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GAUGING OF CONCRETE CROSSTIES TO INVESTIGATE LOAD PATH IN LABORATORY AND FIELD TESTING

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ABSTRACT

To meet the demands of increasing freight axle loads and cumulative gross tonnages, as well as high-speed passenger rail development in North America, the performance and service life of concrete railway crossties must be improved. As a part of a study funded by the Federal Railroad Administration (FRA) aimed at improving concrete crossties and fastening systems, laboratory experimentation was performed at the Advanced Transportation Research Engineering Laboratory by researchers from the University of Illinois at Urbana-Champaign. This paper focuses on the behavior of concrete cross-ties as well as characterizing and quantifying the loads transmitted from the wheel/rail interface through the fastening system to the tie in the vertical direction. Concrete embedment strain gauges were cast below rail seat to create a “load cell” to measure the rail seat vertical load. Laboratory instrumentation efforts have been done to calibrate this vertical “load cell”. To understand the rail seat load and load path in the field, experimentation was performed

at the Transportation Technology Center (TTC) in Pueblo, both static loading which were applied by TTC's Track Loading Vehicle and dynamic loading due to real wheel-rail interaction were discussed. Concrete cross-tie bending behavior was also investigated through the use of strain gauges applied in the longitudinal axis of the crossties in both laboratory and field experiments. Results from these findings will be utilized to aid in the recommendations for the mechanistic design of various components within the fastening system.

INTRODUCTION

There is more than one benefit of using concrete crossties to replace standard timber crossties: excellent durability and capacity have been brought to track system along with concrete crossties [1]; improved track geometry retention is also being offered for high speed or heavy freight lines [2]. A wide variety of failure mechanisms of concrete crossties may happen with the continual increasing in annual gross tonnages [3]. The behavior of concrete crossties and the demands of the crosstie and fastening system must be studied. The investigation on the load path, i.e. how the load transfers among each component needs to be done. The load path going through concrete depends on the loading and support conditions, as well as the component properties of prestressed concrete crossties. Both of full-scale laboratory and field experiments formulated by University of Illinois at Urbana-Champaign (UIUC) have been described and discussed in this paper. To investigate the load path in concrete, embedment strain gauges were installed in concrete before it was cast, and surface strain gauges were installed later. With some necessarily analysis, the load path going through concrete can be determined from these strains directly.

MATERIAL PROPERTIES OF CONCRETE

The concrete properties which including the strength and elastic modulus have been given by the crosstie manufacturer. The average strength $f'c$ and Young's modulus Ec obtained from the compressive cylinder test are shown in Table 1.

As the laboratory and field experiments were done one year after the concrete being cast, the 1 year concrete strength and Young's modulus need to be tested. Core drill was used to remove cylinder samples from concrete crossties. Six 3 inches by 3 inches concrete core cylinders have been tested, the average concrete strength obtained from the compressive test has been converted to ACI standardized uniaxial strength. The concrete strength $f'c$ at 1 year is founded to be $11{,}000$ psi which is slightly lower than its 28 days strength, and this can be due to the small sampling size. The Young's modulus is found to be 4.50×10^6 psi which is slightly greater than its 28 days modulus. The tensile strength (cracking stress) of concrete was not measured directly but can be obtained using the equation below:

$$f't = 7.5\sqrt{f'c} = 7.5\sqrt{11{,}000} = 787\text{psi}$$

The material properties obtained from compressive core test are going to be used in the following analysis.

TABLE 1 CONCRETE PROPERTIES

	$f'c\ (psi)$	$Ec\ (psi)$
1 days	--	3.68×10^6
7 days	--	4.00×10^6
28 days	11,730	4.26×10^6

LABORATORY INSTRUMENTATION

In laboratory investigation, static tie tester (STT) was used for load applying. STT is designed to apply load vertically to the concrete crosstie (Figure 1). A loading head powered by a hydraulic pump was used to apply the static load, its capacity was 100 kips. Hydraulic pressure gauges were used and calibrated to read the load being applied. Crosstie center-positive bending test and rail seat compressive test were done with STT.

Concrete crosstie bending behavior was evaluated first. Concrete crossties are reinforced by prestressed strands. The cracking moment at rail seat and crosstie center can be calculated easily using beam theory with the material properties mentioned above, the dimensions of the crosstie cross-section, and the locations of prestressed strands. The calculated cracking moment is shown in Table 2. To validate the applicable of the beam theory, strains need to be recorded from crosstie to compare with their theoretical values. Concrete surface strain gauges were used to measure strain in the longitudinal direction of the crosstie.

FIGURE 1 STATIC TIE TESTER (STT)

In center-positive bending test, the instrumented crosstie was placed on STT, the bottom surface of the crosstie below both rail seats were placed on 2 inches wide wooden supports. A static point load was applied vertically at crosstie center by the hydraulic loading head. The locations of strain gauges are shown in Figure 2. Strain gauges $S_{L1} \sim S_{L2}$ were located below the left rail seat, $S_{L3} \sim S_{L4}$ at crosstie center, and $S_{L5} \sim S_{L6}$ below the right rail seat, all of which were installed at one side surface of the crosstie. Here, actually only the strains recorded at crosstie center were used for analysis in this center-positive bending test, because ideally the strain gauges right above the supports will record nothing. However, the same strain gauge pattern was used in the field experiments, and all the strains recorded will be used in analysis.

TABLE 2 CONCRETE CROSSTIE CRACKING MOMENT (KIPS-IN)

	Rail seat	Crosstie center
Positive	405.6	196.8
Negative	219.6	256.8

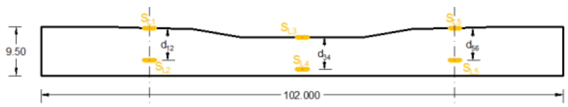


FIGURE 2 LOCATIONS OF CONCRETE SURFACE STRAIN GAUGES

Next, the concrete crosstie compressive behavior was investigated below the rail seat. Concrete embedment strain gauges were installed 2 inches below rail seats before the concrete casting. Four embedment strain gauges forming a 2 by 2 matrix were used for each rail seat. The locations of these embedment strain gauges in a concrete crosstie are showing in elevation and plan view in Figure 3. This embedment strain gauge pattern has been used in both of laboratory and field experiments.

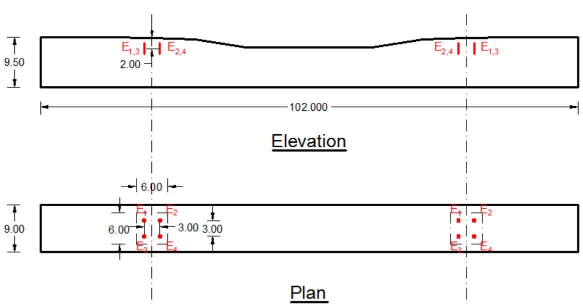


FIGURE 3 LOCATIONS OF CONCRETE EMBEDMENT STRAIN GAUGES BELOW RAIL SEATS

To validate the reading from concrete embedment strain gauges and to study the load path going vertically through the concrete, concrete surface strain gauges were installed in the vertical direction of the crosstie in laboratory experiments. As shown in Figure 4, two rows of strain gauges were installed below the left rail seat. Strain gauges $S_{V1} \sim S_{V5}$ were placed 5 inches above the bottom surface of the crosstie, and strain gauges $S_{V6} \sim S_{V10}$ were placed 2.5 inches lower. All these strain gauges were installed on both sides of the crosstie.

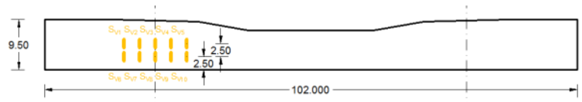
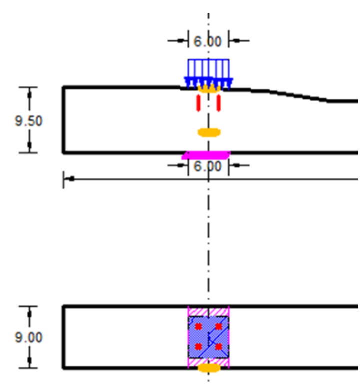


FIGURE 4 LOCATIONS OF CONCRETE SURFACE STRAIN GAUGES BELOW RAIL SEATS

STT was used to apply the rail seat load, the static vertical loading was applied at the rail seat at one side, and the other end of the tie was placed on the rolling shelf of the testing machine. The loading width was 6 inches which is the same as the width of the rail pad, and the loading length (parallel to the concrete crosstie) was tested with three cases: 6 inches, 3 inches and 1.5 inches. As shown in Figure 5, in the 6 by 6 loading case, the compressive load was distributed evenly over the entire rail seat; in the 6 by 3 and 6 by 1.5 load cases, the loading area was narrower, and actually an eccentric loading has been applied on purpose.



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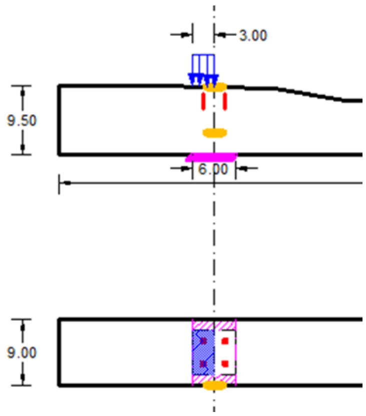

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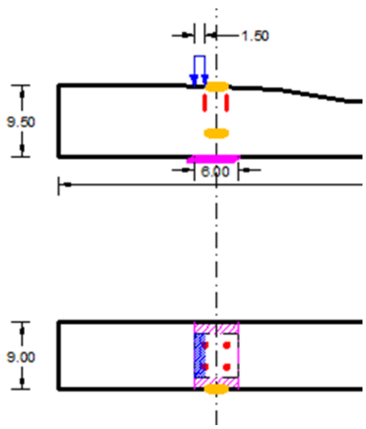

c

FIGURE 5 LOADING AND SUPPORT CONDITIONS FOR RAIL SEAT COMPRESSIVE TEST

Wooden pad was used for support. The support was distributed evenly across the full width of the tie, and the support length was tested with three cases: 6 inches, 12 inches and 18 inches centered at the center line of rail seat. The vertical load was applied starting from zero, took 25 kips increment for each step until hitting 50 kips. In other words, three magnitudes of rail seat loading were being checked, no load, 25 kips vertical load and 50 kips vertical load.

FIELD INSTRUMENTATION

Two sections of track were investigated at Transportation Technology Center (TTC) in Pueblo, CO, including one section on tangent track and one on curved track. The results and analysis from the tangent track is going to be discussed in this paper. Fifteen new concrete crossties with fastening systems were installed for each section; a series of static loading was applied by track loading vehicle (TLV), a passenger consist and a freight consist were also included in the loading tests.

Bending behavior of concrete crosstie was examined using the surface strain gauge pattern shown in Figure 2; the rail seat compressive behavior of the crosstie was examined using the embedment strain gauge pattern shown in Figure 3. As shown in Figure 6, three crossties (CS, EU and GW) were instrumented with surface strain gauges, and four rail seats (marked with orange shade) were instrumented with embedment strain gauges.

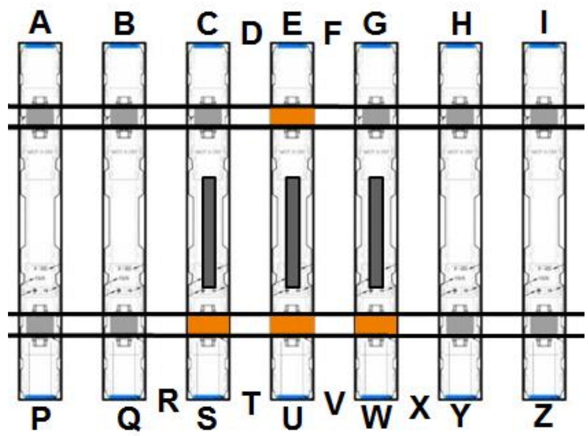

FIGURE 6 INSTRUMENTED CROSSTIES IN FIELD EXPERIMENT

The objective of installing concrete embedment strain gauges below rail seat is to record the compressive strain due to wheel load, and obtain the rail seat vertical load by running the following calculation:

$$V = e_{AVG} \cdot E_C \cdot A \cdot Q_1 \cdot Q_2 \cdot Q_3$$

where,

V – vertical rail seat load

e_{AVG} – average strain taken from embedment gauges

E_c – elastic modulus of concrete

A – rail seat area

Q_1 – correct factor for concrete bearing area

Q_2 – correct factor for loading eccentricity

Q_3 – correct factor for support length

Considering the actual embedding height of the embedment strain gauges in concrete, loading eccentricity and the effect of support length, the rail seat vertical loading was scaled up using factorsQ_1, Q_2, Q_3 , and these factors need to be obtained from laboratory calibration.

RESULTS AND ANALYSIS

In the concrete crosstie center-positive bending test, strains were recorded from the pair of gauges ($S_{L3} \sim S_{L4}$) located at the center of the crosstie (shown in Figure 5). From Figure 7, we can see when the center point load was applied as 10 kips, the top strain was recorded to be -82 ms in compression and the bottom strain was 43 ms in tension. The linearity was good, and when the load has been removed, the strains went back to zero. Using the beam theory, we can find the centroid axis located 3.8 inches below the top surface or 3.7 inches above the bottom surface, which agrees with the location of the actual centroid axis of the original cross-section. And the Young's modulus of concrete can be determined to be 4,525 ksi which is also very close to the modulus we obtained before.

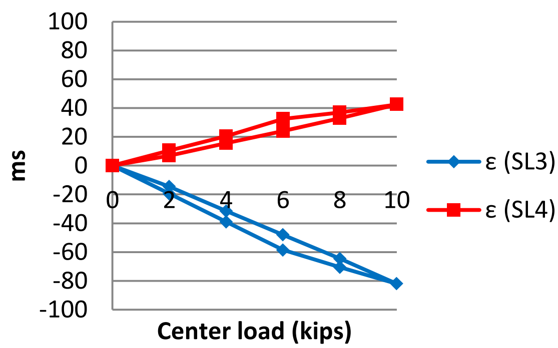

FIGURE 7 STRAINS RECORDED FROM CENTER-POSITIVE BENDING TEST

Let's look at the concrete crosstie compressive behavior now. When the support length was 18 inches and the loading was set to be 50 kips, the average strains recorded from the vertical concrete surface gauges located at the same position from both sides of the cross tie are calculated. The lateral distribution of compressive strain of concrete 5 inches above the bottom surface is shown in Figure 8, and the distribution of compressive strain 2.5 inches above the bottom surface is shown in Figure 9. In Figure 8, we can find, when there is no eccentricity of the applied load (Figure 5, a), the maximum strain was recorded from the center line of rail seat, the value is -111 ms. The strain decreased almost linearly when moving towards both side; at 7 inches away from the center line of rail seat, the compressive strain was close to zero. When the eccentric loading was applied (Figure5, b and c), the compressive load path shifted towards the loading side, but the maximum strain remains similar. Comparing between Figure 8 and Figure 9, we can find, in general, the load spread out in a wider area when moving towards the support, and thus the strain distributed more evenly, and the maximum strain was less.

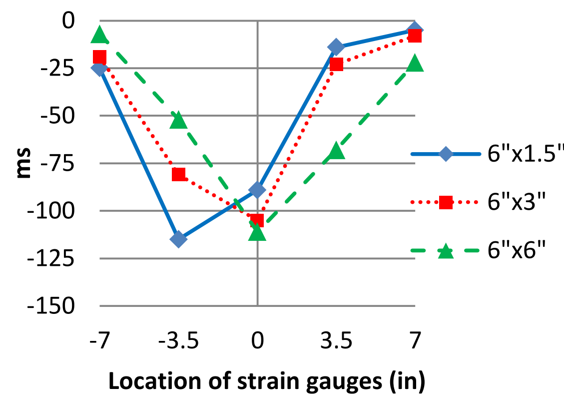

FIGURE 8 COMPRESSIVE STRAIN DISTRIBUTION 5 INCHES ABOVE THE BOTTOM SURFACE

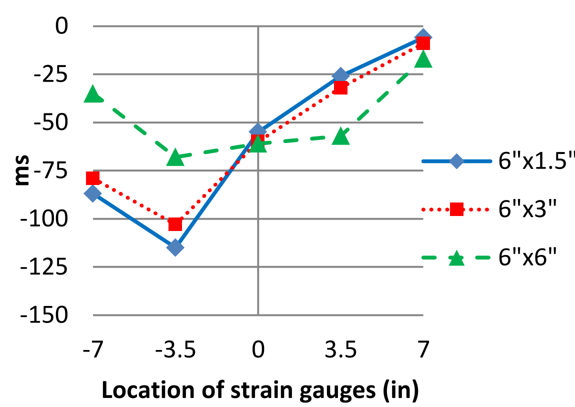

FIGURE 9 COMPRESSIVE STRAIN DISTRIBUTION 2.5 INCHES ABOVE THE BOTTOM SURFACE

Using the methodology mentioned before, rail seat vertical load can be known. Figure 10 is showing the distribution of rail seat loading over three crossties (CS, EU and GW) adjacent to each other. Two loading cases are included: one shown in blue bar is the rail seat loading due to 40 kips pure static vertical wheel load applied by TLV; the other one shown in red bar is due to the combination of 40 kips vertical load and 20 kips lateral load statically applied by TLV. In both of the two cases, TLV applied the wheel load over the center crosstie (EU). From Figure 10, we can find almost 50% vertical wheel load was supported by the center crosstie, and around 25% wheel load went to both adjacent ties, very little vertical load was distributed to crossties over two tie spacing away. Due to the existence of lateral wheel load, there was a wider distribution of vertical load over crossties, but its effect is very small.

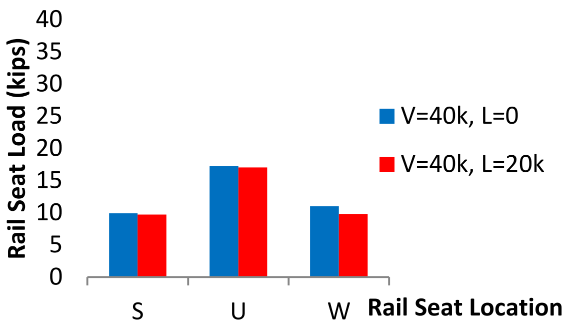

FIGURE 10 DISTRIBUTION OF RAIL SEAT LOAD

When a freight consist which consisted of cars weighting 44 kips, 260 kips, 286 kips and 315 kips, the rail seat vertical reaction can be converted from the compressive strains in concrete which have been recorded by these embedment gauges. The vertical loads applied to rail seat U at different train speed are shown in Figure 11. The correlation between the vertical rail seat reactions and train speeds was not significant. But the maximum rail seat reaction increased with the increasing of train speed. One possible reason for this could be the greater dynamic effect due to the worn wheel profile.

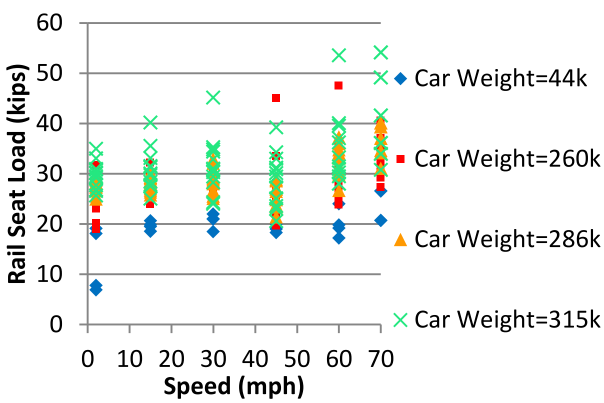

FIGURE 11 RAIL SEAT LOADS AT RAIL SEAT U

CONCLUSIONS AND FUTURE WORK

The bending and compressive behavior of the concrete crossties, as well as the load path going through concrete crosstie were investigated in both laboratory and field environment, the following conclusions have been made:

1. Elastic beam theory can be applied for crosstie bending analysis as long as there is no crack generated.
2. The compressive strain distribution in concrete below the rail seat is related with the loading eccentricity and support conditions.
3. The crosstie right below the wheel-rail interface bears around 50% of vertical wheel load.
4. The correlation between the vertical rail seat reactions and train speeds was not significant. But the maximum rail seat reaction can be influnced by the speed.

In this research, only three adjacent concrete crossties were instrumented with surface and embedment strain gauges, and one tangent and one curved section in field have been examined. The support from the ballast below the crossties remains unclear. The future in-depth laboratory experimentation will consider the limitation of the current test set-up, and better address the load path going through concrete crossties.

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