Proc. 4th Int. Conf. on Protection of Structures Against Hazards, Oct. 2009, Beijing, China: pp. 425-432.

Simplified Model and Design Equations for the Collision between Over-high Truck and Bridge Superstructures

Yan-sheng Zhang, Tsinghua University, China
Xiao Lu, Tsinghua University, China
Xin-zheng Lu, Tsinghua University, China
Shui-tao He, Tsinghua University, China

Abstract

Recently, the accidents of collisions between over-high trucks and bridge superstructures happen frequently, which seriously threaten the safety of bridges and city traffic system. Based on the simulation of collision between over-high truck and bridge superstructures with nonlinear finite element model, this paper discusses the main factors that influencing the collision load, and proposes corresponding simplified calculation model and design equations. The results of the simplified model and the design equations are compared with the finite element model and the comparison shows that both the proposed simplified model and design equations are conservative and accurate enough for engineering applications.

Keywords: Over-high truck, Bridge substructures, collision, Simplified model, Design equations

1. Introduction

Recently, the accidents of collision between over-high truck and bridge superstructure happen frequently which seriously thread the safety of the bridge and the normal operation of urban traffic [1-5]. According to a report declared by the Department of Transportation of Beijing [1], there were about 50% bridge superstructures had been impacted by over-high trucks in Beijing City, and the number of bridges damaged due to this reason was more than 20% of all damaged bridges. Currently, China does not have systematic research on this problem, and also lacks of design or protection countermeasures.

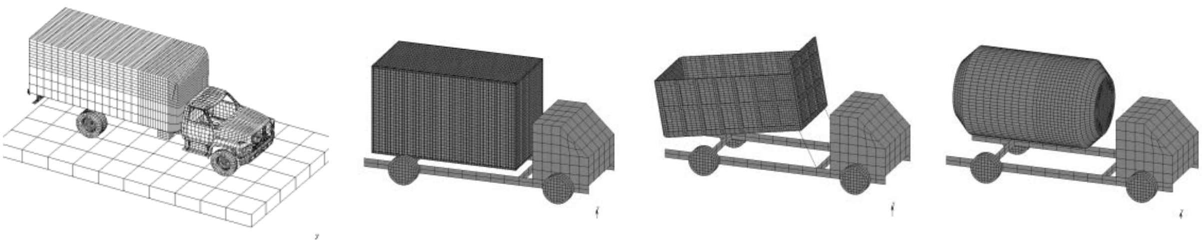
In order to reduce the loss caused by the collision between over-high truck and bridge superstructure and to suggest proper design and prevention for bridge superstructure, the accurate collision load and its influencing factors must be known. Due to the difficulties of experiments on the collision between vehicle and bridge, this paper uses nonlinear finite element (FE) model to study the collision process. And after a number of parametric discussions, simplified calculation model and design equations are proposed for the design of collision between over-high truck and bridge superstructures.

2. Collision load and its influencing factors based on nonlinear FE model

Due to the difficulties of experimental research on the collision between over-high truck and bridge superstructure, numerical simulations based on nonlinear FE models are adopted to study the collision process, which are implemented on the general-purpose FE software, MSC.MARC.

2.1 FE models

The vehicle FE model will greatly influence the simulation results. This work firstly uses the double-axle truck, provided by American National Crash Analysis Center (NCAC) to study the process of collision, and three more typical Chinese vehicles [6], which are *Dongfeng* 145 container truck, *Dongfeng* 3208 tipper truck and the *Dongfeng* EQ140 cement tank truck, are modeled to discuss the influence of different truck types. The FE models of the trucks are shown in Fig.1(a)-(d).

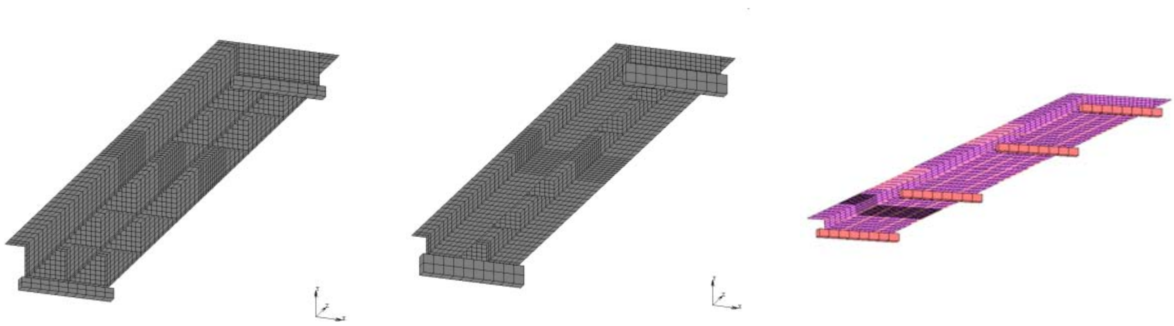


(a) Double-axle truck (b) Container truck (c) Tipper truck (d) Tank truck

Fig.1 FE model of trucks

The carriage of the truck, which is a thin-wall structure, is the mainly impacted zone. So the constitutive model of Cowper-Symonds model is adopted for the carriage of the truck which can consider the yielding, hardening and rate effect of steel material. And the parameters of Cowper-Symonds model are proposed by Liu *et al.*[7] via steel thin-wall beam impact tests. The friction coefficients between the wheel and the pavement, or between the carriage and the bridge, are proposed by Ref [8, 9].

According to the actual types of bridge superstructure in the collision accidents, three typical urban bridges, including a simply supported prestressed concrete (PC) T girder bridge, a simply supported steel box-concrete slab composite bridge and the Chegongzhuang Bridge, which is a three span PC box girder bridge, were modeled and analyzed[10-13]. And the details of the bridge parameters can be found in Ref [6]. In Ref [6], the results of the proposed FE model are compared with the tests which shows a good agreement and verifies the rationality of the propose FE model.

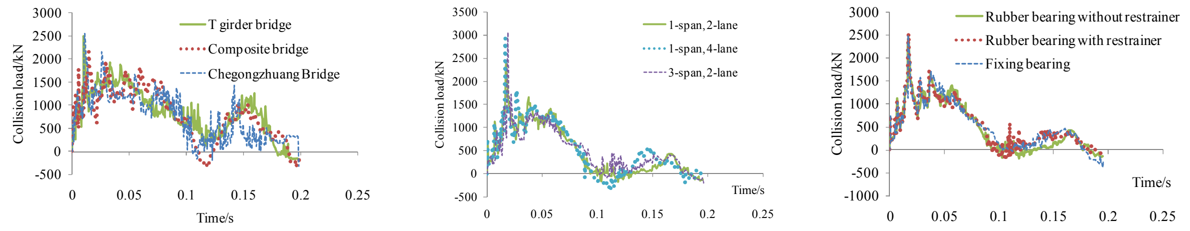


(a) PC T girder bridge (b) Steel-concrete composite bridge (c) Chegongzhuang Bridge

Fig.2 FE model of bridges

2.2 Collision load and its influencing factors

Based on the proposed FE model, the collision between different trucks, different bridges, and different speeds are simulated and some of the results are shown in Fig. 3 and 4. More details can be found in Ref[6]. Generally, because the stiffness, strength and the self-weight of the bridges are much larger than those of the trucks, the types of the bridge have little effect on the results. In contrast, the time-history of the collision load is mainly affected by the vehicle parameters. The collision load of the tipper truck and the tank truck are much larger than that of the container truck when they have the similar velocity and self-weigh.

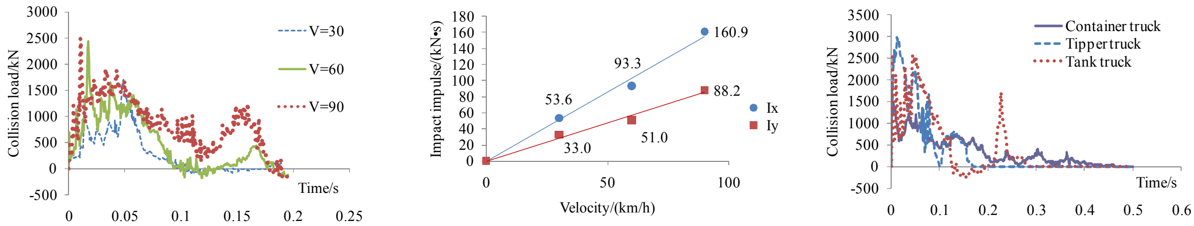


(a) Comparison of lateral collision force for different types of bridge

(b) Comparison of lateral collision force for different length and width

(c) Comparison of lateral collision force for different types of bearing

Fig.3 Comparison of lateral collision loads for different types of bridge parameters



(a) Comparison of lateral collision force for different velocity

(b) Comparison of impulses for different velocity

(c) Comparison of lateral collision force for different types of vehicles

Fig.4 Comparison of collision loads for different types of vehicle parameters

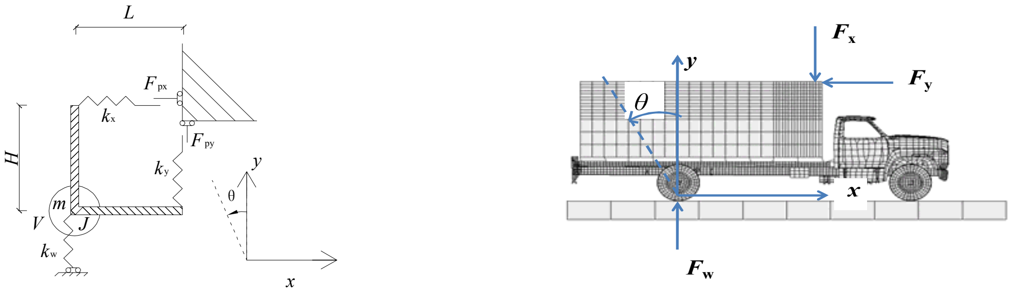
3. Simplified model

Though proposed FE model can accurately calculate the collision load, it is too complicated to derive a design equation. So a simplified model is needed based on the FE model.

According to results of FE models, the following simplifies have little effect on the results[6]: (1) ignoring the friction forces between carriage and bridge; (2) ignoring the friction forces between wheel and pavement; (3) ignoring the gravity of the vehicle; (4) simplifying the bridge to be a rigid wall.

Based on the above assumptions, the simplified model of the collision between over-high truck and bridge superstructure is established (Fig.5). The results of FE analysis show that the displacement response of the over-high truck is the combination of the translations in horizontal and vertical directions and rotation around the rear axle. So the mass of the truck can be concentrated to the rear axle with corresponding rotation inertia and rigid arms (Fig.5(a)). The kinetic coordinate system has three degrees of freedom (x, y, θ). And the origin of the coordinate is located at the initial position of the rear axle (Fig.5(b)). H and L are the vertical and the horizontal distance between collision region and rear axle. J, m and V are the rotational inertia, the mass and the initial velocity of the vehicle, respectively.

Because of the horizontal collision forces F_x and the vertical collision forces F_y (Fig.5(a)), there is obvious plastic deformation of the carriage in the impacted region. Hence, perfect elastic-plastic springs are adopted to model it (Fig.5(b)), where, k_x and k_y are the initial compressive stiffness of the horizontal and vertical springs (but if in tension, they equal to 0), F_{px} and F_{py} are the yield forces of the horizontal and vertical springs. In the same way, the support forces F_w (Fig.5(a)) of the pavement to the truck can also be simulated by a vertical spring and the compressive stiffness of the wheel is k_w (if in tension, it equals to 0).



(a) Simplified model (b) The coordinate-system and force diagram

Fig.5 Simplified model and kinetic coordinate-system

According to Fig.5, the following equations (Eq.1) can be established.

$$\begin{cases} m\ddot{x} = -F_x(k_x, F_{px}, x - H\sin\theta, dp_x) \\ m\ddot{y} = -F_y(k_y, F_{py}, y + L\sin\theta, dp_y) + F_w(k_w, y) \\ J\ddot{\theta} = F_x(k_x, F_{px}, x - H\sin\theta, dp_x)H\cos\theta - F_y(k_y, F_{py}, y + L\sin\theta, dp_y)L\cos\theta \\ x(0) = 0, y(0) = 0, \theta(0) = 0, \dot{x}(0) = V, \dot{y}(0) = 0, \dot{\theta}(0) = 0 \end{cases} \quad (1)$$

where, $x\text{-}H\sin\theta$, $y + L\sin\theta$ are total deformations of the horizontal and vertical springs, and dp_x, dp_y are the accumulated plastic deformation of the horizontal and vertical springs, respectively.

The parameters of the simplified model can be divided into two categories: the first category of parameters can be easily determined by the types of truck and its loading condition, including the mass m, the rotational inertia J, the compressive stiffness of wheel k_w, the lengths of rigid arms H and L and the initial velocity V. And they are shown in the Table.1. In contrast, some other parameters are relatively difficult to determine, such as the compressive stiffness of impacted region k_x, k_y and the yielding forces F_{px}, F_{py}.

Hence, static compression numerical experiments are implemented to determine the value of k_x, k_y, F_{px} and F_{py}. The details of the static compression numerical experiments and curves are shown in Ref [6]. Though the collision between the bridge and the truck is a dynamic process, which has some differences to the static compression, these differences were not so big. And the experiments and calculations of static compression are much easier than the dynamic ones. Therefore, the static compression numerical experiments are adopted to determine the relationship of forces and deformation of the carriage. And Table 2 shows the values of k_x, k_y, F_{px} and F_{py} of different trucks.

Table.1 The value of basic parameters about different vehicles

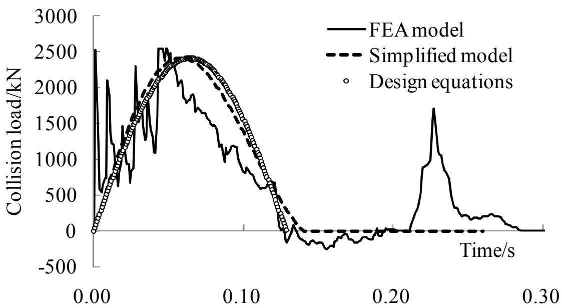
Vehicle types	m(t)	k_w (kN/mm)	H (m)	L (m)
Double-axle truck	7.17	7.64×10^4	3.00	3.25
Container, tipper and tank trucks	10.0	5.00	3.75	4.00

Table.2 the values of J, k_x, k_y, F_{px}, F_{py} in the simplified model

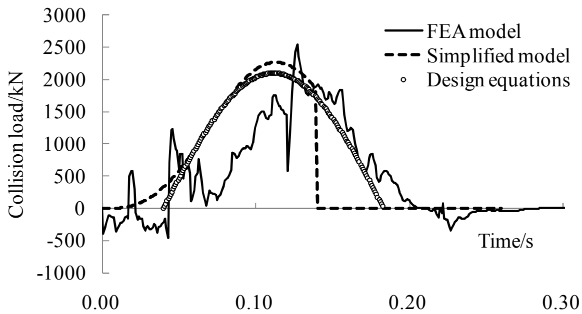
Vehicle types	J (kN·mm·s^2)	k_x (kN/mm)	k_y (kN/mm)	F_{px} (kN)	F_{py} (kN)
Double-axle truck	7.64×10^4	5.00	6.25	1200	1500
Container truck	1.35×10^5	2.00	4.00	800	700
Tipper truck	1.37×10^5	4.00	6.00	3000	3000

Tank truck	1.39×10^5	4.00	5.00	2500	2500

Taking the collision between composite beam and tank truck with the initial velocity of 60km/h for example, the histories of collision forces are shown in Fig.6. And the collision loads of tipper truck and tank truck, which are the control load cases for the bridge damage, are compared in Table 3, in which the effective collision load F_m equals to the average collision load of 0.1s around the peak load[14]. It can be found that the results of simplified model agree well with the FE results and they are conservative.



(a) horizontal direction



(b) vertical direction

Fig.6 Comparison of collision forces for the collision between tank truck and composite beam (V=60km/h)

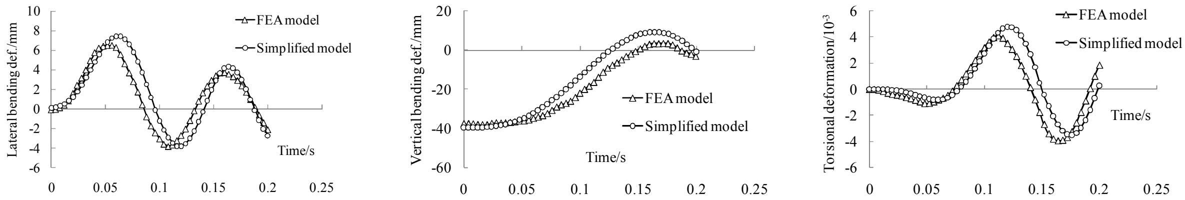
Table.3 Comparison of collision load obtained by different methods

V (km/h)	Collision load	Tipper truck FE model	Tipper truck Simplified model	Tipper truck Design equations	Tank truck FE model	Tank truck Simplified model	Tank truck Design equations
30	I_x (kN·m)	100.5	100.5	103.3	103.7	99.9	98.9
	I_y (kN·m)	80.4	80.4	92.0	79.4	82.7	95.0
	$F_{m,x}$(kN)	862.2	862.2	926.5	914.3	914.0	927.8
	$F_{m,y}$(kN)	773.3	773.3	819.2	662.7	689.3	846.4
60	I_x/(kN·m)	184.2	184.2	206.8	189.7	200.2	197.7
	I_y/(kN·m)	172.3	172.3	182.5	146.6	165.0	190.0
	$F_{m,x}$/kN	1500.2	1500.2	1854.5	1515.9	1833.4	1855.1
	$F_{m,y}$/kN	1671.4	1671.4	1624.2	1158.3	1431.1	1692.8
90	I_x/(kN·m)	251.2	251.2	297.0	251.7	279.3	296.6
	I_y/(kN·m)	264.3	264.3	271.4	234.3	263.2	285.0
	$F_{m,x}$/kN	1821.9	1821.9	2534.9	1930.1	2279.4	2782.8
	$F_{m,y}$/kN	2266.5	2266.5	2417.3	1925.9	2227.9	2539.1

The time-history of collision forces obtained from the simplified model is applied to the bridge superstructure, and the displacement responses are calculated and compared with the results of FE model. Fig.7 shows the comparisons in which the maximum error of displacement response is only 16.30% and the simplified model is conservative.

4. Design equations of impact load

Although the simplified model makes a great progress in simplifying the solution of the collision between over-high truck and bridge superstructure, differential equations (Eq(1)) are still needed to be solved, which is too difficult for engineering design. Therefore, the following section will propose the design equations which are suitable and convenient for engineering design.



(a) Bending deformation in the horizontal direction

(b) Bending deformation in the vertical direction

(c)Torsion deformation

Fig.7 Comparison for the deformation responses of bridge superstructure

The collision loads between the over-high truck and the bridge superstructure in both directions can be simplified to half-sine time-history curves, just as shown in Fig. 8 and Eq. 2, where i=1,2 represents the horizontal and vertical directions, respectively. So if the total impulse I_i and the maximal collision load $F_{\max,i}$, which are the area under the half-sine time-history curve and the peak point of the half-sine time-history curve respectively, are obtained, then the whole time-history curve can be determined.

$$\begin{cases} P_i(\tau) = F_{\max,i} \sin\left(\dfrac{\pi\tau}{t_i}\right) \\ I_i = \int_0^{t_i} P_i(\tau)\mathrm{d}\tau \end{cases} , i=1,2 \tag{2}$$

By referring to the related work on the collision between ship and bridge piers which is sufficiently studied[15-18], The following equations are proposed to calculate I_i and $F_{\max,i}$ in Eq. (2).

$$\begin{cases} I_x = \alpha_x mV \\ I_y = \alpha_y mV \end{cases} \tag{3}$$

$$\begin{cases} F_{\max.x} = \beta_x \sqrt{mk_x}V \\ F_{\max.y} = \beta_y \sqrt{mk_y}V \end{cases} \tag{4}$$

Eq. (3) is based on the momentum conservation theorem approach, and Eq. (4) is based on energy conservation theorem approach, in which α_x, α_y , β_x, β_y are dimensionless factors. After a number of computations, it is found that α_x, α_y , β_x, β_y are controlled by the following three dimensionless factors: the resistance of rotation $J/[m(L^2+H^2)]$, the ratio of stiffness k_y/k_x and the ratio of arm of force L/H.

By changing the value of $J/[m(L^2+H^2)]$、k_y/k_x、L/H in the actual range of engineering application, the corresponding values of α_x,α_y ,β_x and β_y can be derived from the simplified model without considering the plasticity of carriage. Typical values of α_x,α_y ,β_x and β_y are listed in the Table.4 and other value of these parameters can be obtained by linear interpolation.

Taking into account of the plasticity of carriage, a magnification factor of 1.35 should multiply to the value of α_y in Table 4, while the other parameters α_x, β_x and β_y can still using the value in Table 4.

In order to verify the accuracy of the design equations, the results calculated by design equations are compared with the results of simplified model and FE model. Typical comparison is shown in Fig. 8, which is the collision time-history between composite beam and tank truck with an initial velocity of 60km/h. Table 3 shows the comparison of the impact impulse I and the impact forces F_m for tipper truck and tank truck with different speeds. Due to the complicated plastic behavior in the carriage, the maximal error of impact forces F_m is larger than that of impact impulse I. But generally, most errors are smaller than 15% and the design equations are conservative.

Table.4 The value of parameters in Eq (3~4) without considering the plasticity of carriage

$J/[m(L^2+H^2)]$	L/H	k_y/k_x	α_x	α_y	β_x	β_y
0.35	1.0	0.75	0.95	0.65	0.65	0.68
		1.00	1.01	0.91	0.66	0.64
		1.50	1.13	1.00	0.67	0.57
		2.00	1.19	0.96	0.68	0.51
	1.5	0.75	1.31	0.88	0.75	0.66
		1.00	1.39	0.93	0.76	0.60
		1.50	1.48	0.88	0.77	0.50
		2.00	1.50	0.82	0.79	0.43
	2.0	0.75	1.54	0.80	0.82	0.58
		1.00	1.60	0.81	0.83	0.52
		1.50	1.66	0.74	0.84	0.42
		2.00	1.67	0.68	0.86	0.36
0.5	1.0	0.75	1.10	0.55	0.72	0.62
		1.00	1.13	0.71	0.72	0.59
		1.50	1.20	0.90	0.73	0.52
		2.00	1.25	0.93	0.73	0.47
	1.5	0.75	1.39	0.69	0.80	0.60
		1.00	1.44	0.81	0.81	0.55
		1.50	1.51	0.86	0.81	0.46
		2.00	1.55	0.81	0.82	0.40
	2.0	0.75	1.59	0.67	0.86	0.53
		1.00	1.63	0.74	0.86	0.47
		1.50	1.69	0.73	0.87	0.39
		2.00	1.71	0.68	0.88	0.33
0.65	1.0	0.75	1.21	0.50	0.76	0.57
		1.00	1.23	0.63	0.76	0.54
		1.50	1.28	0.79	0.77	0.48
		2.00	1.32	0.86	0.77	0.43
	1.5	0.75	1.47	0.59	0.83	0.54
		1.00	1.50	0.70	0.84	0.50
		1.50	1.55	0.79	0.84	0.43
		2.00	1.59	0.78	0.85	0.37
	2.0	0.75	1.64	0.57	0.88	0.48
		1.00	1.67	0.65	0.89	0.43
		1.50	1.71	0.69	0.89	0.36

Proc. 4th Int. Conf. on Protection of Structures Against Hazards, Oct. 2009, Beijing, China: pp. 425-432.

		2.00	1.73	0.66	0.90	0.31

5. Conclusion

This paper simulates the collision process between the over-high truck and the bridge superstructure. Parameters that influencing the collision process are discussed and simplified calculation model and design equations are proposed to calculate the collision load. By comparing to the FE results, the simplified model and the design equation are accurate enough and conservative.

Acknowledgement

The authors are grateful for the financial support received from National Science Foundation of China (No: 50808106)).

References：

[1] Wang JH, Ye XY. Application of laser collision avoidance system for viaduct [N]. Beijing Evening, 2007-07-31.

[2] Monique CH. Evaluation of the performance of bridge steel pedestals under low seismic: [D]. Georgia Institute of Technology, USA, 2007.

[3] *Bridge design manual* [S]. Texas Department of Transportation. 2001.

[4] University of Maryland. Maryland study. Vehicle collisions with highway bridges[R]. *Maryland State Highway Administration Final Report Contract*. Number SP907B1, USA. 2001.

[5] Chung C. Fu J. Burhouse R, Chang GL. Overheight vehicle collisions with highway bridges [J]. *Journal Transportation Research Record*. 2007, 1865/2004:80-87.

[6] Zhang YS. *Collision between over-high trucks and bridge superstructure: mechanism and loads* [D]. Tsinghua University, 2009.

[7] Liu ZH, Cheng XS, Yang HQ, Cai XL, Liu XX. Deformation and energy-absorbtion characteristics of thin-wall straight beam under central collision [J]. *Journal of Jilin University (Engineering and Technology Edition)*, 2006,36(1):25-30.

[8] Lai Y. *Finite element analysis of impact between heavy vehicle and semi-rigid guardrail* [D]. Shanghai. Tongji University. 2006.

[9] Wei L. Establishment of error bounds for the main effect factor in car-to-car collision model [J]. *China Journal for Highway and Transport*, 2000,13(1):109-113.

[10] Zhang YS, Lu XZ, Ning J, Jiang JJ. Computer simulation for the impact between over-high truck and composite viaduct [J]. *Computer and Communications*, 2007,3 (25) :65-69.

[11] Lu XZ, Zhang YS, Ning J, Jiang JJ, Ren AZ. Simulation of impact between over-high truck and viaduct based on high precision nonlinear finite element analysis[J]. *Journal of Shijiazhuang Railway Institute*, 2007, 20(1): 29-34.

[12] Lu XZ, Zhang YS, Ning J, Jiang JJ, Ren AZ. Simulation for the impact between over-high truck and steel-concrete composite bridge[C]. *Proceedings of the 9th International Conference on Steel Space & Composite Structures*. 2007:91-698.

[13] Lu XZ, Zhang YS, Ning J, Jiang JJ, Ren AZ. Nonlinear finite element simulation for the impact between over-high truck and bridge-superstructure[C]. *Proceedings of the 7th International Conference on Shock & Impact Loads on Structures*. 2007:387-394.

[14] Robert E. Abendroth, Fouad S. Fanous, Bassem O. Andrawes. Steel diaphragms in prestressed concrete girder bridges [R]. *Final Report of Iowa DOT Project TR-424 CTRE Project*. 2004:99-36.

[15] Vrouwenvelder A C W M. *Eurocode 1.Part 2.7. Ship collision analysis* [S]. 1998:123-131.

[16] TB1002.1-99. *Fundamental code for design on railway bridge and culvert* [S]. Beijing, 2000.

[17] JTG D60-2004. *General code for design of highway bridges and culverts*[S]. Beijing, 2004.

[18] AASHTO. *Guide specification and commentary for vessel collision design of highway bridges* [S]. American Association of State Highway and Transportation Officials. Washington D.C.1991.