Computation of Impact Effect of Multi-span Beam Bridge under Light-Rail Vehicle

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Abstract. In this paper, the bending moment impact effect of a 7-span beam bridges under the single-carriage light-rail vehicle at different speeds is investigated. The 7-span composite box girder bridge is modelled using the shell element. The light-rail vehicle is modeled using the rigid beam and the spring-damper elements with 31 degrees-of-freedom. The vehicle-bridge interaction is modeled using the displacement contact method. The computed bending moment envelopes show that for the studied bridges under the concerned light-rail vehicle at the moving speeds from 80 km/h to 120 km/h, the impact effect on the positive bending moment of the first and the sixth span are the most notable: the impact factor will reach 1.742 for the first span and 1.508 for the sixth span.

Introduction

The impact effects on bridges under moving vehicles are the continuous concern among civil engineering communities\(^{[1,2]}\). With the increase of train speed, the dynamic interaction between vehicles and bridges has been paid more and more attention. Zhang and Xia\(^{[3]}\) studied the dynamic response of a five-span continuous girder bridge under the action of heavy-haul trains. Concerning of the variation of the moving train speeds, no obvious variation is observed for the mid-span displacement and acceleration response of the bridge. An and Li\(^{[4]}\) studied the vehicle-bridge coupled dynamic response of a long-span continuous girder bridge and concluded that the impact factor of the bridge will be much larger than that calculated according to the code JTG D60-2004 with the increase of vehicle loads. Zhang\(^{[5]}\) established a three-span continuous beam bridge model in ANSYS and calculated the dynamic response of vehicles and bridges under the action of a train with six carriages. The results show that with the increase of train speed, the vertical displacement in the mid-span of the bridge increases slightly, and the peak vertical acceleration in the mid-span increases first and then decreases. Ye\(^{[6]}\) studied the influence of vehicle weight on impact factor of a simply-supported beam. With the increase of the vehicle weight, the impact factor of bridge increases linearly.

In this paper, a FEM numerical model is established to model a 7-span composite box girder bridge under a single-carriage light-rail vehicle in ANSYS. The impact factors of bending moment of the bridge under the light-rail vehicle with different speed are studied.

Bridge and Vehicle Description

This research is conducted to evaluate the impact effect of a seven-span composite continuous box girder bridge for the long-term light-rail transit planning. The bridge considered is a composite continuous box girder bridge with the span combination of 90m + 5 × 105m + 85m = 700m. Supported by the bearings on the piers, the superstructure is modelled to be restrained with roller supports for bridge vertical behavior analysis. For the composite cross-section, shell elements are adopted to model the concrete deck and the U-shape steel beam. No slip is considered for the connection DOFs between the deck and the beam.
The light-rail vehicle is composed of 1 car body, 2 bogies, 8 wheels, the primary and the secondary suspension systems and other components. The primary and secondary suspension systems are respectively connected between the car body and the bogie, the bogie and the wheels. The vehicle and bogie are considered to be rigid body with 5 DOFs, which are the vertical displacement, lateral displacement, pitch rotation, rolling and head-rolling rotation DOFs. The wheels are considered to be the lumped mass with 2 DOFs, which are the vertical and lateral displacement DOFs. The longitudinal displacement DOFs of the car body, bogies and wheels are not considered and a total of 31 DOFs are considered for the vehicle modeling.

For the vertical vibration behavior of bridges considered, the vibration caused by the irregularity of the bridge deck is not taken into account. It is assumed that the vehicle always contacts with the bridge deck. No hunting behavior of the vehicle is considered.

System FEM Modeling
The FEM model consists of 36232 nodes and 49931 elements. Among them, the bridge is modeled using the SHELL181 element, each element has four nodes, each node has six DOFs. The elastic modulus of the concrete material used in the model is \(3.6 \times 10^{10} \text{N/m}^2\). The Poisson's ratio is 0.2. The density is \(2500 \text{kg/m}^3\). Steel elastic modulus is \(2.1 \times 10^{11} \text{N/m}^2\). Poisson's ratio is 0.3. The density is \(7900 \text{kg/m}^3\). The one-way support and two-way supports are set at each pier supporting DOFs. Herein, the one-way support restraints the transverse and vertical displacement. The two-way support restraints vertical displacement.

For the vehicle, the MPC184 rigid beam element is used to model the car body and bogie. MASS21 mass unit is established at the center of mass of the car body and bogie to model the mass of the car body and bogie. The primary and second suspension systems of light rail train are modeled using the COMBIN14 spring-damper element. In this paper, only the dynamic response of a single vehicle passing through a bridge is calculated. The vehicle model parameters shown in [3] are adopted.

The vehicle-bridge interaction is realized using the displacement contact method. The node-surface contact elements (conta175 and target170) in ANSYS are adopted. Using the transient dynamic analysis solver and APDL command stream loop solution, the vibration response of the bridge under the moving vehicles is computed.

Eigen-mode Analysis
The eigen-mode analysis of the above bridge model is conducted in ANSYS. The first 14 modes are computed as shown in the table 1. It can be seen from the mode shapes that the first mode is a symmetrical vertical bending mode with a frequency of 1.265 Hz, the second to the fourth modes are the vertical bending modes, the fifth mode is a transverse bending mode, the sixth and seventh modes are the vertical bending modes, the eighth mode is a transverse bending mode, the ninth mode is a vertical bending mode, the tenth and eleventh modes are the transverse bending and torsion modes, the twelfth mode is the anti-symmetric torsion mode, the thirteenth mode is the symmetric torsional mode, and the fourteenth order is the anti-symmetric torsional mode.
Table 1. Bridge modal frequencies and mode shape description.

| Mode No. | Frequency (Hz) | Mode description | Mode No. | Frequency (Hz) | Mode description |
|----------|----------------|------------------|----------|----------------|------------------|
| 1        | 1.265          | Symmetric vertical bending | 8        | 2.479          | Vertical and transverse bending |
| 2        | 1.439          | Anti-symmetric vertical bending | 9        | 2.504          | Vertical bending |
| 3        | 1.647          | Anti-symmetric vertical bending | 10       | 2.631          | Transverse bending and torsion |
| 4        | 1.875          | Vertical bending | 11       | 2.875          | Transverse bending and torsion |
| 5        | 2.104          | Transverse bending | 12       | 3.044          | Anti-symmetric torsion |
| 6        | 2.191          | Vertical bending | 13       | 3.117          | Symmetric torsion |
| 7        | 2.392          | Vertical bending | 14       | 3.171          | Anti-symmetric torsion |

For the eigen-mode analysis of the vehicle, all degrees of freedom of wheels are constrained and the fifteenth modal frequencies are computed. It can be seen that the first five modes are the lateral vibration, vertical vibration, head-rolling, pitch and roll modes of the car body, and the last ten modes are the vibration mode of the bogie.

Impact Factors Computation

The vehicle load of $55.355 \times 10^3 \times 9.8N$, and the vehicle speed of 80 km/h, 90 km/h, 110 km/h, and 120 km/h are considered respectively. The vehicle-bridge coupled computation is carried out. Fig. 2 presents the bending moment envelope diagram of the bridge when a single-carriage vehicle passed by. It can be seen in the figure that the peak position of the bending moment caused by the vehicle has different degrees of offset in each span. That means the maximum position of the dynamic bending moment does not coincide with the maximum position of static bending moment. As shown, the offset directions of positive bending moment are opposite to the driving direction for all spans. The maximum offset length are around 30 meters for the fifth and the sixth spans.
Considering the offset of the maximum dynamic bending moment in the moment envelope, the impact factor of the bending moment at the mid-span is too small for the estimation of the peak dynamic bending moment. The impact factors of the maximum dynamic bending moment to the peak static bending moment for each span are computed and listed in table 2. Combining with the bending moment envelope diagram, it can be seen that the bending moment impact effects of the first span and the sixth span are the most notable. Considering the dead load effect, the negative bending moment impact factors are not evaluated in this paper.

Table 2. Impact factor of the maximum dynamic positive moment to the maximum static moment.

| velocity (km/h) | Span 1 | Span 2 | Span 3 | Span 4 | Span 5 | Span 6 | Span 7 |
|----------------|--------|--------|--------|--------|--------|--------|--------|
| 90             | 1.678  | 1.334  | 1.219  | 1.220  | 1.286  | 1.402  | 1.211  |
| 100            | 1.710  | 1.363  | 1.406  | 1.353  | 1.449  | 1.470  | 1.288  |
| 110            | 1.742  | 1.320  | 1.379  | 1.276  | 1.413  | 1.449  | 1.290  |
| 120            | 1.699  | 1.251  | 1.322  | 1.194  | 1.370  | 1.508  | 1.192  |

**Conclusion**

In this paper, the bending moment impact factor of a 7-span continuous composite box girder bridge under a 31-degree-of-freedom light-rail vehicle model is investigated. The vehicle-bridge interactive dynamic system is modelled and computed using the ANSYS FEM software. The computation results show: under different vehicle speeds, the peak positions of the live load dynamic moment envelope are offset from the position of the peak static moment envelope. The impact effect on the positive bending moment of the first and the sixth span are the most notable.

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