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Sustainable FRP–recycled aggregate concrete–steel composite columns: Behavior of circular and square columns under axial compression

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ABSTRACT

This paper presents the results of an experimental study on the behavior of fiber reinforced polymer (FRP)–recycled aggregate concrete (RAC)–steel double-skin tubular columns (DSTCs) under concentric compression. Influences of the concrete strength, DSTC cross-sectional shape, and aggregate replacement ratio were experimentally investigated through the test of 24 hollow-core circular and square DSTCs. Results indicate that the overall behavior and performance of RAC DSTCs closely resemble that of DSTCs manufactured with conventional concrete, which is highly promising for structural use of RAC in the construction industry. The aggregate replacement ratio has limited influence on the ultimate condition of DSTCs. On the other hand, the replacement ratio has some influence on the trend of the stress-strain curve of concrete in DSTCs, and this is more pronounced in square specimens than in circular specimens.

1. Introduction

Modernization and industrialization have generated large amounts of debris from construction and demolition (C & D) waste. The use of such waste in structural composite materials, such as concrete, is becoming increasingly popular. Recycled concrete aggregate (RCA), which is obtained by crushing old concrete elements from C & D waste, has been considered an alternative aggregate material for use in structural concrete to achieve the sustainability of resources in construction industry. Recycled aggregate concrete (RAC) is an environmentally friendly concrete, which partly or totally substitutes natural aggregates (NAs) with RCAs in the concrete mix. The application of RAC in the construction industry is a highly promising technology for conserving natural resources and minimizing the impact of urbanization. Many studies have shown the great potential of RAC as an alternative to natural aggregate concrete (NAC). However, it is understood that the replacement of NA with RCAs affects the mechanical properties of concrete, e.g., decreased compressive strength [1–3] and elastic modulus [4–6], and increased drying shrinkage [7]. Owing to such drawbacks, RAC is mostly used as non-structural concrete at present, and its use in structural concrete is limited.

As it was shown in a recent review [8], the use of fiber-reinforced polymer (FRP) composites as confinement material for concrete has received significant attention over the last two decades. As confinement material, FRP has been mainly used in (i) retrofitting existing concrete columns [9–16], and (ii) the construction of new composite columns in the form of concrete-filled FRP tubes (CFFTs) [17–22]. More recently, a new type of composite system, proposed by Teng et al. [23], which consists of an inner steel tube, an outer FRP tube, and concrete-filling in-between the two tubes (and optionally inside the steel tube), has attracted significant attention. Such FRP–concrete–steel double-skin tubular columns (DSTCs) use the same FRP tube confinement mechanism that is present in CFFTs, and offer improved structural performance; improved durability during the design life, which results in reduced maintenance costs; improved construction processes, which decrease construction costs; and significantly reduced carbon footprint because of the more efficient use of materials, which reduces both the amount of raw materials and the generation of construction and demolition waste. The experimental studies on DSTC systems have demonstrated the system's performance advantages under various loading conditions, including monotonic [23–31] and cyclic axial compression [32,33], flexure [34–36], and combined axial compression and lateral load reversals [37–39]. However, all existing studies have been concerned with the behavior of DSTCs manufactured with NAC, and DSTCs manufactured with sustainable waste-based concretes, such as RAC, are yet to be investigated.

The superior structural engineering properties of high-strength concrete (HSC) over normal-strength concrete (NSC) makes it an attractive alternative in the construction of high-performance composite columns such as CFFTs and DSTCs. Recent studies on HSC DSTCs [26–31] have shown that the combination of such high-strength materials (i.e., HSC, steel, and FRP) maximizes the benefits of the

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Table 1
Details of test specimens.

Specimen ID	Cross- section	Test day strength of concrete (f'_{co}) (MPa)	Strain at peak stress (ε_{co}) (%)	RCA replacement ratio (%)	Number of FRP layers	Fiber thickness per layer (mm)
CN0-1,2	Circular	41.5	0.23	0	2	0.111
CN50-1,2	Circular	40.9	0.23	50	2	0.111
CN100-1,2	Circular	39.1	0.23	100	2	0.111
CH0-1,2	Circular	67.3	0.26	0	4	0.111
CH50-1,2	Circular	66.5	0.26	50	4	0.111
CH100-1,2	Circular	67.1	0.26	100	4	0.111
SN0-1,2	Square	41.5	0.23	0	2	0.165
SN50-1,2	Square	40.9	0.23	50	2	0.165
SN100-1,2	Square	39.1	0.23	100	2	0.165
SH0-1,2	Square	67.3	0.26	0	4	0.165
SH50-1,2	Square	66.5	0.26	50	4	0.165
SH100-1,2	Square	67.1	0.26	100	4	0.165

composite system, resulting in structural members with highly desirable properties. Therefore, it would be of great interest if high-strength RAC can be developed and used in DSTC systems.

As the first study in the literature that reports on the behavior of DSCTs manufactured with RAC, this paper discusses the results of an experimental program that investigated the effect of key parameters on the compressive behavior of FRP–RAC–steel DSTCs. These parameters included (i) the concrete strength, (ii) the cross-sectional shape of the DSTC, and (iii) the replacement ratio of RCAs in concrete. First, the results of the experimental program, and then, the effect of the abovementioned parameters on the compressive behavior of FRP-RAC-steel composite columns are discussed.

2. Experimental program

2.1. Test specimens

Twenty-four circular and square DSTCs were designed, manufactured and tested under axial compression. The details of the specimens are given in Table 1. The 305-mm-high specimens had a cross-section of 152 mm, measured at the concrete core. Square specimens had rounded corners with a 30 mm radius. Half of the specimens were manufactured with NSC and the remaining half with HSC. Similarly, 12 of the specimens had a circular cross-section and the other 12 had a square cross-section. The specimens were divided into three groups according to their RCA replacement ratio of 0%, 50%, and 100%. Two nominally identical specimens were tested for each unique specimen configuration. Because the effect of the steel tube diameter (D_s), thickness (t_s), and shape have been extensively investigated, they were not considered in this study. The same type of circular steel tube with a diameter of 88.9 mm and thickness of 3.2 mm was used in all specimens.

The fiber thickness of the FRP tubes of DSTCs was established by considering the increased confinement demand of concrete with increasing strength and the decreased confinement effectiveness of square tubes compared with circular tubes [40]. Accordingly, the FRP tubes of the NSC and HSC specimens were provided with two and four layers of CFRP, respectively, and the fiber thickness of the FRP sheets used in the circular and square specimens were 0.111 mm and 0.165 mm, respectively. The details are summarized in Table 1.

The specimens in Table 1 are labeled N or H to denote the concrete strength (i.e., NSC or HSC) and C or S (i.e., circular or square) to denote the cross-sectional shape of the DSTC. The number after the letters represents the RCA replacement percentage and is followed by a second number (i.e., 1 or 2) that distinguishes the two nominally identical specimens. For example, CN50-1 is the first of the two nominally identical normal-strength circular DSTCs with an RCA replacement percentage of 50%.

2.2. Materials

The RCAs used in this study were produced by initially removing impurities such as steel bars, leaves, and glass particles from C & D waste and subsequently crushing into coarse aggregates with a particle size ranging from 7 mm to 12 mm. The coarse RCAs are shown in Fig. 1 along with the coarse NAs used in this study, with their physical properties given in Table 2. All coarse RCAs were initially washed to remove impurities and then oven dried for 24 h at 105 °C and subsequently cooled at ambient temperature for more than 3 h before the concrete was mixed.

The coarse NAs used in this study were crushed bluestone gravel from the McLaren Vale Quarry (Fleurieu Peninsula). The selected NAs had similar particle size to that of RACs (i.e., 12 mm nominal maximum size) to maintain consistency in the coarse aggregate size of RAC and conventional concrete mixtures. The natural coarse aggregates were also oven dried for 24 h at 105 °C and subsequently cooled at ambient

(a) (b)

Fig. 1. Coarse aggregates: a) coarse RCA; b) coarse NA.