Finite Element and Simplified Models for Collision Simulation between Over-Height Trucks and Bridge Superstructures

Liangjin Xu¹, Xinzheng Lu², Hong Guan³, and Yansheng Zhang⁴

Abstract: Accidental collisions between over-height trucks and bridge superstructures occur frequently in recent years. These collisions dramatically affect the safety of bridge structures and traffic systems in metropolitan areas. Frequent collision-induced bridge damages have highlighted the importance of scientific research in this field. In this study, considering the inherent difficulties of full-scale laboratory testing, the finite element (FE) method is hence used to simulate the collision procedure. The FE results indicate that collisions between over-height trucks and bridge superstructures induce two types of failure modes, viz global damage and local damage, which are necessary to be incorporated into bridge design guidelines. The numerical results also reveal that the collision forces are mainly influenced by the parameters associated with over-height trucks. To reduce computational costs and facilitate engineering application, a simplified model for calculating the collision forces is also proposed. The predictions of the simplified model, although slightly conservative, are in good agreement with the FE results.

Key words: Collision, Bridge superstructure, Finite element simulation, Simplified model

¹ Doctoral Candidate, Department of Civil Engineering, Tsinghua University, Beijing 100084, China.

² Associate Professor, Department of Civil Engineering, Tsinghua University, Beijing 100084, China (corresponding author).Email: luxz@tsinghua.edu.cn.

³ Associate Professor, Griffith School of Engineering, Griffith University Gold Coast Campus, Queensland 4222, Australia.

⁴ Master, Department of Civil Engineering, Tsinghua University, Beijing 100084, China.

Introduction

Accidental collision between over-height trucks and bridge superstructures is one of the most frequent collision problems in the world. In Beijing, for example, nearly 50% of the overpasses have been involved in collisions, and about 20% of the damages were caused by over-height trucks (Wang and Ye 2007). In the United States, Hite (2007) conducted a statistical investigation in which more than 62% (18 of 29) of the states that responded to the survey reported over-height vehicle collisions to be a significant problem; Shanafelt and Horn (1980) stated that about 162 PC-girder bridges are damaged yearly due to over-height vehicles or heavy vehicular loads; further, Harik et al. (1990) reported that about 14% of bridge damages were due to over-height vehicle collision. Figure 1 shows some of the typical collisions that have led to serious damages to the bridge superstructures.

In many existing international design codes, vehicular impact has not been widely accepted as an important load condition for designing bridge superstructures (Fu et al. 2004). The design specifications and recommendations of Eurocode-1 (CEN 1991) have provided useful guidance for developing a generic design framework. For example, the contact area of collision can be used as a reference for the collision simulation. It also suggests the equivalent collision forces for different traffic situations. However, its recommended collision forces can not be directly adopted by other national codes due to the variation in traffic circumstances internationally (such as speed limitation, weight of vehicles, etc). To date, extensive research has been conducted on ship-bridge pier collisions (El-Tawil et al. 2005; Yuan & Harik 2010; Fan et al. 2011). In addition, other research groups have reported on damage evaluation (Zobel et al. 1997; Bedi 2000; Dawson & Shenton 2005), post-collision repair (Feldman et al. 1998; Abendroth et al. 2004; Kim et al. 2008) and over-height collision protection of highway bridges (Qiao et al. 2004; Sharma et al. 2008). More recently, a series of scaled model tests (with a similarity ratio of 0.2) were conducted by Xu et al. (2012) to investigate the collision phenomenon between over-height trucks and bridge superstructures. Nevertheless, very limited work has been devoted to understanding the mechanism of collision forces, which is critically important for establishing an adequate collision-resistance design method for bridge superstructures.

A full-scale laboratory collision simulation between an over-height truck and a bridge can be labor-intensive, costly and dangerous. Computer simulation, on the other hand, can be a rational alternative due to the increasing capabilities of computer hardware and software in managing such complicated collision scenarios. Computational crash simulation of motor

vehicles has been widely accepted in the automobile industry through the use of general purpose finite element (FE) software, such as LS-DYNA (LSTC 2003). The National Crash Analysis Center (NCAC) of USA (NCAC 2010) provides standard vehicle models, which are freely accessible on the internet. However, these crash analyses are generally focused on the evaluation of safety of vehicles and passengers, whereas damage to the collided structures was not specifically analyzed. To simulate collided structures, simple models, such as the rigid wall model (Maleki 2004), are often adopted. Although some work has been performed on simulating the collision between a vehicle and the highway barrier (Atahan & Cansiz 2005), more attention was paid to the damaged vehicle components rather than on damage to structures. As described above, systematic computer simulations of collisions between over-height trucks and bridge superstructures are generally limited.

In this study, the collision process between over-height trucks and bridge superstructures is simulated with the general purpose FE software MSC.MARC (MSC.Marc 2005). Based on the parametric analysis of the simulation, the mechanism and failure modes of collisions are discussed in some detail which also leads to the development of a simplified computational model for effective calculation of the collision forces in practical design.

Finite element modeling

Rational geometrical dimensions, material constitutive laws and appropriate element models are critical components of an accurate simulation. Therefore, the relevant material, element and contact models are discussed in some detail before they are adopted to simulate the collision procedure.

Material constitutive law for concrete and steel

During the vehicle-bridge collision, a concrete bridge may exhibit crushing or cracking at some specific locations. A strain-rate effect must be considered. The elasto-plastic-fracture constitutive law provided by MSC.MARC is employed to model concrete behavior (MSC.Marc 2005, Lu et al. 2007a), which allows for concrete crushing in compression, concrete cracking in tension, and the strain-rate effect during high-speed deformation. The strain-rate effect of concrete is based on the recommendation of CEB-FIP MC 90 (CEB-FIP 1994).

The Cowper-Symonds model (Jones 1989) is adopted to simulate the steel truck and reinforcement in the bridge superstructure. This model takes into account the yielding, hardening and strain-rate effect of the steel material.

Finite element model of the vehicle

A standard double-axle truck specified by the NCAC is initially modeled to examine the process and the mechanism of collision. The FE model of this truck is shown in Figure 2(a). To investigate the influences of different truck types on the collision process, three other typical Chinese vehicles (DFCLQC 2010), i.e., Dongfeng 145 container truck, Dongfeng 3208 tipper truck and the Dongfeng EQ140 cement tank truck are also modeled. Their respective FE models are presented in Figures 2(b)-(d). According to Eurocode-1 (CEN 1991), the distance between the soffit of the bridge superstructure and the point of impact (the top of the truck) is set as 250 mm.

The Mohr-Coulomb contact model (MSC.Marc 2005) is adopted to simulate contact friction between the vehicle, the pavement and the bridge. Based on site investigations of Chinese vehicles, the friction factors are taken as 0.7, 0.2 and 0.1, respectively, between the wheel and pavement (Wei 2000), truck and concrete bridge, and truck and steel bridge (Lai 2006).

Finite element model of the bridge superstructure

With respect to the actual types of bridge superstructures in collision accidents, three typical urban overpasses are modeled and analyzed herein including a simply-supported prestressed concrete (PC) T-girder bridge, a simply-supported steel box-concrete slab composite bridge and a three-span PC box girder bridge. In general, overpasses in urban areas range from small to medium spans with span length not exceeding 40 m. In this study, both the T-girder and composite bridges are 30 m in span with 2 lanes (a total of 6.4 m in width), and the three-span PC box girder bridge is 32 m+37 m+32 m in span and 14.14 m in width. The corresponding masses for the three types of bridges are 187 t, 138 t and 2400 t, respectively. The construction materials used are: Grade C30 concrete, $7\phi^{s}15.2$ tendon, HRB235 (stirrups) and HRB335 (longitudinal reinforcement) steel bars for the PC T-girder bridge; Grade C50 concrete, HRB335 steel bars and Q345 steel plate for the steel-concrete composite bridge; and Grade C45 concrete, $7\phi^{s}15.2$ tendon and HRB335 steel bars for the three-span PC box bridge. Detailed material properties are summarized in Table 1. The cross-sections and the FE models of these three bridges are demonstrated in Figures 3, 4 and 5. The concrete components of the bridges are modeled using eight-node brick elements. The steel reinforcing bars and prestressing tendons are modeled using spatial truss elements that are inserted into the host brick elements. The displacement compatibility between the concrete and the steel

elements is satisfied by using the “Insert” function of MSC.MARC, which automatically links together the degrees of freedom of the nodes in the inserted and host bodies (MSC.Marc 2005). The steel box of the composite bridge is modeled using shell elements.

In the cross sections of the bridge models, the edge length of the element is approximately 250 mm. In the longitudinal direction, the edge lengths of the elements are approximately 300 mm and 600 mm for the impact and non-impact areas, respectively.

Three typical boundary conditions between the girders and the piers are modeled: i.e., rubber bearing without restrainer, rubber bearing with restrainer and fixed support. The FE simulations of these three types of bearings are based on the work of Zhang et al. (2010). The shear stiffness of the rubber bearing is determined based on the specifications of the Chinese design code for highway bridges and culverts (MTPRC 2004).

Note that the FE models used in this paper are quite similar to the experimental prototypes of Xu et al. (2012) with respect to the bridge types, span lengths, supporting conditions, collision speeds etc. The numerical simulations conducted by Xu et al. (2012) yield a good agreement with the experimental results. This indicates that the FE modeling technique can reliably and accurately simulate the collisions between over-height trucks and bridge superstructures. As such, the FE simulation results presented in this paper, which are based on the same FE modeling technique and similar collision cases of Xu et al. (2012), are proven valid.

It is widely accepted that the accuracy of an FE analysis is greatly affected by the element mesh, especially in complicated contact analysis. A convergence test similar to the one discussed in Lu et al. (2007b) is performed and indicates that further refinement of the meshes presented in Figures 2 to 5 only marginally improves the accuracy of the solution. Therefore, the meshes shown in these figures are adopted in this study.

Typical simulation of collision process

The collision processes between a standard double-axle truck and a steel-concrete composite bridge are studied herein under three different collision speeds, i.e., $V=30$, 60 and 90 km/h when the truck collides with the mid-span of the bridge.

Damages in bridge superstructure

For the collision speed of 90 km/h, which induces the most serious damage, Figure 6 displays the cracked regions in the concrete slab and the plastic regions in the steel box at $t=0.1$ s. Deformations in terms of the cracking strain in concrete and the plastic strain in the steel box

are presented to indicate damages within the bridge superstructure. As expected, the cracking areas and plastic regions become larger when the collision velocity increases. This can be confirmed by earlier FE analysis work (Lu et al. 2007b).

Displacements and deformations of bridge superstructure

The displacements and deformations of the damaged bridge superstructure are categorized as follows:

1. Displacement and deformation around the longitudinal axis of the bridge: Rigid-body rotation and torsion are included, as shown in Figure 7(a).
2. Lateral displacement and deformation: Lateral rigid-body displacement and lateral bending deformation are included, as shown in Figure 7(b).
3. Vertical bending deformation, as shown in Figure 7(c).

Note that the lateral displacement of the flexural center of the end section of the superstructure is taken as the lateral rigid-body displacement (see Figure 7(b)), which can be readily obtainable from the FE simulation. For the composite bridge, the aforementioned lateral displacement and deformation histories due to collision are compared in Figures 8(a) and 8(b). As the total mass of this type of bridge, with only one span and two lanes, is relatively small, the global rigid body motions (i.e., rotation around the longitudinal axis and lateral rigid-body displacement) are much greater than their respective local motions (i.e., torsional and flexural deformations).

Damage modes of bridge superstructure

The modes of damage of bridge superstructures collided by over-height trucks can be classified into two major categories based on the site investigation of accidents and numerical simulation. They are (1) global damage modes and (2) local damage modes.

The global damage modes are induced by the global displacements and deformations, such as lateral or vertical bending deformations (e.g., concrete cracks on the tension side of the slab in the T-girder bridge), torsional damage (e.g., diagonal cracks at the end of the web in the PC T-girder) and girder-falling. Global failures may occur during collision, as for the case of torsional damage; or post collision, as for girder-falling.

The local damage modes are induced by the local punching forces. For the PC T-girder bridge, the local damage includes longitudinal concrete cracking at the web-slab junction, the diagonal cracking and crushing of concrete and the yielding of the reinforcing bars. For steel bridges, local damages are those associated with severe yielding in the steel web of bridge

girder.

The damage modes can be evaluated via the global and local deformations of the bridge structures, as well as the distribution of cracking or plastic strains. Detailed comparisons of the damage modes between the FE simulation and the recorded collisions can be found elsewhere (Zhang et al. 2010).

Collision forces and influencing factors

The influence of the bridge structural types, and the numbers of span and lane on the collision forces is discussed here. In collisions with $V=90$ km/h, a comparison of the collision forces influenced by the PC T-girder, composite and PC box girder bridges is presented in Figure 9. Both the horizontal and vertical components of the collision forces are compared. The comparisons reveal that the type of bridge superstructure has little influence on the collision forces. Similar findings are also achieved for the same PC girder bridge having different numbers of span and lane, as well as different support conditions between the girders and the piers.

The above comparisons indicate that the bridge-related parameters have little influence on the collision forces. This observation is attributable to the overall weight and stiffness of the bridges which are much larger than those of the over-height trucks.

In view of the above, the influence of the speed and truck-related parameters is important to evaluate. With different speeds, the horizontal and vertical components of the collision forces on the PC T-girder bridge collided by the standard double-axle truck are shown in Figure 10, which demonstrates the impact of the vehicle speed on the collision forces. The collision impulse (I_x , I_y about the x- and y-directions, respectively) and speed relationships are demonstrated in Figure 11, which reveals that a linear correlation exists between the velocity and the impulse of collision. Further, due to the horizontal movement of the vehicle, the horizontal components (I_x) of the collision impulse are much larger than their vertical counterparts (I_y), as observed in Figure 11.

To examine the truck-related parameters, the horizontal component of the collision force history is compared in Figure 12 for three different types of trucks: the container truck, tipper truck and tank truck. Note that all three trucks have the same mass of 10 t, and for the purpose of this comparison they are all modeled as traveling at the same velocity of 60 km/h. The results indicate that the collision forces differ significantly for different trucks. This is because the bodies of the trucks have very different structural shapes leading to different collision

patterns. The impulses are different for different trucks. However, such difference is less significant than that of the collision forces.

Simplified model for calculating collision forces

Although FE analyses are able to provide detailed insight into the collision mechanism, the process of determining the collision forces can be rather complicated for design purposes. Therefore, the development of a simplified model for calculating the collision forces is necessary in order to facilitate engineering application. In the simplified model, the time history of the collision force is calculated, which can subsequently be applied to the bridge superstructure to obtain the displacement response of the bridge. In view of the findings described above, only dominant factors are taken into consideration in establishing the simplified model which involves fewer variables. This characteristic makes the model economical in computation and effective for practical applications.

Based on the above FE results, the following simplifications can be made: (1) the friction force between the over-height truck and bridge superstructure can be neglected; (2) the friction force between the wheel and pavement can be neglected; (3) the gravity of the vehicle can be neglected; (4) the bridge can be simplified as a rigid wall. These simplifications are validated in Figure 13 through simulation of the composite bridge collided by the standard double-axle truck travelling at a speed of 60 km/h. Figure 13(a) presents the time-history of the truck-superstructure collision force, in form of the two component forces, i.e., the normal and friction contact forces. It is clearly evident that the normal force is dominant whereas the contribution of the friction force is relatively small which can be neglected. This confirms the validity of the first simplification. Figure 13(b) compares the time-history of the collision forces predicted by the original and simplified models (with the remaining three simplifications). Note that the original model refers to the FE model before making any simplification. It is apparent that all of these simplifications are also valid.

Shown in Figure 14 is the simplified model established for calculating the collision forces between over-height trucks and bridge superstructures. The FE results for the critical stages of collision (Figure 15) indicate that the displacement response of the over-height truck is a combination of the horizontal and vertical translations and rotation around the rear axle. The resultant of the total mass of the truck can therefore be assumed to be located at the rear axle. Figure 14(a) shows that the truck is simplified as two rigid arms with corresponding rotational inertia (J). In the figure, H and L are respectively the vertical and horizontal distances

between the rear axle and the collision point. J , m and V are respectively the rotational inertia, the mass and the initial velocity of the vehicle. In total, three degrees of freedom (x , y , θ) are defined for the truck in the kinetic coordinate system, as illustrated in Figure 14(b). The reference point of the coordinate system is located at the pre-collision position of the rear axle.

The plastic deformation in the collided region is caused by the horizontal and vertical components of the collision force, F_x and F_y (Figure 14(b)). To simulate such plastic deformation, perfect elastic-plastic springs are adopted as presented in Figure 14(a), where k_x and k_y are the initial compressive stiffnesses of the horizontal and vertical springs, respectively. Note that if the springs are in tension, $k_x = k_y = 0$. In Figure 14(a), F_{px} and F_{py} represent the yielding forces of the horizontal and vertical springs, respectively. Similarly, the pavement induced normal force F_w (Figure 14(b)) acting on the truck wheel can also be simulated by a vertical spring, and the corresponding compressive stiffness of the wheel is k_w ($= 0$ if the spring is in tension). Numerical compression experiments are implemented to determine the values of these parameters. The schematics of the experiments are illustrated in Figure 16. A rigid wall is pushed towards the collided region of the truck in the horizontal and vertical directions, respectively. A typical reaction force and displacement relationship for the rigid wall is presented in Figure 17. The relationship can be simplified as a bilinear curve, which yields values of k_x , k_y , F_{px} and F_{py} .

The description of the simplified model (Figure 14) leads to the establishment of the following set of equations (Eq.1).

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

where $x - H \sin \theta$, $y + L \sin \theta$ are respectively the total deformations of the horizontal and vertical springs and dp_x and dp_y are respectively the corresponding accumulated plastic deformations. The values of the parameters (Eq. 1) used for different trucks are listed in Table 2.

A comparison of the collision force histories predicted by the FE analysis and by the simplified model is presented in Figure 18. The composite bridge is considered here and is collided by the tank truck travelling at an initial velocity of 60 km/h. It can be observed that the results of the simplified model, although slightly conservative, agree well with the FE results. A comparison of the collision loads for different trucks using both FE and simplified

models is also given in Figure 19. The tipper truck and tank truck are selected for comparison because they are the controlling cases for bridge damages. In Figure 19, the effective collision force F_m equals the average collision force in 0.1 s (Abendroth et al. 2004).

For the bridge superstructure, the time-histories of the lateral bending obtained from the simplified model are compared in Figure 20 with the results of the corresponding FE model. Despite the discrepancies between the two prediction results, the simplified model yields slightly conservative predictions, which is considered safe.

It is worth mentioning that a series of calculation have been performed, with varying parameter values obtained from the investigation report and relevant literature (DFCLQC 2010; Li et al. 2005). This results in the magnitudes of the design collision forces being in the range of $F_x=700-950$ kN and $F_y=650-850$ kN for $V=30$ km/h, $F_x=800-1900$ kN and $F_y=700-1650$ kN for $V=60$ km/h, and $F_x=2000-2600$ kN and $F_y=2000-2500$ kN for $V=90$ km/h.

Conclusions

The mechanism and damage modes of collision between over-height trucks and bridge superstructures are investigated in this study. The following conclusions can be drawn.

1. Damages of bridge superstructures collided by over-height trucks are resulted from global deformations and local punching forces. Both should be taken into consideration in the process of bridge design.
2. Collision forces are mainly influenced by the parameters associated with the trucks. With the same mass and at the same velocity, tipper and tank trucks generally have larger punching forces than container trucks.
3. Based on the FE results, both the truck-superstructure and the wheel-pavement friction forces, as well as the vehicle gravity can be neglected, and the bridge can be simplified as a rigid wall in deriving the simplified model for calculating the collision forces.
4. The predictions of the proposed simplified model, although slightly conservative, correlate well with the FE solutions. Fewer variables are involved in the simplified model, which makes it more efficient in terms of computational cost and engineering applications. In addition, the proposed simplified model provides a reference for calculating the collision forces in bridge design.
5. On the basis of the present study, future work will be conducted to examine other factors of potential influence and wider ranges of bridge and vehicle types and road conditions..

Acknowledgements

The authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (No. 51222804 and No. 50808106), the Tsinghua University Initiative Scientific Research Program (No. 2010THZ02-1 and No. 2011THZ03), the Major S&T Special Project of the Ministry of Transport of the People's Republic of China (No. 2011-318-223-170) and the Program for New Century Excellent Talents in University (NCET-10-0528).

References

- Abendroth, R. E., Fanous, F. S. and Andrawes, B. O. (2004) "Steel diaphragms in prestressed concrete girder bridges". Final Report of Iowa DOT Project TR-424 and CTRE Project 99-36.
- Atahan, A. O. and Cansiz, O. F. (2005). "Impact analysis of a vertical flared back bridge rail-to-guardrail transition structure using simulation." *Finite Elements in Analysis and Design*, 41(4), 371-396.
- Bedi, A. K. (2000). "Study of a typical bridge girder damaged by vehicle impacts." *Proceedings of the 2nd Forensic Engineering Congress*, American Society of Civil Engineers, Reston, VA, 263-272.
- CEB-FIP. (1994). *CEB-FIP Model Code 1990: Design Code*, Thomas Telford, London.
- CEN. (1991). "Eurocode 1: basis of design and actions on structures. part 1-7: accidental actions." *ENV 1991-1-7*, European Committee for Standardisation, Brussels, Belgium.
- Dawson, M. and Shenton, H. (2005). "Evaluation of steel bridge girders damaged by over-height vehicle collision", Report submitted to NSF-REU, <http://128.175.10.100/cibre/reu/REU05/Dawson_report.pdf> Available online 16 Jun. 2012.
- Dong Feng Cheng Li Special Purpose Vehicle Corporation (DFCLQC). <<http://www.dfclqc.com/>> Available online 11 Dec. 2010.
- El-Tawil, S., Severino, E. and Fonseca, P. (2005). "Vehicle collision with bridge piers." *Journal of Bridge Engineering*, 10(3), 345-353.
- Fan, W., Yuan, W. C., Yang, Z. and Fan, Q. W. (2011). "Dynamic demand of bridge structure subjected to vessel impact using simplified interaction model." *Journal of Bridge Engineering*, 16(1), 117-126.
- Feldman, L. R., Jirsa, J. O. and Kowal, E. S. (1998). "Repair of bridge impact damage." *Concrete International*, 20(2), 61-66.
- Fu, C. C., Burhouse, J. R. and Chang, G. L. (2004). "Overheight vehicle collisions with highway bridges." *Transportation Research Record*, 1865, 80-88.
- Harik, I. E., Shaaban, A. M., Gesund, H., Valli, Y. S. and Wang, S. T. (1990). "United States bridge failures, 1951-1988." *Journal of Performance of Constructed Facilities*, 4(4), 272-277.
- Hite, M. C. (2007). "Evaluation of the performance of bridge steel pedestals under low seismic loads." Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA.
- Jones, N. (1989). *Structural impact*. Cambridge University Press, Cambridge, U.K.
- Kim, Y. J., Green, M. F. and Fallis, G. J. (2008). "Repair of bridge girder damaged by impact loads with prestressed CFRP sheets." *Journal of Bridge Engineering*, 13(1), 15-23.

- Lai, Y. (2006). "Finite element analysis of impact between heavy vehicle and semi-rigid guardrail." M.S. Thesis, Tongji University, Shanghai.
- Li, G. H., Zhang, C. C., Wang, D. W. and Zhang, H. J. (2005). "Study on Live Load Parameter for Highway Bridge." *Journal of Zhengzhou University (Engineering Science)*, 26(1), 20-23.
- Livermore Software Technology Corporation (LSTC). (2003). *A General Purpose Dynamic Finite Element Analysis Program: LS-DYNA Version 970 User's Manual*, Livermore Software Technology Corporation, Livermore, Calif.
- Lu, X. Z., Teng, J. G., Ye, L. P. and Jiang, J. J. (2007a). "Intermediate crack debonding in FRP-strengthened RC beams: FE analysis and strength model." *Journal of Composite for Construction, ASCE*, 11(2), 161-174.
- Lu, X. Z., Zhang, Y. S., Jiang, J. J., Ren, A. Z. and Ning, J. (2007b). "Nonlinear finite element simulation for the impact between over-high truck and bridge-superstructure." *Proceedings of the 7th International Conference on Shock & Impact Loads on Structures*, Beijing, China, 387-394.
- Maleki, S. (2004). "Effect of side retainers on seismic response of bridges with elastomeric bearings." *Journal of Bridge Engineering*, 9(1), 95-100.
- Ministry of Transport of the People's Republic of China (MTPRC). (2004). *General Code for Design of Highway Bridges and Culverts*, China Communications Press, Beijing.
- MSC.Marc. (2005). *Volume A: Theory and User Information*, Santa Ana, California.
- National Crash Analysis Center (NCAC). "Finite element model archive." <<http://www.ncac.gwu.edu/vml/models.html>> Available online 17 Dec. 2010.
- Qiao, P. Z., Yang, M. J. and Mosallam, A. S. (2004). "Impact analysis of I-lam sandwich system for over-height collision protection of highway bridges." *Engineering Structures*, 26(7), 1003-1012.
- Shanafelt, G. O. and Horn, W. B. (1980). "Damage evaluation and repair methods for prestressed concrete bridge members." *National Cooperative Highway Research Program Report 226*, Transportation Research Board, Washington, D.C.
- Sharma, H., Hurlbaas, S. and Gardoni, P. (2008), "Bridge bumper concept and FEA-based design methods to protect bridge girders from overheight vehicle impacts." *Computer-Aided Civil and Infrastructure Engineering*, 23(6), 415-426.
- Wang, J. H. and Ye, X. Y. (2007). "Application of laser collision avoidance system for crossroads." *Beijing Evening*, <<http://news.sina.com.cn/c/2007-07-31/143012303005s.shtml>> Available online 31 Jul. 2007.
- Wei, L. (2000). "Establishment of error bounds for the main effect factor in car-to-car collision model." *China Journal for Highway and Transport*, 13(1), 109-113.
- Xu, L. J., Lu, X. Z., Smith S. T. and He, S. T. (2012) "Scaled model test for collision between over-height truck and bridge superstructure." *International Journal of Impact Engineering*, 49(11), 31-42. (DOI: 10.1016/j.ijimpeng.2012.05.003).
- Yuan, P. and Harik, I. E. (2010). "Equivalent barge and flotilla impact forces on bridge piers." *Journal of Bridge Engineering*, 15(5), 523-532.
- Zhang Y. S., Lu X. Z., He S. T. and Lu X. (2010). "Mechanism and damage modes of collision between over-high trucks and bridge superstructures." *Proceedings of the 2nd International Symposium on Computational Mechanics (ISCM II)*, Hong Kong, China, 255-260.
- Zobel, R. S., Jirsa, J. O., Fowler, D. W. and Carrasquillo, R. L. (1997). "Evaluation and repair of

384 impact-damaged prestressed concrete bridge girders.” Center for Transportation Research Report 1370-3F,
385 Bureau of Engineering Research, University of Texas at Austin, Austin, Texas.

Appendix. Notation

The following symbols are used in this paper:

F_m	the effective collision force
F_{px}, F_{py}	yielding forces of the horizontal and vertical springs, respectively
F_w	pavement support reaction
F_x, F_y	horizontal and vertical components of the collision force, respectively
H	vertical distance between the rear axle and the collision point
I	collision impulse
J	rotational inertia of the vehicle
k_w	corresponding compressive stiffness of the wheel
k_x, k_y	initial compressive stiffness of the horizontal and vertical springs, respectively
L	horizontal distance between the rear axle and the collision point
m	mass of the vehicle
V	collision velocity of the vehicle

Table 1 The material properties

Property	Type	Elastic modulus (MPa)	Density (kg/m ³)	Poisson ratio	Yield strength (MPa)	Ultimate strength (MPa) ^a
Concrete	C30	3.00×10 ⁴	2500	0.2	——	20.1 (C)
						2.01 (T)
	C45	3.35×10 ⁴				29.6 (C)
						2.51 (T)
	C50	3.55×10 ⁴				32.4 (C)
						2.65 (T)
Tendon	7 ϕ ^s 15.2	1.95×10 ⁵	7850	0.3	1720	——
Steel bar	HRB335	2.0×10 ⁵	7850	0.3	335	——
	HPB235	2.1×10 ⁵			235	
Steel plate	Q345	2.0×10 ⁵	7850	0.3	345	——

^a C=Compression, T= Tension

Table 2 The parameters of different vehicles

Vehicle types	Double-axle truck	Container truck	Tipper truck	Tank truck
$m(t)$	7.17	10.0	10.0	10.0
k_w (kN/mm)	3.00	5.00	5.00	5.00
H (m)	3.25	3.75	3.75	3.75
L (m)	3.50	4.00	4.00	4.00
J (kg·mm ²)	7.64×10^8	1.35×10^9	1.37×10^9	1.39×10^9
k_x (kN/mm)	5.00	2.00	4.00	4.00
k_y (kN/mm)	6.25	4.00	6.00	5.00
F_{px} (kN)	1200	800	3000	2500
F_{py} (kN)	1500	700	3000	2500

(a) Dump truck-bridge collision

(b) Cabin vehicle-bridge collision

Figure 1 Photos of collision accidents between over-height trucks and bridge superstructures

(a) Standard double-axle truck

(b) Container truck

(c) Tipper truck

(d) Tank truck

Figure 2 Finite element models of trucks

Figure 3 PC T-girder bridge (unit: mm)

Figure 4 Steel-concrete composite bridge (unit: mm)

(a) Cross-section

(b)Finite element model

Figure 5 Three-span PC box bridge (unit: mm)

Figure 6 Damages in steel-concrete composite bridge superstructure ($V=90\text{km/h}$, $t=0.1\text{s}$)

(a) Sectional twisting angle

(b) Lateral rigid-body displacement and lateral bending deformation

(c) Vertical bending deformation

Figure 7 Types of displacements and deformations of superstructure

(a) Lateral rigid-body displacement history

(b) Lateral bending deformation history

Figure 8 Lateral displacement and deformation history

(a) Horizontal component

(b) Vertical component

Figure 9 Comparison of collision forces for different types of bridge superstructures ($V=90\text{km/h}$)

(a) Horizontal component

(b) Vertical component

Figure 10 Comparison of collision forces for different collision speeds

Figure 11 Comparison of collision impulses for different collision speeds
(x and y represent the horizontal and vertical directions, respectively)

Figure 12 Comparison of horizontal component of collision forces for different types of trucks ($V=60\text{km/h}$)

(a) Comparison of friction and normal contact forces

(b) Comparison of original and simplified collisions

Figure 13 Verification of proposed simplifications

Figure 14 Simplified model and kinetic coordinate-system

(a) Early stage of collision

(b) Final stage of collision

Figure 15 Truck displacement and deformation in each stage of collision

Figure 16 Numerical compression experiments

Figure 17 Typical reaction force and displacement relationship on rigid wall

(a) Horizontal direction

(b) Vertical direction

Figure 18 Comparison of collision force histories between tank truck and composite beam ($V=60\text{km/h}$)

(a) Collision impulse (I_x, I_y)

(b) Effective collision force (F_{mx}, F_{my})

Figure 19 Comparison of collision loads for different trucks using different methods

Figure20 Comparison of lateral bending deformation of bridge superstructure

- Figure 1 Photos of collision accidents between over-height trucks and bridge superstructures: (a) Dump truck-bridge collision; (b) Cabin vehicle-bridge collision
- Figure 2 Finite element models of trucks: (a) Standard double-axle truck; (b) Container truck; (c) Tipper truck; (d) Tank truck
- Figure 3 PC T-girder bridge: (a) Cross-section; (b) Finite element model
- Figure 4 Steel-concrete composite bridge: (a) Cross-section; (b) Finite element model
- Figure 5 Three-span PC box bridge: (a) Cross-section; (b) Finite element model
- Figure 6 Damages in steel-concrete composite bridge superstructure ($V=90$ km/h, $t=0.1$ s): (a) Cracking strain distribution in concrete slab; (b) Plastic strain distribution in steel plate
- Figure 7 Types of displacements and deformations of superstructure: (a) Sectional twisting angle; (b) Lateral rigid-body displacement and lateral bending deformation; (c) Vertical bending deformation
- Figure 8 Lateral displacement and deformation history: (a) Lateral rigid-body displacement history; (b) Lateral bending deformation history
- Figure 9 Comparison of collision forces for different types of bridge superstructures ($V=90$ km/h): (a) Horizontal component; (b) Vertical component
- Figure 10 Comparison of collision forces for different collision speeds: (a) Horizontal component; (b) Vertical component
- Figure 11 Comparison of collision impulses for different collision speeds (x and y represent the horizontal and vertical directions, respectively)
- Figure 12 Comparison of horizontal component of collision forces for different

types of trucks ($V=60$ km/h)

Figure 13 Verification of proposed simplifications: (a) Comparison of friction and normal contact forces; (b) Comparison of original and simplified collisions

Figure 14 Simplified model and kinetic coordinate-system: (a) Simplified model; (b) Coordinate-system and force diagram

Figure 15 Truck displacement and deformation in each stage of collision: (a) Early stage of collision; (b) Final stage of collision

Figure 16 Numerical compression experiments

Figure 17 Typical reaction force and displacement relationship on rigid wall

Figure 18 Comparison of collision force histories between tank truck and composite beam ($V=60$ km/h): (a) Horizontal direction; (b) Vertical direction

Figure 19 Comparison of collision loads for different trucks using different methods: (a) Collision impulse (I_x, I_y); (b) Effective collision force (F_{mx}, F_{my})

Figure 20 Comparison of lateral bending deformations of bridge superstructure