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Laboratory Characterization of Structural Capacity of North American Heavy Haul Concrete Crossties

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Abstract

Over the past few decades, the use of concrete crossties in North America has increased as a high-performance alternative to timber crossties, especially in heavy-haul freight and higher speed rail corridors. To accommodate heavier axle-loads and prevent center cracking, railroads and suppliers have consistently increased the bending moment thresholds that a crosstie must withstand, leading to stiffer elements that may be more prone to brittle cracking. This paper attempts to characterize the structural capacity of the crosstie at two critical design locations, the center and the rail seat cross sections. Concrete crossties were subjected to four-point bending tests at both the center and rail seat, while recording corresponding deflections using protocols adapted from the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual on Railway Engineering. Experimentation was performed on some of the most representative concrete crosstie designs that are currently installed in North America, with 70 individual crossties undergoing tests. The resulting load-deflection curves illustrate the variability of each crosstie's response to load and characterize the flexural performance of the crossties. Results showed that North American crosstie designs frequently have significant reserve capacity and high stiffness. The results also indicate that even severely abraded crossties can have enough flexural capacity to withstand typical field loading conditions.

Crossties are an essential component of ballasted railroad track, and the use of engineered concrete crossties has been increasing in North America on demanding heavy axle load (HAL) freight corridors, often considered as a longer-lasting, lower-maintenance alternative to wood crossties (*1–4*). Such crossties are concrete members that are commonly expected to withstand over 40 years of service (*5*), frequently subjected to severe conditions imposed by heavy axle loads, weather exposure, proximity to ground moisture, cyclic loading, and variable support conditions at the ballast interface. To fulfill these expectations, manufacturers have used high-strength concrete to manufacture monoblock crossties that are highly prestressed with large cross sections, as will be shown in this paper. However, these crossties are commonly overdesigned, having considerable reserve flexural capacity beyond the loading environment requirements as quantified in the field under typical HAL freight service loads (*6, 7*).

As new concrete crosstie designs are introduced in the North American railway industry, it is beneficial to quantify their flexural capacity and additional properties that can contribute to better-informed decisions for future designs and specifications. Current crossties tend to have previously unquantified reserve capacities. This was indicated by Wolf (*6*), who quantified in-track crossties' reserve capacity to range from 25% to 75% with respect to their cracking bending moment and similar findings were noted by Edwards et al. (*7*). Furthermore, more comprehensive tests will be necessary if the design of concrete crossties in North America follows the international trend of shifting from allowable stress to a limit state design approach (*8*). The work presented in this paper contributes to the characterization of the structural capacity of North American heavy haul concrete crossties. New specimens representative of common North American concrete crosstie designs were tested in flexure to obtain the stiffness, ultimate load capacity, and ultimate displacement of these crossties. This was done at the center and rail seat sections, the most common locations for structural analysis of concrete crossties (*6*, *9*). Additionally, aged and abraded specimens were also tested for evaluation of the effect of mild and severe wear on the investigated properties.

In the following sections, a new center negative bending moment test is proposed, which is a modified version of the American Railway Engineering and Maintenance-of-Way Association (AREMA) center negative bending test protocol (Chapter 30, Article 4.9.1.6) (*9*). The crossties are supported

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Figure 1. Severely bottom-abraded specimen (Design 7a).

by half-moon steel bars as opposed to rubber pads to accurately record displacements that are due to bending of the crossties (not from the compression of the rubber pads) and to better control the contact area and friction forces at the support interface with the crossties. In addition, the crossties are loaded to ultimate failure as opposed to a pre-determined load which identifies the presence, or lack-thereof, of a crack. Loading to ultimate failure allows for quantification of flexural reserve capacity and deformation ability before the ultimate state. The test output is the entire load-displacement curve, and the main points of interest are the crosstie displacements in the linearly elastic load range as well as the load and displacement at failure, defined as the peak load and the associated displacement achieved during testing. Similarly, a rail seat positive bending test is developed based on the equivalent AREMA recommended test protocol (Chapter 30, Article 4.9.1.8), with the load-displacement curve being the test output (*9*).

Typical Tests Background and Analysis

The most prevalent evaluative tests for prestressed concrete crossties in the North American railway industry are defined within the recommended practices of the AREMA Manual for Railway Engineering (*9*). Among these, the center negative bending moment test is of particular importance, as it aims to assess a crosstie's flexural strength at one of the two key locations where design bending moments are considered by AREMA. Moreover, it has been reported that center negative crosstie bending is among the five most critical track structure conditions with respect to the occurrence of accidents on concrete crosstie tracks in the U.S. (*10*).

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 crosstie that extend to the "outermost level of reinforcement or prestressing tendons" at the load required to produce the specified negative center design moment (*9*). Consequently, the crosstie is not loaded to an ultimate flexural failure, characterized by either rupture of prestressing material or crushing of concrete, reducing the concept of design failure to the simple presence of hairline cracks that go through the concrete cover on the tensile surface.

Another example of a standard test that could be improved to provide more information is the AREMA rail seat repeated-load test (Chapter 30, Article 4.9.1.5). This test protocol only addresses whether or not there was tendon slippage of more than 0.025 mm (0.001 inch), even though it eventually does load a crosstie rail seat to ultimate failure (*9*). An improvement to the protocol would require documentation of the amount of slippage and generation of the load-displacement curve for the crosstie. In general, the current "pass/fail" approach of AREMA recommended tests for the evaluation of concrete crosstie designs may be leading the industry to limit its ability to explore all the information that could be ascertained from these tests, inhibiting the development of new, more optimized, crosstie designs.

Experimentation Plan

Laboratory experiments assessed the stiffness, ultimate load, and ultimate displacement of concrete crossties subjected to a four-point bending test configuration both for center negative and rail seat positive bending moments. Eight crosstie designs (hereafter referred to as Designs 1 through 8) were subjected to center negative bending moment tests, and four were also subjected to rail seat positive bending moment tests (Designs 1, 2, 3, and 8). Designs 1, 2, 3, and 5 represent some of the most prevalent designs installed on U.S. HAL freight railroads or higher speed passenger lines including UP, BNSF, Amtrak, and CSX. Designs 4 and 6 are emerging designs that adopt differentiated characteristics, the former being pre-tensioned and the latter, post-tensioned. Design 7 represents a crosstie that is no longer manufactured, but is still present on many railroad lines. While the remaining designs were new and unused, all replicates of Design 7 had been removed from service for showing signs of deterioration, typically worn fastening system shoulders. One particular crosstie, however, presented severe bottom abrasion and was very dissimilar to the other Design 7 specimens, leading to the creation of its own category that will be referred to as Design 7a (Figure 1). Finally, Design 8 represents an additional crosstie that is no longer produced, and its specimens were removed from service for the specific purpose of being tested in this study.

The selected designs, although not identical, have similar dimensions, being expected to withstand similar loading conditions (i.e., revenue North American HAL freight and/or higher speed passenger service). The typical rail seat width at mid-height was 244 mm (9.6 in.), while the typical rail seat height was 226 mm (8.9 in.). At the center section, the typical mid-height width and height were 246 mm (9.7 in.) and

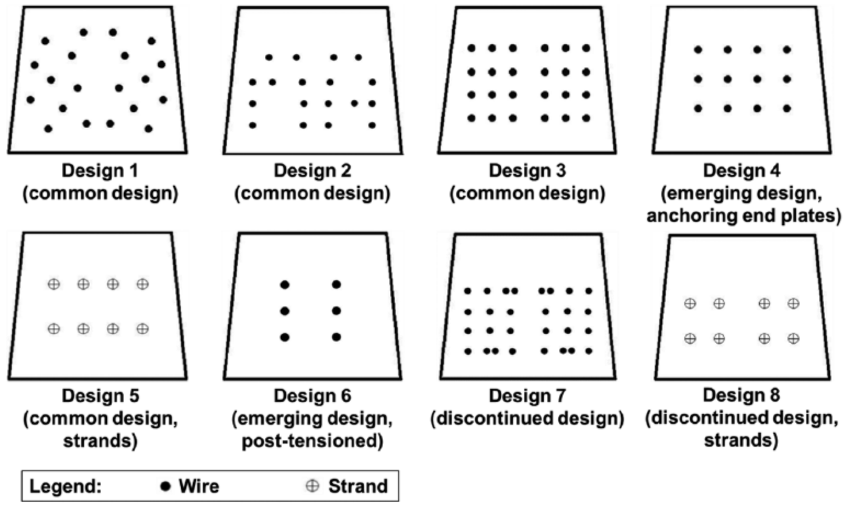

Figure 2. Schematic of prestressing arrangement for tested crosstie designs.

Table 1. Characteristics of Tested Crosstie Designs

		Crosstie design							
		1	2	3	4	5	6	7	8
Concrete compressive strength (lower bound)	ksi	8.2	7.3	7.1	7.7	12.4	–	9.1	9.7
	(MPa)	(56.8)	(50.2)	(49.3)	(52.9)	(85.5)	–	(62.6)	(66.9)
Ratio of steel in cross sectional area	Center	0.011	0.009	0.011	0.009	0.086	–	0.014	0.083
	Rail seat	0.008	0.007	0.009	0.007	0.075	–	0.011	0.061

180 mm (7.1 in.), respectively. Although most crossties were 2,591 mm long (102 in.), the crossties of Design 4 were 2,438 mm long (96 in.) and those of Design 7 were 2,515 mm long (99 in.). In the case of prestressing tendons, the only crossties that had strands were those of Designs 5 and 8, while all the others had wires. Figure 2 shows a schematic of the number and arrangement of prestressing elements for all designs. The ratio of reinforcement area per cross-sectional area is provided in Table 1.

In addition, concrete cylinders were cored from one replicate of each design to estimate the concrete strength of the tested specimens. All cores were drilled in a direction parallel to the casting direction (vertical) with a diameter of 92 mm (3.625 in.) and height of 184 mm (7.25 in.). The resulting height–diameter ratio of 2 is recommended by the ASTM C42/C42M-16 standard (*11*), which also allows for testing cores with embedded metals when impracticable to avoid. To minimize the effect of the presstressing force on the compressive strength of the concrete cylinders, all cores were drilled within the region where the prestressing force had not fully developed in the concrete. The drilling direction and diameter were based on conclusions of related research, but, since steel wires were present in these cylinders, the resulting concrete strengths are expected to be a lower bound of the strength when there was no steel reinforcement (*12–16*). The resulting concrete strength is reported in Table 1.

Replicates were performed to account for experimental and manufacturing variability, and a total of 70 crossties were tested, 54 of these in center negative and 16 in rail seat positive bending. Table 2 shows the number of replicates used for each application. The numbers in the "Total" column vary for several experimental reasons, and tests that deviated from the protocol were removed to ensure accurate results.

Center Negative Bending Moment Test

Individual concrete crossties were placed upside down in a loading frame where both rail seats were simply supported by half-moon steel bars spaced 1,524 mm (60 in.) apart (Figure 3). A vertical load was applied at the crosstie bottom at two locations 152.4 mm (6 in.) apart and symmetrically positioned about the crosstie center line. In addition to being similar to the AREMA center negative bending moment test configuration (Chapter 30, Article 4.9.1.6), the use of four-point bending is appropriate for assessing the crosstie flexural capacity because it applies a constant bending moment between the contact points of the loading head and eliminates shear forces in the same region.

Table 2. Replicates Used to Estimate Properties of Each Crosstie Design

Crosstie design		1	2	3	4	5	6	7	7a	8	Total
Center	Total number of specimens	9	8	9	1	7	7	6	1	6	54
	Ultimate load replicates	8	8	9	1	7	7	6	1	5	52
	Ultimate displacement replicates	8	4	9	1	7	7	6	1	4	47
	Stiffness replicates	9	4	9	1	7	7	6	1	6	50
Rail seat	Total number of specimens	4	4	5	–	–	–	–	–	3	16
	Ultimate load replicates	4	4	5	–	–	–	–	–	3	16
	Stiffness replicates	3	3	4	–	–	–	–	–	3	13

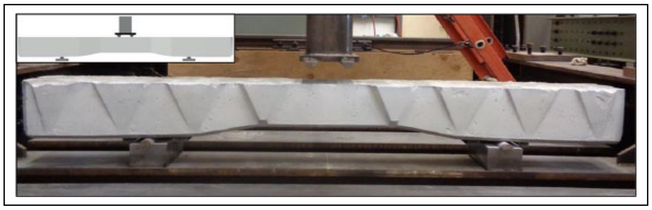

Figure 3. Four-point bending configuration for center section testing (crosstie is upside down when loaded).

To measure the crosstie 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 considered for accurate computation of the crosstie deflection results. The load was applied at a constant rate of 22.24 kN/min (5 kips/min). Crossties that did not present a smooth bottom surface due to irregularities or indentation required application of white gypsum cement to provide a flat contact surface. Additionally, every crosstie was first subjected to three cycles of seating load ranging from 2.22 to 66.7 kN (0.5 to 15 kips) to ensure full contact between the loading head and the specimen during the ultimate test. This seating-procedure also 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 crosstie was loaded continuously from 2.22 kN (0.5 kips) to failure.

Once each crosstie was loaded to failure, the key characteristics considered to be of most interest were the ultimate load, ultimate displacement, and 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 elastic region slope in units of force per displacement, a metric that will be referred to as "stiffness" for the remainder of this paper.

Rail Seat Positive Bending Moment Test

Four crosstie designs were also subjected to a rail seat positive bending moment test in a four-point bending configuration (Figure 4). Two half-moon steel bars were placed underneath the crosstie, each of them located 356 mm (14 in.) away from the rail seat vertical center line. On top of the rail seat, two additional half-moon steel bars were positioned 57 mm (2.25 in.) away from the rail seat vertical center line to apply the load. This configuration is similar to the recommended practices within the AREMA Manual on Railway Engineering (Chapter 30, Article 4.9.1.8), with the difference that steel bars were used in place of the prescribed rubber pads.

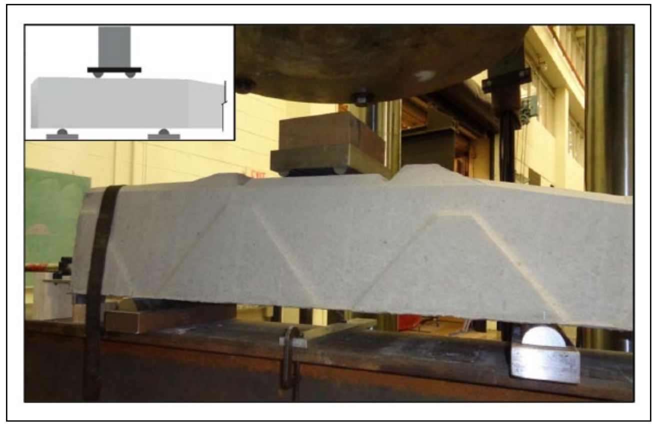

Figure 4. Four-point bending configuration for rail seat section testing.

Unlike the center negative bending test protocol, no seating load procedure was performed for most of the rail seat tests. Consequently, the rail seat load-displacement curves were not as smooth as the crosstie center ones due to the contact adjustment between loading head and crosstie. For this reason, the resulting displacements at ultimate condition are not analyzed in this paper. Nevertheless, it was possible to estimate the linear region stiffness as the mentioned contact adjustment was typically finalized within the elastic portion of the load-displacement curve. For rail seat tests, the stiffness values presented in this paper are the linear slope between the points at 267 kN (60 kips) and 356 kN (80 kips).

Results of Experimentation

Figure 5 displays the resulting load versus displacement curves of the center negative bending moment tests. Every line

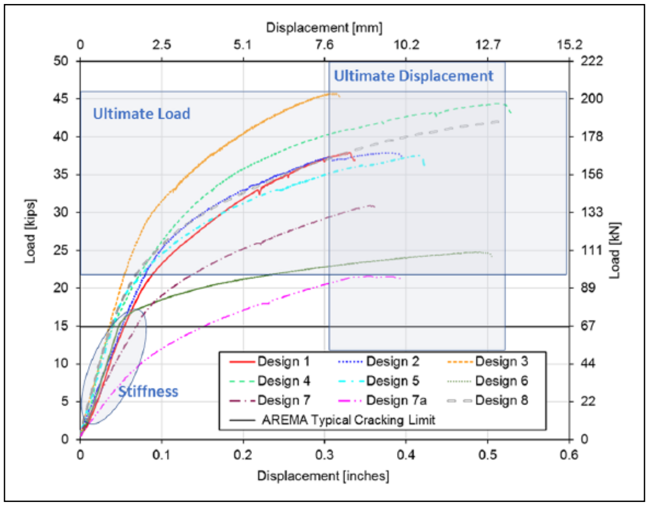

Figure 5. Load-displacement results for center negative bending tests—typical replicates.

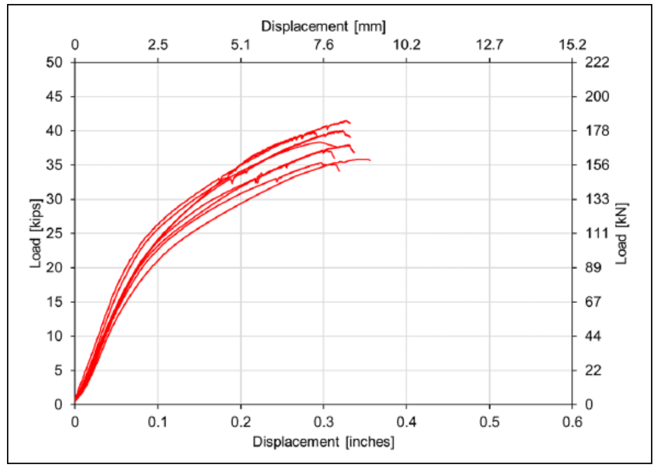

Figure 6. Load-displacement results for center negative bending tests—Design 1 replicates.

represents one typical replicate (i.e., closest to the average properties) of each crosstie design, allowing for a direct qualitative comparison between them. In this figure, three regions are highlighted corresponding to the previously mentioned variables of interest: ultimate load, ultimate displacement, and stiffness. The ultimate load is directly related to the crosstie's ultimate flexural capacity, indicating the crosstie's strength before there is crushing of the concrete in compression or failure of the prestressing steel in tension. The ultimate displacement indicates the capacity of the crosstie to deform and adjust itself to the ballast support conditions before a catastrophic failure takes place. Lastly, the stiffness is also a metric of the crosstie's displacement behavior, but it accounts primarily for elastic deflections in service (as opposed to the ultimate state deflection, which should not be reached under normal service conditions). In addition, a typical AREMA cracking limit (*6*) is presented for reference. The difference between the ultimate load and the AREMA cracking limit can be interpreted as the reserve flexural capacity of the crosstie.

In Figure 5, it is noticeable that all the properties vary significantly among the different designs. The stiffness, however, seem to have the least variability, which is an expected outcome given the similar geometries of the designs tested. It was observed in the experiments that cracking (i.e., cracking reaching the first layer of prestressing steel) occurs roughly at the end of the linear region, thus beyond the plotted AREMA limit for all designs. In addition, the unbonded post-tensioned crosstie design (Design 6) presents a dissimilar post-linear behavior than the other designs, showing the highest displacement rate after cracking. As expected, the severely abraded specimen (Design 7a) shows clear signs of deterioration, but it still presents approximately 70% of the load capacity and 60% of the stiffness of the healthier specimens of the same design (Design 7). This seems to indicate that bottom abrasion may not be a hazardous defective condition for designs with multiple rows of prestressing steel, even though this type of degradation has been reported to generate unsafe scenarios for designs with only two rows of prestressing steel (*17*).

As previously mentioned, replicate tests were conducted for most crosstie designs. Figure 6 illustrates this by showing test results for Design 1. It is evident that there is variability among replicates and a statistical treatment of the results is necessary. Therefore, a confidence interval for the means was estimated using Equation 1, which is derived from the Central Limit Theorem (*18*). In this process, the sample standard error was estimated from the mean square error of a completely randomized design in which crosstie model (design) was the single statistical effect considered.

$$D_{(1-\alpha)} = \frac{t_{\alpha/2,\,n-1} \times s}{\sqrt{n}} \quad (1)$$

where,

n: Number of observations (replicates).

$t_{\alpha/2,n-1}$: two-tailed t-value from t distribution for significance level α and n–1 degrees of freedom.

α: Significance level (0.1 adopted).

s: Sample standard error (square root of mean square error used).

$D_{(1-\alpha)}$: Detectable deviation of sample mean relative to the population mean.

A summary of the experimental results is presented in Table 3, where 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 crosstie Design 1 is 170.2 kN (38.3 kips), with 90% confidence that the error in

Table 3. Experimental Results and 90% Confidence Margin for Center Tests

		Crosstie design								
		1	2	3	4	5	6	7	7a	8
Ultimate load	kip	38.3	36.7	46.9	44.4	38.9	24.8	30.4	21.6	43.3
	(kN)	(170.2)	(163.4)	(208.6)	(197.4)	(173.0)	(110.3)	(135.3)	(96.1)	(192.5)
$D_{0.90}$	kip	1.5	1.5	1.4	–	1.6	1.6	1.8	–	1.8
	(kN)	(6.6)	(6.6)	(6.1)	–	(7.3)	(7.3)	(8.2)	–	(8.2)
Ultimate displacement	in	0.317	0.337	0.324	0.512	0.418	0.456	0.348	0.356	0.486
	(mm)	(8.1)	(8.6)	(8.2)	(13.0)	(10.6)	(11.6)	(8.8)	(9.0)	(12.3)
$D_{0.90}$	in	0.031	0.054	0.028	–	0.034	0.034	0.038	–	0.038
	(mm)	(0.8)	(1.4)	(0.7)	–	(0.9)	(0.9)	(1.0)	–	(1.0)
Stiffness	kip/in	269.7	312.7	358.5	372.1	387.1	415.3	234.3	138.4	334.6
	(kN/mm)	(47.2)	(54.8)	(62.8)	(65.2)	(67.8)	(72.7)	(41.0)	(24.2)	(58.6)
$D_{0.90}$	kip/in	36.8	69.9	36.8	–	43.6	43.6	48.863	–	48.863
	(kN/mm)	(6.4)	(12.2)	(6.4)	–	(7.6)	(7.6)	(8.6)	–	(8.6)

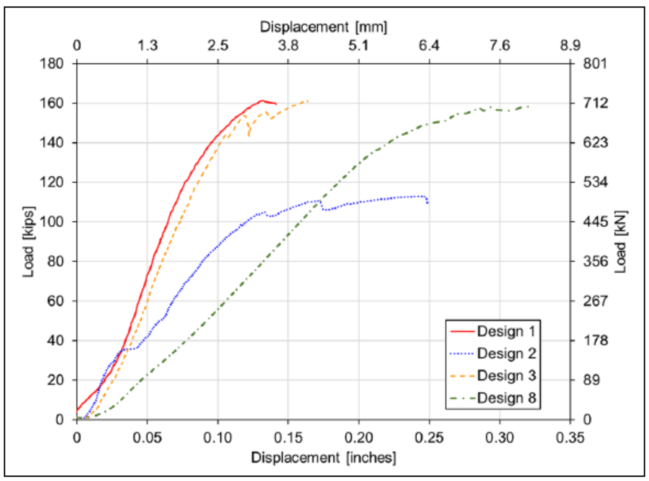

Figure 7. Load-displacement results for rail seat positive bending tests – typical replicates.

estimating the mean is not greater than plus or minus 6.6 kN (1.5 kips). Design 3 had the highest load capacity, while Design 4 presented the highest displacements at failure. In addition, the highest linear elastic displacements were associated with Design 1 (least stiff).

Based on the results presented in Table 3, the crosstie designs with highest displacements and load capacity were identified. Nevertheless, it is necessary to evaluate which characteristics are desirable. While it is generally accepted that high load capacity is a preferable characteristic, the desired level of displacement is not always clear for a system. While extreme displacements can be unsafe for train operations, zero displacement will result in excessively stiff systems that are subjected to higher impact loads and premature cracking in brittle components (*19*, *20*), perhaps even accelerating ballast deterioration. Considering that wood crossties have a modulus of elasticity that is three to five times lower than concrete crossties (*9*), the displacements in Table 3 could likely be increased without posing additional risk for railroad operation (even considering the shorter crosstie spacing in wood crosstie track). Previous research has shown that the bending of one concrete crosstie tested out of track leads to a small gauge-widening effect (approximately 3 mm (0.12 inch) for a typical freight crosstie design in the US) (*21*). When installed in track, the gauge widening effect due to crosstie bending should be even smaller given the contribution of adjacent crossties and the rail itself, which is an indication that crossties that are more ductile would have a negligible effect on railroad safety. In this regard, at least one such reduced-modulus concrete is being developed to "alleviate premature cracking due to high stress concentrations" (*22*). Therefore, while more research is needed to prescribe ideal stiffness values, having greater deflections seems to be a positive attribute in this context, so long as the minimum bending capacity requirements are met.

The load-displacement curves of the rail seat positive bending tests are shown in Figure 7, where one typical replicate is displayed per design. The roughness in the graphs is mostly explained by the lack of a seating load procedure for rail seat tests, yielding inaccurate absolute displacement results, as mentioned earlier. However, the lack of accurate ultimate-state-displacement data should not pose a problem for optimization of future designs since allowing for the rail seat cross sections to go beyond the elastic region and crack should be avoided to prevent an undesirable progressive increase of track stresses and deflections (*23*). In addition, rail seat cracks resulting from positive bending moments originate at the bottom of the crosstie, making it impossible to visually inspect such cracks. This is not the case for the crosstie center, as center cracks originate from the crosstie top – thus being more visible – and pose a smaller risk than at the rail seat (*21*, *23*, *24*).

Table 4 summarizes the rail seat test results in a manner similar to that of Table 3. Designs 1, 2, and 3 are possibly the most prevalent designs of concrete crossties with typical pretensioning wires used in the U.S. and Design 8 is recognized

Table 4. Experimental Results and 90% Confidence Margin for Rail Seat Tests

		Crosstie design			
		1	2	3	8
Ultimate load	kip	155.1	114.4	159.4	153.0
	(kN)	(690.0)	(508.9)	(708.9)	(680.6)
$D_{0.90}$	kip	10.5	10.5	8.5	15.1
	(kN)	(46.8)	(46.8)	(37.9)	(67.1)
Stiffness	kip/in	1937.2	924.3	2306.6	765.6
	(kN/mm)	(339.2)	(161.9)	(403.9)	(134.1)
$D_{0.90}$	kip/in	346.4	346.4	241.8	346.4
	(kN/mm)	(60.7)	(60.7)	(42.3)	(60.7)

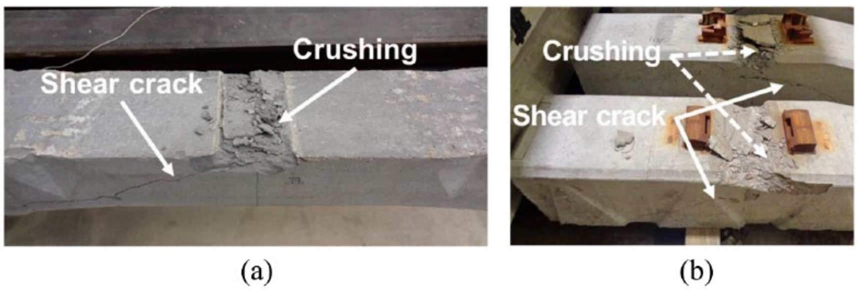

Figure 8. Failed crossties with crushed concrete and shear crack at (*a*) center and (*b*) rail seat.

as being a durable crosstie despite being discontinued. Given that each of these designs have proven performance records in heavy haul lines, it seems that Design 3 has the highest reserve capacity for both center and rail seat cross sections, while Design 2 seems to be a more economical alternative. Based on Tables 3 and 4, some of the most prevalent designs in the U.S. (Designs 1–3) have ultimate capacities within the ranges of 163.4 kN (36.7 kips) to 208.6 kN (46.9 kips) for the center negative bending moment test and 508.9 kN (114.4 kips) to 708.9 kN (159 kips) for the rail seat positive bending moment test. These values correspond to 55.9 kNm (495 kip-in) to 71.5 kNm (633 kip-in) center negative bending moments and 75.9 kNm (672 kip-in) to 105.8 kNm (936 kip-in) rail seat positive bending moments. It is worth noting that common in-service demands are lower than 22.7 kNm (201 kip-in) center negative bending moments and 33.9 kNm (300 kip-in) for rail seat positive bending moments, which are typical AREMA cracking limits (*25*).

It is important to highlight that most tested specimens failed in compression at the center and at the rail seat, with concrete crushing in the outmost fibers. Subsequently, with the exception of a few cases, shear failure also occurred. With the flexural failure happening first, it can be inferred that the experimental protocol succeeded in assessing the flexural strength of the crossties. In some cases, however, 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 the primary failure mode was. Nevertheless, the authors were comfortable in assuming 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 8 shows failed specimens to illustrate the presence of both crushing of concrete and cracking due to shear. The sudden crushing failure seems to be an indication that crossties are compression-controlled beams as defined by the ACI 318-14 code (*26*), which is generally undesirable because the low ductility (i.e., high stiffness) of these elements limits their ability to redistribute loads away from an overloaded section (*27*). This could be prevented by, for example, reducing the amount of tension reinforcement tendons to allow for less stiff beams.

Conclusions

This paper has proposed and implemented testing protocols adapted from AREMA recommendations for assessing the center negative and rail seat positive bending capacities by four-point loading with half-moon steel bars. Load-displacement curves are the test's output, with special attention given to the slope of the linear region to assess stiffness, the ultimate load to assess strength, and the ultimate displacement for the center section to assess the overall deformation capacity before failure. The primary benefits of the proposed test protocol with its revisions to the current AREMA recommended practices are listed below:

- provides opportunity to objectively compare various designs
- provides opportunity to objectively compare crossties of same design to assess deterioration or manufacturing variability
- provides quantifiable results (not simply a pass/fail test)
- associates underlying concept of failure to ultimate condition (as opposed to presence of cracks)
- provides a simple test protocol that can be easily implemented by the rail industry

This new testing approach can provide more details about each crosstie's flexural design characteristics and the possibility of better comparing various designs. Generally, HAL freight railroads are interested in high-toughness crossties that limit brittleness and are ductile enough to conform to the track support conditions without failing due to excessive deformation. Additionally, manufacturers can benefit from this methodology, as it could be used to demonstrate that current crossties tend to have previously unquantified reserve capacities, which could lead to more economical designs with less material. The test protocols proposed in this paper, therefore, have potential benefits for both current and future concrete crosstie design methods.

Structural properties of representative heavy haul concrete crosstie designs in North America were quantified for the rail seat and center sections by testing 70 individual crossties. Variability was observed among the flexural capacity of the designs tested, even if only considering the most prevalent wire-based pre-tensioned crossties. This indicates that some designs have greater reserve capacity while others are more economical. For these designs (Designs 1–3) the ultimate capacities were within the ranges:

- center negative bending moments: 55.9 kNm (495 kip-in) to 71.5 kNm (633 kip-in)
- rail seat positive bending moments: 75.9 kNm (672 kip-in) to 105.8 kNm (936 kip-in)

In addition, the failure mode observed in laboratory experimentation was of sudden crushing both at the center and at the rail seat. Finally, results on center bending of bottom-abraded crossties indicate that even severe abrasion throughout the entire cover may reduce the ultimate capacity of a crosstie to about 70% of its capacity with normal wear.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Josué C. Bastos, Alejandro Álvarez-Reyes, Marcus S. Dersch, and J. Riley Edwards; data collection: Josué C. Bastos and Alejandro Álvarez-Reyes; analysis and interpretation of results: Josué C. Bastos, Alejandro Álvarez-Reyes, Marcus S. Dersch, and J. Riley Edwards; draft manuscript preparation: Josué C. Bastos, Marcus S. Dersch, J. Riley Edwards, Alejandro Álvarez-Reyes, and Christopher P.L. Barkan. All authors reviewed the results and approved the final version of the manuscript.

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