EFFECTS OF UNCONFINED CONCRETE STRENGTH ON FRP CONFINEMENT OF CONCRETE

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Abstract

Research has shown that fibre reinforced polymer (FRP) wraps are effective for strengthening concrete columns for increased axial and flexural load and deformation capacity, and this technique is now used around the world. The experimental study presented in this paper is focused on the mechanics of FRP confined concrete, with a particular emphasis on the influence of the unconfined concrete compressive strength on confinement effectiveness and hoop strain efficiency. An experimental programme was undertaken to study the compressive strength and stress-strain behaviour of unconfined and FRP confined concrete cylinders of different concrete strength but otherwise similar mix designs, aggregates, and constituents. This was accomplished by varying only the water-to-cement ratio during concrete mixing operations. Through the use of high-resolution digital image correlation to measure both axial and hoop strains, the observations yield insights into the mechanics of FRP confinement of concretes of similar composition but with varying unconfined concrete compressive strength.

Keywords: Concrete, columns, confinement modelling, FRP, strengthening, repair.

1. Introduction

Externally bonded fibre reinforced polymer (FRP) circumferential wraps are a method of choice for reinstating or enhancing the strength and deformation capacity of concrete columns. A wealth of experimental evidence exists to support such applications, and many empirically-based analytical models are available for use in designing FRP strengthening schemes for both circular and rectangular columns [1, 2]. The use of FRP wraps for strengthening concrete is widely accepted within the engineering community, and design procedures are available for the design of FRP strengthening schemes to increase the axial load carrying capacity of columns (e.g. [3]). However, a number of questions remain regarding the mechanics of FRP confinement of concrete, in particular related to the possible factors influencing the ultimate failure condition of these elements, which is intimately linked to the ultimate hoop strain in the FRP wrap (and its variability). This paper presents the results of an experimental program conducted to study the effectiveness of FRP confinement for enhancing the strength and axial/lateral stress-strain response of circular concrete columns with different unconfined concrete strengths – varied by changing only the water-to-cement ratio of the concrete mix. The results shed light on both the mechanics of confinement and on the effectiveness of FRP wraps in confining concretes of different unconfined compressive strengths. The primary objectives of the research presented in this paper are:

- to demonstrate and quantify the effectiveness of externally bonded FRP hoop wraps (i.e. FRP confinement) for increasing the strength of circular concrete compressive elements of different unconfined concrete strength but otherwise identical concrete mix designs and FRP strengthening schemes; and
- to investigate the impacts of varying the unconfined concrete compressive strength on the performance and mechanics of FRP confinement of concrete.

2. Experimental Program

The experimental program consisted of uniaxial compressive tests on 30 plain or FRP wrapped concrete cylinders, as outlined in Table 1. Test parameters included: (1) the presence of FRP confinement and (2) the unconfined concrete compressive strength. All tests were performed in triplicate to verify the repeatability of the results.

Table 1 shows that the concrete cylinders were either unwrapped or wrapped in the hoop direction with a single layer of the SikaWrap Hex 230C unidirectional carbon fibre/epoxy FRP system [4]. This was applied by adhesive bonding to the concrete using a wet lay up procedure with a hoop overlap length of 100 mm. This FRP system is typical of the various systems marketed globally for strengthening concrete structures. The manufacturer-specified properties for this system state a design ultimate tensile strength of 4100 MPa at a tensile failure strain of 1.7% with a nominal thickness of 0.12 mm. The specimen designation consists of a letter (U for unwrapped and W for FRP wrapped) followed by the average unconfined compressive strength for each group of six cylinders (individual batches of concrete).

The range of concrete strengths used in the current study were dictated by the minimum and maximum water-to-cement ratios that allowed good consolidation of the selected concrete mix by hand using a standard steel tamping rod. This resulted in a range of mixes with unconfined compressive strength ranging from 25 MPa to 66 MPa, as shown in Table 1.

Fig. 1 provides details of the test specimens, including dimensions and the FRP wrap configuration. All specimens were unreinforced concrete cylinders, 100 mm in diameter and 200 mm in height; all were cast from concrete with a maximum aggregate size of 10mm. Columns were cured for a minimum of three months prior to wrapping.

Table 1. Details of the Experimental Program and Selected Test Results.

GROUP[a]	FRP (Y/N)	AVE. UNCONF. COMP. STRENGTH (MPa)	FAILURE MODE[b]	FAILURE STRESS (MPa)		AXIAL STRAIN AT PEAK STRESS (%)		HOOP STRAIN AT PEAK STRESS (%)	
				Test	$M \pm \sigma^{c}$	Test	$M \pm \sigma^{c}$	Test	$M \pm \sigma^{c}$
U-25	N	25	Shear	22.6	25.1 ± 5.8	0.41	0.28 ± 0.11	0.92	0.55 ± 0.34
			Cone	31.7		0.26		0.25	
			Shear	20.9		0.18		0.48	
W-25	Y		FRP rupture	55.8	58.9 ± 3.6	1.12	1.24 ± 0.11	0.80	0.86 ± 0.06
			FRP rupture	62.8		1.27		0.90	
			FRP rupture	58.1		1.33		0.89	
U-30	N	30	Cone	30.1	30.0 ± 1.4	0.26	0.26 ± 0.02	0.32	0.29 ± 0.06
			Cone	31.3		0.25		0.22	
			Cone	28.5		0.28		0.33	
W-30	Y		FRP rupture	63.6	60.8 ± 2.5	0.91	0.85 ± 0.06	1.05	1.11 ± 0.07
			FRP rupture	60.1		0.84		1.19	
			FRP rupture	58.7		0.79		1.09	
U-36	N	36	Cone	34.9	35.7 ± 2.2	0.27	0.23 ± 0.04	0.32	0.25 ± 0.09
			Cone	38.2		0.24		0.15	
			Cone	34.0		0.19		0.29	
W-36	Y		FRP rupture	64.8	69.3 ± 4.0	0.86	0.89 ± 0.06	0.72	0.78 ± 0.08
			FRP rupture	72.3		0.85		0.75	
			FRP rupture	70.8		0.96		0.87	
U-58	N	58	Cone	55.4	57.5 ± 3.1	0.27	0.28 ± 0.02	0.24	0.23 ± 0.06
			Cone	61.1		0.28		0.17	
			Cone	56.0		0.30		0.28	
W-58	Y		FRP rupture	77.8	79.6 ± 1.7	0.47	0.58 ± 0.22	0.48	0.83 ± 0.31
			FRP rupture	79.9		0.84		0.93	
			FRP rupture	81.1		0.44		1.08	
U-66	N	66	Cone	69.6	66.0 ± 5.2	0.12	0.21 ± 0.13	0.20	0.20 ± 0.00
			Shear	--		--		--	
			Cone	62.3		0.30		0.20	
W-66	Y		FRP rupture	80.9	84.6 ± 5.3	0.58	0.51 ± 0.07	0.62	0.56 ± 0.05
			FRP rupture	90.7		0.51		0.54	
			FRP rupture	82.3		0.45		0.53	

[a] All tests were performed in triplicate.
[b] FRP rupture = tensile rupture of the FRP wrap in the hoop direction outside the overlapping region.
[c] Note that σ is determined for a sample size of $n = 3$, rather than $n - 1 = 2$

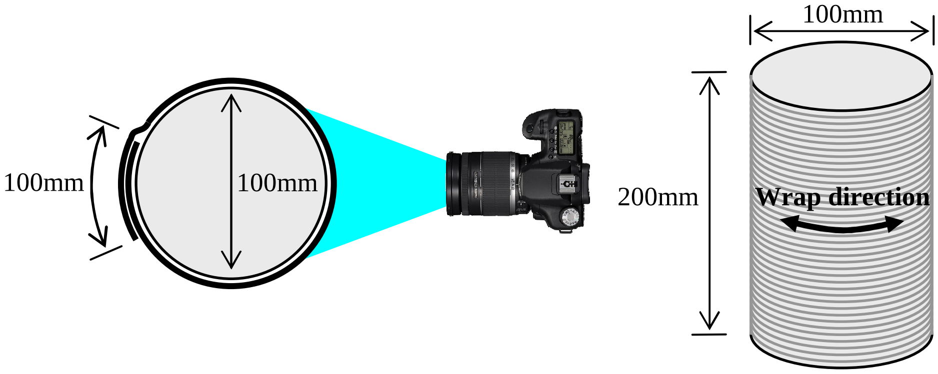

Figure 1. Details of Specimens, FRP Wrap Configuration, and Camera Position.

Once wrapped, the specimens and FRP systems were allowed to cure at room temperature for a minimum of three weeks before testing. Immediately prior to testing each column was capped with rapid-set mortar. Finally, both unwrapped and FRP wrapped columns were painted with a high contrast texturing effect (Fig. 2) – this was done to enable the use of digital image correlation for strain measurement during testing (discussed below).

3. Testing Procedure and Optical Strain Measurement

All specimens were tested under concentric, monotonic, uniaxial compression using a 1000kN structural testing machine. Testing was performed under load control at a rate of approximately 100kN/min. The column bases were rotationally restrained during testing while the tops were effectively pinned by bearing against a load cell with a spherical seat. The total applied load was monitored using this load cell, while axial and hoop strains were monitored using a digital image correlation (DIC) technique – this has been described and validated previously by Bisby and Take [5]. A Canon EOS 5D Mark II camera was used to capture images of the columns every five seconds during testing using a remote trigger. The load corresponding to each image was known from the load versus time curve; hence strain readings were taken approximately every 5kN. The camera was located opposite the centreline of the FRP hoop overlap, as shown in Fig. 1.

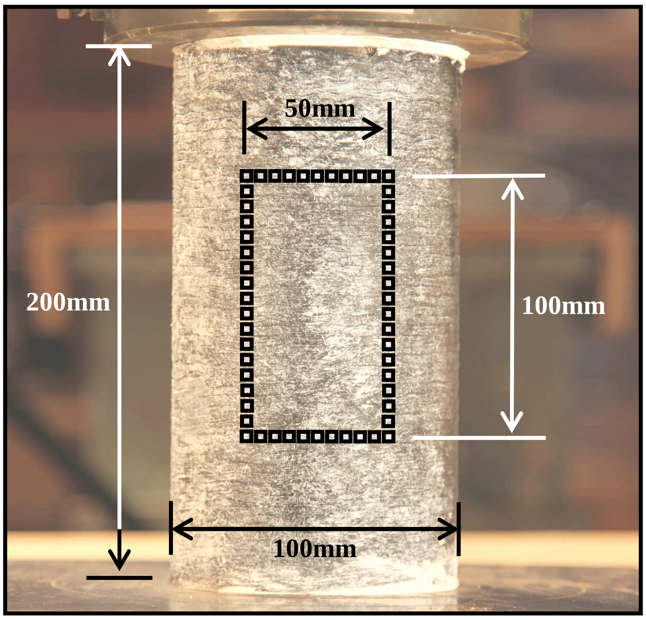

Figure 2. Typical image captured during testing of an FRP wrapped concrete cylinder (strain rectangle used to calculate hoop and axial strains also shown schematically).

After testing, the recorded images were correlated to known applied loads and processed using bespoke pixel tracking software, GeoPIV, coded by White et al. [6]. This software is used to define a patch of pixels in the initial image and this patch is tracked in subsequent images. The location and size of the patch can be chosen anywhere within the field of view of the camera, and it can be tracked in any direction. By defining pairs of patches, in-plane strains can be computed over any chosen gauge length and in any direction. Bisby and Take [5] have validated this technique by comparison with bonded foil strain gauges for measuring hoop and axial strains on circular FRP confined concrete cylinders. The image correlation analysis as implemented herein is accurate to better than one tenth of one pixel [6]. With virtual strain gauge lengths of 75 mm (hoop) and 150 mm (axial), as applied in the current analysis (Fig. 2), strain measurement resolutions better than 0.01% (hoop) and 0.005% (axial) were achieved. Take and Kemp [7] have validated this approach for measuring hoop strains in cylindrical specimens, even though the hoop displacements are slightly out of plane. The authors have previously used the optical technique to quantify the variation of hoop and axial strains in FRP wrapped concrete columns and have found that considerable variability and volatility exist in both directions [8], so that average strains must therefore be calculated.

For the analysis presented in the current paper, strains were measured using a ‘strain rectangle’ (Fig. 2). Hoop strains were measured as the average of 50 virtual strain gauges distributed over the height of the middle 150 mm of the specimens, each with a gauge length of 750 mm. Axial strains were represent the average of 20 strain readings distributed over the width of the middle 75mm of the specimens’ diameter, each with a gauge length of 150mm.

4. Results and Discussion

Table 1 provides a summary of test data including failure mode, peak stress, hoop strain at failure, and axial strain at failure for each group of three specimens. Fig. 3 provides assorted test data related to strength and axial strain enhancement, as well as hoop strain at peak stress.

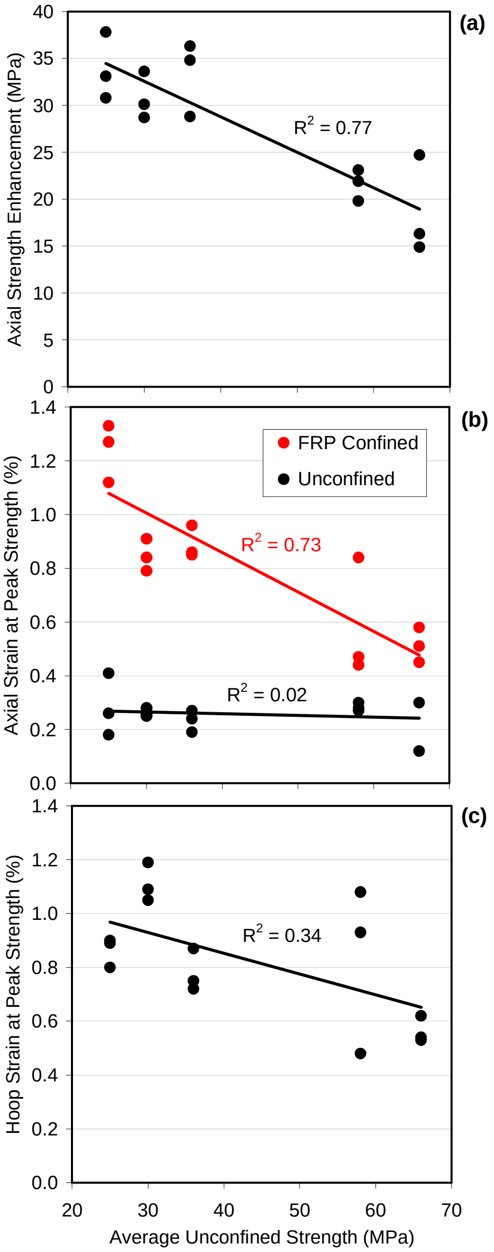

Figure 3. Effect of unconfined concrete strength on (a) strength enhancement, (b) axial strain at peak strength, and (c) hoop strain at peak strength.

Fig. 3(a) confirms the well known fact that large increases in compressive strength can be achieved for both low and high strength concretes by applying FRP hoop wraps. While considerable variability between individual specimens is evident in Fig. 3 (as evidenced by the relatively weak trend line correlation coefficients), the overall impacts of unconfined concrete strength and FRP wrapping are reasonably clear.

Fig. 3(a) highlights the effectiveness of FRP confinement for increasing the strength of concrete of varying unconfined compressive strength by plotting the strength increase due to FRP wrapping over and above the average unconfined strength for each group of FRP wrapped cylinders. While the correlation is reasonably weak, it appears clear that FRP confinement may result in greater proportional and absolute improvements in strength for concretes of lower unconfined compressive strength. A similar result has been reported previously by Mandal et al. [9], however additional testing is required to confirm and better understand this phenomenon and the numerous factors which are likely to play roles. This suggests that the enhancement of concrete strength by FRP confinement is at least partly dependent on the unconfined concrete strength, as has already been suggested [9]. It seems likely that this is due to the smaller dilatancies of higher strength concretes (as clearly visible in Fig. 4), as well as on other fundamental physical characteristics of the concrete mix behaving as a granular material or as a mechanism beyond the peak unconfined strength. For instance, previous authors have highlighted the importance of shear failure wedges [10] that are known to form in FRP wrapped cylinders at loads approaching failure; it is likely that the development and movement of shear failure plains will be different in concretes of different unconfined compressive strength.

Figs. 3(b) and 3(c) show the impacts of FRP confinement on the axial (Fig. 3(b)) and hoop (Fig. 3(c)) strains recorded at peak stress (i.e. failure) for both FRP wrapped and unwrapped columns. Hoop strains are shown only for FRP wrapped columns, since the data for the unwrapped columns displayed an unacceptable level of variability due to the difficulty of using DIC strain measurement once cracks appear in the concrete.

Fig. 3(b) shows that the axial strains in the FRP confined concrete are drastically increased (by more than 100% in all cases) compared to the unconfined concrete. It also suggests that the level of enhancement of axial strain (both relative and absolute) decreases considerably as a function of unconfined concrete compressive strength. This phenomenon is likely due to the well known reduction in deformability of high strength concrete as compared with lower strength concrete, combined with the lower dilatancy of high strength concrete and the resulting reductions in strength enhancement.

Fig. 3(c) shows that the hoop strain at failure (i.e. the tensile rupture strain in the FRP wrap) is highly variable but remains essentially constant (or at least demonstrates no clear reducing trend) with increasing unconfined concrete strength. This suggests that the level of confinement provided by the FRP at the ultimate state is not affected by the unconfined concrete strength, as should be expected. In a sense this contradicts the results given above for axial strain enhancement, and additional research is needed to confirm and better understand this observation.

The observed hoop strain at failure is in the range between 0.5% and 1.2% for all wrapped specimens, corresponding to between 38% and 71% of the manufacturer specified ultimate strain for the FRP material obtained from coupon tests (i.e. 1.7%). This is consistent with previous research on the hoop strain efficiency of FRP wraps for confining circular concrete columns [5, 8, 11, 12], although values below 0.5% are rare in the literature. The reasons for these lower hoop strain efficiencies are not known and additional testing is needed, particularly for the higher strength concrete mixes.

Fig. 4 gives plots of axial stress versus hoop and axial strains for the tested columns. Since the tests were performed under load control, no post-peak softening response was observed in any of the tests, and the data are truncated at peak stress. It is clear that the FRP wrap reduces the dilatancy of all unconfined strengths of concrete at all load levels. While this suggests that the FRP wrap should be more engaged for lower concrete strengths, it must be recognized that the hoop stiffness of lower strength concrete is also reduced, so that the interaction of the FRP with the dilating concrete core appears to be similar (or only slightly reducing) for all specimens, regardless of the unconfined concrete strength.

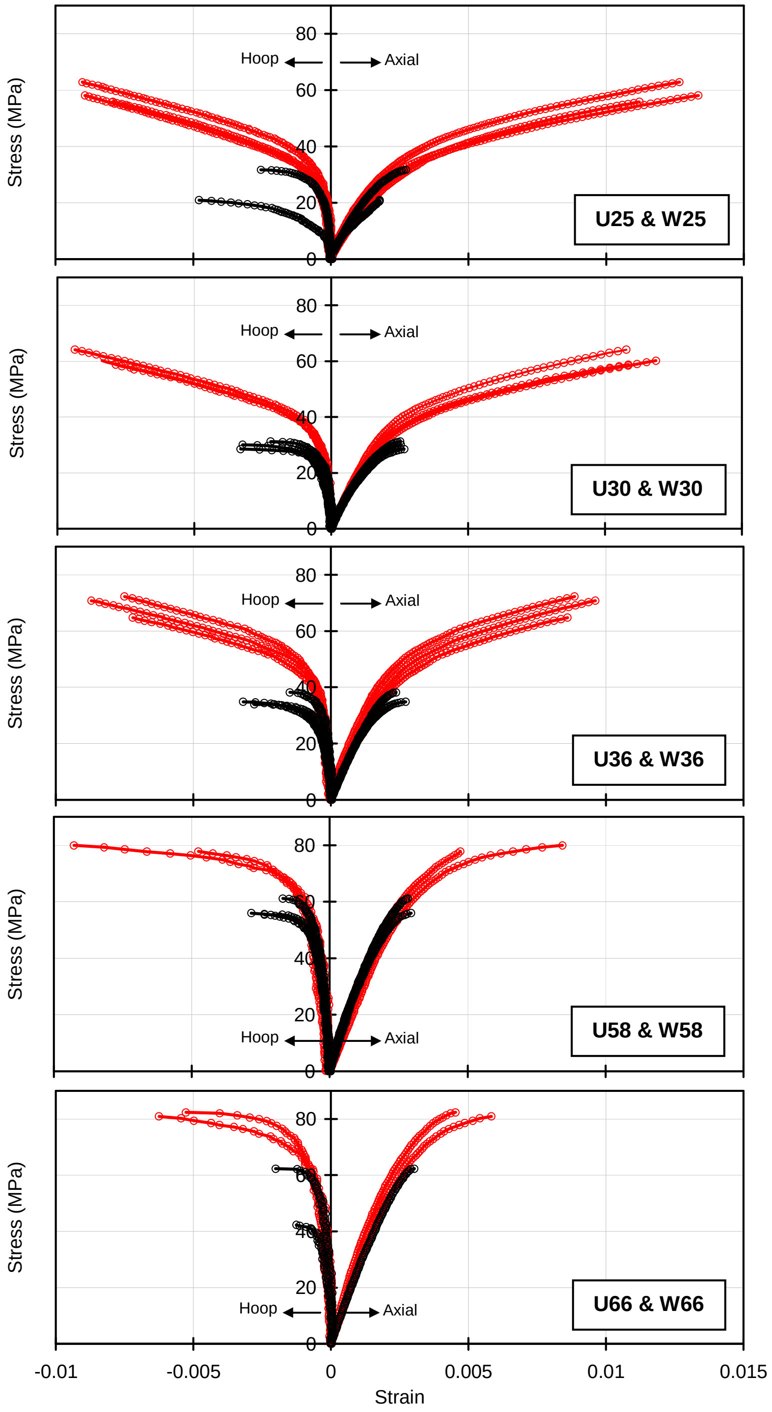

Figure 4. Axial Stress versus Hoop and Axial Strains for Tested Columns.

5. Conclusions

The following conclusions can be drawn based on the testing presented in this paper:

- As already known, large increases in compressive strength can be achieved for both low and high strength concretes by applying FRP hoop wraps; the FRP wrap reduces the dilatancy of all strengths of concrete at all load levels.
- FRP confinement may result in greater proportional and absolute improvements in strength for concretes of lower unconfined compressive strength, as suggested by previous researchers [9].

- The level of axial strain enhancement due to FRP wrapping appears to decrease considerably as a function of unconfined concrete compressive strength, however the precise reasons for this are not clear.
- The level of confinement provided by the FRP at the ultimate state does not appear to be greatly affected by the unconfined concrete compressive strength.

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