AXIAL COMPRESSION TESTS ON HYBRID DOUBLE-SKIN TUBULAR COLUMNS FILLED WITH HIGH STRENGTH CONCRETE

B. Zhang [1], T. Yu [2] and J. G. Teng [2]
[1] Department of Civil and Structural Engineering,
The Hong Kong Polytechnic University, China. Email: zbiceberg@gmail.com
[2] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, China.

ABSTRACT

Hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) are of a new form of hybrid structural members recently developed at The Hong Kong Polytechnic University. A hybrid DTSC consists of an inner steel tube, an outer FRP tube and a concrete infill between them. Hybrid DSTCs possess many important advantages over conventional counterparts, including excellent corrosion resistance as well as excellent ductility and seismic resistance. A large amount of research has been conducted on hybrid DSTCs, but the existing experimental studies have been limited to hybrid DSTCs filled with normal strength concrete (NSC). Since hybrid DSTCs are highly ductile and the absence of reinforcing steel bars ensures good-quality casting of high strength concrete (HSC), they offer a promising opportunity for the use of HSC which is more brittle than NSC. This paper presents results from the first series of axial compression tests on hybrid DSTCs with HSC. The parameters examined in the present study include the section configuration, the void ratio, and the properties of FRP tubes and steel tubes. The test results confirm that hybrid DSTCs with HSC possess very good ductility when the outer FRP tube has a sufficiently large strain capacity in the circumferential direction.

KEYWORDS

FRP, hybrid columns, tubular columns, double-skin columns, high strength concrete, confinement

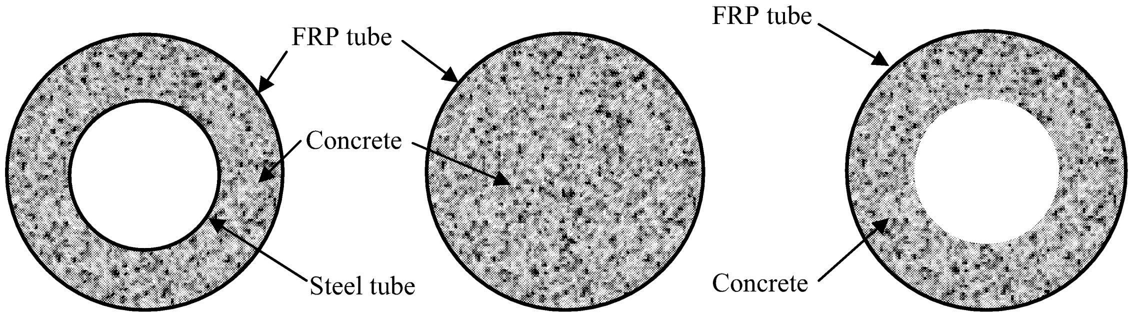
INTRODUCTION

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are of a new form of hybrid columns proposed by the third author. A hybrid DSTC (Figure 1a) consists of an inner steel tube, an outer FRP tube and a concrete infill between them (Teng *et al*. 2004, 2007). In hybrid DSTCs, FRP tubes offer mechanical resistance primarily in the hoop direction to confine the concrete and to enhance the shear resistance of the member. Hybrid DSTCs may be constructed in-situ or precast, with the two tubes acting as the stay-in-place formwork. In this new form of hybrid columns, the three constituent materials are optimally combined to achieve several advantages which are not available in existing columns, including excellent corrosion resistance as well as high ductility and seismic resistance. A large amount of research has been conducted on hybrid DSTCs at The Hong Kong Polytechnic University (PolyU) (Yu 2007; Teng *et al.* 2010), leading to a good understanding of the behaviour of hybrid DSTCs under static loading for which a design procedure has been developed and adopted in the Chinese Technical Code for Infrastructure Application of FRP Composites (GB 50608-2010 2011). The existing research at PolyU and elsewhere, however, has been limited to normal strength concrete (NSC) with a cylinder compressive strength not exceeding 50 MPa. Since hybrid DSTCs are highly ductile and the absence of any steel bars ensures good-quality casting of high strength concrete (HSC), they offer a promising opportunity for the use of HSC which is more brittle than NSC. This paper presents results from the first series of axial compression tests on hybrid DSTCs with HSC. The experimental program included 6 DSTC specimens, 2 FRP-confined solid cylinder (FCSC) (Figure 1(b)) specimens and 2 FRP-confined hollow cylinder (FCHC) (Figure 1(c)) specimens. The performance of DSTCs is compared with those of FCSCs and FCHCs to arrive at a good understanding of the behavior of concrete in DSTCs.

EXPERIMENT PROGRAM

Specimen details

In total, 10 FRP-confined specimens were prepared and tested, including 6 hybrid DSTCs, 2 FCSCs and 2 FCHCs. The specimens all had an outer diameter (the outer diameter of the annular concrete section) of 204 mm and a height of 400 mm. The six DSTC specimens were of three different configurations involving two types of FRP tubes [i.e. 1-ply carbon FRP (CFRP) tubes and 6-ply glass FRP (GFRP) tubes] and two types of steel tubes (i.e. type A tubes with an outer diameter of 159 mm and a thickness of 5 mm and type B tubes with an outer diameter of 120 mm and a thickness of 4.5 mm); two identical specimens were made for each configuration. The two FCSC specimens were nominally identical and each had a 1-ply CFRP tube. The FCHC specimens were also nominally identical and each had a 1-ply CFRP tube and an inner void of 159 mm in diameter. The FRP tubes were formed via a wet-layup process on a hardened(?) concrete core for all the specimens, with the fibers oriented in the hoop direction and with an overlapping zone spanning a circumferential distance of 200 mm. The specimen details are summarized in Table 1. As shown in Table 1, each specimen is given a name, which starts with a letter ("D", "H", or "S") to represent the specimen type, followed by a number "83" to represent the unconfined concrete cylinder strength, and then a letter "A" or "B" to represent the void ratio (0.779 or 0.588) (void ratio = ratio between the inner diameter and the outer diameter of the annular concrete section) for hybrid DSTCs and FCHCs; the numbers and letters following represent plies of CFRP or GFRP and the Arabic number at the end is used to differentiate the two nominally identical specimens.



(a) DSTCs (b) FCSCs (c) FCHCs

Figure 1 Cross-sections of DSTCs, FCSCs and FCHCs

Table 1 Specimen details

Type	Name	FRP tube	Steel tube	Void ratio
DSTC	D83-A1C-1,2	1-ply CFRP	A	0.779
	D83-B1C-1,2	1-ply CFRP	B	0.588
	D83-A6G-1,2	6-ply GFRP	A	0.779
FCHC	H83-A1C-1,2	1-ply CFRP	-	0.779
FCSC	S83-1C-1,2	1-ply CFRP	-	-

Material properties

Three plain concrete cylinders (152.5 mm x 305 mm) were tested to determine the material properties of concrete. The elastic modulus E_c, the peak stress f'_c (i.e. the cylinder compressive strength) and the axial strain at peak stress ε_{co} averaged from these concrete cylinder tests are 37.89 GPa, 83.5 MPa and 0.329%, respectively.

Tensile tests on three steel coupons were conducted for each type of steel tubes. The coupons were cut along the longitudinal direction of the steel tubes and were tested following BS 18 (1987). The average values of the elastic modulus E_s, yield stress f_y, and tensile strength f_u are 210.6 GPa, 353.2 MPa and 512.3 MPa respectively for type A steel tubes, and 199.6GPa, 419.5MPa and 565.7MPa respectively for type B steel tubes. In addition, three hollow steel tubes belonging to the same batch of tubes used in the DSTC specimens were tested under axial compression for each type of steel tubes. The steel tubes used for hollow tube tests all had the same height as those in the DSTC specimens (i.e. 400 mm). All these steel tubes showed large plastic deformation until local buckling occurred in the elephant's foot mode. The average yield load was 835.5 kN for type A tubes and 686.6 kN for type B tubes.

GFRP used in the study had an average tensile strength of 1825.5 MPa and an average elastic modulus of 80.1 GPa, according to 6 tensile coupon tests conducted by Teng et al. (2007) with a nominal thickness of 0.17 mm per ply. The CFRP used in the study had an average tensile strength of 2016.5 MPa and an average elastic modulus of 237.8 GPa, according to the tensile coupon tests conducted by Hu (2010) with a nominal thickness of 0.34 mm per ply.

Experimental set-up and instrumentation

For each specimen, four bi-directional strain rosettes with a gauge length of 20 mm were installed at the mid-height of the FRP tube. For the six hybrid DSTC specimens, two additional bi-directional strain rosettes with a gauge length of 10 mm were attached at the mid-height of the inner steel tube. The circumferential layout of the strain gauges is shown in Figure 2. In addition, four linear variable displacement transducers (LVDTs) were used to measure the axial shortening of the mid-height region of 160mm (Figure 3) 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 strains, loads, and displacements, were recorded simultaneously by a data logger.

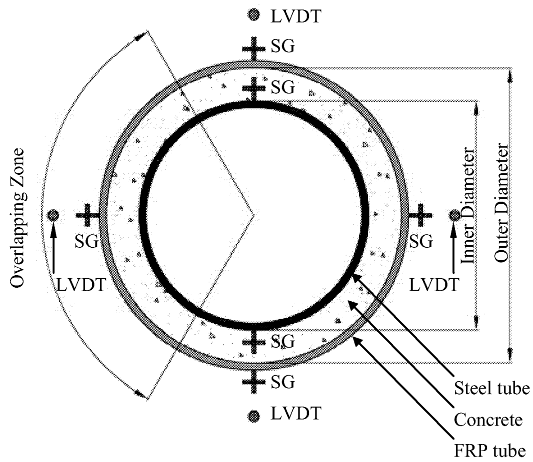


Figure 2 Cross section of the specimen and instrumentation

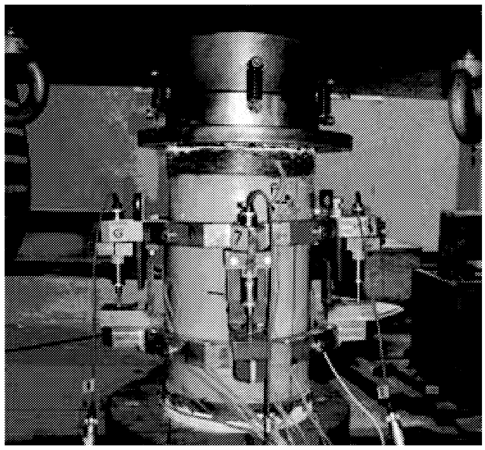


Figure 3 Test set up and instrumentation

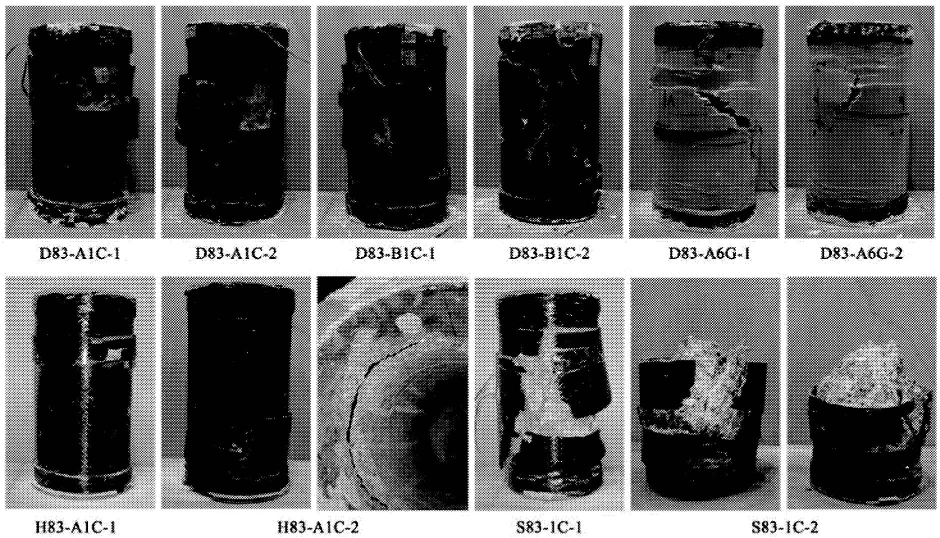


Figure 4 The specimens after test

TEST RESULTS AND DISCUSSIONS

General observations

All the ten specimens failed by rupture of the FRP tube as a result of hoop tension; the rupture generally occurred at or near the mid-height of the specimen outside the overlapping zone except for FCHCs where the rupture was more localized and away from the mid-height region. Figure 4 shows all specimens after test. It is evident from Figure 4 that the failure of DSTCs is less explosive than that of FCSCs, due to the existence of a steel tube which carries a significant portion of the axial load. The rupture of CFRP was found to be generally more explosive than that of GFRP. In FCHCs, FRP rupture was localized in a small region and inward spalling of concrete was found which caused early loss of resistance of the concrete near the inner edge. A careful post-test examination of the DSTC specimens revealed that there was some slight inward deformation on the inner steel tube of each specimen, which may be attributed to the local inward movement of the damaged concrete.

Axial load-axial strain curves

The axial load-axial strain curves of all specimens are shown in Figure 5, while the ultimate loads P_c and ultimate axial strains ε_{cu} of all specimens are summarized in Table 2. In this paper, compressive stresses and strains are taken to be positive while tensile stresses and strains are taken to be negative; axial strains were calculated from the LVDT readings unless otherwise specified. While all the curves of hybrid DSTCs are close to an approximately elastic-perfectly plastic curve, the plastic plateau for those specimens with a GFRP tube is much longer than that for specimens with a CFRP tube (Figure 5). The two hybrid DSTCs with a GFRP tube showed a very ductile response with the ultimate axial strain being over 1.6% and around 5 times the strain of unconfined concrete at peak stress ε_{co} (i.e. 0.329%). On the other hand, the ultimate axial strains of the four hybrid DSTCs with a CFRP tube are all only around 0.7%, despite their different void ratios (i.e. 0.558 and 0.779); the ultimate axial strains of the FCSCs with the same CFRP tube are also similar to those of the hybrid DSTCs, indicating that the existence of an inner void dose not lead to obvious differences to the ultimate axial strain when a CFRP tube was used. The curves of the two FCHCs are considerably shorter than those of DSTCs and FCSCs, with an ultimate axial strain being similar to the axial strain at peak stress of unconfined concrete.

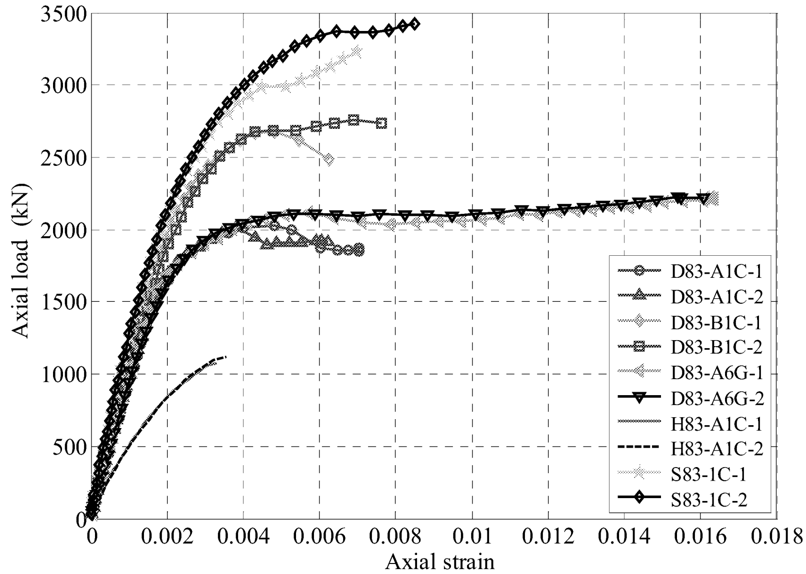


Figure 5 Axial load-axial strain curves

Behaviour of confined concrete

To evaluate the effectiveness of confinement of the concrete in DSTCs, the behavior of the concrete in the DSTC specimens is compared with that of the corresponding FCSC and FCHC specimens. The axial stress of the concrete in the DSTCs and FCHCs is defined as the load carried by the annular concrete section divided by its cross-sectional area. For DSTC specimens, the load carried by the concrete section is assumed to be equal to the difference between the load carried by the whole section and the load carried by the steel tube section at the same axial strain; the latter was found from the compression tests on hollow steel tubes. The peak concrete stresses f'_{cc} deduced from this process for all DSTC specimens and those for all the FCSC and FCHC specimens are summarized in Table 2. These peak concrete stresses are also compared with the unconfined concrete strength f'_{c} to show the effect of confinement in terms of strength enhancement (Table 2). The axial stress-strain curves and axial stress-hoop strain curves for all the specimens are shown in Figure 6, where the hoop strains were averaged from the three hoop strain gauges outside the overlapping zone. The hoop strain at the rupture of FRP $\varepsilon_{h,rup}$ is also summarized in Table 2.

It is evident from Table 2 and Figure 6(a) that both the peak concrete stresses and the ultimate axial strains of FCHCs are considerably lower than those of the corresponding FCSCs, due to the existence of inner void which significantly reduces the confining effectiveness of the FRP tube. The rupture of the FRP tube in FCHCs was also more localized because of the more non-uniform deformation of the concrete, leading to much lower average hoop rupture strains at the mid-height (see Table 2). In the hybrid DSTCs, the existence of a steel tube effectively restrained the inward spalling of concrete, and the ultimate axial strain and the hoop rupture strain are both comparable to those of the corresponding FCSCs. The axial stress-strain curves of the concrete in most hybrid DSTCs with a 1-ply CFRP tube, however, clearly features a descending branch, which is not seen on the curves of the corresponding FCSCs; the peak axial stresses of these hybrid DSTCs are also lower than those of the corresponding FCSCs [Figure 6(b) and Table 2]. This observation differs from that made on existing tests on NSC (Wong et al. 2008), where the concrete in hybrid DSTCs behaves similarly to that in corresponding FCSCs. While further research is needed for clarification, the more brittle behaviour of HSC and the separation of the concrete from the steel tube in the early stage of loading in hybrid DSTCs (Yu et al. 2010) may be the reasons behind this observation.

Table 2 Key test results

Specimen	P_u (kN)	f'_{cc} (MPa)	f'_{cc}/f'_{co}	ε_{cu} (%)	$\varepsilon_{cu}/\varepsilon_{co}$	$\varepsilon_{h,rup}$ (%)
D83-A1C-1	2036.8	94.1	1.12	0.7047	2.15	0.5213
D83-A1C-2	2009.1	91.6	1.09	0.6219	1.89	0.7170
D83-B1C-1	2691.0	93.8	1.12	0.6688	2.04	0.6811
D83-B1C-2	2773.3	97.7	1.17	0.7703	2.34	0.5902
D83-A6G-1	2224.0	108.0	1.29	1.6359	4.98	1.0849
D83-A6G-2	2227.5	108.3	1.29	1.6078	4.89	0.8873
H83-A1C-1	1086.9	84.8	1.19	0.3301	2.22	0.1065
H83-A1C-2	1139.1	88.8	1.26	0.3625	2.61	0.1256
S83-1C-1	3250.2	99.5	1.02	0.7281	1.01	0.6578
S83-1C-2	3441.9	105.4	1.06	0.8563	1.06	0.9314

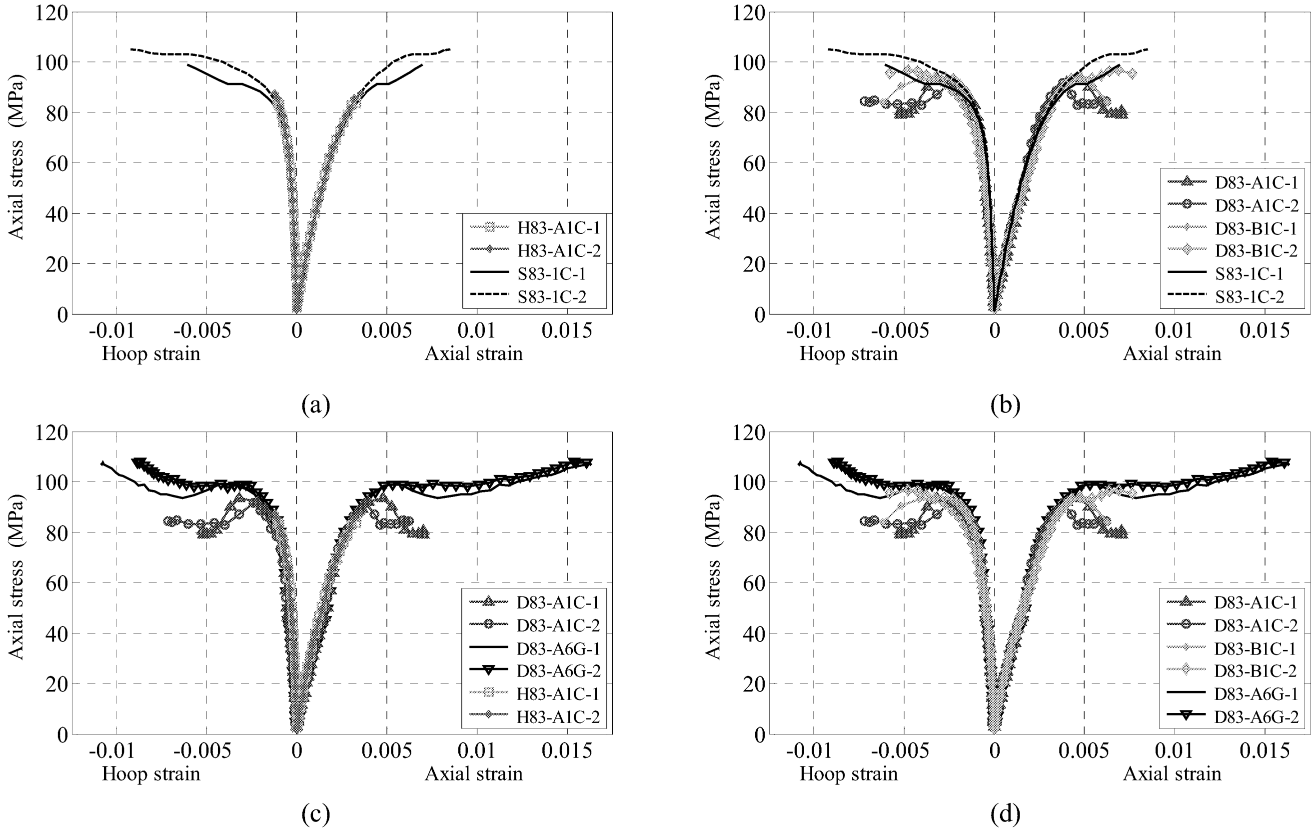


Figure 6 Axial stress-axial strain curves and axial stress-hoop strain curves of the concrete

The hybrid DSTCs with a GFRP tube (i.e. specimens D83-A6G-1, 2) showed significantly better performance than those with a CFRP tube (i.e. specimens D83-A1C-1, 2), in terms of both the peak axial stress and the ultimate axial strain [Figure 6(c)]. As the confining stiffnesses ($E_j t/R?$) of the CFRP and the GFRP tube are similar, this difference is due to the much larger hoop strain capacity of the GFRP tube, which leads to a much larger ultimate axial strain.

CONCLUSIONS

This paper has presented the results of a series of axial compression tests on hybrid DSTCs with HSC. These test results suggest that hybrid DSTCs with HSC still possess high ductility when the outer FRP tube has a sufficiently large strain capacity in the circumferential direction. This advantage, however, may be much less pronounced when a relatively brittle FRP tube is used. Further work on hybrid DSTCs with HSC is being conducted at PolyU, covering a larger range of concrete strength and aiming to develop a unified stress-strain model for both NSC and HSC in hybrid DSTCs.

ACKNOWLEDGMENTS

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

REFERENCES

BS 18. (1987). *Tensile Testing of Metals (including Aerospace Materials)*, British Standards Institution, London, UK.

GB 50608-2010. (2011) *Technical Code for Infrastructure Application of FRP Composites*, China Planning Press, China.

Hu, Y.M. (2010). *Behaviour and Modelling of FRP-Confined Hollow and Concrete-Filled Steel Tubular Columns*, PhD Thesis, The Hong Kong Polytechnic University.

Teng, J.G., Yu, T. and Wong, Y.L. (2004). "Behaviour of hybrid FRP-concrete-steel double-skin tubular columns", *Proceedings, Second International Conference on FRP Composites in Civil Engineering,* December 8-10, Adelaide, Australia, 811-818.

Teng, J.G., Yu, T., Wong, Y.L. and Dong, S.L. (2007). "Hybrid FRP-concrete-steel tubular columns: Concept and behavior", *Construction and Building Materials*, 21(4):846-854.

Teng, J.G., Yu, T. and Wong, Y.L. (2010). "Hybrid FRP-concrete-steel double-skin tubular structural members", *Proceedings, Fifth International Conference on FRP Composites in Civil Engineering*, 27-29 September, Beijing, China, 26-32.

Wong, Y.L., Yu, T., Teng, J.G. and Dong, S.L. (2008). "Behavior of FRP confined concrete in annular section columns", *Composites Part B: Engineering*, 39:451-466.

Yu, T. (2007). *Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns,* PhD Thesis, The Hong Kong Polytechnic University.

Yu, T., Teng, J.G. and Wong, Y.L. (2010). "Stress-strain behavior of concrete in hybrid double-skin tubular columns", *Journal of Structural Engineering*, ASCE, 136(4): 379-389.