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Experimental study of concrete-filled CHS stub columns with inner FRP tubes

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ABSTRACT

An experimental study into the axial compressive behaviour of concrete-filled circular hollow section (CHS) steel columns with internal fibre reinforced polymer (FRP) tubes is presented in this paper. A total of 17 concrete-filled steel tubular (CFST) columns were tested, 15 with an inner FRP tube and 2 with no inner tube. Complementary material tests and tests on 15 FRP-confined concrete (FCC) columns were also carried out. The varied test parameters included the concrete strength, the ratio of the diameter of the steel tube to that of the FRP tube, the diameter to wall thickness ratio of the inner FRP tube and the type (influencing principally the rupture strain) of the FRP. It was found that the presence of the inner FRP tube led to considerably improved axial compressive behaviour due to the greater levels of confinement afforded to the 'doubly-confined' inner concrete core; the load-bearing capacity was increased by between about 10% and 50% and the ductility was also enhanced. Greater benefits arose with (1) increasing diameter of the inner FRP tube due to the increased portion of the cross-section that is doubly-confined and (2) increasing wall thickness of the inner FRP tube due to the increased level of confinement afforded to the inner concrete core. The load-deflection responses of all tested specimens were reported, revealing that failure was generally gradual with no sharp loss in load-bearing capacity, implying that the embedment of the inner FRP tube within the concrete enables it to continue to provide a reasonable degree of confinement even after the initiation of fibre rupture; this is different to the sudden loss of confinement typically observed in FRP externally jacketed concrete columns.

1. Introduction

Concrete-filled steel tubular (CFST) columns are being extensively used in tall buildings, long-span bridges and other mega structures due to their advantages such as high strength, high ductility and large energy absorption capacity. In addition, the use of CFST columns can bring convenience to construction due to the absence of formwork. In the past few decades, a significant number of experimental and analytical studies into the structural behaviour of CFST columns have been carried out [1–17]. In these studies, it was shown that confinement to the concrete in circular CFST columns brings substantial benefit in terms of load-bearing capacity, but this effect degrades dramatically upon yielding or local buckling of the steel tube.

In recent years, fibre reinforced polymer (FRP) jackets have been used to enhance the structural performance of circular CFST columns by providing additional confinement to the concrete and delaying the occurrence of local buckling of the steel tube (Fig. 1(a)). Following the initial work of Xiao [18], a number of studies have been carried out to investigate the behaviour of circular CFST columns externally confined by FRP jackets [18–25]. Besides FRP-confined circular CFST columns, another structural form of column featuring the combined use of FRP and steel tubes is the FRP-concrete-steel double-skin tubular column (DSTC) as displayed in Fig. 1(b), which was originally proposed by Teng et al. [26]. This column has an outer FRP tube and an inner steel tube. A number of experimental studies has been carried out on DSTCs by Teng et al. [27–31], Han et al. [32] and Ozbakkaloglu et al. [33–36]. The above-described types of composite column have demonstrated that the combined use of FRP jackets/tubes and steel tubes can offer substantially improved performance over circular concrete columns. However, the external FRP jackets/tubes may not be ideally suited to building construction due to limitations on their fire resistance arising from the rapid degradation of the mechanical properties of FRP and possible smoke or toxic gas generation during a fire.

This paper is concerned with a new type of circular CFST column with an inner FRP tube, as shown in Fig. 1(c). These cross-sections, referred to hereafter as 'FRP-CFST columns', are expected to have the

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Nomenclature

D_s	diameter of steel tube
D_f	diameter of FRP tube
t_s	wall thickness of steel tube
t_f	wall thickness of FRP tube
As	cross-sectional area of steel tube
A_f	cross-sectional area of FRP tube
A_c	cross-sectional area of concrete
A_{cc}	cross-sectional area of core concrete within the FRP tube
E_s	elastic modulus of steel tube
E_{FRP}	elastic modulus of FRP tube
f_{FRP}	ultimate tensile stress of FRP tube
f'_{co}	cylinder strength of concrete
f_y	yield strength of steel tube
ε_{au}	average axial strain at ultimate load
ε_{FRP}	ultimate rupture strain of FRP tube
ε_{al}	average axial strain corresponding to initiation of local buckling
N_{ue}	ultimate load-bearing capacity of specimens
$N_{ue,CFST}$	ultimate load-bearing capacity of CFST specimens
$N_{ue,FCC}$	ultimate load-bearing capacity of FCC specimens
$N_{ue,FRP\text{-}CFST}$	ultimate load-bearing capacity of FRP-CFST specimens
N_{re}	residual load-bearing capacity of specimens
N_{le}	axial load corresponding to initiation of local buckling

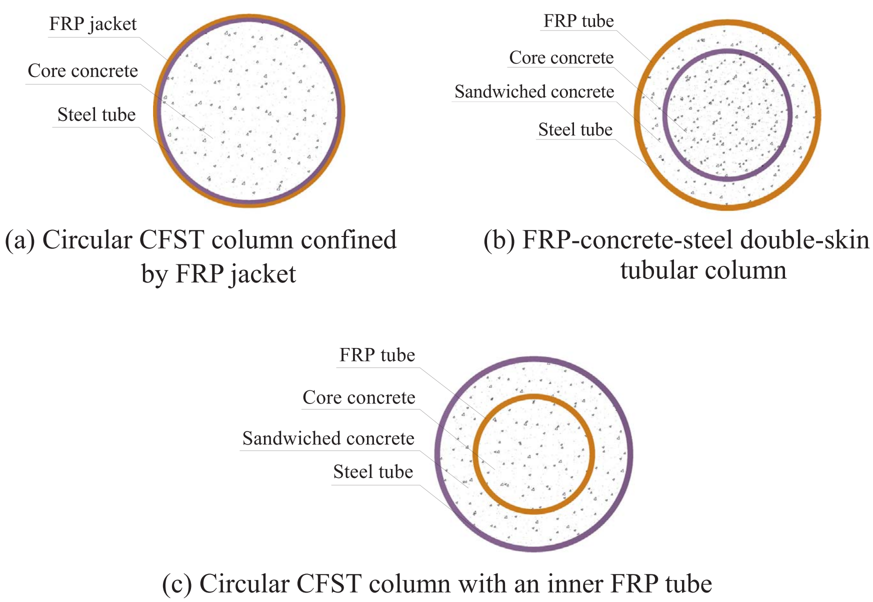

Fig. 1. Different forms of concrete-filled steel and FRP tubular columns.

following distinct features: (1) the inner FRP tube is expected to provide continuous and additional confinement to the core concrete, further improving the ductility and strength of the columns even after yielding of the steel tube; (2) failure of the FRP tubes will be less brittle due to their embedment in concrete, avoiding a sudden loss of the FRP contribution upon rupture; and (3) the existence of the inner FRP tube will restrict the lateral expansion of the concrete, reducing the hoop strains and hence delaying yielding in the steel tube.

A limited number of tests have been performed on square CFST columns with inner FRP tubes by Feng et al. [37,38], demonstrating higher ultimate strengths and better ductility compared to conventional square CFST columns. However, no tests have been conducted on circular FRP-CFST columns, as studied herein. The aim of the present paper is therefore to study experimentally the axial compressive behaviour of circular FRP-CFST columns and to advance the understanding of this new structural form.

2. Experimental programme

2.1. Test specimens

A total of 32 circular composite stub columns, including 15 FRP-CFST columns, 2 conventional CFST columns (without an inner FRP tube) and 15 FRP-confined concrete (FCC) columns were manufactured and tested under axial compression. The measured geometrical and material details of the 15 FRP-CFST specimens (depicted in Fig. 2(a)) and the 2 CFST specimens (depicted in Fig. 2(b)) are listed in Table 1. In the table, the specimens are divided into two groups according to the target concrete strength, with the symbols “L” and “H” representing the lower and higher strength concrete, respectively. The specimen designation system also describes the number of tubes of each type (S = steel and F = FRP), as well as the diameter and thickness of the FRP tube. For instance, specimen 1S1FH-100-2 represents a CFST specimen with an outer steel tube (1S), an inner FRP tube (1F), high strength concrete, D_f = 100 mm and t_f = 2 mm. Among the 15 FRP-CFST columns, 13 of the inner tubes were made from glass FRP (GFRP) tubes and 2 from high rupture strain (HRS) FRP (i.e. polyethylene terephthalate (PET) FRP and polyethylene naphthalate (PEN) FRP) tubes. High rupture strain FRP composites usually possess a rupture strain greater than 5% [39,40] and have been recently studied as jacket material for reinforced concrete members [41–44]. The fibres were oriented in the hoop direction resulting in the FRP tubes having high hoop stiffness but low axial stiffness.

All the FRP-CFST specimens and CFST specimens were 273 mm in diameter and 820 mm in height. The height was chosen to be three times the specimen diameter to avoid global buckling and end effects. The steel tubes used in all the specimens had a nominal thickness of 6 mm, leading to diameter to thickness ratio D_s/t_s of 45.5. The following parameters were considered in the test programme: (i) concrete cylinder compressive strength (i.e. normal strength f'_{co} = 36.5 MPa and high strength f'_{co} = 54.7 MPa), (ii) diameter of inner FRP tube (100 mm, 150 mm and 200 mm), resulting in three different diameter ratios of outer steel tube to inner FRP tube (i.e. D_s/D_f = 2.73, 1.82 and 1.37) and (iii) wall thickness of inner FRP tube (i.e. t_f = 2 mm, 3 mm and 4 mm). As a result, diameter to wall thickness ratios of the inner FRP tube varied between 25 and 100 (i.e. D_f/t_f = 25, 33.3, 37.5, 50,