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Flexural behavior of FRP-HSC-steel composite beams

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ABSTRACT

This paper reports on an experimental study on the flexural behavior of fiber reinforced polymer (FRP)-high-strength concrete (HSC)-steel composite beams. Seven double-skin tubular beam (DSTBs) and a concrete-filled FRP tube (CFFT) with an internal steel I-beam were tested as simply supported beams in four-point bending. The main parameters of the experimental study included the cross-sectional shapes of inner steel reinforcement and external FRP tube, concrete strength, presence (or absence) of concrete filling inside the steel tube, and effects of the use of mechanical connectors on the inner steel tube. The results indicate that DSTBs are capable of developing very high inelastic flexural deformations. However, the results also indicate that slip between the concrete and the steel tube of the DSTB can be relatively large, unless the bond between concrete and steel tube is enhanced through the use of mechanical connectors. The results of the beam tests illustrate that the flexural behavior of DSTBs is influenced significantly by the diameter and thickness of the inner steel tube. Concrete-filling the inner steel tube and increasing the concrete strength increase the flexural capacity of DSTBs without affecting their overall ductility. Furthermore, the shape of the inner steel tube influences both the flexural capacity of DSTBs and the occurrence of slippage between the concrete and the inner steel tube. It is shown that the bond slip between the concrete and inner steel tube can be prevented through the use of mechanical connectors. These results are presented together with a discussion on the influence of the main parameters on the flexural behavior of DSTBs.

1. Introduction

The use of FRP composites in the form of concrete-filled FRP tubes (CFFTs) for the construction of new high-performance structural members has received significant recent attention, with large numbers of studies reporting on the axial compressive [1–14] and seismic behavior [15–20] of CFFT columns. The flexural behavior of CFFTs has also been the focus of a number of studies [21–24], and a few studies have reported on the flexural behavior of CFFT beams reinforced with steel or FRP bars [25,26].

Following research on CFFTs, a new type of composite system was proposed by Teng et al. (27) in the form of a FRP-concrete–steel double-skin tubular (DST) column (DSTC). This composite system consists of an outer FRP tube enclosing a hollow steel tube with concrete sandwiched in between the FRP and steel components. The resulting column combines the advantages of all three materials to achieve a high-performance structural member. A series of experimental studies have been conducted on the axial compressive behavior of DSTCs [28–33]. The results of these tests have demonstrated that the concrete in DSTCs is confined very efficiently, which in turn results in a highly ductile member behavior. A few studies have also reported on the lateral cyclic behavior of DSTCs that were tested under combined axial compression and lateral deformation reversals [34–36]. Reinforcing the findings of the studies on the compressive behavior of CFFTs, these studies revealed that DSTCs exhibit very high inelastic deformation capacities under simulated seismic loading. To date, only a single study has reported on the flexural behavior of DST beams (DSTBs) [37], which was concerned with the behavior NSC DSTBs manufactured with circular glass FRP external tubes. In agreement with the findings of the studies on DSTCs, Yu et al. [37] reported that DSTBs exhibit a very ductile response under flexure. It was also noted, however, that significant slip occurred between the inner steel tube and surrounding concrete of DSTBs.

Along with the studies on DST beams and columns, a number of studies have also been carried out on a different type of FRP-concrete–steel composite system that comprises CFFTs with inner steel I-beams. These early studies on the axial compressive [38–40] and flexural behavior [41] of this composite system demonstrated some of its desirable properties, including a highly ductile behavior.

As, to date, only a single study has dealt with the flexural behavior of DSTBs and no study has reported on the flexural behavior of HSC

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DSTBs, additional studies are required to better understand and be able to model the flexural response of these composite beams. To contribute towards this end, this paper presents the first experimental study on the flexural behavior of HSC DSTBs. The study was aimed at investigating the influence of key parameters on the flexural behavior of DSTBs, with particular emphasis placed on the interface-slip behavior between steel tube and surrounding concrete. In addition, to establish relative performances of the two aforementioned composite systems, the behavior of a FRP-HSC-steel beam that was composed of a CFFT and an inner steel I-beam was also experimentally investigated. The main parameters of the study included the cross-sectional shapes of inner steel reinforcement and external FRP tube, concrete strength, presence (or absence) of concrete filling inside the steel tube, and effects of the use of mechanical connectors to enhance the bond between the steel tube and surrounding concrete. Flexural behaviors of the beams were evaluated using the recorded load–midspan deflection relationships, with additional data provided by the load–slip relationships measured at the ends of the specimens.

2. Experimental program

2.1. Test specimens

Six DSTBs with circular external FRP tubes and a DSTB with a square FRP tube were manufactured and tested as simply supported beams in a four-point bending setup under monotonic loading. In addition, a single specimen that was composed of a circular CFFT and an inner steel I-beam (i.e. I-CFFT) was also tested under the same loading conditions. Each of the specimens was designed as a flexural beam with a 150-mm cross-section. The corners of the square CFFT were rounded with a 30-mm radius (R). The span, measured between the center lines of the supports, was 1.3 m, and the length of the constant moment region between the two point loads was 0.3 m. Seven of the specimens were manufactured using HSC and one with normal strength concrete (NSC). All the specimens were confined with aramid FRP (AFRP) external tubes. Five of the specimens were reinforced with circular inner steel tubes, two with square inner steel tubes, and one with a steel I-beam. Of the five specimens that were reinforced with circular inner steel tubes, three were reinforced with tubes 114.3 mm in diameter and two with 76.1 mm diameter tubes. One of the smaller-diameter specimens was provided with mechanical connectors along the inner steel tube. Table 1 provides a summary of material and geometric properties of the test specimens, and Fig. 1 illustrates their geometry.

The process of DSTB manufacture started with the manufacturing of the outer FRP tube, followed by placing the inner steel tube inside the FRP tube, which functioned as a stay-in-place form during the concrete pour. Concrete mixtures were poured in the space between FRP tube and the inner steel tube, except for DSTB-3 where the concrete was also poured inside the inner steel tube. The process of beam manufacture is illustrated in Fig. 2, with the properties of each material used in the process supplied in the following section.

3. Material properties

3.1. FRP tubes

Aramid fibers were used to manufacture the outer FRP tube in all the specimens. The tubes were manufactured using a manual wet layup process, which involved wrapping epoxy resin impregnated fiber sheets around precision-cut high-density styrofoam molds in the hoop direction. FRP tubes of HSC DSTBs and I-CFFT were made of 2 layers of FRP, whereas the tube of NSC DSTB had a single layer of FRP. FRP sheets were wrapped around the molds one layer at a time, with an overlap length of 100 mm provided for each layer to prevent premature debonding. The overlap region of each subsequent layer was provided on the opposite face at a 180° interval from the previous overlap region. The tubes were manufactured in a manner that the overlap regions formed continuous lines along the length of DSTBs, which were oriented to correspond to the side faces of the beams. The width of each fiber sheet was 300 mm and a small overlap of around 10 mm was provided along the axial direction only to ensure continuity of the tube. The epoxy resin was applied at the fiber sheet coverage rate of 0.6 L/m^2, which resulted in a ply thickness of 0.8 mm for the resulting FRP composite. Table 2 provides the properties of aramid sheets and epoxy resin used in the fabrication of the FRP tubes.

3.2. Concrete

Two different concrete mixes were used in the manufacture of the specimens, namely the HSC mix and NSC mix. Both mixes consisted of crushed bluestone as the coarse aggregate with a nominal maximum size of 10 mm. Superplasticizer and silica fume, added at 8% of the binder content by weight, were used in the HSC mix. Test day concrete strengths of the specimens were obtained through concrete cylinders tests. As shown in Table 1, test day strengths of the HSC mixes varied slightly between 82 and 92 MPa, and the strength of the NSC mix was established as 42 MPa.

3.3. Steel tubes

Five of the DSTBs had circular inner steel tubes with two different external diameters (i.e. 114.3 and 76.1 mm) and thicknesses (i.e. 6.02 and 3.2 mm). One of the DSTBs with 76.1 mm circular inner steel tube (i.e. DSTB-7) was manufactured with

Table 1
Properties of test specimens.

Specimens	f'_c (MPa)	FRP tube		Inner steel tube				A_s/A_c
		Shape	n	Shape	D (mm)	t_s (mm)	Inner void	
DSTB-1	92	Circular	2	Circular	114.3	6.02	Empty	0.28
DSTB-2	92	Circular	2	Circular	76.1	3.2	Empty	0.06
DSTB-3	91	Circular	2	Circular	114.3	6.02	Filled	0.13
DSTB-4	42	Circular	1	Circular	114.3	6.02	Empty	0.28
DSTB-5	84	Circular	2	Square	100	6	Empty	0.27
DSTB-6	84	Square	2	Square	100	6	Empty	0.18
DSTB-7	91	Circular	2	Circular	76.1	3.2	Empty	0.07[a]
I-CFFT	82	Circular	2	Steel I-beam	As in Fig. 1		–	0.10

f'_c=concrete strength, n=number of FRP layers, D=diameter of steel tubes, t_s=thickness of steel tubes, A_s/A_c=reinforcement ratio.

[a] Includes the area of additional mechanical connectors.