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Post-derailment dynamic behaviour of a high-speed train under earthquake excitations

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ABSTRACT

A post-derailment dynamic model of a high-speed train is developed to investigate the post-derailment dynamic behaviours of a high-speed train travelling on a railway bridge during an earthquake. The train model is comprised of two trailer cars and two motor cars. The adjacent two cars are coupled with a coupler model considering the nonlinear characteristic and limit rotation angle of the coupler. A bridge seismic response model is formulated by using the finite element method to evaluate the dynamic responses of the railway bridge under earthquake excitations, and then the responses are used as the input of the post-derailment dynamic model to analyze the post-derailment dynamic behaviours of a high-speed train. Before derailment the high-speed train runs over the rails, the nonlinear Hertzain contact model and the FASTSIM algorithm are employed to estimate the wheel/rail normal forces and tangent forces respectively. After derailment the high-speed train runs on the slab track, the OBBtrees theory is adopted to detect the contact situations between the vehicle components and the track, while the normal forces and tangent forces at the contact points are evaluated by the nonlinear Hertzain contact theory and the Coulomb friction law respectively. Using the post-derailment dynamic model of a high-speed train, the derailment postures of the high-speed train under earthquake excitations are investigated, and the effects of marshalling type of train on the post-derailment dynamic behaviours are further discussed in this study. The results indicate that the trailer car has a better self-protection capacity compared to those of a motor car during a derailment. The marshalling type (TC1 + MC2 + MC3 + TC4) of a high-speed train can easily form the buckling pattern after a derailment, which may contribute considerably to the outcomes of a derailment. Therefore, it is necessary to take some countermeasures to eliminate the buckling pattern of train during a derailment.

1. Introduction

The running safety of the rail vehicle has become an issue of great concern for the railway community since the railway vehicle begins to operate in the world. It is known that the railway vehicle is characterized by the wheel/rail contact compared to other types of vehicle. The wheel/rail contact, as the basic feature of the railway vehicle, is the only constraint applying on the vehicle. Such kind of constraint will lose efficacy leading to a derailment accident when the vehicle experiences large lateral excitations [1]. Although the railway vehicle is regarded as one of the most safety mode of transport, a large amount of casualties and property losses would be caused by derailment accident, especially in high-speed conditions. In addition, the railway bridges, widely adopted in high-speed railway lines, could increase the amplitude of earthquake response and impose greater derailment

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risk for the vehicle during an earthquake. Therefore, the understanding of derailment mechanism has become critical to the avoidance of derailment and reduces the losses of a derailment.

The earliest investigation on derailment mechanism can be backdated to 1896. Nada proposed a derailment coefficient based on the equilibrium principle of static force on a single wheel [2]. This criterion is applicable when the angle of attack exceeds 0.5 degree, while it yields a conservative derailment prediction under small or negative angle of attack. To improve the derailment criterion, a vast amount of researchers have contributed to the investigation of derailment mechanisms [3–5]. Weinstock [3] proposed a less conservative wheel flange climb criterion for predicting incipient derailment by summing the absolute values of L/V of the two wheels of the same wheelset, known as the 'axle sum L/V' ratio. The derailment criteria proposed by Nadal and Weinstock do not consider the procedure of wheel climbing, which means that the wheel would derail instantaneously as long as the derailment ratio L/V exceeds the limit value. Thus, Japan National Railways (JNR) and the Electro-Motive Division (EMD) of General Motors [6] developed a derailment criterion using the time duration, which suggests that the duration of lateral force impulse should be less than 50 msec. Although this criterion is less conservative compared to the Nadal derailment criterion, it still cannot predict the derailment precisely in some cases according to the experiments conducted by Sweet [7] using a scale model.

In the earthquake condition, the derailment mechanism of railway vehicles tends to be more complex, and the derailment criterion considering earthquake excitations has not yet been extensively investigated, and no effective methods are proposed to completely eliminate derailment. It means that the railway vehicles still suffer from the risk of derailment. Therefore, some other researchers begin to propose other countermeasures to reduce the losses of a derailment [8–14]. On the basis of existing derailment accidents, one can speculate that the outcomes of derailments mainly relate to the post-derailment dynamic behaviours of railway vehicles. Consequently, the understanding of post-derailment dynamic behaviour of vehicles becomes critical to reduce the loss of a derailment.

During a derailment the vehicle components usually come into contact with the track, and results in considerable impact forces for the vehicle, which significantly affects the dynamic behaviours of railway vehicle after derailment. Thus, a post-derailment dynamic model that can reflect the contact situations during a derailment is critical for the investigation of post-derailment dynamic behaviour. The finite element method is an effective way to solve the transient collision problems, but is not suitable for the post-derailment dynamic due to huge computing costs. The multi-body dynamic model is thus adopted to describe the post-derailment dynamic behaviours of the railway vehicle. Toma [10] and Paetsch [11] developed a 2D plane train model considering the friction interactions between the car body and the ground to study the derailment postures of the train during a derailment. The results concluded that the train experiences the alternating bucking pattern after derailment. Brabie and Andersson [8,9] developed a more comprehensive 3D post-derailment dynamic model, and estimated the contact forces through the lookup table obtained from a finite element model. Boronenko et al. [12] also developed a post-derailment dynamic model using the multi-body dynamics, while the contact situation during derailment wasn't taken into consideration in that model. On the basis of a derailment experiment Sunami [13] formulated a post-derailment dynamic model to simulate the derailment process, while the contact conditions during derailment also weren't taken into account in the model. As aforementioned investigations, the existing post-derailment dynamic models are limited to the simple dynamic model neglecting the contact or collision situations that may occur in a derailment. Such kind of post-derailment dynamic models cannot reflect the dynamic behaviours of railway vehicles realistically during a derailment.

Therefore, the objective of our studies is to develop a comprehensive post-derailment dynamic model for a high-speed train by considering various contact situations that may occur during derailment. Using this model the structure of vehicle can be optimized in the design stage to reduce the loss in a derailment. As a long-term research plan, various derailment experiments were employed to study the dynamic behaviours of the vehicle and to validate the post-derailment dynamic model primarily. The calibration methodology of the post-derailment dynamic model is showed in Fig. 1. Half-car derailment experiments were performed primarily to validate the collision detection model and contact force model used in the half-car post-derailment dynamic model. By using the experimental data, the contact situations and displacement of the half car were validated in [15]. Passenger car derailments were then employed to correct the contact parameters in the post-derailment dynamic model of the passenger car. Based on the validated post-derailment dynamic model, the post-derailment dynamic behaviours of a passenger car during an earthquake were investigated in [16]. Although the post-derailment dynamic model established in [14] can effectively reflect the contact situations and dynamic behaviours of a railway vehicle during a derailment, only one passenger car was taken into account neglecting the effects of coupler on the post-derailment dynamic behaviours.

In this study, on the basis of the half-car and passenger car post-derailment dynamic model [13,14] a post-derailment dynamic model of a high-speed train is developed to study the post-derailment dynamic behaviours of train under earthquake excitations. The high-speed train model consists of two trailer cars and two motor cars, and each passenger car is incorporated with the coupler. A seismic response model of bridge is developed to calculate the responses of the bridge under the action of earthquake excitations. The interactions between the vehicle and the bridge have been well investigated by a large number of researchers [17–21] and the displacements of the vehicle after derailment are far more than the deflections caused by the vehicle–track–bridge

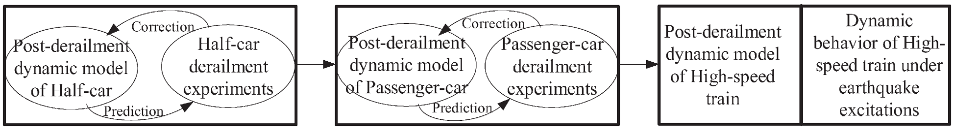

Fig. 1. Procedures of modelling and validation of the post-derailment dynamic models.