

Finite Element Models of Prestressed Concrete Sleepers and Fastening Systems in North America

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ABSTRACT

Understanding the performance and serviceability of concrete sleepers and elastic fastening systems is critical as the loading demands increase as a result of the increasing freight axle loads and cumulative gross tonnages as well as the development of high-speed passenger rail in North America. In light of these ever increasing demands, it is essential to examine and improve current design practices of concrete sleepers and fastening systems. This study focuses on developing an analytical framework for a 3D finite element (FE) model of prestressed concrete sleepers and fastening systems for US high speed rail and joint passenger/freight corridors with the aim of improving the knowledge regarding its mechanical behavior, and recommending a new design guidelines. The following critical features of the concrete sleepers and fastening systems are given special care in the FE model: 1) Contact behavior at the interfaces between various system components, 2) Internal prestress distribution along the concrete sleeper, and 3) Nonlinear constitutive behavior of various component materials. In this study, an advanced submodeling technique is adopted to simulate a track structure in the field, and is compared with data collected from field experiments conducted at the Transportation Technology Center (TTC) in Pueblo, CO, USA. Static loads applied by a Track Loading Vehicle (TLV) are considered in the simulations. The results show that the presented model is efficient and effective in simulating the track structure in field. The validated FE model developed in this study will be used in the next phase of the research to develop new mechanistic design guidelines for the track components in North America through an extensive parametric study. The validated FE models developed in this study can also be expanded to examine the performance of track components utilized in other countries.

1. Introduction

Ensuring the safety and functionality of North America's transportation network is critical. Among the modes of transportation, railroad infrastructure is a key element within this network. The railroad infrastructure and its components have been under increasing demands due to the development of high speed rail corridors and increasing axle loads. Currently, there is little understanding of the mechanistic behavior of the railroad infrastructure and design has relied primarily on empirical methods and experts' experiences. One reason for the lack of mechanistic understanding is due to the fact that the important mechanisms of the structural system, such as the interactions between each component, frictional behavior, geometrical complexity, etc., are not easy to identify empirically. In North America, the American Railroad Engineering and Maintenance-of-way Association (AREMA)'s Recommended Practices, which has been developed empirically, has been widely adopted as a general design guideline for prestressed concrete sleeper and fastening system design (AREMA, 2012). Therefore, this study focuses on developing a finite element (FE) model of prestressed concrete sleepers and fastening systems to improve the knowledge and understanding of the mechanistic behaviors of the railroad infrastructure.

Over the past few decades, a few FE models of the concrete sleeper and fastening system have been developed to address the mechanistic designs and performances of the infrastructure systems. Although the developed FE models are able to quantify the performances of concrete sleepers under certain load scenarios and support conditions, most models were not suitable for understanding the detailed system performance because they did not include the fastening systems, or the models were extremely simplified (Yu and Jeong, 2010; Yu et al. 2011; Lundqvist and Dahlberg, 2005). This study presents a framework for developing 3D FE model of the prestressed concrete sleepers with a

detailed fastening system. Additionally, this paper addresses modeling the structural system under actual field conditions. The authors have studied the performance of the concrete sleeper and fastening system in laboratory tests (Chen et al. 2013). It is important, yet computationally expensive, to build a field representative model consisting of multiple prestressed concrete sleepers, fastening systems, and the ability to implement a variety of support conditions. In this study, an effective and efficient approach to develop the field representative FE model allowing for the analysis of different support conditions is discussed while taking into account the complex interactions of the components. An advanced FE submodeling technique is adopted to simulate the field behavior of prestressed concrete sleepers and fastening systems. The FE models in this study are calibrated and compared with data collected at the Transportation Technology Center (TTC) in Pueblo, CO.

2. Modeling of Concrete Sleepers and Fastening Systems in Field Conditions

2.1 Description of the Modeling Approach

In North America, various combinations of prestressed concrete sleepers and elastic fastening systems have been installed in field. Herein, a typical concrete sleeper and fastening system in North America was selected and modeled. Figure 1 shows a picture of the concrete sleepers and the fastening system in field (a) and a corresponding structural system of a possible FE model (b). The structural system consists of a fastening system and a concrete sleeper including ballast. One of the main requirements of the structural system is to transmit wheel loading from the rail to the sleeper and to the ballast, and to maintain uniform track geometry. The dimensions of the concrete sleeper are 2590 mm (length) x 280 mm (width) x 240 mm (height) (102in x 11 in x 9.5 in) with 20 prestressing strands embedded in the sleeper. The typical fastening system includes shoulders, elastic clips, insulators, a rail pad and an abrasion plate. Component models of the fastening system used in the FE model are shown in Figure 2 in the isometric view. A finite element program, ABAQUS, was utilized in this study (Dassault Systems Simulia, 2013). An eight-node solid element was adopted to model the rail, the fastening system, the concrete sleeper and the supporting ballast, while 1-D truss element was utilized to model the prestressing strands in the sleeper.

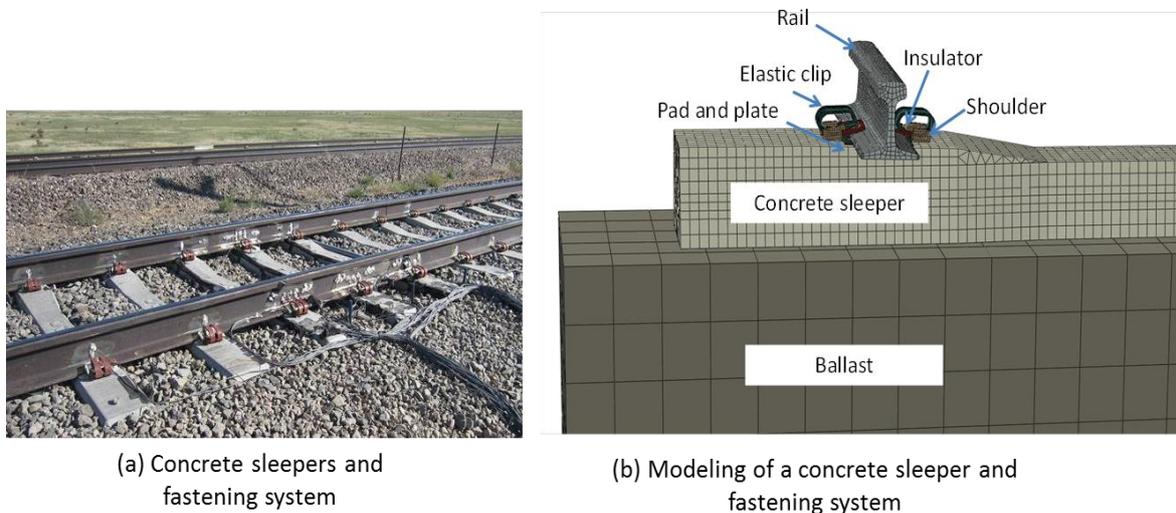


Figure 1. Picture of concrete sleepers and fastening systems in field (a) and a schematic of the FE model of a concrete sleeper and fastening system (b)

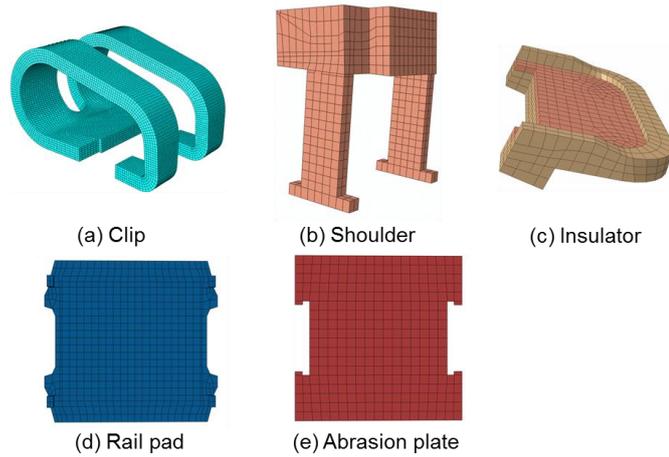


Figure 2. FE component models of the fastening system: (a) clip, (b) shoulder, (c) insulator, (d) rail pad, and (e) abrasion plate

2.2 Global Modeling and Submodeling

In order to model the concrete sleepers and fastening systems in field conditions, implementing different support conditions is inevitable. In this study, an advanced submodel technique was adopted to represent the field behaviors of multiple sleepers with fastening systems. Figure 3 shows a schematic describing the submodeling technique including a global model, the sectional view of the global model with springs, and the submodel (i.e. partial model) extracted from the global model.

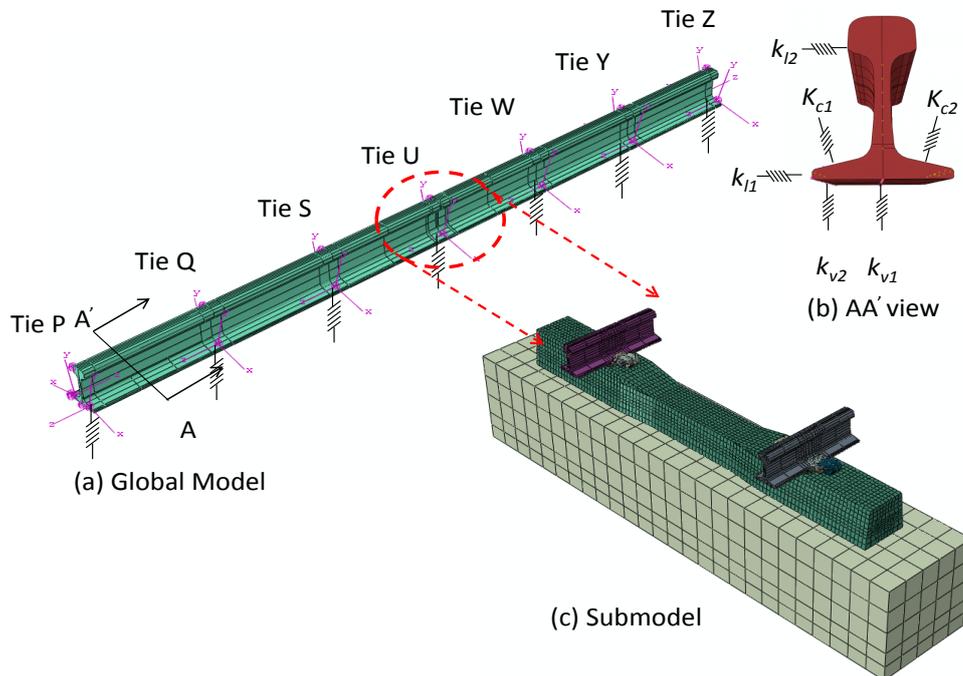


Figure 3. Schematics of the global model (a), corresponding submodel (b), and a rail section with springs at each railseat of the global model (c)

In the global model, the track system was represented by a long rail with different springs at each rail seat. A total of seven sleepers were considered in the global model to incorporate different support conditions in field. At each rail seat, six springs were connected to the rail representing the support condition and the fastening system. K_{v1} and K_{v2} stand for the stiffness of the two vertical springs, K_{c1}

and K_{c2} for the clip springs, and K_{l1} and K_{l2} for the lateral springs. The springs at each rail seat were calibrated until the response of the global model reflected the behaviors of the track structure in the field. After simulating the global model, the detailed responses at one rail seat were simulated through the submodel. One section of the long rail in the global model was cut, and the springs were replaced with a detailed concrete sleeper and fastening system including an elastic support underneath the sleeper. The boundary conditions of each end of the cut rail in the submodel were governed by the simulated responses from the global model. By simulating the submodel after the global model, the intricate interactions between various components would be examined. The mechanical behaviors of the concrete sleeper and fastening system were numerically studied while the different support conditions, and the effects of the adjacent sleepers, were considered as the boundary conditions of the submodel and were imported from the global model.

Concrete material was defined based on the concrete damage plasticity model (Dassault Systems Simulia, 2013). Tensile cracking and compressive crushing were included in the concrete behavior. Each component of the fastening system utilized an elasto-plastic material model in order to predict potential yielding of the components. Table 1 summarizes the important material properties used in this study. The support beneath the concrete sleeper was a ballast block whose dimensions were taken as 610 mm x 610 mm x 3200 mm (24 in x 24 in x 126 in). The material property of the ballast was calibrated with the track stiffness measured in the field.

Table1. Material properties of fastening system components

Component	Young's Modulus (MPa)	Poisson's Ratio	Yielding Strength (MPa)	Ultimate/Peak Strength (MPa)	Cracking Strength (MPa)
Concrete	29,970	0.20	NA	48	5.5
Clip	158,585	0.29	1,262	1,393	
Rail	206,850	0.30	1,034	1,034	
Insulator	7,520	0.39	64	85	
Rail Pad	2,378	0.49	8.2	36	
Abrasion Plate	7,520	0.39	64	85	

In the submodel, interactions between all components were defined with contact pairs (Dassault Systems Simulia, 2013). A master surface and a slave surface were selected at each interface. Mechanical frictional behavior was modeled by the Coulomb friction model. The relationship between the frictional force and the normal force was expressed as follows:

$$F_f = \mu F_n \quad (1)$$

where, F_f is the frictional force, F_n is the normal force and μ is the coefficient of friction. The values of the coefficient of frictions were based on empirical data such as abrasion resistance tests between a concrete block and a polyurethane pad and an nylon 6/6 abrasion material (Shurpali et al. 2013). Detailed descriptions of each component can be found in the study by Chen et al. (2013).

Table 2 summarizes the calibrated springs used in the global model at each rail seat. For the stiffness of the vertical springs at the sleeper P, Q, Y and Z, approximately average value of the U, W, and Y were used. The vertical spring at the sleeper S was relatively higher than the others.

Table 2. Spring constants in the global model (unit: N/mm)

(N/mm)	Spring constant	P	Q	S	U	W	Y	Z
Vertical	1	53	53	91	37	26	53	53
	2	53	53	53	53	53	53	53
Lateral	1	105,071	105,071	105,071	105,071	105,071	105,071	105,071
	2	3,502	3,502	3,502	3,502	3,502	3,502	3,502
Clip	1	922	922	922	922	922	922	922
	2	922	922	922	922	922	922	922

3. Validation of the Modeling

In order to study the field behavior of track, a research team from University of Illinois at Urbana-Champaign measured the responses of a test section of track at the Transportation Technology Center (TTC), Pueblo, Colorado, U.S.A (Grasse, 2013). In these experiments, the track was statically loaded by a Track Loading Vehicle (TLV) through which controlled vertical and lateral load can be applied to the track at the wheel-rail interface. The spacing of the sleepers was 610 mm (24 in). Figure 4 shows a schematic of the track with the nomenclature for the specific sleepers.

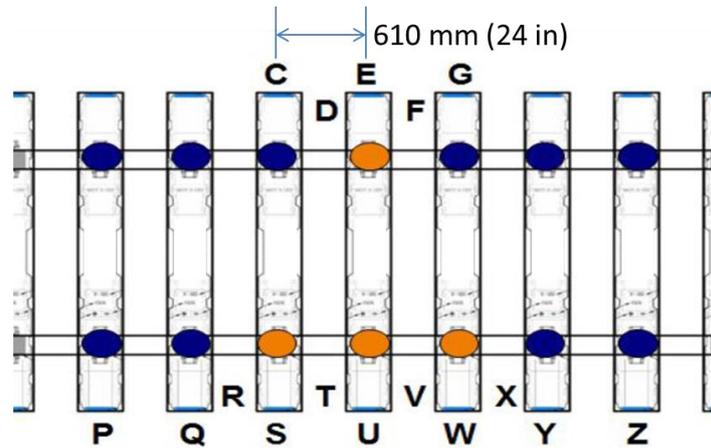


Figure 4. Schematic of the field-instrumented track structure at TTC (Grasse, 2013)

Using the TLV, a vertical load was applied at the middle sleeper (Sleeper E-U) up to 178 kN (40 kips), and the vertical displacement at the sleepers C-S, E-U and G-W were monitored simultaneously. Figure 5 shows the relationship between the applied vertical load and measured vertical displacement. As shown in Figure 5, the support conditions underneath each sleeper were significantly different although they were installed adjacent to one other. Therefore, it was crucial to implement varied support conditions into the model. In Figure 5, the numerical results of the global model were drawn in the dashed line, and they strongly agree with the field measurements. Then, a lateral load was applied up to 89 kN (20kips) while keeping the vertical load of 178 kN (40 kips) constant using the TLV at the sleeper E-U. The lateral displacements at the base and the web of the rail were monitored and shown in Figure 6. The numerical simulation of the global model was able to represent the behavior of the track. The realistic boundary conditions in the particular field at the TTC were successfully captured in the global model.

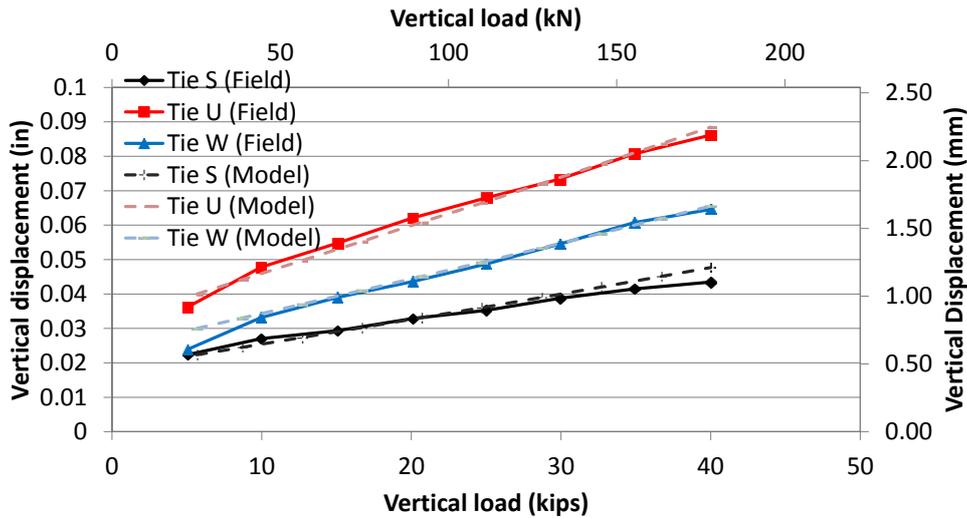


Figure 5. Vertical force and displacement relationships of the sleeper S, U and W: the measured data (solid line), and the numerical results (dashed line)

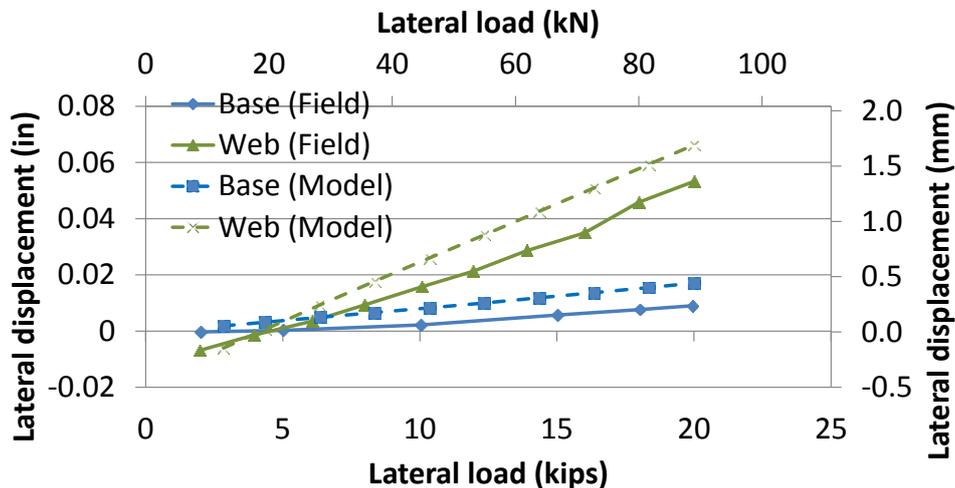


Figure 6. Comparisons of the lateral force and displacement relationships of the rail

Based on the simulation of the global model, a submodel which represented the middle sleeper (sleeper E-U) was developed. Figure 7 shows the various stress contour diagrams of the concrete sleeper and fastening system including some individual components under a vertical load of 178 kN (40 kips) and a lateral load of 89 kN (20 kips). The highest stress was observed in the clips due to the large deformation during the installation (see Figure 7.a and b). The change of the clamping force normal to the clip toe in the field and the gage side was 460 N (103.4 lb) and 52 N (11.8 lb), respectively. The changes of the clamping force was within the elastic limit, and the change of the clamping force normal to the clip toe was greater in the gage side clip than the field side clip. 20 kN (4.6 kips) of the lateral load was transmitted into the shoulder in the field side under the highest lateral load. Under the same loading condition, the highest compressive stress on the top of the concrete surface was found to be 15 MPa (2183 psi) (see Figure 7.c). Approximately 36% of the vertical load transmitted into sleeper E-U due to the relatively soft support condition under sleeper E-U compared with that under sleeper C-S. A common design assumption is that 50% of the vertical wheel load is transmitted to one sleeper when the support condition is uniform throughout the several ties.

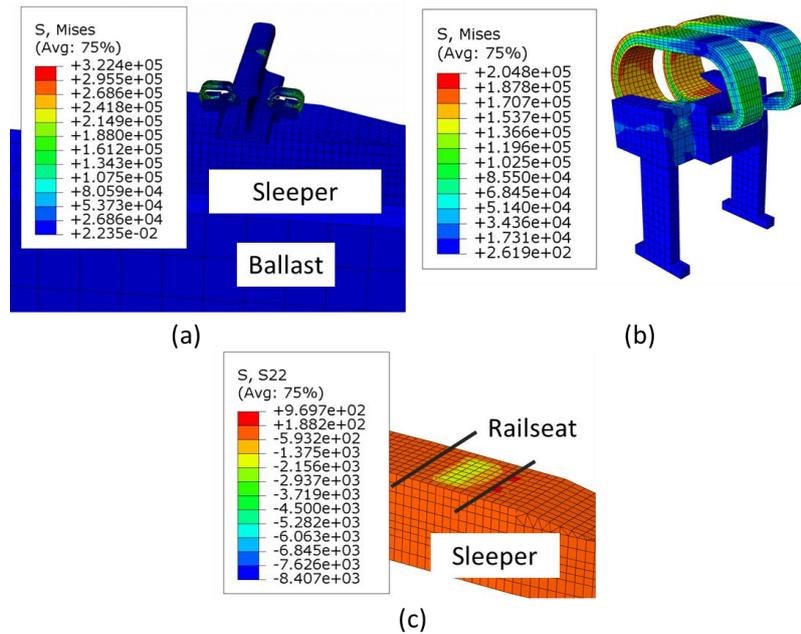


Figure 7. Responses of the submodel of the concrete sleeper and fastening system: (a) assembly of the structural components, (b) a shoulder and clip in the field side, and (c) concrete sleeper. (Unit in psi, 1psi = 0.00689 MPa)

4. Conclusions

This study focused on developing an effective and efficient finite element framework for modeling concrete sleepers and fastening systems under actual field conditions. Each component in the model was developed according to the product material behavior and geometry from the manufacturer. The interactions between all the components were defined using contact pairs. Nonlinear constitutive behaviors of the materials were implemented in the model. Various support conditions in the field were represented by different spring constants in the global model. By simulating the global model, realistic boundary conditions were imposed onto the submodel which represented the track section of the field test. The simulation result from the global model showed strong agreement with the field test data in terms of the relationship between the global vertical/lateral displacement and force. The detailed submodel of the track structure was used to analyze the local response of each component; the changes of the clamping force, the compressive stress in the railseat region of the concrete sleeper, and the loading demand on the shoulder. Furthermore, the simulation identified that 36% of the vertical load and 54% of the lateral load was transmitted to the sleeper at the loading point. The validated FE models developed in this study are effective and efficient in simulating the behavior of the multiple sleepers and fastening systems in field conditions. By using the validated FE models, an extensive parametric study will be conducted to develop new mechanistic design guidelines for the track components in North America under future phases of this research program. The advanced submodeling technique coupled with the global behaviors of track systems can also be adopted to examine the performances of track components placed in other countries.

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