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Analysis on the Damage Assessment Method of Reinforced Concrete Girder Bridge under Collision Based on Trace Theory

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Abstract

Whether the main girder of a bridge hit by a super high vehicle can continue to be used is related to traffic safety. To reveal the damage of the bridge caused by the impact, the damage assessment method of the main girder of the affected bridge based on trace theory and nonlinear calculation theory was studied. First, the collision accident between a super high truck and a reinforced concrete girder bridge was taken as the research object, and a nonlinear finite element model of the vehicle–bridge collision was established by using ANSYS/LS-DYNA software. The posture of the vehicle body and the bridge, and the deformation of the vehicle body after collision were obtained by calculation and analysis of multiple working conditions with super high vehicle weight and impact speed as the variables. The collision speed of the vehicle and the impact force were established by using the method of multiparameter curve fitting. Finally, the damage of the crashed bridge was assessed by inputting the vehicle speed or impact force parameters in the vehicle–bridge collision model, which considers the material constitutive relation. Results demonstrate that, the deformation of the van body is linearly positively correlated with the speed and weight of the impacted vehicle. The average value and the peak value of the horizontal impact force with vehicle weight and vehicle speed are positively correlated, but the correlation ratio is 0. The average value and the peak value of the vertical impact force have a quadratic relationship with the vehicle velocity and the vehicle mass. When the vehicle weight reaches 25 t or the vehicle speed reaches 65 kph, the average value and the peak value of the vertical impact force reach the maximum values. The duration of the impact has a quadratic relationship with the vehicle speed and a nonlinear increasing relationship with the vehicle weight. This study provides a theoretical basis for the damage assessment of impacted bridges.

Keywords: Bridge engineering, Vehicle–bridge collision, Damage assessment, Nonlinear, the deformation of the vehicle body

1. Introduction

Many overpasses were built to solve the traffic jam in recent years. Collision accidents [1-3] frequently happen between super high vehicles and the main girder of flyover bridges due to the negligence of the driver. The large vehicle body undergoes unrecoverable deformation, and the main girder of the impacted bridge is seriously damaged after the main girder of the bridge is hit by a super high vehicle. Ensuring driving safety is important, and the damage degree of the main girder of the hit bridge must be evaluated to determine whether the hit bridge can be used in the future. At present, two main methods are used for the damage assessment of impacted bridge: One is to check the appearance in depth by means of visual inspection, measurement, and ultrasonic, and then assess the state of the impacted bridge according to the bridge technical state assessment specification [4] to determine whether the bridge can remain in service. Because the concrete at the lo
wer edge of the main girder is seriously damaged, it is often misjudged as a dangerous bridge, and the damaged bridge needs to be demolished and rebuilt by this method, which will cause large economic losses and adverse social repercussions. The second is that some evaluators use static and dynamic tests of bridges based on technical state assessment to evaluate the bearing capacity of the impacted bridge. However, this method has a large workload, high cost, and high risk. The current method of computer simulation calculation is widely popular, which is fast, efficient, and low cost, and has high reliability of calculation results. Using the simulation calculation method to evaluate the damage degree of the impacted bridge is a better choice, but the key to this method is to obtain the accurate vehicle speed or impact force model before the collision. The speed of the vehicle at the time of the collision is mostly provided by the driver who caused the accident, but the speed provided by the driver before the collision is much lower than the actual speed of the vehicle to reduce his own responsibility. After the ultrahigh vehicle body collides with the bridge, the vehicle body retains "traces" of serious deformation. Therefore, the method of "trace theory" can be used for reference, and the whole process of the vehicle–bridge collision can be reversed by using the finite element simulation method according to the deformation data of the vehicle body and the shape after the collision.

In this study, based on trace theory and the finite element method, the damage of the main girder of the bridge hit by the super high vehicle was assessed. Starting from nonlinear elastic–plastic mechanics and contact mechanics, a refined finite element model of super high moving objects and overpass bridges was established, the relationship between the deformation of the collision vehicle body and the

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instantaneous vehicle speed before the collision was analyzed, and the calculation model of the impact force was studied.

2. State of the art

At present, there are many studies on vehicle–bridge collision. For example, Liu et al. [2] studied the method of fine modeling of vehicle collision with bridge pier based on the method of finite element simulation. Fan, Abdelkarim and Cao et al. [5-16] adopted the test method, theoretical method, and finite element method to solve the vehicle–bridge collision problem. BUTH et al. [16] carried out two real vehicle collision tests between large trucks and bridge piers, analyzed the test results, and provided suggestions for the anticollision design of bridge piers, which were later adopted by the American Bridge Design Code. Shuitao He, Xinzheng Lu et al. [17] carried out a series of model tests of vehicles impacting the main girder combined with numerical simulation calculations, mainly studied the failure modes and damage mechanisms of different types of impacted girders, and examined the impulse of collision and local impact force. A simplified calculation model and impact force formulas were proposed. Tian Li et al. [18] established a refined prestressed box girder model to calculate the effects of vehicle weight, vehicle speed, and vehicle's action position on the collision result. The above studies mainly studied the impact process and the calculation method of the impact force but did investigate not the damage of the impacted bridge in depth.

After the main girder of the flyover bridge is hit by a super high vehicle, does the main girder have any microscopic damage except for the damage at the impact part? To what extent is the damage? These issues are addressed in the condition assessment of the impacted bridge. When damage occurs in a structure, then the force characteristics of the structure change [19]. Therefore, the information of structural static and dynamic characteristics changes can be obtained through structural appearance inspection, static load test, modal test, and other related tests, and the damage of the structure can be identified based on this information. The bridge evaluation method based on appearance survey is carried out according to the "Technical Condition Evaluation Standard for Highway Bridges" (JTGTH21-2011) [4]. This assessment method is clear and uncomplicated to operate, and is widely used by bridge management, but the judging of this method is more subjective, and the assessment results are closely related to the engineering experience of the assessor. The bridge assessment method based on analytical calculations is based on the "Highway Bridge Regulations" [20] and the "Regulations for the Testing and Assessment of the Bearing Capacity of Highway Bridges [21]. The actual bearing capacity of the bridge is calculated by introducing correction factor to the bearing capacity of nondestructive beams through conventional tests, such as concrete strength, concrete carbonation, and reinforcement corrosion, to assess the condition of the bridge. The value of the correction factor in this method is critical, and the experience of the appraiser is extremely important, if the appraiser's experience is not sufficient to obtain a large deviation assessment conclusion [22]. Although the method of static load test [23] on the impacted bridge can intuitively evaluate the remaining bearing capacity of the bridge, it has high cost, few test sections, and high-risk factor. Wang et al. [24] removed components from the crashed bridge and transported them back to the laboratory for static load tests to study the damage assessment method of the crashed bridge, which also had the problems of small number of samples, high cost, and low efficiency. Liu et al. [25] carried out parametric analysis on the vehicle–bridge collision through LS-DYNA, based on the theoretical background of traces, established the functional relationship curve between the deformation of the carriage, vehicle factors (vehicle speed, vehicle weight), and the impact force, and determined the impact. In addition to the deformation of the vehicle body, referring to the shape of the vehicle body after collision is necessary.

The remainder of this study is organized as follows. Section III constructs a refined finite model of the main girder of the bridge colliding with the ultrahigh vehicle body and describes the method of multiparameter curve fitting. Section IV obtains the collision calculation of multiple conditions for different vehicle speeds and different vehicle weights, and the postures of the vehicle and the bridge under each condition, and establishes the models of the vehicle deformation with vehicle speed and vehicle weight and the models of the impact force with vehicle speed and vehicle weight. The last section concludes the study and presents relevant conclusions.

3. Methodology

To study the influencing factors of the impact force in the vehicle–bridge collision, a refined analysis model of the vehicle–bridge collision is established by taking the impact of a super high van vehicle on a simply supported beam bridge across the line as the research object.

3.1 Finite element modeling

3.1.1 Basic parameters

Taking a two-span simply supported flyover bridge as the research object, the bridge superstructure is a 30 m standard span prestressed concrete simply supported T-girder with a width of 12 m. The superstructure consists of five T-girder girders, the width of the side girders and center girders are 2.0 m, and six cross-girders are set on the main girders. Considering the most unfavorable collision situation, the bridge collision is in the middle of the span between the two cross-girders.

The material parameters of the impacted bridge are shown in Table 1.

The van-type vehicle consists of six parts, namely, front end, chassis, wheels, engine, carriage, and counterweight block. The cargo inside the vehicle is realized by adjusting the weight of the counterweight block inside the carriage. Owing to the complex structure of the vehicle, to better realize the vehicle–bridge collision simulation, the vehicle model in this study adopts the standard two-axle van truck F800 finite element model [26] introduced by the National Crash Analysis Center of the United States. The calculated parameters of the vehicle are shown in Tables 2 and 3.

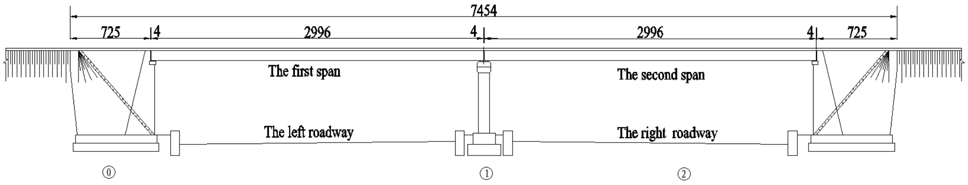


Fig. 1. Bridge facade layout (unit: cm)

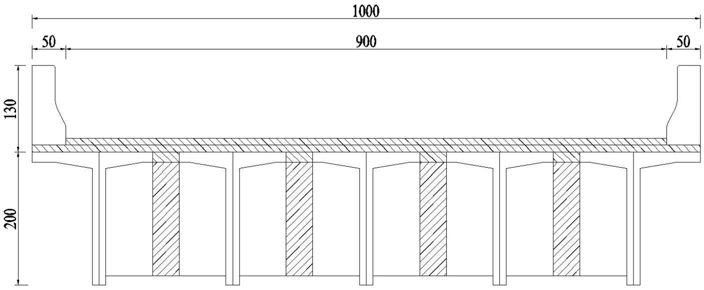


Fig. 2. Bridge cross-section layout (unit: cm)

Table 1. Parameters of bridge superstructure materials

Material	Grade	Elastic Modulus ($\times 10^4$ MPa)	Poisson's ratio	f_{ck}	f_{tk}	f_{sk}	Density (kg/m^3)
concrete	C50	3.45	0.2	32.4	2.65		2600
rebar	HPB335	20	0.3			335	7850
	HPB235	21	0.3			235	7850

Table 2. Geometric parameters of van-type vehicle

Weight	Wheelbase	Length	Width
7.17 t	5.29 m	8.54 m	2.44 m

Table 3. Material parameters of van-type vehicle

Component name	Material	Modulus of elasticity (10^{11} Pa)	Poisson's ratio	Density ($10^3 kg/m^3$)	Constitutive relation
Front end	Steel	2.05	0.3	7.85	Piecewise linear plastic model
Chassis	Steel	2.05	0.3	7.85	Piecewise linear plastic model
Wheel	Rubber	0.02	0.32	2.59	Isotropic linear elastic model
Engine	Custom	1.1	0.3	4.12	Isotropic linear elastic model
Carriage	Steel	2.05	0.3	7.85	Isotropic follow-up reinforcement material model
Counterweight block	Custom	0.02	0.3	0.533	Isotropic linear elastic model

3.1.2 Finite element model

The van engine and the counterweight block are simulated by SOLID164 solid unit, and the front end, chassis, carriage, and wheels are simulated by SHELL163 shell unit. The van is built using the Cowper–Symonds architecture. The entire vehicle model has 38949 nodes and 35400 units. The vehicle model is shown in Fig. 3.

The main girder in the bridge superstructure adopts C50 concrete, the calculation model adopts Solid164 element simulation, and the concrete adopts HJC constitutive suitable for blast impact. The reinforcement in the beam is simulated using LINK160 rod unit, and the Cowper–Symonds principal structure is used for the reinforcement. The superstructure model is shown in Fig. 3 and Fig. 4.

The super high vehicle impacting the bridge is 0.25 m from the lower edge of the main beam [27], the carriage and the main beam of the bridge structure have a face-to-face automatic contact, the friction coefficient of the carriage–concrete beam is 0.2 [28], and the wheel–road friction coefficient is 0.7 [29]. The vehicle impact bridge superstructure model is shown in Fig. 5.

3.2 Vehicle body deformation measurement

The deformation of the vehicle is the change of the coordinates of each point of the car in the space before and after the collision, taking the location of an undeformed position on the car as the coordinate origin. The collision between the van and the main beam of the span bridge is a collision between the upper part of the carriage and the main beam. Usually, the carriage is composed of a thin steel plate and steel skeleton, and the rigidity of the compartment is low and uneven. The carriage deforms along the forward direction of the car and along the height direction, as shown in Fig. 6.

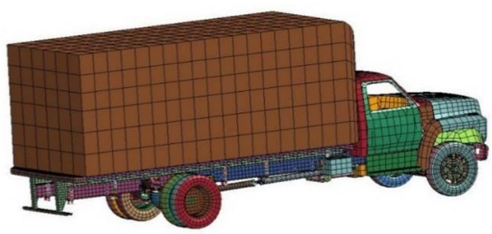


Fig. 3. Van-type car model

Fig. 4. Refined model of the upper structure of the flyover bridge

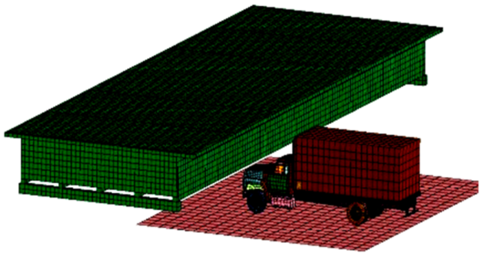


Fig. 5. Van vehicle–collision calculation model of a simply supported girder bridge

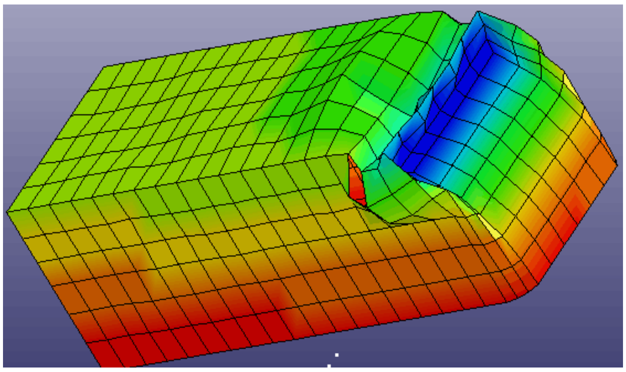


Fig. 6. Carriage deformation

This study draws reference from the literature [25] to measure the deformation of the car body by using the sampling multipoint mean method and the volumetric method.

3.3 Multiparameter curve fitting

Liu et al. [25] stated that because the impact between the super elevation vehicle and the main girder of the bridge occurs in an instant, the structural form of the main girder, the cross-section form, the size of the calculated span, and the constraint conditions have very minimal influence on the impact force. The magnitude of the impact force is related to the momentum, that is, the weight of the vehicle and the instantaneous speed of the vehicle before the collision. Therefore, this study focuses on the relationship of impact force with vehicle speed and vehicle weight.

When establishing the relationship of vehicle body deformation and impact force with vehicle weight and vehicle speed after a super high vehicle collision, the deformation (or impact force) is regarded as a function of vehicle weight and vehicle speed to solve the problem. For the formula containing two variables, the multiparameter curve fitting method of impact force in reference [30] is used to separate the variables, and vehicle speed and vehicle weight are regarded as two independent variables. Therefore, the formula can be set as follows:

$$y = f(m, v) = f(m) \cdot g(v) \tag{1}$$

In the formula, m is the mass of the colliding vehicle, v is the speed of the vehicle before the collision, and y is the deformation of the vehicle body before and after the collision of the ultrahigh vehicle.

Four points on the curve, namely, (m_1, v_1, y_1), (m_2, v_1, y_2), (m_1, v_2, y_3), and (m_2, v_2, y_4), are substituted into equation (2) to derive the following:

$$\begin{cases} y_1 = f(m_1) \cdot g(v_1) \\ y_2 = f(m_2) \cdot g(v_1) \\ y_3 = f(m_1) \cdot g(v_2) \\ y_4 = f(m_2) \cdot g(v_2) \end{cases} \tag{2}$$

The following can be obtained by transformation:

$$V = f(m, v) = R_1 F_1(m) G_1(v) \tag{3}$$

Similarly, for the impact force,

$$P = f(m, v) = R_2 F_2(m) G_2(v) \tag{4}$$

In the analysis of actual collision accidents, the deformation of the car body can be measured, and the weight of the car can be determined, so the speed of the vehicle before the collision can be obtained by using equation (3). Through many finite element numerical calculations, the direct relationship of deformation with vehicle speed and vehicle weight and the relationship of impact duration and impact force with vehicle speed and vehicle weight can be established in equation (4).

4. Result Analysis and Discussion

4.1 Calculated working conditions

To obtain the relationship of vehicle weight and vehicle speed with vehicle body deformation and impact force on the main girder of the bridge, the collision calculation and analysis of thirty cases are carried out.

Table 4. Vehicle–bridge collision calculation working conditions

Case	Vehicle Weight (t)	Vehicle Speed (km/h)	Case	Vehicle weight (t)	Vehicle Speed (km/h)
1		30	6		30
2		40	7		40
3	8	50	8	10	50
4		60	9		60
5		70	10		70
11		30	16		30
12		40	17		40
13	15	50	18	20	50
14		60	19		60
15		70	20		70
21		30	26		30
22		40	27		40
23	25	50	28	30	50
24		60	29		60
25		70	30		70

4.2 Relationship of deformation with vehicle weight and vehicle speed

The various working conditions in Table 4 are calculated, and the deformation of the vehicle body under different vehicle weights and different vehicle speeds is obtained.

4.2.1 Relationship between deformation and vehicle weight

The data in Table 5 are arranged, and the deformation values of the car body are extracted under various speed collisions under the condition of a certain speed. On this basis, the deformation values of various vehicle weights are normalized, that is, each deformation value is divided by the maximum deformation value at the same vehicle speed, and the ratio of the multipoint mean method and the volumetric method is obtained.

Table 5. Deformation of vehicle body after collision with different vehicle weights

Vehicle weight(t)	Vehicle speed(km/h)	Multipoint mean method	Multipoint mean method ratio	Volumetric method (m^3)	Volumetric method ratio
30	30	0.530	1.000	2.197	1.000
25		0.453	0.855	1.474	0.671
20		0.387	0.730	1.194	0.543
15		0.365	0.689	0.790	0.359
10		0.283	0.534	0.664	0.302
8		0.218	0.411	0.040	0.018
30	40	0.676	1.000	3.291	1.000
25		0.642	0.950	2.484	0.755
20		0.522	0.772	2.143	0.651
15		0.417	0.617	1.161	0.353
10		0.370	0.547	1.056	0.321
8		0.360	0.533	0.465	0.141
30	50	0.831	1.000	3.746	1.000
25		0.713	0.858	2.588	0.691
20		0.635	0.764	2.043	0.546
15		0.501	0.603	1.260	0.336
10		0.387	0.466	1.491	0.398
8		0.384	0.462	0.901	0.241
30	60	1.284	1.000	3.923	1.000
25		1.034	0.805	3.025	0.771
20		0.796	0.620	2.475	0.631
15		0.648	0.505	2.245	0.572
10		0.431	0.336	1.260	0.321
8		0.394	0.307	1.027	0.262
30	70	1.438	1.000	5.143	1.000
25		1.090	0.758	4.538	0.882
20		0.938	0.652	2.858	0.556
15		0.758	0.527	2.339	0.455
10		0.549	0.382	1.662	0.323
8		0.461	0.321	1.468	0.285

Fig. 7 and 8 show the following: (1) The relationship between the deformation ratio and the vehicle weight obtained by the multipoint mean method and the volumetric method is linear. (2) The linear expression between deformation ratio and vehicle weight can be obtained by fitting the scatter points. (3) The slope of the line obtained by the volumetric method is larger than that by the multipoint mean method because the deformation of the roof is considered in the volumetric method.

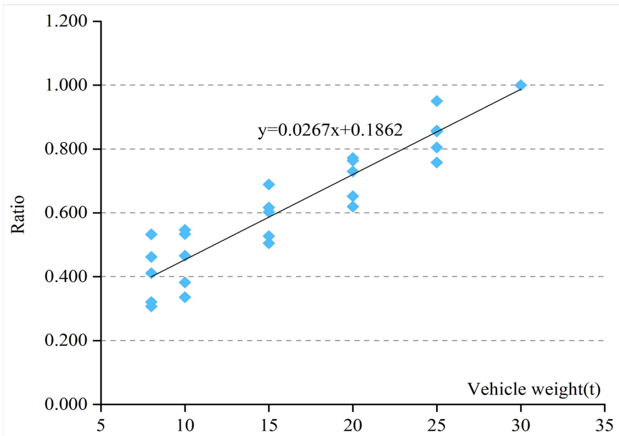


Fig. 7. Relationship between body deformation ratio and vehicle weight (multipoint mean method)

$$G_{DD}(M) = 0.0277M + 0.1862 \tag{5}$$

$$G_{DT}(M) = 0.0342M - 0.0689 \tag{6}$$

In the formula, G_{DD}, G_{DT} are the deformation ratios calculated by the multipoint mean method and the volumetric method, respectively, and M is the mass of the collision car.

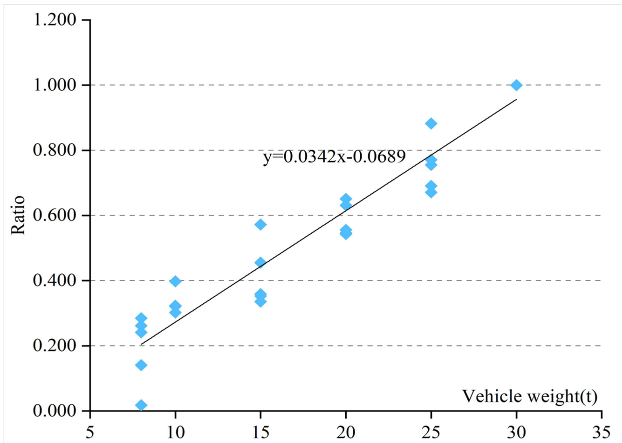


Fig. 8. Relationship between body deformation ratio and vehicle weight (volumetric method)

4.2.2 Relationship between deformation and vehicle speed

Similarly, using the data in Table 5, the deformation values of various vehicle speeds are normalized, that is, each deformation value is divided by the maximum deformation value of the same vehicle weight, and the ratio of the multipoint mean method and the volumetric method is obtained.

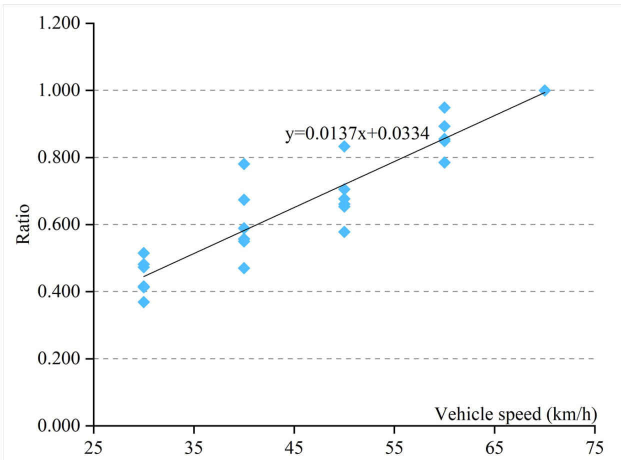


Fig. 9. Relationship between vehicle body deformation ratio and vehicle speed (multipoint mean method)

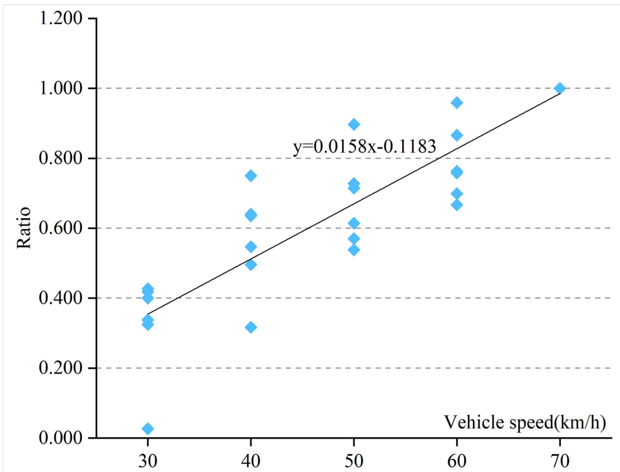


Fig. 10. Relationship between vehicle body deformation ratio and vehicle speed (volumetric method)

Fig. 9 and 10 show the following: (1) The relationship between the deformation ratio and the vehicle speed obtained by the multipoint mean method and the volume method is linear. (2) The linear expression between deformation ratio and vehicle weight can be obtained by fitting the scatter points. (3) The slope of the straight line obtained by the volumetric method is slightly larger than that by the multipoint mean method.

$$G_{VD}(v) = 0.0137v + 0.0334 \tag{7}$$

$$G_{VT}(v) = 0.0158v - 0.1183 \tag{8}$$

In the formula, G_{VD}, G_{VT} are the deformation ratios obtained by multipoint average method and the volume method, respectively, and v is the speed of the collision car.

4.2.3 Formula for estimating vehicle speed based on vehicle body deformation and attitude after collision

Substituting equations (5), (6), (7), and (8) into equation (3), the expressions of deformation, vehicle speed, and vehicle weight can be obtained.

$$V_D = R_1(0.0277M + 0.1862)(0.0137v + 0.0334) \tag{9}$$

or

$$V_T = R_1'(0.0342M - 0.0689)(0.0158v - 0.1183) \tag{10}$$

In the above formula, V_D , V_T are the functions of deformation, mass, and velocity obtained by the multipoint mean method and the volumetric method, respectively; R_1 , R_1' are unknown parameters, which are solved by the undetermined coefficient method. In the analysis and calculation, $R_1 = 1.3064$ and $R_1' = 5.4320$ are substituted into the above formula to arrive at the following:

$$V_D = 1.3064 \times (0.0277M + 0.1862)(0.0137v + 0.0334) \tag{11}$$

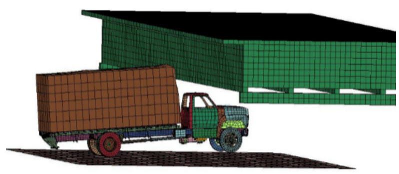
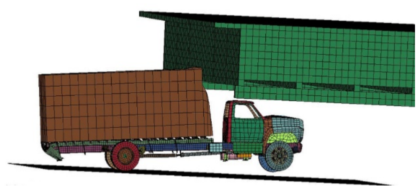
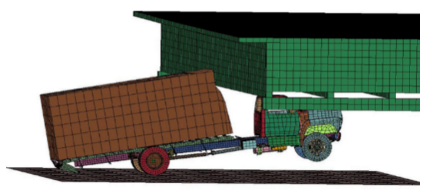
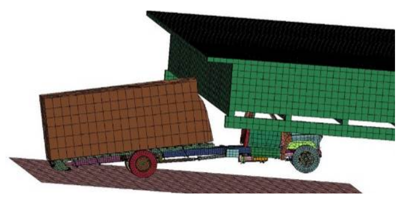
$$V_T = 5.4320 \times (0.0342M - 0.0689)(0.0158v - 0.1183) \tag{12}$$

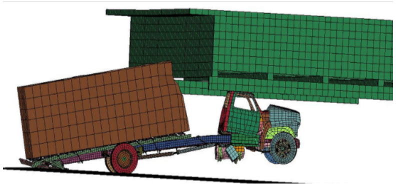
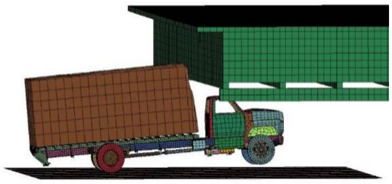
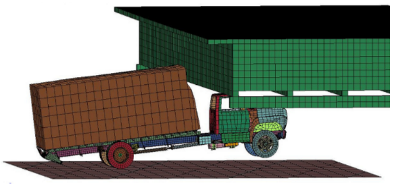
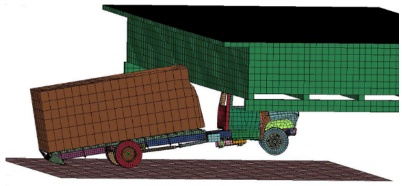
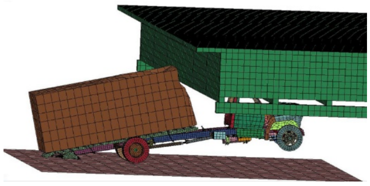
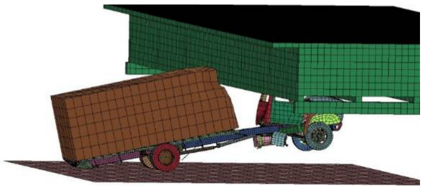
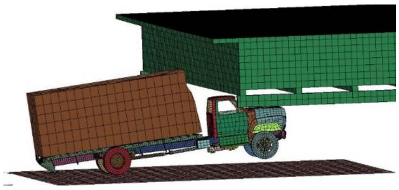
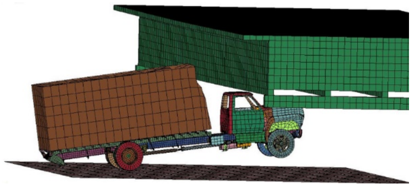
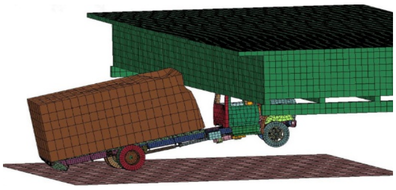
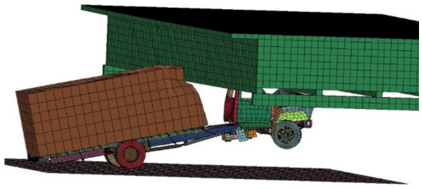
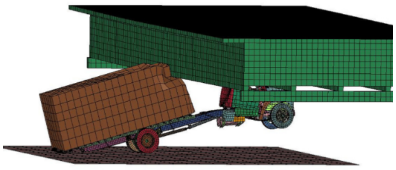
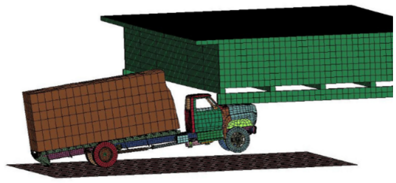
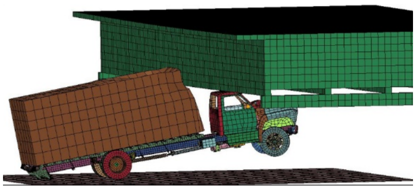
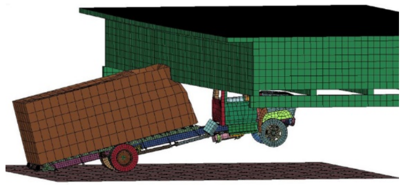
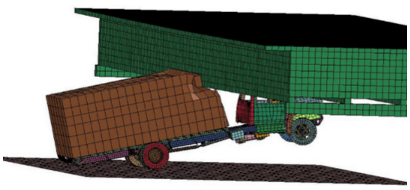
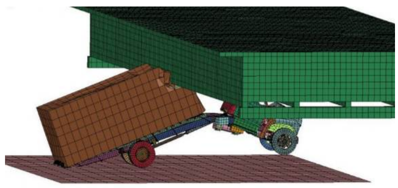
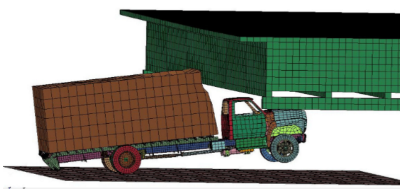
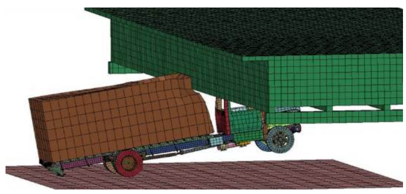
In the formula, the unit of V_D is m, and the unit of V_T is m^3 .

4.3 Vehicle–bridge attitude after collision

The vehicle speed before the collision can be obtained by substituting the vehicle weight and the vehicle body deformation values obtained by means of measurement into equations (11) and (12). To ensure the inferred vehicle speed is more accurate, the attitude of the vehicle after the collision can be used to further verify the vehicle speed. Fig. 11 shows the posture of the super high vehicles with various vehicle weights and speeds after they collide with the overpass bridge.

Table 6. Vehicle body posture after collision

Cases	Attitude	Cases	Attitude
8t, 30km/h		8t, 40km/h	
8t, 50km/h		8t, 60km/h	
8t, 70km/h		10t, 30km/h	

			
10t, 40km/h		10t, 50km/h	
10t, 60km/h		10t, 70km/h	
15t, 30km/h		15t, 40km/h	
15t, 50km/h		15t, 60km/h	
15t, 70km/h		20t, 30km/h	
20t, 40km/h		20t, 50km/h	
20t, 60km/h		20t, 70km/h	
25t, 30km/h		25t, 40km/h	
25t, 50km/h		25t, 60km/h	

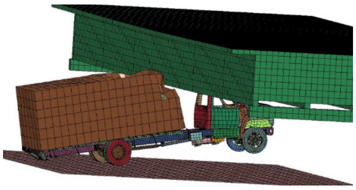
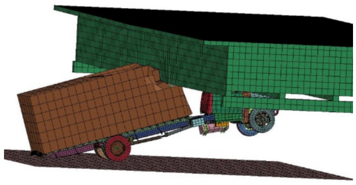
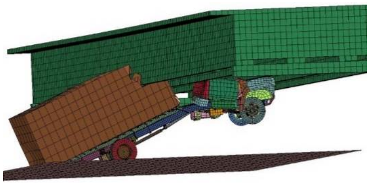
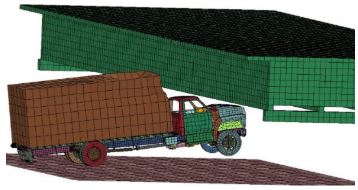
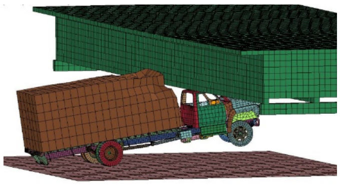
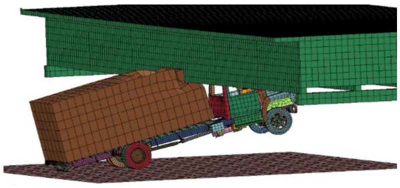
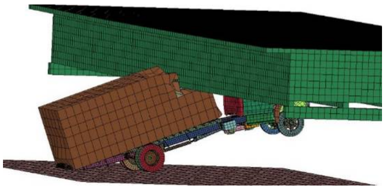
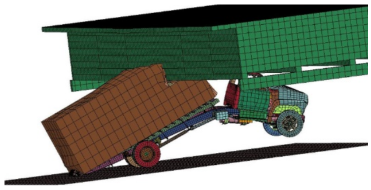
			
25t, 70km/h		30t, 30km/h	
30t, 40km/h		30t, 50km/h	
30t, 60km/h		30t, 70km/h	

Table 6 reveals the following: With the increase of vehicle speed under the condition of constant vehicle weight, the deformation of the vehicle body increases. With the increase of the vehicle weight under the condition of constant vehicle speed, the deformation of the box of the vehicle changes from the deformation of the entire surface facing the bridge (8t70) to the punching deformation of the contact surface (30t70). The attitude of the vehicle after the collision is different, especially in terms of the deformation of the vehicle's chassis. Therefore, the vehicle speed can be further verified by referring to the posture of the vehicle body after the collision.

4.4 Relationship between maximum impact force and vehicle speed

The method of curve fitting is also adopted to express the relationship of impact force and impact force duration with vehicle speed.

The relationship equations of the peak ratio and the mean ratio of horizontal impact force with vehicle weight can be obtained, as shown in Fig. 11 and 12, respectively.

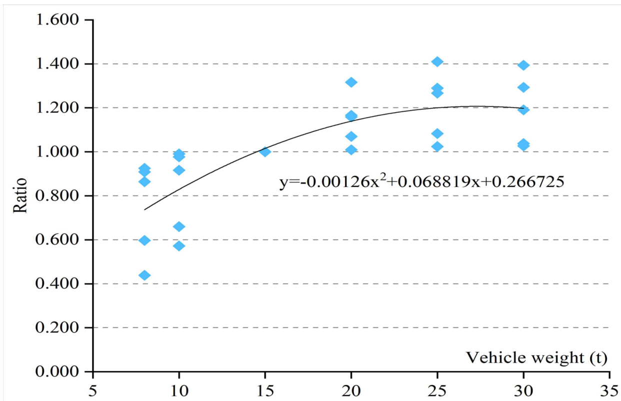


Fig. 11. Relationship between the peak value of the horizontal impact force and the vehicle weight

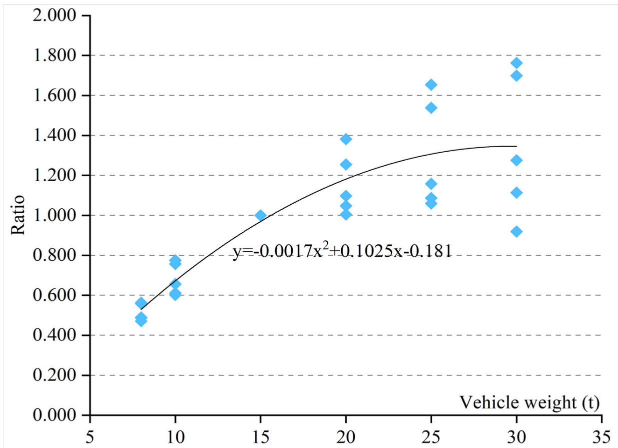


Fig. 12. Relationship between the average value of the horizontal impact force and the vehicle weight

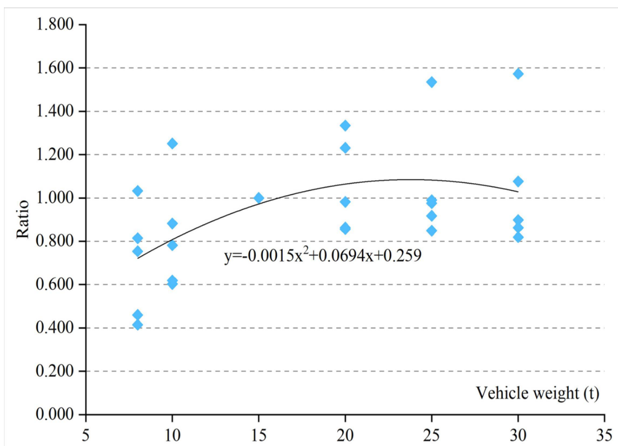


Fig. 13. Relationship between the peak value of the vertical impact force and the vehicle weight

$$F_{2H}(M) = -0.00126M^2 + 0.068819M + 0.266725 \tag{13}$$

$$\bar{F}_{2H}(M) = -0.0017M^2 + 0.1025M - 0.181 \tag{14}$$

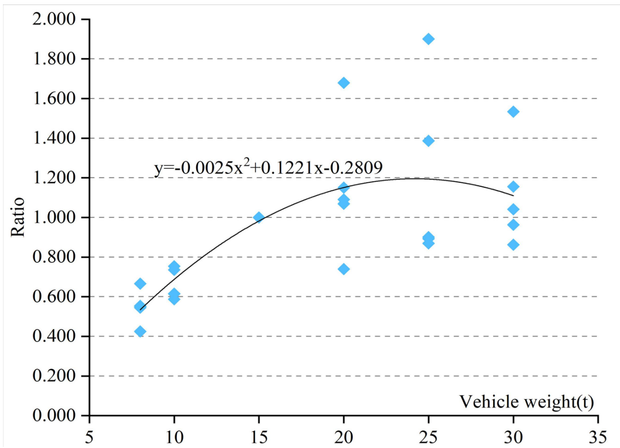


Fig. 14. Relationship between the average value of the vertical impact force and the vehicle weight

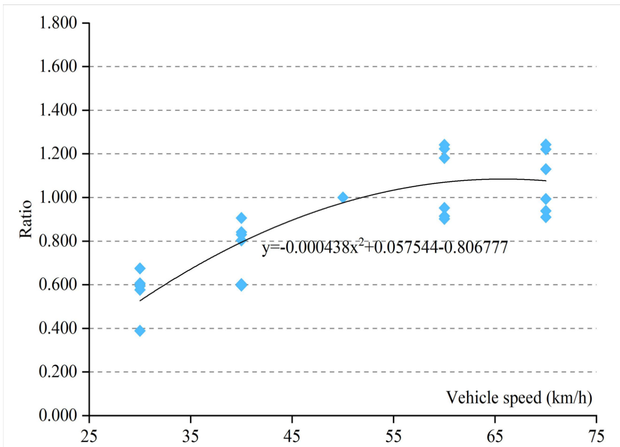


Fig. 15. Relationship between the peak value of the horizontal impact force and the vehicle speed

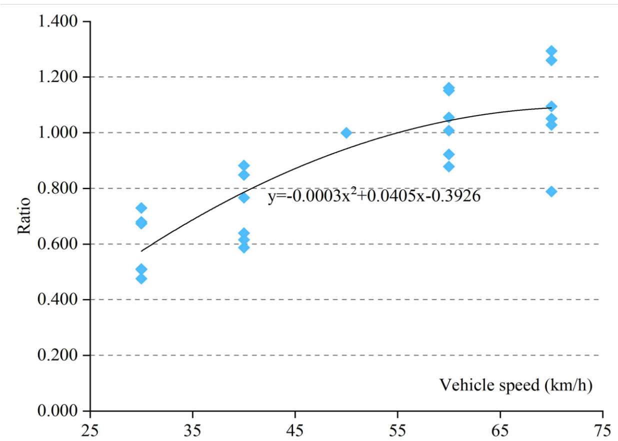


Fig. 16. Relationship between the average value of the horizontal impact force and the vehicle speed

The relationship equations of vertical impact force peak ratio and mean ratio with vehicle weight is shown in Fig. 13 and 14, respectively.

$$F_{2V}(M) = -0.0015M^2 + 0.0694M + 0.259 \tag{15}$$

$$\bar{F}_{2V}(M) = -0.0025M^2 + 0.1221M - 0.2809 \tag{16}$$

The relationship equations of the peak ratio and the mean ratio of horizontal impact force with vehicle speed are shown in Fig. 15 and 16, respectively.

$$G_{2H}(v) = -0.000438v^2 + 0.057544v - 0.806777 \tag{17}$$

$$\bar{G}_{2H}(v) = -0.0003v^2 + 0.0405v - 0.3926 \tag{18}$$

The relationship equations of peak ratio and mean ratio of horizontal impact force with vehicle speed are shown in Fig. 17 and 18, respectively.

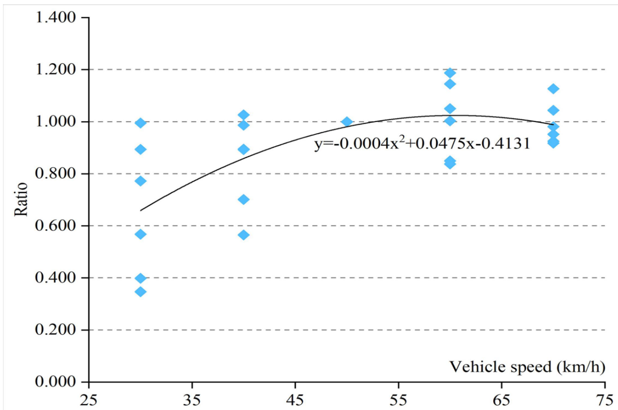


Fig. 17. Relationship between the peak value of the vertical impact force and the vehicle speed

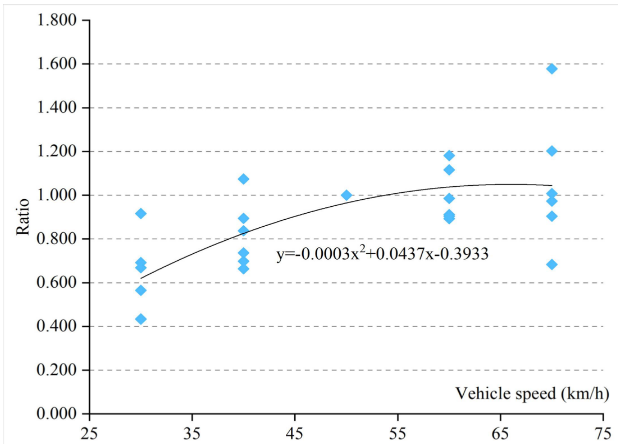


Fig. 18. Relationship between the average value of the vertical impact force and the vehicle speed

$$G_{2V}(v) = -0.0004v^2 + 0.0475v - 0.4131 \tag{19}$$

$$\bar{G}_{2V}(v) = -0.0003v^2 + 0.0437v - 0.3933 \tag{20}$$

Shi et al.[25] stated that the horizontal impact lasts 0.1 s, and the vertical impact lasts 0.15 s, but the impact time is related to the impact speed and the quality of the ultrahigh vehicle. The relationship equation of the ratio of horizontal impact duration with vehicle weight and vehicle speed can be obtained. The relationship equation of the ratio of vertical impact duration with vehicle weight and vehicle speed can be obtained. Similarly, the expressions of collision duration with vehicle speed and vehicle weight can be obtained.

$$t_H(v,M) = 0.1172(0.0002v^2 - 0.0251v + 1.7782)(0.0007M^2 - 0.0087M + 0.9726) \tag{21}$$

$$t_V(v,M)=0.1243(0.0002v^2-0.0251v+1.7782)(0.0007M^2 -0.0087M+0.9726) \tag{22}$$

Likewise, the values of $R_{2H}, R'_{2H}, R_{2V}, R'_{2V}$ can be obtained by fitting the data results of all working conditions. Then, the relationship of impact force with vehicle speed and vehicle weight are expressed as equations (23)~(26).

$$P_{H\max}=3.6247(-0.0013M^2+0.0688M+0.2667)(-0.0004v^2 +0.0575v-0.8068) \tag{23}$$

$$P_{Haver}=1.9253(-0.0017M^2+0.1025M-0.181)(-0.0003v^2 +0.0405v-0.3926) \tag{24}$$

$$P_{V\max}=2.1941(-0.0015M^2+0.0694M+0.259)(-0.0004v^2 +0.0475v-0.4131) \tag{25}$$

$$P_{Vaver}=0.9642(-0.0025M^2+0.1221M-0.2809)(-0.0003v^2 +0.0437v-0.3933) \tag{26}$$

In the formula, M is the vehicle weight, unit t; v is the vehicle speed at impact, unit $\mathrm{km/h}$; $P_{H\max}$ is the maximum horizontal impact force, unit MN; $P_{H\,aver}$ is the average horizontal impact force, unit MN; $P_{\mathrm{v}\max}$ is the maximum vertical impact force, unit MN; $P_{\mathrm{v}aver}$ is the average vertical impact force, unit MN.

4.5 Calculation formula of impact force based on vehicle traces

The inverse function of equations (11) and (12) is calculated, and the deformation of the vehicle body is used to represent the speed of the vehicle to derive the following:

$$v=\frac{V_D}{0.0005m+0.0033}-2.4379 \tag{27}$$

$$v=\frac{V_T}{0.0029m-0.0059}+7.4873 \tag{28}$$

Therefore, combined equations (23)–(28) are used for calculating the impact force based on the traces of the vehicle body.

The steps for engineering application are as follows:

(1) Measure the vehicle weight M and the deformation V_D or V_T of the vehicle body.

(2) Use equation (27) or (28) combined with the attitude of the car body after the collision to obtain the vehicle speed before the collision.

(3) Use equations (23)-(26) to determine the horizontal impact force and the vertical impact force.

4.6 Damage assessment method for struck bridges based on vehicle body deformation

Sections 4.1 to 4.5 show that by the weight of the vehicle, the deformation and attitude of the vehicle after the collision and the speed of the vehicle before the collision can be calculated using equations (27) and (28), and the impact force on the bridge in the collision can be computed using equations (23)-(26). At this time, the impact force is applied to the bridge calculation model or the vehicle speed is applied to the super high vehicle in the vehicle–bridge collision model, and the dynamic response of the impacted bridge during the collision and the damage status after the collision can be calculated.

5. Conclusions

To explore the damage of the main girder of the bridge after being hit by a super high car body, this study uses numerical simulation technology to analyze the relationship of the deformation of the vehicle body with the speed and weight of the vehicle before the collision, and the relationship of the impact force with the speed and weight of the vehicle. Finally, the following conclusions could be drawn:

1) Vehicle body deformation has a linear relationship with the increase of vehicle speed and vehicle weight.

2) The peak value and average value of horizontal impact force increase with the increase of vehicle weight and speed, but the growth rate gradually slows down. The peak value and average value of vertical impact force first increase and then decrease with the increase of vehicle weight and vehicle speed. When the vehicle weight reaches 25 t or the vehicle speed reaches 65 kph, the peak value and average value of vertical impact force reach the maximum value.

3) The duration of the impact force has a quadratic relationship with the speed and weight of the vehicle. When the vehicle weight is constant, the duration of the impact force decreases first and then increases with the increase of the vehicle speed. When the vehicle speed reaches about 60 kph, the duration of the impact force is the shortest. However, when the speed of the vehicle is constant, the duration of the impact force and the weight of the vehicle show a nonlinear increasing trend.

4) After the collision accident, the speed of the vehicle before the collision or the impact force in the accident can be accurately determined by combining the attitude of the vehicle body and the bridge after the collision. On this basis, digital simulation technology is used to solve the damage of the bridge. This method is fast, economical, and highly safe for assessing the bearing capacity of the bridge.

This study combines mathematical experiments and theoretical research to propose a new method for bridge damage assessment in the accident of ultrahigh vehicles hitting bridge main girders. The established preimpact velocity and impact force models are more simplified and closer to the engineering reality, which is a reference for the subsequent studies of bridge damage assessment after vehicle–bridge collision. This study only focuses on van-type over height vehicles, so the crash cases of other over height vehicle bodies should be examined in depth in future studies and the data of other vehicle types should be combined with the model proposed in this work and modified to provide a more accurate understanding of the damage assessment methods of struck bridges.

Acknowledgements

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