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Parametric study on damage and load demand of prestressed concrete crosstie and fastening systems

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A B S T R A C T

There is an increasing interest in the performance and serviceability of concrete crossties and elastic fastening systems due to the loading demands of increasing freight axle loads and the development of new high-speed passenger rail infrastructure in North America. In the light of these increasing demands, it is essential to examine and improve current design practices of prestressed concrete crossties and fastening systems. This study focuses on developing an analytical framework for a 3D finite element (FE) model of prestressed concrete crossties and fastening systems to improve the knowledge regarding its mechanical behavior. Parametric studies are conducted based on the detailed FE model to analyse the damage and load demands associated with two major failure mechanisms in concrete crosstie and fastening system, namely the tensile-cracking failure of concrete crosstie and the damage of fastening system. The following parameters are considered in the studies: bond-slip behavior between concrete and prestressing strand, support conditions of concrete crosstie, material properties of rail pad assembly, and wheel load position. The parametric studies presented the detailed stress state of the failure mechanisms and the thresholds for performance.

1. Introduction

With the development of high-speed rail corridors and ever increasing axle loads in North America, there is increasing demand on the railroad infrastructure and its components. The dominant design approach for the concrete crosstie and fastening system still remains primarily empirical. This is evident by the fact that the relation using speed and traffic to determine the design load in American Railroad Engineering and Maintenance-of-way Association (AREMA)'s Recommended Practices has been developed empirically [1]. To ensure that freight and passengers are transported safely, components remain in track for their intended service life, and that proper track geometry is maintained, further investigation into the behavior and interaction of the concrete crosstie and fastening systems is needed. In addition, a mechanistic design approach based on detailed structural analysis would be beneficial for infrastructure manufacturers to reduce costs on over-designed components and efficiently to improve the designs of the components to next generation.

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To date, few models have been developed to address the mechanistic design and performance of concrete crossties and fastening systems. González-Nicieza et al. [2] have developed a failure analysis of a railway track used for transporting heavy-haul industrial freight. Based on data collected from field investigation, single-crosstie model and multiple-crosstie model have been built to look into the cause of crosstie cracking. However the model assumed elastic material property for all the track components, and the fastening system was ignored. Rezaie et al. [3] also used an FE model to investigate the cause for longitudinal cracks in concrete crossties. Nonlinear material property was defined in the model, but the study mainly focused on the concrete crosstie response under increasing shoulder insert pressure. Some mathematical and FE models have been developed to investigate the dynamic interaction between the vehicle and the track structure. Frohling [4] proposed a mathematical model to predict the track deterioration due to dynamic wheel loading and spatially varying track stiffness. Kaewunruen and Remennikov [5] also presented a dynamic FE model of the concrete crosstie to investigate its dynamic response. The model only included the concrete crosstie and all other components were replaced with springs. In addition, many analytical/numerical studies have focused on the behaviors of the systems under the vertical wheel loading. Among those, Yu and Jeong [6] presented a 3D finite element model including a prestressed concrete crosstie and ballast. Prestress and direct uniaxial, static rail-seat loading were considered in the model. A quarter-symmetric model was used to compare the performance of the concrete crosstie on different support conditions. One of the model's limitations was assuming full bond between the concrete and strand, hence ignoring the possibility of relative slip of strands causing the effect of prestress to be magnified. Yu et al. [7] presented an improved finite element model of the concrete crosstie with ballast and subgrade support. In this model, the interaction between concrete and strands was modeled as cohesive element, and the cohesive element was incorporated between concrete and strands to simulate a linear bond-slip relationship. Dahlberg and Lundqivst [8] investigated the effects of different support conditions on the rail track systems using a 3D finite element model. They concluded that the higher vertical force would be transmitted to adjacent concrete crosstie as the loaded crosstie was poorly supported. In conclusion, using currently available models to assess the mechanical behaviors, especially interactions of each component of the prestressed concrete crossties and fastening systems is not feasible since the models consisted of only some of the components. Therefore, this study focuses on developing an FE model of a prestressed concrete crosstie with detailed fastening system components that can be a tool to explore the mechanical interactions and behaviors of the crosstie and fastening systems. Nonlinear material properties are defined for all the components, and the model considers the effect of vertical loading, lateral loading and concrete prestress. Fig. 1 shows a schematic of a prestressed concrete crosstie with fastening system on ballast (a) and a typical fastening system that consists of clips, cast-in shoulders, insulators and rail pads (b). With the developed FE model, parametric studies are conducted to investigate the two major failure mechanisms of the concrete crosstie and fastening system, namely, the damage of the fastening system and the tensile cracking of concrete crosstie.

1.1. Current design practice

As an element of the track structure, a crosstie is designed to transmit vertical, lateral and longitudinal forces to ballast and subgrade while supporting rails and fastening systems. This study specifically focuses on the prestressed concrete crosstie since it has replaced timber crossties in certain applications and has been installed in field for last several decades [9]. Based on experimental studies and numerical models, some understanding about the behavior of the track structure has been established. For example, the AREMA manual, Australian Standard, and UIC design standard [1,10,11] have all recommended different methodologies to quantify the flexural demand of concrete crosstie. However, some of the failure mechanisms, including center binding and rail seat concrete damage due to insufficient prestress, are not explicitly considered in the current standard. Using the detailed FE model, one objective of this study is to investigate the component demand and component interaction that is related to the failure mechanism of the concrete crosstie and fastening system.

Fastening systems, which are designed to behave elastically given the nature of the materials used to construct them, are placed to fasten rails to crossties. The main functionalities of the fastening system include gauge restraint, transferring the

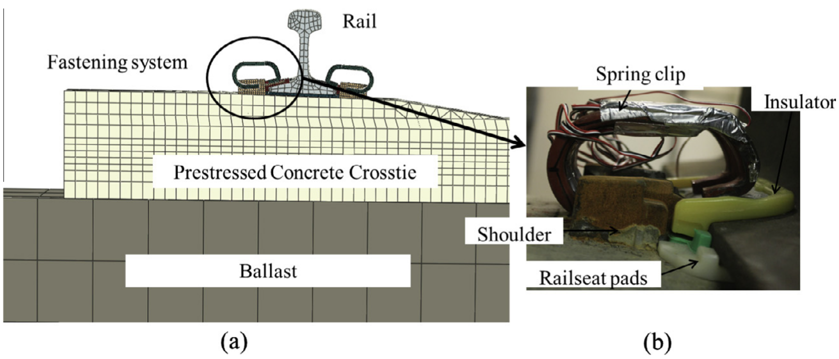

Fig. 1. Schematic of a prestressed concrete crosstie and fastening system (a) and a typical fastening system (b).