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A novel FRP–dual-grade concrete–steel composite column system

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ABSTRACT

This paper presents an experimental study that was designed to investigate the compressive behavior of a new type of fiber reinforced polymer (FRP)-concrete–steel composite column system. This composite column system has recently been developed by the author as a special form of double-skin tubular columns (DSTCs), with the column manufactured using two different grades of concrete (referred to as dual-grade concrete (DGC) DSTCs in this paper). In this system, the annular section of the column (i.e. the section between FRP and steel tubes) is filled with normal-strength concrete (NSC) and the core section inside the steel tube is filled with a higher grade concrete mix. Based on the understanding that confinement demand of concrete increases with its strength, the system was designed to maximize the effectiveness of the composite column. To establish the performance levels of this new column system with respect to those of the conventional DSTCs manufactured with normal- and high-strength concrete (NSC and HSC), a comprehensive experimental investigation was undertaken where 28 circular and square DSTCs were tested under concentric compression. Results of the experimental program indicate that the proposed DGC DSTC system exhibits a superior compressive behavior compared to those of the conventional NSC and HSC DSTCs. It is observed that both circular and square DGC DSTCs exhibit extremely high axial load and deformation capacities, which in turn results in a much higher system and concrete ductility compared to those in companion single-grade concrete DSTCs. The results also show that companion square and circular DGC DSTCs can be designed to develop similar axial load capacities under the same level of FRP confinement. It is found that, under these conditions, the axial deformation capacities of square DGC DSTCs exceed those of their circular counterparts.

1. Introduction

As was demonstrated in a recent review by Ozbakkaloglu et al. [1], the use of fiber reinforced polymer (FRP) composites as a confinement material has received a great deal of attention over the past two decades. Together with their use in retrofitting applications (e.g. [2–6]), the use of fiber reinforced polymer (FRP) composites in the construction of new high-performance composite members in the form of concrete-filled FRP tubes (CFFTs) has become increasingly popular, with a large number of studies that have been reported on the compressive (e.g. [7–11]), flexural (e.g. [12,13]) and seismic behavior (e.g. [14–17]) of CFFT beams and columns.

Following from the research on CFFTs, a new type of composites system, which consists of an inner steel tube, an outer FRP tube and a concrete-filling in-between the two tubes (and if preferred, inside the steel tube), has received significant recent research attention. These FRP-concrete-steel double-skin tubular beams and columns (the latter is referred to as DSTCs in this paper) benefit from the same FRP tube confinement mechanism that is present in CFFTs and they offer a long list of advantages, including: (i) improved structural performance, (ii) improved durability that prolongs the design life, thereby reducing the cost of structural maintenance and urban renewal, (iii) significant improvements to the ease of construction that results in reduced construction costs, (iv) significant reduction to carbon footprint through more efficient use of materials that reduces both the required amount of raw materials and generation of construction and demolition waste. A large number of experimental studies that were recently undertaken on these composite FRP-concrete–steel members demonstrated the performance advantages offered by the double-skin tubular system under various loading conditions, including monotonic [18–24] and cyclic [25,26] axial compression, flexure [27–29], and combined axial compression and lateral load reversals [30,31].

In the construction of DSTCs the use of high-strength concrete (HSC) is particularly attractive, as this ensures that the properties of the concrete complements those of the other two high-strength constituents (i.e. steel and FRP) in a composite system that is designed to maximize the advantages offered by each constituent. To gain clear insights into the compressive behavior of HSC DSTCs,

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the research group led by the author has undertaken a large number of experimental studies on circular [20–23,26] and square [24] DSTCs manufactured with carbon [20,21], aramid [20,23,24] or S-glass [22,26] FRP tubes and tested under monotonic [20–24] or cyclic [23,26] axial compression. The key parameters investigated in these studies included the: (i) cross-sectional size [20–24,26] and shape [20, 24], thickness [20,21,26], and strength [21] of inner steel tube; (ii) amount [20,21,26] and type [20,26] of FRP confinement; (iii) concrete strength [20,21,23,24,26]; and (iv) presence/absence of a concrete-filling inside the inner steel tube [21–26].

Motivated by the observations from these studies, the author has recently developed a new composite DSTC system [23] that was aimed at further improving the performance of concrete-filled DSTCs. This composite column system is manufactured using two different grades of concrete (referred to as dual-grade concrete (DGC) DSTCs in this paper), where the annular section of the column (i.e. the section between FRP and steel tubes) is filled with NSC and the core section inside the steel tube is filled with a higher grade concrete mix. The design of this system is inspired by the understanding that confinement demand of concrete increases with its strength [14,32]. Therefore, the proposed column system is aimed at maximizing the effectiveness of the confinement provided by the two tubes through the placement of the higher grade concrete inside the inner steel tube, where it receives confining effects from both the steel and FRP tubes; whereas the section between the two tubes, which relies on the confinement of the FRP tube, is filled with NSC. The pilot tests reported in Ref. [23] have shown the favorable properties of the proposed column system, demonstrating the significant performance advantages offered by the system over the conventional DSTCs.

The study reported in the present paper was aimed at undertaking a comprehensive experimental investigation on the compressive behavior of DGC DSTCs to establish relative performance levels of this new column system with respect to those of the conventional DSTCs manufactured with normal- and high-strength concrete (NSC and HSC). To this end, axial compression tests were undertaken on a series of square and circular DSTCs manufactured with NSC, HSC or DGC. The results of the experimental program are first presented and followed by discussions on relative performance levels of the different DSTC systems.

2. Experimental program

2.1. Test specimens

A comprehensive experimental program was designed to investigate the relative performance of the proposed DGC DSTC system compared to those of the conventional DSTCs manufactured with a single-grade concrete (SGC) of normal- or high-strength. To this end, a total of 28 circular and square DSTCs, all with a nominal cross-section of 150 mm and height of 300 mm, were designed, manufactured, and tested under axial compression. 18 of the specimens had circular external FRP tubes, whereas the remaining 10 had square FRP tubes that had rounded corners with a radius of 30 mm. The specimens had circular inner steel tubes that were either (i) left hollow (H series), (ii) filled with the same concrete used in the annular section of the specimen (F series), or (iii) filled with a concrete of higher strength than that used in the annular section (DGC series). In circular DSTCs, the size of the inner steel tube was also investigated as a test parameter, with specimens manufactured using either of the two steel tubes with diameters (D_s) 88.9 and 114.3 mm. Two nominally identical specimens were tested for each unique specimen configuration. The resulting test matrix is presented in Table 1, which allowed comparisons of the performances of circular and square DGC DSTC specimens with those of the companion hollow and filled SGC DSTCs, manufactured with NSC or HSC.

2.2. Materials

The specimens were prepared using NSC and HSC mixes, which consisted of crushed bluestone as the coarse aggregate with a nominal maximum size of 10 mm. Silica fume was added to the HSC mix at 8% of the binder content by weight. A polycarboxylic ether polymer-based superplasticizer was also added to the HSC mix to attain a workable mix. Mix proportions of the NSC and HSC mixes are given in Table 2. As can be seen in Table 1, test day compressive strengths of the mixes ranged between 47 and 50 MPa for the NSC and between 98 and 113 MPa for the HSC. The average test day concrete strength (f'_{co}) of each DSTC pair is also given in Table 1. For the DGC DSTC specimens this strength was calculated as the weighted average of the strengths of the concrete inside the steel tube (i.e. f'_{ci}) and that of the concrete in between the two tubes (i.e. f'_{ce}).

The properties of the two types of unidirectional aramid fiber sheets used in the manufacture of the FRP tubes are shown in

Table 1
Details of test specimens.

Specimen	Cross-section	External diameter of inner steel tube, D_s (mm)	Thickness of inner steel tube, t_s (mm)	Unconfined concrete strength (MPa) Outer ring, f'_{ce}	Inner core, f'_{ci}	Average, f'_{co}	FRP type	Number of FRP layers	Specimen type
C-D1-H-NSC-3L-1&2	Circular	88.9	3.2	49.8	–	49.8	AFRP1	3	Hollow NSC DSTC
C-D1-F-NSC-3L-1&2	Circular	88.9	3.2	47.3	47.3	47.3	AFRP1	3	Filled NSC DSTC
C-D1-DGC-3L-1&2	Circular	88.9	3.2	50.7	102.5	66.3	AFRP2	3	Dual-grade DSTC
C-D1-F-HSC-6L-1&2	Circular	88.9	3.2	104.6	104.6	104.6	AFRP1	6	Filled HSC DSTC
C-D1-DGC-6L-1&2	Circular	88.9	3.2	47.3	104.6	64.9	AFRP1	6	Dual-grade DSTC
C-D2-H-HSC-6L-1&2	Circular	114.3	6.0	113.8	–	113.8	AFRP1	6	Hollow HSC DSTC
C-D2-F-HSC-6L-1&2	Circular	114.3	6.0	104.6	104.6	104.6	AFRP1	6	Filled HSC DSTC
C-D2-DGC-6L-1&2	Circular	114.3	6.0	50.7	102.5	76.7	AFRP2	6	Dual-grade DSTC
C-D2-DGC-3L-1&2	Circular	114.3	6.0	50.7	102.5	76.7	AFRP2	3	Dual-grade DSTC
S-D2-H-NSC-3L-1&2	Square	114.3	6.0	50.7	–	50.7	AFRP2	3	Hollow NSC DSTC
S-D2-F-NSC-3L-1&2	Square	114.3	6.0	50.7	50.7	50.7	AFRP2	3	Filled NSC DSTC
S-D2-DGC-3L-1&2	Square	114.3	6.0	50.7	102.5	72.0	AFRP2	3	Dual-grade DSTC
S-D2-F-HSC-8L-1&2	Square	114.3	6.0	98.2	98.2	98.2	AFRP2	8	Filled HSC DSTC
S-D2-DGC-8L-1&2	Square	114.3	6.0	50.7	102.5	72.0	AFRP2	8	Dual-grade DSTC