Thin-Walled Structures 61 (2012) 196–203

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Behavior of hybrid FRP-concrete-steel double-skin tubular columns subjected to cyclic axial compression

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ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form
6 June 2012
Accepted 6 June 2012
Available online 11 August 2012

Keywords:
Concrete
Cyclic compression
FRP
Hybrid columns
Steel
Tubular columns

ABSTRACT

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns which consists of a layer of concrete sandwiched between an inner steel tube and an outer FRP tube. While a large amount of research has been conducted on the monotonic behavior of this novel form of columns, only a limited amount of work has been conducted on their behavior under cyclic loading. This paper presents the first ever study on the behavior of circular hybrid DSTCs under cyclic axial compression. Results from a series of stub column tests, where the hybrid DSTCs were subjected to cyclic axial compression, are first presented and discussed. The test results show that hybrid DSTCs are very ductile under cyclic axial compression, with the envelope axial load-strain curve being almost the same as the axial load-strain curve of a corresponding DSTC under monotonic compression. It is also shown that repeated unloading/reloading cycles have a cumulative effect on the permanent strain and the stress deterioration of the confined concrete in hybrid DSTCs. The experimental stress–strain curves of the confined concrete in hybrid DSTCs are then compared with predictions from two existing models: (1) a monotonic stress–strain model for the confined concrete in hybrid DSTCs; and (2) a cyclic stress–strain model for the concrete in FRP-confined solid columns. The comparison suggests that the combined use of the two models can give reasonably accurate predictions of the test results.

1. Introduction

Hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) are a new form of hybrid columns recently developed at The Hong Kong Polytechnic University (PolyU) [1,2]. Such a column consists of a layer of concrete sandwiched between an outer tube made of fibre-reinforced polymer (FRP) and an inner tube made of steel (Fig. 1). The inner void may be filled with concrete if desired. The FRP tube is provided with fibers which are predominantly oriented in the circumferential direction to provide confinement to the concrete and additional shear resistance. In this novel hybrid column, the three constituent materials are optimally combined to achieve several important advantages, including their excellent corrosion resistance and excellent seismic resistance.

A large amount of research has recently been undertaken at PolyU on the monotonic behavior of circular hybrid DSTCs with two circular tubes, through laboratory testing of small-scale columns subjected to axial compression [3], bending [4] and combined bending and compression [5] as well as finite element modeling [6,7]. A design-oriented stress–strain model for the confined concrete in circular hybrid DSTCs subjected to monotonic axial compression has also been proposed [8]. In addition to research carried out at PolyU, work has also been undertaken by Xu and Tao [9], Yu [10], Liu [11] and Han et al. [12]. These studies have further confirmed some of the performance advantages of hybrid DSTCs under different loading conditions.

Existing studies conducted at PolyU on hybrid DSTCs have been limited to monotonic loading. As a structural form particularly suitable for use in seismic regions, the behavior of hybrid DSTCs subject to cyclic loading is of particular importance. Liu [11] and Han et al. [12] presented results from small-scale hybrid DSTCs subject to combined axial compression and cyclic lateral loading, but no existing studies have been concerned with hybrid DSTCs under cyclic axial compression. This paper presents the first ever study on the behaviour of circular hybrid DSTCs under cyclic axial compression. The experimental program included stub column tests on four pairs of hybrid DSTCs subjected to either monotonic or cyclic axial compression. The study presented in this paper is part of an ongoing research project at PolyU aimed at the development of a procedure for the seismic design of these columns.

2. Experimental details

2.1. Test specimens

In total, eight identical hybrid DSTCs were tested, covering four loading schemes; two specimens were prepared for each

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0263-8231/$ - see front matter
http://dx.doi.org/10.1016/j.tws.2012.06.003

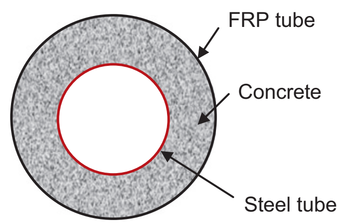

Fig. 1. Cross section of hybrid FRP-concrete-steel double-skin tubular column.

loading scheme. The specimens had an outer diameter (i.e., the outer diameter of the annular concrete section) of 205.3 mm, an inner diameter (i.e., the inner diameter of the annular concrete section and the outer diameter of the inner steel tube) of 140.3 mm, and a height of 400 mm. The outer glass FRP (GFRP) tube had fibers in the hoop direction only and was formed by a wet-layup process on hardened concrete [2], with an overlapping zone of 150 mm. Both of the upper and lower ends of each specimen were strengthened with an additional three-ply GFRP strip of 25 mm in width. The nominal thickness of the two-ply FRP tube was 0.34 mm (i.e., the nominal thickness was taken to 0.17 mm per ply) while the thickness of the steel tube was 5.3 mm.

2.2. Material properties

Tensile tests on steel coupons cut from the same long steel tube that provided the individual short steel tubes for the DSTCs were conducted. These tests showed that the steel had a yield stress of 325.5 MPa, a tensile strength of 431.6 MPa, and a Young's modulus of 195.6 GPa. In addition, three hollow steel tubes also cut from the same original long tube were tested under monotonic axial compression (for two of the three tubes) or cyclic axial compression (for one of the three tubes). In these tests, four bidirectional strain gauges with a gauge length of 10 mm were attached at the mid-height, and three linear variable displacement transducers (LVDTs) were used to measure the axial shortening. All the three tubes failed by local buckling in the elephant's foot mode and the average ultimate load of these tubes was 832.1 kN. The axial strains found from strain gauges remained very similar to those found from LVDTs until an axial strain of around 0.019 when significant buckling deformation began to be observed. Fig. 2 shows the axial stress–strain curves of the three hollow tubes, where the axial strains were found from LVDTs. The slope of the unloading/reloading path of the cyclic stress–strain curve found from the cyclic axial compression test was almost the same as the elastic modulus of the steel (i.e., no stiffness degradation). Tensile tests on five FRP coupons were also conducted. These tests showed that the FRP had an approximately linear stress–strain curve, with an average tensile strength of 1752 MPa based on a nominal thickness of 0.17 mm per ply, and an ultimate tensile strain of 0.0196. The elastic modulus, compressive strength and compressive strain at peak stress of the concrete averaged from three concrete cylinder tests (152.5 mm $\times$ 305 mm) were 31.8 GPa, 43.9 MPa and 0.00264, respectively. The stress–strain curves of the three concrete cylinders are shown in Fig. 3, where the axial strains were found from two strain gauges with a gauge length of 100 mm installed at the mid-height.

2.3. Experimental set-up and instrumentation

For each hybrid DSTC specimen, two bi-directional strain rosettes (gauge length = 10 mm) were installed at the mid-height of the steel tube, and four bi-directional strain rosettes (gauge length = 20 mm) were installed at the mid-height of the FRP tube

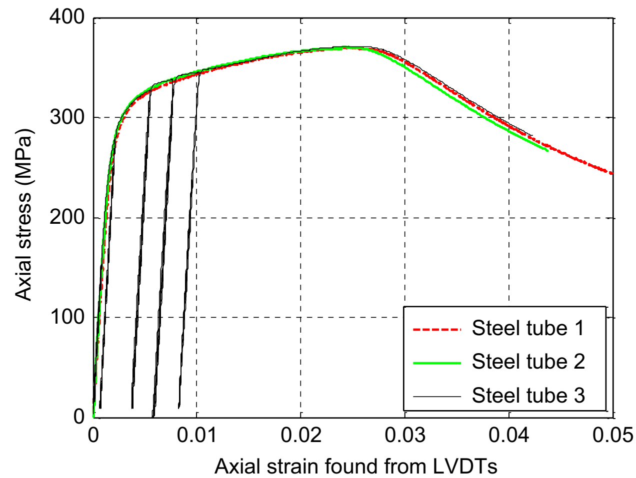

Fig. 2. Axial stress–strain curves of steel tubes.

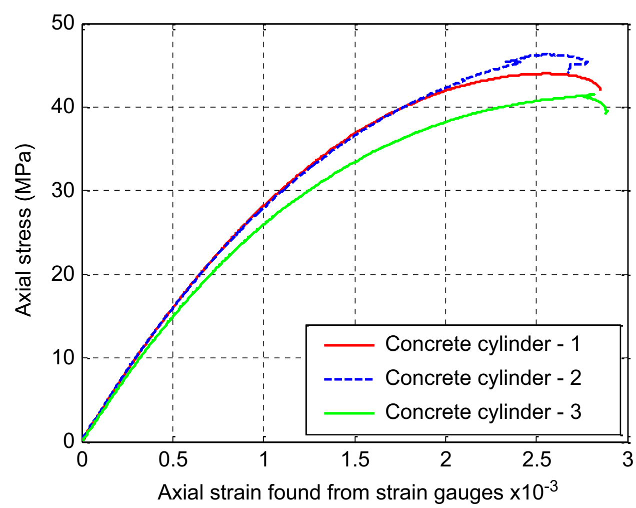

Fig. 3. Axial stress–strain curves of concrete cylinders.

(Fig. 4). The four strain rosettes on the FRP tube were evenly distributed over the circumference, with one of them being in the middle of the overlapping zone. In addition, four LVDTs were used to obtain the axial deformation of the middle region of 160 mm over the height for each specimen. All compression tests were carried out using an MTS machine with a displacement control rate of 0.24 mm/min. All test data, including the strains, loads, and displacements, were recorded simultaneously by a data logger.

2.4. Loading scheme

Two of the eight specimens (i.e., specimens M1 and M2) were tested under monotonic axial compression while the other six were tested using three different cyclic loading schemes. Among the six cyclic loading specimens, specimens F1 and F2 were designed for cyclic compression involving full unloading/reloading cycles, where the unloading part of each cycle was designed to terminate at zero (or a near-zero) load and the reloading part of each cycle was designed to terminate at the unloading displacement of the same cycle (i.e., where the unloading started) or after reaching the envelope curve [13]; specimens PU1 and PU2 were designed for partial unloading cycles where the unloading part of each cycle was terminated at a load level significantly larger than zero while the termination point of reloading was the same as in a