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An explicit periodic nonlinear model for evaluating dynamic response of damaged slab track involving material nonlinearity of damage in high speed railway

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HIGHLIGHTS

- A novel explicit periodic nonlinear model for the damaged slab track.
- Involving material nonlinearity of damage of slab track in high speed railway.
- Employing periodic spectral method to solve the vibration equations of the nonlinear model.

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ABSTRACT

For evaluating the vibration response of the damaged slab track efficiently, a novel explicit periodic nonlinear model for the damaged slab track in high speed railway involving material nonlinearity of damage is presented based on the theory of continuum damage mechanics and the constitutive relationship of concrete under uniaxial tension, where the infinite periodically supported composite beam for the track on the elastic foundation is truncated into a beam section with the length of a single vehicle by introducing periodic boundary conditions. The vibration equations of the nonlinear model are discretized into ordinary differential equations (ODEs) in space domain by the periodic spectral method, and then by applying the explicit central difference method these ODEs are solved with time-domain difference ultimately. The validity of the model is verified by the comparison of the results from the periodic model, finite element method (FEM) and the field test, and the reasonable values of the key computational parameters are recommended. Moreover, the influence of track structural parameters on the vibration response and damage evolution of CRTS II slab track of China's high speed railway is investigated with the periodic nonlinear model. And some practical conclusions for design and construction are acquired.

1. Introduction

Due to years of service, damage accumulation under the train loads will inevitably occur in quasi-brittle concrete structure of the ballastless track system for high-speed railway. The long-term damage evolution of structure will inescapably lead to the continuous deterioration of dynamic service performance of the ballastless track system, which can further deteriorate the track line state and reduce the train operation quality, and even endanger operation safety [1]. Therefore, it is urgent to investigate the vibration response of the damaged track for evaluating the influence of structural damage on the performance of high-speed track and exploring the evolutional mechanism of dynamic performance of high-speed railway infrastructure.

The ballastless track structure is currently simplified as a composite beam [2–6] or beam-plate [6–9] system on the elastic foundation for rapid dynamic response analysis of the track system. For the presence of structural defects and complicated boundary conditions, there is no closed-form analytical solution for the high-order vibration equations of the track structure with damage. So approximation approaches and numeric methods are mainly employed to solve the vibration response of the damaged track. Focusing on the influence of structural deterioration of the track on dynamic response of the whole system, many scholars utilized the composite beam model [10], the beam-plate model [11,12] and the solid model of FEM [13–17] to simulate the track structure for analyzing the dynamic response of the track system with defects, where it was assumed that the existing damage defects of track

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structure do not continue to evolve under external loads. Obviously it does not conform to the physical laws and the actual situation of structural service. The damage effect will induce the reduction of structural stiffness and the increase in deformation, while the increase of deformation will expedite damage growth in return. Hence, it can more accurately evaluate the real stress state and service performance of the track structure to consider the material nonlinearity of damage and simulate the further damage growth under the train load.

Thus, refined numerical FEM simulations are implemented to investigate the mechanism and process of damage for the track structure, where the evolutions of the damage and defects are considered delicately by the theories and methods of fracture [18–20], damage [21,22], fatigue [22] and interface mechanics [23]. These analyses are not confined to the elastic constitutive relationship of materials and the theories and methods for nonlinear mechanical behaviors of concrete are utilized to analyze the variation of mechanical properties for the damaged track structure. However, to minimize wave reflections from artificial truncations of the numerical models, the actual model range is often extended, which makes the refined numerical models even more enormous and time-consuming. Especially, in dealing with long-term structural cumulative damage analysis, structural optimization, random analysis and parameter identification, there is a need for thousands or even more calculations of the models. Then it is clearly inconvenient to apply the refined numerical models.

In this paper, for evaluating the vibration response of the damaged slab track rapidly, a novel periodic nonlinear model is proposed for the damaged slab track based on the theory of continuum damage mechanics. The developed periodic model is based on the periodic characteristics of the vibration response along the track. And by imposing periodic boundary conditions, the infinite long track beam can be truncated to a composite beam section with the length of a single vehicle to reduce the size of the model and minimize the impact of artificial boundary. The developed periodic model is distinct from the existing periodic models for the track structure, which are solved by several special methods, such as the transfer matrix method [24], the Flouquet transformation method [25], the Fourier method [5,26,27], and so on. It should be noted that these conventional periodic methods cannot handle material nonlinearity directly, while the periodic model presented in this paper could involve the material nonlinearity of damage owing to the application of spectral method.

The spectral method is derived from the Ritz-Galerkin method and it is a collective name for the Galerkin spectral method, the Tau method, and the pseudo-spectral method, which are approximation approaches based on orthogonal polynomials (Fourier polynomials, Chebyshev polynomials, Legendre polynomials, etc.) with good approximation properties [28]. The Galerkin spectral method is suitable for linear problems and the pseudo-spectral method can handle nonlinear boundary-value problems [29]. Many studies employed Chebyshev polynomials to solve the vibration response of beams and plates in Refs. [29–35], while Fourier polynomials were utilized more to handle periodic problems in Refs. [34,36,37]. It should also be noted that the Fourier Galerkin spectral method based on the Galerkin weighted residual principle is distinct from the Fourier series approach used in Refs. [5,27]. In addition, the collocation points of Chebyshev pseudo-spectral method is non-uniform [32-35], while Fourier pseudo-spectral method is implemented with collocation points uniformly distributed [36,37].

Since the truncated track section with periodic boundary conditions is periodically supported at the location of fasteners, a periodic spectral method based on Fourier polynomials is utilized to discretize the vibration equations of the periodic nonlinear model into ODEs in space domain. And then the ODEs are solved by applying the explicit central difference method with time-domain difference ultimately. The validation indicates the developed semi-analytical periodic model has high accuracy and efficiency. It is a very promising method for long-term cumulative damage analysis, structural optimization, random analysis and parameter identification. Even more significantly, structural material nonlinearity of damage is introduced into the macroscopic level of the structure system in this paper, and the dynamic characteristics of the ballastless track structure are investigated from the viewpoint of material-component-structure system. A cross-scale link between the evolution of material damage and the service performance of the track structure is established.

2. Hypothesis and simplification of the model

2.1. Periodic model for CRTS II slab track of China's high speed railway

The time history of the measured rail vertical vibration displacement of a certain point [6] is shown in Fig. 1, when an eight-section high-speed EMU train travels at the speed of v_0.

It can be seen from Fig. 1 that when the multi-section EMU train passes at the high speed of v_0, the vibration responses of the track structure manifest periodic characteristic in time domain due to the similarity of each section of the train. More exactly, all points of the track structure are undergoing quasi-periodic motion. But each point has a certain phase difference induced by the time difference of the wheel loads. In spatial domain, the wave fluctuation along the longitudinal direction of the track also shows approximate periodic characteristic.

Intercepting a section of track with the length of $3 \times L_C$, where L_C denotes the length of a single vehicle, as is shown in Fig. 2, the cars are completely occupying the selected track section at the beginning time t_0 of observation and then the train moves forward at speed of v_0, until the Car B nearly completely occupies the original location of Car A in the track section at the time of t_2. In the process of a multi-section train traveling through, the force state of the track structure is almost the same in each sub segment, so the dynamic response of them is approximately the same. From the point of view of the longitudinal wave propagation along the track, the period of wave fluctuation can be regarded as L_C. Owing to the continuous periodic axle loads, the vibration responses of the selected track section are quasi-periodic with period equal to L_C/v_0. Therefore, based on periodic characteristics of wave propagation in ballastless track structure, truncating a section of track with the length of L_C and calculating the vibration responses of points in the selected section, the dynamic responses of the whole track can be approximately reconstructed by artificial extension. Since the selected slab track section is only as long as the length of one period, the boundary conditions at both ends are periodic.

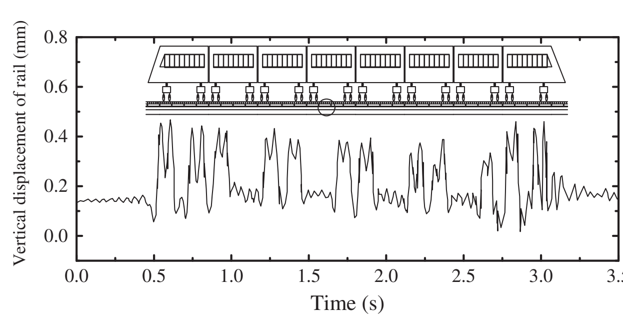

Fig. 1. The measured vertical displacement of the rail when high-speed train passing through.