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Interface damage and its effect on vibrations of slab track under temperature and vehicle dynamic loads

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ABSTRACT

This paper presents a three-dimensional finite element model to investigate the interface damage occurred between prefabricated slab and CA (cement asphalt) mortar layer in the China Railway Track System (CRTS-II) slab track system. In the finite element model, a cohesive zone model with a non-linear constitutive law is introduced and utilized to model the damage, cracking and delamination at the interface. Combining with the temperature field database obtained from the three-dimensional transient heat transfer analysis, the interface damage evolution as a result of temperature change is analyzed. A three-dimensional coupled dynamic model of a vehicle and the slab track is then established to calculate the varying rail-supporting forces which are utilized as the inputs to the finite element model. The non-linearities of the wheel–rail contact geometry, the wheel–rail normal contact force and the wheel–rail tangential creep force are taken into account in the model. Setting the maximum interface damaged state calculated under temperature change as the initial condition, the interface damage evolution and its influence on the dynamic response of the slab track are investigated under the joint action of the temperature change and vehicle dynamic load. The analysis indicates that the proposed model is capable of predicting the initiation and propagation of cracks at the interface. The prefabricated slab presents lateral warping, resulting in severe interface damage on both the sides of the slab track along the longitudinal direction during temperature drop process, while the interface damage level does not change significantly under vehicle dynamic loads. The interface damage has great effects on the dynamic responses of the slab track.

1. Introduction

In recent years, high-speed railway lines have been widely constructed in the form of slab track owing to several advantages it offers over ballasted track. Some structural advantages are the impossibility of rail buckling, a higher lateral and longitudinal permanent stability, and a reduced sensitivity to uneven settlements. Operational advantages of slab tracks are a lower maintenance (reduction of 70–90% compared with ballasted track [1]), resulting in higher availability and the possibility of longer possession times, which is important for high-speed connections, the prevention of churning up of ballast particles at high speed, and an increase of riding comfort as well as safety, owing to the higher track stability and better alignment [2,3]. As an example, 42 high-speed passenger railway lines and intercity railways with a total length of 13,000 km are put into operation by the year 2012 [4].

Fig. 1 shows the CRTS-II slab track and its components. The primary components of the slab track system are the rails, rail pads, prefabricated slab, CA mortar layer, and concrete basfdee.

At present, most of the literatures are focused on slab track design and dynamic behavior of the slab track. Steenbergen [5] studied the design parameters of a slab track railway system from a dynamic viewpoint. Auersch [6] calculated the dynamic interaction of the railway slab track in detail through a combined finite element and boundary element method. Bezin [7] developed a flexible track system model integrated with a multi-body dynamics software tool to simulate the dynamic interaction between a vehicle and two innovative slab track designs, and to compare their performance with respect to conventional ballasted track. Gulgou-Carter [8] carried out an analytical and experimental study of the sleeper SAT S 312 in a slab track Sateba system. Galvin [9] used a general and fully three-dimensional multi-body-finite element-boundary element model to study the vibrations due to train passage non-ballast tracks. Zhai [10] presented a framework to investigate the dynamics of overall vehicle and slab track systems and with emphasis on theoretical modeling, numerical simulation and experimental validation. Lei [11] investigated the

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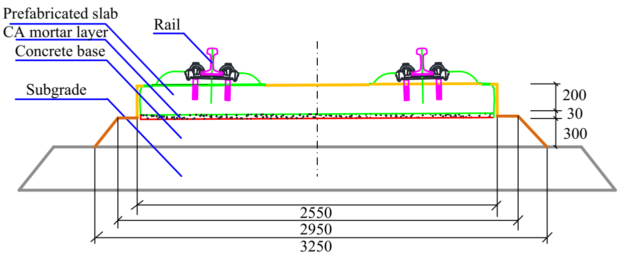

Fig. 1. CRTS-II slab track.

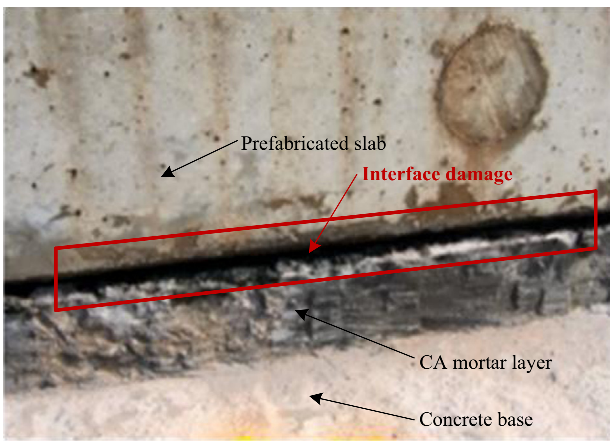

Fig. 2. Delamination at the interface between the prefabricated slab and CA mortar layer.

dynamic behavior for slab track of high-speed railway based on the vehicle and track elements.

Although the slab track has gained successful improvements and applications in high-speed railway lines compared with traditional ballasted tracks, slab track still represent some disadvantages including the high initial investment costs, more importantly, the premature structural damage caused by a variety of factors such as vehicle dynamic loads due to wheel–rail interactions associated with the wheel–rail irregularities, and the temperature loads attributed to temperature change. In practice, it was recently found that severe interface damages and cracks appeared at the interface between prefabricated slab and CA mortar layer on Chinese railway lines after a short time operation, as shown in Fig. 2. Such damage mode might cause significant loss of structural integrity of the slab track system and, therefore, strongly affect the dynamic behavior of slab track and produce the potential for failure of the slab track. Consequently, it will influence the running behavior of railway vehicles in terms of motion stability, riding comfort and derailment safety. Therefore, modern railway designers as well as maintenance engineers have requirements for increasing fundamental understanding of how the interface damage produces and how it effects the vibrations of slab track. However, so far very few studies have been published on the slab track damage and its effect on the dynamic response of slab track. Zhu [12] developed a vertical dynamic coupled model of vehicle and double-block ballastless track with roadbed cracks using the finite element method on the basis of theories of linear elastic fracture mechanics and vehicle–track coupled dynamics, and investigated the value of stress intensity factor in the crack tip field varying with the dynamic loads as well as the influence of roadbed cracks on roadbed dynamic responses. Zhu [13] adopted the concrete damaged plasticity model to describe the mechanical characteristics of concrete base of double-block ballastless track, and analyzed the inherent damage of track bed slab and its influence on dynamic behavior of track bed slab under the joint action of change temperature and vehicle dynamic load. Colla [14] reported a test methodology for investigating the bond condition between sleepers and slab on two different railway slab track constructions.

The objective of the present paper is to investigate the damage occurred at the interface between prefabricated slab and CA mortar layer on the CRTS-II slab track under temperature and vehicle dynamic loads, and also to study the effects of interface damage on the dynamic behavior of the slab track. The damage, cracks or delamination at the interface is investigated by using cohesive elements in a three-dimensional FE model of the slab track. The interface damage evolution under the condition of temperature change is analyzed based on the temperature field database obtained from the three-dimensional transient heat transfer analysis. Then, a three-dimensional vehicle–track coupled dynamic model is then built to calculate the dynamic rail-supporting forces which are utilized as the inputs to the finite element model. Setting the maximum interface damaged state calculated under temperature change as the initial condition, the interface damage evolution and its influence on dynamic responses of the slab track are investigated under the joint action of temperature change and vehicle dynamic loads. The numerical results obtained are very useful in the design and maintenance of slab tracks and the evaluation of material deterioration.

2. Finite element modeling

2.1. Cohesive zone model

Cohesive zone model (CZM) introduced by Dugdale [15] and Barrenblatt [16,17] has gained considerable attention over the past years, as it represents a computationally efficient technique and has the simplicity and the unification of crack initiation and growth within one model for the fracture studies. This approach is attractive because it combines the classical fracture mechanics concept of a fracture toughness criterion for crack propagation with the damage mechanics assumption of a zone ahead of the crack tip. Pioneering works on the FE implementations of CZM technique can be found in Refs. [18,19] while applications to the modeling of delamination in fiber-reinforced composites are introduced in Refs. [20–25].

In this paper, a cohesive element in Fig. 3, with zero thickness in normal direction and a 8-node, is applied to analyze interface damage by embedding the cohesive element at the interface between prefabricated slab and CA mortar layer. Normally, stress that occurs inside the cohesive element is calculated through relative displacements between two bordering elements.

Before crack initiation, the cohesive element is assumed to have a high stiffness in order to prevent separation of two bordering elements, and is also provided for preventing node interpenetration when the cohesive element is under compression. Damage is assumed to be initiated when a quadratic interaction function involving the nominal stress ratios reaches a value of one, as

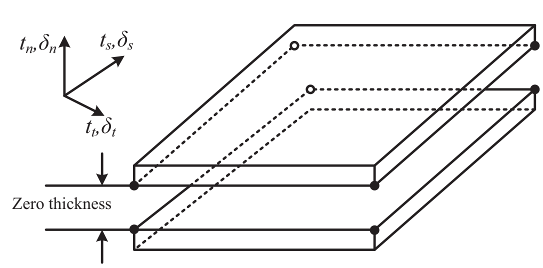

Fig. 3. Cohesive element with zero thickness.