Finite Element Analysis of Mechanical Characteristics of Arch Ribs under Vehicle Impact

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Abstract: In order to explore the impact of vehicle on mechanical property of arch ribs when it hits the arch foot of the arch bridge, with the 80m through truss CFST(Concrete Filled Steel Tubular) arch bridge as background, this paper uses madis/civil finite element analysis software to model by establishing two different working conditions of changing impact speed and impact angle, analyzing the changes of axial force, bending moment and vertical displacement of the left arch foot, 1/4 arch rib, 1/2 arch rib, 3/4 arch rib and right arch foot, and finally, the variation rules of mechanical characteristics of arch rib under different impact of vehicle speed and impact angle are obtained.

1. Introduction

With the rapid development of our country's economy, the traffic volume of highway is increasing sharply. Accidents of heavy-duty vehicles impacting bridge structures occur from time to time. For the bridge structure, the displacement and collapse of the main girder may be caused by vehicle impact on the upper structure, and the displacement and damage of the bridge pier may be caused by vehicle impact on the lower structure. Therefore, vehicle impact on bridge structure has become an increasingly important factor in the field of bridge construction.

The through truss CFST tied arch bridge is a typical self-erecting system bridge. It is widely used in engineering practice because of the advantages of the withstanding thrust of tie bar and the pier abutment not being subjected to horizontal thrust. The arch rib of an arch bridge is a key component affecting the mechanical characteristics of the arch bridge, and its stress condition determines the safety performance and normal use of the arch bridge. The mechanical properties of arch ribs are closely related to the bearing capacity of arch bridges.

Domestic scholars have done a lot of research on the mechanical characteristics of arch bridges and the calculation of vehicle impact force. Qin Shiqiang[1] and others used subspace iteration method to calculate the influence factors of dynamic characteristics of long-span basket-lift arch bridge, such as rise-span ratio, inclination angle, arch rib stiffness, etc. Sun Guangjun[2] and others studied the safety performance and internal force redistribution of tied arch bridges under three conditions: suspender damage, suspender failure and arch rib damage. Based on the principle of vehicle-bridge coupling vibration, Chen Hao[3] and others analyzed the vibration response of through truss concrete-filled steel tube tied arch bridge under different vehicle speed, different lanes, different dampers and different road conditions. Through ANSYS finite element modeling, Wang Peng[4] and others analyzed the influence of different vehicle mass, speed and impact angle on the local stress and overall displacement caused by the impact of pier with or without outer concrete protection. Based on the vehicle-bridge coupling system model, Zhang Nan[5] and others simulated the whole process of vehicle impact force acting on
pier and train passing bridge, and analyzed the dynamic response of vehicle-bridge system. Tianli[6] and others established the coupling model between vehicle and superstructure of box girder bridge by LS-DYNA software, and studied the damage of bridge and vehicle and the overall displacement of bridge.

However, there are few studies on the combination of automobile impact force and mechanical properties of arch bridges. In this paper, based on the background of the through truss concrete filled steel tube tied arch bridge with the main span of 80m, the following two working conditions are established by using the finite element software madis/civil. The position of the impact point of the automobile is 1.4m at the arch foot. In case 1, the impact angle is 0 degree, and the vehicle speed varies from 60 km/h, 80 km/h, 100 km/h and 120 km/h; in case 2, the vehicle speed is 120 km/h and the impact angle varies from 15, 30, 45 and 60 degrees; by comparing the changes of the left arch foot, 1/4 arch rib, 1/2 arch rib, 3/4 arch rib, the axle force, bending moment and vertical displacement of the right arch foot under different conditions, the final results are obtained. The influence of through concrete filled steel tube tied arch foot impacted by automobile on the mechanical properties of arch rib of arch bridge is studied.

2. Calculation of Equivalent Static Force of Vehicle Impact

Impact action refers to a dynamic load consisting of a single, arbitrary main impulse with a short duration. Therefore, the arch rib of an arch bridge can achieve the maximum response in a very short time after being impacted by a vehicle.

Based on the principle that the deformation effect of impact load and static load on pier model is equal, Wang Hui[7] and others established the calculation formulas of equivalent impact force of sinusoidal impact load waveform and triangular impact load waveform. Song Fudong[8] based on the change of impact velocity and ship load, simulated the process of ship collision with bridge in various situations by LS-DYNA finite element modeling software, and summarized the simplified calculation formula of impact force. Cui Kuipeng[9] and others used LS-DYNA collision analysis software to calculate and analyze the impact force of Ford trucks on piers at different speeds, and used global average method, local average method, equivalent displacement method and simplified impulse load method to calculate the equivalent static value of vehicle impact force. Because the process of vehicle impacting bridge structure is a transient process within 0.2s, the peak impact force will appear at some point in the process. Therefore, in dealing with the problem of vehicle impact on bridge structure, we can treat such a transient impact process force as a static load to simplify the dynamic problem to the static problem.

This paper[9] refers to the time history of Ford truck impacting the pier side impact force of an interchange bridge in Suzhou by using LS_DYNA and the finite element model of 8t Ford truck with different impact velocities of 60km/h, 80km/h, 100km/h and 120km/h. The impact force time history is shown in Fig. 1.

![Fig.1. Impact force curve of a vehicle at 60-120 km/h speed.](image)

The local average method[9] refers to the average value of the impact force of two peaks or valleys between time $t_1$ and $t_2$. $t_1$ and $t_2$ are usually the corresponding time of two peaks or valleys. The time history of the impact force is integrated in the time domain in the time period $t_1$ to $t_2$, and then the ratio of the impact time to the impact time is taken as the equivalent static $P_p$, that is, the equivalent static $P_p$. 


Relevant literature[10] shows that the impact force of a vehicle depends on the mass of the vehicle, the angle of impact and the speed of the vehicle. Therefore, an 8t Ford truck is built in this paper. The initial speed of the truck is 60km/h, 80km/h, 100km/h, 120km/h and Ford truck is 120km/h. The impact angle is from 0, 15, 30, 45 and 60 degrees to the arch foot of the arch bridge. The impact height is 1.4m above the ground (the height of the center of gravity of the vehicle). The equivalent static forces of four different speeds of Ford truck calculated by local average method are shown in Tables 1 and 2.

**TABLE 1. Equivalent static force of impact force at different speeds.**

| Speed per hour (km/h) | 60 | 80 | 100 | 120 |
|-----------------------|----|----|-----|-----|
| Angle(°)              | 0  | 0  | 0   | 0   |
| Equivalent static force (KN) | 130 | 150 | 310 | 420 |

**TABLE 2. Equivalent static force of impact force at different angles.**

| Speed per hour (km/h) | 120 | 120 | 120 | 120 |
|-----------------------|-----|-----|-----|-----|
| Angle(°)              | 15  | 30  | 45  | 60  |
| X Equivalent static force (KN) | 108.7 | 210 | 297 | 363.7 |
| Y Equivalent static force (KN) | 405.7 | 363.7 | 297 | 210 |

3. **Engineering examples**

The calculated span of the main girder of a simply supported through concrete filled steel tube tied arch bridge is 80m. The bridge deck width is 15.5 m and the width near the arch angle is 16.9 M. There are two concrete filled steel tube arch ribs in the whole bridge. The inner elevation of the arch ribs is 16m in plane, and the rise-span ratio is 1/5. There are three one-word wind braces between the two arch ribs. The arch axis is quadratic parabola, and seven suspenders are arranged on one side of the arch rib. The elevation of the bridge is shown in Fig. 2.

4. **Finite Element Modeling**

In this paper, the finite element model is established by using the finite element software madis/Civil. The main girder and arch rib are simulated by beam element, and the suspender is simulated by truss element. The bridge has 259 nodes and 331 elements. The finite element model of the whole arch bridge is shown in Fig. 3.

5. **Analysis of mechanical properties**

The impact of automobile on arch foot at different speed has a dynamic effect on the internal force and deformation of arch bridge, and the axial force, bending moment and vertical displacement of arch bridge under different arch rib arrangement under impact load are also different. Relevant literature shows that the maximum internal force of arch rib appears at arch foot and the maximum vertical displacement occurs at 1/4 of arch rib. Therefore, the left arch foot, 1/4 arch rib, 1/2 arch rib, 3/4 arch rib and right arch foot are selected as the control sections of internal force and displacement, and their
mechanical characteristics under the impact of 8t Ford truck are analyzed. The results of FEM calculation are shown in Fig. 4 and Fig. 5, and the part of FEM calculation cloud of working condition 1 is shown in Fig. 6.

5.1. Finite element analysis and analysis
From figs. 4 and 5, it can be seen that the internal force and displacement of the arch rib increase with the increase of vehicle speed and impact angle. From figs. A and e, we can conclude that under the impact of vehicle, the axial force of the arch rib arch foot is the largest, and the change trend of the axial force curve tends to be gentle as the distance from the impact point decreases gradually, and the values of the axial force are greater than 0, indicating that under the impact load, the arch rib arch foot has the largest axial force. The arch axis is compressed; from figure B and f, we can conclude that under the impact of vehicles, the negative bending moment of the arch rib foot is the largest, and the positive bending moment of the arch rib is the largest in one fourth. In the process of impact, the bending moment value increases first and then decreases, which indicates that the arch rib is under positive torsion at 1/4 arch rib foot and negative torsion at 1/4 arch rib to right arch foot under impact load. From Figs C and g, we can conclude that the vertical displacement of the arch rib is first decreased, then increased and then decreased under vehicle impact. The arch rib deflects downward near the impact point and warps upward away from the impact point.

5.2. 1 part finite element calculation cloud chart
6. conclusions

In this paper, the model of 80m through concrete-filled steel tube arch bridge is established by madis/civil finite element analysis software. By changing the speed impact and the impact angle impact, the following conclusions are obtained:

1) With the increase of vehicle speed, the internal force and displacement of arch rib also increase.
2) The internal force and displacement of the arch rib increase with the increase of the impact angle.

Finally, it should be pointed out that the calculation of vehicle impact is affected by many complex factors. This paper preliminarily discusses how to simulate vehicle impact arch rib by equivalent static force of vehicle impact force. If conditions permit, model or full-scale experiments should be carried out to further verify its accuracy.

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