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Research on Vehicle-Bridge Coupled Vibration of Long-span Continuous Rigid Frame Bridges with High Piers

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Abstract: Vehicle-bridge coupled vibration of long-span continuous rigid frame bridge with high pier is serious due to its own characteristics. A series study has been done based on a long-span continuous rigid frame bridge with high pier. Dynamic response of bridge was analyzed using the special bridge dynamic analysis software. A series of points for dynamic strain and dynamic deflection measure were arranged on the real bridge, so as to measure the axle coupling vibration dynamic deflection and dynamic strain value. In order to study the reliability of the calculated dynamic effect of high pier and long-span continuous rigid frame bridge, the measured real data are compared to the calculated ones. The results show that the calculated vehicle-bridge coupled vibration data is very closed to the real one. In conclusion, this analytical method is accurate and reliable which can be used as a reference in the study of vehicle-bridge coupled vibration dynamic response of the same type of bridge.

Keywords *High pier, Long-span, Continuous rigid frame bridge, Vehicle-bridge coupled vibration, Dynamic structural analysis.*

1. Introduction

With the rapid development of national economy and the modern transportation, the demand of large span bridges is increasing and long-span continuous rigid frame bridge with high piers revealed its importance in the field. Due to a variety of advantages of long-span continuous rigid frame bridges with high piers, it has been widely used in our country [1-3]. But the vehicle-bridge coupled vibration is obvious due to the characteristics of long-span continuous rigid frame bridges with high piers.

After the professor Brandon Lee studied the domestic vehicle vibration problem, domestic scholars began to do the research. The vehicle-bridge coupled vibration analysis model was established based on Darren Bell principle by the professor Shen Huo-ming of southwest jiaotong university. It was analyzed by Numerical analysis method [4]. The Vibration equation was established based on virtual work principle and mode superposition method by the professor Liu Hua of southeast university. Its uncoupled equations were solved separately by an iterative procedure while the geometrical compatibility condition and equilibrium condition of the interaction forces between bridge and vehicle were satisfied [5]. Dr. Yan Zhi-gang of Harbin Institute of Technology studied the effect degree of different pavement roughness conditions on vibration of long span concrete filled steel tube arch bridges using finite element method combined with pavement roughness [6]. With the obvious increase of vehicle speed, traffic and overloading vehicles, the long-span continuous rigid frame bridge with high piers of vehicle-bridge coupling vibration is getting wide concern [7-10]. As the load is heavier, the coupling vibration phenomenon is more obvious.

The vehicle-bridge coupled vibration phenomenon was analyzed and the reliability of the calculated value of long-span continuous rigid frame bridge with high piers dynamic effect was studied by comparing the results of the finite element calculation and the measured ones.

2. The vibration differential equation of vehicle-bridge coupled vibration:

Take the bridge and vehicle as two sub-systems and establish the vibration differential equation respectively. The vibration differential equation of vehicle-bridge coupled vibration is shown below.

$$M_q\ddot{Z}_q(t)+C_q\dot{Z}_q(t)+K_qZ_q(t)=P_q(t) \quad (1)$$

M_q, C_q, K_q, $Z_q(t)$, $\dot{Z}_q(t)$ and $\ddot{Z}_q(t)$ denote the mass matrix, damping matrix, stiffness matrix, displacement vectors, velocity vectors and acceleration vectors respectively. $P_q(t)$ denotes the force vector of vehicles acting upon the bridge.

The vibration differential equation of vehicle vibration is shown below.

$$M_c\ddot{Z}_c(t)+C_c\dot{Z}_c(t)+K_cZ_c(t)=P_c(t) \quad (2)$$

M_c, C_c, K_c, $Z_c(t)$, $\dot{Z}_c(t)$ and $\ddot{Z}_c(t)$ denote the mass matrix, damping matrix, stiffness matrix, displacement vectors, velocity vectors and acceleration vectors of vehicles respectively. $P_c(t)$ denotes the force vector of bridge reacting upon the vehicles.

In the analysis of vehicle-bridge coupled vibration, assume that the wheel and bridge deck is always staying in touch. The vertical displacement of a bridge and wheel is shown below.

$$\Delta Z(t) = Z_q(t) - Z_c(t) + r(x) \tag{3}$$

There are $Z_q(t)$, $Z_c(t)$ and $r(x)$ to denote the vertical displacement of the bridge, the vertical displacement of the vehicle and the irregularity of the bridge deck respectively.

The action and reaction are equal on the contact surface, the value is shown below.

$$P_q(t) = -P_c(t) = C_l(\Delta\dot{Z}(t)) + K_l(\Delta Z(t)) \tag{4}$$

C_l, K_l and $\Delta\dot{Z}(t)$ denote the damping, stiffness of the wheel and the vertical relative velocity between the bridge and wheel respectively.

The vehicle and bridge vibration differential equation is combined together by equilibrium of forces and displacement coordination method, so as to carry out the solution of the vibration differential equation of vehicle-bridge coupled vibration.

3. The support project:

The certain bridge is a long-span continuous rigid frame bridges with high piers. The span of the bridge is 75+140+75 meters and the piers are double thin wall pillar. The height of pier in the small and large station is 49 and 45 meters respectively. The girder is pre stressed concrete box-girder.

This paper established the bridge and vehicle model of coupled vibration by using the special bridge dynamic analysis software based on the analysis of vehicle-bridge coupled vibration. The interaction of the bridge and vehicles is calculated by equilibrium of forces and displacement coordination method.

Vehicles getting cross the bridge at a certain speed under the barrier-free condition and the real dynamic response are tested at the same time. Using the vehicles of 35 tons as the certain vehicle.

Condition 1: one vehicle get cross the bridge at a constant speed of 20 km/h.

Condition 2: one vehicle get cross the bridge at a constant speed of 30 km/h.

Condition 3: one vehicle get cross the bridge at a constant speed of 40 km/h.

Condition 4: three vehicles get cross the bridge at a constant speed of 30 km/h, the vehicles start at 0s, 10s, 20s respectively.

The dynamic strain measuring point and dynamic deflection measuring point were decorated in the mid-span of the bridge (the section Ⅰ-Ⅰ). They are arranged to record the vibration response while vehicles getting across the bridge. The acceleration sensor was decorated at the 1/8 length of mid-span(the section Ⅱ-Ⅱ). The acceleration sensor was decorated at the 1/6 length of side span (the section Ⅲ-Ⅲ). They are arranged to record the dynamic behavior parameters both in longitudinal and transverse direction of the bridge. The arrangement of points is shown below.

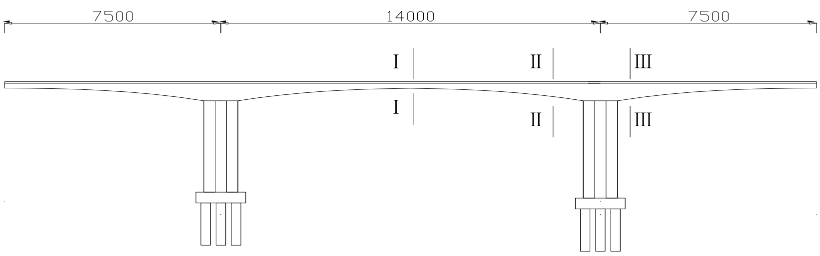

Fig 2 *Vertical section of the bridge (unit: cm)*

4. Analysis of dynamic characters:

4.1. The analysis of natural vibration character:

Natural vibration characters are the important factors in the analysis of vehicle-bridge coupled vibration. Measure the bridge dynamic response under the influences of environment and vehicle and compare the real frequency and the finite element calculation results. The comparison of the bridge self-vibration frequency is shown below.

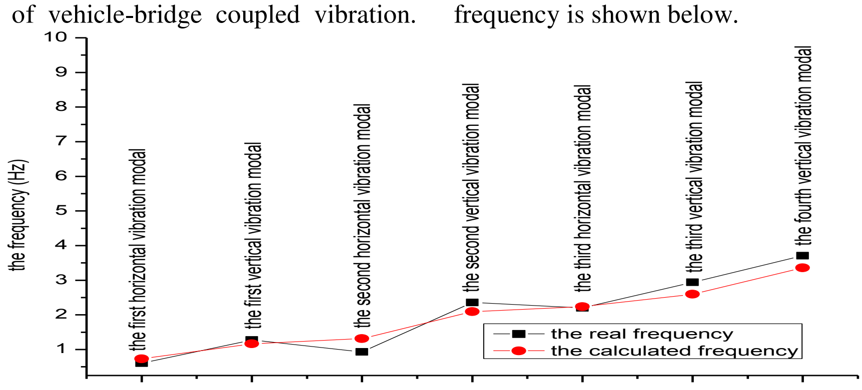

Fig 3 *The comparison chart of the bridge self-vibration frequency*

The comparison of natural vibration character shows that the real frequency fluctuates compared with the finite element calculation. The comparison shows that the finite element calculations are accurate.

4.2. The analysis of dynamic response of mid-span:

The dynamic reactions include the bridge dynamic strain and dynamic deformation of the bridge structures will occur under the moving vehicle load. Comparing the dynamic deformation between the real and calculate value under all conditions is essential. The comparison of dynamic deformation maximum appearance time is shown below.

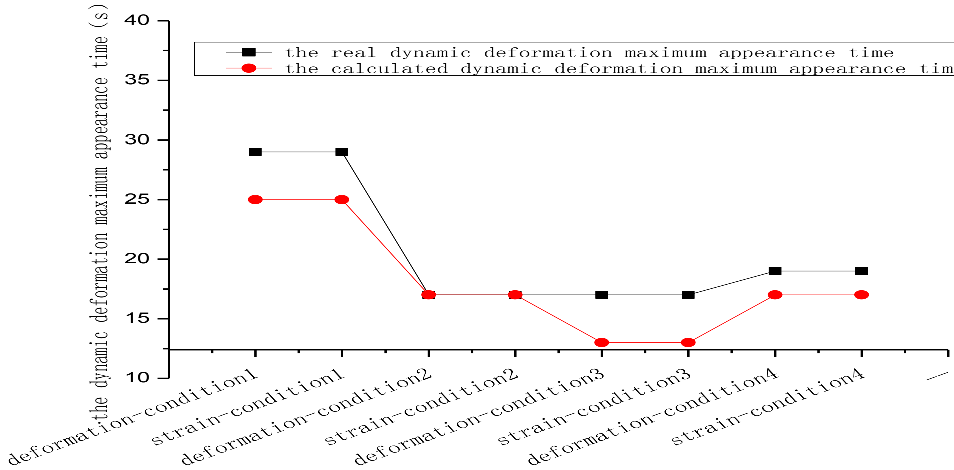

Fig 4 The comparison chart of dynamic deformation and strain maximum appearance time on the bridge mid-span

The dynamic deformation maximum appearance time shows that the trend of appearance time is the same. The real and calculate value of appearance time has a difference of about 3 seconds. The reason is that the speed of vehicles cannot be totally uniform during the test and there are some unexpected factors as well. The conditions of one vehicle show that the larger speed make the calculate value more accurate. The conditions of 30 Km/h show that the larger weight make the calculate value more accurate.

4.3. The amplitude analysis of structure time-history recorded responses:

According to the numerical regression analysis of the mid-span deflection time-history recorded response, the maximum of dynamic time-history recorded responses and the static time-history recorded responses were selected to be analyzed. The comparison of the calculated results and real ones of the bridge maximum amplitude is shown below.

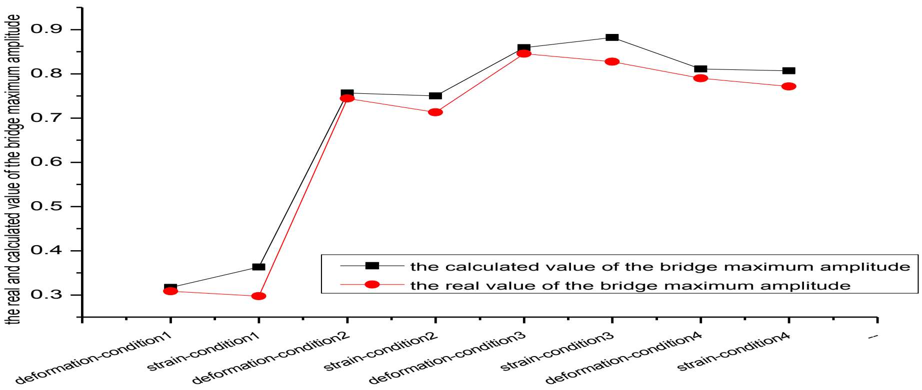

Fig 4 The comparison chart of the real and calculated value of the bridge maximum amplitude

The result shows that the real value of vehicle-bridge coupled vibration is smaller than calculate value. Under the condition of same vehicles, when the speed of the car is larger, the real value is more close to the calculated value. Under the condition of same speed, when the number of the car is larger, the real value is more close to the calculated value. Compared with the strain, the deflection response is closer to the calculated value. The real response has the same trend with the calculated value.

4.4. The analysis of impact coefficient:

The calculate impact coefficient is compared with the real value of the dynamic strain measuring point and dynamic deflection measuring point. The comparison of the bridge impact coefficient is shown below.

The bridge deck is uneven; the speed of vehicles can't keep uniform due to the environment disturbance. The real impact coefficient was greater than calculated value and the code value. The frequency of bridge is the only factor which was taken into consideration in the code value, so the impact coefficient is constant in the same bridge. The frequency of bridge, vehicles and same factors are considered in the calculate value, so the calculate impact coefficient is changing. The result shows that the calculated impact coefficient, the code and the real is different. The calculated impact coefficient and the code are shown the same trend. Due to the environment disturbance, the real impact coefficient is larger than others.

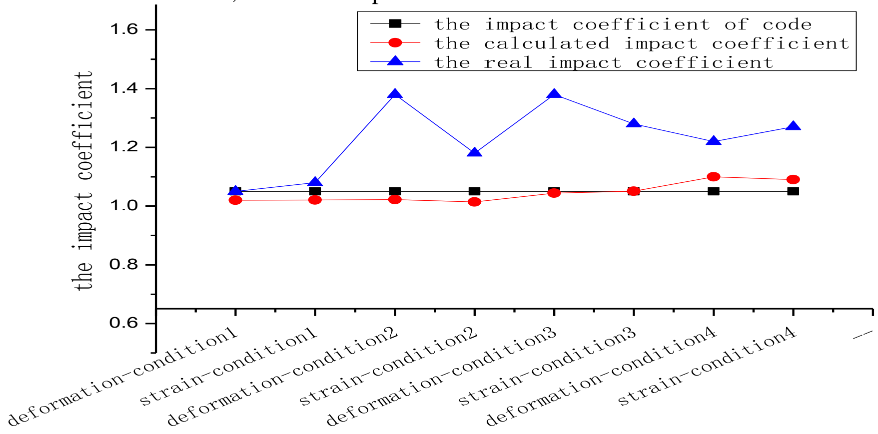

***Fig 5.** The comparison chart of the bridge impact coefficient*

5. Conclusions:

The dynamic response maximum appearance time shows that the trend of appearance time is the same. The real value of vehicle-bridge coupled vibration is smaller than calculate value. Under the condition of same vehicles, the larger speed and weight make the calculate value more accurate.

The environment disturbances make the real impact coefficient greater than calculated value and the code value. The different conditions make the different impact coefficient, when the vehicle and the speed is smaller, the impact coefficient is closer to each other.

The calculated bridge vehicle-bridge coupled vibration data is very closed to the real one, this analytical method is accurate and reliable and it can be used as a reference in the study of vehicle-bridge coupled vibration dynamic response of the long-span continuous rigid frame bridges with high piers

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