Simulation of a Shinkansen train running on the bridge at high speed during an earthquake

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Abstract

A computational method for the simulation of a Shinkansen train running on the bridge during an earthquake is given. The motion of the train is expressed in multibody dynamics. Mechanical models to express contact-impact behaviors between wheel and the track structure during an earthquake are given. Rail and track elements with multibody dynamics and FEM used are described. The motion of a bridge is modeled with various finite elements and rail and track elements. Equations of motions of the train and bridge are solved under the interaction between wheel and track structure. A modal reduction is applied to solve the equations effectively. Numerical examples are demonstrated.

Keywords – simulation, high-speed train, dynamic interaction, bridge, earthquake

1 Introduction

Computational methods for the simulation of a high-speed train running on the railway structure such as bridge have been developed by using multibody dynamics together with finite element method [1-4]. However, very little work related to the simulation of the train running on the railway structure during an earthquake has been reported so far.

In this paper, an efficient computational method for the simulation of a Shinkansen train (high-speed train in Japan) on the railway structure during an earthquake is given. The motion of the train is modeled in multibody dynamics. Mechanical models to express contact-impact behaviors between wheel and track structure are given for the simulation during an earthquake. Rail and track elements have been developed using multibody dynamics together with finite element method.

The motion of railway structure is modeled with various finite elements and rail and track elements. The nonlinear dynamic response during an earthquake is obtained by solving equations of motions of the train and railway structure subjected to the interaction between wheel and the track structure. A modal reduction is applied to the equations to solve the practical problem effectively.

Based on the present method a computer program, DIASTARS, has been developed for the simulation of a Shinkansen train running on the railway structure during an earthquake. Numerical examples are demonstrated.

2 Interaction between wheel and track structure

2.1 Interaction between wheel and rail

Assuming that the yawing and rolling of wheel-set are relatively small for the contact behavior between wheel and rail considered here, two dimensional geometries of the cross sections of wheel and rail are considered, and the contact-impact behavior in the normal direction on the contact surface is modeled simply in two modes of the contact in the vertical and transverse directions as shown in Fig.1.

When the relative displacement between wheel and rail in the normal direction, \( d_z \), exceeds derailment criterions \( \mu_z \), or

\[ \delta_x = \delta_x(z_R, z_w, d_z) \]  

(1)

The contact displacement \( \delta_x \) in the normal direction on the contact surface between wheel and rail is obtained from the contact angle at the contact position. When wheel contacts on rail, there is a contact force created on the contact surface. The contact force on the contact surface between wheel and rail in the normal direction, \( H \), is expressed as a function of \( \delta_x \) and \( d_z \) as follows

\[ H = H(\delta_x, d_z) \]  

(2)

Regarding the transverse mode of the contact between wheel and rail, the contact displacement in the transverse direction \( \delta_y \) is also expressed as a function of \( d_y \) and \( \delta_y \) depending on the geometry of the cross sections of wheel and rail as

\[ \delta_y = \delta_y(d_y, \delta_z) \]  

(3)

When a wheel contacts on the rail in the transverse direction, the contact force is obtained in the same manner as the contact mode in the vertical direction described above.

Regarding the tangential and longitudinal directions on the contact surface between wheel and rail, constitutive equations to describe the relationship between creep forces and slipping rates of wheel are given based on Kalker’s linear theory [5]. When a wheel lifts on the rail, there is no impact and creep forces created between the wheel and rail.

2.2 Derailment Criterion

When the relative displacement between wheel and rail in the transverse direction, \( d_y \), exceeds derailment criterions \( \mu_y \), or
After derailment of wheel from rail during an earthquake the wheel touches down on the track structure.

2.3 Contact between wheel and guard after derailment

Guards are attached on the track structure to prevent wheel deviating from the track after derailment during an earthquake to build an earthquake-safe railway system as shown in Fig. 3 [6]. After the derailment of a wheel, it contacts on the guard of the track structure in the transverse direction. The contact force $Q_{gy}$ is expressed here as a function of the embedded area $A_{gy}$ between the wheel and the guard as

$$Q_{gy} = Q_{gy} (A_{gy})$$

Fig. 3 Contact between wheel and guard on the track structure in the transverse direction

If the guard has an enough height and strength for the impact force between wheel and guard, the wheel is guided well between left and right guards in the rail direction.

3 Mechanical model of railway structure

Long railway components in the rail direction such as rail and track are considered to move as rigid bodies of the motion in plane of the cross-section. Rail and track elements have been developed to solve contact-impact behaviors between wheel and rail in the pre-derailment and between wheel and the track structure in the post-derailment for the actual railway structure. A railway structure is modeled with various finite elements and rail and track elements for long railway components such as rail and track. Assembling all elements in the model, the equation of motion of a railway structure is obtained.

4 Numerical example

The simulation of a Shinkansen car running at a speed of 200 km/h on the ladder track with guards attached on the five spanned viaduct with the height of 10 m, the span-length of 8 m and the width of 11.6 m during an earthquake as shown in Fig. 4 has been conducted. The ladder track is made of ladder-shaped composite concrete beams to support rails tied with steel pipes where guards are attached to prevent wheel deviating from the track even after derailment during a strong earthquake [6]. Fig. 5 shows the vertical displacement response of the right wheel of the 1st wheel-set. It is shown that the wheel runs onto the rail about 7 cm in height due to the impact between wheel and rail in the vertical direction, derails, touches down on the track, and lifts on the track surface during the earthquake.

5 Conclusions

A computational method for the simulation of a high-speed train running on the railway structure was given. Efficient mechanical models to solve contact-impact behavior between wheel and the track structure were described. Simulation of a Shinkansen car on the five spanned viaduct during an earthquake was demonstrated. The computational method developed here would be effective to design an earthquake-safe railway system.

References