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EXPLORATION OF ALERNATIVES FOR PRESTRESSED CONCRETE MONOBLOCK CROSSTIE DESIGN BASED ON FLEXURAL CAPACITY

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ABSTRACT

Recent North American railway trends signify a transition to increased axle loads and higher train speeds. The use of concrete crossties is common practice in these applications for a variety of reasons, including higher load-carrying capacity and improved ability to maintain proper track geometry. Currently, prestressed concrete monoblock crossties share many geometric and structural properties regardless of manufacturer. For multiple reasons, some manufacturers are investigating the potential benefits of new geometries for crosstie design. One alternative currently being explored is to modify the length and cross-section of the crosstie in order to increase the bending stiffness while using a similar amount of material. In this paper the benefits and implications of these changes will be explored both through theoretical calculations and laboratory testing. This alternative design will be evaluated and compared to concrete crossties representative of those currently found in North American. Comparison of the designs will be based on structural cracking at critical locations along the crosstie. These results will be used to provide guidance on critical design parameters for concrete crossties capable of withstanding future loading and performance demands.

INTRODUCTION

Throughout the world, the majority of railroad track infrastructure is supported by ballast. A ballasted track system typically consists of rail, fastening systems, crossties, ballast, sub-ballast, and subgrade. The most commonly used material for crossties in the United States is timber, which is used for approximately 90-95% of the crossties in revenue service [1]. Concrete is the second most common material for crossties, making up most of the remaining 5-10%. Steel and composite crossties are also used, but they make up a negligible share of the total number of crossties [1]. Typically, concrete crossties are used in the most demanding service conditions (e.g. high curvature, steep grades, heavy tonnage, high speed passenger traffic, etc.).

As a material, concrete is very weak in tension, but very strong in compression. Because of this, concrete crossties must be held in compression, or “prestressed”, with tensioned steel [2]. This can be achieved by tensioning steel wires or strands before or after the concrete is cast; members made this way are referred to as “pre-tensioned” and “post-tensioned”, respectively. Pre-tensioning is the more common practice for the manufacture of prestressed concrete crossties in the United States. Prestressing significantly increases concrete’s flexural strength, ductility, and resistance to cracking. With this improved strength and ductility, prestressed concrete crossties can withstand the demanding dynamic loading environment imparted by passing trains [2] [3].

The primary purpose of the crosstie is to maintain track geometry (e.g. gauge, cross level, etc.) and to transfer applied wheel loads to the track substructure [4]. When a concrete crosstie supported on ballast is loaded vertically, the load is transferred from the wheel to the track system through the rail, fastening system, crosstie, ballast, sub-ballast, and subgrade. The ballast support conditions play a critical role in the type and severity of bending that the crosstie will experience under loading from a passing train [5]. The ballast support is affected by a variety of factors that include loading during train operations, tamping, fouling, and voids [6]. Common failure modes for concrete crossties, as ranked by six Class I railroads, include rail seat deterioration, cracking from center binding (center negative bending), and cracking from dynamic loads [2].

Currently, most concrete crossties used in freight applications in North America are 8'-6" in length, but recently an 8'-0" crosstie has been developed. This shortened length allows for a larger cross section while maintaining a similar weight as its longer counterparts. This paper will focus on the effects that decreased length and larger section have on the flexural analysis and behavior of a concrete crosstie.

FLEXURAL ANALYSIS

Rail Seat Positive Bending

Figure 30-4-3 in Chapter 30 (Ties) of the 2014 American Railway Engineering and Maintenance-of-Way Association (AREMA) Recommended Practices [7], hereafter referred to as the "AREMA Manual," specifies a rail seat positive bending moment (M_{RS+}) for 8'-0" of 250 in-kips, compared to 300 in-kips for an 8'-6" crosstie. This is supported by basic structural analysis, by solving for M_{RS+} using the free body diagram shown in Figure 1. This is shown in more detail below. M_{RS+} for a crosstie with a rail seat load acting at a single point and newly-tamped support assumption (shown in Figure 1), can be calculated with Equation 1 below.

Figure 1. Support assumption for rail seat positive bending [5]

$$M_{RS+} = \frac{R(L-g)}{8} \qquad (1)$$

Where: M_{RS+} = rail seat positive bending moment
R = rail seat load
L = crosstie length
g = rail-center spacing

Under a 60 kip rail seat load with 60" rail-centers, the M_{RS+} is found to be 315 in-kips for an 8'-6" crosstie and 270 in-kips for an 8'-0" crosstie. This shows that the M_{RS+} demand should decrease through the use of a shorter crosstie. The shorter length of the crosstie reduces the length from the end of the crosstie to the rail seat center, which acts as the moment arm for rail seat bending. This reduced demand could support a reduced section size, lower prestress forces, or fewer wires, all of which could result in a more economical crosstie.

Center Negative Bending

Table 30-4-1 of the 2014 AREMA Manual specifies factors to be applied to the M_{RS+} values stated earlier to calculate the center negative bending moment (M_{C-}). The factor for 8'-0" crossties is 0.92 while it is 0.67 for 8'-6" crossties, resulting in center negative bending moments of 230 kip-in and 201 kip-in, respectively. This suggests that center negative bending becomes even more critical as crosstie length decreases. This is supported mechanically with Equation 2, where the ballast reaction is assumed to act over the entire length of the crosstie (Figure 2).

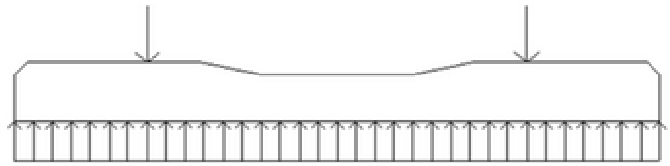

Figure 2. Support assumption for center negative bending [5]

$$M_{C-} = R\left(\frac{g}{2} - \frac{L}{4}\right) \qquad (2)$$

Where: M_{C-} = rail seat positive bending moment
R = rail seat load
L = crosstie length
g = rail-center spacing

Under a 60 kip rail seat load with 60" rail-centers, the M_{C-} is found to be 270 in-kips for an 8'-6" crosstie and 360 in-kips for an 8'-0" crosstie. This shows that center negative bending demand is higher for shorter crossties. The increased center negative bending demand can be explained by the reduced moment provided by the area of the tie between the rail seat and end of tie that resists center negative bending. For the 8'-0" tie, the shorter moment arm between the rail seat and end of the tie results in a lower moment to resist the center negative moment between the rail seat and tie center.

THEORETICAL FLEXURAL CAPACITY

A comparison was conducted between theoretical bending moments for the 8'-0" and 8'-6" crossties. These calculations were found using strain-compatibility analysis in the program Response 2000 [8]. To protect proprietary information, the prestress arrangement, initial prestress force, section dimensions, and material dimensions are not included within this paper. However, a simplified cross section at the rail seat and center of each crosstie, and the moment of inertia, sectional area, height of prestress of centroid, and neutral axis are given in Table 1 below.

In a strain-compatibility calculation, it is assumed that the compressive and tensile forces in the section are equal about the neutral axis. An important parameter in the design of prestressed concrete is the distance between the neutral axis and centroid of prestress, which is referred to as the eccentricity. A positive eccentricity means that the prestress centroid is below the neutral axis, and negative eccentricity means that the prestress centroid is above the neutral axis [9]. To counteract the negative bending moment experienced at the tie center, a negative eccentricity is commonly used. The 8'-0" crosstie has eccentricities that are 4.9% and -2.3% of the section height for the rail seat and center section, respectively. The 8'-6" crosstie has eccentricities that are 15.0% and -5.7% of the section height for the rail seat and center section, respectively.

Table 1. Cross-sectional properties of crossties

Crosstie Section	Area (in^2)	Moment of Inertia (in^4)	Height of Prestress Centroid (in)
8'-0" RS	97	670	4.1
8'-0" C	77	458	4.1
8'-6" RS	90	650	3.9
8'-6" C	60	296	3.9

The results of the strain-compatibility analyses are given in Table 2. These values most closely represent what the AREMA Manual defines as a structural failure – a crack propagating from the extreme tensile fiber of the crosstie to the first layer of prestress. They show that the 8'-0" crosstie has a greater theoretical bending moment capacity than the 8'-6" crosstie in all areas but rail seat positive bending. All of these values exceed the AREMA-recommended values. This shows that with the current design, the 8'-0" crosstie should perform equivalent to or better than the 8'-6" crosstie in the AREMA specified flexural tests for center negative, rail seat negative, and center positive. The 8'-6" crosstie should outperform the 8'-0" crosstie in the rail seat positive flexural test. It is important to remember that as was discussed in the previous section, the flexural demand at the center will be greater for the 8'-0" crosstie than for the 8'-6" crosstie. Similarly, the flexural demand at the rail seat should be greater for the 8'-6" crosstie than the 8'-0" crosstie.

Table 2. Theoretical flexural capacity

Moment	8'-0" Crosstie Length (in-kips)	8'-6" Crosstie Length (in-kips)
M_{RS+}	349.2	387.6
M_{RS-}	288.0	270.0
M_{C+}	272.4	207.6
M_{C-}	288.0	242.4

Although not considered in this analysis, it is important to note that the 8'-0" crosstie uses steel plates to anchor the prestressing steel. This idea is new to concrete crosstie design and manufacture, but is common practice in building and bridge design [10]. It is likely that this anchor plate helps decrease the transfer length, improve bond strength, and reduce the concrete stress along the prestress wire, which could reduce end splitting. Lastly, the 8'-0" crosstie has a rail seat section that is 10-25% wider than that of the 8'-6" crosstie, which increases ballast contact area in this region. Because of the difference in lengths, both crossties have nearly the same total base area. The increased size of the rail seat section has the potential to reduce the rail seat pressure and shoulder face pressure.

DETERMINATION OF PRESCRIBED MOMENTS AND LOADS

Article 30.4.4.1 of the 2014 AREMA Manual focuses on the flexural performance requirements for prestressed monoblock crosstie designs and outlines the methodology for determining the prescribed loads and moments for concrete crossties based on crosstie geometry, crosstie spacing, and factors for speed and tonnage. Values for crosstie spacing, speed, and tonnage were chosen to represent field conditions where concrete crossties are installed on North American Class I railroads [11], and were held constant for both crosstie types that were tested. These factors are combined in Equation 3 to determine the prescribed rail seat positive bending moment, which is subsequently factored to determine bending moments for rail seat negative, center positive, and center negative testing.

$$M_{RS+} = BVT \tag{3}$$

Where: M_{RS+} = rail seat positive bending moment
B = the bending moment in inch-kips for a particular crosstie length and spacing
V = the speed factor
T = the tonnage factor

Crosstie spacing, length, speed, and tonnage values are used in conjunction with Figures 30-4-3 and 30-4-4 of the 2014 AREMA Manual to determine the bending moment, and speed and tonnage factors, respectively, used in Equation 3. The values used in determining bending moments for this analysis are presented in Table 3.

Prescribed bending moment values for rail seat positive (M_{RS+}), railseat negative (M_{RS-}), center positive (M_{C+}), and center negative (M_{C-}) testing were determined based on the above factors, and have been tabulated in Table 4.

Table 3. Design values and factors used to determine bending moments prescribed in the AREMA manual

Factor	Assumed or Determined Value
Crosstie Spacing (in)	24
Speed (mph)	80
Annual Tonnage (MGT)	75+
B (8' Crosstie) (in-kips)	250
B (8'6" Crosstie) (in-kips)	300
V	1
T	1.1

Table 4. Moment factors and prescribed moments based on procedures found in the AREMA manual

Test	Moment Factor (8’)	Moment Factor (8’6”)	Prescribed Moment (8’) (in-kips)	Prescribed Load (8’6”) (in-kips)
M_{RS+}	1	1	275	330
M_{RS-}	0.64	0.53	176	175
M_{C+}	0.56	0.47	154	155
M_{C-}	0.92	0.67	253	221

The following loads, shown in Table 5, were selected as a baseline to compare the two crosstie designs. These loads are representative of common values used by North American freight railroads with many years of heavy-haul concrete crossties experience.

Table 5. Loads used for crosstie testing

Test	Load (kips)
M_{RS+}	64
M_{RS-}	32
M_{C+}	12
M_{C-}	17

TESTING PROTOCOL

The sequence of tests is described in Article 30.4.9.1 of the AREMA Manual, and this sequence was followed for all crossties tested. The testing sequence was as follows:

1. Rail seat negative test (seat A)
2. Rail seat positive test (seat A)
3. Center negative test
4. Center positive test
5. Rail seat negative test (seat B)
6. Rail seat positive test (seat B)
7. Rail seat repeated-load test, modified

Rail Seat Testing

Rail seat negative and positive testing was performed in accordance with Article 30.4.9.1.4 of the AREMA Manual. For both tests, load was applied to the rail seat continuously, as shown in Figure 3 and Figure 4, until the desired load was reached. This load was held for three minutes while the crosstie was inspected for structural cracks. Structural cracking in this and all tests is defined as a crack that propagates from the tensile edge of the crosstie to the outermost layer of prestress wire. If no structural cracking was observed the test was concluded and the crosstie was recorded as having passed the test. The value “X” shown is 18 and 21 inches for the 8’-0” and 8’-6” crosstie, respectively.

Center Testing

Center negative and positive tests were performed in accordance with Articles 30.4.9.1.6 and 30.4.9.1.7 of the AREMA Manual. As with the rail seat tests, load was applied continuously until the desired load was reached. The load was held for three minutes while the crosstie was inspected for structural cracks. If no structural cracks were observed the test was concluded and the crosstie was recorded as having passed the test. Figure 5 and Figure 6 show the setup of the center negative and positive tests, respectively.

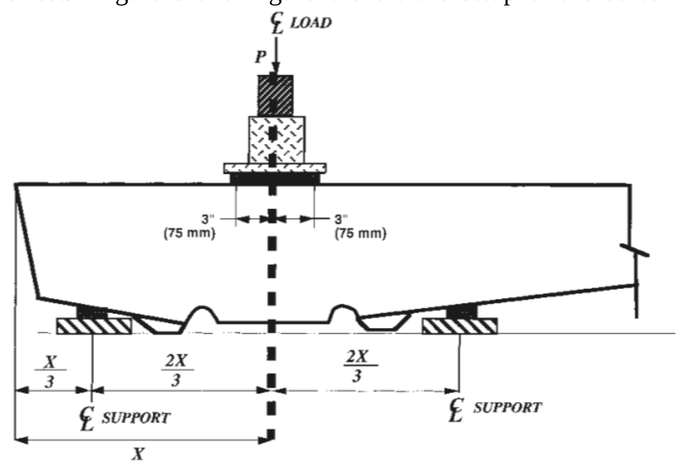

Figure 3. Rail seat negative test

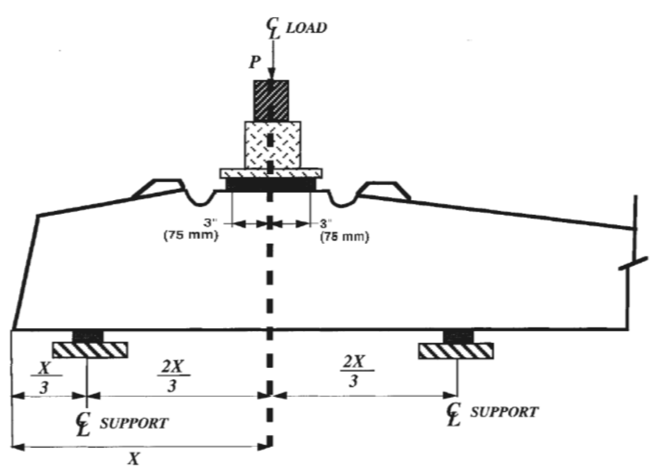

Figure 4. Rail seat positive test

Rail Seat Repeated-Load Test (modified)

Upon completion of the positive moment test for rail seat B the rail seat repeated-load test was initiated. This test was modified due to the design and capabilities of the testing machine, and only the first part of the test as described in the AREMA Manual was performed. Load was applied to the rail seat until a structural crack was observed. Once the crack was observed the load was recorded and the test concluded. From this load, the bending moment induced at failure was calculated using Equation 4. This equation is presented in Figure 30-4-8 of the AREMA manual to determine the prescribed load for the rail seat positive test, solved M_{RS+}.

$$M_{RS+} = \frac{P_{RS+}\left(\frac{2X}{3} - 2.25\right)}{2} \quad (4)$$

Where: M_{RS+} = rail seat positive bending moment
P_{RS+} = test load for rail seat positive failure
X = length from crosstie end to rail seat center

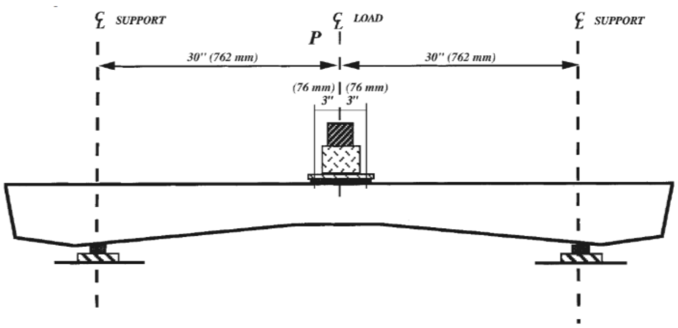

Figure 5. Center negative test

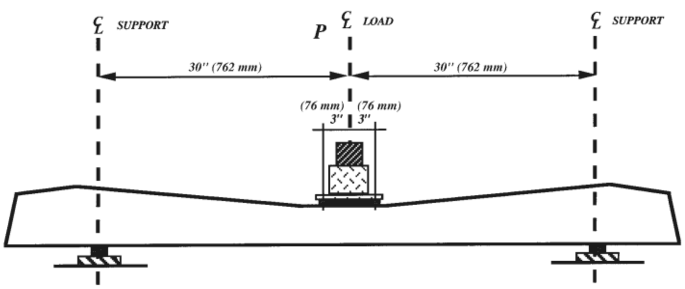

Figure 6. Center positive test

EXPERIMENTAL TESTING RESULTS

8'-0" Crossties

Three 8'-0" crossties were tested per the before mentioned protocol. These crossties were labelled S1, S2, and S3, and will be referred to by those names for the remainder of this paper. There was only one failure recorded of all the tests performed on these crossties; crosstie S1 failed the center positive test. All three crossties exhibited capacity well above the prescribed rail seat positive load, as shown in the results of the modified rail seat repeated-load test. Results of all tests for crossties S1, S2, and S3 have been summarized in Table 6.

8'-6" Crossties

Three 8'-6" crossties were tested per the before mentioned protocol. These crossties were labelled L1, L2, and L3, and will be referred to by those names for the remainder of this paper. Two failures were recorded for tests performed on these crossties: crosstie L1 and L2 both failed the center negative test. All three crossties exhibited capacity well above the prescribed rail seat positive load, as shown by the results of the modified rail seat repeated-load test. Results of all tests for crossties L1, L2, and L3 have been summarized in Table 7.

Table 6. Summary of results for 8'-0" crossties

Test	Crosstie		
	S1	S2	S3
$M_{RS-,A}$	Pass	Pass	Pass
$M_{RS+,A}$	Pass	Pass	Pass
M_{C-}	Pass	Pass	Pass
M_{C+}	Fail	Pass	Pass
$M_{RS-,B}$	Pass	Pass	Pass
$M_{RS+,B}$	Pass	Pass	Pass
Structural Failure			
Test Load (kips)	73.0	77.4	78.5
Moment (in-kips)	355.9	377.3	382.7

Table 7. Summary of results for 8'-6" crossties

Test	Crosstie		
	L1	L2	L3
$M_{RS-,A}$	Pass	Pass	Pass
$M_{RS+,A}$	Pass	Pass	Pass
M_{C-}	Fail	Fail	Pass
M_{C+}	Pass	Pass	Pass
$M_{RS-,B}$	Pass	Pass	Pass
$M_{RS+,B}$	Pass	Pass	Pass
Structural Failure			
Test Load (kips)	85.1	74.9	85.9
Moment (in-kips)	500.0	440.0	504.7

DISCUSSION

Both crossties achieved the established rail seat positive test loads without experiencing structural failure. On average, the 8'-6" crosstie withstood a higher test load than the 8'-0" crosstie without failure. However, the 8'-6" crosstie was observed to fail more frequently in center negative bending, a more critical flexural region [12].

CONCLUSION

Shorter crossties are expected to be subjected to lower rail seat positive bending moments and greater center negative bending moments. The shorter length of the crosstie reduces the support length (X), which acts as the lever arm for rail seat bending. The center negative bending then increases in magnitude as there is a shorter length acting against the rail seat load.

For the two crosstie designs compared in this study, theoretical bending moment calculations suggest that the shorter crosstie, with its larger section, has a greater flexural capacity for center positive and negative, and rail seat negative bending. The longer crosstie has a greater flexural capacity for rail seat positive. This is supported by the testing results, as two of the 8'-6" crossties failed in center negative bending, but exhibited higher rail seat positive flexural capacities than the

8'-0" crossties. Comparatively, the only failure experienced by the 8'-0" crossties was in center positive bending.

Additionally, both crosstie types exhibited load capacity beyond the prescribed test loads. In addition, both crosstie types exhibited flexural capacity beyond the theoretical bending moments.

For the 8'-0" crosstie, future work could be performed to quantify the effects of other design characteristics of the crosstie, particularly the effect of anchor plates for prestressing steel on the flexural capacity of crossties. This innovation could potentially increase the ultimate flexural capacity and ductility of the crosstie, by preventing prestress pull-out, loss of prestress force, and end splitting. The larger rail seat section has the potential to reduce rail seat pressure on the crosstie, and could additionally reduce ballast pressure and subsequent ballast degradation.

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