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MAXIMUM USABLE STRAIN OF FRP-CONFINED CONCRETE CYLINDERS

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ABSTRACT

This study investigates the maximum usable strain and the progressive failure of FRP-confined concrete. Ten FRP-confined concrete specimens were divided into two groups with different jacket stiffness. One specimen in each group was tested until failure while the others were loaded to target strains and then unloaded in order to monitor the residual strength of the concrete cores. At 1% axial strain of FRP-confined concrete, the residual strength of the concrete cores were reduced more than 56% compared to the reference specimens. Experimental results have shown that the maximum usable strain of 1% is un-conservative for FRP-confined concrete. The residual strength of the column cores is equal to the ordinate of the intersection between the unload curve and the unconfined concrete curve. The maximum usable strain of FRP-confined concrete is not a constant. It depends on the unconfined concrete strength and the jacket stiffness.

KEYWORDS

FRP, confinement, concrete columns, strain, stress strain relation, progressive failure.

INTRODUCTION

Fiber Reinforced Polymer (FRP) has been commonly used to strengthen existing reinforced concrete (RC) columns in recent years (Hadi and Widiarsa 2012; Hadi et al. 2013; Pham et al. 2013). In such cases, FRP is a confining material for concrete in which the confinement effect leads to increase the strength and ductility of columns (Pham and Hadi 2014a; Pham and Hadi 2014b). In early experimental studies of FRP retrofitted RC columns, the axial capacities of strengthened columns increased significantly as compared to reference columns. Lee and Hegemier (2009) collated a database that contained FRP-confined concrete cylinders having axial strain between 0.6% and 4.2%. Teng et al. (2009) showed that the axial strain of specimens varied from 0.8% to 3.7%. Pham and Hadi (2013) collected a database of 167 FRP-confined concrete columns and showed that the axial strain of these columns ranged between 0.5% and 4%. Ilki et al. (2008) conducted experiments on FRP-confined circular and rectangular RC columns. Experimental results from that study had shown that the axial strain of FRP-confined concrete ranged from 1.3% to 8.6%. From the literature, it can be seen that the axial strain of FRP-confined concrete varies in a broad range and no study has shown a maximum usable strain of confined concrete. Meanwhile, ACI-440.2R (2008) and Concrete Society (2012) provided maximum usable strain of 1% for FRP-confined concrete to prevent excessive cracking and the resulting loss of concrete integrity.

As mentioned above, experimental studies have shown that the axial strain of FRP-confined concrete varies in a wide range from 0.5% to 8.6%. However, these studies did not investigate the integrity of the concrete during testing. No study has investigated the precise nature of the progressive failure mechanisms occurring during experimental tests. In other words, a limit of 1% recommended by two guidelines (ACI 440.2R-08 2008; Concrete Society 2012) seems small as compared to the experimental results. Therefore, determining the nature of the progressive failure mechanisms and the maximum usable strain of FRP-confined concrete is essentially necessary. This study conducted experimental tests to investigate the progressive failure mechanisms of FRP-confined concrete at many stages of testing.

EXPERIMENTAL PROGRAM

Design of Experiments

A total of thirteen standard concrete cylinders were cast and tested at the High Bay laboratory of the University of Wollongong. The dimensions of the specimens were 150 mm by 300 mm and the design compressive strength of concrete was 50 MPa. The specimens were classified into three groups, namely, the reference group (R), two layers group (C2) and three layers group (C3). Details of the specimens are presented in Table 1. The notation of the specimens consists of two parts: the first part is "R", "C2", and "C3" stating the name of the groups. The second part indicates the target strains of the specimens at which the loading was stopped. For example, Specimen C2-1.9 indicates the specimen which was wrapped with two layers of FRP and loaded up to 1.9% axial strain.

After 28 days, each specimen was symmetrically bonded at the midheight with two 60 mm strain gages in the vertical direction and two 60 mm strain gages in the horizontal direction. The specimens were then fully wrapped with FRP layers as described in Table 1. The adhesive used was a mixture of epoxy resin and hardener at 5:1 ratio. Before the first layer of CFRP was attached, the adhesive was spread onto the surface of the specimen and CFRP was attached onto the surface. After the first layer, the adhesive was spread onto the surface of the first layer of CFRP and the second layer was continuously bonded. The third layer of CFRP was applied in a similar manner, ensuring that 100 mm overlap was maintained. In order to measure the lateral strain of the specimens, four strain gages were symmetrically bonded in the hoop direction of the jacket. Details of the positions of the strain gages are shown in Fig 1. During the testing, FRP jacket would cause confining pressure perpendicularly to the concrete surface and thus the strain gages on the concrete surface. This confining pressure could affect readings from these strain gages.

Table 1. Test matrix

ID	Target axial strain (%)	Actual axial strain (%)	Predicted lateral strain (%)	Actual lateral strain (%)	Predicted strength (MPa)	Actual strength (MPa)	No. of FRP layers
C2-0.6	0.6	0.62	0.46	0.44	69	70	2
C2-1.0	1.0	1.12	0.77	0.68	80	83	2
C2-1.2	1.2	1.33	0.91	0.94	84	89	2
C2-1.4	1.4	1.56	1.04	0.92	88	88	2
C2-1.9	1.9	1.99	1.25	1.40	95	97	2
C3-0.6	0.6	0.66	0.37	0.34	73	77	3
C3-1.0	1.0	1.02	0.62	0.67	87	90	3
C3-1.4	1.4	1.35	0.83	0.70	98	96	3
C3-1.9	1.9	1.87	1.05	1.08	109	106	3
C3-2.4	2.4	2.64	1.25	1.31	120	124	3

Instrumentation

The Denison 5000 kN testing machine was used for testing all the specimens. The columns were capped with high strength plaster at both ends to ensure full contact between the loading heads and the column. Calibration was then performed to ensure that the columns were placed at the centre of the testing machine. The tests were conducted as displacement controlled with a rate of 0.5 mm/min. All the strain gages were connected with a data logger and simultaneously saved in a control computer. Furthermore, the longitudinal compressometer as shown in Fig. 2 was used to measure the axial strain of the specimens and then these readings were compared to those from the strain gages. A linear variable differential transformer (LVDT) was mounted on the upper ring and the tip of the LVDT rests on an anvil. The readability, the accuracy, and the repeatability of the LVDT comply with the Australian standard (Australian Standard-1545 1976). This LVDT was also connected to the data logger and the readings were saved in the control computer.

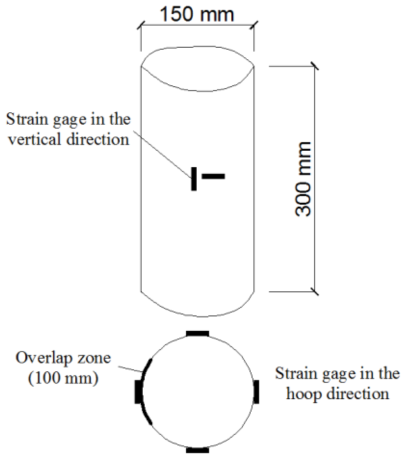

Figure 1. Position of strain gages

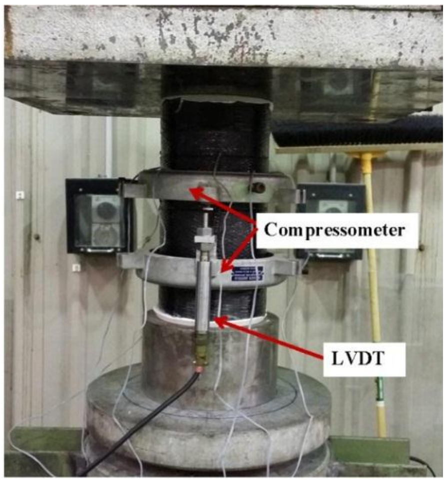

Figure 2. Compressometer

Testing Scheme

The axial stress and strain of the specimens were predicted using the study by Jiang and Teng (2007). Since the maximum strain of the specimens was determined, each specimen was tested to reach the single target axial strain as described in Table 1. The first specimen in that group was tested until the axial strain reached 0.6% that was the average value between 0.2% and 1%. The value of 0.2% was adopted from the widely accepted maximum axial strain of unconfined concrete while the value of 1% was proposed by ACI-440.2R (2008) for the maximum usable strain of FRP-confined concrete. The other specimens were tested to a target axial strain that range equally from 1% to the maximum axial strain of the group. After the tested specimens were loaded to the target strains, these specimens were unloaded and unwrapped in order to investigate any cracks which may have developed during the testing. The concrete cores of these specimens were then tested again under compression load to examine their residual strengths.

EXPERIMENTAL RESULTS

Preliminary tests

The actual compressive strength of unconfined concrete calculated from three reference Specimens (R-1, R-2, and R-3) was 52.08 MPa. The axial strain of unconfined concrete at the maximum load was 0.24%. CFRP used in this study was 75 mm in width with a unidirectional fibre density of 340 g/m2. Five CFRP coupons were made according to ASTM D7565 (2010) and tested to determine their mechanical properties. The coupons were made of three layers of FRP and had a nominal thickness of 1.45 mm. The average width of the coupons was 24.86 mm and the average maximum tensile force per unit width was 2037 N/mm. The strain at the maximum tensile force and the average elastic modulus were 0.0165 mm/mm and 123 kN/mm, respectively.

The axial strain of specimens was measured by both strain gages attached on the surface of concrete and LVDT mounted on the compressometer. Two readings were almost identical at early stages of the testing. However, the strain gages on the concrete failed at a strain about 0.6 - 0.7%, which may have resulted from the high confining pressure of the jacket. As a result, the experimental axial strains reported in this study are the readings from the LVDT.

Stress-strain Relation

Specimens C2-1.9 and C3-2.4 were tested until failure. These specimens failed by FRP rupture, resulting in loud explosive sounds. The rupture strain of FRP is the average values from three strain gages outside the overlap zone. The other specimens were loaded to the target strains and then their jackets were peeled off to investigate the damage level of the column cores. Specimens with high axial strain (C2-1.2, C2-1.4, C3-1.4, and C3-1.7) had wide and long cracks on the cores as shown in Fig. 3. These cracks were formed vertically and they cut throughout the core from the top to the bottom. These specimens were damaged and could not be used as the section of the cores was significantly reduced. Cores of the remaining specimens were loaded again until failure to examine the residual compressive strength and the results are shown in Table 2. The residual strength of these specimens was less than 20% as compared to the reference specimens. Meanwhile, specimens with lower axial strain (C2-0.6, C2-1.0, C3-0.6, and C3-1.0) had less serious cracks and the cores still kept the cylindrical shape as shown in Fig. 4. These cracks formed locally and they had small width and short length. The residual strength of these specimens ranged from 40% to 60% as compared to the reference specimens (Table 2).

Table 2. Residual strength of the tested specimens

ID	Residual strength (MPa)	Compared to f_c' (%)	Ordinate of intersection* (MPa)
C2-0.6	28	54	33
C2-1.0	17	33	18
C2-1.2	-	-	13
C2-1.4	9	17	8
C3-0.6	30	58	32
C3-1.0	23	44	20
C3-1.4	9	17	12
C3-1.7	9	17	-

* The intersection was made between the unload curve of the corresponding specimen and the unconfined concrete curve.

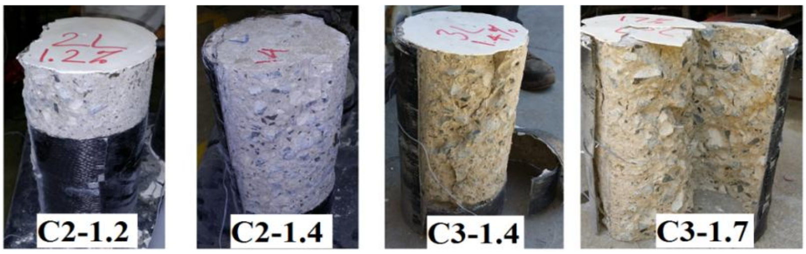

Figure 3. Damage of tested specimens with high axial strain

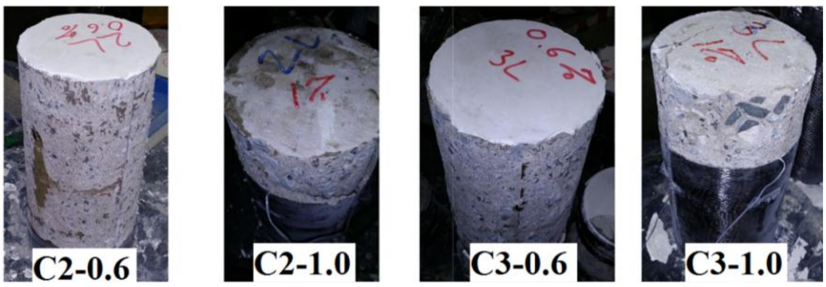

Figure 4. Damage of tested specimens with low axial strain

Residual Strength of the Cores

It is obvious that FRP prevents the cores from expanding under the applied loads. At the same value of axial strain, the lateral strain of specimens in Group C3 is lower than that of specimens in Group C2. Thus the residual strength of specimens in Group C3 is expected to be higher than that of the corresponding specimens in Group C2. Fig. 5 shows the residual strengths of Group C2 and Group C3. These experimental results confirm that with a similar axial strain the core of specimens that were wrapped with a thicker jacket will have higher residual strength as compared to the one wrapped with a thinner jacket. Thus it can be seen that the damage level of the cores is due to both the axial strain and the lateral strain, which is controlled by the stiffness of the jacket.

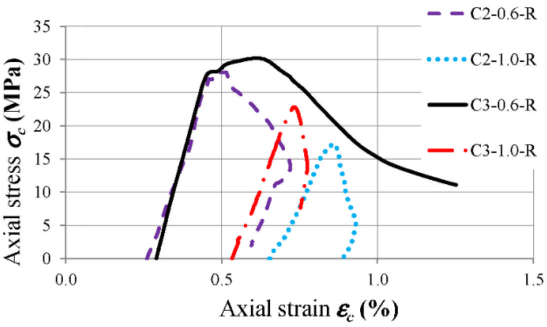

Figure 5. Residual strength of tested specimens

From the experimental results presented in Figs. 6-7, it can be seen that the residual strengths of the cores had values very close to the ordinate of the intersection between the unload curve and the unconfined concrete curve. These values are summarized in Table 2. Thus it is assumed that the residual strength of the column cores is equal to the ordinate of the intersection between the unload curve and the unconfined concrete curve.

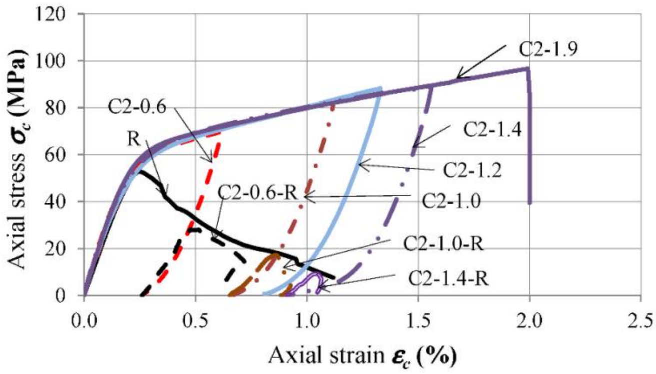

Figure 6. Stress-strain relation of Group C2

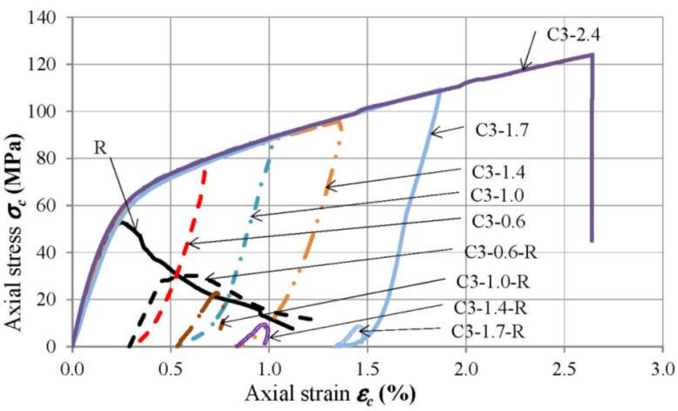

Figure 7. Stress-strain relation of Group C3

CONCLUSIONS

This study investigated the maximum usable strain and the progressive failure of FRP-confined concrete. The residual strengths of the concrete cores were determined experimentally at many axial strain levels. The findings presented in this paper are summarized as follows:

1. The residual strengths of the concrete cores were reduced more than 56% at the axial strain 1% of FRP-confined concrete.
2. The residual strength of the column cores is equal to the ordinate of the intersection between the unload curve and the unconfined concrete curve.
3. The maximum usable strain of FRP-confined concrete is not a constant. It depends on the unconfined concrete strength and the jacket stiffness.

Finally, the experimental results show that the maximum usable strain of FRP-confined concrete should be determined from the maximum usable strain of unconfined concrete.

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