Engineering Structures 173 (2018) 251–268

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Performance and sensitivity analysis of UHPFRC-strengthened bridge columns subjected to vehicle collisions

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ARTICLE INFO

Keywords:
Vehicle collision
Crashworthiness
FE modeling
Ultra-high-performance fiber reinforced concrete (UHPFRC)
Residual load-carrying capacity
Response surface model

ABSTRACT

Bridge columns made of normal concrete are evidenced to be susceptible to vehicle collisions. Particularly in the United States, vehicle collision has become one of the primary causes of bridge failures. This is largely due to the low crashworthiness of a conventional reinforced concrete (RC) column. Ultra-high-performance fiber-reinforced concrete (UHPFRC) as one of advanced concrete materials has been experimentally demonstrated to possess excellent strength, durability, impact resistance and energy-absorbing capacity. Accordingly, one type of UHPFRC-strengthened columns was proposed in this study as an alternative to RC columns that may be at risk for vehicle collision incidents. High-resolution finite element (FE) models were developed to investigate the performance of UHPFRC-strengthened columns subjected to vehicle collisions. In the high-resolution FE model, a three-span simply-supported girder bridge (including girder, pier column, column cap, bearing, etc.) was adopted and modelled. Material models regarding normal concrete and UHPFRC as well as the vehicle model were carefully calibrated by experimental data. The influence of initial gravity loads on impact responses was found to be pronounced, and a damping-based method was proposed to efficiently exert permanent loads on pier columns prior to a collision. Three different simplified models, as published in current studies, were investigated to replace the whole bridge model. Two single-column models with different boundaries were shown to have low accuracy. The pier-bent model considering the superstructure gravity was demonstrated as capable of predicting collision-induced responses that are in good agreement with the high-resolution FE model. The impact resistances of both RC and UHPFRC-strengthened columns were extensively investigated using the appropriate simplified model. The crashworthiness of UHPFRC-strengthened column was found to be considerably superior to that of RC column. An extensive parametric study was performed using response surface methodology to explore the influences of reinforcement ratios, thickness of UHPFRC jacket, UHPFRC strength and initial impact speed. The impact-resistant performance is mostly sensitive to changes in the thickness of UHPFRC jacket when the impact speed is not very high. On the contrary, the residual capacity of the bridge column is hardly increased by thickening UHPFRC jacket. In addition, the developed response surface models provided easy estimation of impact-induced responses of an UHPFRC-strengthened column, which have potential use as the surrogates of time-consuming FE simulations to efficiently examine the reliability and optimization of bridge columns under impact loadings.

1. Introduction

A great number of catastrophic accidents on vehicle-bridge collisions have been documented around the world [1–4]. From the bridge failure data recorded during the period 1951–2000 in the United States [1,2], ~17% failures were due to collisions [5], which was the second causes of bridge failures. Also, Buth et al. [4] and Xu [3] reviewed lots of severe vehicle-bridge collision accidents happened in recent years and illustrated the seriousness of the subject.

Among these recent accidents, the damages of bridge structures were often catastrophic when an aberrant vehicle hit one of circular reinforced concrete (RC) columns in a multiple-column bent, such as the Tancahua Street Bridge over IH-37 and the Bridge on 26½ Road over IH-70 [4]. This is partially attributed to the fact that the multiple-column bents have been widely used in overpass bridge structures. More importantly, this indicates that multiple-column bent bridges are susceptible to vehicle collisions. Although much research has been devoted to investigating the performance of infrastructure subjected to

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https://doi.org/10.1016/j.engstruct.2018.06.113
Received 26 January 2018; Received in revised form 9 May 2018; Accepted 28 June 2018
0141-0296/

vehicle collisions [6–9], few studies placed an emphasis on the vulnerable multiple-column bent under vehicle impact loading. Liu [10] and Xu [3] numerically investigated the vehicle-impact-resistant performance of the multiple-column bent, where the cross sections of the columns were rectangular, as opposed to the circular one commonly-used in engineering practice. In addition, some researchers [11,12] investigated the performance of infrastructure subjected to vehicle collisions through simplified single column model, where the fixed or simple-supported boundary was used to consider the influence of the omitted structure. However, the applicability of the simplified single column model has not yet been clarified, particularly for multiple column bents.

On the other hand, the collapses of multiple-column bent bridges are largely attributed to the low crashworthiness of conventional RC columns. For this reason, some retrofit measures have been proposed to improve the impact-resistant performance. For example, steel and FRP (Fiber reinforced plastics) jackets were recommended by Liu [10] and Sha and Hao [13] to strengthen bridge piers that were vulnerable to vehicle or vessel impacts. These studies pointed out that steel jackets and FRP wrapping were effective in reducing damages of bridge piers during vehicle or vessel impacts. However, primary disadvantages of steel jackets are their susceptibility to corrosion and the possibility of metal-to-metal contact with vehicle carrying flammable cargo. With regard to FRP wrapping, adhesive epoxy resin is usually used to secure the FRP well bonded to a column. But, some disadvantages such as the durability of epoxy resin adhesive limit its application into engineering practices. To overcome the limitations of a FRP sheet jacket (e.g., the slackness in the confinement), Choi et al. [14,15] proposed FRP wire winding jackets and applied them into seismic retrofit of circular RC columns. The need is still evident for developing an alternative measure to improve the impact resistance of a bridge column. Ultra-high performance fiber-reinforced concrete (UHPFRC) developed in the mid-1990's has been experimentally demonstrated to have many excellent properties such as superior strength (e.g., compressive strength over 150 MPa and tensile strength over 8 MPa), durability and energy absorption capacity [16–18]. More importantly, UHPFRC materials have been regarded as one of promising engineering materials to resist severe loading conditions such as impact and shock loadings [19,20]. An alternative measure can be developed when UHPFRC jackets are used in multiple column bents. Owing to the excellent properties of UHPFRC, the potential of UHPFRC-strengthened columns is worth exploration.

In this paper, high-resolution finite element (FE) models were developed to investigate the performance of UHPFRC-strengthened pier columns subjected to vehicle impacts. A typical three-span overpass bridge with multiple column bents was finely modelled, including superstructure, bearing, column bent, abutment and so on. To ensure the rationality of FE models, material models regarding UHPFRC and normal concrete as well as the vehicle model were carefully discussed and validated against experimental data. To improve computational efficiency, three different simplified models were examined to address their accuracy and applicability. The impact resistance of the UHPFRC-strengthened pier column was demonstrated to be considerably superior to those of the RC pier column. A detailed parametric study was performed based on response surface methodology to quantify the influences of reinforcement ratios, thickness of UHPFRC jacket, UHPFRC strength and impact speed on impact-resistant performances.

2. Bridge and vehicle FE models and verifications

Many bridge structures with multiple column bents were damaged due to vehicle collisions [4]. For this reason, a typical three-span overpass bridge was selected in this study, as illustrated in Fig. 1. This bridge is similar to the objects of Liu [10] and Xu [3], but cross sections of the columns are different from each other. As mentioned earlier, most of the damaged columns in vehicle-collision accidents were circular. Thus, this study placed an emphasis on circular columns.

2.1. Bridge FE model and parameters

According to the layout of the overpass bridge shown in Fig. 1, the corresponding high-resolution FE model was developed, as presented in Fig. 2. Solid elements were employed to model pier columns, bent caps, footings, bridge girders and abutments as well as bearings. The longitudinal and transverse reinforcements embedded in pier columns were explicitly modelled using beam elements. An overpass bridge is often constructed to cross a highway in the excavation section of mountainous areas. The geological conditions (e.g., soil type) are usually good, and the piles exhibits a very high lateral resistance under impact loadings with a short duration. Hence, like the Refs. [3,9,10], the influence of soil-pile interaction was not taken into account in this study. Fix boundary conditions were arranged on the bottoms of the abutments and the footings. In addition, no obvious damages in abutments were reported in vehicle-bridge collision accidents. Hence, similar to the Refs. [3,9,10], the abutment modeling was simplified in this study to improve the computational efficiency.

In terms of the T-girder, the elastic material model was used to simulate the reinforced concrete. Similarly, the elastic material model was also employed for the abutments, the footings and the bent caps. This means that these members were assumed to be low damage under vehicle impact loading for simplification. Although moderate damages were observed on bent caps in the small number of vehicle-collision accidents, dominated damages (or even collapse) usually occurred in pier columns for most accidents. This was a reason why only single column models were often adopted in much research [11,12,21] to investigate vehicle-impact resistances. Similar to Fan et al. [22], the two-parametric material model (*MAT_MOONEY-RIVLIN_RUBBER) in LS-DYNA was used to describe the behavior of the rubber bearing.

Two different bridge models with various pier columns were developed to compare the vehicle-impact resistant performance of conventional RC columns with UHPFRC-strengthened columns. One bridge model only had the conventional RC pier columns that are shown in Fig. 2(b). An UHPFRC-strengthened column was used to replace the RC column in the other bridge model, as shown in Fig. 2(a) and (c). Compared with the conventional RC column, a 100-mm thickness UHPFRC jacket was arranged to improve the vehicle-impact resistance and a corrugated steel duct (thickness = 1.6 mm) was used to improve the bond between the outer UHPFRC layer and the inner normal concrete core. Nguyen et al. [23] experimentally investigated seismic performance of the similar column and pointed out that the presence of hybrid fiber-reinforced concrete (HyFRC) tube could improve seismic resistances and facilitate the application of accelerated bridge construction in engineering practice. Hence, the impact resistance of an UHPFRC-strengthened column is definitely worth further investigation. All pier columns including the concrete and the reinforcements were modelled using elastic-plastic material models to reasonably capture their damages under vehicle impact loading. Similar to Fan and Yuan [24] and Fan et al. [22], the elastic-plastic model (*MAT_PLASTIC_KINEMATIC) that is able to model isotropic and kinematic hardening plasticity with strain-rate effect was employed to simulate the longitudinal and transverse reinforcements embedded in the column concrete. Since the available reinforcing bars have enough long to avoid the unnecessary connections of longitudinal reinforcements in the 5-meter high columns, the effect of reinforcement connections was not considered in this study. The material parameters used in the bridge are presented in Table 1, which were mainly determined based on the recommendations from China's design specification [25]. With regard to normal concrete and UHPFRC modeling, the detailed discussions are presented in the next section because they play an important role in simulating vehicle collisions with bridge structures.

2.2. Concrete and UHPFRC material models and validations

The previous study [26] performed low-velocity impact tests on