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Flexural behavior of FRP-HSC-steel double skin tubular beams under reversed-cyclic loading

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ABSTRACT

This article presents an experimental study on the cyclic behavior of fiber reinforced polymer (FRP)-concrete-steel double skin tubular (DST) cantilever beams, referred to in this article as DSTBs. Four DSTBs constructed of high-strength concrete (HSC) were tested under reversed-cyclic lateral loading. The main parameters under investigation were the size of the inner steel tube, the provision (or absence) of a concrete filling inside the steel tube, and the installation of mechanical connectors in the form of steel rings welded on the inner steel tube. The results indicate that DSTBs exhibit very ductile behavior under reversed-cyclic lateral loading. The results also indicate that the DSTBs with larger inner steel tubes exhibit lower lateral displacement capacities compared to their counterparts with smaller inner steel tubes. It was observed that installation of mechanical connectors on the inner steel tube and concrete-filling the tube both influence the overall behavior and lateral displacement capacity of the DSTBs. Furthermore, the results show that through the use of mechanical connectors the slippage at the interface between the steel tube and surrounding concrete sleeve can be completely eliminated.

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 the 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. [7–13]], flexural [e.g. [14–16]] and seismic behavior [17–21] of CFFT beams and columns. Following from the research on CFFTs, a new type of composite system, which consists of a steel tube inside an FRP tube with a concrete sleeve sandwiched in between, has received significant recent research attention. These double-skin tubular beams and columns (referred to as DSTBs and DSTCs) rely on the same FRP tube confinement mechanism that is present in CFFTs, and through the combination of the advantages of the three constituent materials they can be designed to exhibit extremely high structural performance levels. A large number of experimental studies have recently been undertaken on these composite members by groups led by Teng in Hong Kong [e.g. [22–24]] and the second author in Australia [e.g. [25–29]]. The results of these studies have shown some of the performance advantages offered by this composite system under various loading conditions.

A recent study by Ozbakkaloglu and Idris [28], where the behavior of DSTCs manufactured with high-strength concrete (HSC) was investigated under combined axial compression and lateral load reversals, illustrated the ability of these columns to develop very high inelastic deformation capacities under simulated seismic loading. In agreement with the observations on the behavior of DSTCs, the two studies reported to date on the behavior of DSTBs have shown that these composite beams exhibit very ductile flexural behavior under four point bending [29,30]. However, no study has been reported to date on the behavior of cantilever DSTBs under reversed-cyclic loading, and addressing this gap formed the aim of the experimental study presented in this article.

The experimental program reported in this article was designed to investigate the performance of FRP-HSC-steel DSTBs subjected to reversed-cyclic lateral loading. The study investigated the influences of: i) varying the size of the inner steel tube, (ii) concrete-filling the steel tube, and iii) installing mechanical connectors on the steel tube. The results of the experimental program are first presented, followed by a discussion on the influence of the main test parameters on the beam behavior.

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2. Experimental program

2.1. Test specimens

Four cantilever DST beams (DSTBs) were manufactured and tested under incrementally increasing lateral displacement reversals. The specimens had 150 mm circular cross-sections and they were 1.2 m long. The inner steel tube of each specimen was groove welded to a 300 × 300 mm steel plate. Lateral loads were applied to the specimens by an actuator at a section 200 mm below the tip of the cantilever, which resulted in a shear span (L) of 1.0 m. The specimens were manufactured using a HSC mix with target compressive strength of 100 MPa, and they were enclosed by aramid FRP external tubes. Table 1 provides a summary of material and geometric properties of the test specimens and Fig. 1 illustrates their geometry.

Table 1
Properties of test specimens.

Specimens	f'_c (MPa)	FRP tube		Inner steel tube				A_s/A_c
		Shape	n	Shape	D_s (mm)	t_s (mm)	Inner void	
DSTB-1	100	Circular	2	Circular	114.3	6.0	Empty	0.28
DSTB-2	100	Circular	2	Circular	114.3	6.0	Filled	0.13
DSTB-3	112	Circular	2	Circular	76.1	3.2	Empty	0.06
DSTB-4	112	Circular	2	Circular	76.1	3.2	Empty	0.07[a]

f'_c=test-day unconfined concrete strength, n=number of FRP layers, D_s=diameter of steel tube, t_s=thickness of steel tube, A_s/A_c=reinforcement ratio.

[a] total steel area includes the additional area of steel rings.

2.2. Materials and specimen preparation

2.2.1. FRP tubes

Aramid fibers were used to manufacture the outer FRP tube in all the specimens. The tubes were manufactured using a manual wet lay-up process, which involved wrapping epoxy resin impregnated fiber sheets around precision-cut high-density styrofoam moulds in the hoop direction. The FRP tubes of each DSTB were made from two layers of FRP. The sheets were wrapped around the moulds one layer at a time, with an overlap length of 100 mm provided for each layer on opposite sides of the beam to prevent premature debonding. The overlap region of each subsequent layer was located on the opposite face at a 180-degree interval from the previous overlap. The tubes were manufactured so that the overlap regions formed continuous lines along the length of the DSTBs, corresponding 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 the continuity of the tube. The epoxy resin was applied to the fiber sheet at a 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 manufacturer supplied properties of the unidirectional fiber sheets used in the manufacture of the FRP tubes. The material properties of the FRP composites, established

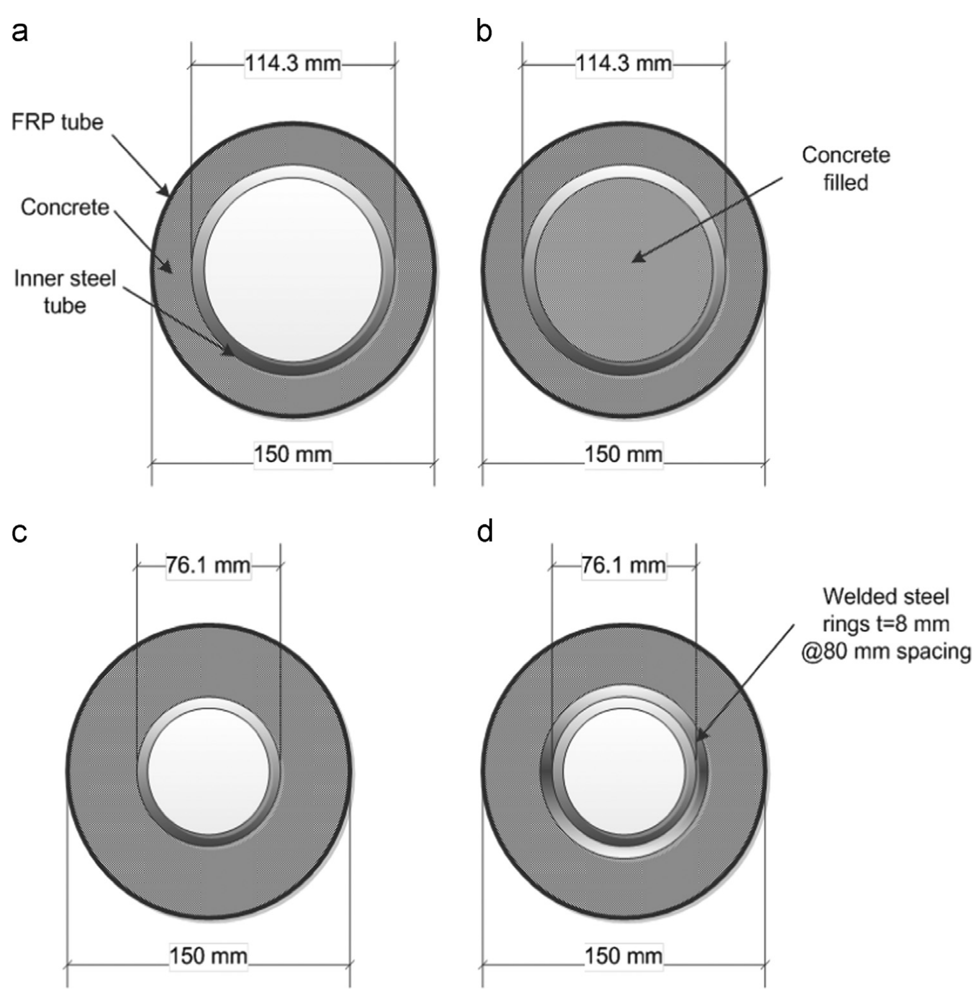

Fig. 1. Beam cross-sections: (a) DSTB-1, (b) DSTB-2, (c) DSTB-3, (d) DSTB-4.