Study on Dynamic Response of Arch Bridge under Vehicle Braking Based on Model Updating

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Abstract. In view of the insufficiency of the current research on special driving, this paper modifies the finite element model based on the static and dynamic measured data, and obtains the benchmark model reflecting the true state of the actual stress state. The influence of braking position and deceleration on key components of arch bridge is studied by establishing the vehicle-bridge coupling model under braking action and choosing three axles to load. The results show that the braking force of vehicle has a great influence on the dynamic response of key parts of arch bridge, and increases with the increase of braking deceleration. At the same time, the influence of vehicle braking force on the arch bridge column is obviously greater than that on the main arch ring.

1. Introduction
At present, in the study of vehicle-bridge dynamic analysis, most of the assumptions are that vehicles are moving at a uniform speed on the bridge deck. The research on bridge dynamic response under vehicle braking condition is relatively less. However, Emergency braking is unavoidable, it is necessary to consider the influence of vehicle braking in vehicle-bridge coupling vibration analysis. Based on the vehicle-bridge coupling vibration model, Deng and Wang studied the influence of vehicle braking on the dynamic impact factors of bridges. The results show that the dynamic response of bridges under vehicle braking is greater than that under vehicle driving at uniform speed [1–2]. Yin studied the influence of deck pavement and braking time on impact factors of bridge under vehicle braking[3].

In view of the current research situation, considering the accuracy of the finite element model, the initial element model should be modified by the static and dynamic measured date, which can reflect the actual stress state of the bridge. Through the establishment of vehicle-bridge coupling numerical analysis model under vehicle braking, typical three-axle vehicle is selected to illustrate the impact of vehicle braking on the key force components of arch bridge.

2. Finite element model updating of arch bridge

2.1 Bridge survey and establishment of initial finite element model
Taking an arch bridge in Guizhou Province as an engineering background, the arch bridge is a reinforced concrete box, whose main span is 122m. The main arch ring is a catenary with equal cross-section, the arch axis coefficient m=1.988, and the ratio of net rise to span 1/5.9. The height of the arch ring section is 210 cm, and the width is 840 cm. The bridge deck is a hollow concrete slab with a span of 9.5m and
a total of 14 spans. The elevation layout of the bridge is shown in figure 1. According to the information of the design drawings, the full bridge model is built and analyzed by the finite element software ANSYS. The finite element model of the bar system is shown in figure 2.

2.2 Dynamic and Static Load Test

In the field static load test, two working conditions are considered in the midspan position: medium load condition and unbalanced load condition. Four trucks are loaded symmetrically in both cases, and three-axle trucks are used in the loading vehicle. The displacement response of the main arch ring under static load condition is tested by setting three deflection measuring points at the midspan arch bottom of the main arch ring. The inherent dynamic characteristics of the structure are tested, and the natural modes and dynamic measured data of the arch bridge are obtained by setting acceleration sensors at each key measuring point to pick up the vibration response of each measuring point.

2.3 Constructing Object Function with

In this paper, the static and dynamic measured data and the modal confidence MAC are used to construct the objective function shown in formula (1): (a is the theory, t is the actual measurement)

\[
f = f_s + f_d + f_{MAC} = \sum_{i=1}^{n_d} \alpha_i (u_{ai} / u_{ti} - 1)^2 + \sum_{j=1}^{n_f} \alpha_j \left( \left( f_{aj} - f_{tj} \right) / f_{tj} \right)^2 + \sum_{j=1}^{n_M} \alpha_{MAC} \left( 1 / \sqrt{C_{MAC}} - 1 \right)^2
\]  

(1)

Among them, \( f_s \), \( f_d \), \( f_{MAC} \) are objective functions based on distortion, frequency and modal confidence MAC respectively. \( u_{ai} \), \( u_{ti} \) are the theoretical and measured displacement values of the measured points under static loading; \( f_{ai} \), \( f_{tj} \) are the theoretical and measured frequency values of the order J, respectively. \( \phi_a \), \( \phi_t \) are theoretical and measured modes. \( \alpha_i \), \( \alpha_j \), \( \alpha_{MAC} \) are weight coefficients of displacement, frequency and modal confidence respectively, and their values are 1[4].

2.4 Sensitivity Analysis of Parameter

The preliminary revised parameters are as follows: main arch ring elastic modulus \( E_t \), column elastic modulus \( E_s \), bridge deck elastic modulus \( E_r \), capping beam elastic modulus \( E_g \); main arch ring mass density \( D_t \), column mass density \( D_s \), bridge deck mass density \( D_r \), column cover beam mass density \( D_g \) [5]. According to the finite element difference method, the sensitivity of the parameters is analyzed, and the influence of the parameters on the frequencies of each order in the modified range is studied. The sensitivity analysis results are shown in figure 3. In the figure, V represents the vertical modal frequency, T represents the transverse modal frequency, L represents the longitudinal mode. According to the analysis results, \( E_t \), \( E_s \), \( E_r \), \( D_t \), \( D_s \), \( D_g \) are selected as the correction parameters.
2.5 Finite element model updating results

The first-order optimization algorithm based on ANSYS is used to iterate the objective function, and the optimal solutions of the modified parameters are obtained. Comparisons between measured and theoretical values are shown in figure 4 and table 1. It can be concluded that the errors between the static and dynamic responses of the modified model and the measured values are reduced, and the modal confidence is very close to 1. In conclusion, the modified model can be used to analyze the dynamic response of bridges under vehicle-bridge coupling.

| Vibration direction | Order | Measured value | Natural frequencies | Relative error/% | MAC/|
|---------------------|-------|----------------|---------------------|-----------------|-----|
|                     |       | Before correction | After correction | Before correction | After correction | After correction |
| Vertical            | 1     | 1.478           | 1.325              | 1.513           | 11.55          | -2.31          | 94.8            |
|                     | 2     | 2.149           | 1.988              | 2.154           | 8.10           | -0.23          | 96.5            |
|                     | 3     | 3.720           | 3.897              | 3.674           | -4.54          | 1.25           | 89.8            |
| Traverse            | 1     | 1.341           | 1.164              | 1.299           | 15.21          | 3.23           | 96.6            |
|                     | 2     | 3.178           | 2.988              | 3.17            | 6.36           | 0.25           | 97.1            |
| Longitudinal        | 1     | 3.429           | 3.745              | 3.469           | -8.44          | -1.15          | 92.3            |
|                     | 2     | 3.499           | 3.125              | 3.517           | 11.97          | -0.51          | 94.2            |

3. Establishment of vehicle-bridge Coupling vibration Program

3.1 Vehicle-bridge coupling dynamic analysis model under vehicle braking

In the vehicle-bridge coupling vibration analysis, the vehicle in the driving process is a multi-degree of freedom vibration system with "mass-stiffness-damping". The vehicle-bridge coupling model includes vehicle sub-model, bridge structure sub model and tire-road interaction sub model [6]. The vehicle-bridge coupling dynamic model considering the braking of the vehicle is shown in figure 5. Vehicle parameters are shown in table 2.
The dynamic equation of the vehicle-bridge coupling system is established according to the relationship between the displacement and contact force of the sub-vehicle and the bridge when the vehicle runs at a uniform speed:

\[
\begin{bmatrix} \mathbf{M} & \mathbf{C} & \mathbf{K} \\ \mathbf{M} & \mathbf{C} & \mathbf{K} \\ \mathbf{M} & \mathbf{C} & \mathbf{K} \end{bmatrix} \begin{bmatrix} \mathbf{z}^* \\ \mathbf{d} \\ \mathbf{d}' \end{bmatrix} + \begin{bmatrix} \mathbf{C}_b + \mathbf{C}_{bb} & \mathbf{C}_v & \mathbf{K}_b + \mathbf{K}_{bb} \\ \mathbf{C}_b & \mathbf{C}_v & \mathbf{K}_b \\ \mathbf{C}_b & \mathbf{C}_v & \mathbf{K}_b \end{bmatrix} \begin{bmatrix} \mathbf{z}' \\ \mathbf{d}' \\ \mathbf{d} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_{bb} \\ \mathbf{F}_{bv} \\ \mathbf{F}_{vb} \end{bmatrix} + \mathbf{G}
\] (2)

In the formula, \( \mathbf{M}, \mathbf{C}, \text{ and } \mathbf{K} \) are respectively mass, damping and stiffness matrices, table b below represents bridge sub-model, \( \mathbf{v} \) represents vehicle sub-model, and \( \mathbf{z} \) and \( \mathbf{d} \) represent vertical displacement vectors of car body and bridge structure respectively. \( \{C_{bb}, C_{vb}, C_{vb}, K_{bb}, K_{vb}, K_{vb}\} \) and \( \mathbf{F}_{vb} \) represent variables caused by vehicle-bridge coupling. And \( \mathbf{G} \) represent vehicle gravity.

When the vehicle takes emergency braking when it encounters unexpected situations on the bridge deck, the position of wheel contact point will generate horizontal braking force \( T_i \), which is:

\[
\sum_{i=1}^{3} T_i = -(m_1 + m_2 + m_3) \mathbf{x}' = -Ma
\] (3)

\[
M_a = -Ma(h + z)
\] (4)

When the brake on the bridge deck is braked suddenly at a certain position at a uniform speed, the friction force on the bridge deck and the horizontal braking force at the contact point between the wheel and the body center will form a pair of pitching moments. As shown in formula (4), \( h + z \) is the height of the center of mass of the vehicle from the bridge deck in the braking process. The vehicle in the braking process will have a pair of pitching moments. Vehicles pitch, and then have a dynamic impact on the bridge structure [1]. When the horizontal braking force \( -Ma \) and the pitching moment \( M_a \) of the vehicle body are applied to the vehicle-bridge coupling vibration analysis model under uniform motion, the vehicle-bridge coupling vibration model under vehicle braking can be obtained.

### 3.2 Road roughness model

In engineering practice, road roughness can be considered as a Gauss stochastic process with zero mean of particle size, which is usually represented by power spectrum. Huang [7] and others suggested the following power spectral density functions in their literature:
In the formula \(K\), the roughness coefficient of pavement is \(m^3/\text{cycle}\), which is determined by the pavement condition. According to the test results of the bridge pavement smoothness, medium pavement grade is adopted, The value of \(K\) is \(80 \times 10^{-6} \ m^3/\text{cycle}\), \(\phi\) is the dispersed frequency (cycle/m), \(\phi_0\) is truncation frequency. Road roughness can be generated by Fourier transform as follows:

\[
r(x) = \sum_{k=1}^{n} 2S(\phi_k)\Delta\phi \cos(2\pi\phi_k + \theta_k)
\]

3.3 Verification of Vehicle-Coupling Dynamic Analysis Model

The above dynamic analysis model is validated by comparing the measured and theoretical displacement and stress response time-history under uniform speed and braking conditions. A Vehicle is selected to cross the bridge at an initial speed of 40 km/h under uniform speed conditions. For braking conditions, the initial speed is set to 40 km/h, and the front wheel is braked at the mid-span position. The braking deceleration is about \(-3.8 m/s^2\) by controlling the braking distance. The comparisons of the theoretical and measured values of the main arch ring under the two conditions are shown in figure 6 and 7. The theoretical and measured curves are basically in agreement, which verifies the correctness of the vehicle-bridge coupling dynamic analysis model under vehicle braking.

4. Dynamic Response Analysis of Arch Bridge under Vehicle Braking

When vehicles on the road suddenly change from uniform speed to emergency braking, the horizontal force of wheels on the bridge deck will suddenly increase, especially for special vehicles, which will produce huge horizontal force in the braking process. This huge horizontal load will cause certain damage or even damage to bridge components. Based on the revised model in Chapter 2, the influence of vehicle braking on key components of arch bridge is analyzed. A vehicle enter the bridge from the left end of the bridge, and the pavement smoothness adopts "medium pavement grade". The initial speed is \(v = 50 m/s\), and the braking deceleration of vehicle is \(a = -2m/s^2, -4m/s^2, -6m/s^2\), respectively. The vehicle brakes at the \(1L/8 \sim 7L/8\) positions of the front wheels to the bridge span respectively.

4.1 Dynamic response of main arch ring

As the main bearing component of the arch bridge, the displacement response and stress response of the main arch ring vehicle will increase due to the action of the braking process. In this paper, the influence of braking position and deceleration on the dynamic response of main arch ring is explained by dynamic impact factors. From the results of figure 8 and 9, it can be seen that the impact factors under braking condition is obviously larger than that of vehicle passing bridge at uniform speed, and the impact factors increases with the increase of the value of braking deceleration, which is consistent with the results in reference [1~2]. The maximum increments of deflection and strain impact factors are 22.3% and 24.2% respectively. And, the deflection impact factors and displacement impact factors are not exactly the same under the same working conditions, but the change trend is the same.
4.2 Dynamic response of upper arch column

The columns are an important force transfer component on the upper part of arch ring. It mainly transmits and bears vertical loads. However, under the vehicle braking, the horizontal braking force exerted by the vehicle on the bridge deck will be transferred to the column through the bearing. Under the action of the horizontal braking force, the bending moment and the shear force at the root of the column will suddenly increase. The extremum of bending moment and shear force at the root of each column are shown in table 3 when a vehicle runs at a uniform speed (columns number is shown in figure 1). It can be concluded that 7# column is the most disadvantageous. Therefore, this paper mainly analyses the dynamic response of the 7# column under various braking conditions. From figure 10 and figure 11, it can be seen that the extremum of bending moment and shear force of column increase obviously under braking condition, and increase with the increase of absolute deceleration. The maximum increase of bending moment and shear force is 52.3% and 40.7%

| Column number | 1#  | 2#  | 3#  | 4#  | 5#  | 6#  | 7#  |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| $M_{\text{max}}$ (kN·m) | 29.25 | 40.36 | 51.52 | 59.54 | 72.51 | 145.26 | 213.1 |
| $\tau_{\text{max}}$ (kN) | 5.9 | 9.8 | 15.6 | 23.4 | 34.7 | 45.8 | 69.3 |

5. Conclusion

1) The exact finite element model of the bridge is obtained by model updating, and the vehicle-bridge coupling analysis model under vehicle braking is established. Through dynamic analysis, the influence of brake position and deceleration on key stress components is discussed.

2) The dynamic response of main arch ring and column increases to a certain extent under vehicle braking, and the trend of increase is more obvious with the increase of deceleration.

3) The impact factors of the arch bridge under vehicle braking is relatively small, but it has a greater
impact on the bending moment and shear response at the root of the column.

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