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# Design and research of bridge anti-vehicle collision device based on stiffness matching

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**Abstract**. In order to reduce the damage caused by vehicle-bridge collisions and improve the safety of road vehicles, a design method based on stiffness matching was proposed. The vehicle-device-bridge dynamic model was established. The optimal design of the vehicle-collision prevention device for bridges was carried out based on stiffness matching. The collision models were established by using Ls-dyna finite element analysis software, and the protective performance of the collision prevention device for car and truck under typical working conditions were studied. The results show that the stiffness of the anti-collision facility is inversely proportional to the deformation and directly proportional to the impact force. Compared with the impact of bare piers, the peak value of the impact force is obviously reduced after the anti-collision device is added. due to the different rigidity of the vehicle, the maximum peak value of the car is reduced by 40% and the maximum peak value of the truck is reduced by 33.6%. The curve is smooth and the peak arrival time is prolonged, thus achieving a better energy consumption buffering effect. The anti-collision device designed by stiffness matching has strong applicability and can exert better anti-collision and energy consumption effects under different collision conditions.

## 1. Introduction

With the development of traffic construction and the rapid development of economy, the traffic and transportation network is increasingly developed, and the number of automobiles is also greatly increased. Frequent accidents of vehicles hitting the bridge piers of the mid-span bridge on the roadside or in the central separation zone seriously threaten the traffic safety of roads, causing the collapse of bridges and the destruction of vehicles when they are serious. Therefore, it is of great practical significance to study the car-bridge collision problem.

At present, the highway traffic safety facilities have carried out relevant regulations for roadside and central separation barriers[1]. The anti-collision design of bridges is mainly about anti-ship collision facilities, and has formed a relatively complete result system. There are also many anti-collision facilities, such as steel sleeve boxes[2,3], composite anti-collision facilities[4], and the design method has achieved a series of results[5]. In terms of impact force standards. Compared with the anti-collision technology of bridges, the research on the anti-collision technology of piers is still in its infancy. Due to the limited space and large impact speed, many key technical problems need to be solved, such as the guiding code for the design of anti-collision devices, the standard of impact force and the calculation method.

This paper puts forward a design method based on stiffness matching, establishes a vehicle-device-bridge dynamic model, optimizes the design of a bridge anti-collision device based on stiffness matching, establishes a collision model by using Ls-dyna finite element analysis software, and studies the protective performance of anti-collision devices of small buses and large trucks under typical working conditions.

## 2. Stiffness Matching Design Method

### *2.1. Dynamic Model*

Considering fortification, the rigidity of vehicles, piers and anti-collision devices is an important factor affecting the impact force during the collision of axles. The pier is relatively rigid and the deformation during impact is small. It can be assumed that the pier is rigid. At the same time, relevant literature shows that the collision process happens in a flash, and the damping has little influence on it, which can be neglected [6]. The collision process can be simplified to a one-dimensional two-degree-of-freedom spring-mass model, as shown in figure 1.

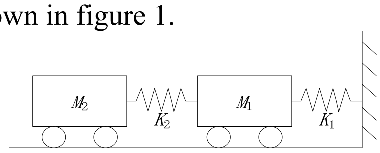


Figure 1. Simplified mechanical model of collision process

In the figure, the mass of the anti-collision device is $M_1$ and the deformation rigidity is $K_1$. The mass of the vehicle is $M_2$, and the local deformation stiffness of the front is $K_2$. According to the D'Alembert principle, the dynamic equation of the vehicle-anti-collision device system is established as follows:

$$\begin{cases} M_1 \ddot{x}_1 + K_1 x_1 - K_2 (x_2 - x_1) = 0 \\ M_2 \ddot{x}_2 + K_2 (x_2 - x_1) = 0 \\ t = 0, x1 = x2 = 0, \dot{x}_1 = 0, \dot{x}_2 = v_0 \end{cases} \tag{1}$$

The deformation and displacement of the anti-collision device and the vehicle in the collision process are set to be $x_1$、$x_2$, Then there are:

$$\begin{cases} x_1 = A_1 \sin(\omega_1 t + \varphi_1) \\ x_2 = A_2 \sin(\omega_2 t + \varphi_2) \end{cases} \tag{2}$$

The formula (2) is brought into the formula (1), and after simplification and deformation, the impact force can finally be solved as follows:

$$F(t) = \frac{K_2 v_0}{B_2 - B_1} \left[ \frac{B_1 - 1}{\omega_1} \sin \omega_1 t - \frac{B_2 - 1}{\omega_2} \sin \omega_2 t \right] \tag{3}$$

Where $B_1$ and $B_2$ are amplitude ratios:

$$\begin{cases} B_1 = \dfrac{K_2 + K_1 - M_1 \omega_1^2}{K_2} \\ B_2 = \dfrac{K_2 + K_1 - M_1 \omega_2^2}{K_2} \end{cases} \tag{4}$$

Where the natural frequency of the system $\omega_1$, $\omega_2$ is:

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$$\omega^2_{1,2} = \frac{1}{2}\left[ (\frac{K_1+K_2}{M_1} + \frac{K_2}{M_2}) \pm \sqrt{(\frac{K_1+K_2}{M_1} + \frac{K_2}{M_2})^2 - 4\frac{K_1K_2}{M_1M_2}} \right] \tag{5}$$

The dynamic analysis method can accurately calculate the impact force, and provide a theoretical basis for the reasonable selection of the stiffness of the anti-collision device.

### *2.2. Stiffness Matching Method*

In the simplified model of the collision system mentioned above, if the equivalent stiffness is $K$, $K$ has the following relationship with $K_1$ and $K_2$:

$$K = \frac{K_1K_2}{K_1+K_2} = \frac{K_2}{1+\frac{K_2}{K_1}} \tag{6}$$

If the stiffness ratio between the deformation stiffness $K_1$ of the anti-collision device and the local deformation stiffness $K_2$ of the vehicle head is made $\frac{K_1}{K_2} = \alpha$, the formula (6) can be simplified as follows:

$$K = \frac{\alpha}{\alpha+1} K_2 \tag{7}$$

It can be seen that when $K_2$ is constant, the stiffness of the system will be transformed into a value problem $\alpha$. The stiffness of the system is an important factor that determines the impact force. In order to reduce the impact force of the vehicle and enhance the passive safety of the vehicle, the deformation stiffness $K_1$ of the anti-collision device should not be greater than the local stiffness $K_2$ of the vehicle head, that is $\alpha \in (0,1]$.

The smaller the $K_1$, the greater the vehicle impact force attenuation. The more energy consumption the anti-collision device will consume, and the better the anti-collision effect will be. At the same time, the greater the deformation of the overall structure of the anti-collision device, the more space the anti-collision device inevitably takes up. Therefore, it needs to be designed according to the actual project.

## 3. Structural Design of Anti-collision Device

According to the concept of stiffness matching, the anti-collision device adopts layered stiffness design. As shown in figure 2, the outer layer of the device uses flexible material as the buffer layer (deformation rigidity $K_1$), the inner side of the device is provided with a steel plate shell and reinforcing ribs (deformation rigidity $K_2$), and is filled with energy-consuming closed-cell core material (deformation rigidity $K_3$) as the main energy-consuming layer. Through adjusting the structural form, size and material parameters, the rigidity of two aspects can be matched:

(1) The overall rigidity of the anti-collision device is matched with the local rigidity of the vehicle head, and reasonable values are taken within the scope $\alpha \in (0,1]$, to ensure that deformation and energy consumption of the anti-collision device are the main factors in the impact process.

(2) The stiffness of each structural layer of the anti-collision device is matched with each other, and the stiffness of each layer shall conform to the following relation $K_3<K_1<K_2$, so as to realize the step-by-step energy consumption mode of buffering first and consuming energy later in the collision process.

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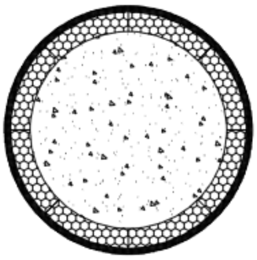


Figure 2. Structural diagram of anti-collision device

## 4. Research on Protective Performance

### *4.1. Establishment of Finite Element Model*

According to the structural design drawings of the anti-collision device, the geometric model is established and finite element mesh is divided. The structural layers of the anti-collision device are simulated by corresponding elastic-plastic materials, and the piers are built by rigid material modelsm, the plastic deformation of the piers is not considered. The purpose is to focus on the characteristics of vehicle impact force and deformation and energy consumption of the anti-collision device, and respectively establish the piers and anti-vehicle impact models, the 1.5t car and the 10t truck models as shown in figure 3 and figure 4.

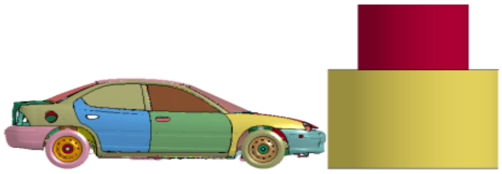


Figure 3. Model of 1.5t car collision with device

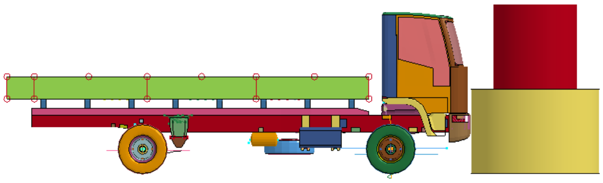


Figure 4. Model of 10t truck collision with device

### *4.2. Calculation Conditions*

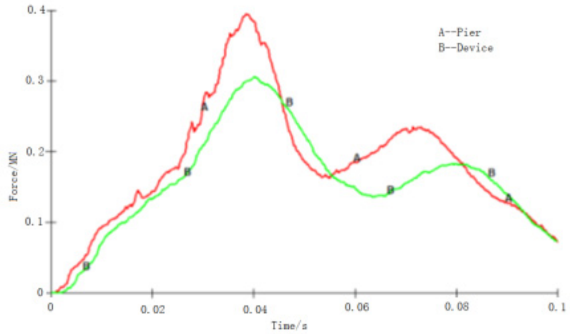
In order to verify the deformation and energy consumption characteristics of the anti-collision device, the applicability under different collision conditions is studied. The various typical working conditions such as different vehicle models and different vehicle speeds are selected to carry out collision simulation on bare piers and additional anti-collision devices respectively. Typical working conditions are listed in table 1.

Table 1. Typical working condition

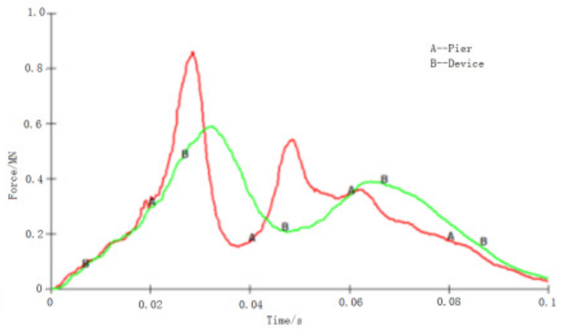
| Condition | Vehicle | Speed v (km/h) | Weight M (t) | Collision angle (°) |
|---|---|---|---|---|
| 1 | | 40 | | |
| 2 | car | 60 | 1.5 | 0 |
| 3 | | 80 | | |
| 4 | | 40 | | |
| 5 | truck | 60 | 10 | 0 |
| 6 | | 80 | | |

### *4.3. Analysis of Calculation Results*

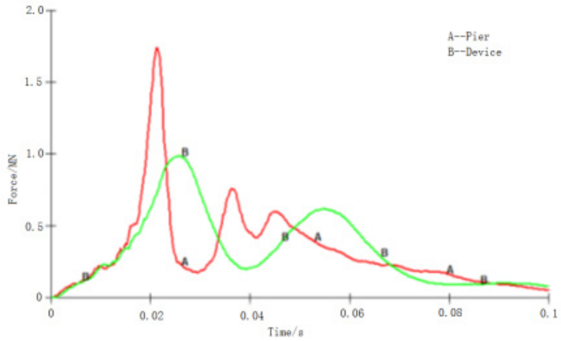
Figure 5 shows the impact force time history curves of the car impacting the bare pier and the anti-collision device under different working conditions. In order to anti-collision device analysis, the calculation results are counted as shown in table 2.



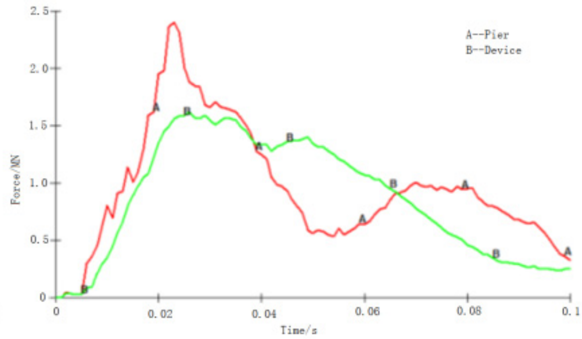

(a) $M$=1.5 t, $v$=40 km/h



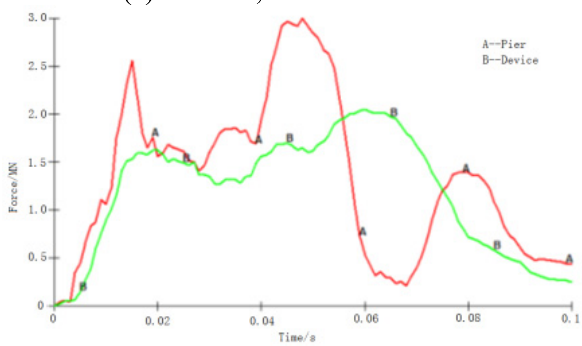

(b) $M$=1.5 t, $v$=60 km/h



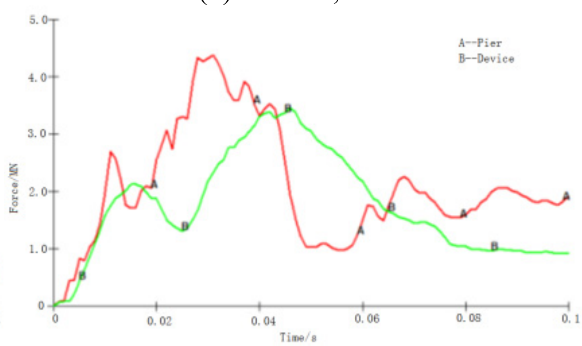

(c) $M$=1.5 t, $v$= 80km/h




(d) $M$ =10 t, $v$=40 km/h




(e) $M$=10 t, $v$=60 km/h




(f) $M$=10 t, $v$=80 km/h

Figure 5. Comparison of impact force time history curves under different working conditions

Table 2. Calculation result statistics

| Condition | Impact force on pier (MN) | Impact force after adding anti-collision device (MN) | Reduction factor of impact force (%) |
|---|---|---|---|
| 1 | 0.4 | 0.29 | 27.5 |
| 2 | 0.9 | 0.6 | 33.3 |
| 3 | 1.75 | 1.05 | 40.0 |
| 4 | 2.41 | 1.6 | 33.6 |
| 5 | 3.0 | 2.1 | 30.0 |
| 6 | 4.5 | 3.5 | 22.2 |

From the simulation results, it can be seen that the impact force varies greatly under different working conditions. Compared with the impact of bare piers, the peak value of the impact force is obviously reduced after the anti-collision device is added. Due to the different rigidity of the vehicle, the maximum peak value of the bus is reduced by 40%, the maximum peak value of the truck can be

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reduced by 33.6%. The curve is smooth, and the peak arrival time is prolonged. This shows that the anti-collision device has good energy consumption buffering effect under different vehicle models and different vehicle speeds, and has good rigidity matching, reasonable deformation mode and strong applicability under different collision conditions.

## 5. Conclusions

Through the study of this article, the following conclusions can be drawn:

(1) The dynamic model of the vehicle-device-pier is established, and the stiffness matching design method is proposed. The stiffness of the anti-vehicle collision facility is inversely proportional to the deformation and is directly proportional to the impact force.

(2) Compared with the impact of bare piers, the peak value of the impact force is obviously reduced after the anti-collision device is added. Due to the different rigidity of the vehicle, the maximum peak value of the bus is reduced by 40% and the maximum peak value of the truck is reduced by 33.6%. the curve is smooth and the peak arrival time is prolonged, which achieves a better energy consumption buffering effect.

(3) The anti-collision device designed according to the stiffness matching concept has strong applicability in different collision conditions.

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