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# Lateral impact response of rectangular hollow and partially concrete-filled steel tubular columns

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ABSTRACT

Under lateral impact, 3 rectangular hollow steel tubular (RHST) and 9 partially concrete-filled steel tubular (PCFST) column specimens were tested. The concrete filling height, the impact direction, and the impact energy were the main factors considered. A digital image correlation method was used to measure the displacement and strain responses of specimens under corner impact. The typical impact force, displacement and strain responses, as well as the failure modes of the specimens, were all analysed. The finite element analysis (FEA) model was established using ABAQUS to simulate the impact test. The predicted results of FEA model were in good agreement with the experimental results. Both the test and model results showed that the PCFST specimens had much better performance than the RHST specimens. The concrete filling height affected the failure mode significantly, especially when the specimens were tested under high-impact energy. The impact direction and energy significantly affected the impact resistance of the specimen.

## 1. Introduction

Concrete-filled steel tubular (CFST) members have been increasingly applied to bridge piers and building columns because of their large load-carrying capacity, good ductility and ease of construction (Han et al. [1]). In recent years, bridge piers in many countries have been increasingly impacted by vessels, trains and vehicles. By reviewing the causes of bridge failures in USA from 1966 to 2005, Sharma et al. [2] found that after hydraulic causes, the second most likely cause of bridge failure was collision (14%). In some serious accidents of vehicle-bridge collision, bridge piers were laterally impacted and destroyed (Fig. 1), which may have been the cause of bridge collapse, as shown in Fig. 1(b). The design demand for structures to withstand impact load has increased, and CFST members are expected to effectively improve structural impact resistance.

Impact behaviours of CFST members have been experimentally and theoretically investigated by researchers. Bambach et al. [3] investigated the flexural impact behaviour of CFST members by conducting transverse impact at the mid-span. The core concrete could reduce the local deformation beneath the impactor, and CFST beams could sustain greater impact load than the hollow section steel beams. Remennikov et al. [4] investigated the anti-impact behaviour of square hollow section steel tubes filled with rigid polyurethane foam (RPF) and concrete by conducting the drop hammer test and the nonlinear dynamic finite element analysis. The concrete-filled tubes possessed the highest impact resistance and energy absorption capacity, followed by the steel tubes filled with RPF and the hollow tubes. Yousuf et al. [5] investigated the behaviours of hollow and concrete-filled section stainless and mild steel tubes under both static and impact loads. The infilling concrete could greatly enhance the resistance to local buckling. The stainless steel specimens showed higher strength and ductility than their mild steel counterparts. Han et al. [6] investigated the flexural behaviour of circular high-strength CFST members under lateral impact load. The high-strength CFST beams deformed in a ductile manner, thereby indicating good resistance under impact load. Yang et al. [7] performed experimental and numerical studies to investigate the performance of recycled aggregate concrete-filled steel tubular (RACFST) members under lateral impact loading. The RACFST columns showed load carrying capacity that was comparable with that of normal aggregate CFST columns. The CFST members studied in abovementioned literatures were all placed horizontally. The lateral impact loads were conducted at the mid-span by drop hammers. The abovementioned studies indicated that CFST members behaved in a ductile manner and showed good impact resistance under lateral impact. Moreover, the impact resistances were significantly affected by the materials of steel and infilling material.

However, vehicle impact usually occurs near the bottom of the columns rather than at mid-span [8]. Moreover, the rebounding of

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(a) Collision of truck with bridge column
(b) Collapse of bridge after being struck by a tractor trailer

**Fig. 1.** Accidents of vehicle-bridge collision. (a) Collision of truck with bridge column (b) Collapse of bridge after being struck by a tractor trailer.

column specimens under lateral impact load provided by drop hammers was affected by the gravity of the hammer. Thus, the drop hammer impact was different from real vehicle impact. To date, few studies have considered the effect of impact location near the bottom of the columns and the gravity of the hammer on the impact response of CFST members. Aghdamy et al. [9] experimentally investigated lateral impact response of concrete-filled double-skin tube (CFDST) columns using an innovative horizontal impact test system. The axial load levels and the impact locations, which were on the mid-span and two-thirds of column length, were the key test parameters that notably affected the response of the CFDST columns. Furthermore, Aghdamy et al. [10–12] numerically investigated the effect of various structural and load parameters, including the impact location on the impact behaviour of CFST and CFDST columns. The results showed that the steel tube thickness to diameter, the slenderness ratio and the impact velocity exerted the most influence on the impact response.

Studies on behaviour of partially concrete-filled steel tubular (PCFST) members were relatively few. Most studies focused on seismic behaviour of PCFST members. The seismic behaviour of PCFST members are reported in Refs. [13–18]. The PCFST members possessed good earthquake-resistance characteristics. Moreover, the seismic behaviour was effectively improved when the concrete filling height was significantly increased. Usami et al. [14] also mentioned that the partially infilling concrete could provide extra protection to steel columns in case of vehicular collision and could reduce the weight of the pier. However, investigations on impact resistances of PCFST members and the effect of the concrete filling height on impact resistance of PCFST members have not been conducted.

Thus, this paper presented an experimental and numerical study on the impact resistance of rectangular hollow steel tubular (RHST) and PCFST columns under lateral impact load. The column specimens were placed vertically. The lateral impact loads were conducted at a height of 320 mm from column bottom by a pendulum hammer. To compensate for the shortcomings of laser displacement sensor in measuring displacement of specimens under corner impact, we used a three-dimensional digital image correlation (3D-DIC) method to measure the displacement response. Responses of the typical impact forces, displacements and strains, as well as the failure modes of the specimens were analysed. The influences of the parameters, including the concrete filling height, the impact direction and the impact energy on the impact resistances of the specimens were also analysed. Moreover, a finite element analysis (FEA) model was established and also validated by comparing the experimental results of RHST and PCFST columns with the predicted results.

## 2. Experimental program

### 2.1. Description of test specimen

A total of three RHST and nine PCFST column specimens were tested. The rectangular steel tubes were fabricated using cold-formed process and welded with high frequency butt weld. The sectional dimensions of the rectangular cold-formed steel tubes were 140 mm × 80 mm × 3 mm. The inner radius of the cold-formed corner ($r$) was 4.5 mm. The total length of the steel tube ($h$) was 1500 mm. The concrete filling heights ($h_c$, from the column bottom) were 400, 700 and 1000 mm. The concrete filling ratio ($\alpha$) was equal to $h_c/h$. More details of the specimens are found in Fig. 2. To accurately obtain the local deformations of the impact region, we divided the surface areas near the impact region into small square grids with dimensions of 10 mm × 10 mm.

The specimen labels were defined according to the concrete filling height, the impact energy ($E_i$) and the impact direction as shown in Table 1: "H" and "P" denoted hollow and partially concrete-filled specimens, respectively; the number represented $h_c$ (mm); the letters "F" and "C" after label "-" represented the impact directions "Front impact direction" and "Corner impact direction", respectively, as shown in Fig. 2(c). For specimens under front impact, the last number separated the different impact energies. For example, the label "P700-F2" showed

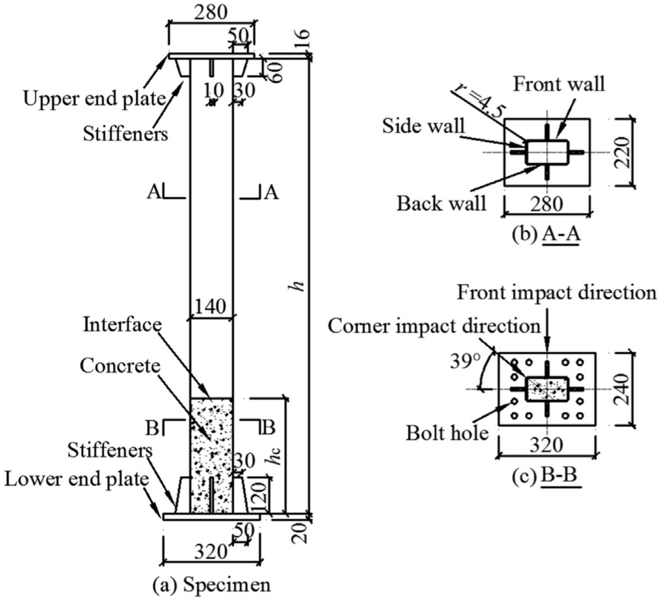

**Fig. 2.** Specification of test specimens.