Engineering Structures 174 (2018) 629–645

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Behavior of large-scale FRP-confined rectangular RC columns under axial compression

J.J. Zeng[a,b], G. Lin[b], J.G. Teng[b,*], L.J. Li[a]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China

ARTICLE INFO

Keywords:
Fiber-reinforced polymer (FRP)
Confinement
Rectangular column
Reinforced concrete (RC)
Stress-strain behavior

ABSTRACT

Fiber-reinforced polymer (FRP) jacketing has become an attractive technique for strengthening/retrofitting reinforced concrete (RC) columns. Extensive research has been conducted on FRP-confined rectangular columns under axial compression, leading to a significant number of stress-strain models for FRP-confined concrete in these columns. However, most of these models have been developed based on test results of small-scale columns, so their applicability to large FRP-confined rectangular RC columns has yet to be properly validated. To this end, the present paper first presents the test results of an experimental study consisting of nine large-scale rectangular RC columns, including eight FRP-confined RC columns and one RC column without FRP jacketing as the control specimen, tested under axial compression. The experimental program examined the sectional corner radius and the FRP jacket thickness as the key test variables. Five representative design-oriented stress-strain models for FRP-confined concrete in rectangular columns, identified from critical reviews of the existing literature, are then assessed using the test results to examine their validity for these large-scale columns.

1. Introduction

Fiber-reinforced polymer (FRP) jacketing has become a widely accepted technique for strengthening/retrofitting reinforced concrete (RC) columns [51,6]. Extensive research has been conducted on FRP-confined concrete columns aiming at gaining an in-depth understanding of the confining mechanism in FRP-confined concrete. While existing studies [51,22,52] have demonstrated that FRP confinement can substantially enhance both the compressive strength and ductility of confined concrete in circular columns, the same method has been found to be much less effective for rectangular columns (e.g., [35,47,23,13]). Corner rounding is generally recommended to enhance the confinement effectiveness in a rectangular column and to reduce the detrimental effect of sharp corners on the rupture strain of the FRP jacket. The lower FRP confinement effectiveness in a rectangular column is mainly attributed to the non-uniform FRP confinement around the column, whereas the concrete in an FRP-confined circular column is nominally uniformly confined. In an FRP-confined rectangular section, the flat sides of the FRP jacket are subjected to bending, to which the jacket has little resistance due to its negligible flexural rigidity; as a result, the concrete near the flat sides receives the lowest confinement, while that in the four corner regions receives the highest confinement [29]. Therefore, only part of the rectangular section is effectively confined by an FRP jacket [23].

A significant number of experimental studies have been conducted on FRP-confined rectangular concrete columns (e.g., [47,23,11,30,64,40,67,19,38,61,62]), leading to many stress-strain models for FRP-confined concrete in such columns (e.g., [23,63,64,67,17,62,27]). However, most of those experimental studies have been conducted on small-scale plain concrete columns; only a limited number of those studies have been concerned with large-scale RC columns (e.g., [59,44,53,13]). FRP jacketing has also been found to be effective to enhance the seismic performance of large-scale rectangular RC columns (e.g., [48,7,39,16,55,58]). The lack of a reliable stress-strain model for FRP-confined concrete in large rectangular columns also makes it difficult to accurately predict the seismic performance of such columns. The existing experimental results indicate that there exists a significant behavioral difference between small and large rectangular columns, which has been referred to as the column size effect (e.g., [42,34,9,45,46,60,13,57]). This size effect, however, has been found to be negligible for FRP-confined circular RC columns [35,33,72,50]. As a result, significant uncertainty exists with the applicability to large columns of existing stress-strain models for FRP-confined concrete in rectangular columns developed on the basis of studies on small-scale columns.

Against this background, the present paper presents the test results

* Corresponding author.
E-mail address: cejgteng@polyu.edu.hk (J.G. Teng).

https://doi.org/10.1016/j.engstruct.2018.07.086
Received 13 November 2017; Received in revised form 26 July 2018; Accepted 29 July 2018

of an experimental study that included nine large-scale rectangular RC column specimens, including eight FRP-confined RC columns and one un-confined RC column, tested under axial compression. The experimental program included the sectional corner radius and the FRP jacket thickness as the key test variables. The test results are then used to assess five existing design-oriented stress-strain models for FRP-confined concrete in rectangular columns. It should be noted that, in this paper, "axial stress-axial strain" is simply referred to as "stress-strain" unless otherwise specified.

2. Experimental program

2.1. Test specimens

Nine rectangular RC columns were cast in two batches and tested. All the columns had a cross-section of 435 mm in depth and 290 mm in width ($h \times b$ = 435 mm × 290 mm) and a column length of 1300 mm. The sharp corners of columns were rounded into a corner radius (r_c) of 25 mm, 45 mm or 65 mm before FRP jacketing, leading to three corner radius ratios ($2r_c/h$) of around 1/9, 1/5 and 2/7. Apart from the corner radius ratio, the experimental program included the FRP jacket thickness as another test variable. The detailed information of the test columns is given in Table 1.

The columns were longitudinally reinforced with 20-mm-diameter deformed steel bars and transversely reinforced with 8-mm-diameter round bars in the form of steel ties. The columns in Batch 1 were reinforced with ten longitudinal steel bars, while those in Batch 2 were reinforced with six longitudinal steel bars, corresponding to longitudinal steel reinforcement ratios of 2.49% and 1.49%, respectively (Fig. 1). A smaller longitudinal steel reinforcement ratio was adopted for Batch 2 to reduce the small additional confinement on the concrete from longitudinal steel bars (e.g., [49,31,1]). Nevertheless, for both longitudinal steel reinforcement ratios used in the present study, the additional confinement as estimated using the model of Sheikh and Uzumeri [49] is much smaller than the confinement provided by the FRP jacket at the ultimate condition for the present tests. It is thus believed that the use of two different longitudinal steel reinforcement ratios had little implication for understanding the behavior of confined concrete in these columns.

The longitudinal steel bars were welded onto a 30-mm-thick steel plate at each end. Each column was designed with a test portion of 700 mm in length in the middle region where failure was expected to occur, and a loading portion of 300 mm in length at each end (Fig. 1. The spacing of steel ties was 100 mm in the loading portions but much larger in the test portion to minimize the confinement effect from the steel ties. However, the tie spacing should not exceed 16 times the longitudinal bar diameter (320 mm) according to ACI 318 [1]. Therefore, the tie spacing arrangement of 200 mm-300 mm-200 mm was adopted in the test portion. The steel ties were bent to 135° hooks at the ends (Fig. 1). The concrete cover thickness, measured from the centers of the longitudinal steel bars to the concrete surface, was 35 mm. All the columns were cast in wooden moulds, demoulded on Day 2 and cured for 28 days or more in the laboratory environment before FRP jacketing.

Eight of the nine columns were wrapped with carbon FRP (CFRP) jackets, with fibers oriented only in the hoop direction (Table 1). The jacket was formed in a wet lay-up process, in which the carbon fiber sheet was impregnated with epoxy resin and then wrapped around the column. A 300-mm-long overlapping zone in the hoop direction was adopted to avoid FRP debonding of the wrapping end. The overlapping zone was horizontally centered at one of the longer sides of the column section. The FRP-wrapped columns were further cured in the laboratory environment for a period much longer than 7 days until testing.

Each column specimen was given a name in the following format: R*m*Lr*n*, where "R" denotes a rectangular column, *m* is the number of FRP layers (plies), and *n* is the radius of the rounded corners. For example, "R1Lr25" refers to a rectangular column with a corner radius of 25 mm wrapped with a one-layer CFRP jacket, and "R0Lr25" refers to the control RC column without FRP wrapping. To avoid unexpected failure outside the testing portion, an additional layer of CFRP of 200 mm in height was wrapped near each end of the column.

2.2. Material properties

Ready-mixed concrete from a local supplier was used in casting the columns. Crushed granite with a maximum nominal size of 20 mm was used as the coarse aggregate. The concrete slump was around 150 mm. Several standard concrete cylinders (150 mm in diameter and 300 mm in height) were cast and tested under axial compression at the time of testing each column to determine the unconfined concrete properties (e.g., compressive strength f'_c and axial strain at peak axial stress ε_{co}) following ASTM C469 [4]. Tensile tests on three steel bar specimens were conducted to determine properties of each type of steel bars (i.e., deformed bars and round bars) according to BS 18 [8]. The yield stress, tensile strength, and elastic modulus of the 20-mm-diameter deformed steel bars were 491.4 MPa, 602.8 MPa and 199.5 GPa, respectively. The corresponding values of the 8-mm-diameter round bars were 380.8 MPa, 448.4 MPa and 187.3 GPa, respectively.

Unidirectional high tensile strength carbon fiber sheets, with a nominal layer thickness of 0.334 mm, were used to form the FRP jackets. The average modulus of elasticity, tensile strength and rupture strain of single-layer CFRP were found to be 245.6 GPa, 3993.3 MPa and 1.71%, respectively, based on the results of three FRP flat coupons tested following ASTM D3039 [5].

It is well known that the hoop rupture strain of an FRP jacket in a column ($\varepsilon_{h,rup}$) is significantly lower than that from FRP coupon tensile tests (ε_f) [24]. Lam and Teng [22] found an average value of 0.586 for the FRP strain efficiency factor ($\varepsilon_{h,rup}/\varepsilon_f$) for CFRP jackets in circular concrete columns. For FRP-confined rectangular concrete columns, this strain efficiency factor is still needed as the analysis of such columns requires some information from an equivalent FRP-confined circular

Table 1
Key information of test columns and test results.

Specimen	Corner radius r (mm)	f'_c (MPa)	f'_{co} (MPa)	E_c (GPa)	ε_{co}	ρ_l (%)	t_f (mm)	f'_{cc} (MPa)	f'_{cc}/f'_{co}	ε_{cc}	$\varepsilon_{cc}/\varepsilon_{co}$	$\varepsilon_{h,max}$	Batch
R1Lr25	25	43.4	40.8	32.0	0.00249	2.50	0.334	46.5	1.14	0.0094	3.76	0.0164	1
R2Lr25	25	37.4	35.2	28.0	0.00251	2.50	0.668	42.1	1.20	0.0143	5.72	0.0120	
R0Lr25	25	42.2	39.6	30.7	0.00252	2.50	0	39.6	1.00	0.0025	1.00	N.A.	
R2Lr45	45	34.1	32.1	26.9	0.00250	1.52	0.668	42.2	1.32	0.0216	8.64	0.0130	2
R2Lr65	65	34.1	32.1	26.9	0.00250	1.54	0.668	44.9	1.40	0.0230	9.20	0.0133	
R4Lr45	45	30.8	28.9	26.3	0.00250	1.52	1.336	45.2	1.56	0.0248	9.92	0.0137	
R4Lr65	65	30.8	28.9	26.3	0.00250	1.54	1.336	51.1	1.77	0.0262	10.48	0.0107	
R6Lr45	45	34.1	32.1	26.9	0.00250	1.52	2.004	63.9	1.99	0.0387	15.48	0.0162	
R6Lr65	65	34.1	32.1	26.9	0.00250	1.54	2.004	68.4	2.13	0.0437	17.48	0.0108	

Note: "N.A." – Not applicable.