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Concrete-encased CFST members with circular sections under laterally low velocity impact: Analytical behaviour

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ABSTRACT

This paper reports an investigation into the impact resistance of concrete-encased concrete-filled steel tube (CFST) members with circular sections. A finite element analysis (FEA) model was established to simulate the impact behaviour of concrete-encased CFST under laterally low velocity impact, in which the strain rate effects of steel and concrete, the element erosion criteria of concrete, the interactions between concrete and steel, as well as the combined effects of axial load and lateral impact, were considered. Experimental data on reinforced concrete (RC), CFST and concrete-encased CFST members under drop hammer impact were used to verify the accuracy of the FEA model and a generally reasonable agreement was achieved for all three types of structures. A full-range analysis of the behaviour of concrete-encased CFST members with circular sections was then carried out with the FEA model to investigate the impact behaviour and impact resistance of the composite structure. The failure modes, sectional moment development, stress and strain development, as well as the contact behaviour between different parts were analyzed to highlight the reasons behind the good impact resistance of the composite structure. A parametric study was finally conducted with the FEA model to investigate the major parameters that may influence the impact resistance of the concrete-encased CFST members.

1. Introduction

Concrete-encased concrete-filled steel tube (CFST) is a relatively new type of steel-composite section used in engineering constructions. It is constructed with one or more CFST components encased in outer reinforced concrete (RC). Two typical sectional shapes are shown in Fig. 1(a). This type of composite member has been increasingly used as columns in high-rise buildings as well as bridge piers in China due to its good structural performance. Concrete-encased CFST columns have several structural advantages compared with the conventional CFST columns, including higher stiffness, higher fire resistance, better durability and convenient connection with RC beam. In addition, the sectional size of the columns could be reduced by using thin-walled high strength steel tube or high strength concrete in the CFST.

Different sectional configurations for concrete-encased CFST columns can be achieved by choosing different sectional shapes for the outer RC and inner CFST. For solid section, there can be square RC - circular CFST section, square RC - square CFST section, and circular RC - circular CFST section. The sectional shapes of the steel tube and the outer RC are generally determined based on the structural type and function. For instance, more than a dozen of high-rise buildings with concrete-encased CFST columns in China have employed the square RC - circular CFST type of section. Using square outer RC enables convenient beam-column joint construction for the buildings while the circular steel tube could provide stronger confinement to the core concrete compared with the square one. On the other hand, the circular RC - circular CFST type of section is generally a better choice for the construction of bridge piers, as have been used in China. The reason is that the circular stirrups in the circular RC could provide higher confinement to the whole section, allowing higher strength and ductility. In addition, the box section concrete-encased CFST columns have also been used as bridge piers in high-earthquake-intensity regions in China [1].

Some studies have been carried out on the structural performance of concrete-encased CFST columns under various types of loads in the past. For example, the axial compressive performance of concrete-encased CFST stub columns was numerically investigated by Han and An [2] and Li et al. [3]. Simplified formulas were suggested to predict the ultimate strength of both square and circular section members. Han et al.

Notation: A, cross-sectional area of composite section ($=\pi D^2/4$); A_{core}, cross-sectional area of core concrete of CFST; A_l, cross-sectional area of longitudinal bars; A_s, cross-sectional area of steel tube of CFST; A_{sc}, cross-sectional area of CFST ($=A_{core}+A_s$); D, outer diameter of the circular concrete-encased CFST members; D_s, outer diameter of the steel tube; E_c, modulus of elasticity of concrete; E_i, internal energy; E_s, modulus of elasticity of steel; E_0, impact energy; F, lateral impact force; f_{ck}, characteristic concrete strength; f_{cu}, cube strength of concrete; f_c', cylinder compressive strength of concrete; f_{yh}, yield stress of stirrup; f_{yl}, yield stress of longitudinal bar; f_{ys}, yield stress of steel tube; H, drop height of the impact hammer; L, length of the specimen; M, moment; M_u^d, dynamic flexural capacity; m_0, drop hammer mass; N_0, axial load; N_{uc}, ultimate axial strength; n, axial load ratio ($=N_0/N_u$); s, stirrup spacing; t, time; t_0, duration of impact force; t_s, thickness of steel tube; V_0, impact velocity; α_l, longitudinal bar ratio ($=A_l/(A-A_{sc})$); α_s, steel ratio of CFST ($=A_s/A_{core}$); ε, strain; $\dot{\varepsilon}$, strain rate; Δ, lateral deflection at mid-span; σ, stress.

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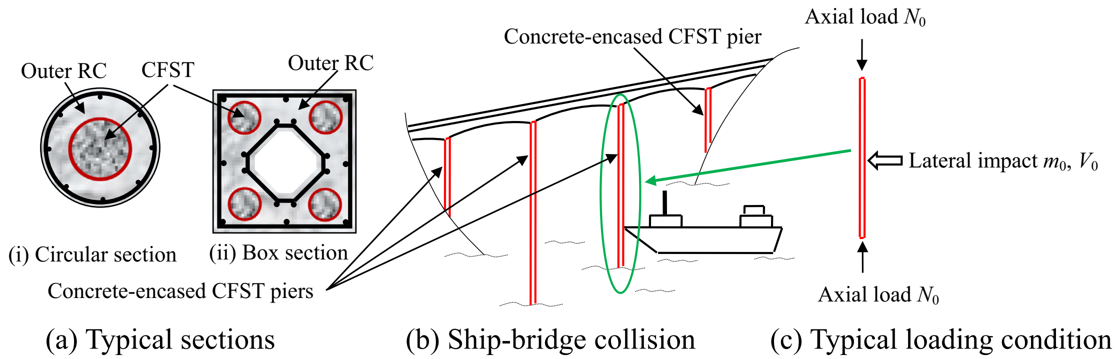

Fig. 1. A schematic view of ship-bridge collision.

[4] conducted thirteen axial tension tests for square concrete-encased CFST members, and six push out tests to study the bond performance between the outer RC component and the inner CFST. Results based on finite element analysis (FEA) analysis showed that, "composite effect" was found between the steel tube and core concrete, while the outer RC component and the inner CFST worked independently. An et al. [5] reported numerically investigations on the flexural performance of square concrete-encased CFST members. It was found that even very thin-walled steel tube could develop full plastic strength without local buckling due to the confinement of both the outer and the core concrete. Simplified formulas for predicting the flexural capacity were derived based on parametric studies. An and Han [6] further investigated the performance of square concrete-encased CFST columns under combined compression and bending, and results showed that the outer concrete failure mode was the failure pattern for the composite columns with slenderness ratio smaller than 60. Park et al. [7] conducted six eccentric loading tests on concrete-encased CFST members, and used various reinforcement details for the concrete encasement. Results showed that the steel fiber-reinforced concrete could effectively restrain the spalling of concrete encasement in the post-peak behaviour of the composite column. In addition, studies on the performance of square concrete-encased CFST members under cyclic loading have also been reported (Han et al. [8]; Ji et al. [9]; Qian et al. [10]). Compared with the conventional RC columns with the same ultimate axial strength, the concrete-encased CFST members showed better ductility and energy dissipation.

It is well known that structure members, such as columns in buildings and bridge piers, may suffer from collisions with vehicles or vessels during their service life. One typical example of a ship-bridge collision is illustrated in Fig. 1, in which both axial load and lateral impact are applied on a bridge pier. Collisions might cause permanent structural damage, economic loss and even casualties. Therefore, it is of great importance to understand the performance of structures under impact load and design the structures which are able to resist such hazards. In the past, a large number of studies have been carried out to analyze the impact behaviour of traditional reinforced concrete (RC) structures and CFST structures. Extensive experimental (Kishi et al. [11]; Saatci and Vecchio [12]; Fujikake et al. [13]; Chen and May [14]; Adhikary et al. [15,16]; Zhan et al. [17]; Erdem et al. [18]) and numerical (Adhikary et al. [15,16]; Jiang et al. [19]; Jiang and Chorzepa [20]; Do et al. [21,22]) investigations have been conducted on the impact behaviour of RC beam under lateral impact load. These studies showed that, the main failure modes of RC members under impact load included the overall flexural deformation, the local failure near the direct impact area and the shear diagonal cracks. Some design methods have also been developed for RC members under impact load (Fujikake et al. [13]; Zhan et al. [17]). Researches on the impact behaviour of CFST members have also been carried out under various loading conditions, including axial impact load (Shan et al. [23]; Xiao et al. [24]; Xiao and Shen [25]; Huo et al. [26,27]), and lateral impact load (Bambach et al. [28]; Qu et al. [29]; Bambach [30]; Remennikov et al. [31]; Yousuf et al. [32,33]; Deng et al. [34,35]; Wang et al. [36]; Han et al. [37]; Aghdamy et al. [38]). CFST members showed favorable impact performance and ductility in these studies.

Due to its high strength and good energy dissipation capacity, it is deemed that the concrete-encased CFST is a good choice for impact-resistant structures, such as bridge piers. However, research on the impact behaviour of concrete-encased CFST members was very limited currently. Hu and Han [39] conducted a series of tests for circular concrete-encased CFST members under lateral drop hammer impact. Test results included time-history curves of impact force and mid-span deflection, as well as failure modes of the test specimens. Nevertheless, studies on the performance of concrete-encased CFST members under static and cyclic loadings, as well as on the impact behaviour of CFST and RC members are the foundation for research on the impact behaviour of concrete-encased CFST members. Detailed information of the experimental work of RC and CFST members under impact load is summarized in Tables 1 and 2, respectively. In the tables, the impact velocity of lateral drop hammer tests is generally within the range of 1.0 m/s to 12.0 m/s. The impact velocity is defined in Eq. (1).

$$V_0 = \sqrt{2gH} \tag{1}$$

where g is gravity acceleration and H is drop height. Therefore, the value of low velocity of lateral impact is tentatively taken as <12 m/s in this paper.

This paper is thus an attempt to study the performance of concrete-encased CFST structure subjected to laterally low velocity impact and

Table 1
Summary of experimental research on impact behaviour of RC members.

No.	Dimension: width × height × length (mm × mm × mm)	V_0 (m/s)	E_0 (kJ)	Number of specimens	Reference
1	150 × 250 × (1400–2400)	1.0–6.0	0.2–5.4	27	Kishi et al. [11]
2	250 × 410 × 4880	8.0	7.0–19.0	8	Saatci and Vecchio [12]
3	150 × 250 × 1700	1.7–6.9	0.6–9.4	12	Fujikake et al. [13]
4	100 × 200 × (1800–3000)	7.3	2.6	18	Chen and May [14]
5	(120–160) × (170–250) × (1700–2000)	1.7–5.6	0.4–4.7	30	Adhikary et al. [16]
6	120 × 120 × 1800	6.3–12.5	0.7–2.6	18	Zhan et al. [17]
7	(100−200) × (100–200) × 710	4.4	0.1	6	Erdem et al. [18]