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USING CFRP TO STRENGTHEN CONCRETE-FILLED STEEL TUBULAR COLUMNS: STUB COLUMN TESTS

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ABSTRACT

This paper describes the axial compression test results of concrete filled steel tubular (CFST) columns with circular and rectangular cross-sections. The test results showed that the carbon fiber reinforced polymer (CFRP) jackets can enhance the load bearing capacity of the circular columns effectively. However, the enhancement is not significant for rectangular columns compared with their circular counterparts. A simple model is proposed to calculate the ultimate strength of CFRP wrapped circular CFST stub columns. The predicted results are generally in good agreement with the experimental results obtained in this study, as well as those available in the literature.

KEYWOEDS

Concrete-filled steel tubes (CFST), Hybrid columns, FRP, Stub column, Strengthening, Confinement

INTRODUCTION

The use of concrete-filled steel tubes (CFST) has increased in recent years. In the past, there have been a large number of research studies on the fire resistance of CFST columns, such as Lie and Stringer (1994) and Han (2004). Another domain which has attracted a growing research interest lately is the residual strength of the composite columns (Han 2003). It maybe used to assess the potential damage caused by fire, and help to establish an approach in calculating the structural fire protection for minimum postfire repair. With an aim to reinstate their original functionity, adequate retrofit measures should be applied to enhance strength and/or ductility of the composite columns due to fire damage. It may also arise if changes in the use of the structures imposing higher functional requirements than those anticipated in the original design are to take place. However, very little study on the retrofit of CFST columns has been carried out up to now (Gu et al. 2004, Xiao 2004).

In this study, experimental results obtained for the CFST stub columns are presented. A simple model is proposed to calculate the ultimate strength of CFRP wrapped circular CFST stub columns.

OUTLINE OF EXPERIMENT

General

A total of nine CFST specimens were prepared and tested. Six of them were with circular cross-section, and three of them were with rectangular cross-section. The specimens can be classified as three categories: columns without fiber reinforced polymers (FRP) confinement; columns strengthened with one ply of FRP and columns strengthened with two plies of CFRP. Table 1 provides a summary of the specimens, in which t_s and t_{frp} are the thicknesses of the steel tube and the FRP jacket.

Material Properties

Tensile tests on steel coupons cut from the same original steel tube were conducted. The measured yield stresses (f_y) are shown in Table 1. The FRP used here had a nominal thickness of 0.17mm per ply, a tensile strength (f_{frp}) of 4,212N/mm^2, and a Young's modulus of 255,000 N/mm^2 determined from tensile tests of flat coupons. One batch of concrete was used to fill the steel tubes. To determine the compressive strength of concrete, three 150mm cubes and three standard cylinders (150mm×300mm) were cast and cured in conditions similar to the related specimens. The average cube strength (f_{cu}) and the average modulus of elasticity (E_c) at 28 days were 47.8 N/mm^2 and 30,800 N/mm^2 respectively. f_{cu} at the time of tests was 57.8 N/mm^2, whilst the average cylinder strength (f_c') was 46N/mm^2. E_c at the time of tests was found to be 35,800 N/mm^2.

Preparation of Specimens

In preparing the CFST columns, the concrete was filled in layers and was vibrated by a poker vibrator. These specimens were then placed upright to air-dry until testing. Prior to testing, the top surfaces of the CFST specimens were ground smooth and flat using a grinding wheel with diamond cutters. A steel plate with a thickness of 12mm was then welded to the top of each of those specimens.

CFRP strengthening of columns was achieved by the external wrapping of unidirectional carbon fibre sheets after the concrete had been cured for 28 days, with the fibres oriented in the hoop direction. The finishing end of a sheet overlapped the starting end by 150 mm. The wrapped specimens were left to cure in the laboratory environment at room temperature for about one month before testing.

Test Setup and Instrumentation

A 5,000 kN capacity testing machine was used for the compression tests of all specimens. A computerized IMP data acquisition system was used for data logging. To assure uniform compression, preliminary test within the elastic range were conducted by carefully adjusting the position of the specimen, based on the measurements of strain gauges attached at the mid-height of the test specimen. The adjustment was terminated until the difference between the measured strain and the average value was no more than 5%. In addition, two linear variable displacement transducers (LVDTs) were used to measure the axial shortening during the tests. A load interval of less than one tenth of the estimated load capacity was used. Each load interval was maintained for about 2 to 3 minutes.

TABLE 1

SPECIMEN LABELS, MATERIAL PROPERTIES AND MEMBER CAPACITIES OF SERIES I

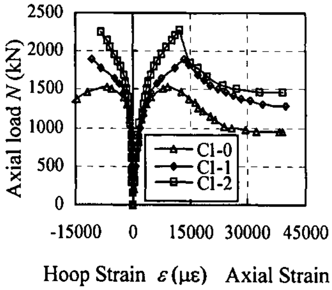
Specimen Label	Section Dimensions	t_s (mm)	f_y (N/mm^2)	Layer(s) of CFRP	ξ_s	ξ_{frp}	N_{ue} (kN)	*SEI*	N_{uc} (kN)	N_{uc}/N_{ue}
C1-0	ϕ156	3.0	213.4	0	0.45	0	1540	—	1314	0.853
C1-1	ϕ156	3.0	213.4	1	0.45	0.51	1890	22.7%	1757	0.929
C1-2	ϕ156	3.0	213.4	2	0.45	1.03	2270	47.4%	2200	0.969
C2-0	ϕ250	3.0	213.4	0	0.27	0	3285	—	2946	0.897
C2-1	ϕ250	3.0	213.4	1	0.27	0.31	3940	19.9%	3655	0.928
C2-2	ϕ250	3.0	213.4	2	0.27	0.62	4780	45.5%	4365	0.913
R-0	□100×150	3.2	380.0	0	1.12	0	1185	—	—	—
R-1	□100×150	3.2	380.0	1	1.12	0.67	1285	8.4%	—	—
R-2	□100×150	3.2	380.0	2	1.12	1.35	1280	8.0%	—	—

EXPERIMENTAL RESULTS AND DISCUSSIONS

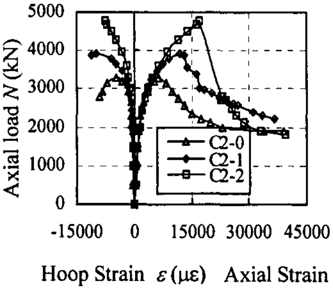
The tested curves of load versus axial and hoop strains are shown in Fig.1. The maximum loads (N_{ue}) obtained in the test are summarized in Table 1. As shown in Fig. 1, the initial portions of stress-strain responses of the confined CFST columns essentially followed the curves of unconfined CFST columns before attained a characteristic point. The characteristic point for specimens of series C2 or R is peak point of unconfined specimen, and that for specimens of series C1 is the point when achieved 80 percent of peak load of specimen C1-0. After attained the characteristic point, the load–axial strain as well as load–hoop strain relationships of confined specimens shown a higher modulus than that of unconfined specimens, and eventually exhibited an almost linear behavior until the sudden failure due to the rupture of carbon fiber composite jackets at the midheight. For the rectangular specimens, the rupture of FRP occurred at the corners, as shown in Fig.2. Generally, the ultimate strain at the peak load increase with the increasing of layers of CFRP jackets.

All specimens exhibited a descending response. Generally, during the post-peak stage, FRP-wrapped specimen had higher residual strength compared with its un-wrapped counterpart. It seems the FRP jacket still had some effects on the residual strength of the wrapped specimen.

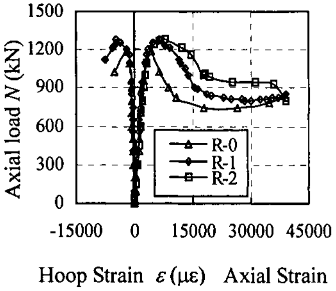
Fig. 2 shows all wrapped and unwrapped CFST specimens after testing.



(a) Circular CFST (D=156mm)

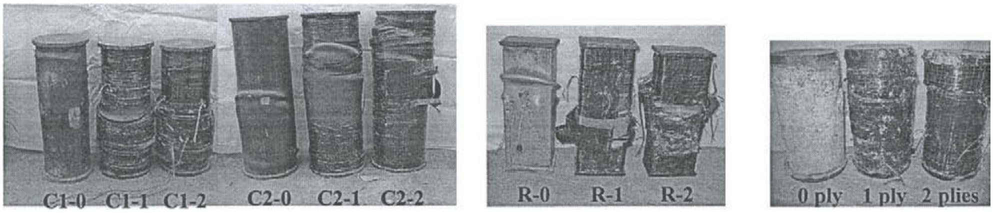


(b) Circular CFST (D=250mm)



(c) Rectangular CFST

Figure 1: Load versus strain curves for CFST columns



(a) Circular CFST (b) Rectangular CFST (c) Plain concrete cylinders

Figure 2: Specimens after testing

Three plain concrete cylinders were prepared and tested for comparison, in which two of them were wrapped with one or two plies of CFRP outside, respectively. The confined concrete showed eventual failure by the sudden rupture of the FRP jacket (see Fig. 2c). The measured peak loads for unconfined and confined concrete cylinders with one and two plies of CFRP are 813kN, 1350kN and 1700kN respectively.

Enhancements in the axial load capacity of wrapped CFST columns due to FRP wrapping can be easily gauged using the strengthening ratio defined as the percentage increase in the ultimate load:

$$SEI=(N_{eU}-N_{eU})/N_{eU} \tag{1}$$

where N_{eS} and N_{eU} are maximum loads for wrapped and un-wrapped specimens. The values of *SEI* are shown in Table 1. It can be seen that the load-carrying capacity of FRP-confined circular CFST column increase with the increasing of layers of CFRP jackets. However, rectangular CFST column wrapped with two layers of CFRP jackets has almost the same peak load compared with specimen wrapped with one layer of CFRP jacket.

Based on the test results of plain concrete cylinders and specimens of series C1, the mutual influence of dual confining system of FRP and steel tube can be evaluated. It is assumed that the enhancement of bearing-capacity in FRP-confined CFST column comes from a joint confinement of steel tube ($N_{c,s}$) and FRP ($N_{c,frp}$). Therefore, $N_{c,s}$ is calculated by

$$N_{c,s}=N_{ue}-N_s-(N_c+N_{c,frp}) \tag{2}$$

where N_{ue} is measured peak load of FRP-confined CFST columns, N_s and N_c are axial loads carried by the steel tube and the concrete respectively, without considering the enhancement of bearing-capacity from confinement. In Eq. (2) the term of $N_c+N_{c,frp}$ can be determined by measured peak load of plain concrete cylinders, and the term of N_s is determined by $A_s f_y$. The values of $N_{c,s}$ are listed in Table 2.

TABLE 2

CONTRIBUTIONS OF DIFFERENT COMPONENTS TO BEARING CAPACITIES FOR SPECIMENS OF SERIES C1

Specimen Label	D (mm)	H (mm)	t_s (mm)	f_y (N/mm^2)	Layer(s) of CFRP	N_{ue} (kN)	N_s (kN)	$N_c+N_{c,frp}$ (kN)	$N_{c,s}$ (kN)
C1-0	156	—	3.0	213.4	0	1540	308	813	419
C1-1	156	—	3.0	213.4	1	1890	308	1350	232
C1-2	156	—	3.0	213.4	2	2270	308	1700	262

From Table 2, it seems that the steel tube had less confinement on concrete in wrapped CFST column compared with its unwrapped counterpart in the current test. The reason is attributed to the fact that the volume dilation rate is slower under dual confining system than that of concrete confined only by steel tube.

LOAD-CARRYING CAPACITY PREDICTION

Since the FRP confinement has no significant effect on bearing capacity of rectangular CFST columns, calculation method is discussed only for FRP-confined circular CFST columns. According to research results reported by Han (2004) and Yu (2002), for CFST column and FRP-confined concrete, the "Composite action" between the steel tube and concrete or the FRP jackets and concrete can be described by confinement factors of ξ_s and ξ_{frp} respectively. They are expressed as:

For CFST: $$\xi_s = A_s f_y / A_c f_c' \tag{3}$$

For FRP-confined concrete: $$\xi_{frp} = A_{frp} f_{frp} / A_c f_c' \tag{4}$$

where A_s, A_{frp} and A_c are the cross-sectional area of the steel tube, the FRP jackets and the concrete respectively. The higher is the confinement factor, the higher the confinement on the concrete core.

For circular CFST stub column, the following formula was put forward by Han (2004) to calculate its section capacity:

$$N_u = (1.14 + 1.02\xi) f_{ck} A_{sc} \tag{5}$$

in which ξ is confinement factor, $\xi = A_s f_y / A_c f_{ck}$, f_{ck} ($=0.67 f_{cu}$) is characteristic concrete strength.

For FRP-confined concrete, its ultimate strength can be calculated by (Yu, 2002):

$$N_u = (1 + 1.15\xi_{frp}) f_c' A_c \tag{6}$$

Based on Eq. (5) and Eq. (6), the following formula is proposed in this paper, where the reduction effect of dual confining system on confinement is considered:

$$N_u = (0.95 + 1.02\xi_s) f_c' A_{sc} + \xi_{frp} f_c' A_c \tag{7}$$

The predicted section capacities (N_{uc}) using Eq.(7) are compared with the experimental values (N_{ue}) obtained in this paper and independent tests reported by Gu et al. (2004). The comparisons are shown in Table 1 and Table 3 respectively. A mean ratio (N_{uc}/N_{ue}) of 0.905 is obtained with a COV (coefficient of variation) of 0.043. In general, the predictions are reasonable and somewhat conservative.

CONCLUSION

The main conclusions obtained by this study can be summarized as follows:

1) Similar to FRP-confined concrete, sectional shape has significant influence on the confining effect of FRP jackets. CFRP jackets can enhance the load bearing capacity of the circular CFST columns effectively, whilst the enhancement is not significant for rectangular CFST columns.
2) The load-carrying capacity of FRP-confined circular CFST column increase with the increasing of layers of CFRP jackets. However, this phenomenon was not observed in rectangular CFST column in the current test.
3) Generally, during the post-peak stage, FRP-wrapped specimen has higher residual strength compared with its un-wrapped counterpart.

4) A design formula is proposed for predicting bearing-capacity of FRP-confined circular CFST stub column. In general, the predictions are reasonable and somewhat conservative.

TABLE 3

COMPARISONS OF BEARING CAPACITIES BETWEEN CALCULATING RESULTS AND TEST RESULTS

Specimen Label	D (mm)	t_s (mm)	f_y (MPa)	f_{cu} (MPa)	Layer(s) of CFRP	f_{frp} (MPa)	t_{frp} (mm)	ξ_s	ξ_{frp}	N_{ue} (kN)	N_{uc} (kN)	N_{uc}/N_{ue}
0-1.5	127	1.5	350	55	0	—	0	0.465	—	889.8	830	0.933
0-2.5	129	2.5	350	55	0	—	0	0.781	—	1139.7	1050	0.922
0-3.5	131	3.5	310	55	0	—	0	0.977	—	1292.6	1207	0.933
0-4.5	133	4.5	310	55	0	—	0	1.265	—	1527.8	1432	0.937
1-1.5	127	1.5	350	55	1	1260	0.167	0.465	0.189	1085.8	935	0.861
1-2.5	129	2.5	350	55	1	1260	0.167	0.781	0.192	1293.6	1157	0.894
1-3.5	131	3.5	310	55	1	1260	0.167	0.977	0.195	1347.5	1315	0.976
1-4.5	133	4.5	310	55	1	1260	0.167	1.265	0.198	1689.3	1542	0.913
2-1.5	127	1.5	350	55	2	1260	0.334	0.465	0.378	1282.8	1040	0.811
2-2.5	129	2.5	350	55	2	1260	0.334	0.781	0.384	1506.3	1264	0.839
2-3.5	131	3.5	310	55	2	1260	0.334	0.977	0.390	1592.5	1423	0.894
2-4.5	133	4.5	310	55	2	1260	0.334	1.265	0.396	1846.3	1652	0.895

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