



Development of a new load-deflection method for characterization of North American heavy haul concrete sleepers

J.C. Bastos, A. Álvarez-Reyes, M.S. Dersch, & J.R. Edwards
University of Illinois at Urbana-Champaign, Urbana, USA

ABSTRACT: Over the past few decades, the use of concrete sleepers in North America has increased as a high-performance alternative to timber sleepers, especially in heavy-haul freight corridors. In order to accommodate heavier axle-loads and prevent center cracking, railroads and suppliers have consistently increased the center bending moment threshold that a sleeper must withstand, leading to stiffer elements that may be more prone to brittle cracking. In order to develop an alternate performance assessment method and ultimately improve the design practice for concrete sleepers, laboratory experiments were executed at the University of Illinois at Urbana-Champaign (UIUC). Using a loading frame, concrete sleepers were subjected to a four-point bending test, while recording the deflection at the center of the sleeper, using a protocol that was adapted from the Manual of Railway Engineering of the American Railway Engineering and Maintenance-of-Way Association (AREMA). Experimentation was performed on some of the most representative concrete sleeper designs that are currently installed in North American heavy-haul freight corridors. The resulting load versus deflection curves illustrate the variability of each of the sleeper's response to load and characterize the stiffness of the sleepers. These results will be used as the basis to develop standardized laboratory tests aimed at optimizing future sleeper designs, to prevent failures due to excessive stiffness or brittleness.

1 INTRODUCTION

The most prevalent evaluative tests for prestressed concrete sleepers in the North American railway industry are defined within the recommended practices of the AREMA Manual for Railway Engineering (American Railway Engineering and Maintenance-of-Way Association 2015). Among these, the center negative bending moment test is of particular importance, as it aims to assess a sleeper's flexural strength at one of the four key locations where design bending moments are considered by the referred manual (Wolf et al. 2015). Moreover, it has been reported that center negative sleeper bending is among the top five most critical track structure conditions with respect to the occurrence of accidents on concrete sleeper tracks in the US (Bastos et al. 2015).

Nevertheless, despite its conceptual importance, the current AREMA center negative bending moment test falls short of its potential benefits. The single test output is whether or not there are cracks originating in the tensile face of the sleeper that extend to the "outermost level of reinforcement or prestressing tendons" at the load required to produce the specified negative center design moment (American Railway Engineering and Maintenance-of-Way Association 2015). Consequently, the sleeper is not loaded to an

ultimate flexural failure, characterized by either rupture of prestressing material or crushing of concrete, and the concept of design failure is reduced to the simple presence of hairline cracks that go through the concrete cover.

In general, the current "pass/ fail" approach of AREMA recommended tests for the evaluation of concrete sleeper designs has implicitly led the industry to not explore all information that could be otherwise assessed from these tests. Another example is the AREMA rail seat repeated-load test procedure, which ultimately does load a crosstie rail seat to failure, however, the only output is whether or not there was tendon slippage of more than 0.025 mm (0.001 inch), without quantifying and documenting the amount of slippage or determining the load versus displacement behavior of the crosstie.

In this paper, a new center negative bending moment test is proposed, which is a modified version of the AREMA recommended practices center negative bending test protocol (Chapter 30, Article 4.9.1.6). The sleepers are supported by half-moon steel bars (as opposed to rubber pads) and are loaded to ultimate failure (as opposed to a pre-determined load which only helps to identify the presence, or lack thereof, of a crack). The test output is the entire load-displacement curve, and the main points of interest are the

sleeper displacements in the linearly elastic load range as well as the displacement and load at failure, as defined as the peak load achieved during testing.

This new approach, if adopted by the North American railway industry, can provide more details about each sleeper's flexural design characteristics and the possibility of better comparing various designs. Generally, freight railroads are interested in high-toughness sleepers that limit brittleness and are ductile enough to conform itself with the track support conditions without failing due to excessive deformation. Additionally, manufactures can benefit from this methodology, as it could be used to demonstrate that current sleepers tend to have previously unquantified reserved capacity, which could lead to more economical designs with less material. This was recently indicated by Wolf (2015), who measured reserved capacity ranging from 25 to 75% of in-track sleepers with respect to their cracking bending moment.

2 EXPERIMENTATION PLAN

Laboratory experiments were performed by the Rail Transportation and Engineering Center (RailTEC) at the Research and Innovation Laboratory (RAIL) at the Harry Schnabel, Jr. Geotechnical Laboratory in Champaign, Illinois, to assess the stiffness, the displacement at ultimate capacity, and the ultimate load of concrete sleepers when subjected to a four-point bending test configuration. Individual concrete sleepers were placed upside down in a loading frame where both rail seats were simply supported by half-moon steel bars apart 1524 mm (60 inches). A vertical load was applied at the sleeper bottom at two locations 152.4 mm (6 inches) apart from each other and symmetrically positioned about the sleeper center line (Fig. 1). In addition to being similar to the AREMA test configuration, the use of four-point bending is appropriate for assessing the sleeper flexural capacity because it applies a constant bending moment between the contact points of the loading head while eliminating the shear forces in the same region.

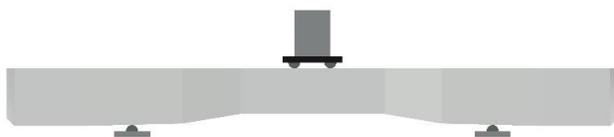


Figure 1. Four-point test configuration (sleeper is upside down)

To measure the sleeper center displacement, potentiometric linear transducers and one linear variable-differential transformer were employed. All devices were calibrated, and the loading frame displacements were monitored to ensure that boundary condition movements (if any) were taken in consideration for accurate computation of the sleeper deflection results. The load was applied with an MTS actuator at a constant rate of 22.24 kN/min (5 kips/min), and the data was collected using National

Instruments equipment. A photo of the experimental layout is shown in Figure 2.

To ensure full contact between the loading head and the specimen during the ultimate test, the sleeper was first subjected to three cycles of seating load ranging from 2.22 to 66.7 kN (0.5 to 15 kips). Additionally, this seating-procedure reduced small surface irregularities that would chip off during the cycles; thus, producing a smoother displacement curve in the final test. After the seating load procedure was completed, the sleeper was loaded from 2.22 kN (0.5 kips) to failure.

Three prestressed concrete sleeper designs were tested, four of them representing the most prevalent designs installed on US heavy haul lines today (design numbers 1, 2, 3, and 5), and one being an emerging design that adopts a novel prestressing method (design number 4). Replicates were performed to account for experimental and manufacturing variability.

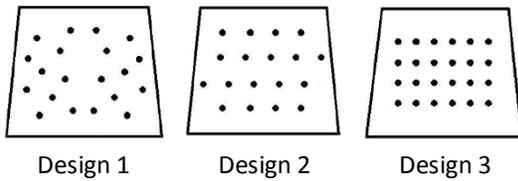


Figure 2. Experimental layout photography

The selected designs, although not identical, had similar dimensions and are subjected to similar loading (e.g. revenue North American heavy haul and/or higher speed passenger service). The average rail seat width was 254 mm (10 inches), while the average rail seat height was 218 mm (8.6 inches). At the center section, the average width and height were 241 mm (9.5 inches) and 178 mm (7.0 inches) respectively. All designs were 2591-millimeter (102-inch) long. Design number 1 presented 20 prestressing wires arranged in 10 rows. Design number 2 adopted 18 wires

arranged in two rows of four and two rows of five. Finally, design number 3 used 24 wires distributed over four rows (Fig. 3).

Figure 3. Schematic of prestressing tendons arrangement for tested sleeper designs



Once each sleeper was loaded to failure, the key characteristics considered to be of most interest were the ultimate load, the corresponding displacement (ultimate), and the displacement at 33.4 kN (7.5 kips). This last data point was within the linearly elastic region of the load versus displacement curve, and it was used for calculating the elastic region slope. Eight replicates were obtained for designs of number 1, 2 and 3. However, one of the specimens of design 1 was

not loaded to failure, and four replicates of design 2 did not have proper displacements recorded (Table 1).

Table 1. Number of replicates used to estimate the properties of each sleeper design

Sleeper Design	1	2	3
Total number of specimens	8	8	8
Ultimate load replicates	7	8	8
Ultimate displacement replicates	7	4	8
33.4-kN (7.5-kip) displacement replicates	8	4	8

3 RESULTS OF EXPERIMENTATION

Figure 4 displays the resulting load versus displacement curves of the ultimate loading tests, and each line represents one typical replicate of a particular sleeper design. This is a powerful output that allows for easy comparison between designs with regards to the center negative bending capacity. In addition, this figure is of great value to qualitatively understand the behavior of concrete sleepers currently manufactured and installed in the US.

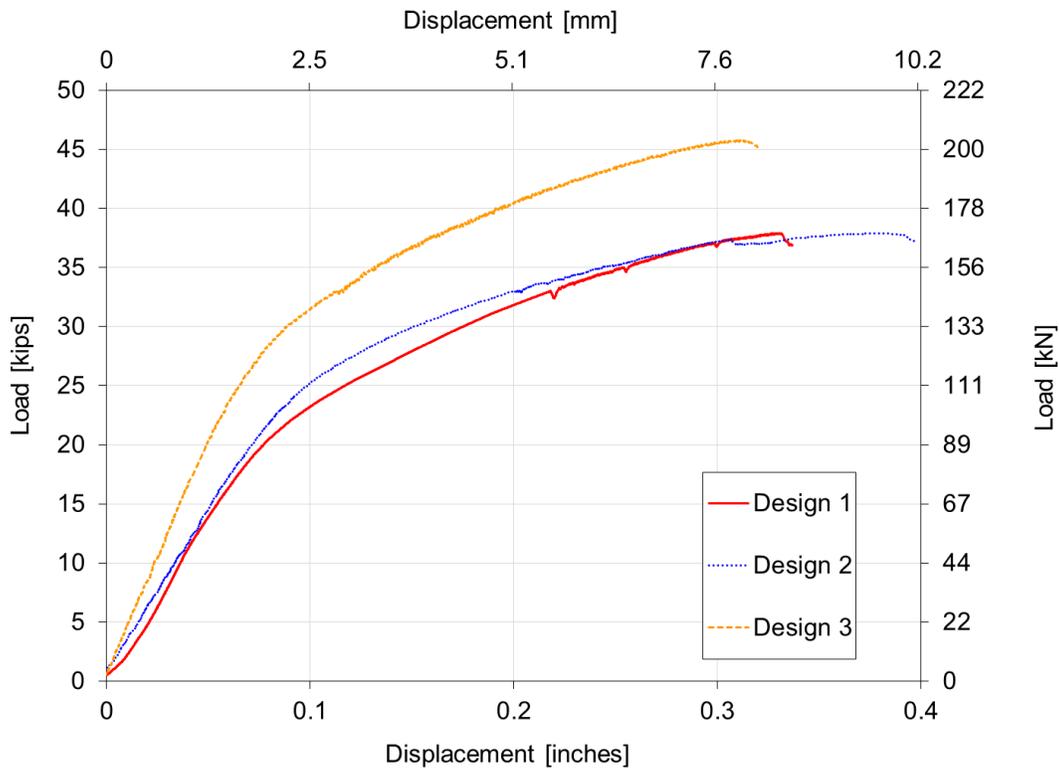


Figure 4. Load versus displacement results for typical tested replicates.

A summary of the experimental results is presented in Table 2. In this table, each design characteristic takes four rows: two for the mean result in different unit systems, and two for the 90% confidence margin also with different unit systems. For example, the mean ultimate load for sleeper design 1 is 170.1 kN (38.2 kips), with 90% confidence that the error is not

greater than plus or minus 5.3 kN (1.2 kips). It can be seen that sleeper design number 3 had the highest load capacity, while design number 2 presented the highest displacements at failure. In addition, the highest linear elastic displacements were associated with design number 1.

Table 2. Experimental results and 90% confidence margin

		Sleeper Design		
		1	2	3
Ultimate load	kip	38.2	36.7	45.9
	(kN)	(170.1)	(163.4)	(204.0)
$D_{0.90}$	kip	1.2	1.1	1.1
	(kN)	(5.3)	(4.9)	(4.9)
Ultimate Displacement	in	0.320	0.337	0.330
	(mm)	(8.1)	(8.6)	(8.4)
$D_{0.90}$	in	0.023	0.031	0.022
	(mm)	(0.6)	(0.8)	(0.6)
33.4-kN (7.5-kip) Displacement	in	0.0266	0.0225	0.0199
	(mm)	(0.68)	(0.57)	(0.50)
$D_{0.90}$	in	0.0017	0.0024	0.0017
	(mm)	(0.04)	(0.06)	(0.04)
7.5-kip Slope	kip/in	266.5	312.7	360.6
	(kN/mm)	(46.7)	(54.8)	(63.2)
$D_{0.90}$	kip/in	25.2	35.6	25.2
	(kN/mm)	(4.4)	(6.2)	(4.4)

The confidence interval of Table 2 was estimated using Equation 1, which is derived from the Central Limit Theorem (Ott & Longnecker 2008).

$$D_{(1-\alpha)} \approx \frac{z_{\alpha/2} \times s}{\sqrt{n}} \quad (1)$$

where,

- n: Number of observations (replicates).
- $z_{\alpha/2}$: z-value from standard normal distribution.
- α : Significance level (0.1 adopted).
- s: Sample standard deviation (square root of mean square error used).
- $D_{(1-\alpha)}$: Detectable deviation of sample mean relative to the population mean.

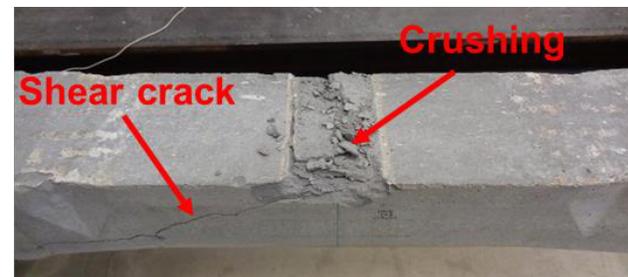
Based on the results presented in Table 2, the sleeper designs with highest displacements and load capacity were identified. However, it is necessary to evaluate which characteristics are actually desirable.

While it is generally accepted that high load capacity is a positive characteristic, it is not always clear when high displacements are wanted. Surely, extreme displacements can be unsafe for train operations, but zero displacement can also result in excessively stiff systems that are subjected to higher impact loads and premature cracking in brittle components. Considering that wood sleepers have a three to five times lower modulus of elasticity than concrete sleepers (American Railway Engineering and Maintenance-of-Way Association 2015), the displacements in Table 1 could likely be increased without posing additional risk for railroad operation (even considering the shorter sleeper spacing in wood sleeper track). Previous research has shown that bending of one concrete sleeper tested out of track leads to small gauge widening effect (approximately 3 mm (0.12 inch) for a

typical freight sleeper design in the US) (Bastos 2016). When installed in track, the gauge widening effect due to sleeper bending should be even smaller due to the contribution of adjacent sleepers and the rail itself, which is an indication that more ductile sleepers would have negligible effect on railroad safety. In fact, researchers at the University of South Carolina, US, have developed a reduced-modulus concrete specifically for concrete sleeper applications to “alleviate premature cracking due to high stress concentrations” (Rizos 2016). Therefore, having greater deflections is a positive attribute in this context, so long as the minimum bending capacity requirements are met.

It is significant to highlight that most tested specimens failed in compression at the center, with concrete crushing in the outmost fibers. Subsequently, except in a few cases, shear failure also happened. With the flexural failure happening first, it can be inferred that the experimental protocol succeeded in assessing the flexural strength of the sleepers. However, in some cases it was difficult to determine which failure mode happened first (i.e. shear or flexural failure), as they seem to happen simultaneously. In these cases, the ultimate load could indicate either the flexural or the shear capacity of the specimen depending on which was the primary failure mode. Nevertheless, the authors were comfortable to assume that the ultimate load represented reaching the bending capacity of the specimen, as crushing of concrete still happened, even if only as a secondary failure mode. Figure 4 shows a failed specimen to illustrate the presence of both crushing of concrete and cracking due to shear.

Figure 5. Failed sleeper with crushed concrete in outmost fibers and shear crack



4 CONCLUSIONS

The work presented in this paper focused on proposing a new testing methodology for assessing the center negative bending capacity of prestressed concrete sleeper designs. A four-point loading procedure with half-moon steel bars was adopted, modifying the current protocol recommended by AREMA. The test was performed on representative sleeper designs in North America and it proved to be effective in assessing the flexural strength of the sleepers. A full load versus displacement curve is produced as the test output,



with the major variables being the ultimate load and displacement, as well as the displacement at 33.4 kN (7.5 kips), which is an indication of stiffness. The major benefits of the proposed test protocol in relation to the AREMA standard test are listed below:

- Provides opportunity to compare various designs;
- Provides quantifiable results (not simply a pass/ fail test);
- Associates underlying concept of failure to ultimate condition (as opposed to presence of cracks).

Furthermore, as the design of concrete sleepers tends to shift from allowable stress to a limit state approach (Murray 2015), more comprehensive design validation tests are necessary. Therefore, the newly proposed test protocol has potential benefits for both current and future concrete sleeper design methods.

Lastly, the presented experimental results can be useful for understanding the center bending behavior of the typical North American concrete sleeper designs in freight application. Such results can be a comparison baseline for future tests.

5 ACKNOWLEDGEMENTS

This research effort is funded by the Federal Railroad Administration (FRA), part of the United States Department of Transportation (US DOT). The material in this paper represents the position of the authors and not necessarily that of FRA. The authors also would like to acknowledge the following industry partners: Union Pacific Railroad; BNSF Railway; National Railway Passenger Corporation (Amtrak); PRS; GIC; Hanson Professional Services, Inc.; CXT Concrete Ties, Inc.; and LB Foster Company. Finally, the authors would like to thank undergraduate research as-

sistant Robert Wolf for assisting with the work presented in this paper. J. Riley Edwards has been supported in part by the grants to the UIUC Rail Transportation and Engineering Center (RailTEC) from CN, Hanson Professional Services, and the George Krambles Transportation Scholarship Fund. Alejandro Álvarez-Reyes has been partially supported by the National Council of Science and Technology of Mexico (CONACYT)

6 REFERENCES

- American Railway Engineering and Maintenance-of-Way Association. 2015. Chapter 30 – Ties. *AREMA Manual for Railway Engineering*, AREMA, Landover, Maryland.
- Bastos, J.C., Dersch, M. & Edwards, J.R. 2015. Determination of Critical Track Conditions and Their Impact on the Performance of Concrete Crossties and Fastening Systems. In: *Proceedings of the AREMA 2015 Annual Conference*, AREMA, Minneapolis, Minnesota, USA, 2015.
- Bastos, J.C. 2016. *Analysis of the Performance and Failure of Railroad Concrete Crossties with Various Track Support Conditions*. M.S. Thesis. University of Illinois at Urbana-Champaign, Urbana, IL, USA.
- Murray, M. 2015. Heavy Haul Sleeper Design – A Rational Cost-saving Method. In: *IHHA 2015 Conference*, Perth, Australia, June 2015.
- Ott, R. & Longnecker, M. 2008. *An Introduction to Statistical Methods and Data Analysis*. Cengage Learning.
- Rizos, D.C. 2016. High-Strength Reduced-Modulus High Performance Concrete (HSRM-HPC) for Prestressed Concrete Tie Applications. V001T01A027.
- Wolf, H.E. 2015. *Flexural Behavior of Prestressed Concrete Monoblock Crossties*. M.S. Thesis. University of Illinois at Urbana-Champaign, Urbana, IL, USA.
- Wolf, H.E., Edwards, J.R., Dersch, M.S. & Barkan, C.P. 2015. Flexural Analysis of Prestressed Concrete Monoblock Sleepers for Heavy-haul Applications: Methodologies and Sensitivity to Support Conditions. In: *International Heavy Haul Association Conference*, International Heavy Haul Association, Perth, Australia, June 2015, pp. 393–402.