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Investigation of rail irregularity effects on wheel/rail dynamic force in slab track: Comparison of two and three dimensional models

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Rail irregularity is one of the most significant load amplification factors in railway track systems. In this paper, the capability and effectiveness of the two main railway slab tracks modeling techniques in prediction of the influences of rail irregularities on the Wheel/Rail Dynamic Force (WRDF) were investigated. For this purpose, two 2D and 3D numerical models of vehicle/discontinuous slab track interaction were developed. The validation of the numerical models was made by comparing the results of the models with those obtained from comprehensive field tests carried out in this research. The effects of the harmonic and non-harmonic rail irregularities on the WRDF obtained from 3D and 2D models were investigated. The results indicate that the difference between WRDF obtained from 2D and 3D models is negligible when the irregularities on the right and left rails are the same. However, as the difference between irregularities of the right and left rails increases, the results obtained from 2D and 3D models are considerably different. The results indicate that 2D models have limitations in prediction of WRDF; that is, a 3D modeling technique is required to predict WRDF when there is uneven or non-harmonic irregularity with large amplitudes. The size and extent of the influences of rail irregularities on the wheel/rail forces were discussed leading to provide a better understanding of the rail-wheel contact behavior and the required techniques for predicting WRDF.

1. Introduction

Discontinuous slab tracks as a cost-effective pavement system are extensively used in the high-speed railways. Dynamic forces between wheel and rail are an important factor in the analysis and design of slab tracks. They are substantially influenced by rail irregularities [1–3]. The effects of rail irregularities on the Wheel/Rail Dynamic Force (WRDF) have been investigated in the literature using two dimensional (2D) and three dimensional (3D) numerical models. The vehicle/slab track interaction problem has been mostly evaluated by the 2D models because of their lower computational cost compared to the 3D models, while their level of accuracy is questionable.

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Qingsong et al. [4] were the first to evaluate the influence of the harmonic rail irregularity on the WRDF in discontinuous slab tracks. In their 2D model, the slab track was simulated by a continuous three layered beams, the vehicle was modeled as a harmonic moving point load and the problem was solved in the frequency domain. The effect of random rail irregularity on WRDF in the discontinuous slab track was investigated by Zhang et al., using a 2D model [5]. They simulated the slab track by a three layered continuous beam system. In their research, the vehicle was modeled as a wagon with ten Degrees of Freedoms (DOF), the wheel/rail contact was considered as a linear Hertz spring and the problem was solved in the frequency domain. Song et al. [6] evaluated the influence of the cosine harmonic track irregularity on the WRDF in the discontinuous slab track using a 2D model. In their study, the discontinuous slab track was modeled as a three layered beam system which comprises a continuous rail layer, a discontinuous concrete slab layer and a continuous concrete base layer.The vehicle, wheel/rail contact and solution approach of their model were the same as that of Zhang et al. model [5]. The effect of the harmonic rail irregularity on the WRDF was also investigated by Lei and Wang [7] through a 2D model of the continuous slab track in the time domain. The slab track, vehicle and wheel/rail contact of their model were modeled by a three layered beam system, a wagon with ten DOF and linear Hertz spring respectively. The most recent work was made by these authors, in which the effects of harmonic rail irregularities on the WRDF were investigated using a 2D model of vehicle/discontinuous slab track interaction [8]. They improved the model of Song et al. [6] by taking into account the nonlinear properties of the wheel/rail contact [8].

A review of the 2D models in the literature indicates that they have two main limitations. Only half of the slab track is simulated taking the advantage of the symmetric structure hypothesis about the slab track center line [9,10]. It means that, the right and the left sides of the slab track have similar conditions although irregularity profiles of the left and the right rails might be different [11,12]. Moreover, in the majority of the 2D models, the wheel/rail contact has been considered linear which makes their accuracy questionable [13]. To overcome these limitations, several 3D models of vehicle/slab track dynamic interaction have been developed in the literature. Kumar and Rastogi [14], Naeimi et al. [15] and Ambrosio [16] developed 3D models to evaluate the effects of irregularities of the right and left rails on the WRDF. In their models, the track was represented as one layered rigid structure, the vehicle was modeled as a vehicle with 17 DOF, and the wheel/rail contact was considered as a nonlinear Hertz spring. Zhai and his colleges [17] developed a 3D model of the vehicle/slab track interaction to investigate the influence of dissimilar random vertical rail irregularities on the WRDF. In their work, the vehicle was modeled as a wagon with 35 degrees of freedom, the wheel/rail was considered as a nonlinear Hertz spring and the slab track was simulated as a two layered system.

A review of the available literature indicates that there are two areas which need further investigation. First, none of the available 3D models consider the slab track structures in three layers. This indicates that the concrete base layer has been omitted in the available models. Second, while the computational cost of the 2D model is less compared to the 3D models, the accuracy of the 2D results compared to those of 3D models is questionable, indicating the necessity of investigating an optimum modeling technique. This research is a respond to these needs. For this purpose, two and three dimensional numerical models of the vehicle/discontinuous slab track interaction were developed. Validation of the results obtained from both models was investigated through a comparison between the results obtained from the models and those of comprehensive field tests carried out in this research. Using the 2D and 3D models, the effects of various amounts of rail irregularities (of the left and right rails) on the results were investigated, indicating the effectiveness of the current modeling technique in prediction of WRDF.

2. Development of 2D and 3D models

In this study, two models of vehicle/discontinuous slab track dynamic interaction in two and three dimensions were developed. The models comprise a continuous rail layer, a discontinuous concrete slab layer, and a continuous concrete base layer. In the 2D model, all the layers were modeled by the Euler–Bernoulli beam formulation. In the 3D model, the slab track was considered in three layers for the first time. The rail was modeled using the Euler–Bernoulli beam element and the other layers were modeled by the bending plate elements. The vehicle was modeled as a wagon with ten and seventeen DOF in the 2D and 3D models, respectively. The wheel/rail contact was considered as a nonlinear Hertz spring in both models. The governing differential equations of motion of the vehicle and the track for both models were derived based on the multi-body dynamic system approach and the finite element method, respectively. They were developed in the coupled form and solved in the time domain.

2.1. Development of 3D model

Schematic views of the longitudinal and cross sections of the 3D model are presented in Figs. 1 and 2 respectively. As shown in Fig. 1, the 3D model comprises vehicle and slab track. The slab track was assumed to have a continuous rail layer (left and right rails), a discontinuous concrete slab layer, and a continuous concrete base layer (Figs. 1 and 2). Both rails were modeled by Euler–Bernoulli beam elements [18]. The concrete slab and concrete base layers were modeled by Melosh–Zienkiewicz–Cheung (MZC) plate elements [19]. As presented in Fig. 1, the rails are connected to the slab parts discontinuously. The slab parts are connected to the concrete base layer. The concrete base layer is attached to the subgrade. These connections were modeled by