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The Ultimate Condition of FRP Confined Concrete Columns: New Experimental Observations & Insights

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ABSTRACT: A large body of research is available on FRP confinement of concrete. Many hundreds of tests have been performed and dozens of empirical models are available. However, some of the key mechanics of FRP wrapped concrete are still not understood. Research is needed to understand, quantify, and rationally account for the hoop strain variation in FRP wraps at failure; since failure is fundamentally defined by hoop rupture of the FRP in tension. In this paper, a digital image analysis technique is used to quantify the variation of axial and hoop strain over the surface of FRP wrapped concrete cylinders. Tests on FRP wrapped cylinders of varying aspect ratio are presented to study factors influencing strain variability. The first ever quantified statistical description of hoop strain variability is provided, and the consequences of this variability are discussed.

1 INTRODUCTION

Confinement of circular concrete columns by circumferential wraps is one of the most widely accepted applications of fibre reinforced polymers (FRPs) for repair and strengthening of structures (Bisby & Take 2009). FRPs are wrapped, with fibres oriented in the hoop direction, around the perimeter of columns and bonded in place with an epoxy adhesive; the effect of this is to restrain dilation of the concrete when loaded in compression, creating a triaxial stress condition and drastically improving the concrete's strength and deformability. This has clear benefits for axial strengthening and seismic enhancement which have led to FRP wraps being applied to many thousands of columns around the world. However, key aspects of the mechanics of FRP confined concrete remain poorly understood (Bisby & Take 2009); one area is in understanding the variability of strains in FRP wraps at failure.

1.1 *Background*

The ultimate compressive strength of FRP confined concrete is reached when the FRP wrap ruptures in hoop tension. Available research (Lam & Teng 2004) suggests that this occurs at hoop strain values between 30% and 50% less than expected on the basis of direct tensile tests on the FRP. The ratio of the tensile hoop strain in the FRP at failure to the average failure strain observed in direct uniaxial tensile coupon tests is termed the strain efficiency, η. From numerous observations, Jiang & Teng (2006) have suggested $\eta = 0.5$ for carbon FRP wraps and $\eta = 0.7$ for glass FRP wraps for design. ACI 440 (2008) suggests $\eta = 0.55$ for circular FRP wrapped columns.

Various causes have been suggested to explain strain efficiencies of less than 1.0 (Lam & Teng 2004), despite the fact that much higher strain efficiencies have been observed (even exceeding 1.0). None of these have been satisfactorily proven. Furthermore, all available empirical hoop strain data on which current design procedures are based were obtained using localized foil strain gauges, which provide no real insights into the variation of strains over the surface of FRP wraps. This issue is fundamental to the development of accurate and rational confinement models (Lam & Teng 2004).

1.2 *Observing Strain Variation*

Bisby & Take (2009) have recently presented the first ever detailed experimental measurements quantifying the axial and hoop strain variation on the surface of short FRP confined concrete cylinders under concentric axial compressive loads. This was accomplished using a digital image analysis technique to optically measure strain distributions using high-resolution image correlation. Their observations clearly showed that accurate measurement of hoop and axial strains on FRP confined concrete cylinders is possible using image analysis and that good correlation was observed between the optical technique and conventional bonded foil strain gauges; hoop strains vary over the surface of FRP confined short circular concrete cylinders at failure by as much as 50% of the coupon failure strain, even away from the frictional confinement provided by the loading platens; and the coupon failure strain is, in fact, achieved in virtually all cases, albeit only very locally.

A recent numerical study by Tabbara & Karam (2008) suggests that hoop strain variations may be due to localization of shear failure planes within the concrete followed by movement of solid concrete wedges along those failure planes. Using this hypothesis, they numerically predicted hoop strain localizations of similar overall shapes and magnitudes to those experimentally observed by Bisby & Take (2009). This suggests that one mechanism causing much of the hoop strain variation is localization of shear failure planes. Notably, Tabbara & Karam's (2009) study also suggests that cylinders of 2:1 aspect ratios (as used in the majority of testing on FRP confined concrete) may be insufficiently slender to avoid the influence of frictional confinement from the loading platens. A large proportion of the available data on hoop and axial strains in FRP confined concrete may therefore be corrupted by end effects. Hence, there is a need for a detailed comparison of strain variation for 2:1 cylinders against that observed for cylinders with larger aspect ratios.

2 EXPERIMENTAL PROGRAM

Table 1 shows details of the experimental program. Concentric uniaxial compression tests were performed on 16 unreinforced concrete columns, each 150 mm in diameter and 300 mm, 600 mm, or 900 mm tall. Nine of the cylinders (three at each length) were wrapped in the hoop direction over their full height with a single layer of a unidirectional carbon/epoxy FRP strengthening system (Sikawrap^{TM} Hex 230C). The wraps were applied using hand lay-up procedures with a hoop overlap of 100 mm. The concrete's compressive strength was 29.8 ± 0.5 MPa at the time of testing (based on three cylinder tests).

The test setup is shown in Figure 1. Digital images with the fields of view shown in Figure 1b were captured every five seconds during testing as each cylinder was loaded to failure. Because only two cameras were available and it was important to maintain similar image resolution for all cylinders during testing, strains were only recorded over the bottom two-thirds of the 900 mm long columns.

After testing, a bespoke image processing algorithm was used to calculate virtual (optical) hoop strains along a single vertical line for each cylinder. Details of the image analysis technique are discussed by Bisby & Take (2009). The technique defines particular regions of interest, called patches, in the first image of each set, and then tracks the displacements of patches in subsequent images, allowing optical measurement of hoop strains by strategically-located patches. Each patch must contain sufficient variation in the intensity and distribution of colours to be unmistakable in subsequent images. A high-contrast texture was thus applied to each cylinder before testing. The gauge length for the optical strain gauges was 15 mm in the current analysis. A validation of the technique is given by Bisby & Take (2009).

Table 1. Details of experimental program and selected results.

ID	Length, H (mm)	H/D	Repeats	Ave. strength (MPa)	Std. dev. (MPa)
U300	300	2	3	29.8	0.5
W300	300	2	3	38.5	2.1
U600	600	4	1	29.0	--
W600	600	4	3	37.1	0.9
U900	900	6	3	28.9	0.4
W900	900	6	3	39.1	1.5

* H = Column length (mm), D = Column diameter (mm)

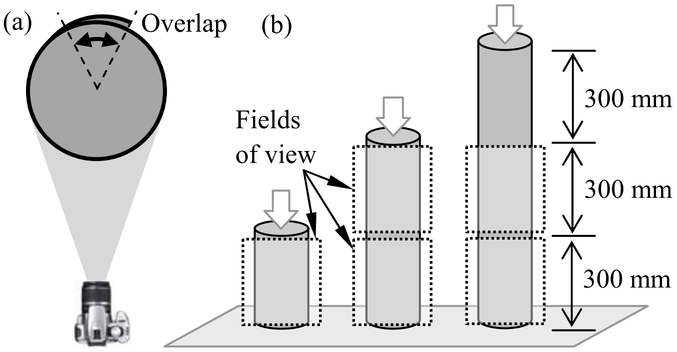

Figure 1. (a) Plan view of test setup & (b) imaging locations.

3 RESULTS & DISCUSSION

The purpose of the testing described above was to study the variability of hoop strains for FRP confined concrete cylinders of increasing aspect ratios, and subsequently to determine if end effects arising from frictional confinement in standard 2:1 cylinders influence hoop strain variability near the cylinders' mid-heights. The goal was to determine if data from 2:1 cylinders are appropriate for calibrating empirical FRP confinement models. It was also desired to study the hoop strain variability in cylinders of realistic slenderness to determine if this has any effect of strain variability at failure.

Table 1 shows the average axial compressive strength observed for both unconfined and FRP confined cylinders. These data show that all unconfined cylinders of different lengths displayed similar strengths, as did FRP confined cylinders of different lengths. This suggests that second-order (slenderness) effects did not influence the results. This is expected since the columns tested herein would be classified as 'short' according to most available concrete design codes, assuming an effective length of

0.7*H*. The FRP strengthening increased the cylinders' strength by about 30%, which agrees well with predictions of available design models for FRP confined concrete (e.g. ACI 440 2008).

Figure 2 show typical vertical hoop strain profiles recorded during the 25 seconds leading up to failure for selected tests, along with post-failure photographs to show the correlation between hoop strain peaks and failure initiation locations. Included on the profiles are markers indicating the average axial compressive stress at the instant that each strain profile was recorded. Black profiles represent the final data recorded before failure (these may have preceded failure by up to five seconds).

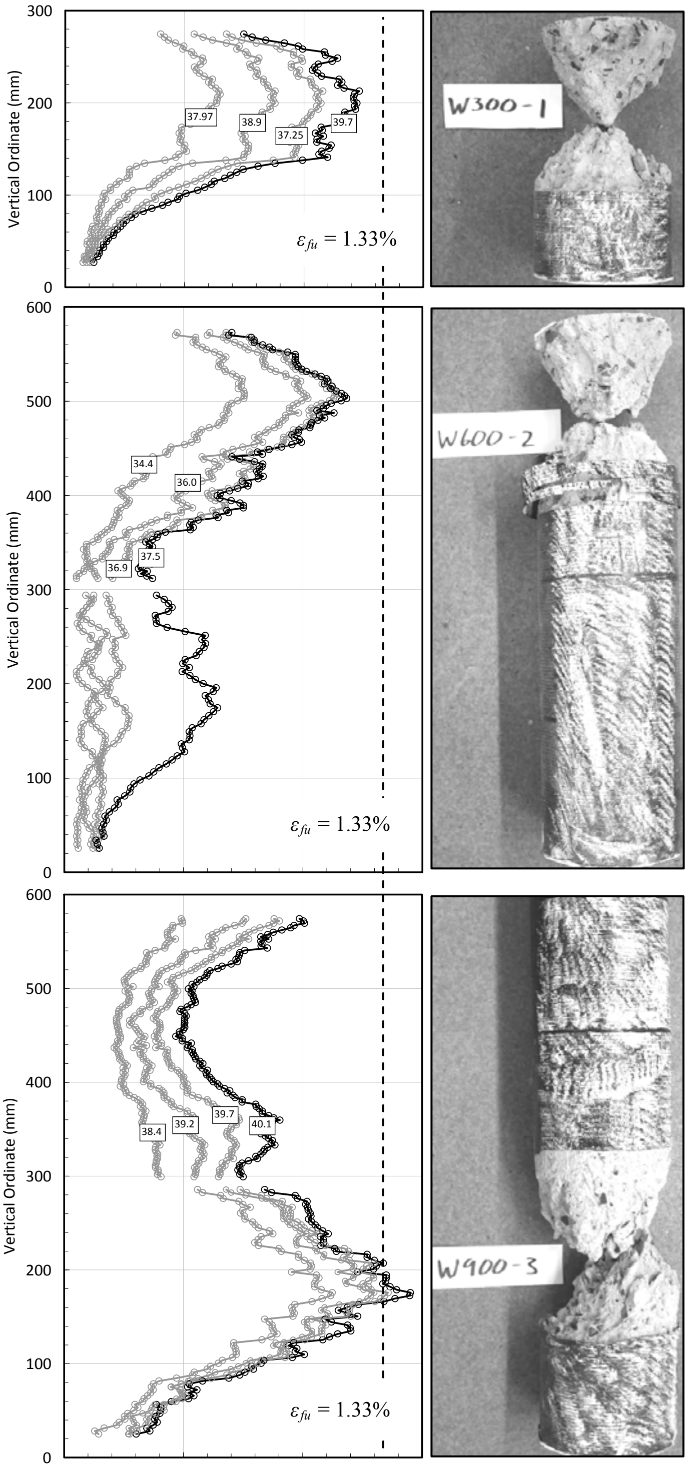

Figure 2. Vertical hoop strain profiles recorded during the 25 seconds prior to failure for selected cylinders.

Several features of Figure 2 (and all of the data) are noteworthy. Considerable hoop strain variation was observed in all tests. The shape of the hoop strain profiles and the amount of variability appeared to be random phenomena and it is unlikely that generalizations can be made with respect to these issues.

The hoop strain profiles evolved rapidly near ultimate, and again generalizations are difficult to make. The rapid, apparently random evolution of strain profiles suggests non-uniform deformations occurring inside the confined concrete cylinders, which lends support to the Tabbara & Karam (2008) hypothesis mentioned previously.

For the 2:1 cylinders (W300) hoop strains were largest close to mid-height. This is expected given that frictional confinement from the loading platens is almost certainly active within the top and bottom 75 mm of the specimens. However, even within the middle 150 mm where this effect can be assumed absent, hoop strain still varied by up to 70% of the coupon failure strain. For 4:1 and 6:1 cylinders (W600 & W900) the hoop strain variation outside the top and bottom 75 mm was random, and generalizations are not possible. Up to 75% hoop strain variability was observed outside the end regions.

As in previous tests by Bisby & Take (2009) on 2:1 cylinders, the average coupon failure strains for the FRP (ε_{fu} = 1.33%) were nearly achieved in most tests (even exceeded in one case), albeit only locally. Bisby & Take (2009) have shown that hoop strains vary radially as well as vertically by up to 50% of the average coupon failure strain. Measuring hoop strains along a single vertical line thus provides no guarantee that the maximum hoop strain is observed.

Comparison of the hoop strain profiles with images of the cylinders taken after failure shows a striking correlation between locations of maximum hoop strain and locations of failure initiation.

3.1 *Statistical Variability & Consequences*

In the authors' view, it has now been convincingly proven that considerable hoop and axial strain variability exists in FRP wrapped concrete cylinders, both longitudinally and circumferentially. The practical consequences of this variability for existing empirical confinement models, all of which have been calibrated (or validated) on the basis of apparently incomplete, localized strain measurements, remain unclear. While the current work makes no serious attempt to address consequences, by providing a quantified statistical description of the observed hoop strain variability it is hoped that the uncertainty inherent in the available test data can be explicitly included in the calibration of confinement models.

Figure 3 shows a statistical summary of hoop strain efficiencies recorded for each FRP confined cylinder (only strains recorded outside the top and bottom 75 mm of the cylinders are included). The data shown represent by far the most detailed statistical description of hoop strain variability ever presented. For the W300 specimens, each population represents ≈ 175 readings (525 in total), whereas the W600 & W900 populations contain ≈ 200 individual readings for each cylinder (600 in total).

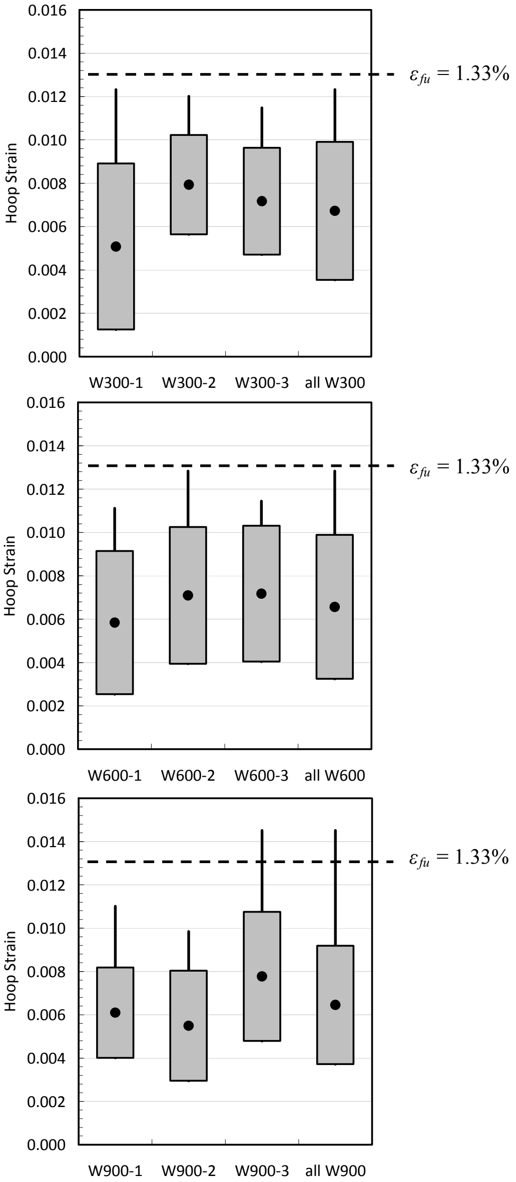

Figure 3. Summary plots for observed hoop strains at failure for FRP wrapped cylinders (mean, mean ± 1 std. dev., max. value).

Figure 3 shows that the distributions of hoop strains were similar from one cylinder to the next, and also between cylinders of different aspect ratios. The mean hoop strain varied between 0.51% and 0.78% (η = 0.38 and η = 0.59) for individual specimens, but was almost uniformly ≈ 0.66 for each cylinder length group (η = 0.50). This agrees with the value of η = 0.5 recommended by Jiang & Teng (2006) for carbon FRP wraps, which makes sense given that even isolated strain gauges on multiple columns (as used by Jiang & Teng) should yield the same statistical populations of hoop strain data as given in Figure 3. It therefore appears that currently recommended hoop strain efficiencies are close to the mean hoop strain values which are actually achieved in practice. Interestingly, the standard deviation of hoop strain efficiency is also fairly consistent and ranges between 0.18 and 0.31. These data could be used to calibrate available FRP confinement models with a prescribed level of statistical confidence. Such a calibration is currently underway.

4 CONCLUSIONS

The data presented in this paper show that considerable hoop strain variability exists in FRP confined concrete at loads approaching failure. In combination with prior work by others (Tabbara & Karam 2008), the data suggest that the observed strain variation is caused at least in part by localization of shear failure planes within the concrete. Zones of high hoop strain localization correlate well with observed locations of failure, indicating that failure of FRP confined concrete is indeed initiated by tensile rupture of the FRP wraps at strains close to (or exceeding) the coupon failure strain, albeit locally. A statistical summary of the observed hoop strains has shown that the hoop strain variability is similar for cylinders of aspect ratios from 2:1 to 6:1, so that empirical confinement models derived on the basis of localized strain measurement from 2:1 cylinders may be used in model calibration. Considering all hoop strain measurements presented herein (1667 hoop strain readings) gives a mean hoop strain efficiency, η, of 0.50 with a standard deviation of 0.30. This agrees exactly with the strain efficiency of 0.5 recommended by Jiang and Teng (2006) for carbon FRP confined concrete and can be used in future reliability studies on empirical confinement models.

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6 REFERENCES

ACI 440. 2008. *Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. Farmington Hills, USA: American Concrete Institute.

Bisby, L. A. & Take, W. A. 2009. Strain Localizations in FRP Confined Concrete: New Insights. *Structures and Buildings* 162(5): 301-309.

Jiang, T. & Teng, J. G. 2006. Strengthening of short circular RC columns with FRP jackets: A design proposal. In Mirmiran & Nanni (eds.), *3rd Intern. Conf. on FRP Composites in Civil Eng., Miami, 13-15 December 2006*.

Lam, L. & Teng, J. G. 2004. Ultimate condition of fiber reinforced polymer-confined concrete. *Journal of Composites for Construction* 8(6): 539-548.

Tabbara, M. & Karam, G. 2008. Numerical investigation of failure localization and stress concentrations in FRP wrapped concrete cylinders. In Mufti & Neale (eds.), *5th Intern. Conf. on Advanced Composite Materials in Bridges and Structures, Winnipeg, 22-24 September 2008*.