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Tao Yu

University of Wollongong, taoy@uow.edu.au

Shi Shun Zhang

University of Wollongong, shishun@uow.edu.au

Le Huang

University of Wollongong, lh794@uowmail.edu.au

Chun Wa Chan

University of Wollongong, cwc263@uowmail.edu.au

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Abstract

Hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular columns (DSTCs) consist of an outer tube made of FRP and an inner tube made of steel, with the space between filled with concrete. A significant amount of research has been conducted on hybrid DSTCs with an outer tube made of glass FRP (GFRP), carbon FRP (CFRP), or aramid FRP (AFRP). One important finding of the existing research is that the ductility of the column depends significantly on the rupture strain of the FRP tube, among other factors. Against this background, this paper presents an experimental study where hybrid DSTCs with a large rupture strain (LRS) FRP tube, namely, polyethylene terephthalate (PET) FRP tube, were tested under axial compression. PET FRP composites have emerged recently as an economical and environmentally friendly material with a rupture strain of over 7%. Results from a total of four DSTC specimens are presented, with the main test variable being the thicknesses of the steel tube. The test results confirmed the ample ductility of the column and suggested that the diameter-to-thickness ratio of the inner steel tube is a more critical parameter in such DSTCs than in DSTCs with a GFRP, AFRP or CFRP outer tube.

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HYBRID DOUBLE-SKIN TUBULAR COLUMNS WITH A LARGE RUPTURE STRAIN FRP OUTER TUBE: STUB COLUMN TESTS

T. Yu, S. S. Zhang, L. Huang and C. Chan

School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences,
University of Wollongong, New South Wales, Australia. Email: taoy@uow.edu.au

ABSTRACT

Hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular columns (DSTCs) consist of an outer tube made of FRP and an inner tube made of steel, with the space between filled with concrete. A significant amount of research has been conducted on hybrid DSTCs with an outer tube made of glass FRP (GFRP), carbon FRP (CFRP), or aramid FRP (AFRP). One important finding of the existing research is that the ductility of the column depends significantly on the rupture strain of the FRP tube, among other factors. Against this background, this paper presents an experimental study where hybrid DSTCs with a large rupture strain (LRS) FRP tube, namely, polyethylene terephthalate (PET) FRP tube, were tested under axial compression. PET FRP composites have emerged recently as an economical and environmentally friendly material with a rupture strain of over 7%. Results from a total of four DSTC specimens are presented, with the main test variable being the thicknesses of the steel tube. The test results confirmed the ample ductility of the column and suggested that the diameter-to-thickness ratio of the inner steel tube is a more critical parameter in such DSTCs than in DSTCs with a GFRP, AFRP or CFRP outer tube.

KEYWORDS

FRP, steel, concrete, large rupture strain, confinement, buckling

INTRODUCTION

Hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular columns (referred to as hybrid DSTCs) are an emerging form of hybrid columns proposed at The Hong Kong Polytechnic University (Teng et al. 2004, 2007). A hybrid DSTC consists of an outer tube made of FRP and an inner tube made of steel, with the space between filled with concrete (Figure 1). In hybrid DSTCs, the three constituent materials (i.e. FRP, steel and concrete) are optimally combined to achieve several advantages including their excellent corrosion resistance and ductility (Teng et al. 2007). A significant number of studies have been conducted on hybrid DSTCs (e.g. Wong et al. 2008; Yu et al. 2010; Yu and Teng 2013; Fanggi and Ozbakkaloglu 2013; Ozbakkaloglu and Louk Fanggi 2014). The existing studies, however, have generally been limited to the use of an outer tube made of glass FRP (GFRP) (e.g. Wong et al. 2008), carbon FRP (CFRP) (Fanggi and Ozbakkaloglu 2014) or aramid FRP (AFRP) (Fanggi and Ozbakkaloglu 2013). GFRP, CFRP and AFRP are referred to collectively as conventional FRPs hereafter in this paper. One important finding of the existing research is that the ductility of the column depends significantly on the rupture strain of the FRP tube, among other factors. Against this background, this paper presents results from stub column tests of four hybrid DSTCs with a large rupture strain (LRS) FRP tube, namely, Polyethylene terephthalate (PET) FRP tube. PET FRP composites have emerged recently as an economical and environmentally friendly material with a rupture strain of over 7%. During the test, the buckling of steel tube in hybrid DSTCs, which is expected to occur under large axial deformations, was paid special attention to.

TEST SPECIMENS

The hybrid DSTC specimens included two pairs of specimens; each pair of specimens were nominally identical. The specimens all had a nominal diameter (i.e. the outer diameter of concrete) of 208 mm and a height of 500 mm. The FRP outer tubes were all composed of three plies of PET-FRP, while two types of steel tubes (i.e. Types A and B) were used. Types A and B steel tubes had the same outer diameter of 139.7 mm, but had thicknesses of 3.5 mm and 5.4 mm respectively, leading to two different diameter-to-thickness (D/t) ratios (i.e. 39.9 and 25.9 respectively). For ease of reference, each specimen is given a name, which starts with a letter to

indicate the type of the steel tube (i.e. A or B) together with an Arabic numeral to indicate the number of plies of FRP (i.e. 3); the Roman numeral at the end is used to differentiate two nominally identical specimens.

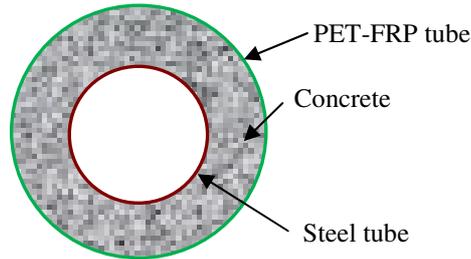


Figure 1 Cross-section of hybrid DSTCs with a PET-FRP tube

All specimens were cast in one batch using ready-mix concrete from a local manufacturer. Results from three standard concrete cylinder (150 mm x 300 mm) tests showed that the elastic modulus, compressive strength and compressive strain at peak stress of the concrete were 25.2 GPa, 28.4 MPa and 0.0025 respectively. For each type of steel tube, tensile tests of two steel coupons were conducted. The average values of elastic modulus, yield stress and tensile strength are 193 GPa, 325 MPa and 470 MPa respectively for Type A steel tubes, while are 194 GPa, 270 MPa and 360 MPa for Type B steel tubes. In addition, tensile tests on six coupons were conducted to determine the mechanical properties of the PET-FRP tube and these tests showed that the the PET-FRP used in the present study had an average rupture strain of 0.0956 and an average tensile strength of 823.9MPa based on a nominal thickness of 0.819 mm per ply.

TEST SET-UP AND INSTRUMENTATION

For each specimen, four axial strain gauges and four hoop strain gauges with a gauge length of 20 mm were installed on the outer surface of the FRP tube. These strain gauges were evenly distributed around the circumference at the mid-height of the specimen, with one located at the centre of the overlapping zone. In addition, two axial strain gauges with a gauge length of 10 mm were applied at the mid-height of the steel tube for each specimen. For each specimen, two linear variable displacement transducers (LVDTs) placed 180° apart from each other were used to measure the overall axial shortening, while another two LVDTs placed 180° apart from each other were used to measure the axial deformation of the 150 mm mid-height region. The layout of these LVDTs and the test set-up are shown in Figure 2. To monitor the buckling process of the inner steel tube in the DSTC specimens, a portable action camera was installed on the bottom surface of the top loading plate (Figure 2). All the compression tests were conducted at the University of Wollongong using a 500 ton Denison Compression Testing Machine with a displacement control rate of 0.6 mm per minute.

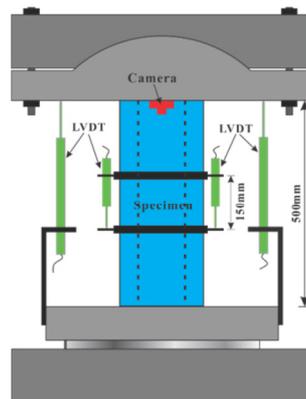


Figure 2 Test set-up

TEST RESULTS AND DISCUSSIONS

General Behaviour

All specimens failed by hoop rupture of the FRP tube at or close to the mid-height of the specimens (Figure 3a). The inner steel tube experienced significant buckling (Figure 3b) which led to considerable load reduction during the test; such load reduction, however, could be recovered in the later stage of testing, and at the ultimate

state (i.e. FRP rupture) the specimens could take even a higher load than the first peak (Figure 4). This observation is clearly different from that from tests of DSTC specimens with a conventional FRP tube (Wong et al. 2008; Yu and Teng 2013; Fanggi and Ozbakkaloglu 2014), and is mainly due to the extremely large axial shortening that the steel tube in the PET-FRP DSTC specimens experienced. Another test observation associated with the extremely large axial deformation was the partial debonding and local buckling of the PET-FRP tube at the finishing end of the overlapping zone (Figure 3). Nevertheless, such debonding/buckling only happened within a small region at the very late stage of tests (i.e. close to the ultimate state), and is thus believed to have little effect on the overall behaviour of the specimens.

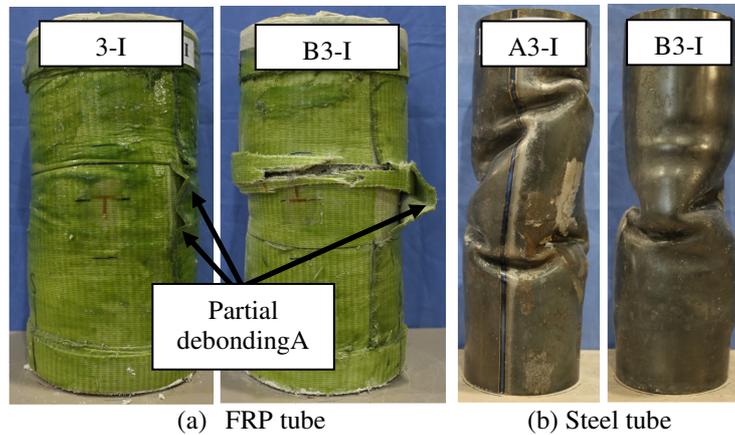


Figure 3 Typical failure mode

Axial Load-Shortening Behaviour

The axial load-shortening curves of the four specimens are shown in Figure 4, where all the curves are terminated at the point of FRP rupture. The curves of Specimens A3-I, II can generally be divided into three branches (Figure 4): (1) an approximately bilinear ascending branch before the peak load; (2) a gradual descending branch which was caused by inward buckling of the inner steel tube and the associated inward concrete spalling; (3) another ascending branch where the axial load increased approximately linearly with the axial shortening until the final failure by rupture of the FRP tube. It is evident that the curves shown in Figure 4 are significantly different from the axial load-shortening curves of DSTCs with a conventional FRP tube (Wong et al. 2008; Yu and Teng 2013; Fanggi and Ozbakkaloglu 2014) which typically had an approximately bilinear shape (i.e. similar to the first branch of the curves shown in Figure 4). This is not surprising as the rupture of FRP usually occurs before the first peak if conventional FRPs, which have a much smaller rupture strain than PET-FRP, are used to fabricate the outer tube. For Specimens B3-I, II, Figure 4 shows that the curves of may also be divided into three branches in the same way as discussed above for Specimens A3-I, II, but the load decrease in the second branch and the load increase in the third branch were both much less pronounced. The second and third branches of Specimens B3-I, II may thus also be seen as a single branch with an approximately constant load. It is evident that all the hybrid DSTCs possessed extremely good ductility with ultimate shortenings of up to around 16% of their heights (i.e. 500 mm).

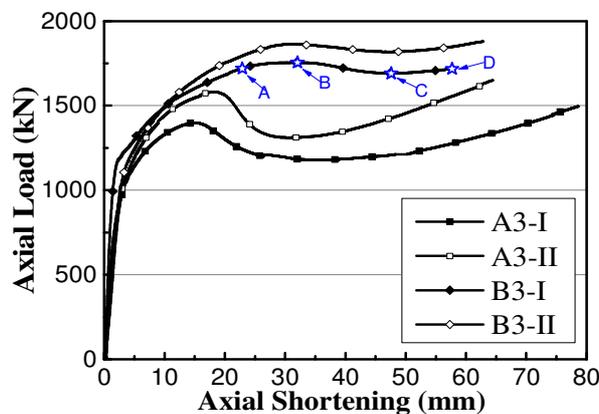


Figure 4 Axial load-shortening curves

Buckling Behaviour of Inner Steel Tube

The inner steel tubes in the DSTC specimens experienced significant local buckling due to the extremely large axial shortening that they were subjected to, as well as the lack of internal support (Figure 3b). The deformed shapes of the inner steel tube at different stages of loading, as recorded by the action camera (see Figure 2), are shown in Figure 5 for Specimen B3-II. The four subfigures in Figure 5 are corresponding to four points on the load-shortening curve shown in Figure 4, respectively. The buckling process of the inner steel tube can be described as follows: (1) no apparent buckling occurred before the first peak (i.e. Point B), as evident from the deformed shape of the steel tube at Point A when the axial load was 98% that of Point B; (2) at Point B, a slight wrinkle was noticed (Figure 5-B); (3) the first wrinkle developed with the decrease of load, and new wrinkles appeared at various circumferential locations close to the mid-height of the tube (the numbers in Figure 5 indicate the order in which the wrinkles occurred); the wrinkles became quite significant at the trough point of the load-shortening curve (i.e. Point C, see Figure 5-C); (5) after Point C, no new wrinkles were formed, but the existing wrinkles kept progressing with an increasing load until the rupture of the FRP tube (see Figures 5-D).

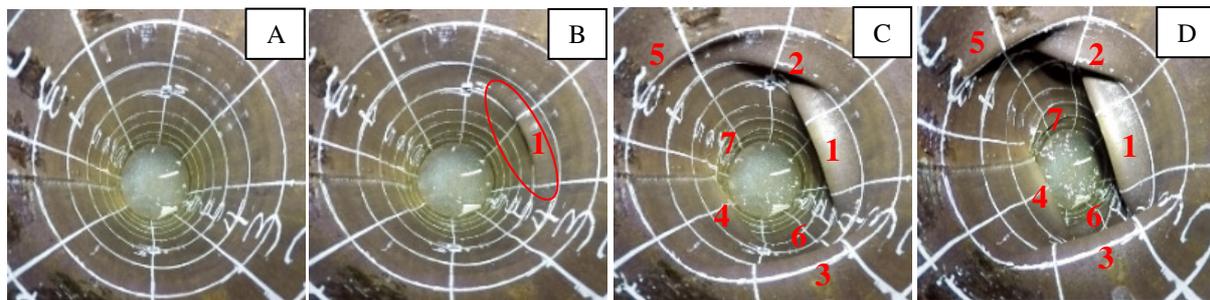


Figure 5. Buckling process of inner steel tube

CONCLUSIONS

This paper has presented results from four stub column tests on hybrid DSTCs with a large rupture strain FRP tube (i.e. PET-FRP tube). The test results showed that hybrid DSTCs with a PET-FRP tube possess extremely good ductility despite the severe buckling of the inner steel tube. The test result also showed that the behaviour of PET-FRP DSTCs depends significantly on the diameter-to-thickness ratio of the inner steel tube.

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