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Dynamic responses and failure modes of bridge columns under vehicle collision

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ABSTRACT

The dynamic responses and failure modes of reinforced concrete bridge columns under vehicle collision have been numerically investigated in this study by using a numerical model verified against some experimental testing data. The numerical results show that the Peak Impact Force (PIF) from the collision is governed by the vehicle engine and the vehicle velocity while the impulse of the impact force is influenced by the initial momentum of the total mass. It is, therefore, suggested that not only the total vehicle mass and the vehicle velocity but also the engine's weight need to be considered to determine the impact force on structures under vehicle collision. The engine's mass significantly affects the peak impact force, the moment, the shear force and thus the damage of the column. The lateral impact force considerably affects the column axial force and a relation between the PIF and the increase of the axial force is proposed for the design purpose. The numerical model is able to reproduce and provide an explanation of most of the common failure modes observed in real impact events including flexural failure, shear failure, and punching shear damage. In addition, the influences of four different methods of the superstructure modelling, i.e. uniformly distributed load, lumped mass, simplified beam model, and 3D detailed model on the behaviour of the bridge column under vehicle impact are also investigated.

1. Introduction

Due to the significant development of cities and transportation infrastructure as well as the increase of traffic in urban areas, vehicle collision with bridge structures or buildings occurs more often around the world [1,2]. Heavy trucks collide to bridge structures may cause catastrophic consequences on human life and infrastructure systems. According to Federal Highway Administration, a vehicle or a vessel collision is the third leading reasons which cause a bridge collapse in the United States (US) [2]. Buth et al. [1] reported 19 extreme cases of vehicle collision with bridge columns in the US. Among these accidents, some collisions led to the collapse of the superstructures, such as the truck accident in Texarkana, 1984 or in Corsicana, 2002 as shown in Fig. 1a. In the world, in April 2009, a heavy tank truck hit a bridge column in Beijing – Zhuhai Expressway in Hunan, which caused a severe damage to the column (see Fig. 1b), the deaths of two passengers, and resulted in the closing down of the traffic systems for over two months [3]. Despite the occurrence of such accidents and their devastating consequences, the impact-resistant capacity of concrete columns under vehicle collision is still not well predicted and designed. The behaviours of the column during an impact event, i.e. the axial force, bending moment, shear force, and failure modes need to be investigated.

To design structures against vehicle impact, an Equivalent Static Force (ESF) approach is provided in several design codes and reports [4–7]. Buth et al. [8] used a tractor trailer to conduct a large-scale collision test on a steel column. A series of finite element models were also built based on the experimental results. Based on these results and the open literature, AASHTO-LRFD [4] recommended that an ESF of 2668 kN acting on bridge columns or piers at a distance of 1.5 m above the ground level is used for the design purpose. BSI [5] recommended a simplified equation to determine the impact force on structures based on the vehicle's kinetic energy, the vehicle's deformation, and the column deformation, as follows:

$$ESF = \frac{0.5mv^2}{\delta_c + \delta_d} \tag{1}$$

in which ESF is the impact force on structures (kN), m is the gross mass of the vehicle (kg), v is the vehicle's velocity (m/s), δ_c is the deformation of the vehicle model, which is defined as the change in length between the centre of mass and vehicle nose (mm), and δ_d is the deformation of the barrier at the impact point (mm).

El-Tawil et al. [9] conducted numerical simulations of two detailed bridge structures and vehicle models to study truck collisions on bridge

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(a) Corsicana, Texas in 2003 (b) Hunan, China in 2009

Fig. 1. Truck collision with bridge columns.

columns. The peak impact force (PIF) and the ESF from the simulations were also reported. The ESF was defined as the static force required to generate the similar lateral displacement which is equal to that of displacement under dynamic load at the impact point. The results indicated that the current AASHTO-LRFD design provision could be unconservative in some circumstances. Calibrated with El-Tawil et al. [9] simulation results, Abdelkarim and ElGawady [7] conducted a series of numerical simulations of reinforced concrete bridge columns under different vehicle impact conditions to evaluate the AASHTO-LRFD vehicle collision force provisions. The effects of 13 column parameters on the impact force were also studied. The equation for estimating kinetic-energy based equivalent static force which is a function of the vehicle mass and the vehicle velocity was proposed without finite element analysis requirements as follows:

$$ESF = 33\sqrt{mv^2} \tag{2}$$

where ESF is the equivalent static load (kN), m is the mass of the vehicle (ton) and v is the vehicle velocity (m/s).

It is worth mentioning that the dynamic behaviours of bridge columns such as vibration and dynamic capacity were not considered in these provisions and the proposed methods. Previous studies [10,11] showed that the dynamic bending moment and shear force of a reinforced concrete (RC) beam against impact loading are significantly different from those under static loading. Because of the effects of the inertia force varied along the beams, both positive and negative bending moments were observed in the simply supported beam with the positive bending moment at the mid-span and the negative bending moment at the two ends. Besides, the maximum shear force was recorded at the mid-span of the beam [10]. These phenomena are unique for beams against impact force and it is difficult for the static equivalent method to capture these behaviours. Sharma et al. [12] modelled the collision with some vehicle models with different velocities to examine the shear force of concrete columns. The numerical results indicated that the dynamic shear force of the reinforced concrete column under vehicle impact is not only greater than the static counterpart but also varying with different collision conditions. A proposed procedure to estimate the dynamic shear force demand based on the performance level of the column was also developed. These previous studies indicated that the impact response of a bridge column including bending moment, shear force, and axial force need to be taken into consideration, whereas the ESF method does not necessarily lead to accurate estimations.

In terms of the failure modes of bridge columns subjected to a collision, several types of failure modes, i.e. flexural cracks, shear failure, punching shear failure, and brutal damage were observed in real impact events and documented [1] as shown in Fig. 2. It is very clear from the figure that the failure modes of the bridge columns are significantly different under various loading conditions. These failure modes could not be predicted by using the ESF method but can only be observed in real dynamic analyses. An experimental test of a scaled column under pendulum impact force by Zhang et al. [13] showed severe flexural cracks occurred at the column mid-height while a diagonal shear failure was observed at the column base. Besides, the experimental tests by Demartino et al. [14] showed that a brittle shear failure starting from the column base to the impact point and some flexural cracks at the column mid-height were observed on RC columns subjected to lateral impact. Moreover, bending moment variation along a column under impact loading was presented by Thilakarathna et al. [15]. The results showed that the impacted column generated the third order vibration mode under impact load resulting in high bending moment and shear force at the column top, which may lead to an excessive shear failure. These variations of the failure modes have not been thoroughly explained in the literature and require more studies to understand the mechanism behind.

Furthermore, to study bridge or building columns under dynamic loads, superstructures previously were simulated by a constant uniformly distributed load [16], a lumped mass [17], or a simplified beam model [9]. It is well-known that the inertia force and the damping produced from the structural mass and stiffness, i.e. superstructure components are crucial to resist the dynamic loading. Different types of superstructure modelling may lead to different failures of the column due to its inertia force distribution. Therefore, the detailed 3D model should be developed and the effects of the superstructure modelling simplifications on the performance of the bridge column need be examined.

In this paper, the impact responses and performances of bridge columns under vehicle collision are investigated with a detailed 3D model which is built with the commercial software LS-DYNA [18]. The accuracy of the numerical model is verified against the testing results of the pendulum impact tests on a conventional column by Zhang et al. [13]. The impact force, vibration, axial force, bending moment, shear force, and the failure modes of columns under different loading conditions, i.e. different vehicle mass and vehicle velocities are examined. The influences of the superstructure model on the performances of bridge column are also investigated.

2. Numerical model calibrations

2.1. Experimental pendulum impact tests

The experimental test of a scaled column under pendulum impact reported by Zhang et al. [13] is simulated in this study to verify the numerical model. The testing data including the detailed design of the column, material properties, and the pendulum impact system is briefly described in this section.

The overall dimension of the rectangular testing column was 800 mm in height, 100 mm in depth, and 100 mm in width, which was a quarter-scale column model, as shown in Fig. 3. A footing of