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

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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 cannot 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.
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).

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, 7φ5/15.2 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, 7φ5/15.2 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
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 \((x, y, \theta)\) 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).

\[
\begin{align*}
    m \dddot{x} &= -R_x(k_x, R_{px}, x - H \sin \theta, dp_x) \\
    m \dddot{y} &= -R_y(k_y, R_{py}, y + L \sin \theta, dp_y) + R_y(k_y, F_{py}) \\
    \dddot{\theta} &= \frac{R_y(k_y, F_{py}) H \cos \theta - R_x(k_x, F_{px}, x - H \sin \theta, dp_x) L \sin \theta, dp_y)}{I} L \cos \theta \\
    x(0) &= 0, y(0) = 0, \dot{\theta}(0) = 0, \ddot{x}(0) = F_{px}, \ddot{y}(0) = 0, \ddot{\theta}(0) = 0
\end{align*}
\]

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.
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References


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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

<table>
<thead>
<tr>
<th>Property</th>
<th>Type</th>
<th>Elastic modulus (MPa)</th>
<th>Density (kg/m³)</th>
<th>Poisson ratio</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
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<td>0.2</td>
<td>——</td>
<td>29.6 (C)</td>
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<td>7850</td>
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a C=Compression, T= Tension
Table 2 The parameters of different vehicles

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<th>Container truck</th>
<th>Tipper truck</th>
<th>Tank truck</th>
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<td>L (m)</td>
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<td>$F_{py}$ (kN)</td>
<td>1500</td>
<td>700</td>
<td>3000</td>
<td>2500</td>
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Figure 1 Photos of collision accidents between over-height trucks and bridge superstructures
Figure 2 Finite element models of trucks

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Figure 2 Finite element models of trucks: (a) Standard double-axle truck; (b) Container truck; (c) Tipper truck; (d) Tank truck

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