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Structural behaviour of recycled aggregate concrete filled steel tube columns strengthened by CFRP

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ABSTRACT

This paper presents experimental research on structural behaviour of normal and recycled aggregate concrete filled steel tube (RACFT) columns externally strengthened with carbon fibre reinforced polymer (CFRP) sheets and subjected to axial loading. A total of 22 specimens were tested to investigate the influence of the following variables: (1) tube configurations, circular or square, solid or hollow; (2) types of concrete, normal or recycled aggregate concrete; and (3) strengthening arrangements, full wrapping or partial wrapping. The results show that the recycled aggregate concrete may degrade the concrete strength during the curing period for the first 28 days. However, the ultimate strength and stiffness (90-day curing period) for the square and circular solid steel tubes filled with recycled aggregate concrete show slightly higher values than the ones filled with normal concrete, but this is reversed for the steel hollow section tubes. The test results indicate that both reinforcing arrangements enhance the ultimate strength greatly in comparison to the control column, and that the full wrapping arrangement is much more effective than the partial wrapping one. Moreover, stiffness of the strengthened columns is increased significantly due to the restraint offered by the external CFRP wrapping on hoop deformations during compressive loading. In addition, theoretical calculations of the bearing capacity of the composite columns are presented and compared with the experimental results.

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1. Introduction

Composite construction encompassing the use of steel and concrete has been widely utilised in structural engineering. Currently, normal concrete filled steel tube (CFT) columns have increasingly found their applications in high-rise buildings, offshore structures, bridges and warehouses, particularly in the region with a high risk of seismic loading, due to the combined advantages of steel and concrete. Such columns possess a high strength-to-weight ratio, better seismic performance, high fire resistance and increased deformability [1–3]. Through experimental work, theoretical approaches and the finite element analysis, a number of studies has been conducted to investigate the effects of the cross section shape [4,5], the concrete strength [2,6–11], the depth-to-thickness ratio [2,10–13], the loading conditions [14,15] and the types of filling materials [16] on the failure mode, load carrying capacity and ductility of CFT columns.

In recent years, with the increasing demand for infrastructure development, the consumption of concrete as a main construction material keeps growing. However, the emission of carbon dioxide from the production processes is estimated about 1.35 billion tons annually or about 7% of the total greenhouse gas emissions to the earth's atmosphere. Therefore, the recycled aggregate concrete filled steel tube (RACFT) columns have increasingly attracted structural engineers, as this is beneficial for the saving of natural resources and the environmental preservation and is also the need for a low carbon economy. The earthquake on 12 May 2008 in Sichuan was one of the most destructive earthquakes in modern Chinese history, which generated approximately 382 million tons of construction wastes from the collapsed buildings [17]. Some studies have been undertaken to investigate the structural behaviour of the recycled aggregate concrete columns made with different proportions of recycled aggregate [18,19] and other types of waste materials [20,21]. However, limited research has been conducted on the structural behaviour of steel tube columns filled with recycled aggregate concrete to produce RACFT columns. Yang and Han [22] studied the structural performance of steel tube columns with circular and square sections filled with normal and recycled aggregate concrete. They found that the typical failure modes of RACFT columns were similar to those of CFT columns, but the ultimate load carrying capacities and ductility of RACFT columns were slightly lower than those of CFT columns.

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However, RACFT columns can be strengthened by fibre reinforced polymer (FRP) jackets. Confinement of CFT columns by means of FRP jackets is a technique being frequently used to seek enhancement of load carrying capacity of such compressive members [23]. There have been a number of theoretical and experimental studies related to strengthening of CFT columns with FRP, which have shown a particular enhancement on the load carrying capacity due to the restriction and postponement of buckling failure offered by FRP. Research has been undertaken on the effect of cross-sectional types, i.e. square hollow [24–26], circular hollow [27,28], square solid and circular solid [29] and the other section types [30], as well as the effect of loading conditions (cyclic or eccentric load) on square and circular solid [31,32] CFT columns strengthened with carbon and/or glass fibre reinforced polymer (CFRP/GFRP) composites. The results have also shown that there is a significant enhancement on both the load carrying capacity and the stiffness of CFT columns with externally bonded FRP. Moreover, Zhao and Zhang [33] gave a comprehensive review of research on FRP strengthened steel structures and suggested that the future research would likely be focused on the stability of the FRP strengthened steel hollow section members.

There has been extensive experimental research on either the behaviour of RACFT columns or the FRP confined CFT columns, as indicated above. Also some attempts have been made to study the structural behaviour of the columns filled with recycled aggregate concrete [17,18,34–36]. However, such the research together with external strengthening on the columns by FRP materials is limited. This paper presents experimental study of RACFT columns strengthened with CFRP sheets subjected to axial loading. Twenty two specimens of circular and square steel tube columns were manufactured and tested, which are comprised of 11 solid and 11 hollow ones, and filled with natural or recycled aggregate concrete and externally strengthened with two layers of CFRP sheets along the circumferential direction. The main parameters studied in the tests are (1) tube configurations, circular or square, solid or hollow; (2) types of concrete, natural or recycled aggregate concrete; and (3) strengthening arrangements, full wrapping or partial wrapping. Deformation and failure modes of the RACFT columns are also presented and discussed. In addition theoretical calculations of the load bearing capacity of the composite columns are undertaken and compared with the experimental results.

2. Experimental program

2.1. Materials

Ordinary Portland cement with a 28-day compressive strength of 42.5 MPa was used to produce specimens. River sand with the maximum size of 2.36 mm was used as the fine natural aggregate. The coarse aggregates used in this research consisted of natural coarse aggregates (NCAs) and recycled coarse aggregates (RCAs). The RCA used were obtained by crushing the waste concrete, taken from the collapsed concrete structures in Dujiangyan after the Sichuan earthquake on 12 May, 2008. Recycled and natural coarse aggregates have the same fraction size, 4/16 mm (1), 16/27 mm (2) and 27/32 mm (3), in accordance with the Chinese Standard GB/T 14685-2001 [37]. It is well known that the physical properties of RCA are dependent on both the quality and quantity of adhered mortar. Here, the quantity of adhered mortar was approximately 47% for fraction 4/16 mm, 31% for fraction 16/27 mm and 6% for the 27/32 mm fraction. The other main physical properties of the NCA and RCA are shown in Table 1. It can be seen that the RCA has a lower density but higher water absorption and crushing index than those of the natural coarse aggregate, which indicates that the RCA likely gives a lower compressive strength than that of the NCA.

Cold-formed steel tubes with circular solid (CS), circular hollow (CH), square solid (SS) and square hollow (SH) sections were used to manufacture specimens. Standard tensile tests were conducted to measure material properties of the steel tubes, with dimensions in accordance with the Chinese Standard GB/T228-2002 [38]. The averaged yield strength, tensile strength, elastic modulus and Poisson's ratio obtained from three tension coupons are listed in Table 2.

The CFRP sheets (supplied by the Shanghai Keep Strong in Building Technology Engineering Co. Ltd.), which have a nominal thickness of 0.11 mm per ply, were bonded externally onto the steel tubes along their circumferential direction by using a two-part epoxy mixed in a weight ratio of 2:1 and cured at room temperature. The tensile strength, elastic modulus and ultimate elongation of the CFRP sheets are 4103 MPa, 242 GPa and 1.7%, respectively.

2.2. Mix proportions

Before mixing, the recycled coarse aggregates were pre-soaked to minimise their effects on the workability and water/cement ra-

Table 1
Physical properties of NCA and RCA.

Coarse aggregate	Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Crushing index (%)
Natural	4.75–31.5	1782 ± 6	2746 ± 8	0.87 ± 0.04	4.9 ± 0.06
Recycled	4.75–31.5	1493 ± 24	2471 ± 22	2.95 ± 0.12	15.4 ± 0.14

Table 2
Material properties of steel.

Steel section	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson's ratio
CS and CH	300.3 ± 2.1	390.0 ± 1.9	195.4 ± 3.0	0.27 ± 0.02
SS and SH	335.5 ± 2.3	435.0 ± 3.2	193.3 ± 2.6	0.29 ± 0.02

Table 3
Mix proportions of normal and recycled aggregate concrete.

Concrete	RCA replacement ratio	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	W/C
Normal	0	170	347	663	1232	0	0.49
Recycled	50	170	347	645	599	599	0.49

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