FINITE ELEMENT MODEL VALIDATION OF PRETENSIONED CONCRETE CROSSTIE BASED ON FIELD INSTRUMENTATION

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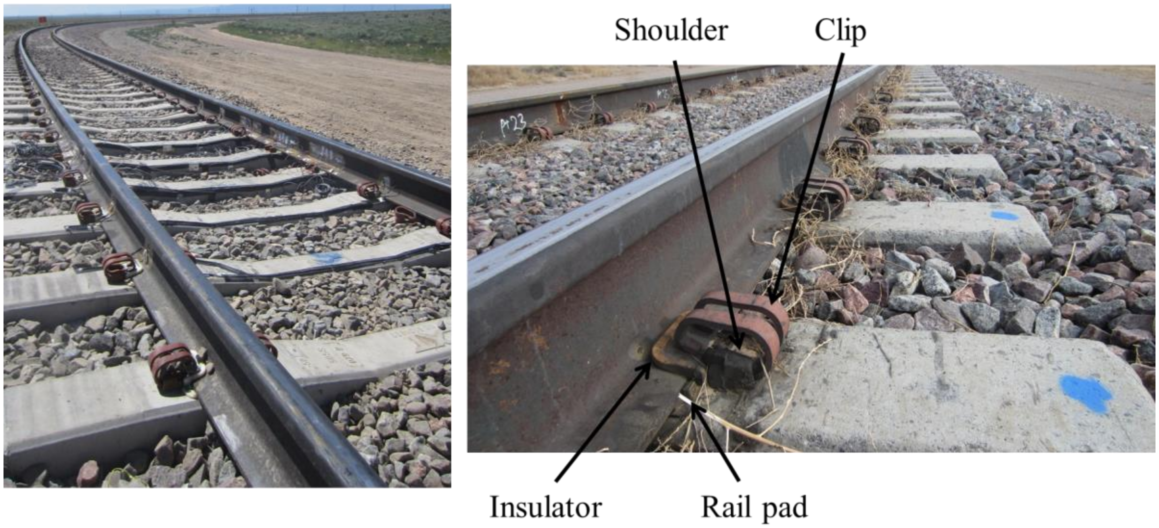
ABSTRACT

As the primary structural component in railroad track, prestressed concrete crossties have been widely applied in North America to accommodate the increase of freight axle load, and the development of high-speed passenger train. However, the design standard of American Railway Engineering and Maintenance-of-Way Association (AREMA) remains unclear about the relationship between wheel load and the flexural demand of prestressed crossties. In this study field experimentation was conducted at the Transportation Technology Center at Pueblo, CO, and the test data was compared with a finite element (FE) model of the track structure for model validation. Embedded strain gauges and potentiometers were installed in the experimentation to measure the response of the concrete crosstie. The FE model consists of two parts: a detailed single-crosstie model to capture the local response of the loaded crosstie, and a global multi-crosstie model to provide realistic boundary conditions for the detailed model. The bond-slip behavior between concrete and prestressing wire, and inelastic material property are incorporated in the FE model. Good agreement is observed between the test measurement and model output. The validated FE model will be used for future parametric studies on the flexural design of concrete crossties.

Keywords: Finite element analysis, Prestressed concrete crosstie, Model validation, Track engineering.

INTRODUCTION

Concrete crosstie is a structural component used on railroad track to support and distribute the wheel load over a larger area upon ballast. To provide uniform running surface to the wheels and transfer wheel load to the crossties, fastening systems of different designs are installed onto crossties in the track. Fig. 1 shows a typical design of prestressed concrete crosstie and fastening system used on North America freight track.



a) b)

Fig.1 Typical design of a) the prestressed concrete crosstie and b) the fastening system used on North American freight track.

Concrete crossties are mainly designed as prestressed concrete flexural components, however the flexural demand of concrete crossties defined in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering was determined empirically[1]. In the AREMA Manual, the flexural demand at different sections of the crosstie is determined as a function of the crosstie length, crosstie spacing, vehicle speed, and track tonnage. And the flexural demand was derived based on field experimentation conducted on some revenue tracks in the 1980s[2]. Due to the ever-increasing needs for freight traffic of heavier axle load and higher-speed passenger rail, the loading spectrum on North America railroad has changed considerably. As a result the empirical relationships are no longer representative of the track condition, and should be replaced with a mechanistic design approach that considers the variation of track structure demand under different wheel loads.

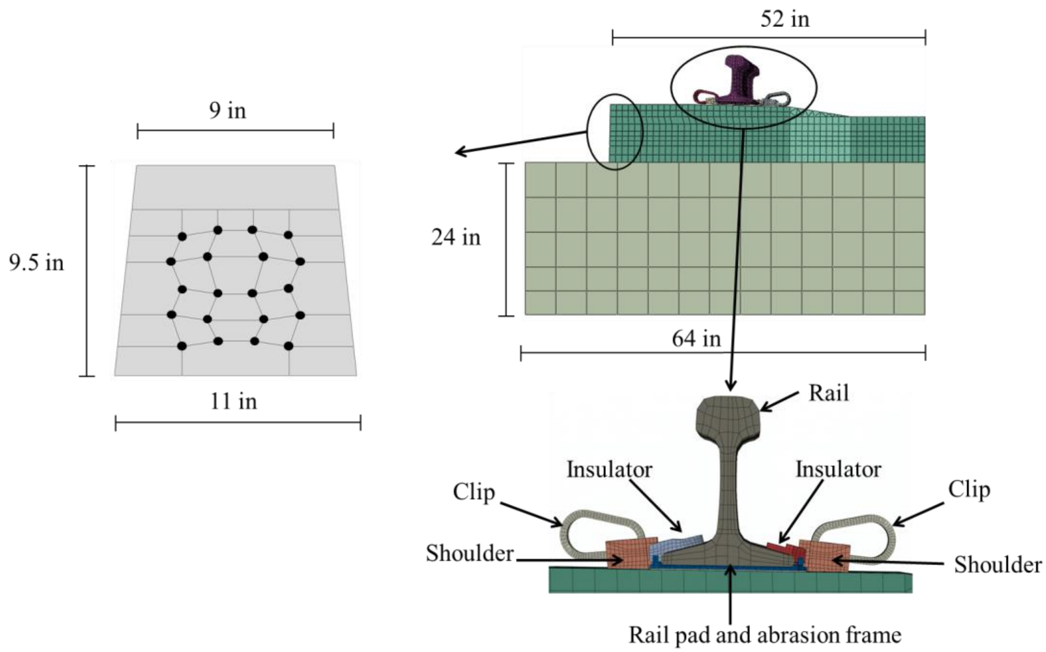
Researchers have used FE analysis to gain a better understanding of the behavior of concrete crossties and fastening systems, and their research work provided some insight into the application of this technique. For example, Gonzalez-Nicieza et al.[3] developed a failure analysis of heavy-haul freight track. Both single-crosstie models and multiple-crosstie models were built in the analysis based on data collected from field experimentation to look into the cause of crosstie cracking. However elastic material property for all track components was assumed in the model, and the fastening system was ignored. Yu et al.[4] conducted FE analyses that included 3D model of single concrete crosstie with ballast and subgrade support. In this model, the interaction between concrete and strand is modeled as cohesive element, which is incorporated between them to simulate the bond-slip relationship. Several factors that could affect the performance of the concrete crosstie are investigated including different loading application and strand pattern. Kaewunruen and Remennikov[5] presented a dynamic FE model of single concrete crosstie to investigate its transient response under impact load. However, the fastening system and track substructure were replaced with springs. In summary, the existing FE models did not consider the distribution of wheel load among multiple rail seats with fastening systems of detailed geometry and material property. Therefore there are considerable room for model improvement to investigate the interaction between fastening system components, and between the fastening system and the concrete crosstie.

To investigate the load path through the prestressed concrete crosstie and fastening system that is representative of North America railroad, field experimentation was performed at the Transportation Technology Center (TTC) in Pueblo, CO by researchers from the University of Illinois at Urbana-Champaign (UIUC). This experimentation is part of a research project aimed at the improved design of concrete crosstie and fastening system funded by the Federal Railroad Administration (FRA). In this project a detailed 3D finite element (FE) model of prestressed concrete crossties and fastening systems was developed for analytical purpose, and this paper focus on the validation of the FE model with field experimentation. The 3D FE model was developed using the FE program ABAQUS[6], and nonlinear material property was defined in the model based on manufacturer information. Friction interaction was defined at the interfaces of different components, and the model was able to consider the distribution of wheel load among multiple rail seats. In the field experimentation, controlled vertical and lateral wheel load was applied to the track structure, and linear potentiometers and embedded strain gauges were installed to measured displacement and concrete internal strain respectively. Good agreement was observed in the comparison of model output and field measurement, and some conclusions were summarized about track condition.

MODELING CONFIGURATION

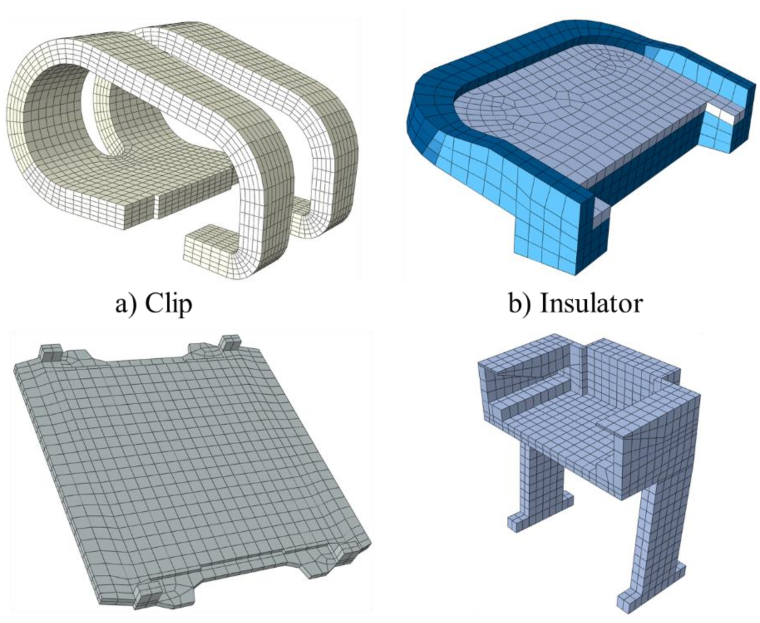
FINITE ELEMENT MODEL CONFIGURATION: DETAILED MODEL

In order to examine the responses of the prestressed concrete crosstie and fastening system under different loading scenarios, a 3D FE model that includes one set of fastening system on a single symmetric concrete crosstie with simplified support is developed. Fig. 2 illustrates the layout of the fastening system in the FE model. As the track structure is symmetric as designed, and symmetric wheel load was applied in the field experimentation, only half of the track structure is simulated. In this model the geometries of all the components are simplified, and some of the component models are shown in Fig. 3.



a) Layout of prestressing strands b) Configuration of the fastening system

Fig. 2 Configuration of the 3D concrete crosstie and fastening system FE model.



a) Clip b) Insulator

c) Rail pad d) Shoulder

Fig. 3 Component FE models of: a) clip, b) insulator, c) rail pad, and d) shoulder

As shown in Fig.2, the model consists of one set of fastening systems, and a single symmetric prestressed concrete crosstie. The dimension of the crosstie is 102 in (length) x 11 in (width) x 9.5 in (height) with 20 embedded prestressing wires. The section area of the prestressing wire is 0.034 in^2, and the distribution of prestressing wires in the concrete crosstie is shown in Fig. 2.

Concrete damaged plasticity model was used in this model, and two main failure mechanisms were considered, namely concrete tensile cracking and compressive crushing. Under uniaxial tension, concrete maintain the same stiffness in the linear-elastic stage, and after the cracking stress is reached it follows a softening stress-strain relationship. Under uniaxial compression, concrete remains linear-elastic until the yielding stress is reached. In the plastic stage, the concrete is first characterized by strain hardening and then strain softening after reaching the ultimate compressive stress. The material property of concrete crosstie and fastening system was defined based manufacturers' information, and was also presented by Chen et al[7]. As the proposed FE model focused on the performance of prestressed concrete crosstie and fastening system, a support block was introduced as the general representation of the track substructure, which consists of ballast, subballast, subgrade, etc. The material property of the support block was determined based on field experimentation, and is discussed in later section.

Interactions between different components of the fastening system, and between crossties and ballast were defined with contact pairs in ABAQUS[6]. A master surface and a slave surface of different mesh densities were identified. Some of the coefficient of friction (CoF) values were based on a series of large-scale abrasion resistance tests that were conducted recently at the UIUC[8], and others were determined based on empirical data[9, 10].

The interaction between the concrete crosstie and shoulder inserts was complex as it involves multiple pairs of interaction surfaces. To simplify the mesh of concrete and to avoid numerical singularity, "embedded region" in ABAQUS was used to model the interaction. With this constraint, the nodes of the embedded element (shoulder element) are restrained by the nodes of the host element (concrete element). And with "embedded region" the bond characteristics between concrete and shoulder insert can be reasonably represented until damage occurs.

Connector elements were used to define the interaction between the concrete and prestressed wires. The concrete was meshed in a way that element nodes along the line of the wires coincided with wire nodes and a connector element connected coincident concrete and wire nodes. The Cartesian connector section was assigned to the connector element, and the connector element acted as a spring based on the relative displacements of the connected nodes. For simplification the bond-slip behavior is averaged over the length of reinforcement, and an elastic force-displacement relationship was defined for all the connectors. The stiffness along the direction of the wires was defined based on the pullout test results of similar materials[11]. In addition, rigid connection was defined in the other two directions of connector elements.

In total, the model includes seven static analysis steps, and the loadings and boundary conditions are as shown in Fig. 4. In the initial step a total prestress force of 140 kips was assigned to 20 wires based on manufacturer design, which is 80% of the wire tensile capacity, and prestress was gradually released. In the same step, clips were lifted with pressure loading while the clip base was restrained with boundary condition. In the second step, clips were inserted into shoulders with displacement boundary condition and clamping force was applied to the system with the pressure loading removed. In the following three steps, stabilizing boundary conditions and loadings were gradually removed from the model, and at the end of the fifth step the model was ready for wheel load. At this time a vertical boundary condition was applied was at the bottom of the support block to provide support for the system, and a symmetric boundary condition was applied at the centerline section of the track structure. In the sixth step, and vertical wheel load was applied and linearly increased to the maximum value. While the vertical loading remained constant, in the seventh step the lateral wheel load was applied on the lateral surface of the rail head, and linearly increased to the target value. The loading scenarios are discussed in details in later sections.

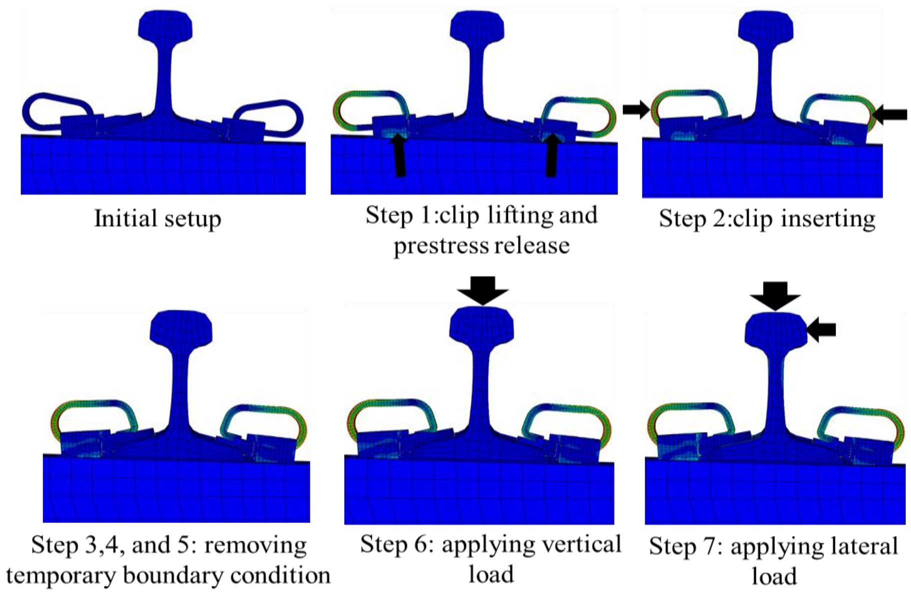
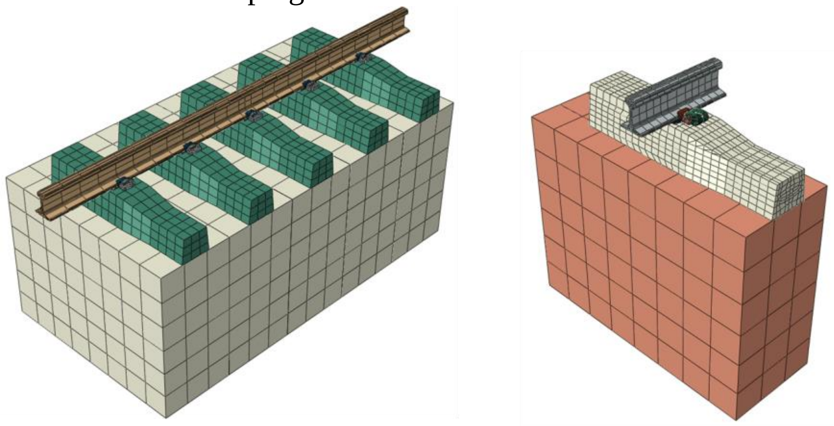


Fig. 4 Loading sequence of the model

The modeling work was carried out using ABAQUS[6] Standard. The rail, fastening system, concrete crosstie and supporting ballast were all modeled with eight-node brick element that has three translational degrees of freedom (DOF) at each node, and the prestressing reinforcement was modeled with 1-D truss element that only had stiffness along the longitudinal direction. Based on the geometry of the components and the result of mesh sensitivity analysis, different mesh densities were assigned to different components. For the clip, as the component response was sensitive to mesh density when applying clamping forces, dense mesh was assigned; and as the ballast only served as the general representation of the track substructure, it was coarsely meshed. Fig. 3 shows the relative density of mesh.

FINITE ELEMENT MODEL CONFIGURATION: GLOBAL MODEL

To simulate the behavior of continuous rail supported by multiple concrete crossties and fastening systems, a simplified global model was built to collaborate with the detailed model. As shown in Fig. 5, the symmetric global model includes 5 concrete crossties and 5 sets of fastening system at a spacing of 24 inches based on the field condition. The length of the rail considered in the global model was determined based on a set of preliminary sensitivity analysis. And it was determined that under a single vertical/lateral wheel load, the deflection of the track structure mainly occurs within the five nearest concrete crossties. In the global model, the material property definition, as well as the loads and boundary conditions are the same as that in the detailed model. In addition, the mesh and the component geometry are simplified to reduce calculation time. Instead of inserting the rail clips to apply clamping force, pressure is defined on the surface of insulators to simulate the clamping force.



a) b)

Fig. 5 Comparison between a) the global model and b) the detailed model

To simulate a loading scenario, the global model is used first. Afterwards during the calculation of the detailed model, the displacement at the end of rail segment in the global model is introduced so that the rail segment in the detailed model behaves the same as part of the longer rail segment in the global model. In addition, as shown in Fig. 6, the vertical and lateral load shared by adjacent concrete crossties in the global model is resisted by the displacement boundary condition at the end of the rail segment in the detailed model. In this way the concrete crosstie in the detailed model behaves identically as the center crosstie in the global model, while the output accuracy is considerably increased.

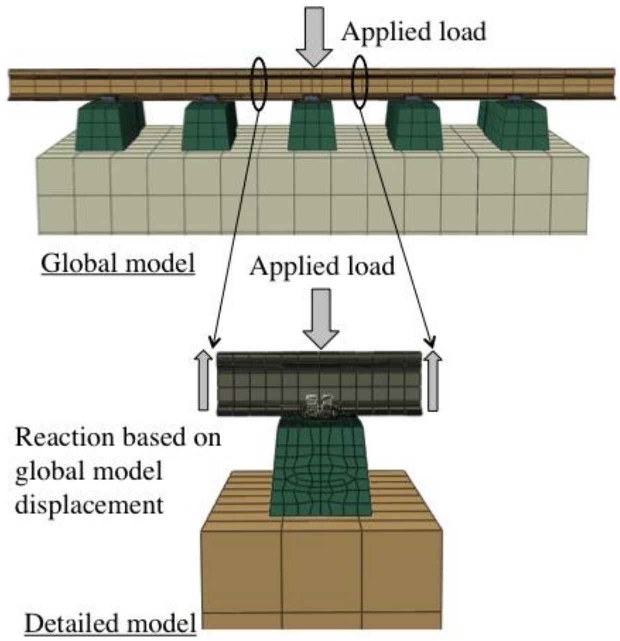


Fig. 6 Collaboration between the global model and the detailed model

FIELD INSTRUMENTATION

In May 2013 field experimentation of concrete crosstie track was performed at the TTC in pueblo, CO. During the experimentation both static and dynamic testing were conducted, and the instrumentation program included the use of strain gauges, linear potentiometers and matrix based tactile sensors (MBTSS)[12]. In this paper the discussion is focused on validation and calibration of the FE model using displacement and concrete strain measurement under static wheel load. A comprehensive description of the testing program and field testing data was presented by Grasse[12] and Wei et al.[13]. On the tangent segment of Railroad Test Track (RTT) at TTC, controlled static wheel loads were applied from track loading vehicle (TLV), as shown in Fig. 7 a). Upon each concrete crosstie symmetric vertical wheel load was first applied on the two rails and the magnitude gradually increased to 40 kips. While the vertical wheel load is maintained at 40 kips, symmetric lateral wheel load was later applied and the magnitude increased to 20 kips.

The support stiffness of track substructure is critical about the performance of railroad track. As track substructure consists of multiple layers of inhomogeneous materials including ballast, subballast and subgrade, the support stiffness of the track substructure is often determined with field measurement. As shown in Fig. 7 b), during the field experimentation, linear potentiometers were installed on multiple concrete crossties to measure the vertical crosstie displacement under different loading scenarios. In addition, embedded strain gauges were embedded into concrete crossties to measure the internal strain of concrete. The location of embedded strain gauges was as shown in Fig. 8. For each rail seat, four strain gauges were placed in concrete to measure the vertical concrete strain in the rail seat region.

a) b)

Fig. 7 a) TLV applying wheel load on the instrumented segment of RTT and b) linear potentiometer installed on concrete crosstie.

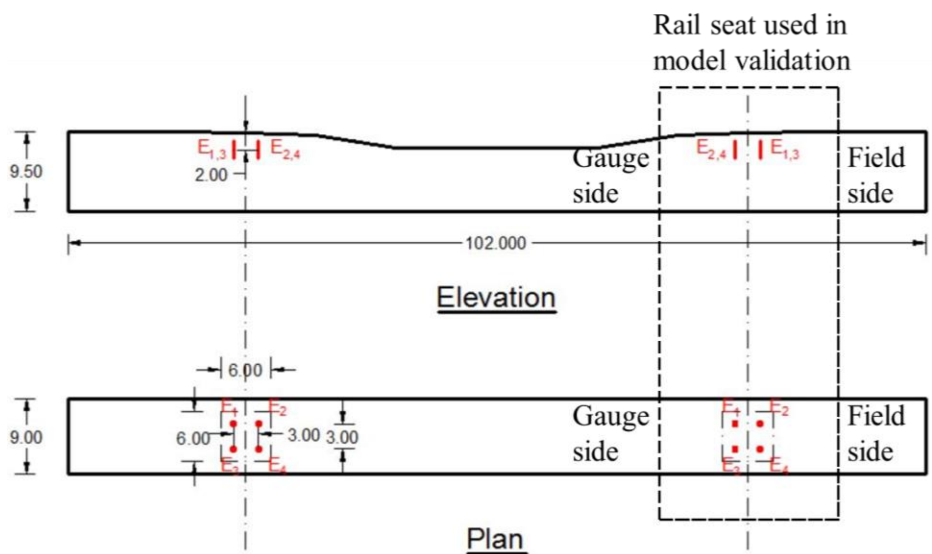
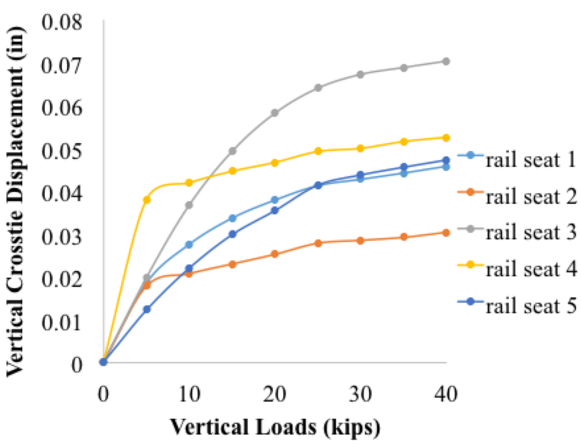


Fig. 8 Position of the concrete embedded strain gauges within concrete crosstie (unit: inches)

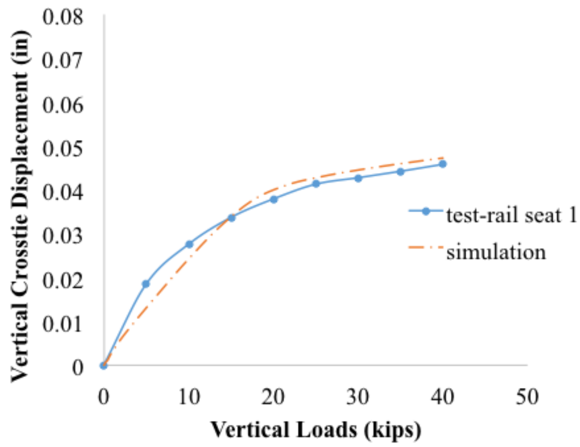
MODEL VALIDATION

CROSSTIE VERTICAL DISPLACEMENT

Fig. 9 a) summarizes the relationship between vertical crosstie displacement, measured with linear potentiometers, and vertical wheel load at different rail seats. Each line in the figure represents the vertical wheel load-deflection relationship for each rail seat when the wheel load was applied upon it. It can be observed that at different rail seats the support stiffness varied considerably. For two rail seats the support stiffness have abrupt change at a magnitude of the vertical load. This is most likely due to the fact that voids of different sizes existed between some concrete crossties and ballast. After the vertical wheel load increased to a certain magnitude, the voids were closed and higher support stiffness was observed afterwards. For the other three rail seats, the support stiffness gradually increased with higher vertical wheel load. The field measurement at rail seat 1 was used for model calibration as it was more representative of the track condition. To capture the change of support stiffness, hyperelastic model was used to define the material property of the support block in the FE model. This material model is usually used for nonlinear elastic materials with little compressibility. In ABAQUS the test result can be used as input to define the hyperelastic model. After calibration, the comparison between model output and field-test measurement of vertical crosstie displacement is shown in Fig. 9 b), and good agreement was observed. It is shown that the FE model is able to capture the nonlinear support stiffness of the track substructure.



a)



b)

Fig. 9 a) relationship between vertical crosstie displacement and vertical wheel load at different rail seats and b) comparison between model output and test measurement of vertical crosstie displacement at rail seat 1

CONCRETE EMBEDDED STRAIN GAUGES

As shown in Fig. 8, four embedded strain gauges were casted into each rail seat region to measure vertical concrete strain and they were named from 1 to 4. The embedded concrete strain gauges were placed 2 inches below the rail seat surface, and were placed 3 inches from each other. In the four strain gauges, strain gauge 2 was damaged and only the data from strain gauge 1, 3 and 4 were collected. Fig. 10 and Fig. 11 show the change of strain measurement under increasing vertical and lateral wheel load along with the corresponding prediction of the FE model. Under vertical wheel load, which was applied onto the rail head with eccentricity to the gauge side, the vertical reaction in the rail seat region was more concentrated on the gauge side (strain gauge 1 and 3). As a result, under the same vertical wheel load the strain measurement of gauge 1 and 3 is larger than that of gauge 4. Under increasing lateral wheel load, the strain measured on the field side (strain gauge 4) continued to increase, while the strain measured on the gauge side (strain gauge 1 and 3) gradually decreased. This was because the lateral wheel load applied moment to the rail, which balanced the eccentricity moment due to vertical wheel load, and continued to rotate the rail head to the field side.

As embedded strain gauges were placed symmetrically about the centerline of the crosstie, theoretically identical measurement should be observed between strain gauge 1 and 3. However, under the same loading scenario the strain measured from strain gauge 3 is considerably larger than that of strain gauge 1. The difference between concrete vertical strains measured from strain gauge 1 and 3 could be most likely related to the asymmetric support condition at the bottom of the crosstie. Under field condition, concrete crossties were supported on the uneven surface of ballast, and as a result the symmetry of crosstie-ballast support about the centerline of the crosstie is not guaranteed. In addition, the dislocation of embedded strain gauges in the casting process could also contribute to the difference observed.

In comparison, in the FE model identical concrete vertical strain were predicted at the position of gauge 1 and 3, and 2 and 4. Therefore the model outputs were combined into a single line in Figure 10 and Figure 11. This was due to the fact that the track substructure was modeled as continuous material with flat surface, which was symmetric about the centerline of the crosstie. In general the FE model was able to capture the rotation of rail under vertical and lateral wheel load, as good correlation was observed between the change of concrete vertical strain in the model output and that in the field measurement. Besides, the magnitude of strain in field measurement is close to that of model output, which indicates that the model is able to capture the distribution of vertical and lateral wheel load among multiple rail seats. For strain gauge 1 and 3, the corresponding model output was between the field measurements of the two strain gauges, which support the assumption that uneven support condition existed under the crosstie. In addition, as the strain measured at strain gauge 3 and 4 are both higher than that in the model output, it is most likely that the support stiffness under the corresponding side of the crosstie was higher than that of the other side.

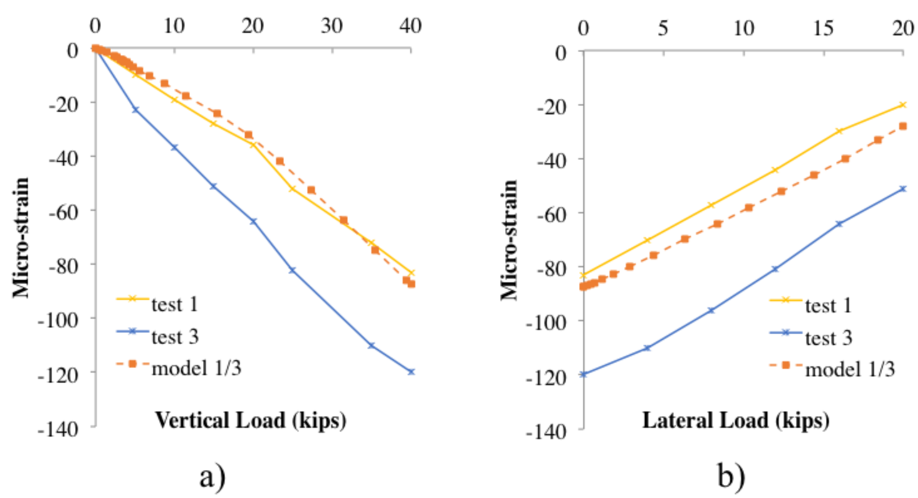


Fig. 10 The relationship between the measurements of embedded strain gauge 1, 3 and a) vertical wheel load (lateral wheel load = 0), and b) lateral wheel load (vertical wheel load = 40 kips).

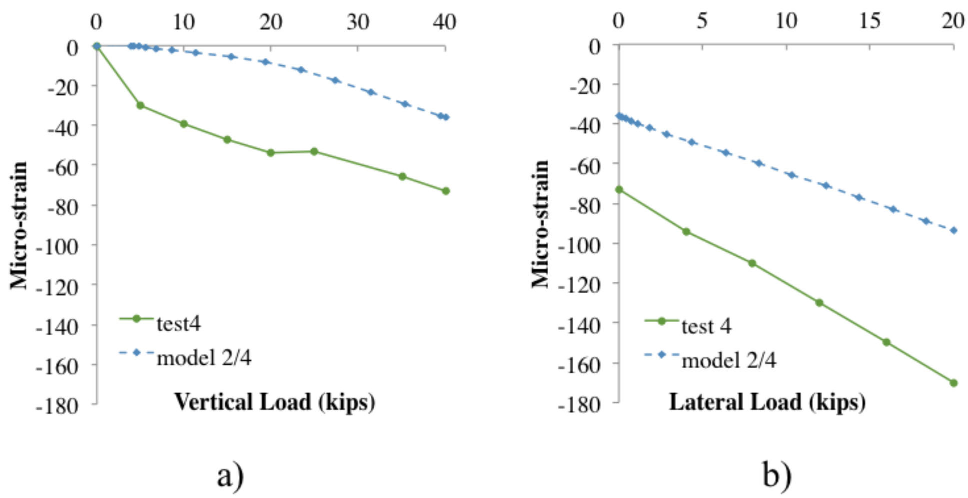


Fig. 11 The relationship between the measurements of embedded strain gauge 2, 4 and a) vertical wheel load (lateral wheel load = 0), and b) lateral wheel load (vertical wheel load = 40 kips).

CONCLUSIONS AND FUTURE WORK

In this paper a set of 3D detailed FE models of prestressed concrete crosstie and fastening system was presented, and the models were validated with static field experimentation conducted at the TTC in Pueblo, CO. The model was built based on manufacturer information and field track condition. It was able to consider nonlinear material property, frictional interaction of different components, and realistic bond-slip behavior between concrete and reinforcement. Based on the validation of the FE models, some conclusions could be summarized:

- The support stiffness of track substructure varied considerably between different rail seats. In addition, significant increase was observed in the support stiffness under higher vertical wheel load.
- The material property of the support block in the FE model was calibrated based on field measurement of vertical crosstie displacement, and good agreement was observed.
- Based on the comparison of concrete vertical strain between model output and field measurement, it was observed that the FE models were able to capture the distribution of wheel load among multiple rail seats, and the rotation of the rail under vertical and lateral wheel load.
- Uneven support condition was likely to exist under the instrumented concrete crosstie, and asymmetric response was captured in the field experimentation.

Based on the validation presented above, it can be observed that the proposed FE models is able capture some important mechanisms of the track structure. Besides, further validation of the FE models based on field data is in progress. The further improved models will be used in a series parametric studies to better understand vertical and lateral load path through the concrete crosstie and fastening system, and evaluate the effect of some design parameters on critical system responses.

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