging Moment Testing

The schematic diagram for the experimental setup of centre negative moment test is shown in Figure 3. The strain gages were installed 10 mm from the top and bottom surface at the centre of sleeper. LDVT was used to measure deflection at the load point. The rotation at supports that represent the gauge rotations can be measured using inclinometers. The test had been implemented at small rate displacement control that provides loading rate at approximately 10 kN/min as indicated in AS1085.14 that the loading rate should be lesser than 25 kN/min. The equipment required in these tests includes:

- LDVT at middle span,
- Inclinometers at rail seat supports,
- Strain gages and wires at top and bottom fibres,
- Load cell,
- Loading frame,
- DataLogger, and
- Electronic load control

Figure 1: General Australian concrete sleepers

2.3 *Materials Testing*

After performing the ultimate test, the concrete sleeper has been drilled for materials testing specimens, in order to investigate the mechanical properties of concrete materials at that condition. The specimens were subjected to uni-directional axial loading tests, as illustrated in Figure 4. The LDVT was used to measure the displacement under loading. It is found that the average strength of concrete is 88.5 MPa.

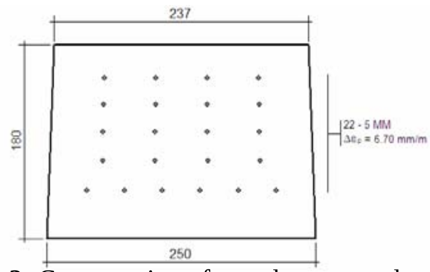


Figure 2: Cross section of tested concrete sleepers

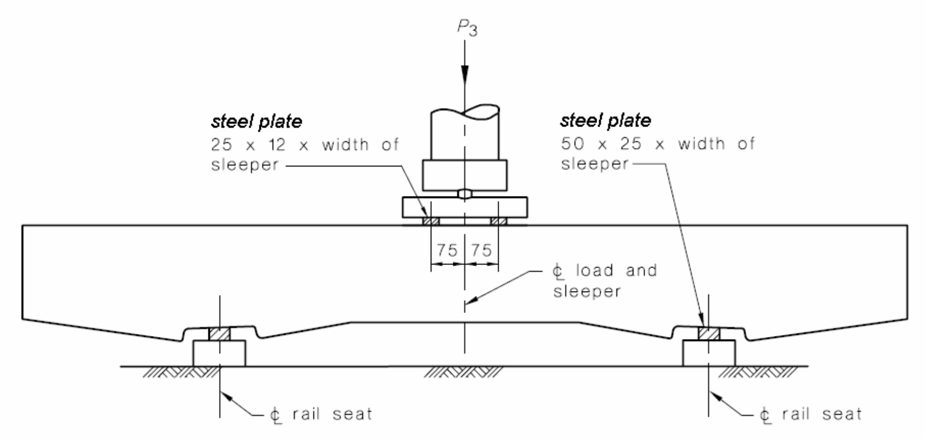


Figure 3: Centre-negative moment test (AS1085.15-2003, L1) at mid span (in mm.)

3 EXPERIMENTAL RESULTS

Figure 5 shows the real setup and instrument for the negative moment test at middle section. The maximum load experimentally found is 133.3 kN, equivalent to bending moment about 45kNm.

Figure 4. Uni-axial testing

Figure 5. Hogging moment test

The load-deflection relation is presented in Figure 6a, while the moment-deflection can be seen from Figure 6b. The crack initiation load was detected visually during each test as well as determined by the use of the load-deflection relation. Crack initiation was defined as the intersection between the load-deflection relations in stages I and II as shown in Figure 7. This simplified definition was employed to obtain a consistent method for the crack initiation load determination[2]. This method provides a slightly higher cracking load that that from the first deviation point from the linear elastic part of load-deflection relationship. Comparisons of measured and visualized crack initiation loads showed very good agreement. The visualized crack initiation load is about 79 kN while the measured one is about 75 kN.

a)

b)

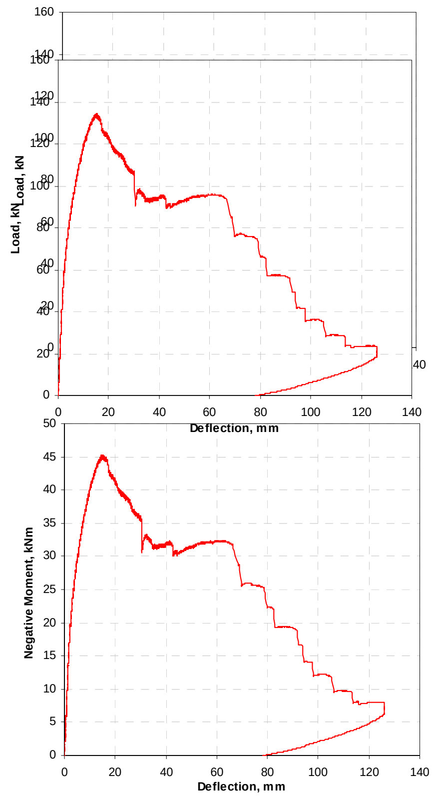


Figure 6: Load and moment versus deflection curves

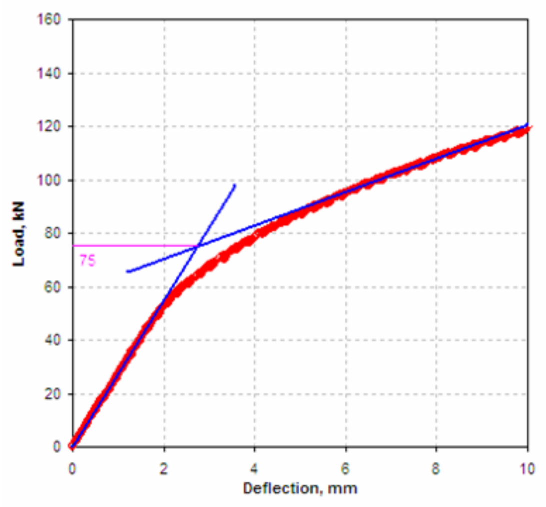


Figure 7: Cracking moment

The first crack during the test was a flexure crack appearing in the line of loading, see Figure 8. As the load was increased, the flexure-shear cracks formed at each side after the bending cracks stopped at a distance of about one third of the sleeper depth. All cracks were initiated at the base of the sleeper and propagated towards the compressive zone beneath the applied load. When the load reached the maximum, the concrete crushed and spalled as seen in Figure 9. At this stage, the applied load decreased while the deformation continued from that about 16mm. The prestressing wire seemed to govern the sleeper strength and slightly yield. Combined flexure and shear failure seems to be suitable to explain the crack behaviors. The behaviours of the sleeper after failure can be explained based on its load-deflection curve. At certain deflections, the prestressing wires started to damage one by one, resulting in a sudden significant vertical drop of load in load-defection curve, approximately 10kN per wire damage. The wire damage started from the lowest layer of such prestressing wires as can be seen from Figure 10.

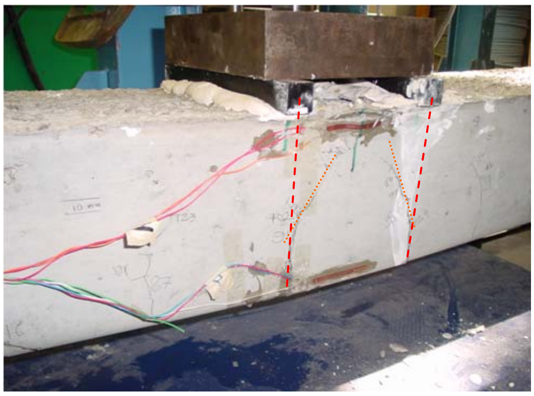


Figure 8: Initial cracks

Figure 9: Concrete crushing

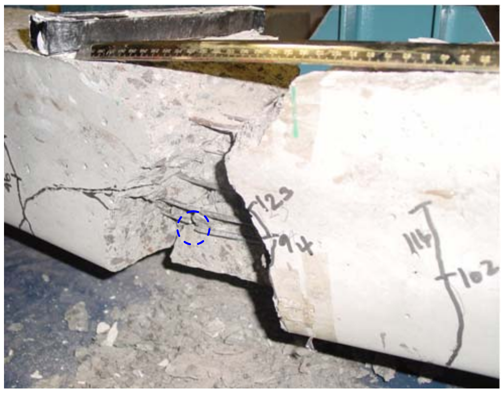


Figure 10: Prestressing wire damages

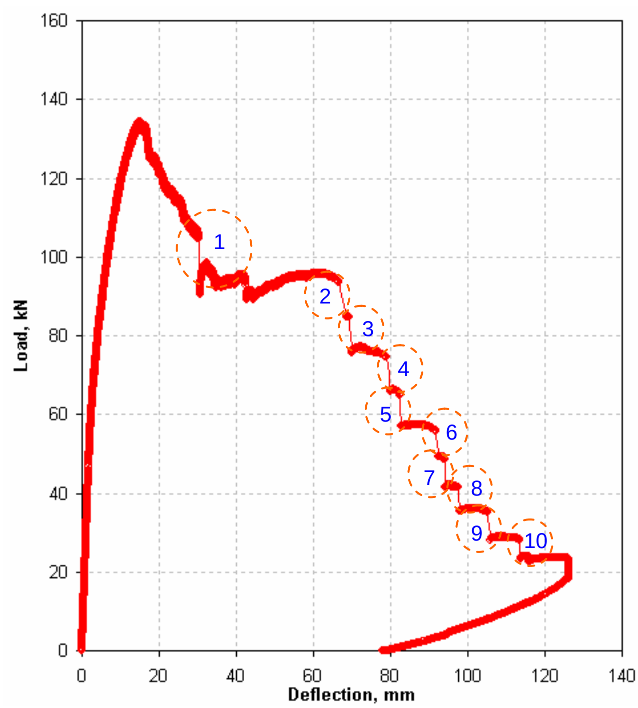


Figure 11: Residue load-carrying capacity

Recalling the load-defection curve of this test in Figure 11, each dash orange circle in the curve locates the damage of each wire starting from the lowest layer of prestressing. Each sudden drop releases the breaking

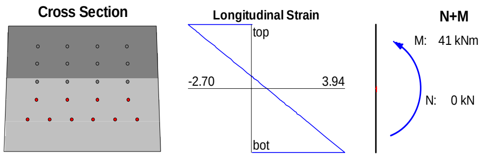
noise and loses the residue carrying load about 10 kN. Definitely, ten wires were damaged and about 100kN residue load-carrying capacity was disappeared. It also shows that the concrete sleeper tends to have small ductility, especially smaller after the wires begin to tear off.

4 SECTIONAL ANALYSIS

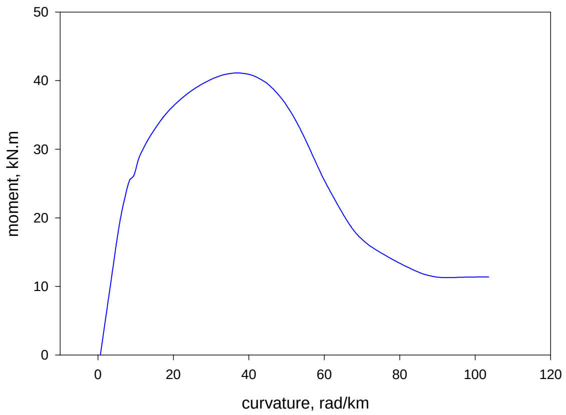
Cross section of the concrete sleeper is presented in Figure 1. Sectional analysis of prestressed concrete section can be computed from a computer package, Response-2000. Response-2000 sectional analysis is based on the modified compression field theory[11]. In this section, Response-2000 has been employed to evaluate all moment capacities of all prestressed concrete sleepers. For this specimen, the measured initial strain of wires due to prestressing is about 6.70 mm/m. Each prestressing wire has a proof stress of 1860 MPa.

4.1 Positive Moment Capacity

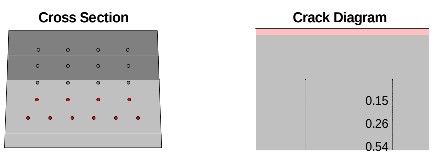
Sectional analysis of the specimen for ultimate positive moment of middle section is shown in Figure 12a. Figure 12b displays the moment curvature relationship and Figure 12c presents the crack width of the sleeper at ultimate load. It is found that the ultimate moment is 41 kNm, while the decompression moment is about 15 kNm.



a) ultimate state



b) Moment-curvature relation

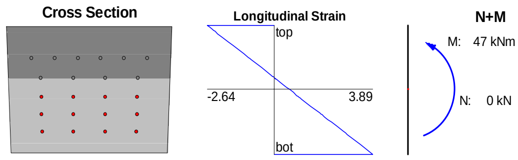


c) crack width analysis

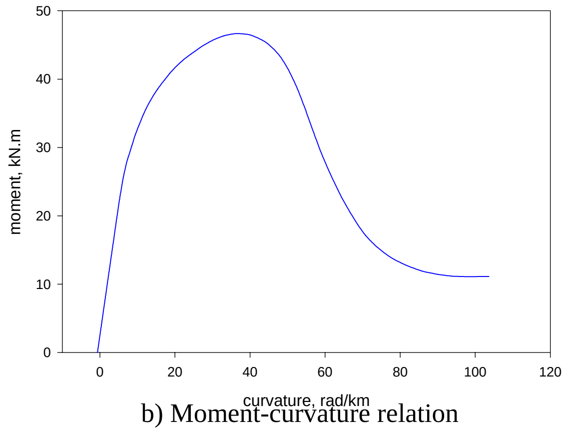
Figure 12: Ultimate positive moment capacity

4.2 Negative Moment Capacity

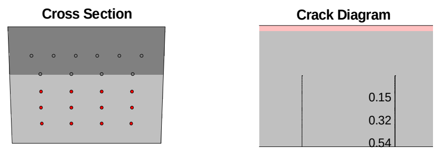
Analogously, sectional analysis of the specimen for ultimate negative moment of middle section is shown in Figure 13a. Figure 13b displays the moment curvature relationship and Figure 13c presents the crack width of the sleeper at ultimate load. It is found that the ultimate negative moment is 47 kNm, while the decompression moment is about 19 kNm.



a) ultimate state



b) Moment-curvature relation



c) crack width analysis

Figure 13: Ultimate negative moment capacity

5 CONCLUSIONS

In design and analysis of building structures, failure mechanisms seem to indicate such procedures in addition to considering only collapse loads. Post-failure mechanisms and the residual load-carrying capacity provide the safety allowance to evacuate residents. In railway tracks, the concrete sleepers is a main component subjected to hogging or negative moment at the mid-span due to the axle load at both rail seats. To identify capability of holding rail gauges, the behaviors after failure of the concrete sleeper are required. This paper determined the post-failure mechanism and the residual load-carrying capacity of railway concrete sleeper. An Australian concrete

sleeper was employed for the test in accordance with AS1085. The post-failure load-deflection curves have been first presented here.

The remaining part of the concrete sleeper was used to core for some samples. The concrete strength of 88.5MPa is found for the concrete material of this sleeper. Each prestressing wire has a proof stress of 1860 MPa. The sectional analyses have been conducted using Response-2000 based on the modified compression field theory. The theoretical results of all sections of prestressed concrete sleepers have been achieved. The experimental results from static tests gave very good correlation with the sectional analysis data. Flexure cracks tend to be the first cracks arising. Cracking loads or moments from visual inspection are quite close to those from the measured cracking ones, computed from the intersection of two initial slopes of a load-deflection curve. It is found that each prestressing wire restrains approximately 10kN residual load-carrying capacity of the concrete sleeper.

Acknowledgement

This investigation has been financially supported by CRC for Railway Engineering and Technologies (Rail-CRC). The supports from Industry partners: QR, RailCorp, AUSTRAK, ROCLA, and PANDROL, are deeply appreciated. Sincere thanks are also extended to UoW Technical Officers, Alan Grant, Ian Bridge, and Bob Rowland for making these pilot testing scenarios successful.

References

[1] S. Kaewunruen and A. Remennikov: A state-of-the-art review report on vibration testing of ballasted track components, *July-December Research Report*, CRC Railway Engineering and Technologies, Australia, 2004.

[2] R. Gustavson: Static and dynamic finite element analyses of concrete sleepers, *Licentiate of Engineering Thesis*, Department of Structural Engineering, Chalmers University of Technology, Sweden, 2000.

[3] S. Kaewunruen and A. Remennikov: In-field dynamic testing and measurements of railway tracks in Central Queensland, *March-June Research Report*, CRC Railway Engineering and Technologies, Australia, 2005a.

[4] S. Kaewunruen and A. Remennikov: Typical dynamic, impact loading on railway tracks, *June-September Research Report*, CRC Railway Engineering and Technologies, Australia, 2005b.

[5] Standards Australia: Railway track material - Part 14: Prestressed concrete sleepers, *Australian Standard: AS1085.14-2003*, 2003a.

[6] Standards Australia: Railway track material - Part 19: Resilient fastening assemblies, *Australian Standard: AS1085.19-2003*, 2003b.

[7] R.F. Warner, B.V. Rangan, A.S. Hall, and K.A. Faulkes: *Concrete Structures*, Addison Wesley Longman, Melbourne, Australia, 1998.

[8] M. Murray and Z. Cai: Prestressed concrete sleeper: Literature review, *Report ARA Project Ref: 15250*, Australasian Railway Association Inc, 1998.

[9] A. Remennikov: *Discussion paper: Experimental and numerical studies for predicting dynamic responses of prestressed concrete sleepers to impact loading*, September, CRC Railway Engineering and Technologies, Australia, 2004.

[10] H. Wakui, and H. Okuda: A study on limit-state design method for prestressed concrete sleepers, *Concrete Library of JSCE*, 1999, no. 33, pp. 1-25.

[11] E.C. Bentz: Reinforced concrete sectional analysis using the modified compression theory, *Ph.D. Thesis*, Department of Civil Engineering, University of Toronto, Canada, 2000.