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Performance-based Risk Assessment of Reinforced Concrete Bridge Piers subjected to Vehicle Collision

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Abstract:

Along with the increase of motor vehicles on the roads, the number of vehicle collision with highway bridge piers has increased. The collision can cause severe damage to the structure and hamper the functionality of the transportation network. Thus, risk assessment of bridge piers subjected to collisions is of vital importance to mitigate structural damage and hazard consequence. This paper presents a framework for the performance assessment of reinforced concrete (RC) bridge piers under vehicle collision incorporating risk. The probabilities of collision under different scenarios are assessed by considering distance from structural component to road, angle of collision, and initial velocity, among others. Additionally, probabilistic structural demand and capacity models are developed considering different damage states within the evaluation process. Then, fragility contours of the investigated RC bridge are obtained. Furthermore, the consequence of structural failure under collisions is incorporated within the process of performance assessment. Overall, the proposed framework can be used to aid the design and management of RC bridge piers subjected to vehicle collision.

Keywords: Vehicle collision; Risk assessment; Performance-based engineering; Bridge piers; Uncertainty quantification.

1. Introduction

Bridge piers may be hit by vessels and vehicles, which could lead to severe damage or even collapse of bridges resulting in serious secondary disasters and consequences [1-2]. Compared with vessel collisions, the problem of vehicle collisions on bridge piers has not received much attention until the last decade. Buth *et al*. [2] documented a series of vehicle crashes on bridge piers, where tremendous economic loss and live loss were reported. Similar events occur all over the world. For instance, in April 2009, a tanker truck collided with the bridge piers located at the intersection between G4 expressway and S322 highway in China. The event led to instantaneous death of two truck passengers, serious injury to the third, and severe damage to the bridge. The traffic had to be shut down in the vicinity of the accident for over two months [3]. Along with the increase of the numbers of vehicles and bridges, risk of bridges subjected to vehicle collision would increase significantly. Thus, it is of great significance to take into consideration of potential vehicle collision during the design and maintenance of bridges.

Nowadays, many bridge design codes have included anti-collision measures and design methods regarding vehicle collisions on bridge piers (e.g., the *AASHTO LRFD Bridge Design Specifications* [4] and *Eurocode 1-Part 1-7* [5]). However, these codes usually adopt a design method based on a single or multiple equivalent static forces and do not take into full consideration of the dynamic characteristics of both vehicles and piers. El-Tawil *et al*. [6] demonstrated that the then-current AASHTO code is not always conservative in this regard. Recent simulation work conducted by Abdelkarim and Elgawady [7] reported similar findings with respect to the AASTHO code [4], although the design force in the code had been increased from 1,800 kN to 2,670 kN. Clearly, developing a reliable design and assessment method for bridges against vehicle collision is still challenging. The uncertainty and consequence associated with the collision event should also be incorporated within the process.

Performance-based engineering (PBE) is a method to investigate the performance of infrastructure systems under hazard effects [8-10] in the context of life-cycle engineering [11, 12]. The Pacific Earthquake Engineering Research (PEER) Center has developed performance-based seismic design and assessment approach, which consists of several parts: (a) hazard analysis, (b) structural analysis, (c) damage analysis, and (d) loss analysis with decision variables (e.g., repair loss, downtime, and fatality) [13]. The PBE has been widely used within the design and assessment of civil infrastructure systems under different hazard effects. In recent years, some researchers have tried to develop the PBE approach for reinforced concrete (RC) bridge piers under vehicle collisions [7, 14-19], where the performance objectives, damage classifications of the bridges, and structural responses were discussed. However, a systematic approach by considering different aspects of the PBE is still missing. On the other hand, Chen *et al*. [20,21] proposed an efficient model to simulate truck collision with bridge piers, which could be used in the structural response analysis within the PBE framework. Chen *et al*. [22] conducted a series of numerical simulations of RC bridges under vehicle collision, and proposed an evaluation method for the shear performance of RC piers under vehicle collision. It was found that the major failure mode of RC bridges under vehicle collision was shear failure. Some previous studies defined different performance and damage levels of RC bridges subjected to vehicle collisions. However, shear performance of the bridge piers under such extreme loadings was not fully considered. More studies are needed to systematically incorporate the structural shear performance under vehicle collision within the PBE approach.

Performance of bridges can be represented by different indicators. For instance, reliability indicators consider uncertainties associated with loads and resistance [23-25], they are not able to account for the consequences incurred from bridge failure. Risk-based indicators provide the means to combine the probability of structural failure with the consequences associated with this event [25]. Vrouwenvelder [26] and Björnsson *et al.* [27] assessed the failure probability of bridge piers subjected to vehicle collision in order to determine the appropriate design loads. However, they did not consider the failure consequence to develop a complete risk assessment framework, neither did they discuss the performance evaluation of the in-service bridges. Sharma *et al*. [28,29] developed probabilistic impact demand and capacity models, and proposed a performance-based framework for the fragility analysis of bridge piers under vehicle collision. However, they only conducted fragility analysis for a single column without considering the hazard analysis and consequences. In this study, a comprehensive PBE approach incorporated within the risk assessment framework is applied to vehicle collision with bridge piers.

Within this paper, a generalized performance-based risk assessment framework of RC bridges under vehicle collision is presented, considering the specific mechanical characteristics of vehicle collision. This paper links the vehicle collision event with the probabilistic pier damage and loss assessment for the first time. The obtained analytical results could aid the design of bridge columns under vehicle collision by considering the failure probabilities and consequences associated with different failure modes. The paper consists of the following sections: introduction, framework of performance-based risk assessment, hazard scenario analysis, structural performance and damage assessment, risk assessment, illustrative example, and conclusions.

2. Framework of Performance-based Risk Assessment

Generally, quantitative risk assessment for collisions has received growing attention and is of vital importance to the design and maintenance of highway bridges. Highway traffic volume has increased significantly in the last few decades; consequently, risk associated with vehicle collision has increased and should be assessed to aid the decision making. This paper formulates a framework to assess the risk of RC bridge piers subjected to vehicle collision in a probabilistic manner.

The performance-based risk assessment for bridge piers under vehicle collision can be divided into three parts: (a) hazard scenario analysis; (b) structural performance and damage assessment (i.e., vulnerability analysis); and (c) consequence and loss evaluation associated with decision variables (e.g., repair loss). The hazard exposure procedure determines the probability of occurrence of collision. The vulnerability analysis aims to assess the probability of exceedance of each damage state under the given collision scenarios. Given the consequences associated with each damage state, the risk could be quantified. In this study, the concept of risk is integrated within the PBE to assess the performance of RC bridge piers subjected to vehicle collision. In order to compute the collision risk, the probability of collision, probability of structural failure under collision, and consequences of structural failure to the economy, society, and environment, should be assessed. The flowchart regarding the performance-based risk assessment of bridge piers under vehicle collision is shown in Fig. 1. The risk can be computed as [30]

$$R = P(H) \cdot \sum_{DS} C(Cons \mid DS) \cdot P(DS \mid H) \tag{1}$$

where $P(H)$ is the occurrence rate of extreme event H; $C(Cons|DS)$ is the conditional consequence under a given damage state DS (e.g., minor, severe, or complete); and $P(DS|H)$ is the conditional probability of being damage state DS given the extreme event H. Based on the theorem of total probability, the total risk/loss is the sum of consequences weighted by the probability of experiencing these consequences associated with different damage states.

3. Hazard Scenario Analysis

In order to compute the risk, the hazard scenarios should be identified first, and the occurrence probability of vehicle collision should be computed.

3.1 Probabilistic collision model

Vrouwenvelder [26] established a mathematical model for calculating the probability of vehicle collision with a single roadside column based on the probabilistic event of road vehicle running off an intended course (hereinafter referred as the run-off-the-road (ROR) event). Since bridges usually consist of multiple columns, the mathematical model of [26] is adapted to calculate the occurrence probability of vehicle collision with the multi-column bridge piers.

As shown in Fig. 2, an impact will occur if a vehicle leaves its intended course with a large enough speed within a certain critical angle. Obviously, the distance from the structural component to the road, the initial speed of vehicle, and the topographical characteristics of the terrain determine whether the vehicle has sufficient speed to impact on the structure or not. Regarding the multi-column bridge pier, it is reasonable to assume that the columns (except the column 1, which is the nearest from the vehicle) might be collided only if the front column is not collided. Assuming that the traffic density N_0 on the road segment and the vehicle failure intensity λ_0 (e.g., ROR event occurs) are constants, the occurrence probability of a collision event for a bridge pier with n columns within a reference period of T could be calculated as follows

$$P_{collision}(T) = \sum_{i=1}^{n} P_{collision}^{i}(T) \tag{2}$$

$$P_{collision}^{i}(T) = \begin{cases} N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^i < 0\right) \cap \left(v_r^i > 0\right)\right] \mathrm{d}x & i = 1 \\ N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^{i-1} \geq 0\right) \cap \left(G_1^i < 0\right) \cap \left(v_r^i > 0\right)\right] \mathrm{d}x & i = 2 \sim n \end{cases} \tag{3}$$

$$G_1^i = \left|\theta - \varphi_i\right| - \tan^{-1}\left(b / 2r_i\right) \tag{4}$$

$$v_r^i = \sqrt{v_0^2 - 2ar_i} \tag{5}$$

where v_r^i is the residual velocity of vehicle when it starts to contact with the column i after deceleration; v_0 is the initial velocity of vehicle; a is the deceleration of vehicle; r_i is the distance between the vehicle and column *i*; θ is the departure angle of vehicle; φ_i is the angle between the roadside line and the line passing through the centers of the vehicle and column *i*; *b* is a projected width, which may be taken as the vehicle width [27]; *n* is the total number of columns; *x* is defined as the coordinate originated from the column *n*, which is the furthest from the vehicle; G_1^i is a function associated with travelling direction of vehicle, and $G_1^i < 0$ indicates that the vehicle with such a departure angle will collide with the column *i* if $v_r^i > 0$; and, $P\left[\left(G_1^i < 0\right) \cap \left(v_r^i > 0\right)\right]$ is the collision probability of the column *i* given that an ROR event occurs at position *x*.

3.2 Mechanical impact model

In order to evaluate the hazard intensity caused by vehicle impact, the impact severity should be identified. Chen *et al*. [22] recommended using maximum impact force as the indicator of the impact severity, as it has a monotone increasing relationship with the impact responses of bridge piers (e.g., deflection). Vrouwenvelder [26] and Björnsson *et al*. [27] employed a single-degree-of-freedom (SDOF) mass-spring model to estimate the maximum impact force, which could be determined by the vehicular kinetic energy. However, recent finite element (FE) simulation studies [22,31] have found that the vehicular impact force is influenced by many factors, such as the vehicle mass, velocity, and engine mass, among others.

Chen *et al*. [20-22] proposed a coupled-mass-spring-damper (CMSD) model to simulate truck collision with bridge pier based on FE simulations, where the truck was simplified as a two-degree-of-freedom (TDOF) mass-spring-damper model considering the typical double-peak impact characteristics due to engine and cargo impacts. As illustrated in Fig. 3, m_1 and m_2 represent the mass of the engine and the rest of the truck (including cargo), respectively. Springs 1 and 2 characterize the nonlinear force-deformation relationships of the truck during the collision process. The friction damper is employed to account for the energy dissipated by friction during collision. It has been proved that the simplified truck model could estimate the peak impact forces reasonably well. According to Chen *et al*. [22], the maximum impact force F_m is calculated as

$$F_m = \max\left(F_{r1m},\, F_{r2m}\right) \tag{6}$$

$$F_{r1m} = \begin{cases} \sqrt{k_{1t}(m_1 v_0^2 - 2 f_{1y}\Delta_1) + f_{1y}^2} + f_{2y} & if \quad v_0 > \sqrt{2 f_{1y}\Delta_1 / m_1} \\ f_{1y} + f_{2y} & if \quad v_0 \le \sqrt{2 f_{1y}\Delta_1 / m_1} \end{cases} \tag{7}$$

$$F_{r2m} = \begin{cases} \sqrt{\dfrac{k_{2t}(m_2 v_0^2 - 2 f_{2y}\left(1+\mu_s\right)\Delta_2)}{1+\mu_s} + f_{2y}^2} & if \quad v_0 > \sqrt{2 f_{2y}\left(1+\mu_s\right)\Delta_2 / m_2} \\ f_{2y} & if \quad v_0 \le \sqrt{2 f_{2y}\left(1+\mu_s\right)\Delta_2 / m_2} \end{cases} \tag{8}$$

where F_{r1m} and F_{r2m} are the peak impact forces caused by engine and cargo impacts, respectively; Δ_1 and Δ_2 are the lengths of the plateau associated with springs 1 and 2, respectively (Fig. 3); in fact, Δ_1 corresponds to the distance between engine and bumper, while Δ_2 reflects the distance between cargo (or truck container) and bumper; k_{1t} and k_{2t} are the loading stiffness for the springs 1 and 2, respectively; f_{1y} and f_{2y} are the plateau forces for the springs 1 and 2, respectively; and μ_s is the coefficient for the friction damper. More information about the simplified truck model can be found in Chen *et al.* [22]. It is worth noting that the simplified truck model in Fig. 3 is a general truck model, because the parameters m_1, m_2, Δ_1, Δ_2, k_{1t} and k_{2t} have clear physical meanings, and can be altered to accommodate other types of trucks.

4. Structural Performance and Damage Assessment

Buth *et al.* [2] collected and summarized the vehicle-pier collision accidents and found that the main failure mode of the RC piers under vehicle collision was shear failure, which was further verified by FE simulations [22,31]. In this paper, the damage states of RC piers are divided into three levels, namely minor damage, severe damage (shear failure of pier), and complete damage (collapse of bridge frame), as shown in Fig. 4. With the increasing of the impact load, damage states would increase from minor damage to shear failure of pier, and even further collapse of the whole frame of the bridge if the gravity load from the superstructure is large enough. The failure criteria for shear failure of pier and collapse of bridge frame are discussed subsequently.

4.1 Shear performance assessment of RC pier under vehicle collision

Chen *et al*. [22] conducted a series of FE simulations regarding the vehicle collisions with a three-column RC pier, and found that the major failure mode of the column was shear failure. The limit state function associated with shear failure of the column *i* under vehicle collision is

$$G_2^i = 1 - \frac{F_m^i}{\lambda_v V_c^i} \tag{9}$$

where V_c^i is the static shear capacity of the RC column *i* calculated by the Biskinis model [32]; λ_v is a coefficient of the nominal shear capacity of the RC column under vehicle collision, which has a mean of 3.0 [22]; and F_m^i is the maximum vehicular impact force for the column *i*, which can be calculated by Eqs. (6-8). Obviously, $G_2^i < 0$ indicates a shear failure of the column *i* under vehicle collision, i.e., the damage state "shear damage of pier" reaches; $G_2^i = 0$ is the critical limit state; and $G_2^i > 0$ indicates that the column *i* would not fail in shear.

4.2 Collapse assessment of RC bridge under vehicle collision

Currently, there are few studies investigating the collapse behavior of RC bridge under vehicle collision. Tsang and Lam [33] analyzed the ultimate displacement of an RC single column before it collapsed under vehicle impact. However, to the best of the authors' knowledge, the collapse assessment method for multi-column RC bridge under vehicle impact has not been developed. As shown in Fig. 4, if the side column of the three-column pier fails due to vehicle collision, the gravity loads from superstructures might further fail the center column and then lead to collapse of the whole bridge frame; in this case, the top section of the center column becomes the critical section, i.e., the largest moment and axial force appear at this position. Similarly, if the center column is collided and failed, the top section of the side columns becomes the critical section, and the whole bridge frame might also fail if the gravity loads are large enough. The moment and axial force at the critical sections (i.e., M_d and N_d) could be easily determined through classical structural mechanics.

On the other hand, according to Ministry of Housing and Urban-Rural Development of the People's Republic of China [34], the bearing capacity of RC circular columns could be determined by solving the following equations

$$N = \alpha \alpha_1 f_c A \left(1 - \frac{\sin 2\pi\alpha}{2\pi\alpha}\right) + \left(\alpha - \alpha_t\right) f_y A_s \tag{10}$$

$$M_u = \frac{2}{3} \alpha_1 f_c A r \frac{\sin^3 \pi\alpha}{\pi} + f_y A_s r_s \frac{\sin \pi\alpha + \sin \pi\alpha_t}{\pi} \tag{11}$$

where α_1 is a coefficient, which equals to 1.0 if the nominal cubic compressive strength of concrete is less than 50 MPa; r and r_s are the radius of the column cross section and circumference of longitudinal steel center, respectively; A is the cross-section area of the column; A_s is the cross-sectional area of all the longitudinal steel; f_y and f_c are the yield strength of longitudinal steel and cylinder compressive strength of concrete, respectively; α is the central angle of the cross-sectional area of the concrete compression zone divided by 2π; and $\alpha_t = 1.25 - 2\alpha$, and $0 \le \alpha_t \le 1$. Let the axial load N equal to N_d, then α can be determined by Eq. (10), and thus the flexural capacity of the RC column (M_u) is calculated using Eq. (11).

In this study, it is reasonable to assume that the bridge frame would collapse if M_d is larger than M_u. The corresponding limit state function is

$$G_3^i = M_u^i - M_d^i \quad (12)$$

where G_3^i is the limit state function with respect to the collapse of the bridge frame; M_u^i is the flexural capacity at the critical section of the bridge after removal of the column *i*; M_d^i is the static moment at the critical section after removal of the column *i*. Obviously, $G_3^i < 0$ indicates that the bridge frame would collapse (i.e., the damage state "collapse of bridge frame" reaches) given that the column *i* is failed by vehicle collision.

5. Risk Assessment

Risk is an important indicator, which combines the probability of occurrence of a specific event and the consequence associated with this event [35]. In order to quantify the risk, the probability of structural system failure under vehicle collision and consequences associated with the structural failure events should be assessed. As various uncertainties exist within the structural systems and load scenarios, the structural failure is assessed in a probabilistic manner. Both direct and indirect economic consequences are investigated herein for RC bridge piers under vehicle collisions. For instance, the consequences include the rebuilding and repair costs, extra travel time and distance that drivers must endure, in addition to any fatalities that may occur, and among others [36,37]. The evaluation of a wide variety of consequences associated with structural failure plays a fundamental role in the structural performance assessment process.

5.1 Structural failure probability

The performance assessment process of highway bridges under loading effects has aleatory and epistemic uncertainties in the prediction or estimation of reality [38]. These uncertainties are present within the modeling of the structural resistance (e.g., material properties and geometrical characteristics), the occurrence and magnitude of hazards, loading cases, among others. In order to compute the failure probability, the limit state function associated with the investigated three damage states (see Fig. 4) should be established firstly. Since there is currently no appropriate method to assess the minor damage state, it is assumed to be reached once the errant vehicle impacts on the piers, considering that the piers would normally experience more or less damage once they were collided by vehicles in practice. Therefore, the exceeding probability associated with the minor damage state is equal to the collision probability, which is computed by Eqs. (2-5).

Section 4.1 introduces the limit state function for severe damage (shear failure of pier). As discussed in Section 4.1, $G_2^i < 0$ indicates that the column *i* under vehicle collision would fail in shear. Therefore, the column *i* would fail in shear if a vehicle leaves its intended course within a certain critical angle with large enough impact severity to make G_2^i less than zero. Similar to the discussion on the collision probability in Section 3, the exceeding probability of severe damage (shear failure of pier) of an RC bridge frame with *n* columns within time period *T* can be calculated as

$$P_{shear}(T) = \sum_{i=1}^{n} P_{shear}^{i}(T) \tag{13}$$

$$P_{shear}^{i}(T) = \begin{cases} N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^i < 0\right) \cap \left(G_2^i < 0\right)\right] \mathrm{d}x & i = 1 \\ N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^{i-1} > 0\right) \cap \left(G_1^i < 0\right) \cap \left(G_2^i < 0\right)\right] \mathrm{d}x & i = 2\sim n \end{cases} \tag{14}$$

where $P\left[\left(G_1^i < 0\right) \cap \left(G_2^i < 0\right)\right]$ is the shear failure probability of the column *i* given that an ROR event occurs at position x_i.

As discussed in Section 4.2, $G_3^i < 0$ indicates that the bridge frame would collapse given that the column *i* failed by vehicle collision. Similarly, the RC bridge frame would collapse (regarding vehicle collision with the column *i*) if a vehicle leaves its intended course within a certain critical angle with large enough impact severity to make G_2^i less than zero, meanwhile the gravity loads from the superstructure should be large enough to make G_3^i less than zero. Therefore, the exceeding probability of complete damage state (collapse) of an RC bridge frame with *n* columns can be calculated as

$$P_{collapse}(T) = \sum_{i=1}^{n} P^i_{collapse}(T) \tag{15}$$

$$P^i_{collapse}(T) = \begin{cases} N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^i < 0\right) \cap \left(G_2^i < 0\right) \cap \left(G_3^i < 0\right)\right] \mathrm{d}x & i = 1 \\ N_0 T \lambda_0 \int_{-\infty}^{\infty} P\left[\left(G_1^{i-1} > 0\right) \cap \left(G_1^i < 0\right) \cap \left(G_2^i < 0\right) \cap \left(G_3^i < 0\right)\right] \mathrm{d}x & i = 2 \sim n \end{cases} \tag{16}$$

where $P\left[\left(G_1^i < 0\right) \cap \left(G_2^i < 0\right) \cap \left(G_3^i < 0\right)\right]$ is the collapse probability given that an ROR event occurs at position x_i with respect to the column *i*.

In this way, given the uncertainties of the structural resistance (e.g., material properties and geometrical characteristics) and loading cases, the failure probability of the bridge under vehicle collision could be computed using numerical or simulation methods.

5.2 Consequence quantification

The subsequent step of the collision risk assessment is consequence quantification of structural failure with respect to different damage states. The consequence considered in this study consists of direct loss and indirect loss. The direct loss is considered as the repair cost of the collision-induced structural damage. The indirect loss includes the running costs of the vehicles following the detour and time loss for users due to the inaccessibility of the highway.

The direct loss of the damaged bridge under a certain damage state (DS) is expressed as [39,40]

$$C_{RE,DS} = RCR_{DS} \cdot c_{RE} \cdot W \cdot L \tag{17}$$

where RCR_{DS} is the repair cost ratio for the bridge at damage state *DS*; c_{RE} is the rebuilding cost of the bridge per square meter (RMB/m^2); *W* represents the bridge width (m); and *L* donates the bridge length (m). The expected direct loss is calculated as the sum of weighted repair loss for all the damage states, the probabilities of the bridge being in each DS serve as the weighting factors.

After the collision event, the collided bridge may be closed or partially closed due to the possible structural damage; some of the users are forced to follow the detour causing additional running cost and time losses. The running cost associated with a certain DS can be expressed as [40]

$$C_{Run,DS} = \left[c_{Run,car}(1-R_T) + c_{Run,truck} \cdot R_T\right] D_l \cdot ADTD_{DS} \cdot d_{DS} \tag{18}$$

where $c_{Run,car}$ and $c_{Run,truck}$ are the average costs for running cars and trucks per unit length (RMB/km), respectively; R_T represents the average daily truck traffic ratio; D_l represents the length of the detour; $ADTD_{DS}$ is the average daily traffic to detour at damage state DS, which is related to the functionality level of the bridge after collision; and d_{DS} is the duration of detour for a certain DS.

The time loss for the users following the detour and damaged link for a certain damage state is quantified in terms of monetary value and can be expressed as [40]

$$C_{TL,DS} = \left[c_{AW} \cdot o_{car}(1-R_T) + c_{ATC} \cdot o_{truck} \cdot R_T\right] \cdot \left[\frac{D_l \cdot ADTD_{DS}}{S} + ADTE_{DS}\left(\frac{l}{S_{d,DS}} - \frac{l}{S_0}\right)\right] \cdot d_{DS} \tag{19}$$

where c_{AW} is the average wage per hour (RMB/h); c_{ATC} is the average total compensation per hour (RMB/h); $ADTE_{DS}$ is the daily traffic remaining on the damaged link for a certain damage state; o_{car} and o_{truck} are the average vehicle occupancies for cars and trucks, respectively; S_0 and $S_{d,DS}$ are the average speed on the intact link and damaged link (km/h), respectively; l is the length of the link; and S is the average detour speed (km/h). The total economic loss is calculated as the sum of direct loss and indirect loss, which includes the repair cost, vehicles running cost of following the detour, and time loss due to the inaccessibility of the highway.

The total expected loss is quantified by the sum of weighted loss for all damage states, the probabilities of being different damage states serve as the weighting factors. The economic loss is considered in this paper. Given the relevant parameters, other types of consequences could also be incorporated within the computational process (e.g., social and environmental impacts).

6. Illustrative Example

In this section, the proposed methodology is applied to assess the vulnerability and risk of an actual RC bridge subjected to vehicle collision.

6.1 Bridge description

The investigated bridge is a viaduct that crosses the S322 highway on the G4 expressway in China. As illustrated in Fig. 5, the frame 3 of the bridge is located in the middle zone of the S322 highway, thus leaving a danger of collision from both traffic directions. In reality, the column 6 of the frame 3 was collided and broken by heavy cement tankers in 2009, leading to the collapse of the adjacent bridge spans. Therefore, this study focuses on the collision risk associated with the frame 3 of the bridge.

The investigated bridge has five spans and four lanes (excluding emergency lanes) in two directions, with a total length and width of 98 m and 27 m, respectively. The bridge is supported by piers and abutments. The geometric dimensions of transverse frame 3 are shown in Fig. 6. The frame 3 consists of 6 columns and each of 3 columns serve as an independent structure in both directions of travel. Each column is evenly reinforced with 16 longitudinal steel bars with 20 mm in diameter along the circumference of the section. The spiral stirrups with a diameter of 8 mm are arranged along the column height. The nominal values of the total cross-sectional area of the longitudinal bars A_s and the cross-sectional area of stirrups A_{sw} are 5027.2 mm^2 and 50.3 mm^2, respectively. According to the geometrical dimensions of the superstructure and the material density, the nominal dead load F_D on the cap beam of the frame 3 (half) from the superstructure is calculated as 4393 kN. The nominal live load F_Q is determined as 1020 kN based on the Ministry of Transport of the People's Republic of China [41]. The F_D and F_Q are considered to follow the normal distribution and the extreme value distribution (type I), respectively. The line load *q* on the top of the half of frame 3 can be calculated as

$$q = \frac{F_D + \eta_Q \cdot F_Q}{l_{cap}} \tag{20}$$

where l_{cap} is the length of cap beam and in this study it is equal to 16,574 mm; η_Q is the dynamic factor for live load. The moment and axial force at the critical sections (i.e., M_d and N_d) could be determined through classical structural mechanics subsequently. In this study, the mean value of the variable is considered as the product of the nominal value and ratio of the mean to the nominal (RMTN). The variables of the bridge involved herein are shown in Table 1.

6.2 Traffic and vehicle description

The S322 highway where the frame 3 of the bridge is located is a provincial-level main road with a speed limit of 60 km/h. The traffic flow in the area where the bridge is located is assumed to be 2,000 trucks per day. The truck mass and travel speed follow the normal distribution and lognormal distribution, respectively [26]. The mean value and coefficient of variation (COV) for truck mass are taken as 20 tons and 0.6, respectively [26]. The travel speed of vehicle is assumed to have a mean and COV of 60 km/h and 0.1, respectively.

Obviously, the ROR accident rate of vehicle (λ_0) directly affects the probabilities of vehicle collision, shear failure of pier and collapse of bridge frame. The ROR accident rate λ_0 suggested by Björnsson *et al*. [27] is adopted in this study, i.e., 1.0×10^{-10} vehicle^{-1}·m^{-1}. According to Björnsson *et al*. [27] and Vrouwenvelder [26], the departure angle θ and the deceleration a of the vehicle deviating from the travel route follow the Rayleigh distribution and lognormal distribution, respectively, and the mean values are 10° and 4 m/s^2, respectively. The COVs for θ and a are 0.52 and 0.325, respectively. The projected width b is difficult to be determined. Geometrically, it should equal to column diameter plus vehicle width. However, if the vehicle runs off the road at the threshold angle, it would physically only scratch with the column leading no damage to the pier. In this case, the projected width b should be decreased or the impact demand (e.g., maximum impact force) should be decreased instead. Due to the fact that the eccentric collision of vehicle has been seldom studied regarding the impact demand, b is assumed to follow a normal distribution with a mean of 2.5 m [27], which is roughly equal to the width of trucks, and the COV is 0.1.

In regards to the simplified truck model (Fig. 3), the parameters m_1, Δ_1, Δ_2, k_{1t}, and k_{2t} are set as random variables considering the uncertainties associated with different types of trucks. Normal distributions are assumed for these parameters with COVs equal to 0.1, and the mean values are determined based on the F800 truck [20,21].

6.3 Fragility and risk assessment

In this study, fragility is defined as the conditional probability of exceeding a specified damage state of the bridge pier under vehicle collision with given impact velocity and truck mass [28], which can be estimated through Eq. (21)

$$P^i_{fragility}\left[DS\left|(m,v_0)\right.\right]=\begin{cases} P\left[\left(G_2^i<0\right)\left|(m,v_0)\right.\right] & DS=\text{Pier shear failure} \\ P\left[\left(G_2^i<0\right)\cap\left(G_3^i<0\right)\left|(m,v_0)\right.\right] & DS=\text{Frame collapse} \end{cases} \tag{21}$$

Fig. 7 shows the fragility contours of the bridge pier under vehicle collision. As shown in the figure, the fragility contours exhibit strong nonlinear characteristics, and the influences of truck mass and velocity on the fragility of the bridge under vehicle collision are significantly different. This is mainly attributed to the nonlinear mechanical characteristics of vehicle impact (e.g., the typical double-peak impact characteristics due to engine and cargo impacts). It is found that the fragility for shear failure of pier is identical to that for collapse of bridge frame due to collision on the side column (see Fig. 7a), indicating that the whole bridge frame will collapse when the side columns fail. On the contrary, Fig. 7b shows that the pier will most probably not collapse when the center columns are collided, as the failure probabilities regarding collision with center columns are always very close to zero, no matter what truck mass and velocity are. As shown in Fig. 7a, when the truck mass is relatively large (e.g., more than 30 tons), even if the impact velocity is very low (e.g., 40 km/h), the probability of shear failure/collapse is close to 1, hence, the maximum value of vehicle mass is considered as 40 tons. When the truck mass is small (e.g., less than 10 tons), the probability of shear failure/collapse of the bridge pier is very sensitive to the impact velocity; for example, when the impact velocity increases from 80 km/h to 120 km/h, the probability of shear failure/collapse will increase from slightly less than 0.1 to slightly greater than 0.9. When the truck mass is in the range of 10-30 tons, both the truck mass and the impact velocity have a significant impact on the probability of shear failure/collapse. Fig. 7a also indicates the scenario for the real accident. As shown in the figure, when the truck mass and velocity equal to 40 tons and 80 km/h, respectively, the probabilities for shear failure of pier and collapse of bridge frame due to collision on side columns are almost equal to 1.0, which are coincident with the collision results by the accident, i.e., collapse of the bridge.

Fig. 8 shows the probabilities per unit length along the road in the traffic direction for vehicle collision, shear failure of pier and collapse of bridge frame. It can be seen from the figure that the probabilities of vehicle collision, shear failure of pier, and collapse are in deceasing order. The probability of vehicle collision and shear failure of pier mainly goes through two stages of platform and descent as the distance between the vehicle and the pier increases. There is an obvious trough phenomenon for the collapse probability of the bridge frame. This is because when vehicles are located in these positions, they are most likely to hit the center column of the frame, but the failure of the center columns is significantly less likely to cause the collapse than the failure of the side columns.

Fig. 9 shows the probability of each bridge column suffering vehicular collision, shear failure, and collapse for one traffic direction. The column 1 is the nearest column when vehicle approaches the pier. It can be seen from the figure that the probabilities of vehicle collision, shear failure of pier and collapse of bridge frame for the column 1 are the highest among all the columns, indicating that the column 1 has significant protective effects on the other columns. The collapse probability of the bridge associated with the columns 2 and 5 is almost zero, which indicates that the shear failure of the center columns generally does not cause the bridge to collapse in this scenario. The expected annual probability for vehicle collision, shear failure and collapse are computed according to Eq. (2), Eq. (13) and Eq. (15) as 3.280×10^{-3}, 1.702×10^{-3}, and 1.243×10^{-3}, respectively.

Consequence is evaluated by considering the direct and indirect loss. The direct loss (e.g., repair cost) for a given damage state is computed using Eq. (17). Given the probability of being in each damage state, the expected direct loss is computed as the sum of weighted repair loss for all the damage states. The indirect loss consists of running cost and time loss and are quantified using Eqs. (18) and (19), respectively. The total economic loss is the sum of direct and indirect loss. The risk under given collision scenario (as listed in Table 1) can be quantified as the product of loss and the collision occurrence probability as indicated in Eq. (1), the quantified risk is 1.2605×10^{5}. The input parameters used in consequence quantification are listed in Tables 2 and 3.

6.4 Sensitivity analysis

In this section, the influences of several main variables on the probabilities of vehicle collision, shear failure of pier, and collapse of bridge frame are analyzed, as shown in Fig. 10, where the abscissa is the ratio of the modified mean value of each variable to the original mean value (as listed in Table 1). Fig. 10a shows that the three variables that have large influences on the collision probability are the departure angle (θ), projected width (*b*), and impact velocity (v_0). Increasing the mean value of the projected width and impact velocity would increase the probability of collision, while the increase of the departure angle could reduce the collision probability. Comparing Figs. 10b with 10c, it is found that the influence of the investigated variable on the probabilities of pier shear failure and frame collapse is quite similar; and the variables that have relatively large impact on the relevant probabilities are the impact velocity (v_0), truck mass (*m*), and the parameter Δ_2 in the simplified truck model (see Fig. 3); in addition, the pier diameter (*d*) also has a significant effect. Increasing the mean value of the impact velocity and truck mass could significantly increase the probability of shear failure/collapse, while increasing Δ_2 and the pier diameter could reduce the corresponding probability. Clearly, in order to conduct an accurate risk analysis of bridge piers under vehicle collision, the probability distribution functions of truck mass and velocity should be carefully investigated. Moreover, increasing the pier diameter is an effective way to improve the safety of the piers subjected to vehicle collision.

The economic loss under different velocities and vehicle masses (m = 5 tons, m = 12 tons, and, m = 30 tons) is presented in Fig. 11. As illustrated in Fig.11, the loss increases significantly subjected to the same velocity levels (especially for lower levels) when the truck mass increases from 12 tons to 30 tons, while the effects of truck mass on loss are not significant when it changes from 5 tons to 12 tons. The velocity ranging from 40 km/h to 80 km/h has insignificant influence on loss when m = 5 tons or 12 tons, while the loss increases dramatically when the velocity rises from 80 km/h to 120 km/h. The effects of velocity on loss when m = 30 tons is less significant compared with lower mass cases. Additionally, the relative contribution of indirect loss and direct loss to total loss is investigated for various truck masses and velocity values. The ratios of indirect loss to total loss are presented in Fig. 12. For m = 5 and m = 12 tons, the direct loss contributes more to the total loss compared with indirect loss under low velocity levels (e.g., 40 km/h to 70 km/h), the indirect loss dominates the consequences under high velocity levels (e.g., 90 km/h to 130 km/h). For m = 30 tons, the indirect loss has dominating contribution to total loss under all investigated velocity values. Fig. 13 illustrates the contribution (proportion) of loss associated with different damage states to the total loss. When m = 5 tons, the loss of severe damage state has insignificant contribution. The contribution of loss associated with complete damage state is significant under high velocity levels, while the contribution of loss associated with minor damage state is more apparent under low velocity levels. When m = 30 tons, the loss associated with complete damage state has a large contribution to total loss.

7. Conclusions

In this paper, a performance-based method is proposed to assess the risk of multi-column reinforced concrete (RC) bridges under vehicle collision in a probabilistic manner. This probabilistic method consists of three parts, i.e., hazard scenario analysis, structural performance and damage assessment (i.e., vulnerability analysis), and consequence evaluation. The probability and mechanical characteristics of vehicle impact, column damage and collapse are fully considered within the methodology. The proposed method is illustrated with a prototype RC pier under different collision scenarios. The specific conclusions are:

1. A probabilistic collision model is established, which can be used to identify the probabilistic hazard scenarios for piers with multiple columns under vehicle collisions.
2. Three different damage states are considered for the RC piers, i.e., minor damage, severe damage (shear failure of pier), and complete damage (collapse of bridge frame), the shear failure of pier is assessed, while a limit state function is proposed to assess the collapse of bridge frame with multiple columns under vehicle collisions.

3. The fragility contours of the investigated RC pier show that there are strong nonlinear relationships between truck mass (or velocity) and failure probability, and the contributions of truck mass and velocity on the impact effects are very different. The reason lies in that the nonlinear mechanical characteristics of vehicle impact are considered in the mechanical impact model (e.g., the typical double-peak impact characteristics due to engine and cargo impacts).
4. Due to the protective effect of the first column (closest to the approaching vehicle), the probabilities for the other columns with respect to vehicle collision, shear failure of pier and collapse of bridge frame are all significantly reduced. Besides, it is found that a vehicle impacting a side column is more likely to cause a pier to collapse compared with impacting a center column.
5. Sensitivity analysis reveals that the truck mass and impact velocity have the greatest influences on the probability of shear failure/collapse, while increasing the pier diameter is an effective way to improve the safety of the bridge pier under vehicle collision. The loss conditioned on truck mass and velocity facilitates the safety control of the bridges subjected to vehicle collision. Different types of vehicles and different speed limits can be prescribed based on the acceptable risk or loss level.

The proposed methodology can be used in assisting decision making regarding the traffic control and risk mitigation activities to improve the traffic safety within a transportation network. This paper provides the main framework for performance assessment of RC piers subjected to collision. Given more information and theoretical models (e.g., damage models of different materials, failure mechanism, collision model), the proposed framework could be adopted to assess the relevant structural performance by considering different collision scenarios and bridge materials. Additionally, vehicle crash accidents are often accompanied by fires and further studies are need to incorporate fire from vehicle collision with probabilistic performance assessment of bridges subjected to collision.

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Table 1 Descriptors of random variables

Variable	Designation	Distribution	Nominal	RMTN*	COV**
m	Truck mass	Normal	20 t	1.0	0.6
m_1	Engine mass	Normal	0.84 t	1.0	0.1
v_0	Impact velocity	Lognormal	60 km/h	1.0	0.1
N_0	Number of truck per day	Deterministic	2000	1.0	/
T	Reference time	Deterministic	100 year	1.0	/
λ_0	Accident rate	Deterministic	1×10^{-10} vehicle$^{-1}\cdot$m^{-1}	1.0	/
a	Deceleration	Lognormal	4 m/s^2	1.0	0.325
θ	Departure angle	Raleigh	10°	1.0	0.52
b	Vehicle projected width	Normal	2.5 m	1.0	0.1
Δ_1	Parameters of the used truck model (see Fig. 4)	Normal	0.55 m	1.0	0.1
Δ_2		Normal	2.7 m	1.0	0.1
k_{1t}		Normal	300 kN/mm	1.0	0.1
k_{2t}		Normal	350 kN/mm	1.0	0.1
F_D	Dead load on pier cap	Normal	4393 kN	1.0148	0.0431
F_Q	Live load on pier cap	Extreme value (Type I)	1020 kN	0.7187	0.0769
η_Q	Dynamic factor for live load	Extreme value (Type I)	1.1776	1.0	0.0428
l_d	Distance between column center and road line	Normal	1.0 m	1.0	0.1
d	Column diameter	Normal	1.0 m	1.0	0.007
h	Column height	Normal	5.4 m	1.0	0.007
b_{cap}	Cap beam width	Normal	1.7 m	1.0013	0.0081
h_{cap}	Cap beam height	Normal	1.1 m	1.0064	0.0255
A_s	Cross-section area of longitudinal bars	Normal	5027.2 mm^2	1.0	0.035
A_{sw}	Cross-section area of hoops	Normal	50.3 mm^2	1.0	0.035
s	Spacing of hoops	Normal	200 mm	1.0	0.1
c	Thickness of concrete cover	Normal	30 mm	1.0178	0.0496
f_y	Yield strength of longitudinal bars	Normal	340 MPa	1.0840	0.0719
f_{yw}	Yield strength of hoops	Normal	240 MPa	1.0821	0.1211
f_c	Concrete cylinder compressive strength	Normal	21 MPa	1.5012	0.1773
λ_v	Coefficient for limit state function G_2	Normal	2.75	1.0	0.1

Note: *. RMTN represents the ratio of the mean to the nominal value; **. COV is the coefficient of variation.

Table 2 Parameters used in consequence assessment (adopted from [42])

Variable	Unit	Value
Daily truck traffic ratio	/	13%
Length of link	km	5
Detour additional distance	km	2
Vehicle occupancies for cars	/	1.5
Vehicle occupancies for trucks	/	1.05
Rebuilding costs	RMB/m^2	16142
Compensation for truck drivers	RMB /h	209.1
Operating costs for cars	RMB /km	2.7
Operating costs for trucks	RMB /km	3.99
Wage for car drivers	RMB /h	83.37
Detour speed	km/h	50
Link speed	km/h	60

Table 3 Traffic information associated with different damage states (adopted from [43,44])

Damage states	Duration of detour (days)	Remaining traffic flow capacity	Damage cost ratio	Remaining flow speed
Slight	7	100%	0.03	75%
Major	120	50%	0.75	50%
Complete	400	0%	1	-

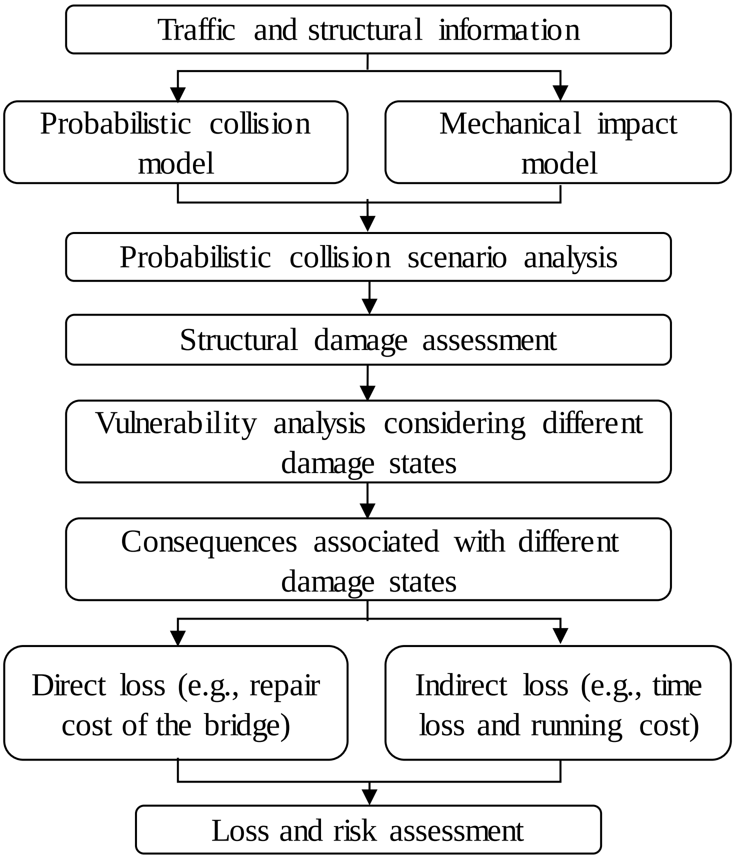


Fig. 1 Flowchart of the performance-based risk assessment of bridge piers subjected to vehicle collision

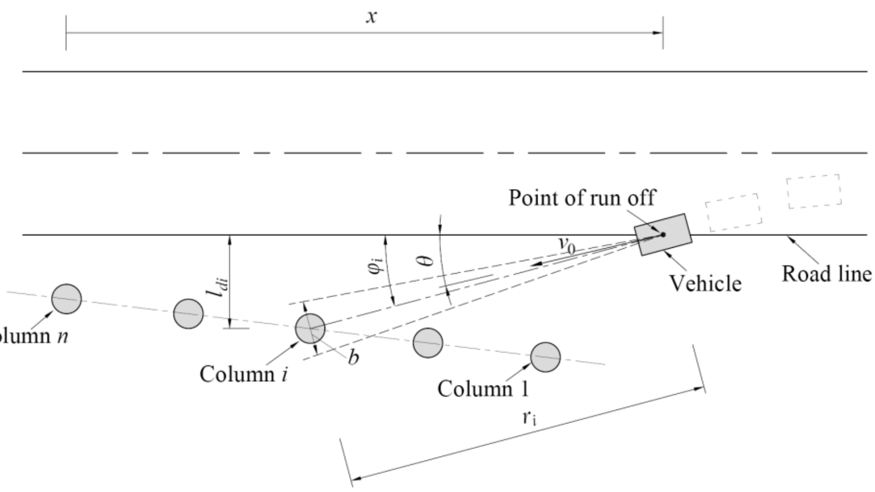
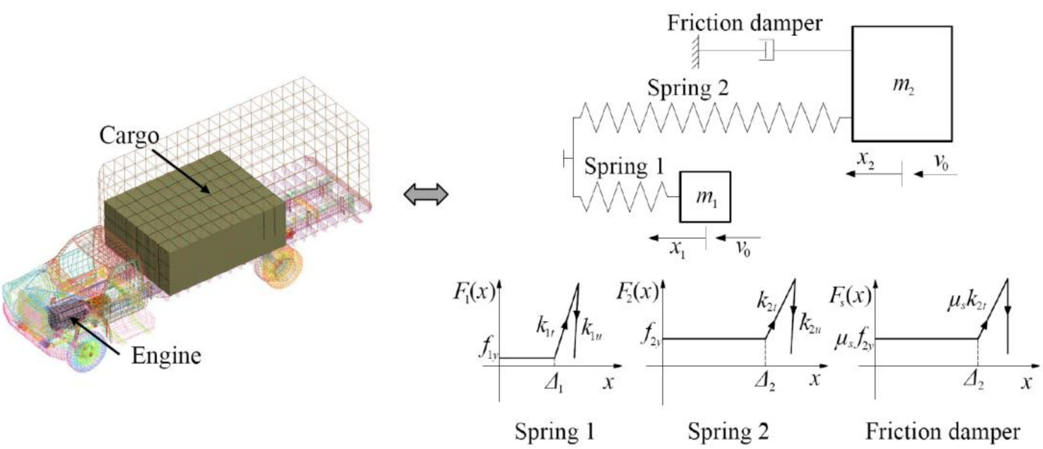
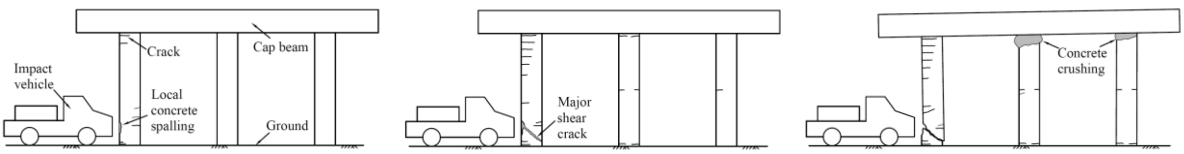


Fig. 2 Vehicle collision with multi-column bridge pier



(a) FE truck model (b) Simplified truck model

Fig. 3 FE truck model versus simplified truck model



(a) Minor damage

(b) Severe damage (Shear failure of pier)

(c) Complete damage (Collapse of bridge frame)

Fig. 4 Illustration of damage states of RC bridge pier subjected to vehicle collision

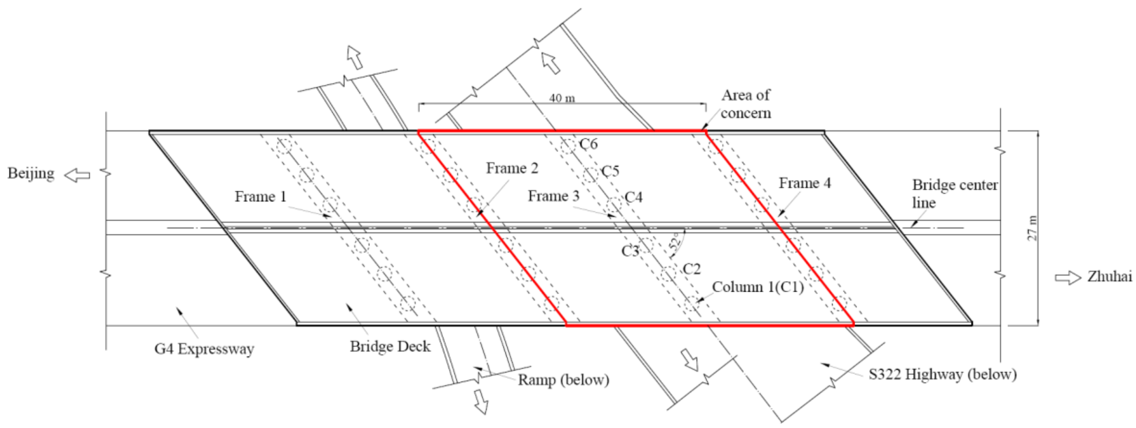


Fig. 5 Investigated bridge plan

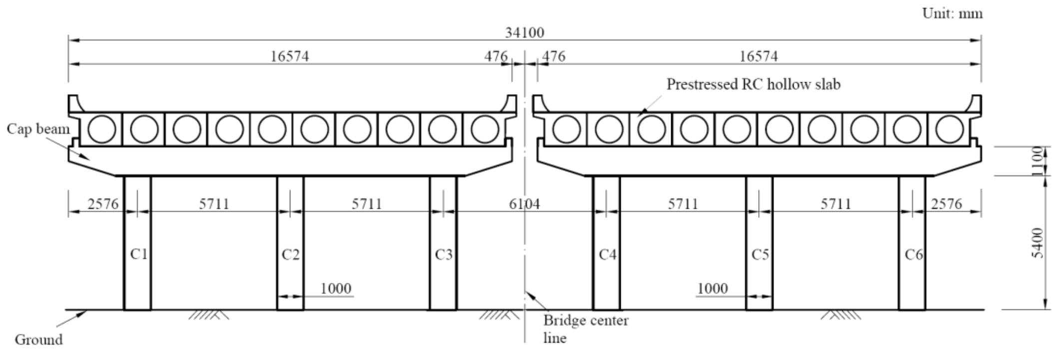
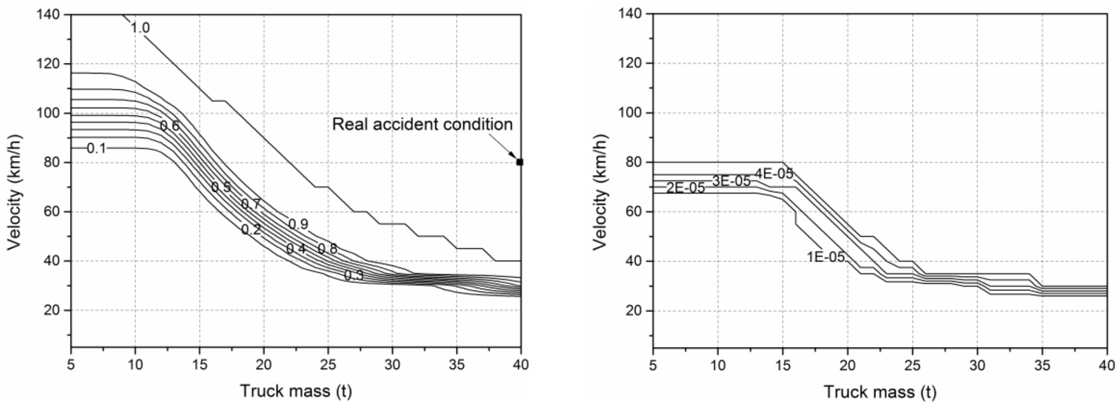


Fig. 6 Dimensions of the bridge frame 3



(a) Shear failure of pier/Collapse of bridge frame due to collision on side column

(b) Collapse of bridge frame due to collision on center column

Fig. 7 Fragility contours with respect to vehicle collision by considering different truck masses and velocities

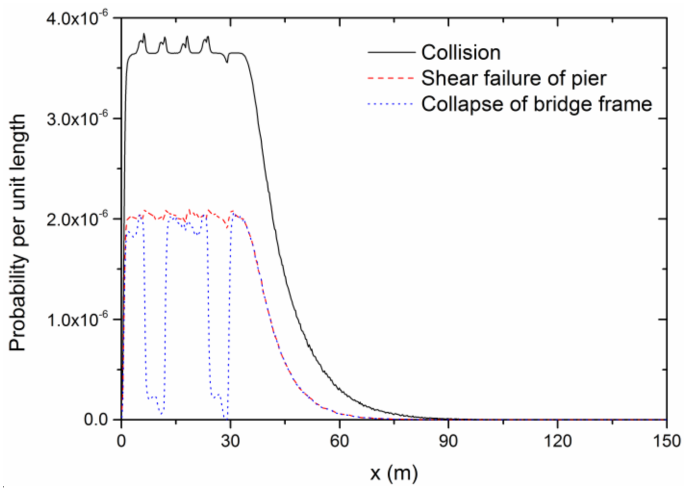


Fig. 8 Probability per unit length along the road (T = 100 year; One traffic direction)

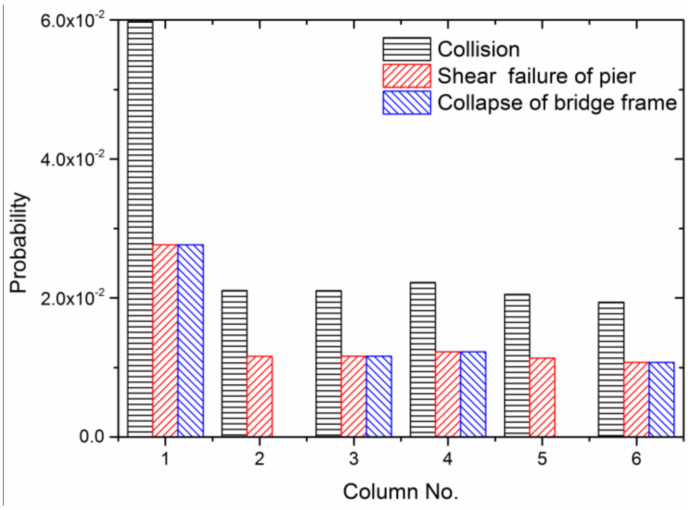


Fig. 9 Probability for each column (T = 100 year; One traffic direction)

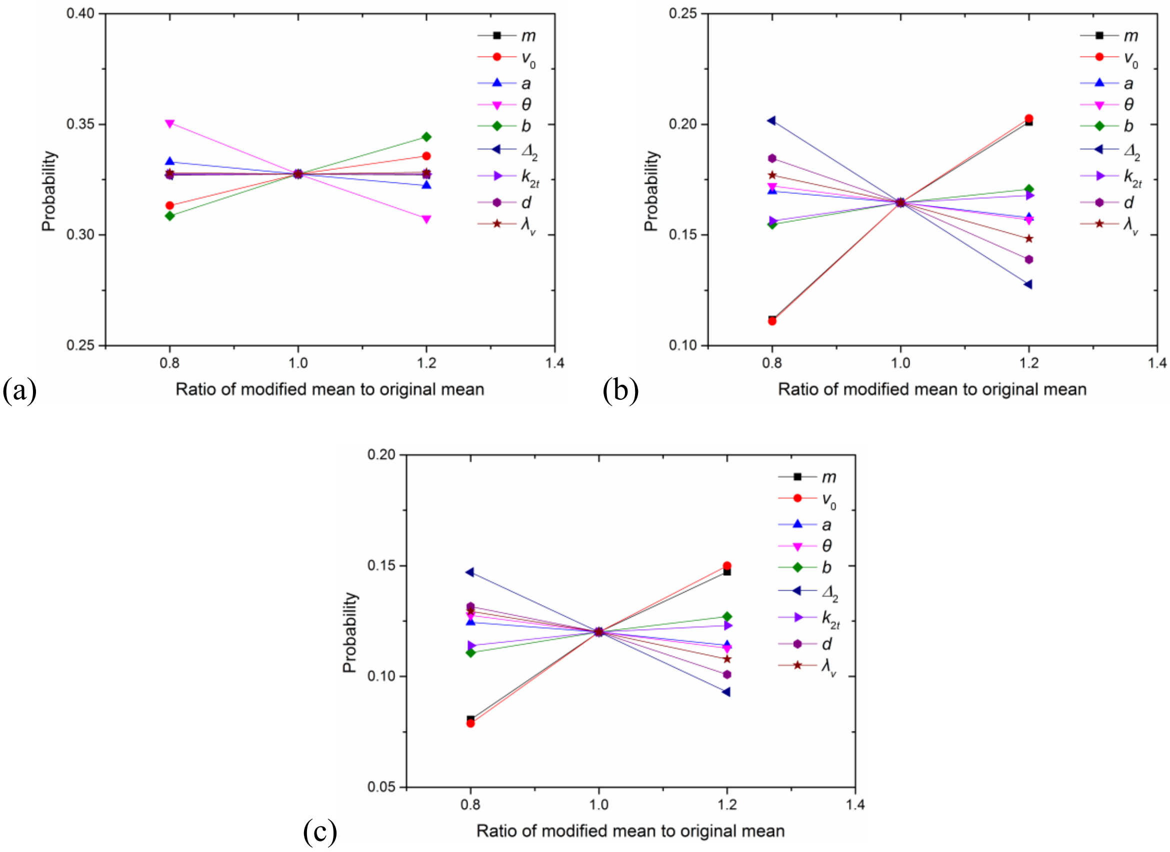


Fig. 10 Sensitivity analysis of main variables on the probabilities: (a) collision; (b) shear failure of pier; and (c) collapse of bridge frame

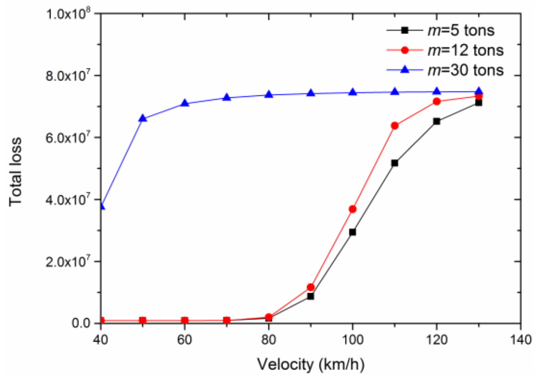


Fig. 11 Collision induced loss under different velocities and vehicle masses

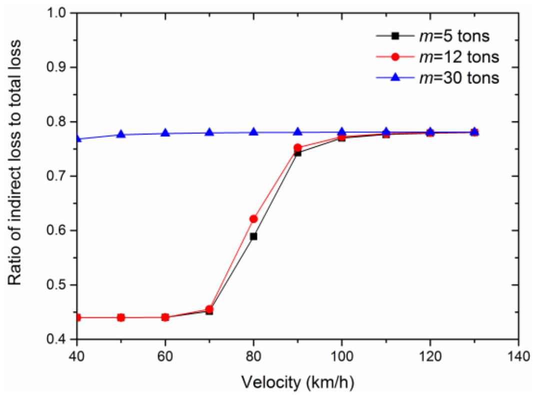


Fig. 12 Ratio of indirect loss to total loss under different velocities and vehicle masses

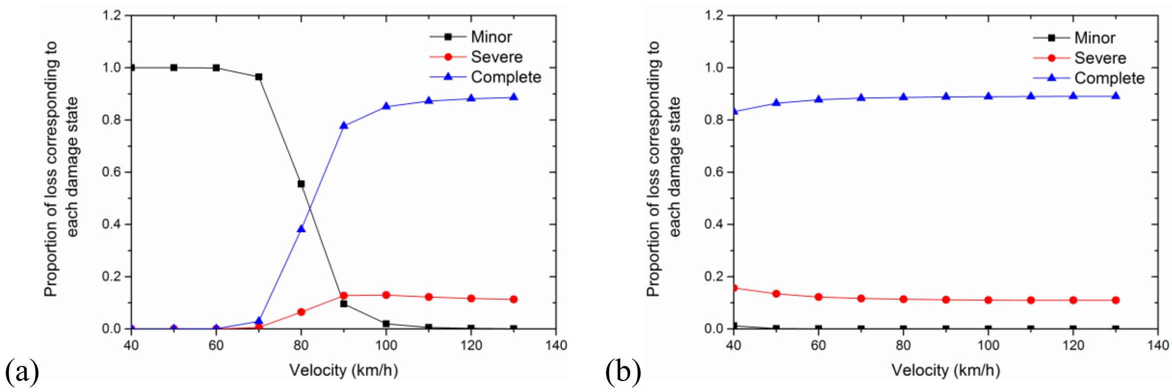


Fig. 13 Proportion of loss corresponding to each damage state: (a) *m* = 5 tons; and (b) *m* = 30 tons