Considering the Dynamic Response of Transverse and vertical Vehicle-bridge Coupled Curved Bridge

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Abstract. In order to explore the dynamic response of curved bridge under the coupling action of transverse and vertical vehicle-bridge, a three-span concrete continuous curve bridge model and a vehicle model are established by using the finite element software ANSYS. The coupling action of transverse and vertical vehicle-bridge is simulated by using the equilibrium and geometric coordination conditions of the forces between the two models, and the transverse vibration of the vehicle model is considered. The dynamic response of curved bridge is studied by establishing the dynamic model of vehicle-bridge interaction. The results show that the maximum transverse force of 1# mid-span section increases by 1.43% under the action of 70t vehicle weight compared with that without considering the coupling effect of transverse and vertical vehicle-bridge; and the maximum transverse displacement of 1# mid-span section increases by 10.25% compared with that without considering the coupling effect of transverse and vertical vehicle-bridge. Therefore, it is necessary to take into account the vehicle-bridge coupling in the dynamic response analysis of curved bridges; the transverse displacement of curved bridges can be prevented by limiting load and weight.

1. Introduction

When a vehicle travels on a bridge, a curved bridge will produce a certain dynamic response[1]. The vehicle-bridge coupling must be taken into account in the analysis of the dynamic response of the structure under vehicle loads[2], while the existing research results rarely consider the transverse vehicle-bridge coupling. However, if the transverse coupling vibration is not considered or the transverse coupling vibration is not well considered, there will be some deviation in the analysis of the real vehicle-bridge coupling vibration. Through the comparative analysis of the dynamic response of the concrete continuous curve bridge under whether to consider the coupling effect of transverse and vertical vehicle-bridge, the dynamic of the concrete continuous curve bridge can be more clearly understood. In order to ensure the safety of bridge during operation, prolong service life and reduce economic losses, it is of great significance.

At present, scholars at home and abroad have done a lot of research on vehicle-bridge coupling: Li Qinghai and Tan Duguang[3] use cubic interpolation function to establish bridge-related motion equation by considering multi-axle and multi-vehicle acting on bridges under various supporting conditions, and introduce super-element method to establish vehicle load motion equation and analyze vibration response of bridge structures. Marchesiello et al[4] established a three-axle vehicle model of seven-degree-of-freedom system and crossed the bridge at constant speed. The numerical analysis of a three-span bridge was carried out to study the dynamic response of the torsional modal shape of the
bridge. Willis[5] did not consider the self-weight of the bridge itself, and obtained an approximate analytical solution by establishing the vehicle-bridge coupling vibration equation. It is found that the stress and deformation of bridge under static force are less than that of bridge under dynamic force. However, most of the research on vehicle-bridge coupling vibration focuses on the vertical vibration, while the research on transverse coupling vibration is seldom involved.

Therefore, on the basis of vertical vehicle-bridge coupling, the dynamic response of concrete curved bridge with transverse vehicle-bridge coupling is further considered in order to get the exact solution of transverse displacement of concrete curved bridge, it provides a reference for preventing and curing the transverse creep of concrete curved bridges.

2. Curved bridge model

2.1. Overview of curved bridge
The concrete continuous curved bridge of 3×25 m is taken as the research object, and the corresponding finite element model is established. The curved bridge is a single box and single chamber section. The center line of the bridge is located on the circular curve of 80.25 m. The width and thickness of the top plate of the box girder are 8.5 m and 0.25 m, the width and thickness of the bottom plate are 4.5 m and 0.2 m, the thickness of the web plate is 0.5 m, the length of the cantilever plates on both sides is 2 m, the thickness of the root is 0.4 m, and it changes linearly from the end to the root. The cross section is shown in Figure 1:

![Figure 1. Standard cross-sectional map of mid-span and fulcrum of curved bridge (Unit: mm)](image)

2.2. Finite element model
Through the finite element software ANSYS, the curved girder bridge model is established, and the mesh is divided at the same time. The solid element solid65 is used in the main girder part. The material parameters selected are elastic modulus 3.45×104 MPa, material density 2600 kg/m³ and Poisson's ratio 0.2. For the cover girder, cushion and pier, the model is established with the same parameters as the main girder. The finite element model of curved bridge is shown in Figure 2:

![Figure 2. Solid element model of curved bridge](image)
3. Coupled vibration vehicle model

3.1. Vehicle system composition
Vehicles are composed of tires, suspensions, car bodies and other related components. Each component has six degrees of freedom in space. Because the expansion of each component along the driving direction has little effect on the study of transverse and vertical vehicle-bridge coupling effect, the expansion displacement of each rigid body can be ignored. Thus, for each rigid body, the expansion displacement of each rigid body can be neglected. In the course of motion, only 5 degrees of freedom can be considered[6], that are transverse motion, roll, float and sink, shake and nod. In order to better reflect the dynamic process of the vehicle on the bridge deck, a three-axle vehicle (double rear axle) model is proposed, which is divided into seven rigid bodies, namely six wheels and one body. The degree of freedom of the vehicle is 17[7]. The elevation and side diagrams are shown in Figure 3:

![Figure 3. Schematic diagram of three-axle vehicle model](image)

3.2. Vehicle parameters
In order to more truly reflect the dynamic process of the vehicle on the bridge deck, the parametric model of the vehicle is proposed by using the relevant parameters of the three-axle dump truck[8-10]. The body mass is 28500 kg. The vehicle technical parameters are shown in Table 1:

| Vehicle position | Quality (kg) | Distance from body center of mass (m) |
|------------------|--------------|--------------------------------------|
| Front axle       | 500          | 3.8                                  |
| Middle axle      | 1450         | 0.4                                  |
| Rear axle        | 1450         | 1.2                                  |

3.3. Establishment and solution of dynamics equation of coupled system
According to the motion equations and structural damping matrix of bridge structure, the motion equations of vehicle-bridge coupling system can be derived. The expressions of vehicle-bridge subsystems are as follows:

\[
\begin{align*}
M_v \ddot{\delta}_v + C_v \dot{\delta}_v + K_v \delta_v &= F_v \\
M_b \ddot{\delta}_b + C_b \dot{\delta}_b + K_b \delta_b &= F_b
\end{align*}
\]

Formula (1): \( M_v, C_v, K_v, M_b, C_b, K_b \) is the mass, damping and stiffness matrices of bridges and vehicles respectively presented; \( F_v, F_b \) is the integral external force vectors of vehicles and bridges respectively; \( \delta_v, \delta_b \) represent the freedom vector of vehicles and bridges respectively; So it can be expressed by the following formula:
The geometric compatibility condition at the contact point between vehicle system and bridge system can be expressed as:

\[ F_v = F_x(\delta_x, \dot{\delta}_x, \gamma(x)) \]

\[ F_v = F_y(\delta_y, \dot{\delta}_y, \rho(x)) \]

The geometric compatibility condition at the contact point between vehicle system and bridge system can be expressed as:

\[ \delta_v^i = \delta_b^i + \epsilon \theta_b^i + r^i(x) \]

Formula (3): \( \epsilon \) is transverse eccentricity; \( r^i(x) \) is pavement irregularity at the contact of the first wheel with the bridge.

The equilibrium condition of vehicle and bridge at contact can be expressed as:

\[ F_{vb} = -F_{vb} \]

Formula (4): \( F_{vb}^i \) is the force acting on the bridge; \( F_{vb} \) is the force acting on the vehicle; \( i \) is contact points representing a wheel. Formula (4) is a linear time-varying equation. In order to facilitate calculation, \( \Delta \) is chosen for any period of time, and it is approximately assumed that the equation will remain linear for \( \Delta \) hours. In order to ensure the accuracy of the calculation results, Newmark - \( \beta \) is used to establish the dynamic equilibrium conditions for any \( \Delta \) starting and ending points[11]. According to the General Code for Design of Highway Bridges and Culverts[12], the centrifugal force caused by vehicle loads should be calculated for curved bridges. Because of the friction effect between the vehicle and the bridge deck, the curved girder will produce a transverse force acting on the contact between the vehicle and the road surface, which is the transverse force of the curved bridge under the coupling vibration.

4. Dynamic response of transverse and vertical vehicle-bridge coupling curved bridge

4.1. Ignoring transverse and vertical vehicle-bridge coupling

4.1.1. Transverse force of curved bridge.

Without considering the transverse and vertical vehicle-bridge coupling effect, the vehicle weights of 10 t, 30 t, 50 t and 70 t are adopted respectively, and the speed of 50 km/h is used to cross the bridge. Through operation analysis, the forces along the radius direction at the mid-section of the curved bridge under different vehicle weights are analyzed. The time-history curves are shown in Figure 4:

From Figure 4, the following conclusions can be drawn: When the vehicle approaches the mid-span of 1#, 2#, 3#, the transverse force of curved bridge will gradually increase. When a vehicle passes through the mid-span, the transverse force changes abruptly, because the vehicle is a three-axle vehicle.
and the mass is concentrated on three axles, so the abrupt change will occur three times. When the rear axle of the vehicle moves away from the mid-span section, the transverse force of the curve bridge reaches the maximum reverse value, and the transverse force decreases gradually as the vehicle moves away from the curve bridge. When a vehicle passes through the mid-span, the transverse force changes abruptly, because the vehicle is a three-axle vehicle and the mass is concentrated on three axles, so the abrupt change will occur three times. The maximum transverse force of different trucks on the bridge increases obviously, which indicates that the influence of truck weight on the transverse force of curved bridge is significant. In order to further determine the influence of vehicle weight on transverse force, the maximum transverse force of mid-span section under different vehicle weight is summarized. The maximum transverse force of mid-span section is shown in Table 2:

| Weight | Mid-span (kN) | Mid-span (kN) | Mid-span (kN) |
|--------|--------------|--------------|--------------|
| 10t    | 41.20        | 31.30        | 25.93        |
| 30t    | 108.60       | 93.15        | 77.05        |
| 50t    | 177.70       | 152.55       | 129.40       |
| 70t    | 244.75       | 213.75       | 180.05       |

Table 2 shows that with the increase of vehicle weight, the maximum transverse force of the same span increases gradually. Under the action of 70 t vehicle weight, the maximum transverse force of 1# mid-span section can reach 244.75 kN. Under the same vehicle weight, the transverse force of different mid-span sections is different, and the transverse force of 1# mid-span section is higher than that of other sections.

4.1.2. Transverse displacement of curved bridge

In order to clarify the real change of curved bridge, the transverse displacement of mid-span section is extracted and the relevant time-history curve is drawn, as shown in Figure 5:

From Figure 5, the following conclusions can be drawn: With the increase of vehicle weight, the tangential slope of curve increases, which indicates that the influence of vehicle weight on the transverse displacement of curve bridge mid-span is obvious. The transverse displacement of 1# mid-span section increases gradually with the three axles of the automobile going on the bridge in turn, after 0.5 s, the rear axle of the vehicle enters the bridge deck, and the time-history curve no longer fluctuates. About 1.2 s, the center of the vehicle passes through the mid-span section of 1# beam, and its transverse displacement reaches the peak value, then gradually decreases. For the 2# mid-span section, when the time reaches about 2.8 s, the transverse displacement of the vehicle reaches its peak when it enters the mid-span section. The transverse displacement of 3# mid-span section and 1# mid-span section have a symmetrical trend of change. In order to further determine the influence of vehicle weight on transverse displacement, the maximum transverse displacement of mid-span section under different vehicle weight is summarized. The maximum transverse displacement of mid-span section is shown in Table 3:
Table 3. Maximum transverse displacement in midspan

| Weight | 1# Mid-span (mm) | 2# Mid-span (mm) | 3# Mid-span (mm) |
|--------|-----------------|-----------------|-----------------|
| 10t    | 0.104           | 0.072           | 0.096           |
| 30t    | 0.312           | 0.216           | 0.286           |
| 50t    | 0.517           | 0.359           | 0.474           |
| 70t    | 0.722           | 0.501           | 0.659           |

Table 3 shows that with the increase of vehicle weight, the maximum transverse displacement of all mid-span sections increases gradually; under the same vehicle weight, the transverse displacement of the cross-section located in the side span is larger than that of the mid-span section. Under the action of 70t vehicle weight, the maximum transverse displacement of 1# mid-span section can reach 0.722 mm.

4.2. Consideration of transverse and vertical vehicle-bridge coupling

4.2.1. Transverse force of curved bridge

Considering the transverse and vertical vehicle-bridge coupling effect, the vehicle weights of 10 t, 30 t, 50 t and 70 t are used to bridge at the speed of 50 km/h. Through the analysis of vehicle-bridge coupling effect on different vehicle weights, the force along the radius direction at the middle section of the curved bridge is extracted. The time history curve is shown in Figure 6:

From Figure 6, when the vehicle approaches the mid-span of 1#, 2#, 3#, the transverse force of curved bridge will gradually increase, because considering the coupling effect of vertical and horizontal vehicle-bridge, the variation curve of transverse force will produce fluctuation. When vehicles leave the curved bridge, the transverse force decreases gradually, and the time-history curve of the transverse force of the curved bridge will fluctuate and decrease gradually. The maximum transverse force of each mid-span section under different vehicle weights is shown in Table 4:

Table 4. Maximum transverse force in midspan

| Weight | 1# Mid-span (kN) | 2# Mid-span (kN) | 3# Mid-span (kN) |
|--------|-----------------|-----------------|-----------------|
| 10t    | 41.24           | 31.64           | 26.02           |
| 30t    | 109.65          | 95.55           | 77.70           |
| 50t    | 178.05          | 153.55          | 130.10          |
| 70t    | 248.25          | 214.15          | 181.80          |

From Table 4, it can be seen that the maximum transverse force in the middle of the same span increases gradually with the change of vehicle weight and without considering the coupling effect between vehicle and bridge. Under the action of 70 t vehicle weight, the maximum transverse force of 1# mid-span section of the same vehicle weight is larger than that of other sections, it shows that the more unfavorable the transverse force of curved bridge increases with vehicle weight, the maximum transverse force of 1# midspan section can reach 248.25 kN.

4.2.2. Transverse displacement of curved bridge

The transverse displacement of the middle section of the curved bridge under the coupling action of transverse and vertical vehicles and bridges is extracted, and the time history curve is drawn for analysis, as shown in Figure 7:
From Figure 7, the following conclusions can be drawn: Considering the coupling effect of transverse and vertical vehicles and bridges, the time-history curve of transverse displacement of mid-span section has certain fluctuation, especially when the vehicle just enters and leaves the bridge deck, the fluctuation is obvious, but the trend of transverse displacement of mid-span section of 1#, 2#, 3# is the same as that without considering the coupling of transverse and vertical vehicles and bridges. With the increase of vehicle weight, the curve shape becomes steeper, which is consistent with the change trend without considering vehicle-bridge coupling. Whether vehicle-bridge coupling is considered or not, the time point of peak transverse displacement is different within 0.2 s, but the difference is not significant. In order to further determine the influence of vehicle weight on transverse displacement, the maximum transverse displacement of mid-span section under different vehicle weight was extracted. The maximum transverse displacement of the mid-span section is shown in Table 5:

| Weight | 1# Mid-span (mm) | 1# Mid-span (mm) | 3# Mid-span (mm) |
|--------|------------------|------------------|------------------|
| 10t    | 0.128            | 0.090            | 0.116            |
| 30t    | 0.350            | 0.219            | 0.306            |
| 50t    | 0.573            | 0.359            | 0.495            |
| 70t    | 0.796            | 0.504            | 0.668            |

Table 5 shows that with the increase of vehicle weight, the maximum transverse displacement of each section increases gradually, which is consistent with the result without considering the coupling effect between vehicle and bridge. Under the action of 70 t vehicle weight, the maximum transverse displacement of 1# mid-span section can reach 0.796 mm, which is 10.25% higher than that without considering the coupling effect between transverse and vertical vehicle and bridge. When the transverse dynamic response is studied, it is necessary to consider the vehicle-bridge coupling effect.

5. Conclusion

Starting with vehicle deadweight, the dynamic response of curved bridges under different vehicle weights is analyzed, and the following conclusions are obtained.

(1) Regardless of vehicle-bridge coupling, the time-history curves of transverse force and transverse displacement of curved bridges are smooth and have no fluctuation. Considering the coupling effect of vertical and horizontal vehicles and bridges, the time-history curves of transverse force and transverse displacement will produce fluctuation, especially when the vehicle just enters and leaves the bridge deck.

(2) With the increase of vehicle weight, the maximum transverse force and transverse displacement of the middle section of the same span increase gradually, which is consistent with the change trend without considering the coupling effect between vehicle and bridge.

(3) When the vehicle weight is the same, the transverse force and displacement of each mid-span section are larger than those without considering the coupling effect of the transverse and vertical vehicle-bridge.
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