

## Field Measurements and Proposed Analysis of Concrete Crosstie Bending Moments

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### ABSTRACT

As the use of concrete crossties increases for heavy-haul freight railroad lines in North America, it is becoming more critical to quantify their flexural performance in revenue service traffic in an effort to improve upon design recommendations and maintenance practices, leading to longer service lives, lower life cycle costs, and fewer in-service failures. Currently, center cracking is regarded as one of the most common concrete crosstie failure mechanisms in North America. Improving the understanding of crosstie flexure can help reduce the occurrences of center cracked crossties by ensuring designs are adequate for the field conditions that are encountered. Past work conducted at the University of Illinois at Urbana-Champaign (UIUC) found that crosstie flexure is highly dependent on ballast support conditions and this support can vary greatly from crosstie to crosstie. To measure the bending moments experienced in North American heavy-haul freight service, surface strain gauges were installed on ten concrete crossties along a high-tonnage, heavy-haul North American freight railroad line. These gauges were used to record strains at five critical locations along each crosstie. These strains were converted to bending moments using a calibration factor found in laboratory testing. Data has been collected from nearly 40,000 axles from 70 train passes over 8 site visits spanning 10 months. Prior to instrumentation, micro-cracking was observed at the center of most crossties in this test section, but among hundreds of thousands of measured bending moments, only two center bending moments of one crosstie exceeded the current industry standard design limits. Ballast support conditions were found to be a major source of variation in crosstie flexure and were found to be highly variable in both the direction of traffic and length of the crosstie.

### 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. Currently in the United States, concrete is the second most common material used in the manufacture of crossties, and pre-tensioning is the most common practice in the manufacture of concrete crossties (1, 2). Because of the increased flexural strength, ductility, and resistance to cracking produced by the “pre-tensioned” steel wires, prestressed concrete crossties can withstand the high dynamic loading environment imparted by passing trains, and are commonly used in the most demanding service conditions (e.g. high curvature, steep grades, heavy tonnage, high speed passenger traffic, etc.) (2, 3).

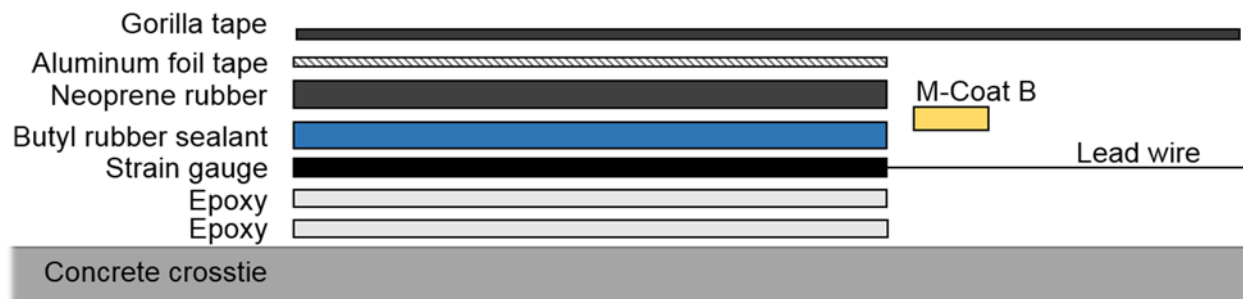
According to a survey of railroads, concrete crosstie manufacturers, and researchers from around the world, crosstie cracking from center binding was ranked as the third most critical problem with concrete crossties (4). North American respondents considered center cracking to be slightly less critical than their international counterparts, ranking it as the fifth most critical issue associated with concrete crossties. However, North American respondents ranked cracking from dynamic loads as the third most critical issue, one place ahead of international respondents. This survey shows that crosstie cracking is a critical issue in railroad track infrastructure and is a failure mechanism that is experienced both domestically and internationally.

Because of the increasing application of prestressed concrete crossties in the high-demand environments, it is important to understand the factors that cause the crossties to crack at the center. Assumptions regarding these potential factors could be made based on both the loading and support conditions. High impact and cyclic loads induced by revenue service traffic could potentially increase the flexural demand of concrete crossties (5). Furthermore, flexural analysis has shown that 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 (6). In order to justify these assumptions, researchers in the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) decided to quantify the bending behavior of concrete crossties under revenue service traffic. The field experimentation is currently ongoing and expected to last over a year so that an adequate amount of data will be collected and analyzed. This paper will provide an update on findings to date.

### Instrumentation Technology

UIUC researchers have selected surface-mounted strain gauges to measure the bending moments experienced by concrete crossties under revenue service heavy-haul freight train loads. Data from all strain gauges were collected using National Instruments’ (NI) compact data acquisition system (cDAQ) (7). The strain gauges were wired as quarter bridges and designed to be temperature compensating. Previous experimentation conducted by UIUC in both laboratory and field settings has implemented this instrumentation technology, and it has proven to be both cost effective and reliable (8).

Prior experience has also shown the importance of providing adequate protection for the strain gauges. As such, the protection plan shown in Figure 1 and explained in Table 1 was implemented for each strain gauge placed on the concrete crossties.



**FIGURE 1 Strain Gauge Protection Plan**

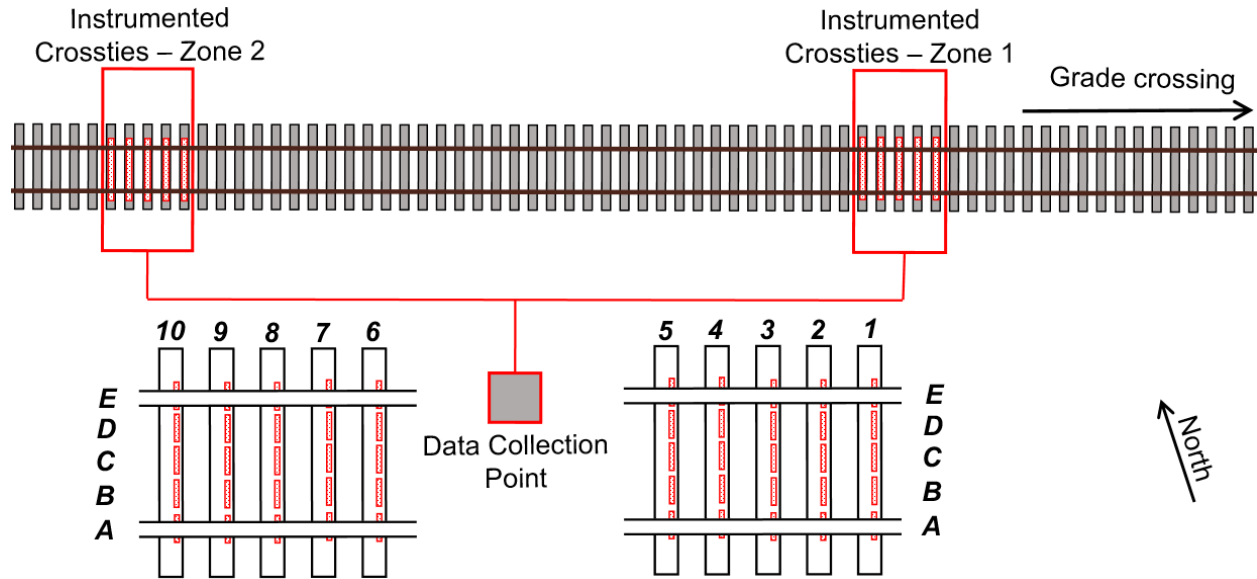
**TABLE 1 Explanation of Strain Gauge Protection Plan**

<b>Layer (from bottom)</b>	<b>Description</b>	<b>Purpose</b>
Epoxy	Two-part 1 hour set time epoxy, applied in two coats: primer and secondary	Primer coat bonds with concrete surface and provides smooth surface to mount strain gauge, secondary coat bonds strain gauge to primer coat
Strain gauge	Sensor that measures change in resistance caused by small induced strains	Measures the change in strain experienced by the concrete under an applied load
Butyl rubber sealant	Sticky rubber layer	Provides moisture and mechanical protection for gauge
Neoprene rubber	Harder, stiffer rubber layer	Provides mechanical protection for gauge
Aluminum foil tape	Reflective tape layer	Provides moisture protection to gauge and holds all lower protection layers in place
Lead wire	Three-wire insulated bundled wire	Transmits strain signal recorded by gauge to data acquisition
M Coat-B	Liquid rubber sealant	Provides additional moisture protection to lead wire ends
Gorilla tape	Resilient tape layer	Provides mechanical protection to lead wire and holds all lower protection layers in place

### Experimentation Plan

Field experimentation was conducted on a ballasted North American heavy-haul freight line in the western portion of the United States. Because of the high variability of support conditions seen in past experimentation (8), instrumentation was placed in two locations, or “zones,” of tangent track, spaced approximately 60 feet (18.3 m) apart on centers (Figure 2). Each zone consisted of five crossties, based on the widely accepted distribution of vertical load to five crossties (4) (Figure 2). UIUC researchers determined that the complete site of ten crossties would adequately address the need for replicate data and encompass the variability associated with support conditions in this specific section of track. The sampling frequency for this experimentation was set at 2,000 Hz, based on prior experience and expert recommendation.

The east zone (Zone 1) consisted of Crossties 1 – 5 and served as the example for poor support. Zone 1 was located near a group of crossties that had chronic surfacing defects during geometry car inspections, which is an indicator for poor subgrade. These defects were repaired before the beginning of this experimentation, but it was believed that the issues could re-emerge. Additionally, all crossties in Zone 1 had some level of visible center negative cracking and displayed evidence of ballast pumping. The west zone (Zone 2) consisted of Crossties 6 – 10 and served as the well-supported or control zone. Crossties 6, 7, 8, and 9 showed some center cracking, but there was no visible pumping upon train passes. Furthermore, Zone 2 deflected noticeably less than Zone 1. Finally, there was a grade crossing located approximately 180 feet (55 meters) east of Zone 1. The track at this location consisted of 133RE rail and Safelok I fastening systems. Rail, fasteners, and crossties were all installed in 1999. As of early 2015, the track was last surfaced in an out-of-face fashion in 2011. The timetable speed at this site was 40 mph (65 kmh), the predominant direction of the traffic on this track was eastbound, and the dominant type of railcar was loaded 286 kip (129.7 tonne) coal cars.

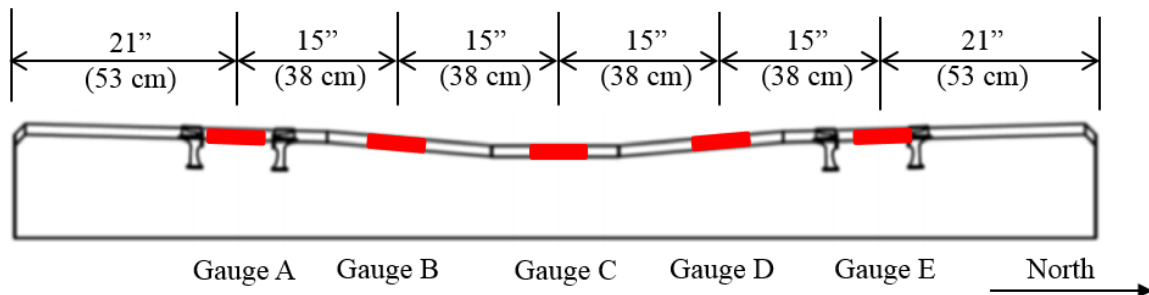


**FIGURE 2 Field Experimentation Site Layout**

### Instrumentation Methods

Bending strains along the length of the crosstie were measured to quantify the flexural behavior of the crosstie under train loading. Surface strain gauges were applied oriented longitudinally along the chamfer near the top surface of the crosstie. A total of five strain gauges (labeled A – E) were used on each crosstie, with one at each rail seat, one at the center, and another located approximately halfway between each rail seat and center (Figure 3).

To relate the measured strains to a bending moment, calibration factors were determined. This calibration factor was found by instrumenting three crossties of the same model and similar year of manufacture as those installed in track with the strain gauge layout shown in Figure 3. The testing was performed on a loading frame at UIUC called the static tie tester (STT). The STT applies load to a crosstie using a hydraulic cylinder. These loads are monitored through a calibrated pressure gauge. Loading configurations used for these calibration tests were adapted from tests specified in Chapter 30, Section 4.9 in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering (MRE) (5). The calibration factors were found to be 768,572.9 kip-in/ $\mu\epsilon$ , 615,979.3 kip-in/ $\mu\epsilon$ , and 504,946.7 kip-in/ $\mu\epsilon$  for Gauge A and E, Gauge B and D, and Gauge C, respectively.



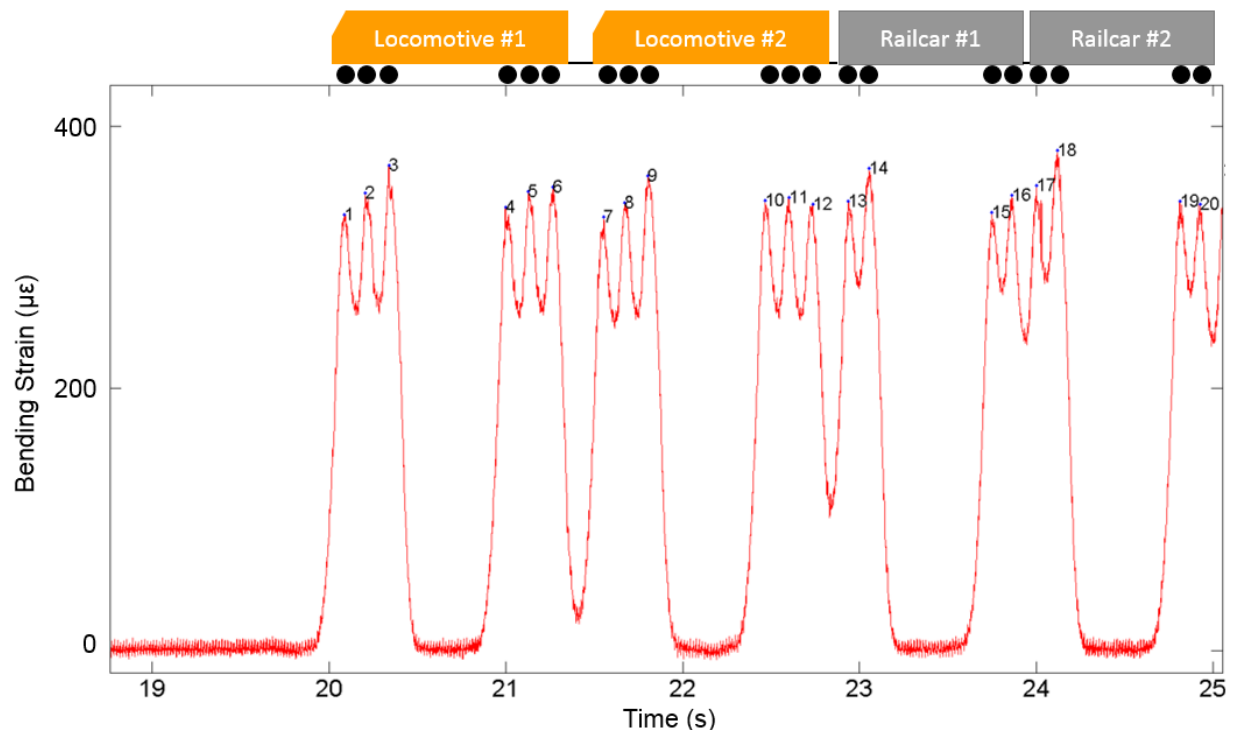
**FIGURE 3 Profile View of Instrumented Crosstie**

### DATA ANALYSIS PROCEDURE

To quantify the bending moments concrete crossties experience in revenue service, peaks in the strain gauge signal caused by crosstie bending due to an axle load must be extracted from the data stream. This was accomplished using the "findpeaks" function in MATLAB (9). To improve the performance of this function for this application, several of the built-in options were utilized. To ensure that the true peaks were being captured by the program, as opposed to false peaks that did not represent the extreme strain

reading for a given axle pass, a minimum spacing between the peaks was specified and a minimum value for all peaks was set. To improve this process, a simple algorithm utilizing a while loop was implemented, which used the number of axles on the train as an input. The number of axles were determined using either wheel impact load detector (WILD) data, visual inspection of the passing train, or a manually-adjusted findpeaks function.

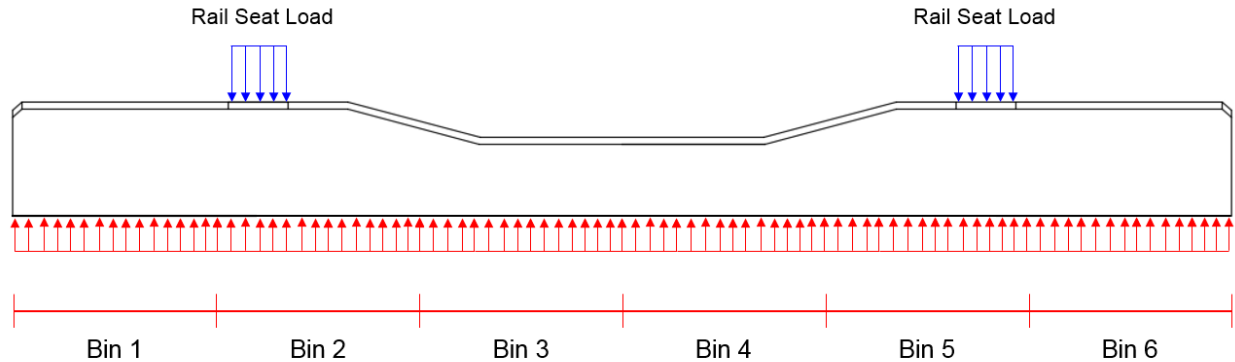
Before these peaks were obtained, the strain signal was zeroed, smoothed using a moving average filter of five data points, and the baseline was corrected to adjust for any signal drift. To aid in signal processing, data collection was started several seconds prior to the arrival of the leading axle of the first locomotive into the experimental zone. This provided a stable zero point for the crosstie under no applied load. Additionally, the data collection was ended several seconds after the passing of the final axle of the train to serve as an end point for the baseline correction. Figure 4 shows an example of a typical signal for a center gauge with each peak labeled. Each peak was then stored in a column vector with one row for each axle on the train and one column for each crosstie, and the peak strains were eventually converted into bending moments using the calibration factors mentioned previously.



**FIGURE 4 Typical Strain Signal Captured Under the Passage of a Loaded Train**

To quantify the ballast reaction below the crosstie, a ballast support back-calculator was developed in MATLAB. Figure 5 illustrates the 2-D crosstie model that the computation was based on. The crosstie was divided into 6 discrete bins of equal size, and within each bin, the ballast reaction force was assumed to be uniformly distributed. The rail seat loads were also assumed to be uniformly distributed over 6 in. (15 cm) on each rail seat, and the magnitudes of the rail seat loads can be calculated by using the formula from AREMA MRE with wheel load values obtained from the nearby WILD site. The goal of this back-calculator was to find a combination of reaction forces within the 6 bins that would generate bending moments at the 5 strain gauge locations along the crosstie similar to the values converted from the strain gauges themselves. Boundary conditions were set such that reaction forces added up from all bins should equal the sum of both rail seat loads and no bin can experience a negative value. Pareto distribution and simulated annealing were used in the computation algorithm, because they were proven to be effective at finding the global optimum (10, 11). The calculation was set to complete when the difference between the calculated moments and measured moments reached its minimum, and the calculator would output the reaction force within each bin. The reaction force distribution shown in Figure 5 is an assumed scenario when the crosstie experiences a uniformly distributed ballast reaction, and it is

not intended to represent any actual result from the back-calculator. The ballast reaction force could be later converted to ballast pressure by dividing the force over the width of the crosstie.



**FIGURE 5 Crosstie Model for Ballast Support Back-Calculator (with Assumed Uniform Support Condition)**

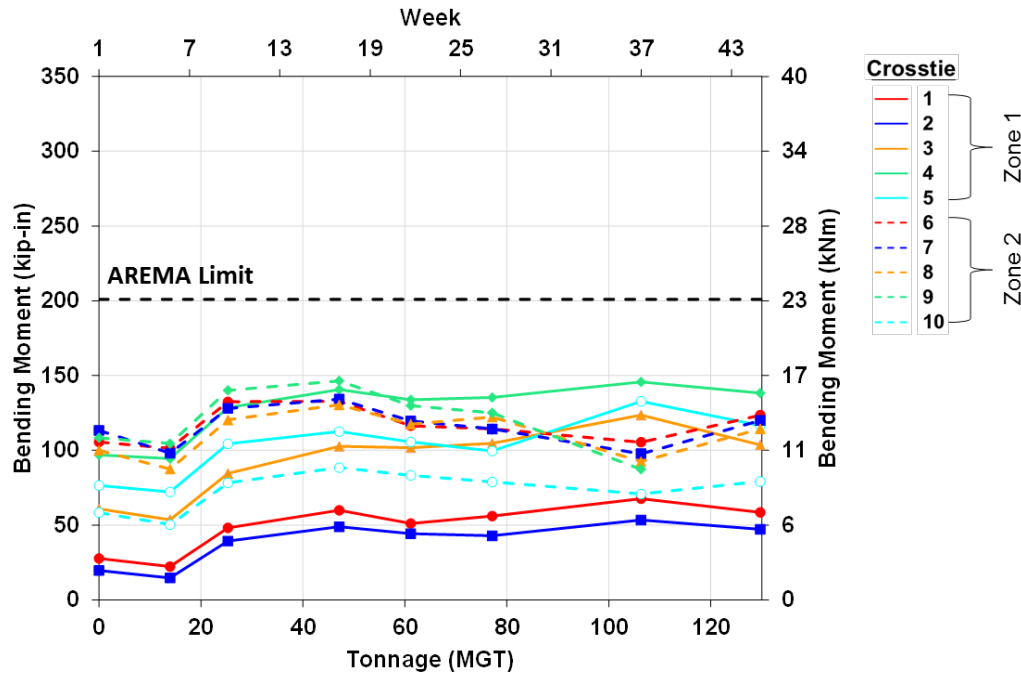
## RESULTS

From March 27<sup>th</sup>, 2015, to January 5<sup>th</sup>, 2016, 8 visits to the site were made with approximately 6 to 8 weeks apart from each visit, and a total of 70 train passes and 38,954 loaded axles were collected. During the period, UIUC researchers were able to analyze the bending moments induced by loaded axles from the signals of all strain gauges mounted on all 10 crossties. One exception occurred during the January visit, as the data from the center gauge of Crosstie 9 were lost due to the incorrect placement of one module into the data acquisition system. Overall, the entire instrumentation plan was proven to be robust, as no surface strain gauge was damaged over this time period.

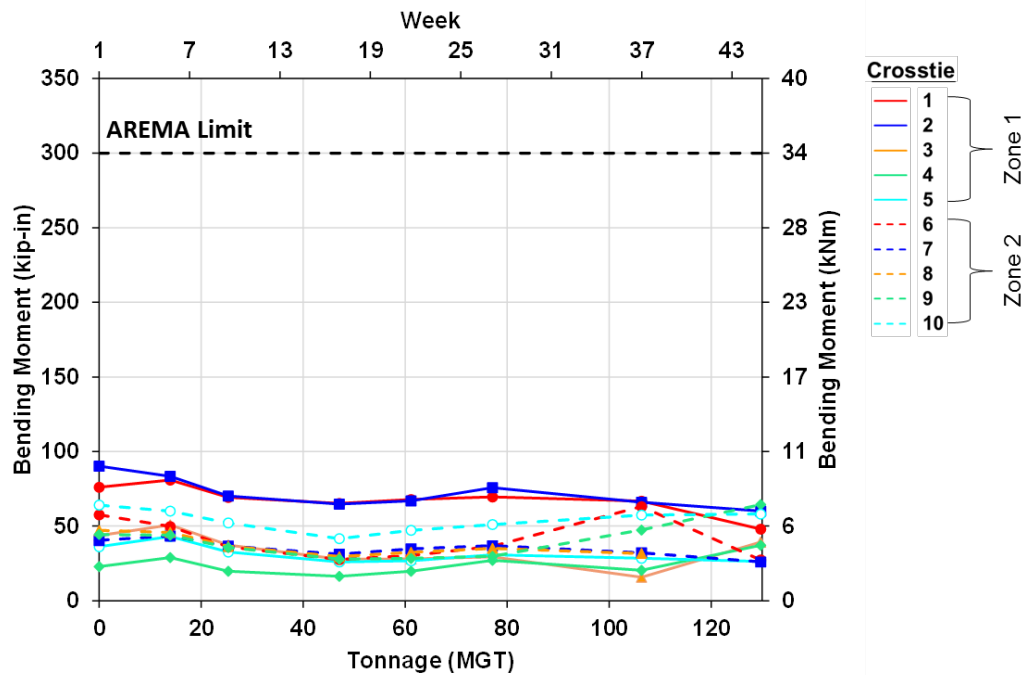
### Overview of Measured Bending Moments

Over 120 million gross tons (MGT) of heavy-haul traffic had accumulated on the site since the first visit in March, 2015. Figure 6 (a) and (b) show how the average center negative bending moments and rail seat positive bending moments changed as tonnage increased. In general, average center negative bending moments exhibited a relatively steady trend, with the majority of the crossties experiencing a slight increase over the entire time (i.e. 10% for Crosstie 7 and 8) and a few crossties experiencing a slight decrease during a shorter period (i.e. 4% for Crosstie 9 and 5 % for Crosstie 10 from August to September). Average rail seat positive bending moments remained relatively steady as well, but overall showing a slight decrease (i.e. 9% for Crosstie 3 and 10). Furthermore, as average center moments increased, average rail seat moments tended to decrease, and vice versa. It is hypothesized that this behavior is explained by the re-distribution of ballast support below the crossties. For instance, if the ballast moved towards the center of the crosstie from its ends, a center binding support condition would develop, which would cause an increase in center bending moment and a decrease in rail seat bending moments.

It is noticeable that no crosstie's average bending moments reached the AREMA recommended design limit, especially at the rail seats, as their average moment values were less than one-third of the 300 kip-in (33.9 kNm) that AREMA recommends, meaning that AREMA recommendations might overestimate the flexural demand at the crosstie rail seat section (5). Compared to rail seat moments, average center bending moments were closer to the AREMA recommended value of 201 kip-in (22.7 kNm), with the highest average moment being almost two-thirds of that value, indicating that center bending could be more demanding than rail seat bending (5). This agrees with the previous survey, which suggested that center cracking of concrete crossties was more commonly seen in the field (4).



(a) Average Center Negative Bending Moment

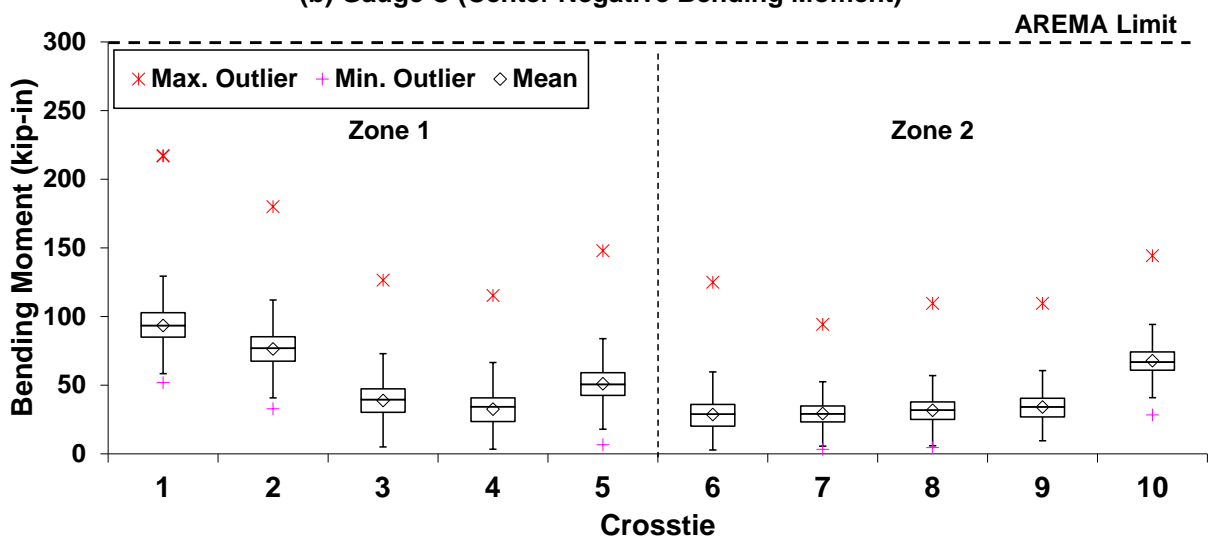
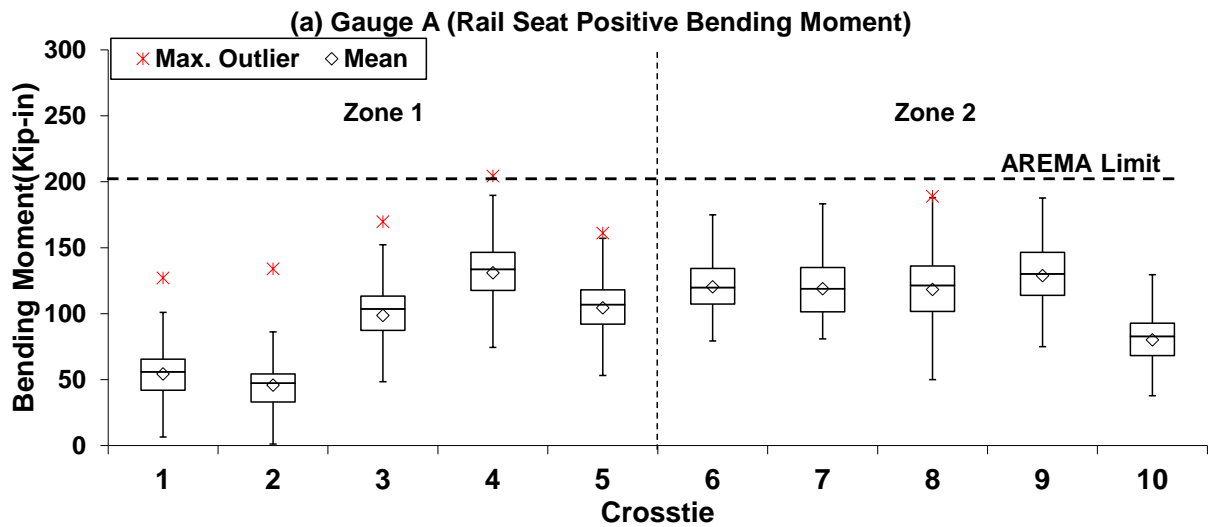
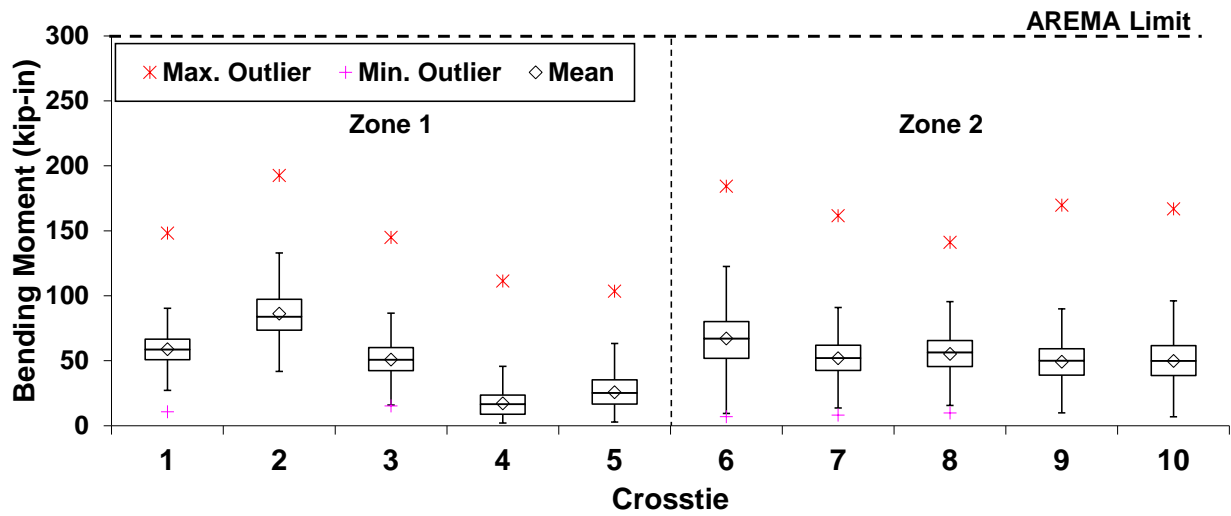


(b) Average Rail Seat Positive Bending Moment

FIGURE 6 Effect of Tonnage on Average Crosstie Bending Moments

### Variation of Measured Bending Moments

Each point in Figure 6 represents a value averaged from thousands of data. To visualize the distribution of measured bending moments of each crosstie over time, box-and-whisker plots were developed (Figure 7) for each crosstie.



**(c) Gauge E (Rail Seat Positive Bending Moment)**  
**FIGURE 7 Box-and-Whisker Plots of Measured Bending Strains**



The top line of the box represents the 75<sup>th</sup> percentile bending moment (Q3). The middle line is the median bending moment. The bottom line of the box represents the 25 percentile bending moment (Q1). The interquartile range (IQR), found as Q3 minus Q1, can provide an estimate of the variability of the data set – the greater the IQR, the higher the variability. The upper whisker shown in Figure 6 is the limit for upper outliers, which are defined as data points greater than Q3 plus 1.5 times the IQR (or  $Q3 + 1.5 \cdot IQR$ ) (12). Similarly, the lower whisker is the limit for lower outliers, which are defined as data points smaller than Q1 minus 1.5 times the IQR (or  $Q1 - 1.5 \cdot IQR$ ) (12).

As can be seen in Figure 7, moment distributions for crosstie centers and rail seats are quite different. To be more specific, both rail seats had more occurrences of outliers than crosstie centers. These outliers are hypothesized to be the result of high impact loads caused by flat wheels. The presence of more rail seat outliers suggests that rail seat bending is more sensitive to wheel defects than center bending. In addition, center bending moments appeared to be more variable, since they had larger IQRs than rail seat bending moments. This indicates that center bending is more sensitive to support conditions than rail seat bending.

The values of the center bending moment outliers are closer to the AREMA recommendations than the rail seat bending moment outliers. It should be noted that Crosstie 4's center bending moment outliers exceeded the AREMA recommended design value twice. That is, of the 38,954 loaded axles that passed over the crosstie, only two axles induced center bending moments over the AREMA recommendation of 201 kip-in (22.7 kNm). The probability of exceedance was calculated to be 0.005% for Crosstie 4 and 0.0005% for all 10 instrumented crossties. Both of the probabilities were considered to be insignificant, thus indicating that the bending of the crossties at this location would only cause center moments to exceed the recommended values under very rare circumstances or if the support conditions were to vary more than they already had. Besides that, Crosstie 4 appeared to have no distinct center cracks that would constitute a failure per Code of Federal Regulations (CFR) 213, the Federal Railroad Administration (FRA) Track Safety Standards (TSS) (13). Therefore, even though center bending moments exceeded the design limit for Crosstie 4, it still served its functionality. It is also more evident in Figure 7 (a) and (c) that AREMA might overestimate the flexural demand on rail seats, as all the outliers of rail seat bending moments were below the AREMA limit.

### **Variation of Support Conditions**

It is hypothesized that the primary source for the difference in bending strains between crossties is the ballast support conditions. This is because the wheel loads experienced by each crosstie generally varied within 3 kips. Furthermore, only 2% of all the wheel loads imparted on the site exceeded 65 kips, the magnitude of high-impact wheel loads that indicates the need for wheel inspection as set by the Association of American Railroad (AAR) (14). Additionally, only 0.2% of all those wheel loads exceeded the AAR defined condemnable limit of 90 kips. Therefore, Crosstie-to-crosstie support condition variability, even between adjacent crossties, can be seen in Figure 7. For example, although Crosstie 9 and 10 are adjacent to one other, the center support varied to the extent that Crosstie 9 experienced a bending moment that was nearly 50 kip-in (5.6 kNm) higher than Crosstie 10. The support conditions were also found to be inconsistent in the transverse direction (i.e. length of the crosstie). This is seen by comparing the boxes of Gauge A and E (Figure 7). Even though some of the crossties (i.e. Crosstie 10) indicated symmetric support, with similar medians for Gauge A and E, the IQR and outlier magnitudes varied greatly. However, more often, Gauge A and E showed different behaviors (i.e. Crosstie 4) where Gauge A's low bending moment suggests that the rail seat was poorly supported. This poor rail seat support is also suggested when noticing that the center negative bending moments at crosstie 4 were greater than any other crosstie.

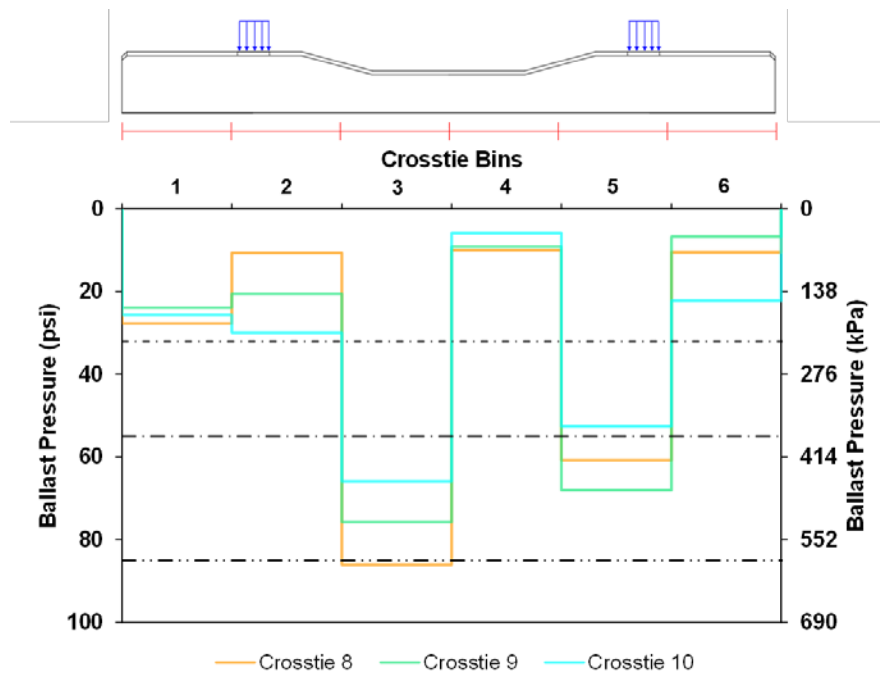
It is important to note the difficulty in assessing support conditions from a surface-level inspection. As mentioned previously, when installing instrumentation at this site, Zone 2 was expected to be the region with less center binding and lower center negative bending moments while Zone 1 was expected to be more center bound with higher center negative bending moments. However, two opposing conclusions could be drawn from the bending moments recorded with respect to the two zone's actual support conditions. First, the initial visual inspection prior to instrumentation was accurate, given the highest center negative bending moment recorded throughout the entire data collection period was on Crosstie 4 located in Zone 1, and given the center moments experienced by crossties in Zone 1 experienced greater variation than those in Zone 2. Conversely however, on average, Zone 1 experienced lower center negative bending moments and higher rail seat positive bending moments,

when compared to Zone 2. This could indicate that the ballast support within Zone 2 was better maintained. Given that currently there is no standard to assess the well-being of ballast support conditions, neither of these conclusions can be verified.

Although it is difficult to visually inspect the ballast support condition, the ballast reaction along the bottom of the crosstie can be calculated using the ballast support back-calculator. Figure 8 shows the resultant distribution of ballast support when wheels passed over the crosstie and induced a rail seat load of approximately 18 kips on each rail seat. The vertical axis is in reverse order, indicating a larger magnitude of ballast reaction (in pressure) when the bar extends further down to the bottom of the graph. For instance, in Figure 8 (a), Crosstie 8 experienced its highest ballast reaction of 86 psi (592 kPa) at Bin 3 and its lowest ballast reaction of 10 psi (69 kPa) at Bin 4. If the support condition was assumed to be uniform, then the ballast pressure would be 32 psi (221 kPa) for all bins, and this value is represented as the top black dashed line labelled "Uniform Ballast Pressure" in both Figure 8 (a) and (b). The middle black dashed line represents the ballast pressure when the subgrade stress reaches the allowable value that AREMA recommends (25 psi (172 kPa)) (5). This ballast pressure was calculated based on the Talbot Equation using the allowable bearing stress of subgrade, assuming a typical ballast depth of 12 in (30 cm), and a typical subballast depth of 6 in (15 cm) (5). AREMA recommends 85 psi (586 kPa) as the allowable ballast surface stress for concrete crossties, and this value is represented in the bottom dashed line (Figure 8).

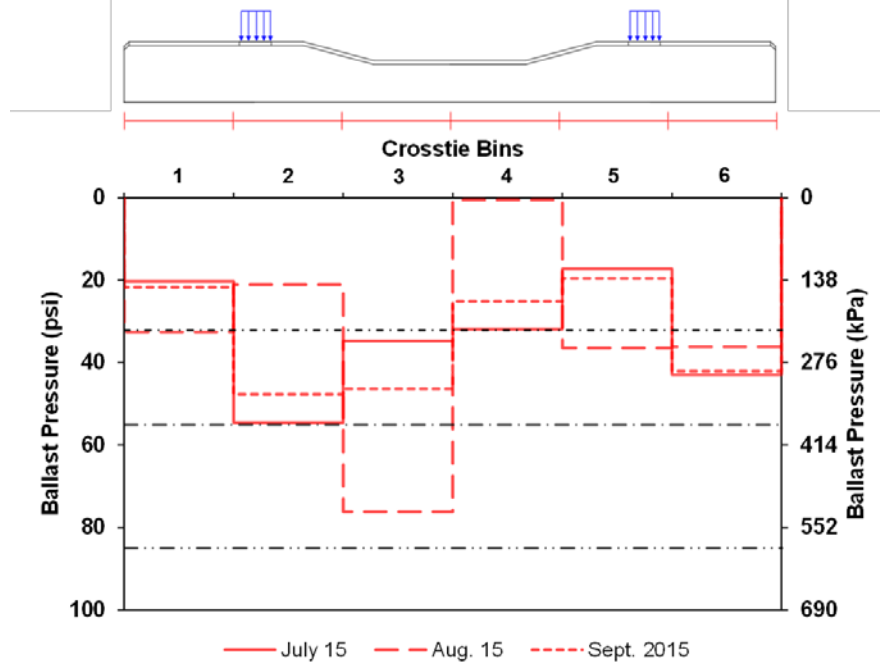
As can be seen in Figure 8, support conditions varied from crosstie to crosstie (Figure 8 (a)) and as tonnage increased (e.g. from month to month) (Figure 8 (b)). Figure 8 (a) shows that the ballast reaction below the crossties can vary though the crossties are only 24 in (61 cm) apart from one another. The greatest difference occurred at Bin 2, where there was a 48% difference in reaction between Crosstie 8 and 9, and 31% between Crosstie 9 and 10. In Figure 8 (b), a distribution of ballast support for Crosstie 3 was selected from each month for 3 months starting in July, 2015, and differences between reaction forces were observable at every bin. Bin 4 exhibited an extreme case, where in August, 2015, the reaction decreased to nearly zero, indicating a gap was created between the crosstie bottom and the ballast surface within the bin, when a particular wheel passed over the crosstie.

It is noticeable that in both Figure 8 (a) and (b), the reaction of some bins exceeded the ballast pressure calculated based on the allowable subgrade bearing stress. If this exceedance continued to occur, it could lead to subgrade bearing capacity failure. In Figure 8 (a), the ballast reaction in Bin 3 of Crosstie 8 exceeded the allowable ballast surface stress. If this exceedance happened frequently, it could cause the accelerated deterioration of ballast within those bins, and even ballast crushing. Track geometry defects could also develop due to these higher ballast pressures. Therefore, certain maintenance activities (i.e. tamping) might be needed for the track to function properly without having any obvious crosstie issues.



--- Calculated Ballast Pressure Based on Uniform Support Assumption  
 --- Calculated Ballast Pressure Based on AREMA Allowable Subgrade Bearing Stress  
 --- AREMA Allowable Ballast Surface Stress under Concrete Crosstie

(a) Distribution of Ballast Reaction for Crosstie 8, 9, and 10



--- Calculated Ballast Pressure Based on Uniform Support Assumption  
 --- Calculated Ballast Pressure Based on AREMA Allowable Subgrade Bearing Stress  
 --- AREMA Allowable Ballast Surface Stress under Concrete Crosstie

(b) Distribution of Ballast Reaction for Crosstie 3 from July, 2015 to September, 2015  
 FIGURE 8 Investigation of Ballast Reaction through Ballast Support Back-Calculator

## CONCLUSIONS

Overall, this project was successful in measuring the bending strains and resulting moments experienced currently in North American heavy-haul freight traffic. The effectiveness of surface-mounted concrete strain gauges in measuring crosstie bending behavior was demonstrated. From this work, several conclusions were drawn relating to the flexural behavior and support conditions of concrete crossties at this location on a revenue heavy-haul freight service:

- Bending strains measured at center and rail seats of concrete crossties on a heavy-haul freight tangent track in North America remained relatively constant over a tonnage accumulation of over 120 MGT.
- Bending strains measured at the crosstie rail seat are less variable but more sensitive to high impact wheel loads than those experienced at the center. This could be due to more direct loading from the wheel, less sensitivity to support conditions, or more uniform support conditions under the rail seat.
- On only two occasions, bending moments measured at this test site exceeded current AREMA MRE design recommendations, however, most of the instrumented crossties showed micro-cracking. This could be because the cracking does not propagate to the top layer of prestressing steel. It should be noted that although center-cracking is seen on these crossties, they are performing sufficiently and have not been the source of any geometry defects.
- Bending moments measured at this test site show a high degree of variability in support conditions. Varying bending behavior under similar wheel loads suggests that support conditions can be variable in both the longitudinal and transverse directions, even between adjacent crossties.
- Ballast pressures below crossties were highly variable based on the results from the ballast support back-calculator. At times, the allowable subgrade bearing stress and allowable ballast surface stress were exceeded, with crossties showing no failure, thus indicating the potential for accelerated ballast deterioration.

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# Field Measurements and Proposed Analysis of Concrete Crosstie Bending Moments



Zhengboyang Gao, Henry Wolf, Riley  
Edwards, Marcus Dersch, and Yu Qian



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# Outline

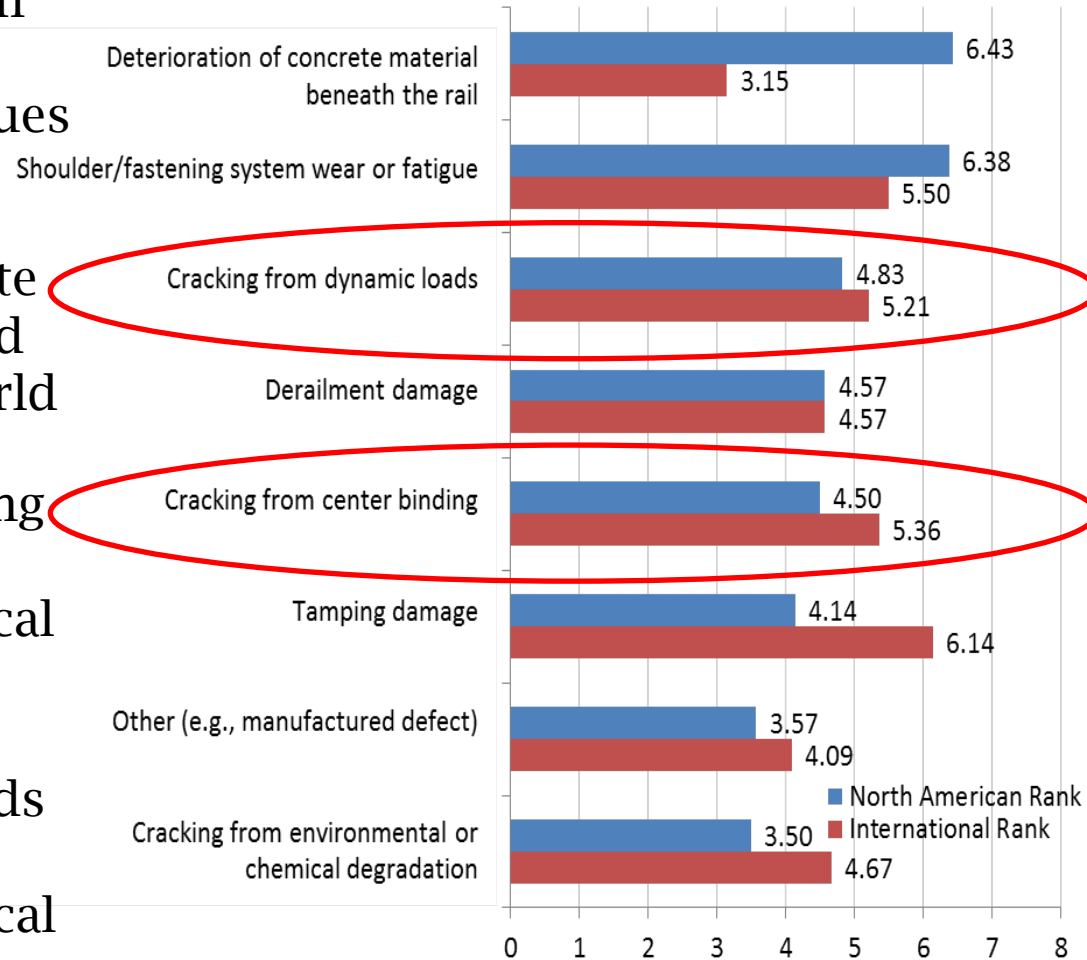
- Background and motivation
- FRA laboratory experimentation
- Field experimentation
- Ballast support back-calculator
- Conclusions
- Future work





# Project Background

- In 2013, UIUC conducted an international survey to determine most critical issues in concrete crosstie track
- Survey of railroads, concrete crosstie manufacturers, and researchers around the world
- Cracking from center binding (3<sup>rd</sup> most critical problem – International, 5<sup>th</sup> most critical – North America)
- Cracking from dynamic loads (4<sup>th</sup> most critical problem – International, 3<sup>rd</sup> most critical – North America)



# Motivation for Research

- Previous analysis of FRA accident database indicated that deteriorated concrete crossties and support conditions are among the major track related accident causes in the US

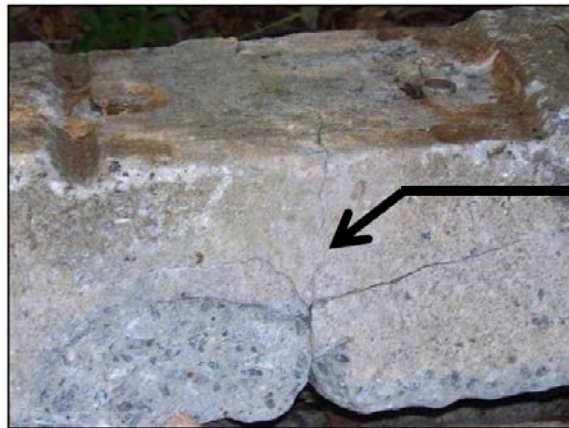


Broken crosstie



Fouled ballast

- Industry partners stated that rail seat positive cracks are rarely seen in the field



Rail seat positive crack



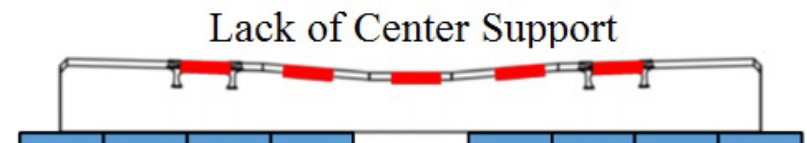
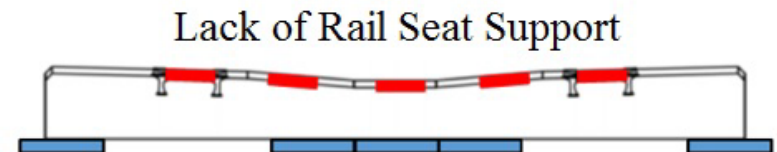
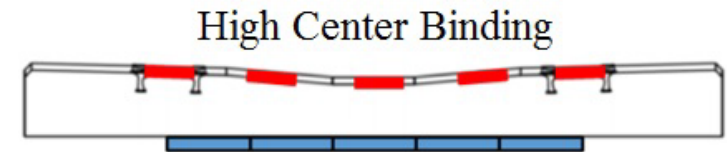
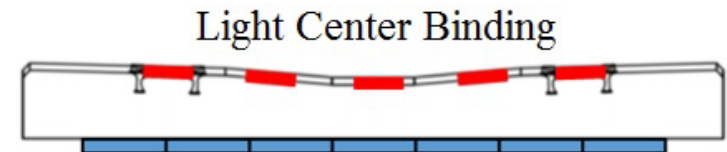
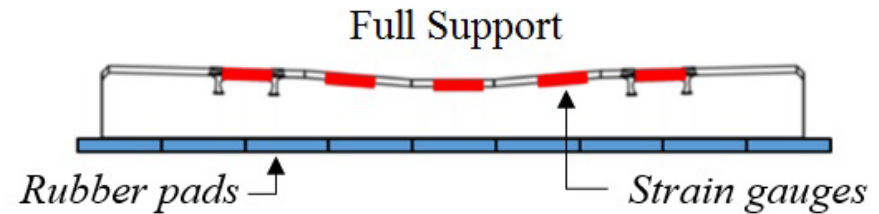
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# Laboratory Experimentation

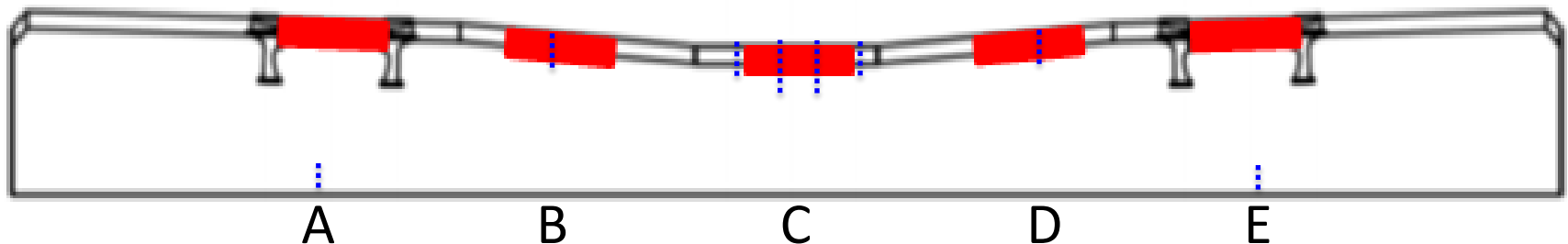
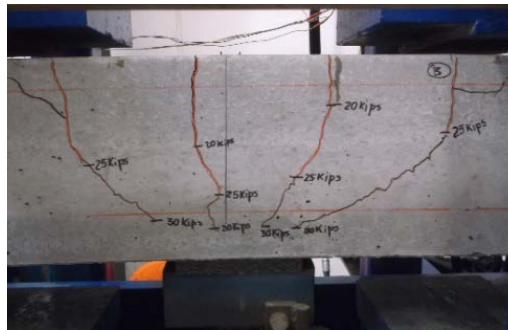
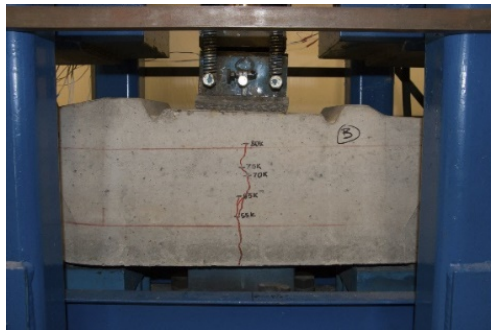
- Measure bending moments with different support conditions
- Support conditions
  - Proper support
  - Center binding
  - Rail seat positive
- Cases were based on:
  - Field conditions
  - Expert opinion
  - Industry partners feedback on draft experimental matrix



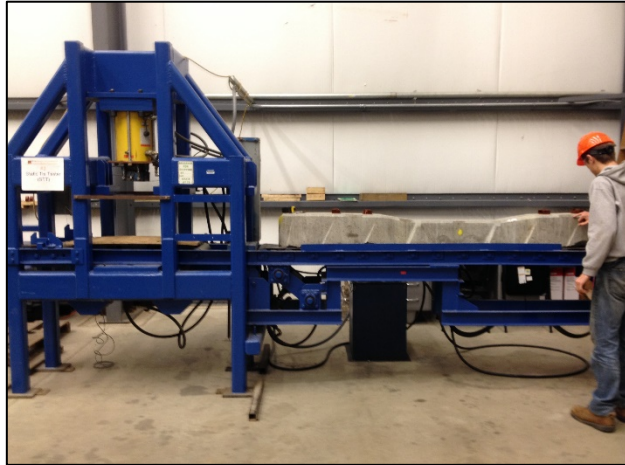


# Crosstie Instrumentation

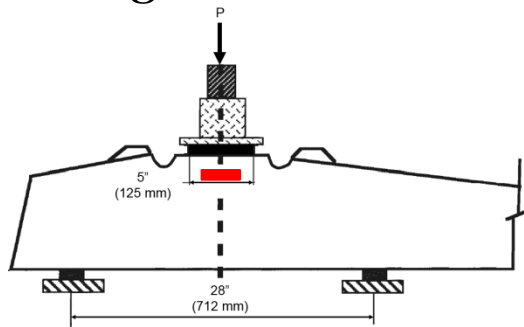
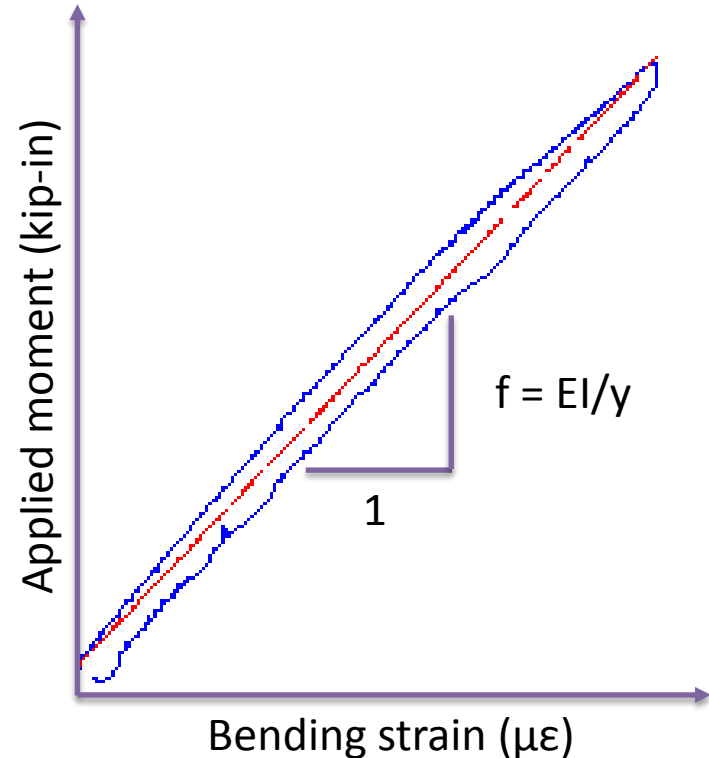
- 5 surface strain gauges installed on each crosstie:
  - Rail seat gauges (to measure rail seat positive bending)
  - Center gauge (to measure center negative bending)
  - Intermediate gauge (to measure asymmetric loading or support)



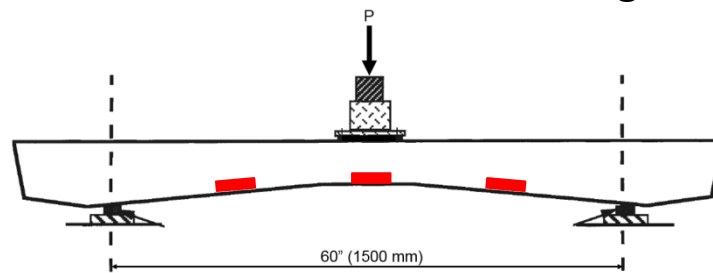
# Strain to Moment Laboratory Calibration



Known moment applied with Static Tie Tester (STT) to crosstie in controlled loading configurations, record bending strain and find slope of curve



Rail Seat Positive

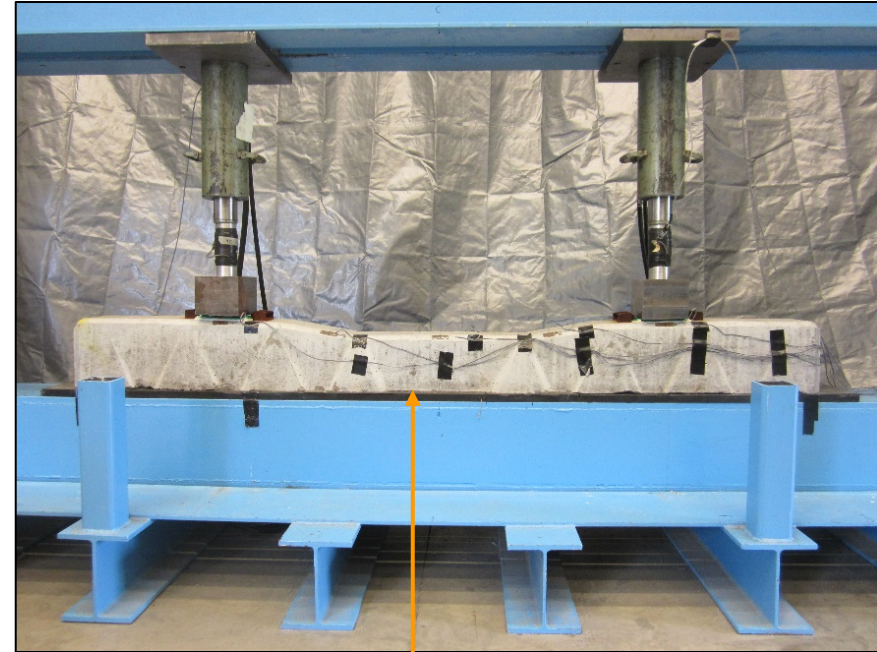
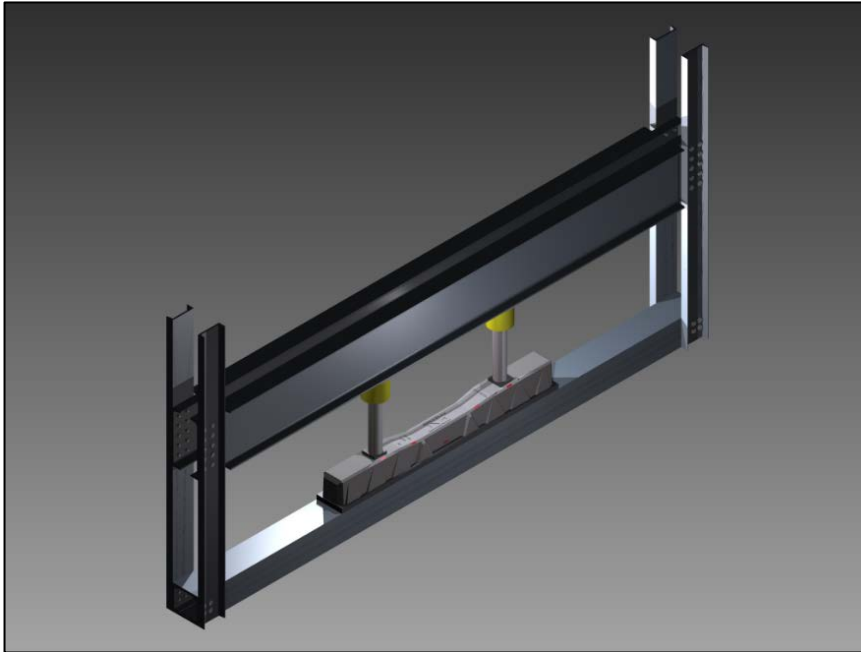


Center Negative



# Laboratory Experimentation Equipment

- Loading frame - Static Load Testing Machine (SLTM)



- Supporting rubber pads

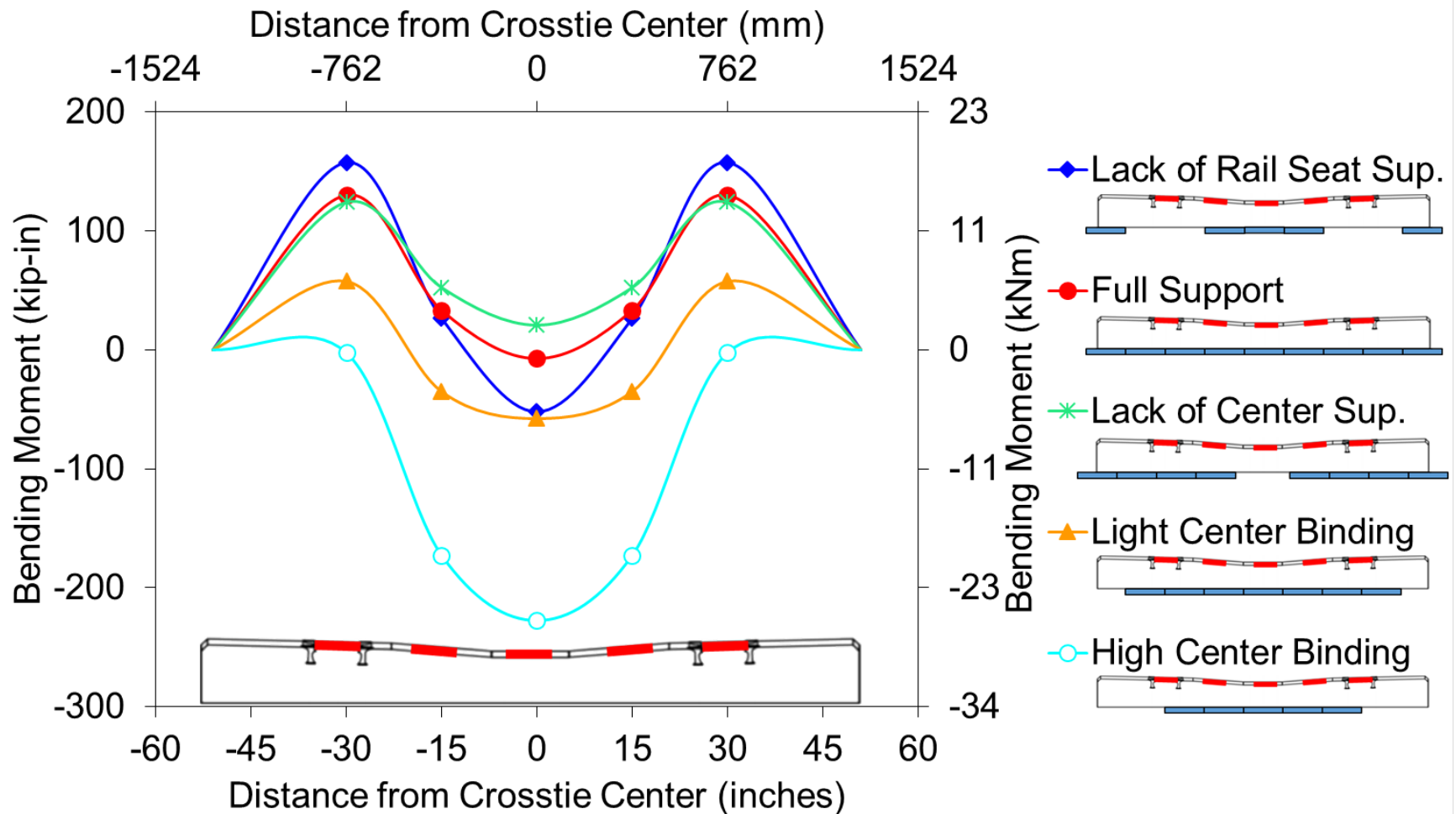


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# Flexural Performance under Different Support Conditions

*Rail Seat Load: 20 kips (89 kN), Healthy Crosstie*



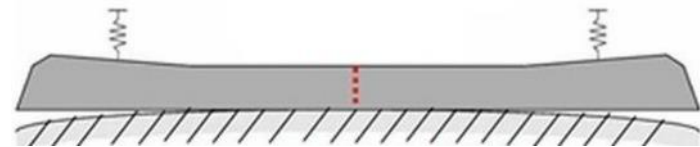
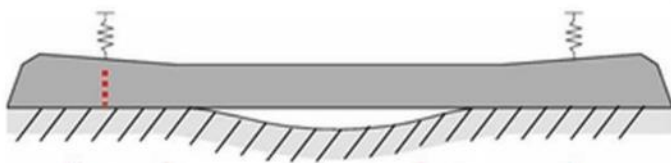
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# Laboratory Experimentation: Preliminary Conclusions

- Small amounts of center binding can result in large differences in center moment:
  - 241.2 kip-in change for high center binding (at center)
  - 78.6 kip-in change for light center binding (at center)
- Rail seat moments are less sensitive to changes in support:
  - 33.4 kip-in change for lack of rail seat support (at rail seat)
- Center negative cracks are more likely than rail seat positive cracks and support conditions play a major role in the crosstie performance



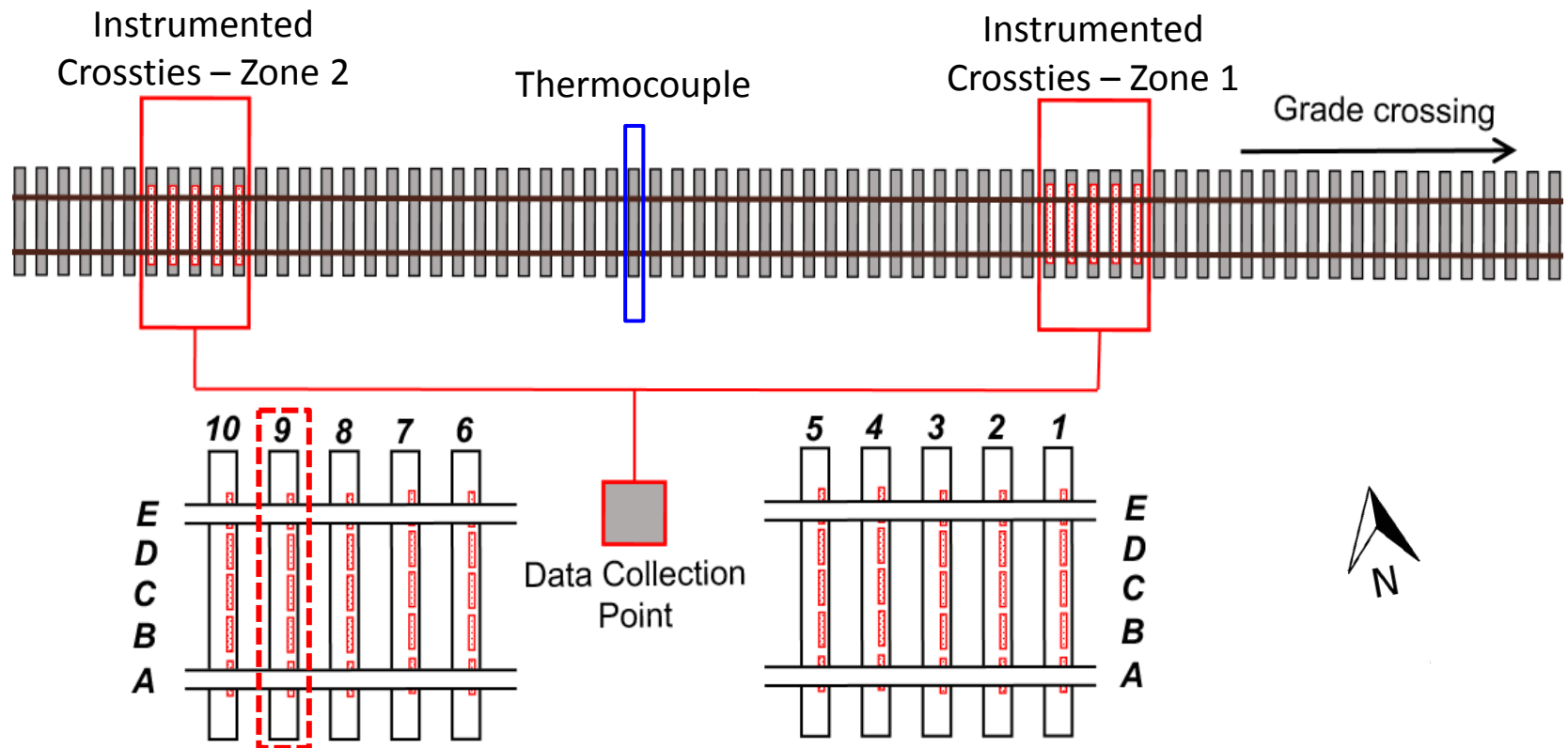
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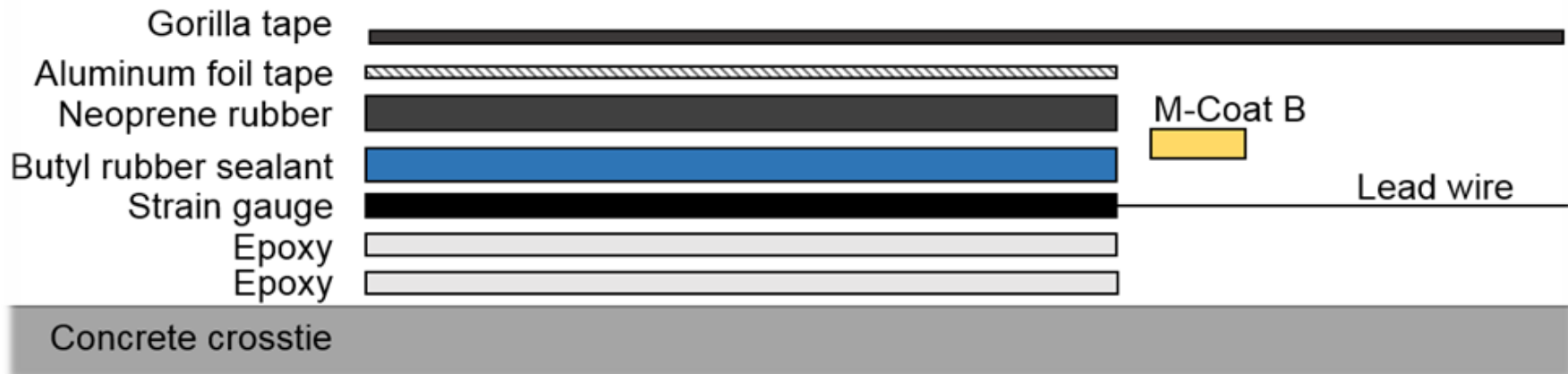
# Field Site Layout

- Site split into two zones of five crossties each
- Concrete surface strain gauges installed on 10 crossties



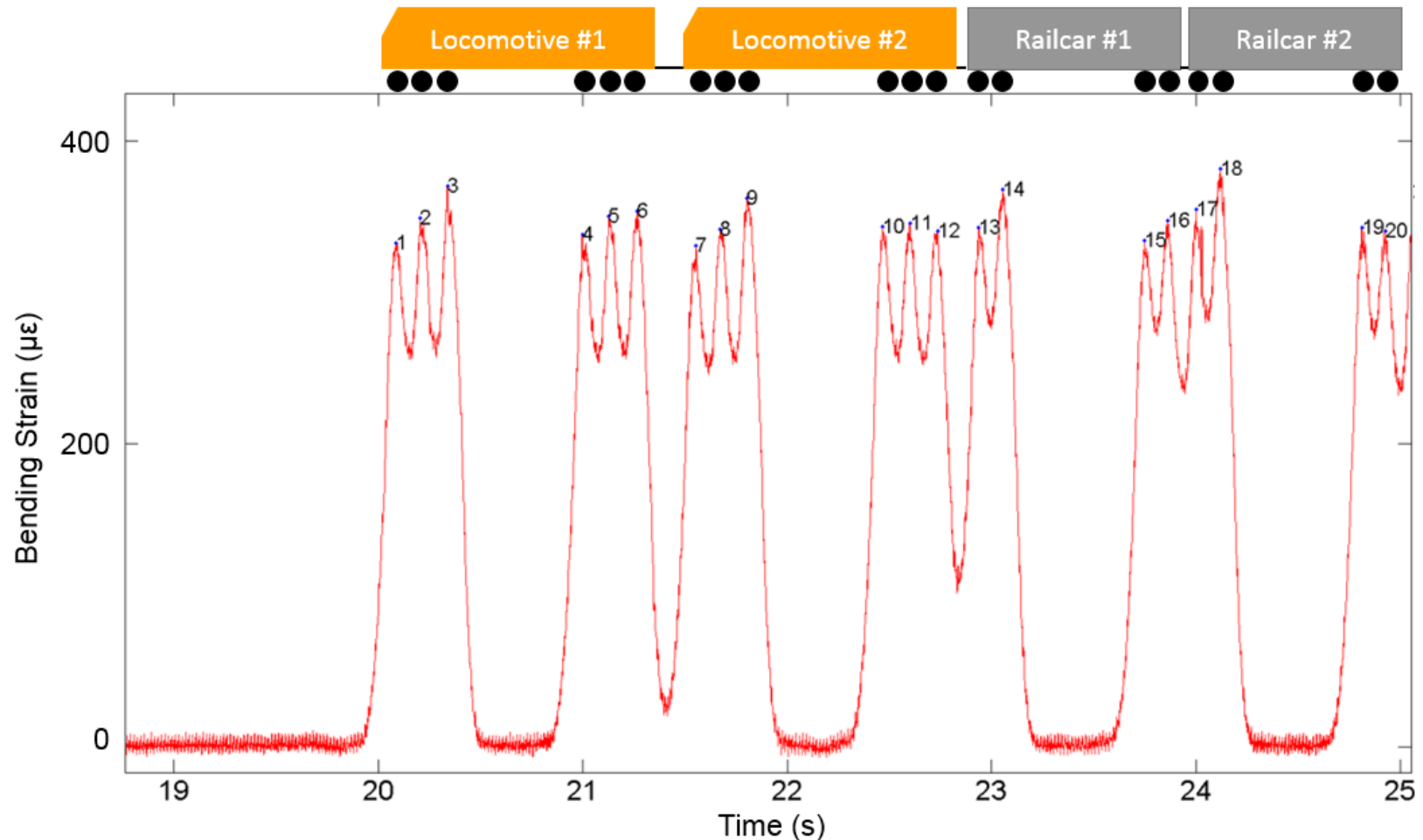
# Instrumentation Protection Plan

- Surface strain gauges are delicate sensors and must be protected
- Potential types of damage:
  - Mechanical damage – impacts or pressures caused by train passes or maintenance activities
  - Moisture damage – ingress of water can cause wire shorts and failures

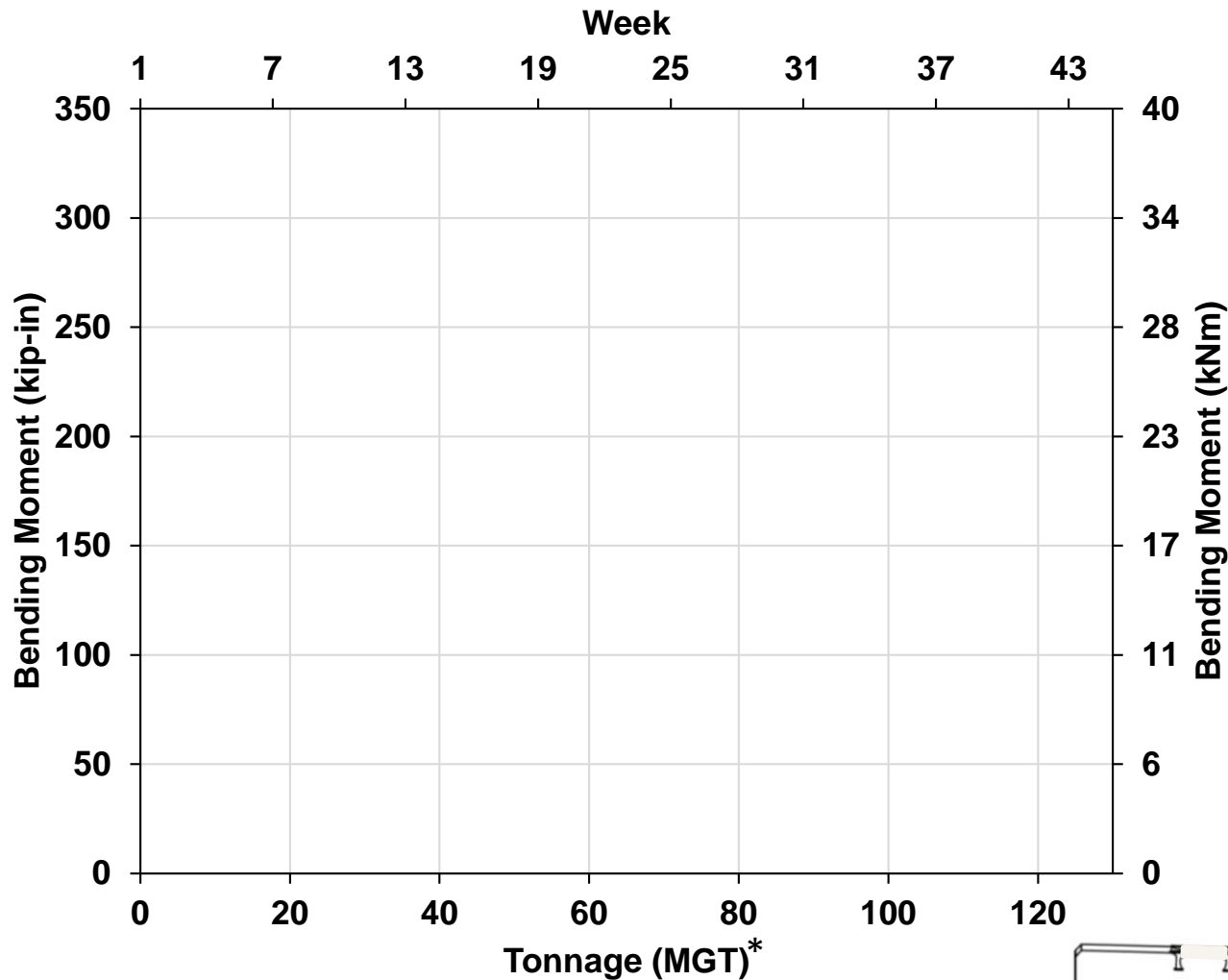


# Example Strain Signal (Gauge C)

- Strain peaks correspond to loaded axles



# Average Center Negative Bending Moment vs. Time/Tonnage (Gauge C)



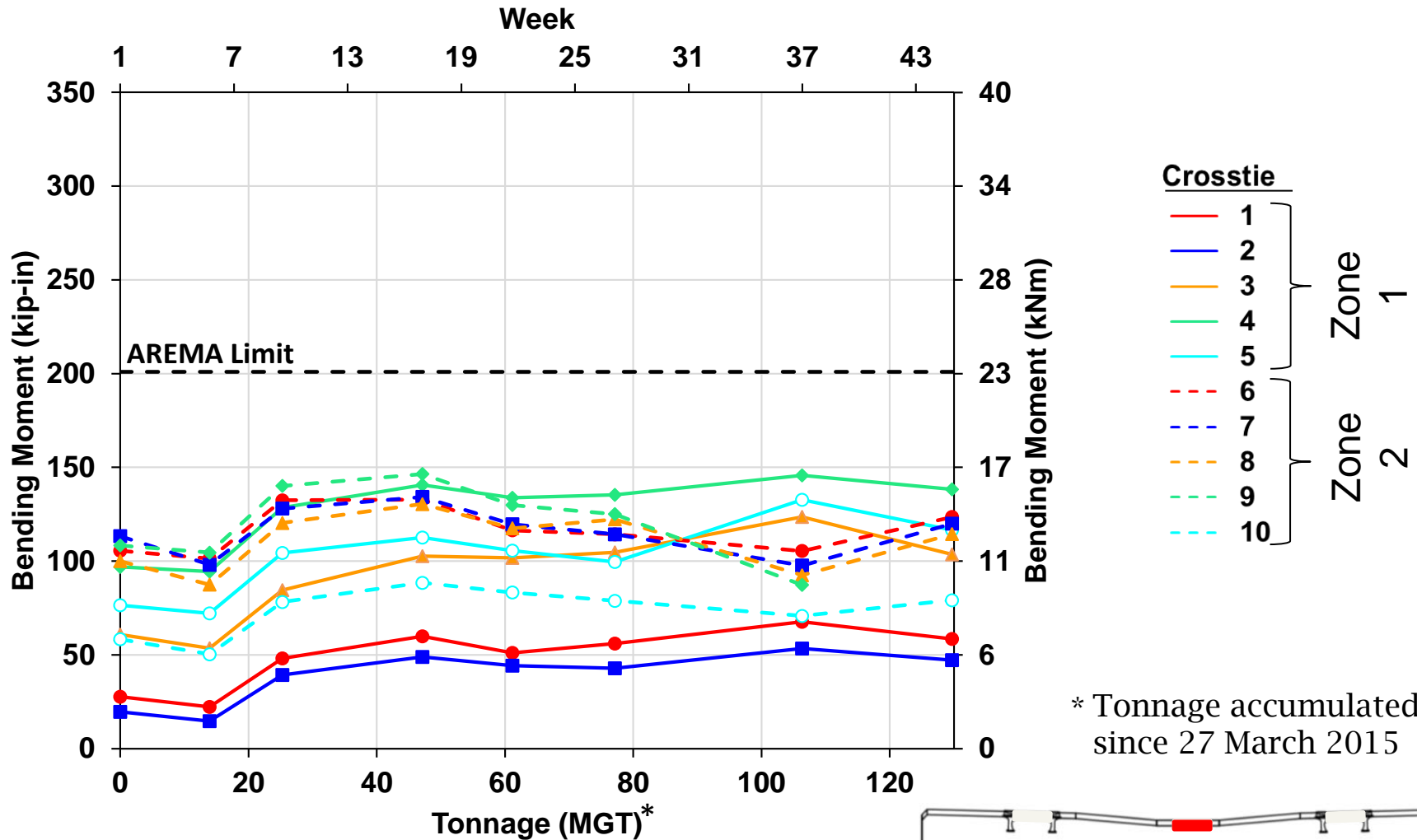
\* Tonnage accumulated since 27 March 2015



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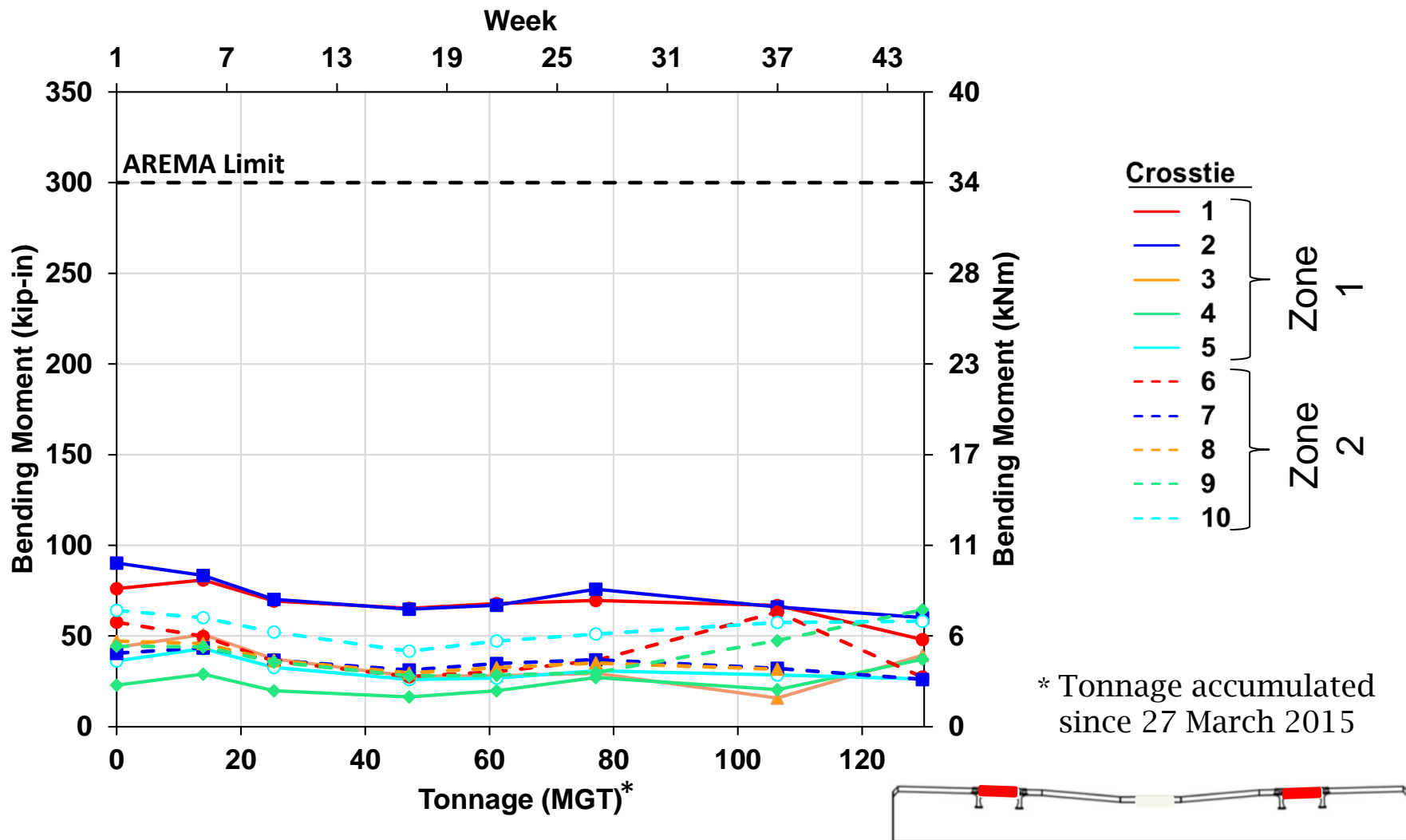
# Average Center Negative Bending Moment vs. Time/Tonnage (Gauge C)



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# Average Rail Seat Positive Bending Moment vs. Time/Tonnage (Gauge A & E)



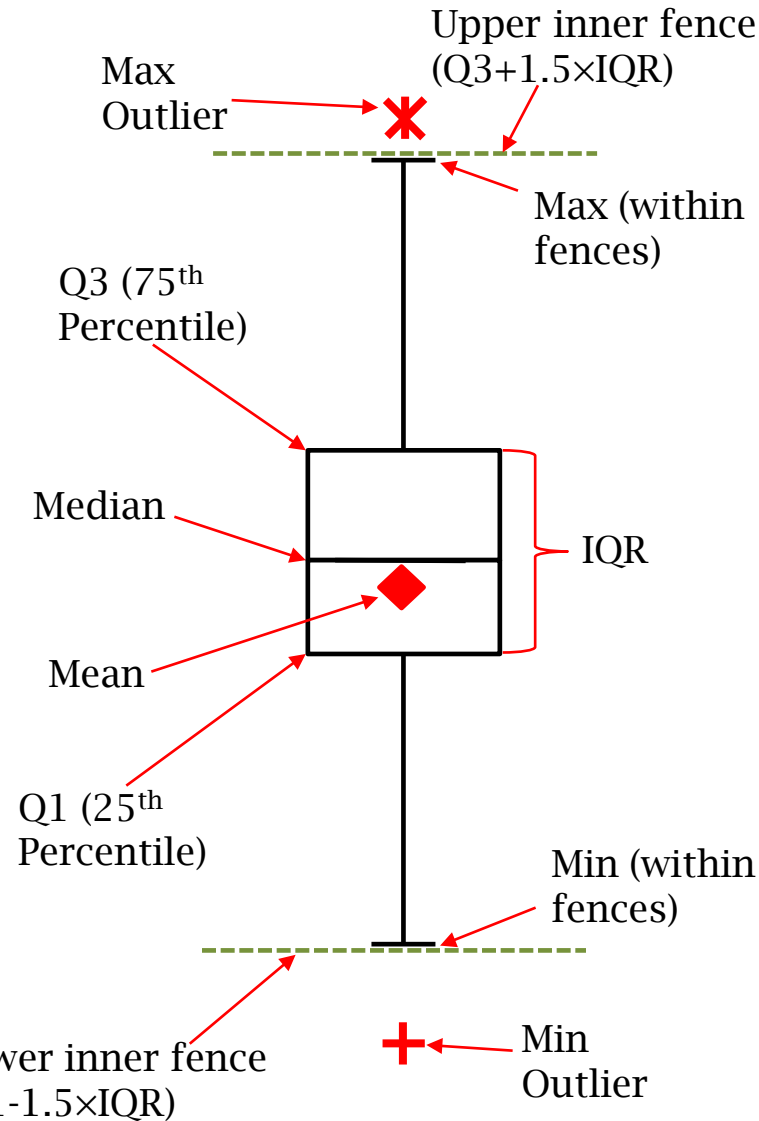
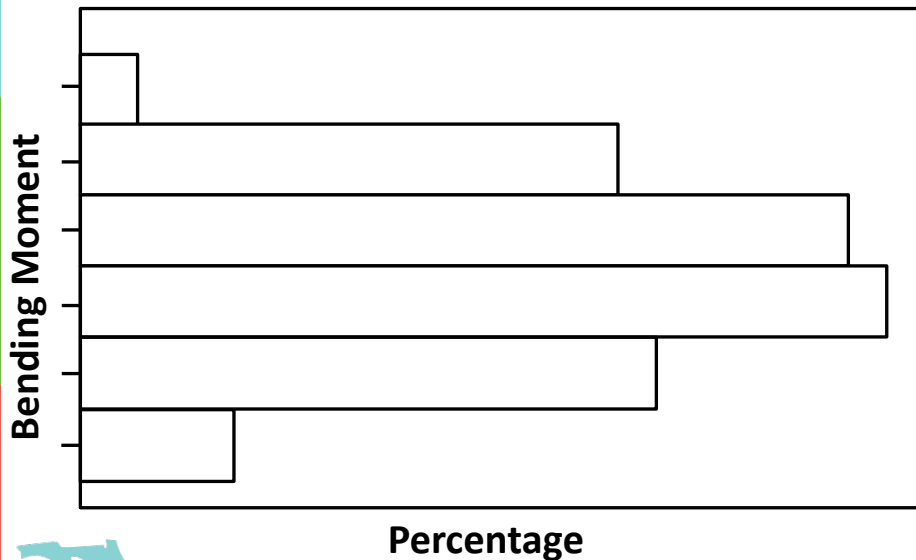
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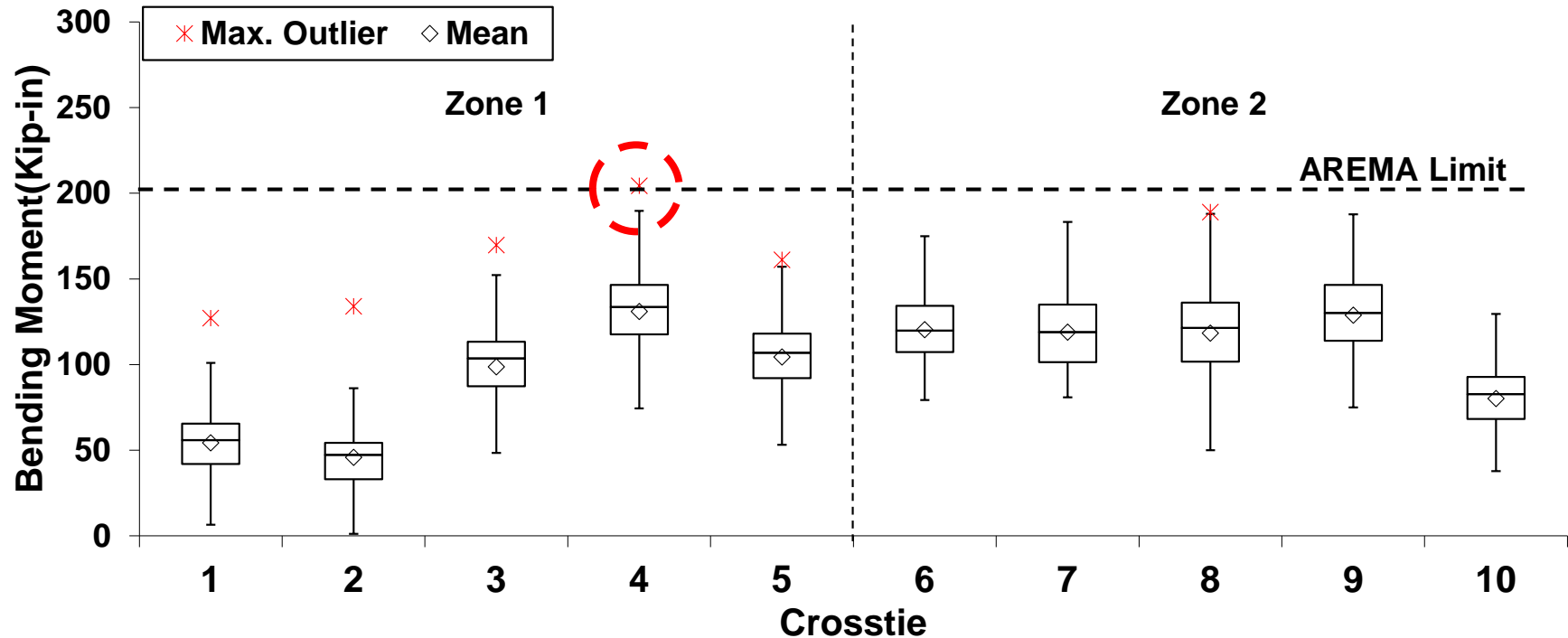


# Box Plot Background

- Box plots are great to:
  - Visualize outliers
  - Compare variability of different cases
  - Check for symmetry
  - Check for normality



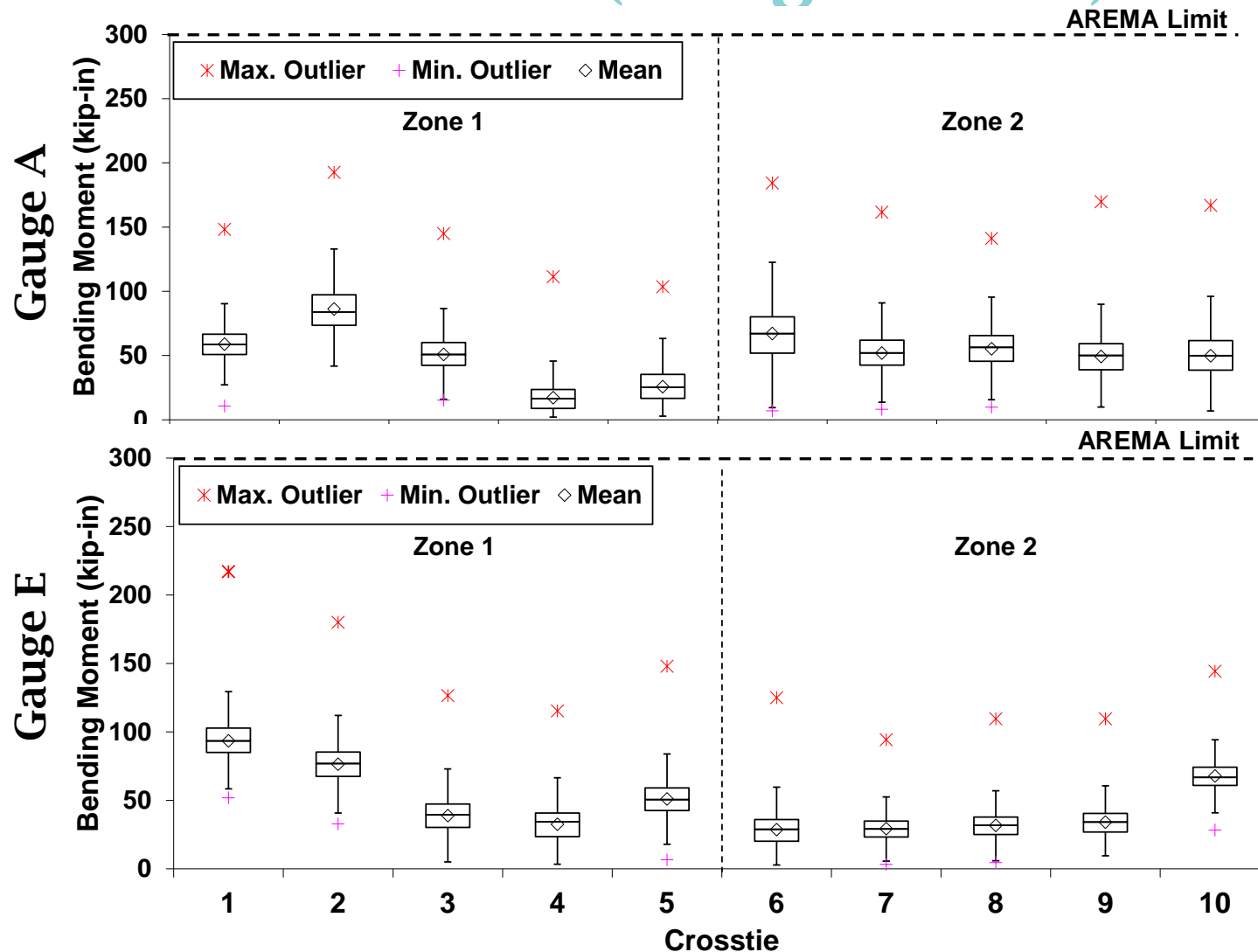
# Box Plot for Center Negative Bending Moment (Gauge C)



- However, only 2 of 38,954 loaded axles exceeded the AREMA limit
  - 0.005% exceedance probability for Crosstie 4 and 0.0005% for all 10 crossties



# Box Plot for Rail Seat Positive Bending Moment (Gauge A & E)



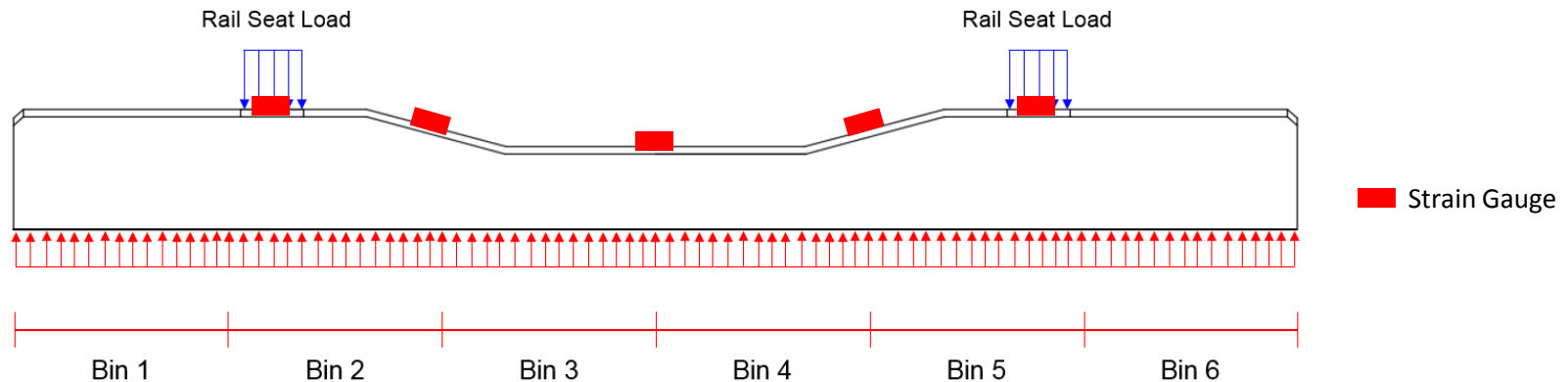
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# 2-D Crosstie Bending Model

- Assume rail seat load is uniformly distributed across rail seat
- Divide the crosstie into 6 bins:
  - Each bin consists a percentage of total reaction force
- 9 inputs:
  - Known bending moments from 7 locations
  - 2 approximated rail seat loads
- 2 boundary conditions:
  - Force equilibrium (sum of all bins should be close to 1)
  - Value of each bin should not be negative



# Ballast Pressure Limit States

- Ballast pressure calculated based on uniform support condition: 32 psi
- AREMA allowable ballast surface stress under concrete crossties: 85 psi
- Ballast pressure calculated based on AREMA allowable subgrade bearing stress (25 psi) using Talbot equation: 55psi

$$h = \left( \frac{16.8p_a}{p_c} \right)^{4/5}$$

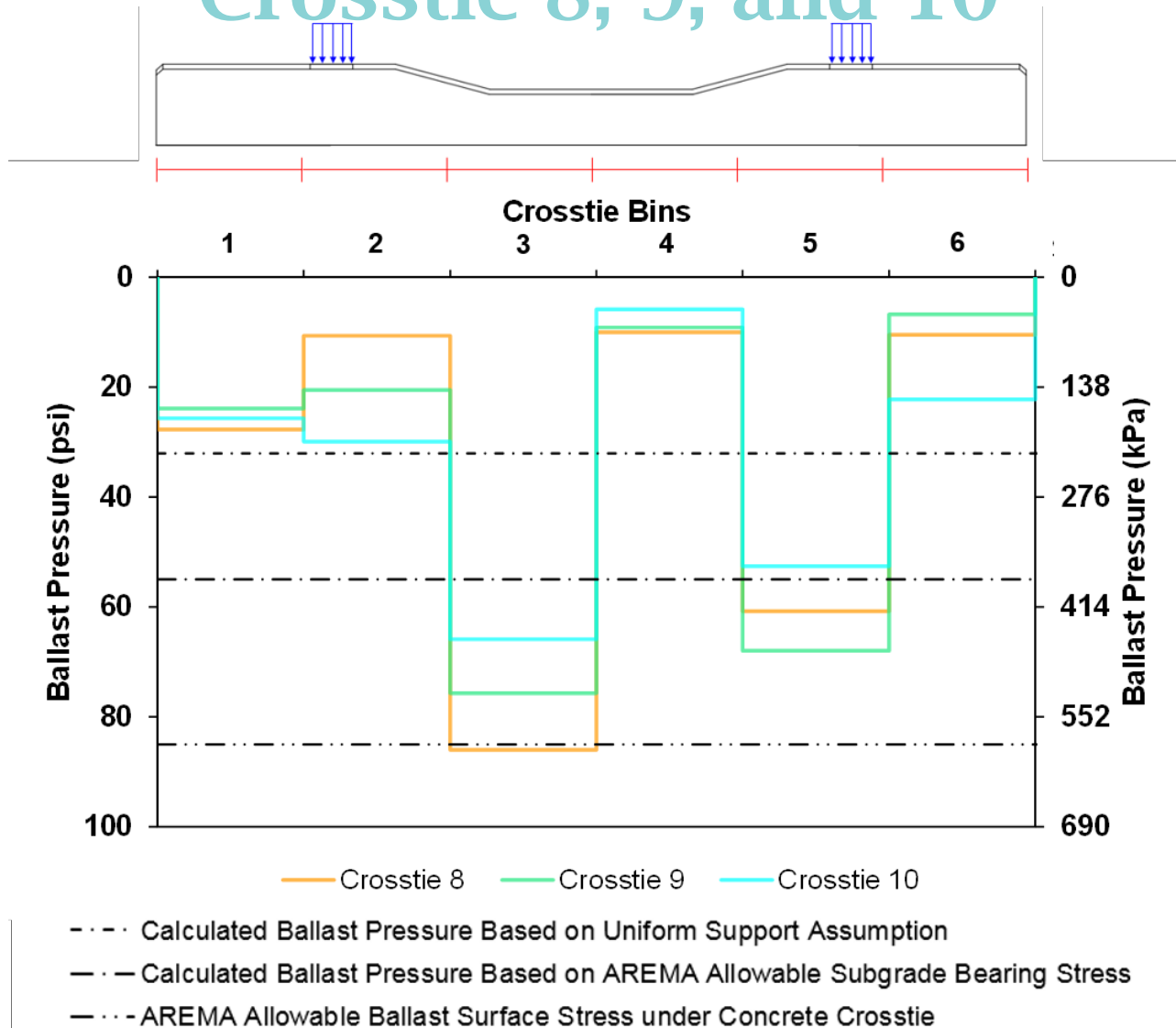
Where, h = Support ballast depth

$p_a$  = Stress at bottom of tie (top of ballast)

$p_c$  = Allowable subgrade stress



# Distribution of Ballast Reaction for Crosstie 8, 9, and 10





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# Conclusions

## Laboratory and Field Findings

- Lab experimentation suggested crossties' bending behavior was sensitive to support conditions
  - Center bending was more sensitive
- Field instrumentation was proven to be successful
  - No failure over 10 month period or accumulation of 100 MGT
- Field-measured moments in a properly maintained track were relatively stable over 100 MGT
- Center negative bending moments approached AREMA recommended design limits

## Resulting Design Implications

- AREMA Committee 30 currently finalizing new design approach which will increase C- and decrease RS+
- UIUC developing support back-calculator to better identify crosstie support conditions to further improve crosstie/track design and maintenance recommendations



# Future Work

- Dynamic laboratory experimentation
  - Crack initiation and propagation
- Continue field data collection and data analysis
  - Collect data before and after tamping
  - Collect data at various locations, under various modes of traffic, and with varying crosstie designs
- Refine ballast support condition back-calculator



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  - TTX Company
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# Any Questions?



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