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Dynamic response analysis of monorail steel-concrete composite beam-train interaction system considering slip effect

Hongliang Wang, Eryu Zhu*

School of Civil Engineering, Beijing Jiaotong University, 100044 Beijing, China

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ABSTRACT

A new finite element model of steel-concrete composite beam which can simulate the slip phenomenon is proposed in this paper. The new model consists of concrete beam unit, shear connector unit and steel beam unit. Based on the improved model, a new steel-concrete composite track beam-train interaction system is derived for the dynamic analysis. Each vehicle of monorail train in the new steel-concrete composite track beam-train interaction system is idealized as a multi-body system with 18 degrees of freedom. The governing vibration equations of the new monorail steel-concrete composite track beam-train interaction system are derived based on Lagrange's formulation. Validity of the model is verified by comparing the calculations with field-test data. The influence of the slip effect on the displacement amplitude of the track beam, vehicle acceleration and riding comfort is analyzed in detail. An interesting feature is that the graphic curves which reflect the dynamic responses of the steel-concrete composite beam-train interaction system under the influence of the slip can be divided into two regions (fluctuating area and smooth area), and there is an obvious critical value (0.8×10^6 N/m) between the two regions. When the connection stiffness reaches the critical value, the values of dynamic responses of the interaction system do not change anymore.

1. Introduction

In the past 20 years, with the rapid development of high-speed railway, the pressure of long-distance transportation between cities has been relieved successfully in China. However, with the rapid development of urban population, short-distance traffic problem in urban area has become another problem which needs to be solved urgently, and this need is promoting the development of the new short-distance transportation technologies. Monorail traffic technology is one of the representatives of the short-distance transportation technologies, which is being built in large quantities in China.

Mechanical property and cost are two important issues which should be treated seriously during the construction procedure. However, the traditional concrete track beam has the problems of long production cycle and poor cost-efficiency. Professor Zhu Eryu and Zhong Minglin [1] creatively put forward a method for the design of the steel-concrete composite track beam, which has successfully solved these two problems. However, since the form of material and structure changes, the stiffness and mass of the steel-concrete composite structure also change significantly. In particular, due to the effect of longitudinal slip, the dynamic performance of this new steel-concrete composite structure changes significantly compared with that of traditional concrete track beams.

In the previous dynamic studies, the bridge has been modeled by grid element [2], beam element [3,6–10,14], shell element and Benoulli-Euler beam element [4,5]. The vehicle has been modeled by two-dimensional or three-dimensional rigid body element [2–23]. The wheel-rail contact relationship between vehicle and bridge is always modeled by a point or disk model [3,9,13,16–18]. The published researches show that the properties of bridge and the contact relationship between vehicle and bridge are very important factors in dynamic analysis of bridge-vehicle interaction system. Moghimi [7] pointed out that velocity and bridge stiffness are the main factors which affect the vibration responses of the bridge-vehicle interaction system. Wang [10] studied the influence of the attenuation of bridge stiffness over the vibration responses of bridge-vehicle interaction system. Majka [15] investigated the action of speed, frequency of the train, mass ratio, span ratio and bridge damping in the dynamic response analysis of bridge-vehicle interaction system. However, there are few studies on the dynamic response analysis of monorail bridge-vehicle interaction system. The only studies that can be found are mainly about the steel track beam and pre-stressed concrete track beam. Lee and Kim [19–21] investigated dynamic responses of monorail steel track beam-train interaction system in Osaka by simplifying each straddle monorail vehicle

* Corresponding author.
E-mail address: zey0604@163.com (E. Zhu).

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as a 15 degrees of freedom system. Kim and Kawatani [23] contrasted the dynamic responses of the conventional steel track beam and the improved steel-concrete composite track beam with lateral bracing system. Naeimi et al. [26] established an innovative model of train-guideway interaction system in which the guideway is simulated by flexible element while the train is simulated by rigid element to increase the accuracy of the numerical simulations in a more realistic way. This model provides a very useful instrument for dynamic analysis of train-guideway interaction system. So far, no publication about the dynamic responses analysis of the monorail steel-concrete composite track beam-vehicle interaction system has considered the slip effect.

This study intends to investigate the impact of slip on the dynamic responses of monorail steel-concrete composite track beam-vehicle interaction system. The governing equations of motion for this new type of monorail bridge-train interaction system are derived based on Lagrange's formulation. Validity of the new analysis procedure is verified by comparing the calculations with field-test data.

2. Theoretical procedure for the dynamic analysis of monorail steel-concrete composite track beam and vehicle interaction system

There are two ways to study the dynamic performance of bridge-vehicle interaction system, one is the direct balance method based on D'Alembert principle and the other is energy method based on Hamiltion principle. Since the parameters of the equations based on the energy method are scalar, the energy method is more suitable than the direct balance method for the analysis of complex structural system. Lagrange's formulation is a type of energy method to establish the motion equations of a complex system [25]. It is expressed as:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_k}\right)-\frac{\partial T}{\partial q_k}+\frac{\partial U^e}{\partial q_k}+\frac{\partial U^q}{\partial \dot{q}_k}=0 \tag{1}$$

where T indicates kinetic energy; U^e denotes elastic potential energy; U^q is the damping potential energy; q_k indicates the generalized coordinates.

In this study, T, U^e and U^q can be expressed as Eq. (2), Eqs. (3) and (4), respectively. T_b, U_b^e and U_b^q are studied in Section 2.1; T_v, U_v^e, U_g^e and U_v^q are studied in Section 2.2.

$$T=T_b+T_v \tag{2}$$

$$U^e=U_b^e+U_v^e+U_g^e \tag{3}$$

$$U^q=U_b^q+U_v^q \tag{4}$$

2.1. Steel-concrete composite track beam system

Since it is a sophisticated mechanical procedure to establish the single beam element which has considered the slip effect, a simplified finite-element model which consists of a concrete beam element, a shear connector element and a steel beam element (as shown in Fig. 2) is proposed to simulate the steel-concrete composite track beam (as shown in Fig. 1).

This new finite-element model proposed in this paper is based on the following assumptions:

(1) The separation between the centroid and twist center of the beam element is taken into consideration.
(2) The concrete beam and steel beam of the composite beam are connected tightly. There is no gap between the two parts.
(3) Only the longitudinal displacement between the concrete beam element and the steel beam element is allowed. Other freedoms of the concrete beam element and steel beam element are the same.

The new element of steel-concrete composite track beam element is

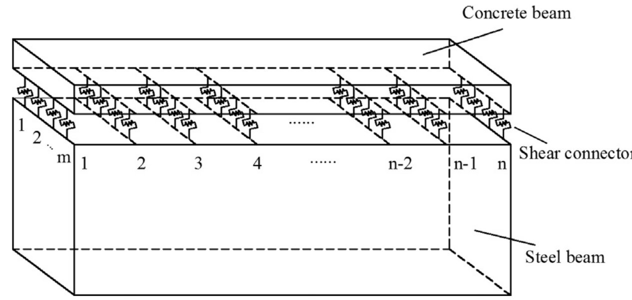

Fig. 1. Schematic diagram of steel-concrete track beam.

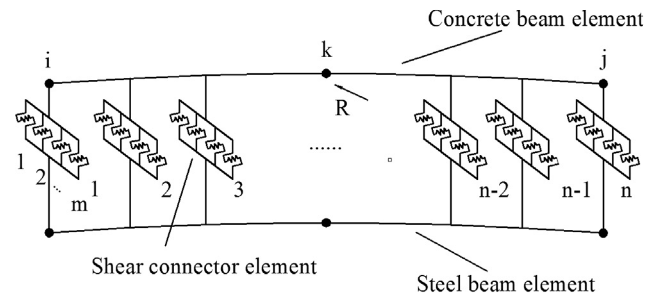

Fig. 2. New finite-element model of steel-concrete track beam.

assumed as a model with 32 degrees of freedom, as seen in Eqs. (5)–(8).

$$[\delta^e]_b=[[\delta_i^e]_b^T\ \ [\delta_k^e]_b^T\ \ [\delta_j^e]_b^T]^T \tag{5}$$

$$[\delta_i^e]_b=[u_{zi}^1,u_{zi}^2,v_{yi},w_{xi},\theta_{xi},\theta_{yi},\theta_{zi},\beta_i^1,\beta_i^2]^T \tag{6}$$

$$[\delta_k^e]_b=[u_{zk}^1,u_{zk}^{1'},u_{zk}^2,u_{zk}^{2'},v_{yk},w_{xk},\theta_{xk},\theta_{yk},\theta_{zk},\theta_{zk}',\beta_k^1,\beta_k^{1'},\beta_k^2,\beta_k^{2'}]^T \tag{7}$$

$$[\delta_j^e]_b=[u_{zj}^1,u_{zj}^2,v_{yj},w_{xj},\theta_{xj},\theta_{yj},\theta_{zj},\beta_j^1,\beta_j^2]^T \tag{8}$$

In Eqs. (5)–(8), u_z^1 and u_z^2 represent the axial displacement of the concrete and steel beam element, respectively; v_y indicates the vertical displacement; w_x denotes the radial displacement; θ_x, θ_y and θ_z indicate the angular displacement about the X-axis, Y-axis and Z-axis, respectively; β^1 and β^2 denote the warping freedoms of concrete and steel beam element, respectively; subscripts i, j and k indicate the nodes of the beam element, respectively; $u_{zk}^{1'}$, $u_{zk}^{2'}$, θ_{zk}', $\beta_k^{1'}$ and $\beta_k^{2'}$ are the derivatives of u_{zk}^1, u_{zk}^2, θ_{zk}, β_k^1 and β_k^2 with respect to Z, respectively.

The equation of kinetic energy is given by Eqs. (9) and (10), where ρ and $N(z)$ denote the linear density of the beam and the shape function of the element, respectively.

$$T_b=\frac{1}{2}[\dot{\delta}^e]_b^T[M^e]_b[\dot{\delta}^e]_b \tag{9}$$

$$[M^e]_b=\rho\int_0^{l_e}[N(z)]^T[N(z)]dz \tag{10}$$

The equation of elastic potential energy is given by Eq. (11), where U^a, U^c and U^s represent the elastic potential energy of the concrete beam element, steel beam element and shear connector element, respectively.

$$U_b^e=U^a+U^c+U^s \tag{11}$$

The elastic potential energy of the concrete beam element and steel beam element can be expressed as:

$$U^a=\int_0^{l_e}\frac{1}{2}(E^aA^a\varepsilon_z^{a2}+E^aI_\omega^aK_\omega^{a2}+E^aI_x^aK_x^{a2}+E^aI_y^aK_y^{a2}+G^aI_k^a\gamma_k^{a2}+G^aI_s^a\gamma_s^{a2})dz \tag{12}$$

$$U^c=\int_0^{l_e}\frac{1}{2}(E^cA^c\varepsilon_z^{c2}+E^cI_\omega^cK_\omega^{c2}+E^cI_x^cK_x^{c2}+E^cI_y^cK_y^{c2}+G^cI_k^c\gamma_k^{c2}+G^cI_s^c\gamma_s^{c2})dz \tag{13}$$