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Federal Railroad Administration

Office of Research, Development and Technology
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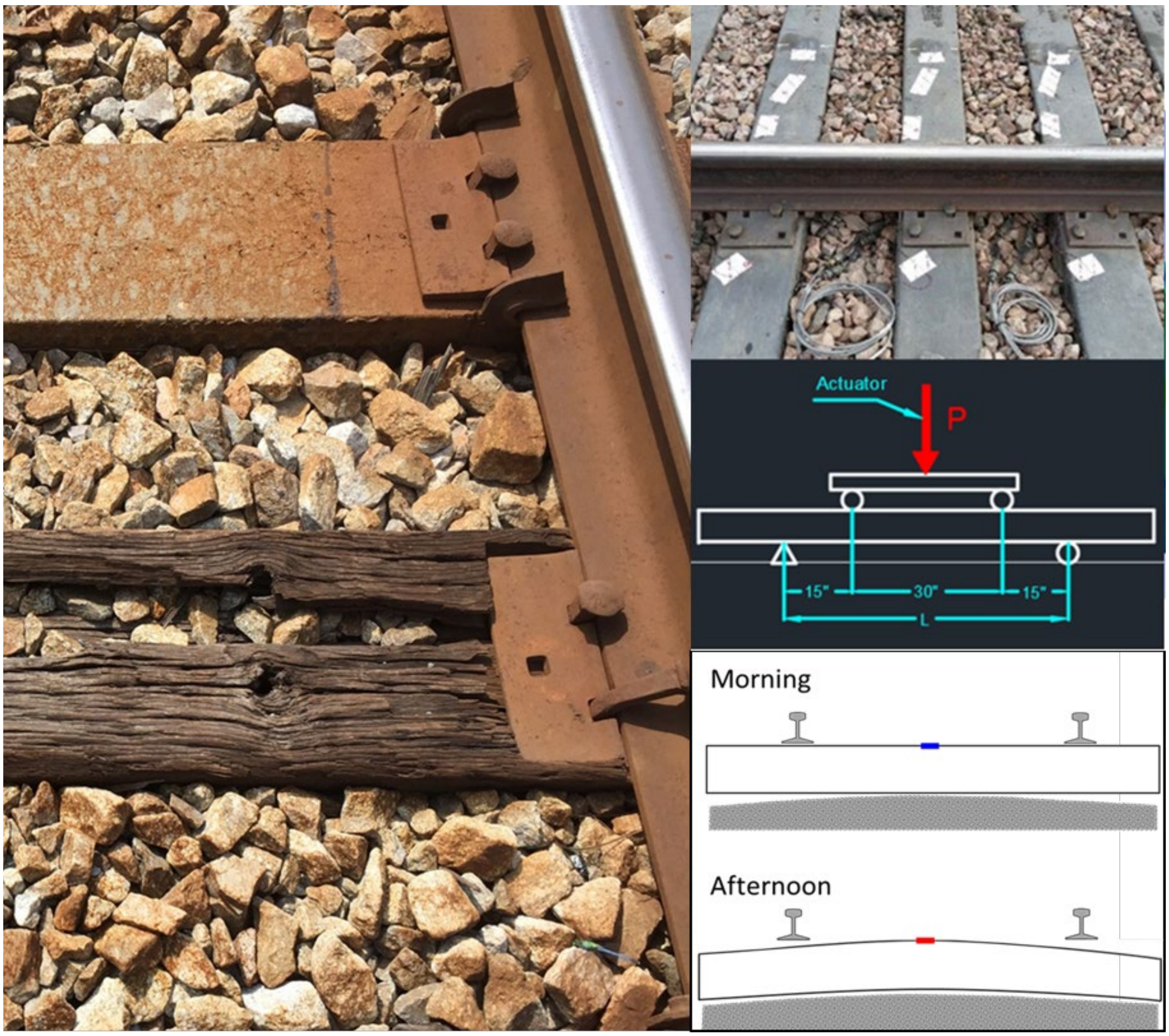
Improved Polymer Composite Tie Performance



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13. ABSTRACT (Maximum 200 words)
For regions experiencing high rot and decay, engineered-polymer composite (EPC) ties offer a potential alternative to solid-sawn timber ties. However, these ties have a history of inconsistent performance and existing AREMA laboratory qualification testing have not proven effective in identifying the chief failure modes before in-track installation. The Federal Railroad Administration and the Association of American Railroads' Strategic Research Initiatives program collaborated to investigate improvements to the design and testing recommendations for EPC ties. AREMA publishes these recommendations in Chapter 30 – Ties of the AREMA Manual for Railway Engineering. Field testing at FRA's Transportation Technology Center and in revenue service showed the two key failure modes for EPC ties are center cracking and spike-hole cracking. Further, these field observations also showed the ambient temperature may significantly affect the loading environment and track gage of EPC ties at any given time of the day. This report presents a new fatigue test setup to address the center cracking issue and proposes a modified AREMA Test 6 to address the spike-hole cracking issue.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

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METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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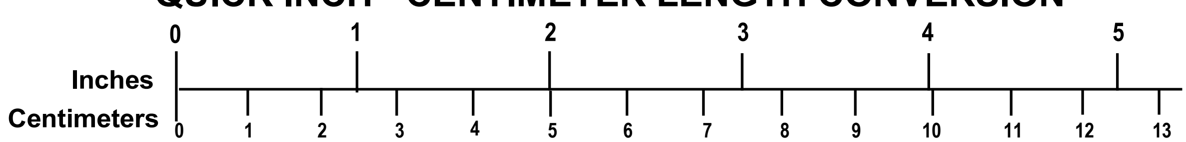
QUICK INCH - CENTIMETER LENGTH CONVERSION



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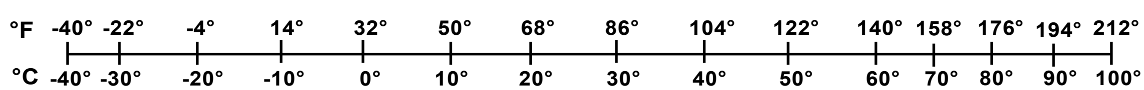

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Together, ties and fasteners act as a synergistic system to (1) transfer vertical and lateral loads from train traffic into the ballast and (2) maintain proper track geometry. Class I railroads use wood ties in more than 90 percent of their track miles. In regions prone to rot and decay, these ties may only remain serviceable for 10 years before replacement is necessary. This is often due to plate cutting and loss of gage strength. Therefore, an opportunity exists for an alternative tie that may offer a longer lifecycle with similar performance. As they are not susceptible to rot or decay, engineered-polymer composite (EPC) ties may be a good alternative to solid-sawn timber ties.

Although the railroad industry has experienced a wide range of composite tie quality and performance issues in revenue service over the years, the two primary failure modes are spike-hole cracking and center cracking. While the American Railway Engineering and Maintenance-of-Way Association (AREMA) publishes design and testing recommendations in Chapter 30 of their *Manual for Railway Engineering*, current qualification testing is not effective in identifying these failure modes before in-track installation, highlighting the need for further study. For this reason, the Federal Railroad Administration (FRA) and the Association of American Railroads' Strategic Research Initiatives Program collaborated to investigate improvements to the design and testing recommendations for EPC ties.

This report summarizes the results of this collaborative research, which led to an improved understanding of how EPC tie and fastener systems perform and how to better evaluate them. Key findings and insights resulting from this study include:

- In-track testing at the Facility for Accelerated Service Testing (FAST) and in revenue service identified spike-hole cracking and center cracking as the two primary failure modes for EPC ties. Of the 300 EPC ties installed at FRA's Transportation Technology Center (TTC), 43 have failed as of May 2017. New fatigue testing recommendations are in development as current methods do not adequately assess these failure modes for EPC ties.
- While more research is needed, modeling and in-track observations suggested that 13-inch plates may perform better on EPC ties, which are more resistant to plate cutting. Larger plates (such as 18-inch AREMA plates) produced larger bending stresses on EPC ties compared to standard 14-inch plates or smaller plates.
- Field measurements showed that temperature variation could affect the static track gage of EPC ties. A 0.2-inch gage variation was recorded within a day throughout three EPC tie test zones at FAST.

Research-driven testing methods and best practices will serve as tools for EPC tie suppliers and railroads to evaluate improved tie and material designs for consistency and capability. In turn, this process will help further the safe and reliable use of EPC in the industry.

Through the course of the project, the research team noted additional concerns for the long-term performance of EPC ties, especially regarding the impact of thermal radiation on track stability. Therefore, future research suggestions include an understanding of the thermal effects on EPC tie performance and, more specifically, the implications on track safety and overall track performance, as well as the implementation of improved recommendations related to this topic.

1. Introduction

Engineered-polymer composite (EPC) ties are the most common composite railroad ties and have been used sparingly in North America for about two decades. These ties are made primarily of post-consumer recycled plastic. While two EPC tie designs tested at the Facility for Accelerated Service Testing (FAST) amassed 1.7 billion and 2.1 billion gross tons of traffic, respectively, the railroad industry has experienced a wide range of quality and performance issues involving EPC ties in revenue service tracks. This has raised concerns about their long-term performance, including problems such as center cracking and warping (i.e., center bending), cracked tie plates, spike-hole cracks, and wide gage situations due to thermal expansion.

The industry has a broad interest in improving the EPC design recommendations suppliers use to ensure safety and performance in revenue service operations. Research needs include recommendations about what load environments to include in design and what testing methods should be necessary to ensure the satisfactory performance of EPC ties. As such, high-level questions facing the industry include:

- How will EPC ties perform in various revenue service conditions?
- How well do EPC ties integrate into existing installation and maintenance procedures?
- What testing is necessary to ensure satisfactory safety and performance?
- How should railroads, third-party laboratories, and supplier quality control departments assess performance?

The current American Railway Engineering and Maintenance-of-Way Association (AREMA) *Manual for Railway Engineering* recommends that suppliers perform the same gamut of testing on EPC ties as recommended for wood and concrete ties and fasteners. These tests include tie center bending, rail seat bending, spike insertion and pullout, spike lateral resistance, plate compression, repeated load or wear/deterioration testing, electrical resistivity, and single-tie lateral push tests. However, the minimum criteria recommended for EPC ties have only been developed for some tests, and those criteria are mostly anecdotal. The necessary criteria for other tests are still unclear.

Transportation Technology Center, Inc., (TTCI), under the sponsorship of the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR), conducted this investigation with the goal of developing revised design and testing criteria for EPC ties. In 2015 and 2016, TTCI acquired 450 randomly selected EPC ties from three major suppliers (i.e., 150 each). In addition, 150 mixed varieties of hardwood ties were incorporated into the testing as the control group against which the EPC ties would be compared. The research team chose 50 ties of each type for laboratory testing and an additional 100 for in-track testing at FAST. As they performed well in previous test zones at FAST, the team also included the two previously mentioned types of polymer composite ties in the study to better understand the characteristics that have proven successful in experimentation.

1.1 Background

EPC ties have been studied since the mid-1990s. Previous work has been preliminary and broad in nature, primarily focused on lab and in-track testing to evaluate their basic performance properties (e.g., tie bending stiffness and spike retention). An FRA study on how composite ties perform during typical handling and installation procedures concluded in 2014 (Reiff, 2014). The testing within the two EPC tie zones at FAST ended in 2015. One zone was installed in 2000 and the other in 2004, and accumulated 2,155 MGT and 1,690 MGT in total, respectively. In both zones, researchers found loose cut spikes and spike-hole kill recurred when the ties were plugged multiple times toward the end of their service life.

However, one Class I railroad reported more than 1 million composite ties installed on its network have shown inconsistent performance, resulting in a shorter service life for these products. More specifically, Class I railroads noted center cracking in EPC ties as a consistent problem in revenue service. Given this, it is unclear how different properties affect EPC tie performance in-track. Also, doubt persists on how best to assess their expected performance in qualification and quality control testing. Better recommendations and design guidelines will target specific properties of EPC ties and try to correlate laboratory testing performance with in-track testing results.

With these industry needs in mind, the team evaluated multiple types of EPC ties to (1) assess their applicability for Class I operating conditions, and (2) improve design guidelines and recommendations provided in the AREMA *Manual for Railway Engineering*. This project includes laboratory and in-track performance evaluation of EPC ties from three major suppliers, a NUCARS® track model[1] tie and fastening system, and improved design guidelines and recommendations for the AREMA manual.

1.2 Objectives

The objective of this project was to better understand the loading environment, failure types, and performance variability of EPC ties, and how these factors affect the use of EPC ties in revenue service. With this information, improved design, testing, and performance guidelines and criteria for polymer composite ties can be developed. These guidelines will then be added to the AREMA *Manual for Railway Engineering* to improve the safety and reliability of EPC ties.

1.3 Scope

The work includes the following tasks:

- Evaluate and document how the polymer composite ties perform when installed at FAST and in revenue service.
- Conduct laboratory tests to address the observed problems in EPC tie performance.
- Use modeling techniques to extend the scope of laboratory tests and better understand the loading environment of the tie and fastening system of EPC ties.
- Recommend improved design guidelines and best practices for EPC ties.

1.4 Organization of the Report

This Technical Report is broken down into six primary sections (Sections 2 through 7), with associated references (i.e., Section 8). Section 2 details the in-track testing that took place both at

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[1] NUCARS® is a registered trademark of TTCI, Pueblo, CO.

FAST and two revenue service locations in the midwestern United States and elaborates on the various failure modes noted at each location. In Section 3, the development of two new testing methods for EPC ties are presented, namely the four-point tie bending fatigue test and the fastener/rail seat fatigue test. Section 4 summarizes the tie plate compressive testing and associated finite element modeling efforts. Section 5 discusses the influence of daily temperature variations on EPC tie performance based on results observed at FAST and at the Western Mega Site. Sections 6 and 7 present future recommendations for continued research and a summary of the efforts presented in this report, respectively. An appendix depicts the development iterations of the recommended EPC tie bending fatigue test discussed in Section 3.

2. In-Track Evaluation of Engineered-Polymer Composite Ties

This section summarizes the characteristics and installation details of the test beds used in the in-track evaluation. The team used three test beds: (1) FAST, located at FRA’s Transportation Technology Center (TTC) in Pueblo, Colorado; (2) the Western Mega Site, a revenue service test bed in western Nebraska; and (3) a revenue service site near Chester, Illinois. This section summarizes observations and findings from the in-track testing of the polymer composite ties at these locations and discuss recommendations related to testing.

In 2015 and 2016, the team selected polymer composite ties for this study from three major suppliers (i.e., A, B, C, which are consistent throughout this report). Samples were composed of ties randomly selected by test engineers to provide a representative sample of ties produced over at least three different months of production. The selected ties all passed through their respective suppliers’ quality control procedures.

2.1 In-Track Testing at FAST

Researchers randomly selected 100 ties from each supplier for installation at FAST. In addition, the research team installed new hardwood ties, representative of Class I tie species and grades, as a control zone. Track workers installed the three continuous tie zones (i.e., A, B, mixed hardwood) in the summer of 2015 and the fourth zone (i.e., C) in the summer of 2016. All the zones were in Section 25 of the High Tonnage Loop at FAST, a 6-degree curve with 5 inches of superelevation. Heavy-axle-load (HAL) tonnage was accumulated with a train of loaded 315,000 lb (i.e., 39 ton axle load) gondolas. The train operated at 40 mph, which is an approximately 2 inch overbalanced speed for the curve; this helped accelerate component wear, particularly on the high rail. Track geometry in Section 25 is maintained to FRA Class 4 track safety standards.

The research team used 14-inch AREMA plates and standard 5/8 inch cut spikes (i.e., the most common fastening system for wood ties) on 50 ties within each zone. The team then used 18-inch Pandrol Victor plates with 15/16-inch Evergrip double-headed drive spikes on the remaining 50 ties in each zone. Table 1 shows the layout of the four zones evaluated and the pre-drill size used during installation. The track workers installing the ties used a half-inch pre-drill for the cut spikes because it was difficult to drive the spikes with a 3/8-inch pre-drill.

Table 1. EPC Tie and Fastening System Test Zones in Section 25 at FAST

Tie Type	No. Ties	Fastening System	Spike-hole Pre-drill Size (depth of spike)	Tonnage as of 5/19/17 (MGT)	Notes
EPC Tie Type A	50	14” AREMA plates and cut spikes	1/2-inch	230	Random sample of production 2014 to 2015
	50	18” Victor plates and drive spikes	11/16-inch		
EPC Tie Type B	50	14” AREMA plates and cut spikes	1/2-inch	230	Random sample of production 2014 to 2015
	50	18” Victor plates and drive spikes	11/16-inch		
EPC Tie Type C	50	14” AREMA plates and cut spikes	1/2-inch	89	
	50	18” Victor plates and drive spikes	11/16-inch		Random sample of production Dec. 2015 to Feb. 2016
Mixed Hardwood	50	14” AREMA plates and cut spikes	3/8-inch	230	Control for comparison
	50	18” Victor plates and drive spikes	11/16-inch		

2.2 In-Track Testing in Revenue Service

A western railroad installed two revenue service tests of composite ties. The research team designed the revenue service tests to observe the composite tie performance under real-world operational conditions as well as to compare against the results at FAST, which is a controlled environment and may not reflect perfectly the performance under real-world operations. The details of the two revenue service tests are presented below.

- The installation (Figure 1) at the Western Mega Site near Ogallala, Nebraska, which is a high-tonnage and high-demand service environment. Two composite tie designs were installed continuously in two zones, each with 50 ties of each tie type spaced at 19.5 inches. . The team chose a premium fastening system (i.e., 16-inch cast plates with drive spikes and SAFELOK I clips) for this test.

Figure 1. Installation at Western Mega Site

- A second test on the Chester subdivision near Chester, Illinois, was designed to examine polymer composite tie performance when installed one-for-one with wood ties as part of a tie replacement gang (Figure 2). Instead of being installed continuously like at the Nebraska site, the EPC ties at this location were interspersed with existing wood ties. In addition, the test zone was along the Mississippi River, which provided a high-moisture environment. Both the mechanical and environmental effects on tie performance were evaluated at this site. A tie replacement gang installed about 500 EPC ties (i.e., 250 each from two suppliers) between MP 66.00 and 66.50 on July 4, 2015. The team installed Type A ties interspersed between MP 66.0 and 66.25, and Type C ties interspersed between MP 66.25 and 66.50. These ties replaced wood ties that were otherwise slated for removal according to the tie inspector's chart for the test section. The 500 ties represented around one-third of approximately 1,625 total ties in the half-mile section of the track. Six-hole, 14-inch AREMA plates were used throughout this section of the track. The intended spiking pattern is shown in Figure 3. However, as noted below, the EPC ties were generally not spiked this way.

Figure 2. Composite ties inserted one-for-one with wood ties in Chester, Illinois

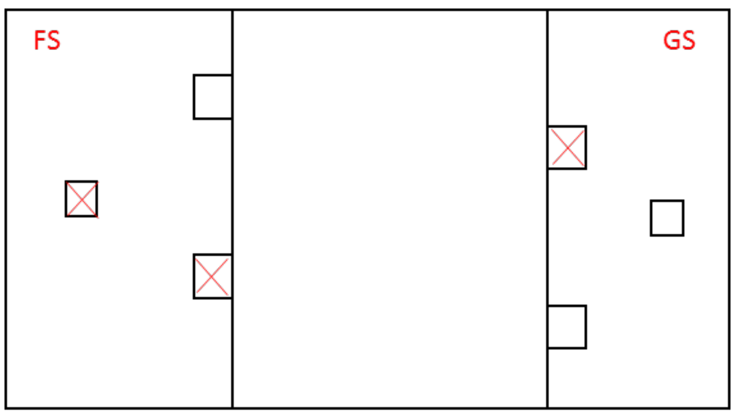


Figure 3. Spiking pattern in use throughout tangent track in Chester, Illinois

2.3 Observed Failure Modes of EPC Tie and Fastener Systems

EPC ties installed at both FAST and in revenue service showed inconsistent performance under repeated train loads (McHenry, 2017). Testing identified spike-hole cracking and center cracking as the two primary failure modes. Most of the tie failure occurred within 200 million gross tons (MGT) of HAL traffic. Failure rates were higher than 5 percent for all three EPC tie types. According to the performance evaluation at FAST, one EPC tie type showed no center cracking, though six of these ties had spike-hole crack failures. A second EPC tie type showed no spike-hole cracking, but 10 ties had center cracked. The third EPC tie type had 27 ties fail through center cracking and spike-hole cracking. Of the 300 total EPC ties installed at FAST, 43 had failed as of May 2017.

2.3.1 Center Cracking

Figure 4(a) shows a center crack representative of that found on 10 ties in one of the EPC tie test zones at FAST. The center cracking was similar at revenue service sites. These cracks appeared to have initiated at a stress riser (i.e., void) in the cross-section of the tie (as shown in Figure 4(b)) and produced striations consistent with fatigue failures. The current static three-point bend test (i.e., AREMA Test 1C) used to characterize tie modulus of elasticity (MOE) and modulus of rupture (MOR) was not sufficient to indicate bending performance under repeated loading. Therefore, the team developed an EPC tie fatigue test, which is described in Section 3.

(a) (b)

Figure 4. Center cracking observed in new EPC tie test zones: (a) Center cracking in tie type A at 120 MGT; (b) Initiation of crack at void (circled)

2.3.2 Spike-Hole Cracking

Figure 5(a) shows a spike-hole crack connecting to an adjacent spike hole beneath the tie plate. Spike-hole cracks generally developed after some tonnage accumulation and not immediately after spike installation. However, the research team did not observe spike-hole cracks during laboratory spike insertion and pullout testing (i.e., AREMA Test 2), indicating that current testing recommendations do not adequately assess this in-track failure mode (McHenry, 2017).

(a) (b)

Figure 5. Spike-hole cracking observed in new EPC tie test zones: (a) Spike-hole cracking in drive spike holes of tie type B; (b) Spike-hole cracking in cut spike holes of tie type C

It is possible that spike drilling on EPC ties could create a stress concentration near the spike holes, which may further contribute to the spike-hole cracking issue. Figure 6 shows a spike that was driven during lab testing. Generally, EPC tie material is nearly incompressible. As such, a "mushrooming" effect can occur after drilling spikes, as shown in the figure. It is important to note that a 3/8-inch pre-drill was used for these holes. Without a pre-drill, it is likely this mushrooming effect would have been more severe.

Figure 6. Mushrooming of composite material after driving a spike in the lab

3. Development of Fatigue Tests for EPC Tie and Fastener Systems

In the in-track evaluation at FAST and in revenue service, researchers documented the two most common failure modes for EPC ties: center cracking and spike-hole cracking, both of which are considered fatigue failure types. However, the current AREMA manual does not feature suitable testing recommendations to adequately assess these in-track failure modes. Therefore, the team developed two new qualification tests to evaluate EPC tie performance under repeated loading.

The first test exercises EPC tie center bending in a four-point setup (Section 3.1). The second modifies the current AREMA tie and fastener wear and abrasion test to exercise rail-seat bending and spike-hole cracking observed under repeated loading (Section 3.2). The test setup (i.e., span lengths and applied load magnitudes) was guided by NUCARS® track model simulations and in-track strain gage measurements. Both tests, once established, will serve as enhanced assessment tools for suppliers to develop improved EPC tie designs.

3.1 Four-Point Tie Bending Fatigue Test

3.1.1 Strain Data Collected from In-Track Testing

Researchers used bending strain measurements, collected on three types of EPC at FAST and in revenue service, to better understand the loading environment of EPC ties and how to better assess their performance in laboratory testing. The team installed bondable strain gages at the center and rail seat area of EPC ties. Researchers selected nine ties at FAST (i.e., three consecutive ties in each of the three test zones) and eight ties at the Western Mega Site (i.e., four consecutive ties in each of the two test zones). The strain gages selected for this test were 1/2 inch quarter bridge bondable gages that allow for high elongation. The test engineer selected the ties in each zone to ensure no severely hanging ties or ties with loose plates were chosen.

The test engineer installed gages on each tie at the following locations:

- Center of the tie (equidistant from each rail), as shown in Figure 8 and Figure 9
- At the top of the side surface of the tie directly under the high rail seat, as shown in Figure 8 and Figure 9

The team collected data at 256 Hz and triggered it on/off at the beginning and end of each train pass. They extracted and statistically analyzed the peak strains to provide a representative distribution of the loading environment experienced by the ties.

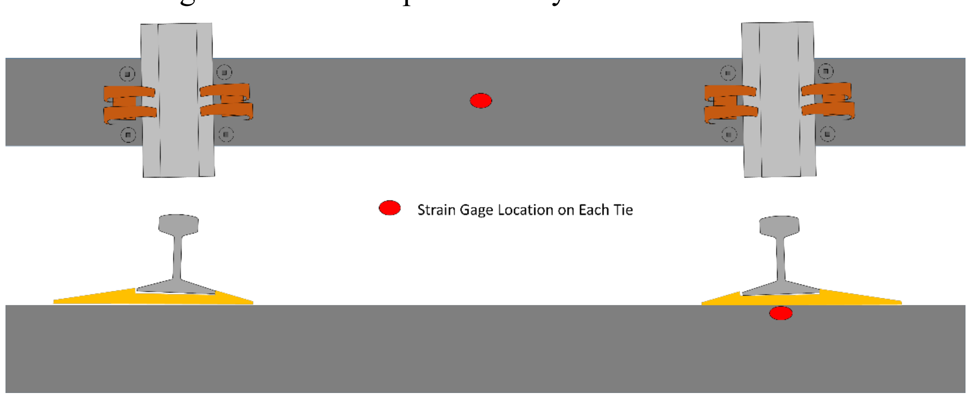


Figure 7. Location of strain gages on one tie

Figure 8. Instrumentation setup on the EPC ties

Researchers collected the strain data under various train speeds and loads and at different times of the day. More specifically, they collected microstrain values for both negative center bending and rail seat positive bending. Figure 10 shows a sample result of the center bending strain data collected at FAST for Type A ties. The strain values changed over time; this is likely the result of temperature variations throughout the day, which will be further discussed in Section 5. Analysts determined the peak strain for each strain gage measurement during post-processing of the data. They then converted the time-history data from these strains into stresses based on material properties of the respective tie types. The research team used the in-track bending strains to guide the loading input for the tie during laboratory testing (Section 3.1.3). The test results are shown in Table 2 and Table 3. For both FAST and revenue service measurements, the center bending strains were generally higher than the rail seat bending strains.

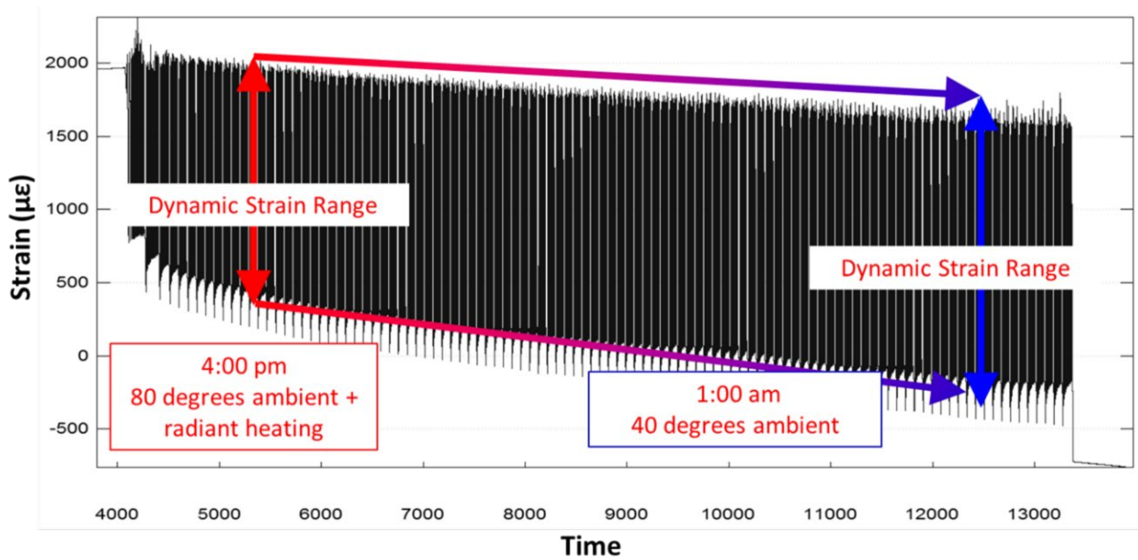


Figure 9. In-track bending strains results

Table 2. Bending strain and stress at the tie center and rail seat at Western Mega Site

Tie Name	Tie Number	Center (A)				Railseat (B)			
		Average (με)		Average σ (psi)		Average (με)		Average σ (psi)	
		Train 1	Train 2	Train 1	Train 2	Train 1	Train 2	Train 1	Train 2
Type A	1	1073.52	981.75	228.08	208.58	522.15	41.22	110.93	8.76
	2	993.08	897.52	210.98	190.68	532.86	550.87	113.21	117.03
	3	1078.98	982.53	229.24	208.74				
	4	939.65	851.17	199.63	180.84	432.94	-241.21	91.98	-51.25
Type C	1	987.67	920.64	179.66	167.47				
	2	958.70	887.62	174.39	161.46	715.38	752.12	130.13	136.81
	3	1056.91	961.23	192.25	174.85	698.68	713.75	127.09	129.83
	4	907.13	834.26	165.01	151.76	619.51	632.24	112.69	115.01

Table 3. Bending strain and stress at the tie center and rail seat at FAST

		Center (A)		Rail seat (B)	
Tie Name	Tie Number	Average (με)	Average σ (psi)	Average (με)	Average σ (psi)
Type A	1	1718.1	365	466.1	99
	2	1681.1	357	286.6	61
	3	1705.4	362	458.5	97
Type C	1	1011.7	184	937.6	171
	2	1119.7	204	1384.3	252
	3	1511.7	275	1117.9	203
Type B	1	1718.8	229	372.5	50
	2	1780.6	238	547.4	73
	3	1836.1	245	244.0	33

3.1.2 Numerical Modeling for Tie and Fastener Loading Environment

3.1.2.1 Model Description

Modeling can provide an approach to research problems that is different from testing and observation and can help guide improved designs and recommendations. Multibody vehicle-track models are commonly used to study vehicle dynamic responses under various track conditions. To a lesser degree, these types of models have been applied to study the transfer of dynamic loading into the track structure. In this section, researchers constructed a vehicle-track model in NUCARS to study the vehicle-track interaction effects on tie and fastener systems. The direction of the modeling efforts was guided by failure modes observed at FAST and in revenue service.

The track model was composed of rails, ties, and tie plates for both wood and EPC tie systems. All three were given bending degrees of freedom. Rails are typically given torsional, lateral, and longitudinal bending degrees of freedom while ties and tie plates, if needed, are given vertical bending degrees of freedom. Connections between individual bodies can be generalized or, in specific locations of interest, augmented to provide a higher resolution. For example, an interest in the vertical load transferred between a tie plate and a tie for a particular tie in the model could necessitate higher connection resolution.

Through modifications to car body, truck, and axle characteristics and connections, the vehicle portion of the model can represent any variety of conventional and non-conventional railway vehicles. Wheel and rail profiles of the vehicle and track portions of the model, respectively, are defined based on assumed or measured data. Vehicle models are modular components of the overall model and can be easily exchanged on top of the track model. Detailed information on the penetration contact model and its applications can be found in the NUCARS manual (NUCARS, 2018). A conceptual plot of the model showing the vehicle loading and track components is presented in Figure 11.

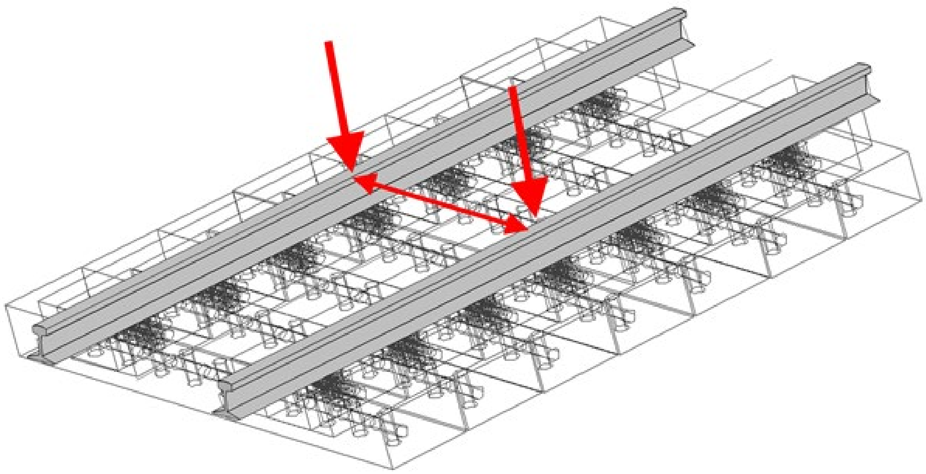
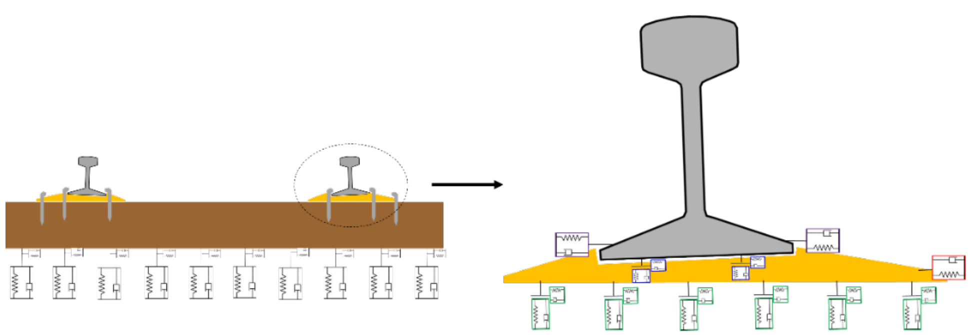


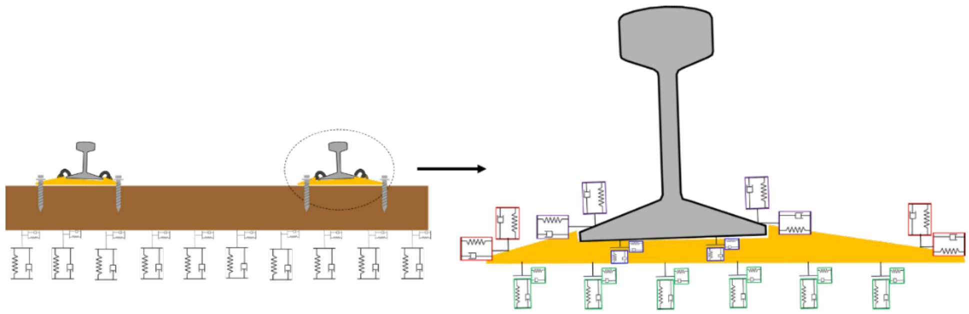
Figure 10. Schematic of the conceptual NUCARS model

Connection characteristics within the track model are input and tuned based on a growing knowledge base of how particular components behave and interact in the track structure. Established references (NUCARS, 2018) and laboratory and in-track testing are being used to guide appropriate stiffness and damping properties of track components and connection characteristics. Established laboratory tests for tie and fastening systems, such tie-center bending, tie-plate compression, and vertical and lateral repeated load tests (established in the AREMA Manual) have been used to guide the stiffness and damping properties of the connections in the model. In-track measurements, such as tie bending strain gage data, are used to fine-tune track model properties. Lastly, track substructure stress-distribution models, such as GEOTRACK™, have been used to characterize and fine-tune tie-ballast connection properties for a range of support qualities. Figure 12 conceptually shows the multibody connections for typical conventional cut spike and elastic fastener systems.



(a)

Figure 11. NUCARS track model for tie and fastening system: (a) conventional cut spike fastener system; (b) elastic fastener system



(b)

Figure 12 (cont.). NUCARS track model for tie and fastening system: (a) conventional cut spike fastener system; (b) elastic fastener system

3.1.2.2 Modeling Results of EPC Tie Bending Behavior

The NUCARS track model constructed for EPC ties allowed researchers to study the loading environment experienced by EPC ties and the associated fastener system. The model consisted of a 60-tie track panel and a 288-kip hopper car with 2 trucks and 4 axles. The model used the AAR 1B wheel profile and the 136 RE rail profile. Ties, tie plates, and ballast also were included in the model. The vehicle was simulated to run 400 feet at 40 mph on the track panel. Although 60 ties were simulated, the track panel could repeat itself to allow the same track to pass under the vehicle continuously. The connection characteristics used in this model are presented in Table 4.

Table 4. Model parameters

Model Parameter	Value
Tie Length	102 (inches)
Tie Bending Rigidity	6.4E8 - 1.7E9 (lb·in^2; depending on tie modulus)
Rail-Tie Plate Vertical Connection	1E8 (lb/inch)
Tie Plate-Tie Vertical Connection	1E6 (lb/inch)
Tie-Ballast Lateral Connection	1E6 (lb/inch)
Tie-Ballast Vertical Connection	8E5 (lb/inch)

The following key parameters were also considered in the model to better understand how loads are transferred through the EPC tie and fastener systems:

- Composite material bending stiffness
- Ballast support conditions

Polymer Composite Material Bending Stiffness

Figure 13 shows the bending moment of EPC ties with varying MOE. Researchers simulated four MOE values, assuming a uniform ballast support condition. Since the loading and boundary conditions were similar for all the ties in the track panel, they selected only one tie to output the bending moment along its lateral direction. As shown in the plot, the rail seat locations had the largest positive bending moment. The tie also experienced center negative bending, but the value was just 60 percent of the value in the rail seat area. To provide a reasonable strain range for the laboratory test input, the simulated bending moment was used to obtain the strain value of EPC ties. The strain values were 2,083 με, 1,470 με, 1,136 με, and 758 με for the MOE of ties that are 120 ksi, 170 ksi, 220 ksi, and 330 ksi, respectively.

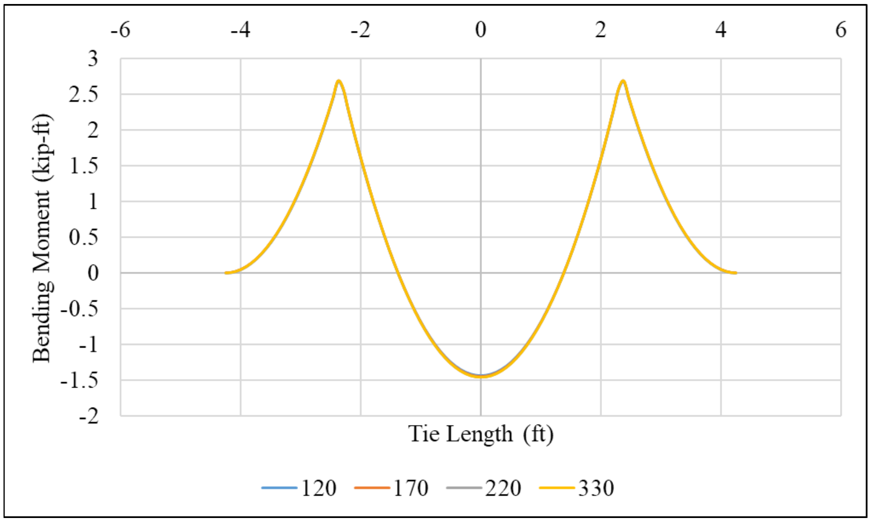


Figure 12. Simulated bending moment of various bending modulus of EPC ties

Ballast Support Condition

The ballast support condition is an important factor that could change the crosstie loading environment significantly. Researchers simulated two ballast support conditions: rail seat support (i.e., uniform support) and center binding. In the NUCARS model, they set up ten tie-ballast connections evenly along the tie length. Uniform support means the stiffness of the connections were equal while the center binding condition means the four connections in the center were stiffer than the outer six connections. The simulated bending moments are plotted in Figure 14. The center-binding condition generated larger bending moment than the uniform support. This finding also matched the in-track strain data collected at FAST and in revenue service. The corresponding strains were 2500 με, 1,764 με, 1,363 με, and 910 με for the MOE 120 ksi, 170 ksi, 220 ksi, 330 ksi, respectively.

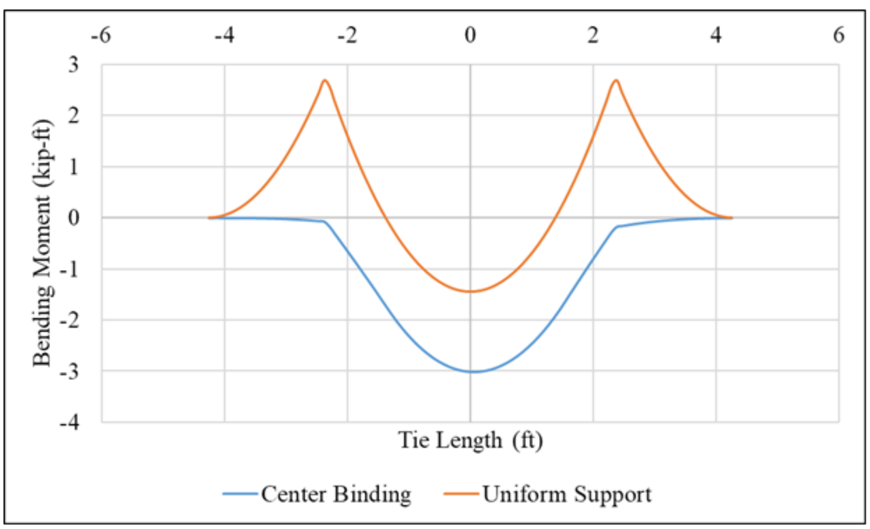


Figure 13. Simulated bending moment for different ballast support conditions

Researchers conducted NUCARS simulations with varying parameters that may affect system performance, such as plate size, curvature, and train speeds. Due to the relatively short length of the plates, NUCARS experienced some difficulty simulating their bending behavior. Therefore, a finite element model that was constructed for the fastening system is presented in Section 4.2. Curvature and train speeds varied within 40 mph and did not show any significant difference in EPC tie performance.

The results from NUCARS simulations showed the bending properties and ballast support conditions significantly affected the bending strains in EPC ties. Also, the model suggests the ties may have had a more severe loading environment in the center-binding condition than in the uniform support condition. Hence, for the development of the laboratory testing criteria, a center-bending test was more appropriate for evaluating EPC tie performance.

3.1.3 Development of Laboratory EPC Tie Bending Fatigue Test

The research team observed center cracked ties at FAST and in revenue service post-installation, which suggested that fatigue failures could initiate at internal voids or stress concentrators inside the tie cross-section. Based on these observations, it was clear that fatigue criteria should be established for these EPC ties. Therefore, a laboratory fatigue test was developed by TTCI to evaluate EPC tie performance under repeated train loads to improve design, quality control, and fatigue performance criteria. The findings will be recommended for incorporation into the AREMA manual.

Researchers used the strain data gathered from FAST and revenue service as inputs for the laboratory test development. To account for the variations in tie modulus, train loading, and tie support conditions, a safety factor of two was applied to the average in-track strain values for the design of the laboratory test. The strain calculated by the safety factor represents a conservative test that exceeds the in-service demand of an EPC tie in center bending. Based on several laboratory test iterations, this safety factor could accelerate the fatigue test and still be able to crack the ties with internal defects without cracking a good EPC tie. However, a more conservative (i.e., higher safety factor) or less conservative test (i.e., smaller safety factor) could be used based on the actual conditions. Researchers chose a four-point bending setup because the maximum bending moment can be applied to a 30-inch constant bending moment zone in the middle of a tie. The center cracks are typically associated with internal voids; the internal voids in EPC ties that could potentially cause center cracking can be anywhere in the middle section of a tie. Therefore, a four-point bending test is more beneficial than just having maximum bending moment at the middle point in a three-point bending test.

Typical fatigue tests are either stress-controlled or strain-controlled. For the development of the EPC tie fatigue test, the team conducted both stress- and strain-controlled tests to determine which test is more suitable for EPC ties. The strain-controlled test matched the in-track loading environment for EPC ties. However, in the stress-controlled test, EPC ties showed an increasing deflection (i.e., creep behavior) under a constant actuator load. The research team did not observe this type of behavior in the field testing results. It is possible that the time between train passages reduces or eliminates the effect of creep in the field; however, the laboratory test was a non-stop cyclic loading test. Further, the rail uplift may also reduce creep behavior for EPC ties. Therefore, the team designed the test to use a strain-controlled setup and the middle two points were rigidly fixed to the spreader bar to make sure the tie and the actuator had in-phase motion, as shown in Figure 15. The current test criterion is up to 1.5 million loading cycles or tie failure, whichever comes first. The 1.5 million cycles are equal to over 216 MGT of HAL traffic. This amount is similar to that accumulated at FAST between 2015 and 2017, when the most center cracked EPC were found. Thus, 1.5 million cycles with a safety factor of two will likely be sufficient to generate fatigue cracks of EPC ties. Details of test development iterations are included in Appendix A. Further development of the center bending fatigue test is needed to better understand and modify the design of this test.

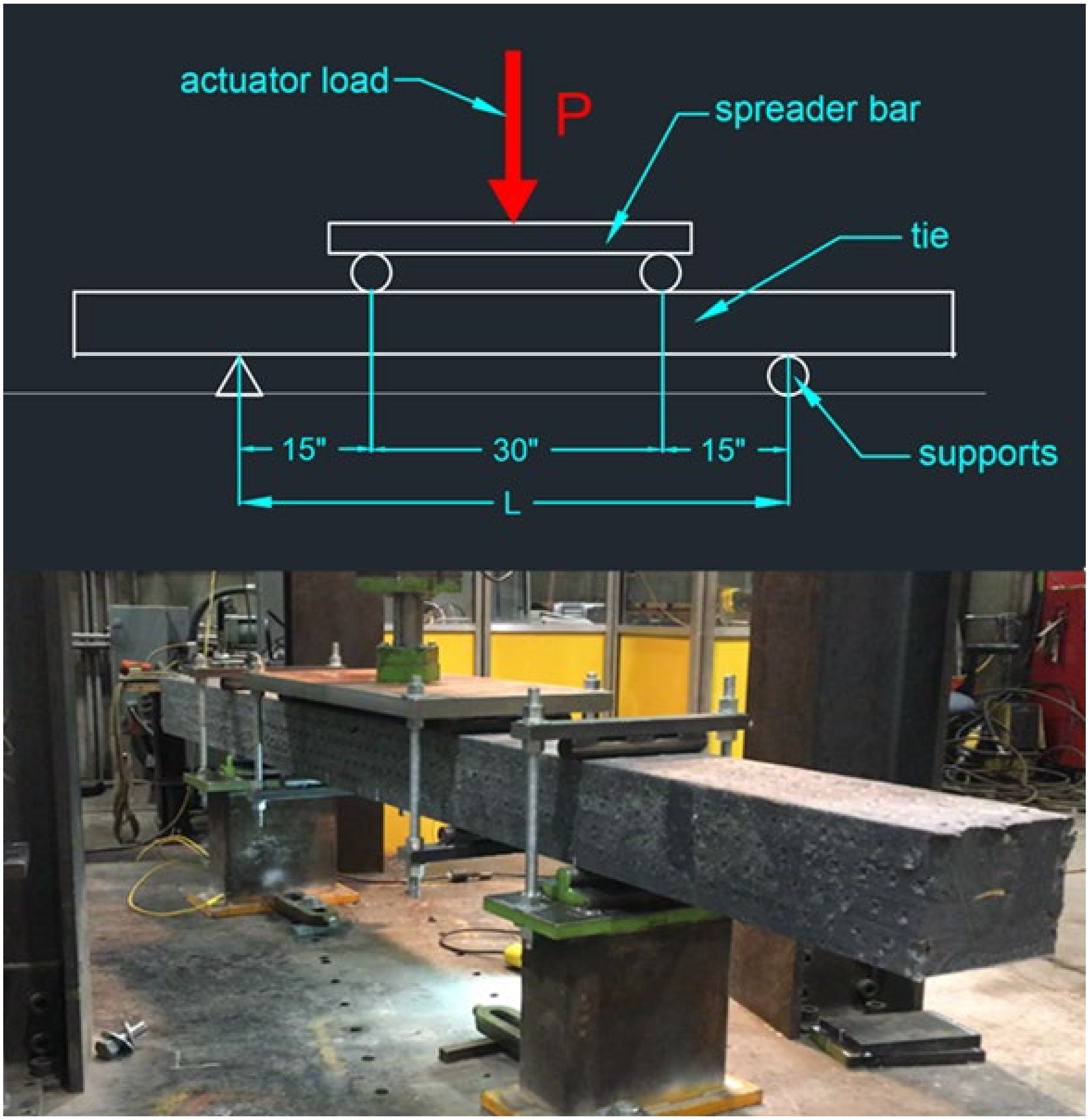


Figure 14. Four-point negative center bending load configuration

3.1.4 Test Results

The research team performed the tie fatigue test on all three types of EPC ties (i.e., Type A, B, and C). It is important to note that these test results are not intended to compare the performance between manufacturers; however, the results identify the failure mechanism and relate the failure to certain defects to improve the manufacturing process/technique(s) and quality control. As shown in Table 5, two types of composite ties experienced center-cracking failure before reaching 1.5 million load cycles. The cracking initiated at the surface of the ties and occurred in the middle 30 inches of the ties. The failure mode seen in the laboratory testing was comparable to that observed in field tests, as depicted in Figure 16.

Table 5. Tie fatigue test results

EPC Tie Fatigue Test Iterations				
Test #	Start Date	End Date	Tie Type	Cycles
1	9/27/2017	10/16/2017	C	1,306,000
2	11/9/2017	12/14/2017	A	1,500,000
3	6/1/2018	6/29/2018	B	1,349,000

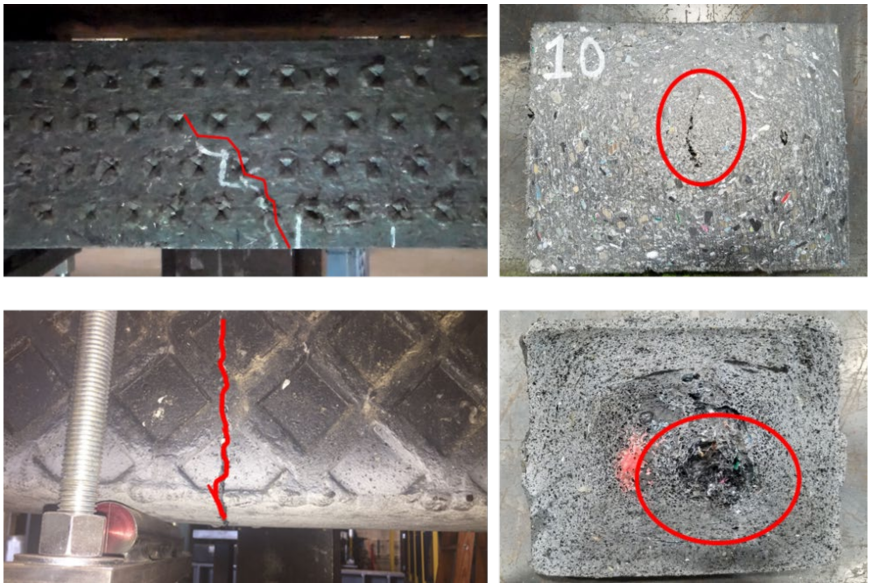


Figure 15. Two failed EPC ties and their internal conditions near the failure planes

The 30-inch constant moment area was sliced into 30 pieces of 1-inch cross sections after testing for further investigation into the internal conditions of these three ties. The field experience indicated that the center cracking is often associated with internal voids or defects at the failure plane. Therefore, the team sliced ties to verify the tie's internal conditions. Figure 17(a) shows an example of the in-track failure for Type A ties: a 2.5 x 1 inch^2 internal void at the tensile stress area (near the top of the tie) in the failure plane. On the other hand, the photo in Figure 17(b) shows a cross-sectional view (i.e., No. 18 slice) of the Type A tie tested in the laboratory. This specimen did not have a center-crack failure. The cross section in this non-failed tie had a smaller porous area and denser internal condition compared to the one failed in track. Also, the voids (circled in the figure) that were present in the No. 18 slice were smaller and located within the compression area, which typically does not experience fatigue problems.

According to the test results from three types of EPC ties, two failed ties had a similar failure mode as the ties that had failed in track and were the result of internal voids and defects like the failed in-track ties. Further, the test tie with an improved internal condition did not crack during the testing. Therefore, the newly developed tie fatigue test at TTCI can effectively replicate the in-track performance of EPC ties and can identify an EPC tie with internal defects without overloading and/or failing a good quality tie.

(a) **(b)**

Figure 16. Internal conditions of Type A ties: (a) in-track failure; (b) a sliced piece from laboratory test (not failed)

3.2 Fastener/Rail Seat Fatigue Test

The research team recorded several EPC tie failures related to spike-hole cracking at FAST, as shown in Figure 18. They noted that spike-hole cracks generally developed after tonnage accumulation and not immediately after spike installation. Further, the team did not observe spike-hole cracks during laboratory spike insertion and pullout testing (AREMA Test 3A). The industry has used this test to arrive at optimal pre-drill hole size for a certain tie material and/or to indicate relative performance between EPC tie suppliers. However, because this simple test does not replicate the spike-hole cracking failure mode observed at FAST, this indicates that current testing recommendations do not adequately assess the performance of EPC ties in this regard. The team proposed a fatigue test modified from the wear/deterioration test (i.e., AREMA Test 6) to assess the performance of the tie and fastener under repeated loads.

Figure 17. Spike-hole failure modes observed in EPC tie test zones

3.2.1 AREMA Test 6: Tie and Fastener Wear/Deterioration Test

AREMA Test 6 is a fatigue test used to determine rail seat deterioration and fastener system performance in HAL environments (i.e., gross railcar weight between 286,000 and 315,000 lb) under repeated loads. The test machine consists of a load frame with a servo-controlled, dual action hydraulic actuator. The load is distributed through two load arms set at an angle of 27.5 degrees from vertical. The load is transmitted equally to each railhead on a full-size tie using the appropriate fastening system. Deflections are monitored at regular (i.e., 500,000 cycles minimum) intervals and tracked throughout the test so there is no excessive movement (i.e., consistent head deflection measurements that exceed 0.2 inch). The test setup is shown in Figure 19.

Evaluators should run this test for at least 3,000,000 cycles (or until failure) at a frequency of 2.5 Hz (±20 percent). This repeated load may generate heat in the elastomeric rail seat pads or composite ties. Heat build-up in such pads or composite ties must not be allowed to exceed 140°F. Test failure occurs when an individual component "breaks" or when rail deflections on any measurement point is greater than 0.2 inch.

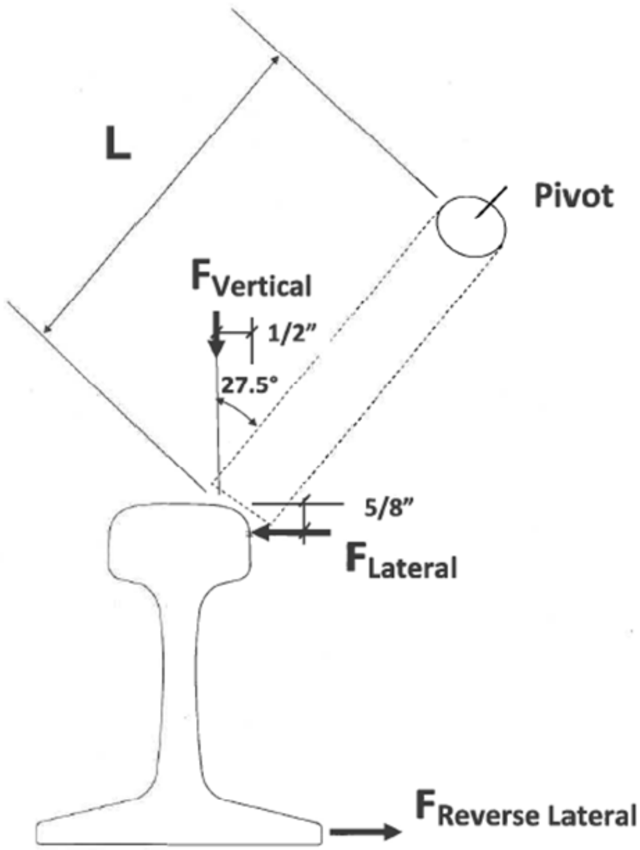


Figure 18. Load diagram for the tie and fastener wear/deterioration test (AREMA, 2018)

3.2.2 Modified Test for EPC Tie Fastener/Rail Seat Fatigue Test

Based on the results observed, TTCI is developing a new bending fatigue test (setup shown in Figure 20) to address the spike-hole cracking issue. The test design modifies the current AREMA tie and fastener wear/deterioration test by adding supports to the tie. The purpose of this modification is to increase the tie bending behavior for more interaction between the tie and its fasteners. The test generates more rail seat bending and is expected to replicate the spike-hole cracking observed under repeated in-track loading.

The details of this test setup (e.g., span length, applied load magnitudes, and loading cycles) are still under development. The test inputs and configuration will be determined by in-track strain gage measurements taken on EPC ties and by numerical simulations. Once the test can reproduce the in-track failure and represent the in-track performance, it will be recommended for the AREMA manual.

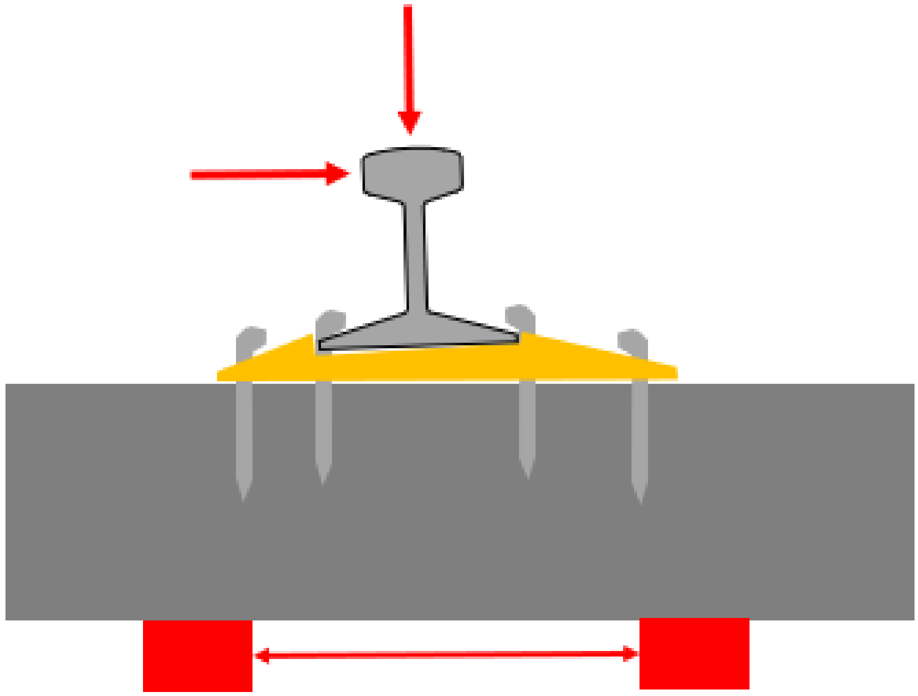


Figure 19. Conceptual test setup to assess EPC tie for rail seat/spike-hole fatigue

4. EPC Tie Plate Compressive Testing and Modeling

Past studies on EPC tie plate performance documented increased plate breakage and plate bending stresses, but a reduction in observed plate cutting compared to wood ties (Gonzales, 2008; Tangtragulwong, 2011). Two EPC tie test zones at FAST with 14-inch AREMA plates (i.e., one installed in 2000 and the other in 2004) exhibited high-rail plate cutting of less than 1/8 inch after accumulating 2,155 MGT and 1,690 MGT, respectively. In comparison, plate cutting up to 3/8 inch occurred in the control hardwood tie zone after 970 MGT (Figure 21). While FAST operates in a semi-arid climate, any significant wood tie rot and/or decay in other climates would likely exacerbate plate cutting.

In this study, researchers established a detailed finite element model to analyze the contact stress between tie plates and ties and understand the induced stress at the crack initiation point. The modeling effort included the influence of different tie plate sizes over a range of tie moduli to provide appropriate recommendations.

(a) **(b)**

Figure 20. Plate cutting at the high rail of (a) an EPC tie after 1,690 MGT and (b) a control hardwood tie after 970 MGT, both installed in a six-degree curve at FAST

4.1 EPC Tie Plate Compression Test

Following AREMA Tie Test 2 (i.e., Rail/Plate Area Compression), the research team used a rail seat compression test to calibrate the input material properties of EPC and timber crossties in the finite element model. Figure 22 shows a schematic of the lab test setup. The size of the loading plate was 7 3/4 inches in width, 14 inches in length, and 1 inch in thickness. The rail was loaded to 100 kips compression in 20-kip increments. The load and deflection values at each increment were then recorded.

Researchers tested four types of crossties: three EPC (i.e., A, B, and C) and one wood (i.e., W). Each EPC crosstie had different MOE values, which were determined by the previous tie bending tests (McHenry, 2016). Table 6 shows the deflection of the plate at different locations under each loading condition. Figure 23 plots the load-deflection results from the test. Crosstie B exceeded the AREMA recommended maximum elastic deformation of 0.25 inch at 100 kips. However, all the ties tested did meet the criterion that maximum permanent deformation at recovery after release of load should be less than 1/8 inch within 1 minute after release of load.

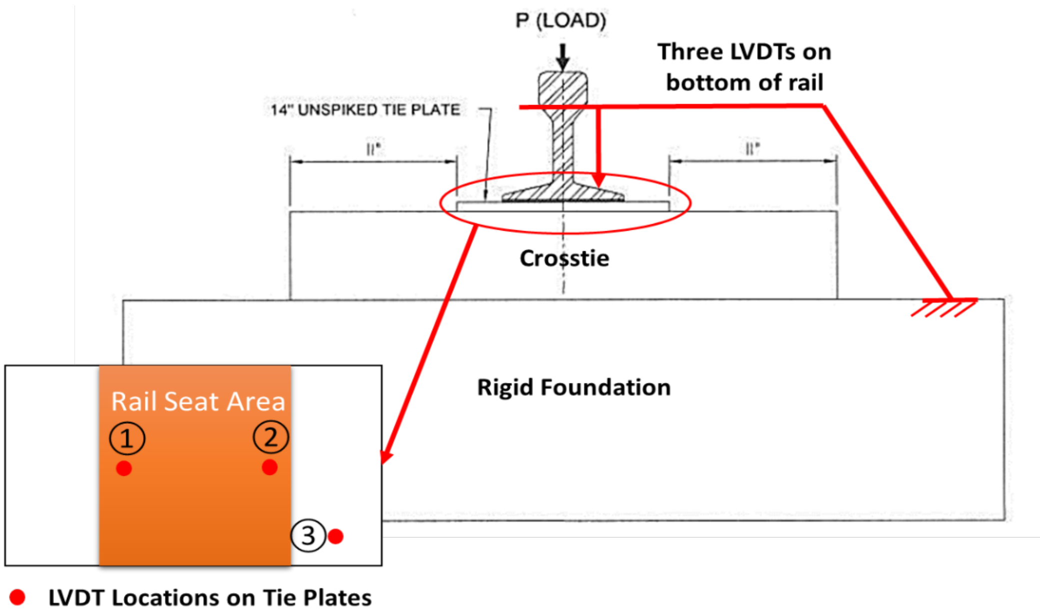


Figure 21. Schematic of the rail seat compression test setup

Table 6. Deflection of crosstie plate under each load increment

Load Increment (kips)	Deflection of Crosstie Plate											
	Crosstie A			Crosstie B			Crosstie C			Crosstie W		
	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
0	0	0	0	0	0	0	0	0	0	0	0	0
20	0.0711	0.0607	0.0793	0.1544	0.1552	0.149	0.0425	0.0364	0.0236	0.064	0.0566	0.0471
40	0.1155	0.0968	0.116	0.195	0.1922	0.1773	0.0611	0.0511	0.0322	0.0916	0.0772	0.0706
60	0.1509	0.1314	0.1471	0.2298	0.2256	0.2026	0.0767	0.0644	0.0394	0.1153	0.0939	0.0913
80	0.1829	0.1645	0.1758	0.2634	0.2594	0.2279	0.0929	0.0808	0.0485	0.1357	0.1082	0.1095
100	0.2014	0.1832	0.1918	0.302	0.2977	0.256	0.1089	0.0976	0.058	0.1556	0.1223	0.1255
0	0.0612	0.0622	0.0719	0.1046	0.1047	0.1035	0.0202	0.0148	0.0171	0.0387	0.021	0.0503

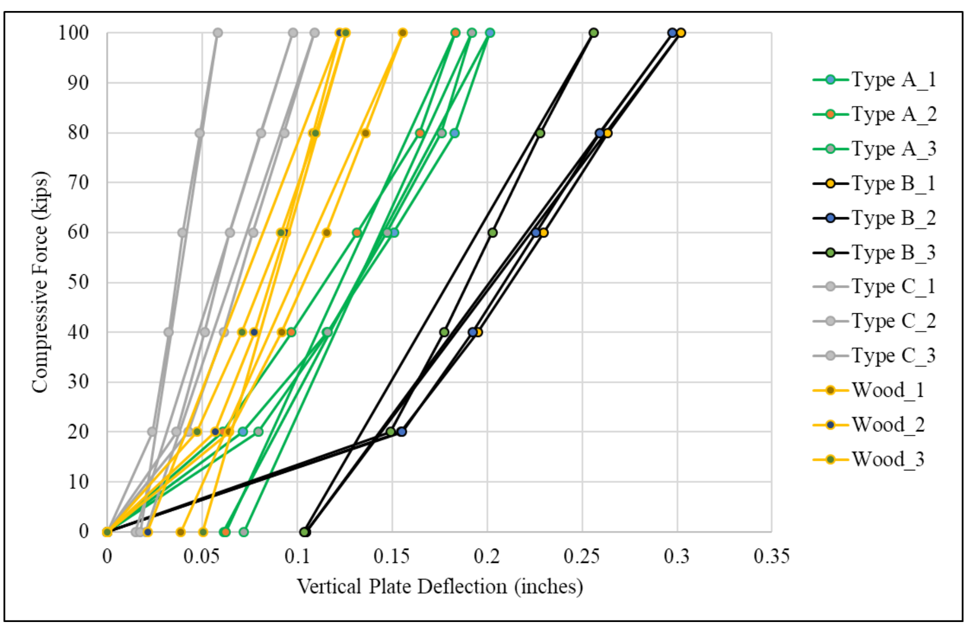


Figure 22. Tie plate compression test results

4.2 Finite Element Model

Figure 24 shows a schematic of the finite element track model used in this study. It was comprised of two 65-foot rails, two tie plates, a tie, and a section of ballast. The model had four contact pairs: (1) rail bottom and rail seat area; (2) lateral surface of the rail's base and lateral surface of the tie plate's ridge; (3) bottom of the tie plate and top surface of the tie; and (4) bottom surface of the tie and top surface of the ballast layer. Each contact pair was connected by a frictional connection with a contact-target relationship. The material properties of the crossties were determined based on the laboratory tests. The bending MOE was taken from the previous center bending test (McHenry, 2016), while the compressive MOE was taken from the tie plate compression test.

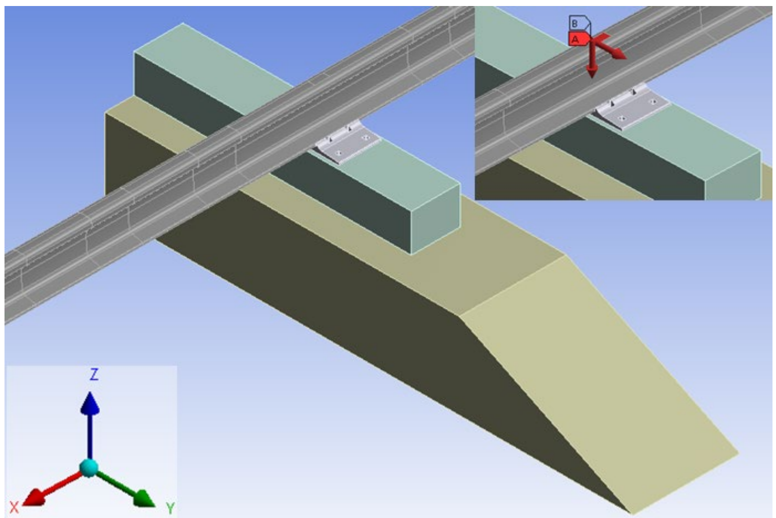


Figure 23. Finite element track model – detailed tie plate (14-inch AREMA plate shown)

For efficient computing, only one detailed tie and fastener set was modeled. Adjacent ties and ballast support were simulated as simple vertical and lateral spring connections to the rail. Longitudinal movements were set to zero at rail ends and elastic supports were applied inside the spike holes to represent cut spikes.

4.3 Modeling Results

The simulation matrix included three AREMA standard rolled tie plate widths (13, 14, and 18 inches). Orthotropic material properties were used for EPC and wood. Upper- and lower-bound bending moduli (i.e., E_y) were determined from recent laboratory-based AREMA bending tests for EPC and wood ties to categorize four tie types: soft composite, stiff composite, soft wood, and stiff wood. The compressive modulus (i.e., E_z) was estimated for each tie type based on AREMA plate compression test results. Results from these tests showed that modern polymer composite ties had compressive moduli 25 to 50 percent that of wood ties. Moduli in the vertical and longitudinal directions (i.e., E_x and E_z) were assumed to be equal for all ties. Figure 25 shows the two lab tests (i.e., tie center bending and plate compression). Model parameters are listed in Table 7. To represent a wide range of loading environments, tangent and curved track were simulated. For tangent, a 36-kip vertical wheel load (with no lateral loading) was applied at the head of the rail. For the curve, researchers simulated the HAL overbalanced operation at FAST: a 45-kip vertical load and a 5.6-kip lateral load. These were based on previous instrumented wheelset measurements within the 5-degree curve at FAST.

Figure 24. Tie center bending test (left) and plate compression test (right) used to tune model parameters

Table 7. Model parameters

Rail-Plate Friction Coefficient	0.4
Plate-Tie Friction Coefficient	0.2
Tie-Ballast Friction Coefficient	0.7
Rail Vertical Support (kip/ft^3)	11500
Rail Lateral Support (kip/ft^3)	6400
Subgrade Support (kip/ft^3)	1600

Tie Type	Modulus	
	E_y (psi)	E_z (psi)
Soft EPC	120	50
Stiff EPC	330	50
Soft Wood	500	91
Stiff Wood	1740	217

As Figure 26 shows, stress contours for all tie plate and tie combinations confirmed previous conclusions that peak stresses are generated near the corners of the rail spike holes (Gonzales, 2008; Tangtragulwong, 2011). Tie plate maximum bending stresses are shown in Figure 27. Modeling results showed that a larger 18-inch plate produces higher bending stresses when coupled with softer EPC ties compared to a 13-inch plate or a 14-inch plate. The 13-inch plate showed the lowest bending stress on EPC ties. Therefore, according to the modeling results, the 13-inch plates reduced plate bending stresses on EPC ties, which have been shown to cause tie plate fatigue failures for 14-inch plates at FAST. While 13-inch plates produce higher plate-tie contact stresses due to smaller tie-plate contact area, field observation showed that EPC ties have more resistance to plate cutting and generally do not have a plate-cutting issue. These results suggest that 13-inch plates may be a cost-effective alternative to 14-inch plates on EPC ties and may reduce the plate cracking occurrence; the use of larger tie plates may not provide substantial performance increase on EPC ties.

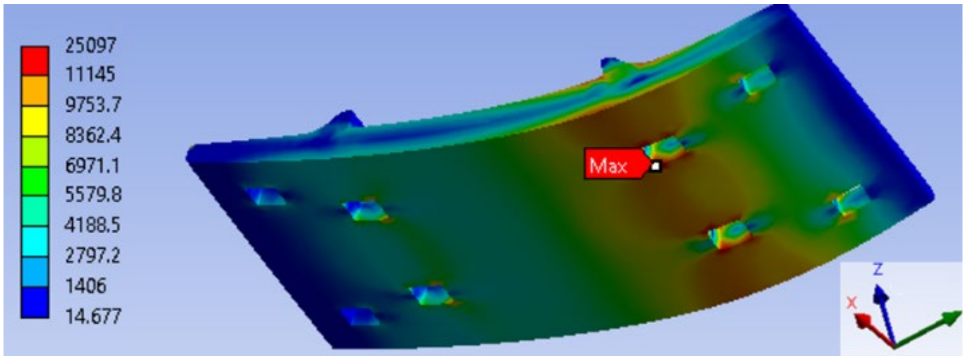


Figure 25. General location of peak stress; 14-inch plate on stiff EPC tie for curve simulations shown (psi)

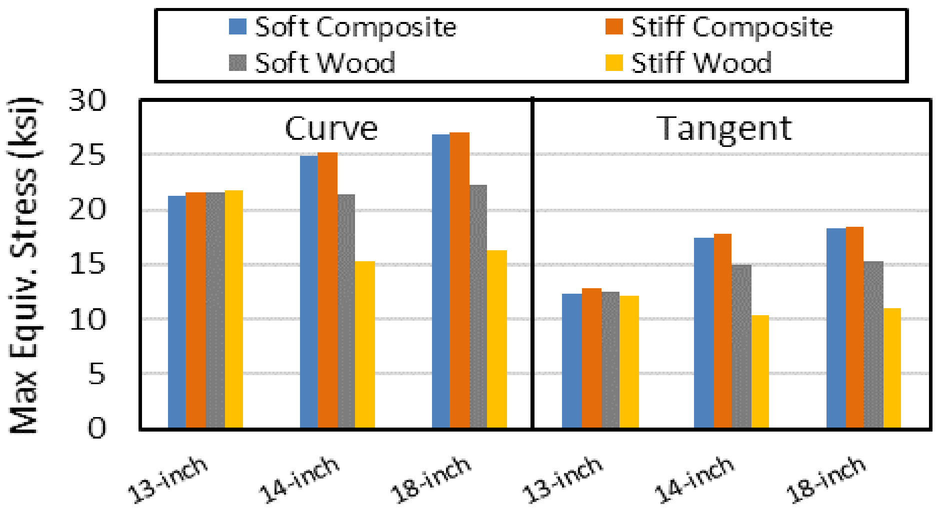


Figure 26. Maximum bending stress of tie plates from simulation

5. Thermal Effect on EPC Ties

According to field measurements and observations, the performance of EPC ties was more sensitive to temperature change when compared to wood ties. Both static track gage and tie loading environment were affected by the daily temperature swing. Wood ties generally are less affected by temperature.

In the fall of 2016, FRA's DOTX-218 track inspection vehicle measured track gage at TTC's HTL at different times throughout the day. At the time of each test run, EPC tie temperatures were measured for a sample of each zone at the ties' tops, ends, and sides. Ambient and rail temperatures were also recorded. Figure 28 shows the gage channel measurement from the coolest tie temperatures recorded at 7:30 am MDT and the warmest tie temperatures recorded at 2:00 pm MDT. Figure 28 also suggests that the bottom of the tie remained insulated by the tie itself and the crib ballast. This behavior created a thermal gradient and caused center negative bending. Linear expansion of the tie coupled with this bending resulted in about 0.2 inch of gage widening, consistent between all three EPC tie zones. No significant gage increase occurred in bordering wood or concrete tie zones throughout the day (McHenry, 2015 & 2017).

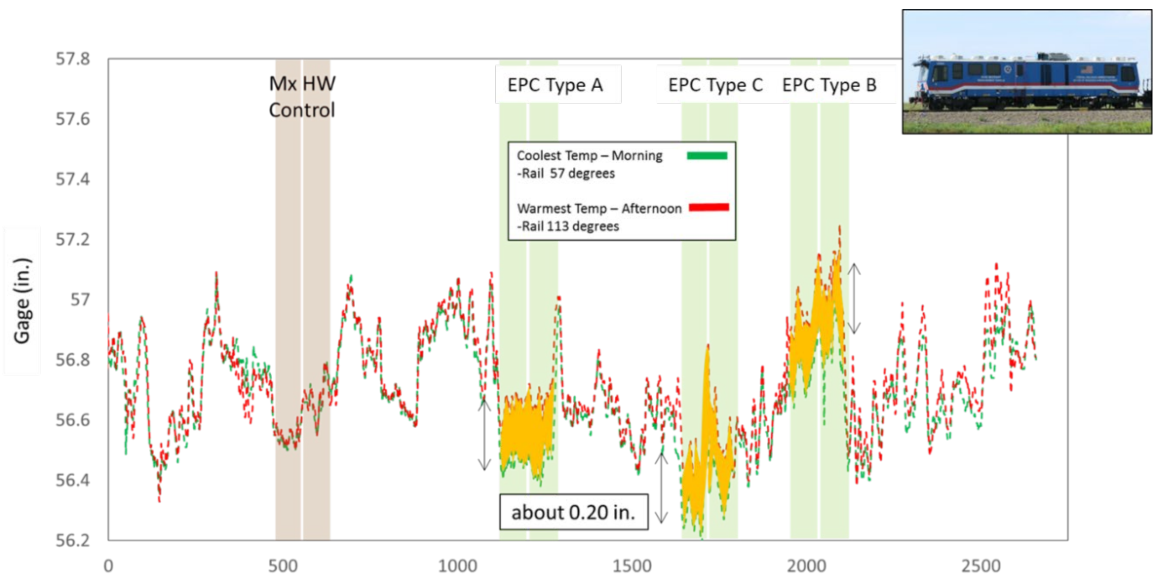


Figure 27. Unloaded gage measurements at two temperature extremes, Sept. 8, 2016

During a field trip to the Western Mega Site in April 2018, the research team measured the in-track strain data on the top surface at the tie center at different times of day. The plot in Figure 29 contains both morning and evening measurements. Top surface temperatures were 50°F and 90°F, respectively. The range in the morning (i.e., 8:00 am MDT, blue lines) was around 1,400 um/m; however, it reduced to 700 um/m in the afternoon (i.e., 3:00 pm MDT, red lines).

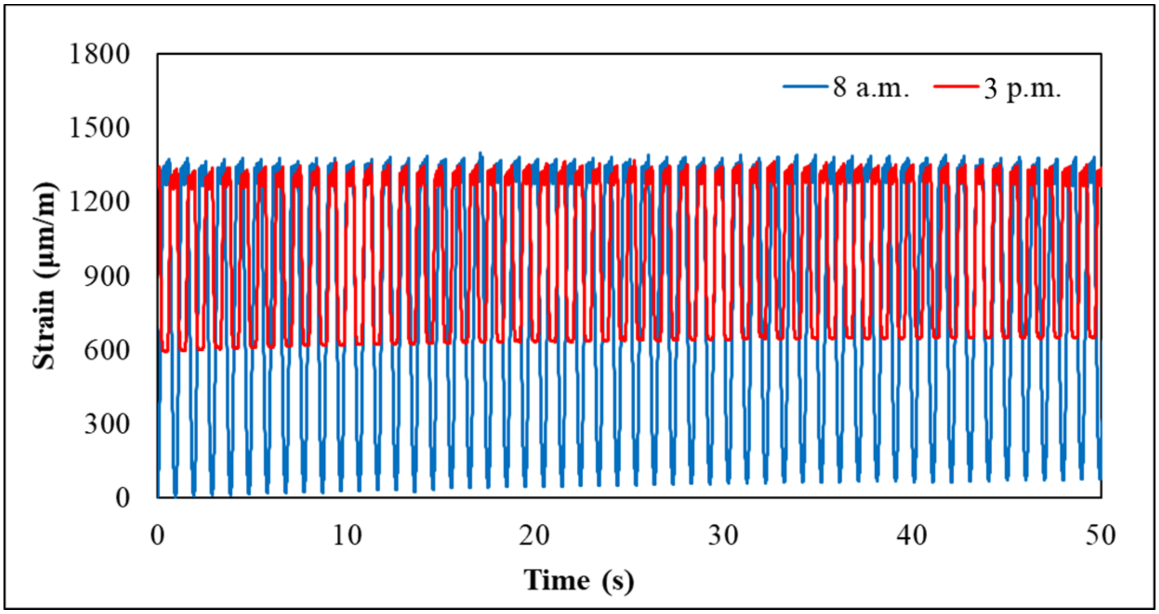


Figure 28. Bending strains on same tie under HAL coal train – 3:00 PM (red) vs. 8:00 AM (blue)

Researchers hypothesized that the gage widening and the change in tie bending strains throughout the day occurred because the EPC ties were straight in the morning since the temperature was uniform within the body of ties. In this condition, the center-bound ballast support condition was only supporting the center of the ties, causing more bending. With the differential temperatures between the top surfaces and the rest of tie in the afternoon, the tie became more conformal with the center-bound ballast surface, improving the support conditions and therefore reducing the strain range, as shown in Figure 30. This shows that once EPC ties have a center-bound ballast support condition, the ties could experience a much higher center bending load (twice as much in this case). This may not be an issue for wood ties since wood material is more forgiving to cyclic loading. However, center cracking, one of the failure modes in EPC ties, is due to the fatigue load in the center region of the tie. Therefore, reducing the effect of the center-bound condition may improve EPC tie life. An appropriate tamping cycle to maintain the uniform ballast support for EPC ties needs to be determined in a future study.

The amount of gage widening was measured at about 0.2 inch, which did not exceed FRA track safety standards for any track class. However, widened track gage could be due to many other causes, including installation tolerances, loading over time, rail gage face wear, plate cutting/reverse rail cant, and spike kill. Allowable gage widening may be reduced by 10 to 30 percent (depending on track class) due to intraday gage widening only.

It is important for the railroad industry to be aware of the performance difference between EPC ties and wood ties and, in turn, consider the difference in track inspection and maintenance practices when EPC ties are involved. Currently, the AREMA manual does not provide sufficient recommendations and guidelines for using EPC ties. An effort to improve the current manual for best practices is needed for both operational safety and efficiency.

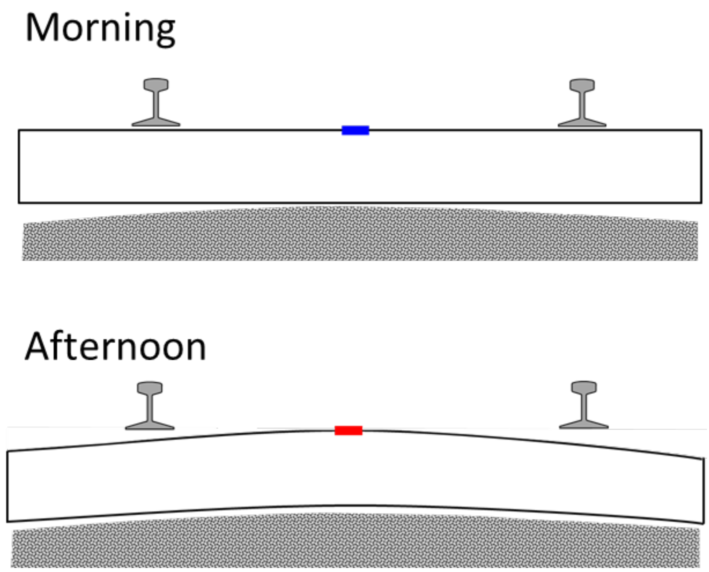


Figure 29. EPC tie shape modes at high and low temperatures

6. Conclusion

This study investigated the performance of EPC ties through in-track testing at both FAST and in revenue service. The research team identified two EPC ties' failure modes that are typically not seen on wood ties. Field observations showed that differential temperature in EPC ties could influence their static track gage, as well as the ties' loading environment.

The research team used in-track measurements, combined with modeling effort, to understand what factors affect the loading environment, failure types, and performance variability of EPC ties. They found that EPC ties performed very differently than wood ties in terms of these three factors. These differences are identified in this study as well as recommendations that take into consideration these differences, including newly developed laboratory fatigue tests and guidelines for best practice of using EPC ties.

Key findings and recommendations include:

- Testing at FAST and in revenue service identified spike-hole cracking and center cracking as two predominant failure modes for EPC ties. Most of the tie failures occurred within 200 MGT at FAST. These two failure modes were both considered as fatigue failures since the tie loading levels measured in track were below the ultimate strength of the ties.
- The team developed a laboratory fatigue test to address the center cracking issue. After a series of test iterations, the team chose a four-point bending test with a 60 inch outer span and a 30 inch inner span. This proposed laboratory test was able to replicate the center crack failure mode of an EPC tie that was found in track and could identify an EPC tie with large internal voids without overloading and/or failing a good quality tie. This test setup provides a performance evaluation tool for EPC ties and could guide manufacturers to improve their tie design and quality control processes.
- Researchers proposed a modified AREMA Test 6 to handle the spike-hole cracking issue. However, the test setup is still under development and will served as the basis for future research.
- Modeling efforts indicated that larger plates produce larger bending stresses and higher relative plate deflections on EPC ties compared to smaller plates. This is due to the tie material's lower bending and compressive modulus and the large spane of the plates. Shorter tie plates may reduce the bending stresses when equipped with EPC ties. Therefore, 13-inch tie plates may have the potential to reduce the plate breakage, which was found as an issue for 14-inch tie plates in the early 2000s.
- Field measurements showed that a differential temperature in EPC ties can affect the static track gage of EPC-tie track. The Gage Restraint Measurement System (GRMS) data showed a 0.2 inch gage widening in a day due to daily temperature swings for all three EPC tie zones at FAST. The research team determined that the shape of EPC ties is susceptible to temperature change. Ties are straight and flat in the morning since the temperature is uniform within the ties. However, when the ambient temperature increases, the top surface of an EPC tie has a higher temperature than the other sides of the tie, generating a differential temperature between the top surfaces and the bottom surface. This differential temperature will make the ties expand more on the top surfaces,

causing a tie to bend and resulting in a widened track gage. Therefore, improvements in the thermal properties of EPC materials and the current AREMA recommendations are needed.

7. Future Research Recommendations

The current AREMA criteria for the coefficient of thermal expansion (CTE) for EPC ties appear to be based on the CTE value for high-density polyethylene (HDPE) plastic and does not appear to have been studied in relation to track gage or track safety. Future research effort should include understanding of the railroad's tolerance of thermal-induced gage widening and should recommend appropriate thermal properties of EPC tie materials. Also, future work will continue to investigate thermal effects on the in-track performance of EPC ties and will provide test and simulation support to AREMA for improving recommendations for EPC ties relating to:

- Appropriate thermal properties based on track class/acceptable gage widening
- Appropriate environment(s) for installation
- Best practices to handle the thermal influence of railroad track with EPC ties
- Appropriate tamping cycle for tracks with EPC ties

An ideal setup to gather the information required would include a comprehensive system of thermocouples and remote track gage monitoring instrumentation to measure the gage under varying different environmental and thermal conditions. Additionally, a thermal expansion model should be built that simulates the properties of EPC ties and induces thermal loads to model expected behavior. The results will further researchers' knowledge of the thermal properties of the tie materials to generate improved recommendations for EPC ties.

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Appendix A. Fatigue Test Development for EPC Ties

This appendix discusses the development of the recommended EPC tie bending fatigue test. The test results should assist in quantifying fatigue performance as well as indicate how EPC ties will perform in-track. Additionally, these lab tests should seek to replicate similar failure modes seen in EPC ties installed at FAST. Ultimately, the research team hopes these evaluation guidelines will be considered for adoption into the AREMA manual, Chapter 30.

The research team began this development with initial fatigue bending tests which were iterated through variations, seeking to design a test that is most indicative of EPC tie fatigue performance in-track. There are two areas of cyclic loading in EPC ties that need to be addressed: negative center bending and positive rail seat bending. Based on the FAST and revenue service results, the center bending strains are generally higher than the rail seat bending strains. Therefore, this test plan will focus specifically on the development of the negative center bending fatigue test.

The initial test for negative center bending will use an entire tie set in a four-point bending orientation. Reverse bending will require that the bottom of the tie receive the load input via a spreader bar attached to the hydraulic actuator, while the top of the tie will be resting on the supports. For the first test, the supported span of the tie will be divided into three equal sections for supporting and loading the tie (see Figure 31). Support conditions will be the same as specified for Test 1C in the AREMA manual, Chapter 30.

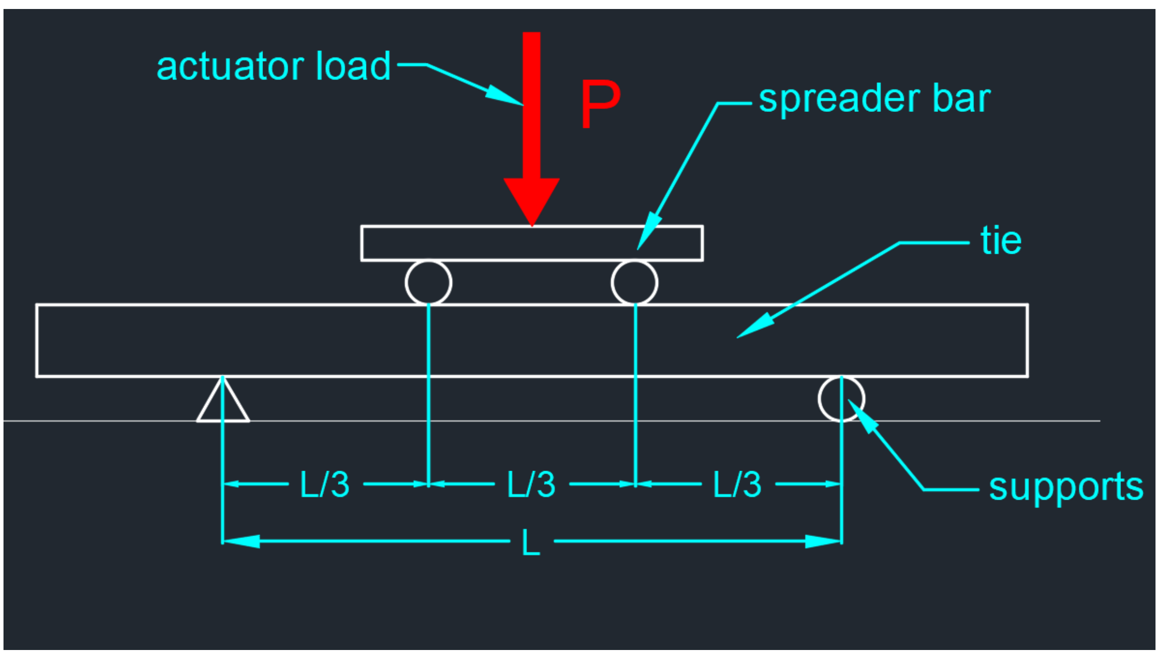

Figure 30. 4-point negative center bending load configuration

For the negative center bending fatigue test, the test sample will initially be loaded to a stress level equivalent to that seen during in-track testing, shown in the equation below:

$$P = \frac{bd^2\sigma}{L}$$

where:

P – load from actuator going into spreader bar
σ – target stress value for tie
b – width of tie
d – depth of tie
L – support length of test sample

After the test sample is loaded to P, it will then be unloaded to the lowest possible value for stable actuator function before being re-loaded back to P. This cycle will be continued until test completion.

Initial strain values should be validated before full testing begins by loading to value P and checking the corresponding strain readings. If values are off by a significant margin, load P should be adjusted to account for the discrepancy.

MOE can be calculated by loading the test sample to P and using the following equation:

$$MOE = \frac{PL}{\varepsilon b d^2}$$

where:

MOE – modulus of elasticity
P – load from actuator going into spreader bar
ε – recorded strain value
L – support length of test sample
b – width of tie
d – depth of tie

Each test should record a time history of strain, actuator loading, actuator displacement, and ambient lab temperature. Strain gages will be installed in locations like those during in-track testing at FAST. The gages for these tests will be bondable 1/2 inch quarter bridge gages which allow for high elongation. A thermocouple will monitor the ambient temperature in the lab throughout the test(s). Strain gages should be placed in the center of the span in the middle of the top side of the tie, i.e., the side facing down in the testing orientation (Figure 32 and Figure 33). This placement should seek to replicate that of the gages during in-track testing.

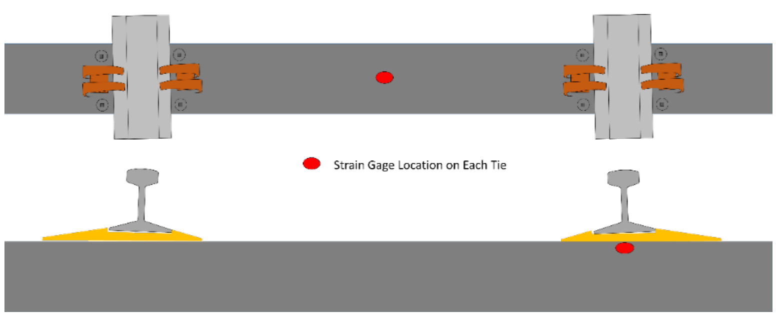

Figure 31. Location of strain gages during in-track testing

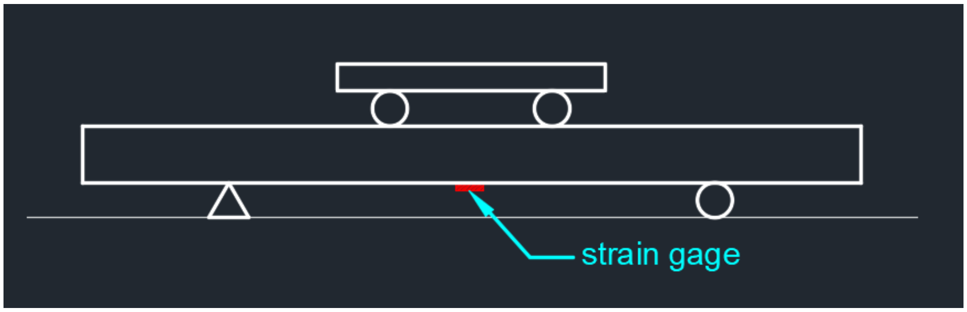

Figure 32. Negative center bending strain gage location

Strain, load, displacement, and ambient temperature data will be recorded throughout the test. Data should be collected at a sample rate of 256 Hz. Cyclic testing will last from the first cycle through to failure of the test sample or until 2 million cycles are achieved. If possible, note at which cycle number a crack initiates and where; crack growth should be monitored throughout the remainder of the test.

Post-data processing will be conducted to evaluate tie performance in fatigue. It is likely that many iterations of testing will have to be conducted to develop an ideal set of procedures that effectively evaluate composite tie fatiguing. The parameters for each unique test should be recorded:

- Dimensions of support and loading inputs on test samples
- Types of support conditions
- Loading rates or cycles/min
- Min/max loading
- Maximum cycles for test completion

Testing Iteration I: First Trial

The first test was performed on a Type A tie. The actuator was force-controlled, meaning the actuator measured the response from the tie and load to a preset value determined by the operator. This value was derived from simple beam bending theory and material mechanics to achieve the same stress value as seen during in-track testing. The outer and inner span lengths were 60 inches and 30 inches, respectively. The test ran at 5 Hz.

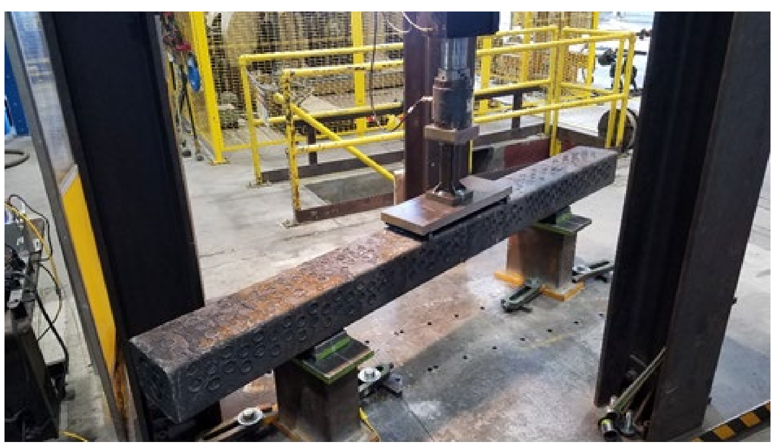

Figure 33. Test setup for Iteration I

In the first iteration, stress ranges were not reaching the predetermined value required to substantially fatigue the tie. Actuator loading rate was seen as a factor in increasing this stress range. Giving the test tie more time to de-stress after loading, between cycles, could potentially increase the stress range.

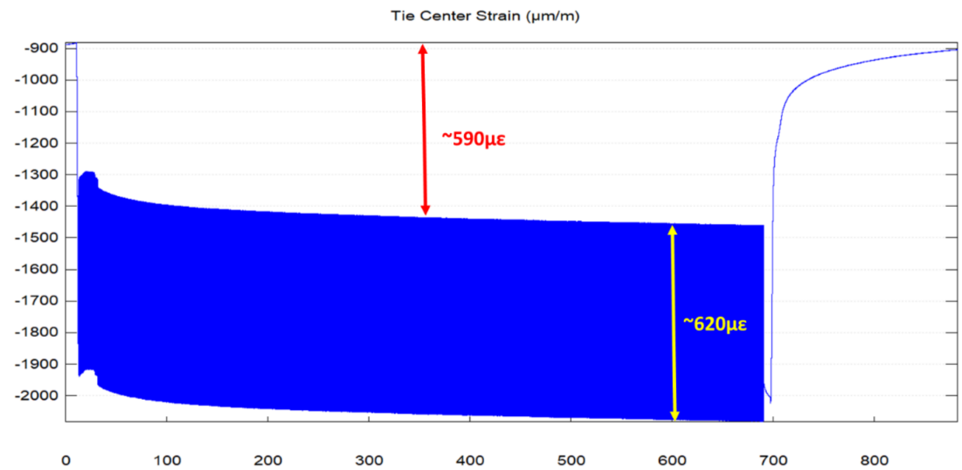

Figure 34. Strain data from Iteration I

Testing Iteration II: Different Loading Frequencies

During the testing iterations, three types of ties were tested with cyclic loading at various loading frequencies. Each tie type was cycled at 1–10 Hz. This was done to determine if loading frequency could be adjusted to maximize stress/strain range for fatigue cycling. The actuator was force controlled. The outer and inner span lengths were 60 inches and 30 inches, respectively.

Ties were initially loaded to a strain value corresponding to the strains collected during the in-track testing. Then they were cycled at frequencies 1–10 Hz while maintaining the same load values used to get the initial strain value in the tie.

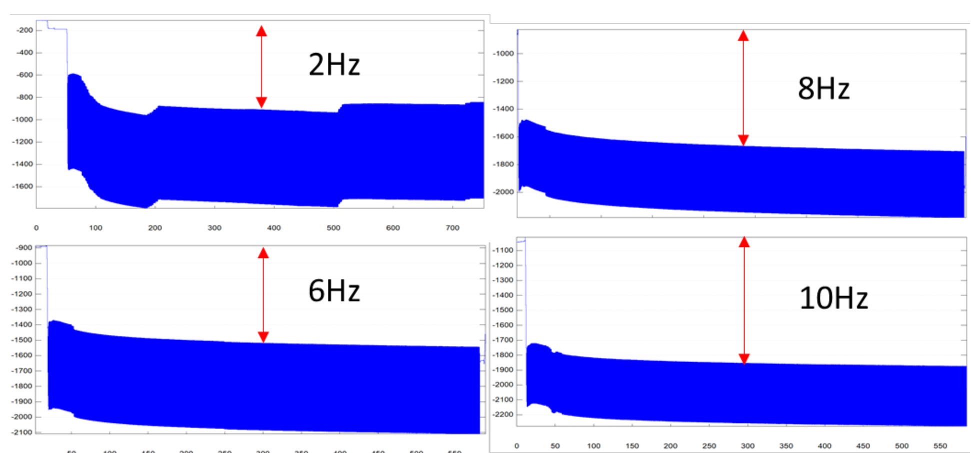

Figure 35. Higher frequency tends toward lower strain range

Across all tie types, and even at low frequencies (approximately 1–2 Hz), the tie did not have enough time to “rebound” from the applied load, resulting in residual stress build-up in the tie. As a result, the desired stress range for fatiguing could not be achieved by way of altering the load-cycle frequency. In addition, these tests should seek to fatigue the tie; however, the tie should also accumulate fatigue cycles within a reasonable amount of time. For example, running a 1–2 Hz fatigue test for 1–2 million cycles would typically take about two months to complete, which is not efficient for EPC fatigue test development. Therefore, testing at higher frequencies (i.e., > 2 Hz) is more reasonable.

Testing Iteration III: Different Support Spans

In Iteration I, the strain range did not reach the value that was measured in track. Therefore, to increase the strain response of the tie to match the in-track strain range, the research team changed the support condition for the tie(s) into the configuration shown below in Figure 37. As shown in this figure, the loading spreader bar remained at 20 inches, but the support span was reduced to 40 inches instead of 60 inches. However, the time history data showed that moving the supports had little effect on the strain range for the tie. The test cycled the tie at 2–10 Hz. The strain range continued to be smaller than the in-track measurement and continued to have residual strain. This led the team to modify the test setup and the loading mechanism, as summarized in the next iteration step.

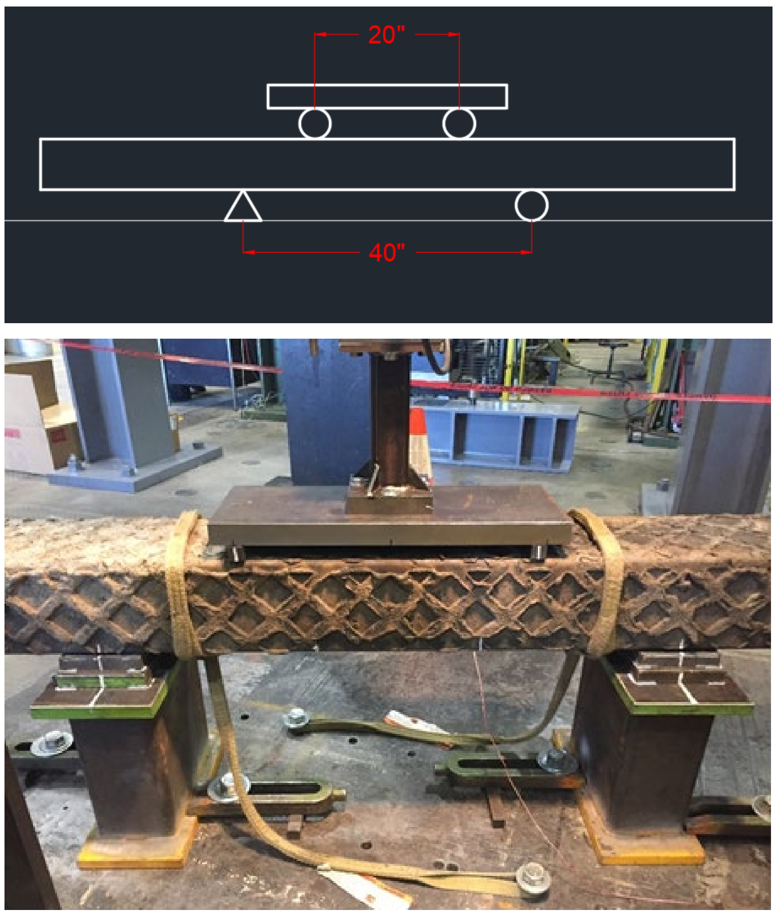

Figure 36. New dimensions for improved strain response

Testing Iteration IV: Add Fixture and Use Safety Factor

For this testing iteration, the research team used a deflection-controlled test setup, which was achieved by adding a fixture (i.e., the four-clamp rigging shown in Figure 38) to the tested tie to make sure the ties loaded at the desired stress/strain values. A new Type C tie was physically attached to the loading spreader bar and the supports (Figure 38). The strain to which the test tie was loaded was increased by a factor of two. The tested tie from the initial iteration of testing was used. The supports were pushed back to the 60 inch span length originally used in the first testing iteration.

The goal of this iteration was to force the tie back to a near-zero strain value at minimum stroke to represent more accurately what the strain responses were for in-track EPC ties. This was achieved by "pulling" the tie back to its initial strain value by attaching the tie to the actuator arm. On its return stroke, the actuator pulled up on the tie and thereby re-set its strain value. The tie was attached to the outer support to prevent any lift-off and creep during cyclic testing.

The tie was able to be loaded to a deflection value that achieved the strain range the tie experienced during in-track testing, as shown in the lower plot in Figure 39.

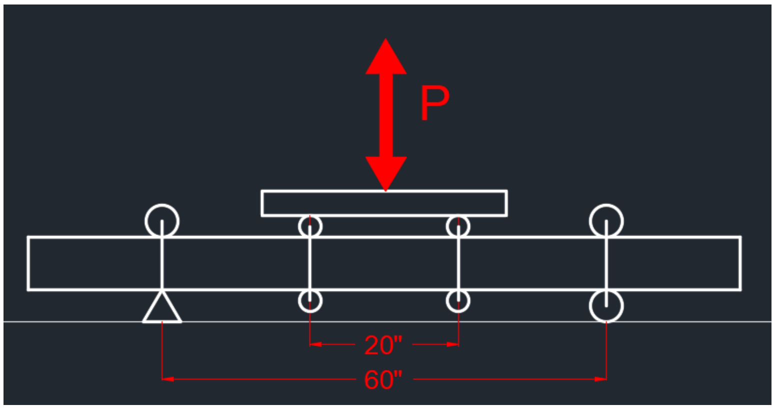

Figure 37. New support configuration for Iteration IV

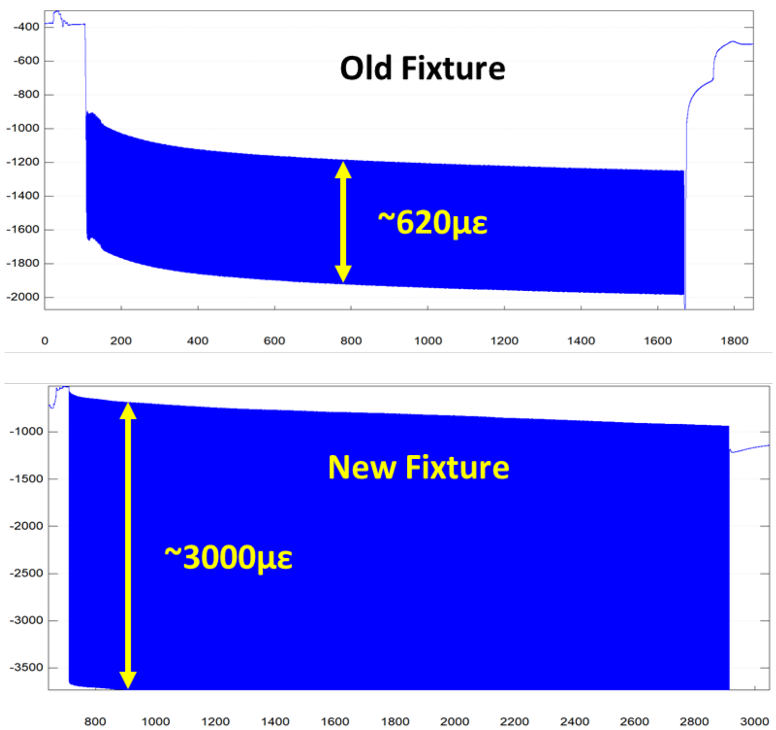

Figure 38. Increased strain levels for cyclic loading in new fixture

After the tie reached the targeted stress range, the research team cycled it until it developed a crack in the tension face near the center of the constant moment region. This crack initiated at approximately 494,000 cycles. The test was run until the tie accumulated 1.3 million cycles, and the crack propagation was monitored. This crack was similar in nature to failures observed at FAST across several tie types. The crack propagated from the corner of the tie toward the tension-side face, the same location as similar cracks found in the EPC ties installed at FAST.

<u>Testing Iteration V: Increase Middle Span</u>

For this test iteration, the research team used a 30-inch test span to test a longer tie section by increasing the constant moment area. The strain input was increased by a factor of two. The tested tie (i.e., Type A) from the initial iteration of testing was used. It had already accumulated almost 800,000 cycles from previous test cycling and frequency analysis.

As before, this test was run in deflection control. The research team ran the tie for an additional 1.5 million cycles under these test conditions. The strain range remained similar throughout the course of the test, but the maximum strain gradually increased with further cycle accumulation. No noticeable, superficial cracking was detected throughout the test.

After test completion, the 30-inch constant moment region of the tie was removed and cut into 30 1-inch cross-sections. As shown in Figure 40, the internal porous area in the laboratory test was smaller and less dense compared to the failed ties found in-track. Moreover, the failed tie had a void (2.5 x 1 inch) in the failure plane. The internal voids in the lab-tested tie were not as large as the one in the failed tie from the field. Even though the test did not replicate the failure found in field, it was able to differentiate the fatigue performance between different ties. The fatigue resistance may be strongly related to the internal condition of the tie. For this reason, the test setup was determined to be satisfactory for future tests on other types of EPC ties.

Figure 39. Internal condition of laboratory tested tie vs. in-track failed tie

<u>Testing Iterations VI and VII</u>

For the next two tests featuring Type B and Type C ties, the research team used the same setup as the previous test that used Type A. Both tests failed around 1.3 million cycles. The constant moment regions were again sliced into 1 inch pieces to investigate the internal conditions. Both failed ties showed internal defects at the failure planes (see Section 3.1.4). This once again suggested that the internal condition is the key factor for controlling the tie bending fatigue performance. This also provided additional evidence that the proposed 4-point bending test was able to replicate the in-track failure and test the tie bending performance. Therefore, this test may be a worthy candidate for Chapter 30 of the AREMA manual for EPC ties.

Abbreviations and Acronyms

ACRONYM	**DEFINITION**
AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance-of-Way Association
CTE	Coefficient of Thermal Expansion
EPC	Engineered Polymer Composite
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
GRMS	Gage Restraint Measurement System
HAL	Heavy Axle Load
HDPE	High-Density Polyethylene
HTL	High Tonnage Loop
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
SRI	Strategic Research Initiatives
STPT	Single Tie Push Test
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.