1-1-2012

Behaviour of hybrid double-skin tubular columns subjected to combined axial compression and cyclic lateral loading

Bing Zhang
Hong Kong Polytechnic University

J G. Teng
Hong Kong Polytechnic University

Tao Yu
University of Wollongong, taoy@uow.edu.au

Behaviour of hybrid double-skin tubular columns subjected to combined axial compression and cyclic lateral loading

Abstract

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns developed at The Hong Kong Polytechnic University. They consist of an outer tube made of fibre reinforced polymer (FRP) and an inner tube made of steel, with the space between filled with concrete. In these hybrid DSTCs, the three constituent materials are optimally combined to achieve several advantages not available with existing forms of columns, including their superior corrosion and seismic performance. This paper presents the test results of a series of large-scale hybrid DSTCs subjected to combined axial and cyclic lateral loads, with an emphasis on the effect of a high strength concrete infill. All column specimens had a circular section with a diameter of 300 mm and a height of 1350 mm (from the point of lateral loading to the top surface of the stiff RC footing). The parameters examined include the concrete strength, the confinement stiffness of the GFRP tube and the axial load ratio. The test results showed that these hybrid DSTCs possess excellent ductility and hence excellent seismic resistance even when high strength concrete with a cylinder compressive strength of around 120 MPa is used.

Keywords

hybrid, double, loading, lateral, behaviour, cyclic, skin, compression, axial, combined, subjected, columns, tubular

Disciplines

Engineering | Science and Technology Studies

Publication Details

Zhang, B., Teng, J. G. & Yu, T. (2012). Behaviour of hybrid double-skin tubular columns subjected to combined axial compression and cyclic lateral loading. Sixth International Conference on FRP Composites in Civil Engineering (pp. 1-7). Rome, Italy:

BEHAVIOUR OF HYBRID DOUBLE-SKIN TUBULAR COLUMNS SUBJECTED TO COMBINED AXIAL COMPRESSION AND CYCLIC LATERAL LOADING

Bing ZHANG
PhD Student
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China
Mr.ZHANG-Bing@connect.polyu.hk

J.G. TENG
Chair Professor of Structural Engineering
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China
cejgteng@polyu.edu.hk *

Tao YU
Lecturer
School of Civil, Mining and Environmental Engineering, The University of Wollongong, Wollongong, Australia
taoy@uow.edu.au

Abstract

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns developed at The Hong Kong Polytechnic University. They consist of an outer tube made of fibre reinforced polymer (FRP) and an inner tube made of steel, with the space between filled with concrete. In these hybrid DSTCs, the three constituent materials are optimally combined to achieve several advantages not available with existing forms of columns, including their superior corrosion and seismic performance. This paper presents the test results of a series of large-scale hybrid DSTCs subjected to combined axial and cyclic lateral loads, with an emphasis on the effect of a high strength concrete infill. All column specimens had a circular section with a diameter of 300 mm and a height of 1350 mm (from the point of lateral loading to the top surface of the stiff RC footing). The parameters examined include the concrete strength, the confinement stiffness of the GFRP tube and the axial load ratio. The test results showed that these hybrid DSTCs possess excellent ductility and hence excellent seismic resistance even when high strength concrete with a cylinder compressive strength of around 120 MPa is used.

Keywords: confinement, double-skin columns, FRP, high strength concrete, hybrid columns, lateral cyclic loading, tubular columns.

1. Introduction

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns developed at The Hong Kong Polytechnic University (PolyU) [1, 2]. These hybrid DSTCs (Figure 1) consist of an inner steel tube, an outer FRP tube and a concrete infill between them. In hybrid DSTCs, the FRP tube offers mechanical resistance primarily in the hoop direction to confine the concrete and to enhance the shear resistance of the column. Hybrid DSTCs may be constructed in-situ or precast, with the two tubes acting as the stay-in-place form. In these columns, the three constituent materials are combined in an optimal manner to achieve advantages not available with existing columns, including their superior corrosion resistance as well as excellent ductility and seismic resistance. A large amount of research has been conducted on hybrid DSTCs with normal strength concrete (NSC) at PolyU [3, 4, 5], resulting in a good understanding of their behaviour under static loading for which a

design procedure has been formulated and included in the Chinese Technical Code for Infrastructure Application of FRP Composites [6]. Hybrid DSTCs filled with high strength concrete (HSC) has also been tested under axial monotonic compression, and the test results demonstrated the excellent ductility of hybrid DSTCs with HSC [7]. Since hybrid DSTCs are highly ductile, and the absence of any steel bars ensures good-quality casting of HSC, they offer a promising opportunity for the use of HSC which is more brittle than NSC. HSC also facilitates the use of a large void ratio for the column without compromising the contribution of concrete to its load-carrying capacity. For the seismic design of these columns, their behaviour subjected to combined axial and cyclic lateral loads needs to be carefully studied. This paper presents the first series of laboratory tests on hybrid DSTCs subjected to combined axial and cyclic lateral loads, with special attention to the use of a high strength concrete infill. The parameters examined in the present study include the concrete strength, the confinement stiffness of the GFRP tube and the axial load ratio.

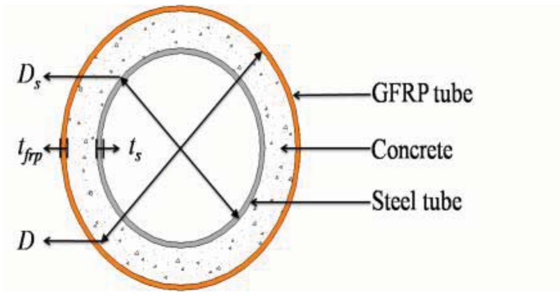

Figure 1. Cross-section of hybrid FRP-concrete-steel double-skin tubular column.

2. Experimental programme

2.1 Specimen details

The experimental programme consisted of 6 hybrid DSTCs as detailed in Table 1. All these specimens had a circular section with a characteristic diameter D (the outer diameter of the annular concrete section) of 300 mm and a void ratio of 0.73 (the ratio between the inner diameter and the outer diameter of the annular concrete section). The inner steel tube had a thickness t_s of 6 mm and an outer diameter D_s of 219 mm, leading to a D_s/t_s ratio of 36.5. The outer GFRP tube had an inner diameter of 300 mm and a thickness t_{frp} of 6 mm or 10 mm. The height was 1350 mm from the point of lateral loading to the top of the stiff RC column footing (4.5 times of the column diameter). Each specimen was given a name for ease of reference as detailed in Table 1.

Table 1. Specimen details.

Specimen Name	Concrete Properties			FRP Tube		Axial Load Ratio n
	f_{co} (MPa)	E_c (GPa)	ε_{co} (%)	t_{frp} (mm)	$2E_{frp}t_{frp}/D$ (MPa)	
DSTC-1	56.0	35.4	0.3031	6	1564.0	0.2
DSTC-2	116.4	51.0	0.3567	6	1564.0	0.2
DSTC-3	80.0	42.3	0.2975	6	1564.0	0.4
DSTC-4	82.7	43.0	0.2831	10	2606.7	0.4
DSTC-5	117.3	51.2	0.3102	6	1564.0	0.4
DSTC-6	114.8	50.7	0.3049	10	2606.7	0.4

2.2 Material properties

Self-compacting concrete (SCC) was adopted to ensure the quality of concrete casting. Each column was cast with a separate batch of concrete, and for each batch of concrete, 3 plain concrete cylinders (152 mm in diameter and 300 mm in height) were prepared and tested. The test results are summarized in Table 1, where f_{co} is the peak axial stress (i.e. the cylinder compressive strength); E_c is the elastic modulus of concrete; ε_{co} is the axial strain at peak axial stress. It is seen that HSC was used in all test columns, although the concrete strength of

DSTC-1 is close to the upper bound compressive strength of NSC according to the conventional classification of concrete based on compressive strength.

For the inner steel tubes which were cut from the same batch of two long steel tubes, tensile tests on three steel coupons were conducted following BS 18 1987 [8] for each long tube. The elastic modulus, yield stress and tensile strength averaged from the six coupons are 200.0 GPa, 360.3 MPa and 490.6 MPa, respectively. The stress-strain curves of the steel coupons all showed a long yield plateau.

The GFRP tubes were designed and fabricated using a filament-wound process. The fibre volume ratio (the ratio of the fibre volume to the total volume) was 0.568 according to data provided by the manufacturer. The fibres were oriented at ± 80 degrees to the longitudinal axis of the GFRP tube. From the classical lamination theory [9], the elastic modulus of the GFRP tubes in its transverse direction E_{frp} was 39.1GPa and the longitudinal value was 5.60GPa. The confinement stiffnesses [4] of the GFRP tubes are given in Table 1.

2.3 Experimental set-up

In order to monitor the behaviour of the column, strain gauges were installed at 4 sections on the GFRP tube and at 6 sections on the inner steel tube. In addition, many linear variable displacement transducers (LVDTs) were mounted at different locations of the column to measure the lateral displacement, the axial shortening, the column head rotation and the distribution and development of curvature. As shown in Figure 2, a large loading frame (named the Computer-Electro-Hydraulic Servo-Controlled Multi-Purpose Testing System) was used to test the column specimens. The testing frame included a vertical actuator with a capacity of 10,000 kN connected to a larger plate (i.e. top plate) and a hinge joint connected to a smaller plate (i.e. bottom plate); rollers were provided between the top plate and the bottom plate so that during the test the horizontal locations of the actuator and the hinge could be aligned. In addition, a horizontal actuator (with a capacity of 1,000 kN in tension and 1,500 kN in compression) was included to apply horizontal loading through a hinge joint. The column head was fixed to the two hinges via a column head fixture as shown in Figure 2. As the column head moved horizontally during the test, the vertical actuator could also move synchronously, which ensured that the axial load was always applied vertically to the column head. The RC footing of each specimen was fixed to the stiff laboratory floor using high strength steel bolts. The two hinges were well lubricated before the test to minimize friction.

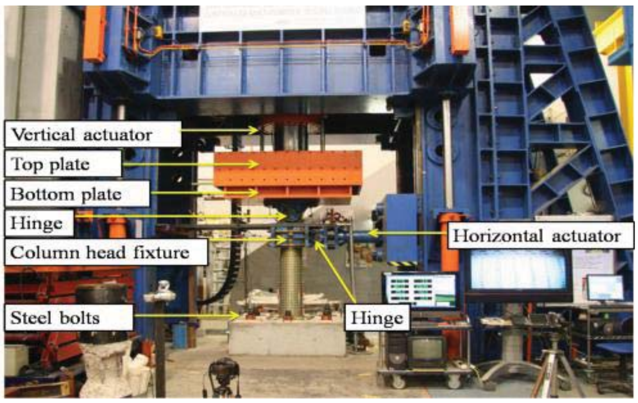

Figure 2. The test frame and experimental set-up.

2.4 Loading scheme

The column was subjected to a constant axial load followed by cyclic lateral loading. The magnitude of the axial load to be imposed on the column for a pre-defined axial load ratio *n* was calculated from the following equation:

$$N = n \cdot (f_y \cdot A_s + f_{co} \cdot A_c) \quad (1)$$

where f_y is the yield stress of the inner steel tube; A_s is the area of the steel tube section; f_{co} is the concrete cylinder compressive strength; and A_c is the area of the annular concrete section. During the test, the axial load on the column was increased gradually at a rate of 50kN/min. The column was then subjected to one cycle of lateral loading at 75% of the maximum lateral load estimated from a section analysis in which the confinement effect of the GFRP tube was ignored. Afterwards, the yield displacement, δ_y, was determined in-situ as the displacement at the point of intersection between a straight line passing through the origin and the point of the load-displacement curve at 75% of the estimated maximum lateral load and a horizontal line at the estimated maximum lateral load [10]. The average of the two values calculated for the two directions of loading was taken as the yield displacement. Once the yield displacement was determined, the subsequent loading sequence was designed to consist of two fully-reversed lateral loading cycles at $\pm\delta_y$, $\pm 2\delta_y$, $\pm 3\delta_y$, $\pm 5\delta_y$, $\pm 7\delta_y$, and one such cycle at $\pm 9\delta_y$, $\pm 11\delta_y$ and $\pm 13\delta_y$. However, different specimens failed at different lateral displacement levels, so most specimens did not complete all the intended cycles. The test was stopped when the lateral load resistance dropped substantially. All the test data were recorded simultaneously by a data acquisition system.

3. General observations

With the imposition of the pre-defined concentric axial load, the readings of all vertical strain gauges on the column were almost the same; however, the hoop strain readings of the inner steel tube were higher than those of the outer GFRP tube due to the higher Poisson's ratio of steel. As a result, interfacial normal compressive stresses developed between the steel tube and the concrete, leading to some confinement of the concrete by the steel tube.

Global view | Damage to the GFRP tube | Damage to the concrete | Damage to the steel tube

Figure 3. Specimen DSTC-5 after test

At the first two lateral displacement levels ($\pm 0.75\delta_y$, $\pm\delta_y$), no obvious damage was observed on the GFRP tube, and the strain gauge readings confirmed that plane sections remained plane for all sections. The first sign of obvious damage was indicated by resin cracking along one of the fibre directions on the tension side of the GFRP tube. As the glass fibres were oriented close to the hoop direction, resin cracking was due to the low tensile strength of resin. Resin cracking of the GFRP tube, was limited mainly to the lowest 240 mm of the column height due to the high moments there. With increases in the lateral displacement at the subsequent load levels ($\pm 5\delta_y$, $\pm 7\delta_y$, $\pm 9\delta_y$), severe damage was developed in the lowest 120 mm region of the GFRP tube due to the combined effect of tensile and compressive straining. The axial shortening of the column then increased rapidly due to the severe damage at the bottom of the column, which caused a sudden increase in the hoop strain readings on the GFRP tube. After that, the axial strain readings indicated that the plane section assumption was no longer correct for sections within the lowest 300 mm region, but was still valid for higher sections (i.e. above 300 mm). The bottom 200 mm of the column had the biggest curvature due to the high moments there and damage localization. The rupture of the GFRP tube, which was due to concrete dilation combined with tension-

compression cycling, finally occurred within the lowest 80 mm from the footing on the compression side of the column. The damage to the concrete was concentrated within the bottom 100 mm region due to cyclic loading. Severe local buckling deformations were found on the inner steel tube in the bottom region. Due to space limitation, only pictures of specimen DSTC-5 are shown in Figure 3.

4. Test results and discussions

Due to space limitation, only the lateral load-lateral displacement curves of specimens DSTC-3 and DSTC-4 are presented in Figure 4, where the envelope curves are shown together with the cyclic curves. The envelope curve of each specimen includes an ascending branch until the peak lateral load, a short horizontal portion over which the lateral load fluctuates within a small range, and a long descending branch in which the lateral load decreases as the lateral displacement increases. The descending branch is affected significantly by the P-Δ effect.

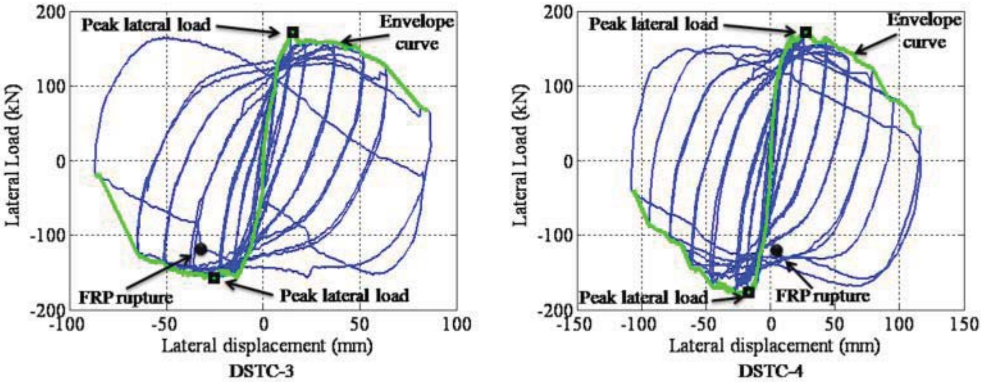

Figure 4. Lateral load-lateral displacement curves.

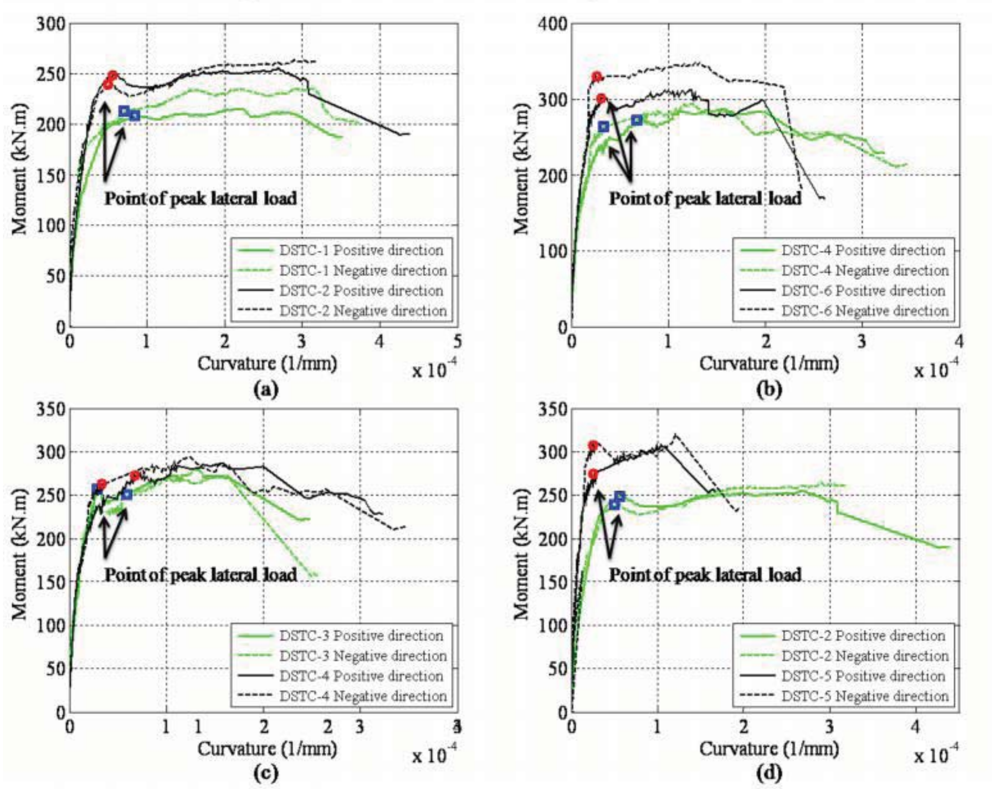

Figure 5. Moment-curvature curves.

Figure 5 presents the moment-curvature envelope curves to show the effect of concrete

strength, the confinement stiffness of the GFRP tube and the axial load ratio, where the moment includes the contribution of the P-Δ effect and the curvature is the average value over the lowest 200 mm of the column calculated from readings of LVDTs. In Figure 5, the positive direction refers to the positive lateral load direction, and the envelope curves for the two directions are in close agreement. These envelope curves have an ascending branch, a long plateau and a short steep descending curve. The long plateau means that the moment at the column bottom section changed little over a wide range of curvature values, which indicates that hybrid DSTCs exhibit very ductile sectional behaviour under combined axial compression and cyclic bending. The effect of concrete strength can be examined by comparing the performance of DSTC-1 with that of DSTC-2 [Figure 5(a)] and the performance of DSTC-4 with that of DSTC-6 [Figure 5(b)]. The specimen with a higher concrete strength in each pair has a higher moment capacity and is likely to have a smaller displacement at the peak lateral load. By comparing performance of DSTC-3 with that of DSTC-4 in Figure 5 (c), it is seen that a thicker GFRP tube leads to a larger moment capacity of the column and better ductility. Figure 5(d) shows DSTC-5 with a higher axial load ratio (n=0.4) failed at a much smaller curvature than its counterpart DSTC-2 with a lower axial load ratio (n=0.2), illustrating the important influence of axial load ratio.

5. Conclusions

This paper has presented the results of 6 large-scale hybrid DSTCs with HSC tested under axial compression in combination with cyclic lateral loading. These test results suggest that hybrid DSTCs can still show excellent ductility and seismic resistance even when high strength concrete with a cylinder compressive strength of around 120 MPa is used. More detailed analysis of the test results will be conducted soon to gain further understanding of the behaviour of these hybrid columns.

6. Acknowledgements

The authors are grateful for the financial support received from the Hong Kong Research Grants Council (Project No: PolyU 5278/07E) and the Niche Areas Funding Scheme of The Hong Kong Polytechnic University.

7. References

[1] TENG, J.G., YU, T., and WONG, Y.L., "Behaviour of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns", *Proceedings, Second International Conference on FRP Composites in Civil Engineering,* 8-10 December 2004, Adelaide, Australia, 811-818.

[2] TENG, J.G., YU, T., WONG, Y.L., and DONG, S.L., "Hybrid FRP-Concrete-Steel Tubular Columns: Concept and Behavior", *Construction and Building Materials,* Vol. 21, No. 4, 2007, pp. 846-854.

[3] YU, T., WONG, Y.L., TENG. J.G, and DONG, S.L., "Flexural Behaviour of Hybrid FRP-Concrete-Steel Double-Skin Tubular Members", *Journal of Composites for Construction,* ASCE, Vol. 10, No. 5, 2006, pp. 443-452.

[4] YU, T., *Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns*, PhD Thesis, The Hong Kong Polytechnic University, 2007.

[5] TENG, J.G., YU, T. and WONG, Y.L., "Hybrid FRP-Concrete-Steel Double-Skin Tubular Structural Members", *Proceedings, Fifth International Conference on FRP*

Composites in Civil Engineering, 27-29 September 2010, Beijing, China, pp. 26-32.

[6] GB-50608., *Technical Code for Infrastructure Application of FRP Composites*, China Planning Press, China, 2010.

[7] ZHANG, B., YU, T. and TENG, J.G., “Axial compression tests on hybrid double-skin tubular columns filled with high strength concrete”, *Proceedings, Third International Postgraduate Conference on Infrastructure and Environment,* 11-12 July 2011, Hong Kong, China, pp. 171-176.

[8] BS 18.1987. *Tensile Testing of Metals (including Aerospace Materials*, British Standards Institution, London, UK, 1987.

[9] Daniel, I.M. and Ishai, O., *Engineering Mechanics of Composite Materials*, New York, N.Y. Oxford University Press, 2006.

[10] HU, Y.M., *Behaviour and Modelling of FRP-Confined Hollow and Concrete-Filled Steel Tubular Columns*, PhD Thesis, The Hong Kong Polytechnic University, 2010.