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Abstract

Fibre-reinforced polymer (FRP) jackets have been widely used to confine concrete columns to enhance their load-carrying capacity and ductility. More recently, the use of FRP jackets to improve the performance of hollow steel tubes and concrete-filled steel tubes has also been explored. This paper presents the results of a recent experimental study in which the behaviour of FRP-confined circular concrete-filled thin steel tubes under axial compression was examined. The experimental study included three series of tests and was focussed on the effects of the diameter-to-thickness ratio of the steel tube and the confinement stiffness of the FRP jacket. The test results revealed that the FRP jacket either substantially delayed or completely suppressed the local buckling failure mode of the steel tube. As a result, the compressive behaviour of the concrete-filled thin steel tube as well as the concrete is significantly improved in terms of both strength and ductility.

Keywords

concrete, circular, axial, frp, filled, thin, jacketed, compression, tests, tubes, steel

Disciplines

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AXIAL COMPRESSION TESTS ON FRP-JACKETED CIRCULAR CONCRETE-FILLED THIN STEEL TUBES

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KEYWORDS

FRP, Steel tubes, Concrete, Hybrid columns, Tubular columns, Strengthening, New construction

ABSTRACT

Fibre-reinforced polymer (FRP) jackets have been widely used to confine concrete columns to enhance their load-carrying capacity and ductility. More recently, the use of FRP jackets to improve the performance of hollow steel tubes and concrete-filled steel tubes has also been explored. This paper presents the results of a recent experimental study in which the behaviour of FRP-confined circular concrete-filled thin steel tubes under axial compression was examined. The experimental study included three series of tests and was focussed on the effects of the diameter-to-thickness ratio of the steel tube and the confinement stiffness of the FRP jacket. The test results revealed that the FRP jacket either substantially delayed or completely suppressed the local buckling failure mode of the steel tube. As a result, the compressive behaviour of the concrete-filled thin steel tube as well as the concrete is significantly improved in terms of both strength and ductility.

INTRODUCTION

Fibre reinforced polymer (FRP) jackets have been widely used to provide lateral confinement to reinforced concrete columns to enhance their load-carrying capacity and ductility [1-3]. The use of FRP jackets to suppress local outward buckling (i.e. elephant's foot buckling) in hollow circular steel tubes and shells has also been explored [4-7]. Results presented in Teng and Hu [6] confirmed that FRP confinement of hollow circular tubes subjected to axial compression can be very effective in improving ductility. Xiao [8] recently proposed a novel form of concrete-filled steel tubular (CFT) columns, named by him as confined CFT columns ((or CCFT columns), in which the end portions are confined with steel tube segments or FRP jackets. In these columns, by providing an FRP or steel jacket at each end, the steel tube is prevented from deforming inwards by the concrete core and outwards by the jacket, so both the ductility and strength of the steel through-tube can be substantially enhanced in the end regions. In addition to Xiao's initial work [8], a number of other studies have been conducted by both Xiao's group [9-11] and other researchers [12-15] on the effectiveness of FRP jacketing in improving the structural behaviour of both circular [9, 10, 12-15,] and square/rectangular CFTs [11, 13].

While the advantages of FRP jacketing of CFT columns have been demonstrated with the limited test results now available, much research is still needed to develop a good understanding of the structural behavior of and appropriate design methods for FRP-confined CFTs, particularly when thin steel tubes which are highly susceptible to local buckling are used in these CFTs. As part of a larger study undertaken at The Hong Kong Polytechnic University (PolyU) [16], three series of axial compression tests were conducted on concrete-filled thin steel tubes confined with glass FRP (GFRP) jackets. This paper presents and interprets the results of these tests to examine the effect of the FRP jacketing on CFTs with thin steel tubes. GFRP was used instead of carbon FRP (CFRP) in these tests as GFRP does not suffer from galvanic corrosion problems which may be a concern for CFRP directly bonded to steel and possesses a larger ultimate tensile strain which is a favorable property for ductility enhancement applications. The attention was focused on CFTs with thin steel tubes as the local buckling problem is more pronounced and the benefit of FRP jacketing is expected to be more obvious for such tubes. Thin steel tubes are also deemed to be particularly appropriate for the CCFT system where the additional confinement available in the critical regions allows the thickness of the steel through-tube to be reduced. All steel tubes used in the present experimental study had an outer diameter-to-thickness (D_{outer}/t_s) ratio exceeding 100.

SPECIMENS AND INSTRUMENTATION

Specimen details

In total, twelve specimens were prepared and tested in three series. Each series included one CFT specimen without FRP jacketing and three FRP-confined CFT (or CCFT) specimens with three different FRP jacket thicknesses respectively. The steel tubes used in each series had the same D_{outer}/t_s ratio, but this ratio was different for different series. Steel plates of 1 mm, 1.5mm, 2 mm in thickness respectively were used to fabricate the steel tubes for the three series. The average values of the elastic modulus (E_s), yield strength (f_y), and ultimate tensile strength (f_u) obtained from tensile coupon tests for the steel tubes of each series are listed in Table 1. The FRP used had an average elastic modulus of 80.1GPa based on a nominal thickness of 0.17mm per ply. The FRP jacket was formed via a wet lay-up process with its finishing end overlapping its starting end by 200 mm. The concrete was cast in three batches for the three series respectively, although with the same mix ratio. The average concrete strength f'_{co} from axial compression tests on three standard concrete cylinders for each series is also given in Table 1. All specimens had an outer diameter of around 200 mm and a height of 400 mm. Other details of the specimens are summarized in Table 1.

The name of each specimen starts with a letter "F" followed by the number of plies forming the FRP jacket. The last 3-digit number (e.g. 102) is used to indicate the D_{outer}/t_s ratio of the steel tube. For example, specimen F1-102 is a specimen with a one-ply FRP jacket whose steel tube had a D_{outer}/t_s ratio of 102.

TABLE 1
DETAILS OF SPECIMENS

Series	*Specimens*	*Steel tube*						*Concrete*	*FRP*
		D_{outer} *(mm)*	t_s *(mm)*	D_{outer}/t_s	E_s *(mm)*	f_y *(MPa)*	f_u *(MPa)*	f'_{co} *(MPa)*	t_{frp} *(mm)*
102	**F0-102** **F1-102** **F2-102** **F3-102**	204	2	102	203	226	331	42.2	N/A 0.17 0.34 0.51
135	**F0-135** **F2-135** **F3-135** **F4-135**	203	1.5	135	204	242	349	42.1	N/A 0.34 0.51 0.68
202	**F0-202** **F2-202** **F3-202** **F4-202**	202	1	202	203	231	334	35.9	N/A 0.34 0.51 0.68

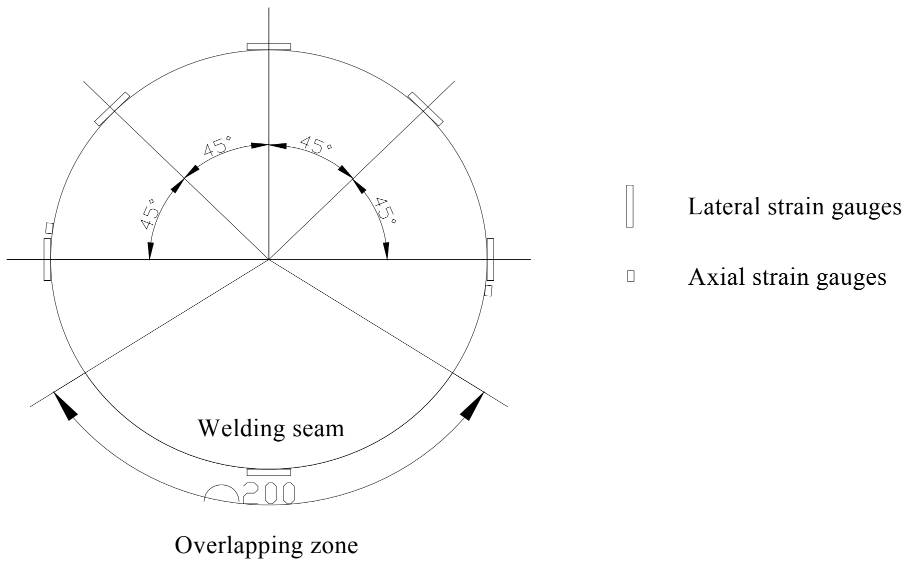


Figure 1: Layout of strain gauges at middle height

Instrumentation and Loading

For each FRP-confined CFT specimen, six strain gauges in the hoop direction and two strain gauges in the axial direction were installed at the mid-height of the FRP jacket. The two axial strain gauges were installed at 180° apart from each other, both being outside the overlapping zone. Of the six hoop strain gauges, one of them was installed inside the overlapping zone while the other five were evenly distributed within the half circumference opposite the overlapping zone. The layout of the strain gauges at mid-height is shown in Figure 1. In addition, five strain gauges in the hoop direction were installed near (20 mm from) each end of each specimen to detect any possible buckling deformation in these regions. The circumferential locations of these strain gauges were the same as the five hoop strain gauges outside the overlapping zone at mid-height. The layout of the strain gauges on bare CFT specimens was exactly the same as that for FRP-confined specimens. All the strain gauges used in FRP-confined CFT specimens had a gauge length of 20 mm while those used in CFT specimens had a gauge length of 5 mm. All the axial compression tests were conducted using an MTS machine with a displacement control rate of 0.5 mm/min until failure. The total axial shortening of the specimens was measured using three linear variable displacement transducers (LVDTs) placed at 120^0 apart from each other.

TEST OBSERVATIONS, RESULTS AND DISCUSSIONS

Failure Modes and Processes

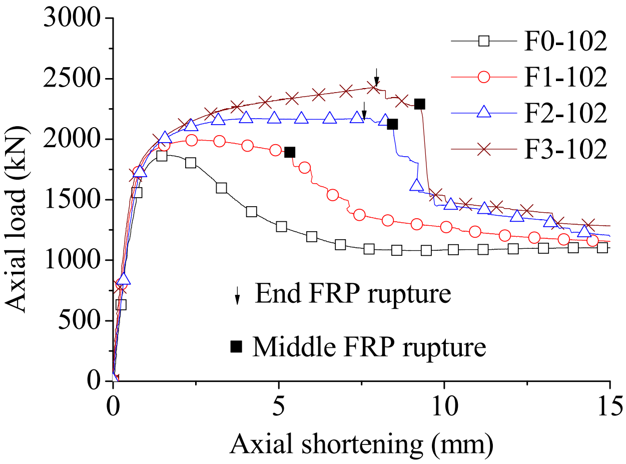
Figure 2 shows the failure modes of specimens in Series 102 while the failure modes of specimens in other series are similar. In the final stage of deformation of bare CFTs, continuous lateral dilation in the mid-height region as well as continuous growth of localized outward buckling deformation of the steel tube near one or both ends were observed as the axial shortening of the specimen increased (Figure 2). The load decreased steadily after the peak load had been reached (Figure 3). All the FRP-confined CFT specimens failed by explosive rupture of the FRP jacket in the mid-height region due to the lateral expansion of concrete and this rupture caused a sudden and rapid load drop. Before this final failure, localized FRP rupture occurred near one end in some specimens (i.e. specimens F2-102, F3-102 and F2-135) due to the localized outward buckling deformation of the steel tube, but this local FRP rupture only had a small effect on the ability of the specimen to carry the applied load (see Figure 3).

Figure 2: Failure modes of specimens of Series 102

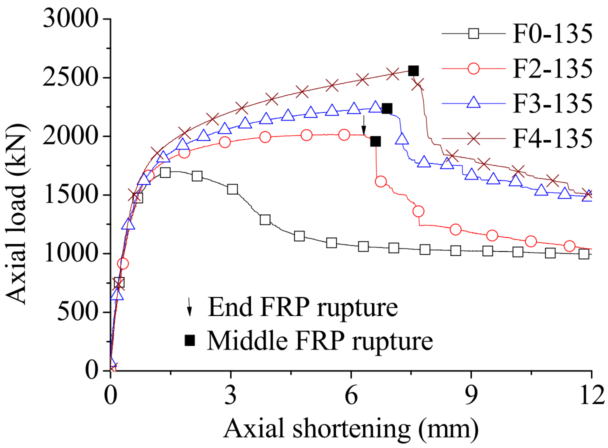
Axial Load-Shortening Behavior

The axial load-axial shortening curves of all specimens are shown in Figure 3, where the axial shortening is averaged from the readings of the three LVDTs. The curves of all the bare

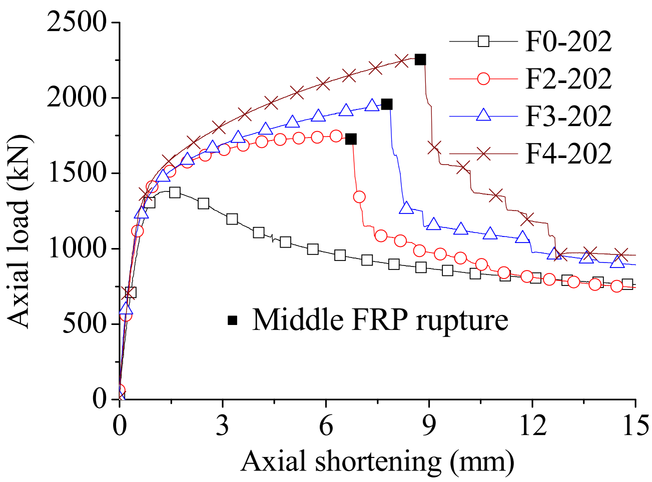
CFT specimens feature a smooth but relatively steep descending branch after reaching the peak load, while the FRP-confined specimens exhibited either an approximately elastic-perfectly plastic curve or an approximately bilinear curve before final failure followed by a sudden load drop.



(a) Series 102



(b) Series 135



(c) Series 202

Figure 3: Axial load-shortening curves

The key test results for all the specimens are summarized in Table 2. N_c and N_u are the peak (ultimate) load and the load at ultimate strain respectively while δ_u is the ultimate axial shortening of a specimen. For example, $N_{c,bare}$ and $\delta_{u,bare}$ are the peak load and the ultimate axial shortening of a bare CFT specimen respectively. $\varepsilon_{frp,rupt}$ is the average hoop rupture strain of the FRP jacket found from the readings of the five hoop strain gauges outside the overlapping zone. For a bare CFT specimen, the ultimate shortening is defined as the value at a load which is 80% of the peak load. For an FRP-confined CFT specimen, the ultimate shortening is reached when explosive rupture of the FRP jacket in the mid-height region occurs. The load at the ultimate shortening of an FRP-confined CFT specimen is seen to be either the same as or only slightly lower than its ultimate load. The short descending branch before the rupture failure of the FRP jacket found for some of the FRP-confined CFT specimens was due to either the local rupture of the FRP jacket near an end (specimens F2-102, F3-102 and F2-135, see Figure 3) or the use of a thin FRP jacket (specimen F1-102, see Figure 3).

TABLE 2
SUMMARY OF TEST RESULTS

Series	***Specimens***	N_c ***(kN)***	N_u ***(kN)***	$N_u / N_{c,bare}$	δ_u ***(mm)***	$\delta_u / \delta_{u,bare}$	$\varepsilon_{frp,rupt}$	$k_{\varepsilon 1}$	$k_{\varepsilon 2}$
Series 102	**F0-102**	1864 14	91	0.8	3.72	1	N/A	N/A	N/A
	F1-102	1993 18	78	1.01	5.28	1.42	-0.0179	0.693	1.133
	F2-102	2172 21	27	1.14	8.45	2.27	-0.0199	0.961	0.910
	F3-102	2427 22	31	1.20	9.43	2.53	-0.019	0.822	1.004
Series 135	**F0-135**	1699 13	59	0.8	3.60	1	N/A	N/A	N/A
	F2-135	2014 19	50	1.15	6.20	1.72	-0.0161	0.737	0.958
	F3-135	2244 22	44	1.32	6.85	1.90	-0.0167	0.892	0.824
	F4-135	2561 25	61	1.51	7.52	2.09	-0.0179	0.936	0.837
Series 202	**F0-202**	1380 1	104	0.8	4.09	1	N/A	N/A	N/A
	F2-202	1749 17	10	1.24	6.73	1.65	-0.0212	0.946	1.003
	F3-202	1961 19	61	1.42	7.76	1.90	-0.0191	0.912	0.919
	F4-202	2265 22	65	1.64	8.68	2.12	-0.0192	0.891	0.944

The effect of confinement from the FRP jacket is obvious in Figure 3 and Table 2. Of the specimens tested, the load-carrying capacity was increased by up to 64% while the axial shortening capacity was more than doubled in some of the cases; the energy dissipation capacity was also substantially enhanced. As expected, such enhancement in performance was greater when a thicker FRP jacket was used. When the same FRP jacket thickness was used, the enhancement in load-carrying capacity is seen to be more pronounced for CFTs with a thinner steel tube where the contribution of the steel tube to the load-carrying capacity was smaller.

Rupture Strain of the FRP Jacket

At the tensile rupture of the FRP jacket, the distribution of hoop strains in the jacket was found to be highly non-uniform. In studies on FRP-confined concrete columns, an FRP efficiency factor, denoted by k_ε, has been defined to evaluate the efficiency of an FRP jacket [17, 18]. This factor is equal to the ratio of the average FRP hoop rupture strain in a confined column to the ultimate tensile strain obtained from flat coupon tests. The FRP efficiency factor k_ε can be found as the product of two components [17]: $k_{\varepsilon 1}$ which is the ratio of the average hoop rupture strain to the maximum measured hoop strain in the FRP jacket at rupture, and $k_{\varepsilon 2}$ which is the ratio of the maximum measured hoop rupture strain in the FRP jacket to the ultimate tensile strain from flat coupon tests.

The values of $k_{\varepsilon 1}$ and $k_{\varepsilon 2}$ for all the FRP-confined CFT specimens are listed in Table 2. In calculating $k_{\varepsilon 1}$, only readings from those strain gauges outside the overlapping zone were used. The values of $k_{\varepsilon 1}$ are seen to vary from 0.693 to 0.961, with a mean value of 0.865 for all specimens. The values of $k_{\varepsilon 2}$ are seen to vary from 0.824 to 1.133, with a mean value of 0.948 for all specimens. The $k_{\varepsilon 1}$ values are found to lie around the average value (i.e. 0.908) found from tests on GFRP-confined concrete cylinders [18], while the $k_{\varepsilon 2}$ values are all higher than the average value (i.e. 0.820) of GFRP-confined concrete cylinders [18]. The larger $k_{\varepsilon 2}$ values observed in the present tests may be attributed to the less severe stress concentration on the surface of a steel tube than that of a concrete cylinder. That is, the maximum strain reading recorded by the limited number of hoop strain gauges on an FRP jacket is believed to be closer to the real maximum strain occurring in the FRP jacket when the FRP jacket is bonded to a steel tube than when it is bonded to a concrete cylinder.

CONCLUSIONS

This paper has presented an experimental study on the behaviour of FRP-confined concrete-filled thin steel tubes under axial compression. The experimental program included three series of tests where the main parameters examined were the thickness (or the diameter-to-thickness ratio) of the steel tube and the stiffness of the FRP jacket. The test results showed that the FRP jacket is very effective in improving the axial compressive behaviour of concrete-filled thin steel tubes in terms of both the load-carrying capacity and the ductility. The local buckling of the steel tube in a concrete-filled steel tubular column can be either substantially delayed or completely suppressed by the FRP jacket. The benefit of an FRP jacket is more pronounced for CFT specimens with a thinner steel tube than for those with a thicker steel tube.

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