Effects of Aspect Ratio on the Observed Hoop Strain Variation in FRP Confined Concrete Cylinders

Effects of Aspect Ratio on the Observed Hoop Strain Variation in FRP Confined Concrete Cylinders

Dr LA Bisby, D Sinclair, M Webster, Dr TJ Stratford & Dr WA Take
Institute for Infrastructure and Environment, University of Edinburgh
King's Buildings, Mayfield Road, Edinburgh, Scotland, UK EH9 3JL

ABSTRACT

Confinement of circular concrete columns by circumferential fibre reinforced polymer (FRP) wraps is among the most widely implemented applications of FRP materials for infrastructure. FRPs are wrapped in the hoop direction around the perimeter of concrete columns and bonded in place with an epoxy adhesive; the effect of this is to drastically improve the columns' strength and deformability, which has clear benefits for axial strengthening, seismic enhancement, and blast damage mitigation. The technique has been applied to many thousands of columns around the world, yet several aspects of the mechanics of FRP-confined concrete remain poorly understood. One area in which additional research is needed is in understanding, explaining, and quantifying the observed variability of hoop strains in the FRP wraps at failure. This paper follows from previous work using a digital image analysis technique to directly measure the variability of both axial and hoop strains over the surface of FRP-wrapped concrete columns. The results of new tests on FRP wrapped cylinders with increasing aspect ratios are presented with a view to understanding and quantifying the factors that influence the variability and effectiveness of FRP confinement for concrete. The focus in the current paper is on the influence of the cylinders' aspect ratio on observed hoop strains at failure.

INTRODUCTION AND BACKGROUND

Confinement of circular concrete columns by circumferential wraps is one of the most widely accepted applications of fibre reinforced polymer (FRP) materials for repair and strengthening of structures [1]. In these applications, FRPs are wrapped (typically with fibres oriented in the hoop direction only) around the perimeter of concrete columns and bonded in place with an epoxy adhesive; the effect of this is to restrain dilation of the concrete when loaded in axial compression, creating a beneficial triaxial stress condition, and to drastically improve its strength and deformability. This has obvious benefits for axial strengthening and for seismic enhancement which has led to the technique being applied to many thousands of columns around the world. Despite its success, key aspects of the mechanics of FRP confined concrete remain poorly understood [1]. One area in which additional research is needed is in understanding, explaining, and quantifying the observed variability of hoop strains in the FRP wraps at failure.

The ultimate compressive strength of FRP confined concrete is reached when the FRP wrap ruptures in hoop tension. Available research [2, 3] suggests that this occurs at a hoop strain value between 30% and 50% less than expected on the basis of direct tensile tests on the FRP material. 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 often referred to as the strain efficiency, η. From numerous test observations, Jiang and Teng [4] have suggested η = 0.5 for carbon FRP wraps and η = 0.7 for glass FRP wraps for design of these systems. ACI Committee 440 [5] suggest η = 0.55 for circular FRP wrapped columns.

Various possible causes have been suggested to explain observed strain efficiencies of less than 1.0 [2, 3], despite the fact that much higher strain efficiencies have been observed in many cases (exceeding η = 1.0 in some cases [1]); none of the available explanations have been satisfactorily proven. Furthermore, all available empirical hoop strain data on which current design procedures (e.g., [5]) are based were obtained using localized strain gauges, and they provide little insight into the widely acknowledged variation of hoop strain over the surface of FRP wraps. The actual hoop and axial strain variability that exists in FRP wraps at loads approaching failure has until recently not been well characterized [1]. This issue is fundamental to the proper interpretation of test results of FRP confined concrete and to the development of accurate and rational confinement models [3].

Bisby and Take [1] have recently presented the first ever detailed measurements quantifying both the axial and hoop strain variation over the surface of short (150 mm diameter × 300 mm height) FRP confined concrete cylinders under concentric axial compressive loading. This was accomplished using a digital image correlation technique, *geoPIV* [6] to optically measure strain distributions using high-resolution photogrammetry. Their results clearly show that [1]:

- accurate measurement of hoop and axial strains on FRP confined concrete cylinders is possible using *geoPIV* and good correlation is observed between the optical technique and conventional 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 near mid-height, away from the frictional confinement provided by the loading platens; and
- the coupon failure strain is actually achieved in virtually all cases, albeit only locally.

Two key issues which remain are to explain the physical mechanism(s) causing the observed hoop strain variation and to determine the possible consequences (if any) of these new insights for the design of FRP confined concrete columns.

A recent numerical study by Tabbara and Karam [7] provides a compelling argument that hoop strain variations may be due at least in part to localization of shear failure planes within the concrete followed by movement of solid concrete wedges along those failure planes. Tabbara and Karam used this concept to independently numerically predicted hoop strain localizations of similar overall shapes and magnitudes to those experimentally observed by Bisby and Take [1] on virtually identical cylinders, suggesting that the mechanism causing a majority of the hoop strain variation is indeed localization of shear failure planes. Notably, Tabbara and Karam's study [7] also suggested that standard cylinders of 2:1 aspect ratio (as used in the vast majority of previous testing on FRP confined concrete) may be insufficiently slender to avoid the influence of frictional confinement from the end regions. Available data on FRP confined concrete may therefore be corrupted to a certain extent by end effects, hence the need for a detailed comparison of strain variation for 2:1 cylinders with that observed for cylinders with larger aspect ratios.

EXPERIMENTAL PROGRAM

Table 1 shows details of the experimental program. Concentric uniaxial compression tests were performed on 16 unreinforced concrete cylinders, each 150 mm in diameter with a height of 300 mm, 600 mm, or 900 mm. Nine of the cylinders (three of each length) were wrapped in the hoop direction over their full height with a single layer of a commercially available unidirectional carbon/epoxy FRP strengthening system (Sikawrap Hex 230C). The FRP wraps were applied using hand lay-up procedures with a hoop overlap of 100 mm. The compressive strength of the unwrapped concrete was 29.8 ± 0.5 MPa at the time of testing (based on three standard cylinder tests). Material properties for the FRPs can be obtained from the supplier.

The test setup for the cylinder tests is shown schematically in Figure 1. Digital images with the fields of view shown in Figure 1b were captured every five seconds during testing (using 10.1 megapixel digital SLR cameras) as each cylinder was loaded, at approximately 10 kN/min, until 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, an image processing algorithm which uses normalised cross-correlation (as implemented in the code *geoPIV* [6]) was used to calculate virtual (optical) hoop strains along a single vertical line for each cylinder. The details of the image analysis technique are provided elsewhere [1, 6]. In general, the technique defines particular regions of interest, called patches, in the first image of each set, and tracks the displacements 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, so a random, high-contrast, image texture was applied to each cylinder. The gauge length chosen for the virtual strain gauges was approximately 15 mm in the current analysis. A validation of the technique for axial and hoop strain measurement has been presented previously [6, 8].

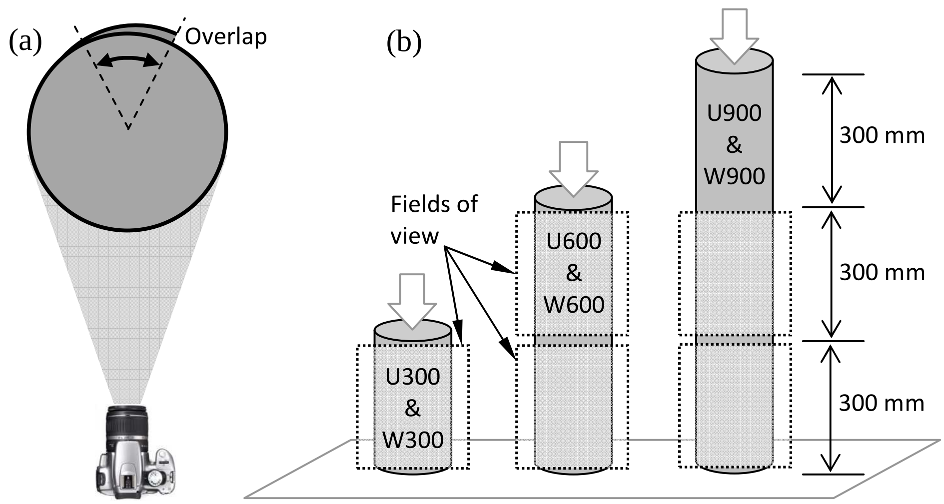

Figure 1. Schematics showing (a) plan view of test setup and (b) imaging locations

Table 1. Details of experimental program and selected results

#	ID	Length (mm)	H/D[1]	Repeat	Strength (MPa)	Average strength (MPa)	Standard deviation (MPa)
1	U300	300	2	1	29.5	29.8	0.5
2				2	29.5		
3				3	30.4		
4	W300	300	2	1	39.7	38.5	2.1
5				2	39.7		
6				3	36.1		
7	U600	600	4	1	29.0	29.0	N/A
8	W600	600	4	1	36.1	37.1	0.9
9				2	37.5		
10				3	37.7		
11	U900	900	6	1	29.2	28.9	0.4
12				2	28.9		
13				3	28.5		
14	W900	900	6	1	39.7	39.1	1.5
15				2	37.4		
16				3	40.1		

[1] H = Column length (mm), D = Column diameter (mm)

EXPERIMENTAL RESULTS AND DISCUSSION

The primary purpose of the tests described above was to study the variability of hoop strains for FRP confined concrete cylinders of increasing aspect ratios. This was done in an attempt to determine if end effects arising from frictional confinement in standard 2:1 aspect ratio FRP confined concrete cylinders influence hoop strain variability near the cylinders' mid-height, and the extent to which this should be accounted for when using data from 2:1 cylinders to calibrate empirical FRP confinement models. A secondary purpose was to study the hoop strain variability in cylinders of more realistic slenderness under concentric uniaxial compression.

Table 1 shows the average axial compressive strengths of all unconfined and FRP confined cylinders. These data show that all unconfined cylinders displayed similar strengths, as did all FRP confined cylinders, indicating that second-order effects did not significantly influence the results (this is as expected, since the columns would be classified as 'short' according to most available concrete design codes assuming an effective length of $0.7H$). It is therefore likely that the hoop strain variation observed below was due predominantly to factors other than non-concentric loading. The FRP confinement strengthened the cylinders by about 30% based on the average strengths of the 300 mm specimens. This agrees well with available design models for FRP confined concrete [5].

Figures 2 through 5 show vertical hoop strain profiles recorded during the last 25 seconds prior to failure for each test, along with post-failure photographs for all FRP confined cylinders tested in the current study. Included on the strain profiles are markers indicating the average axial stress at the instant that each strain profile was recorded. Black profiles represent the last hoop strains recorded before failure, and it should be noted that these may precede failure by up to 5 seconds. Hoop strain profiles for the unconfined concrete are not particularly interesting in the current context and are therefore not shown. Note that a hardware failure caused loss of image data for the bottom half of Cylinder W600-3.

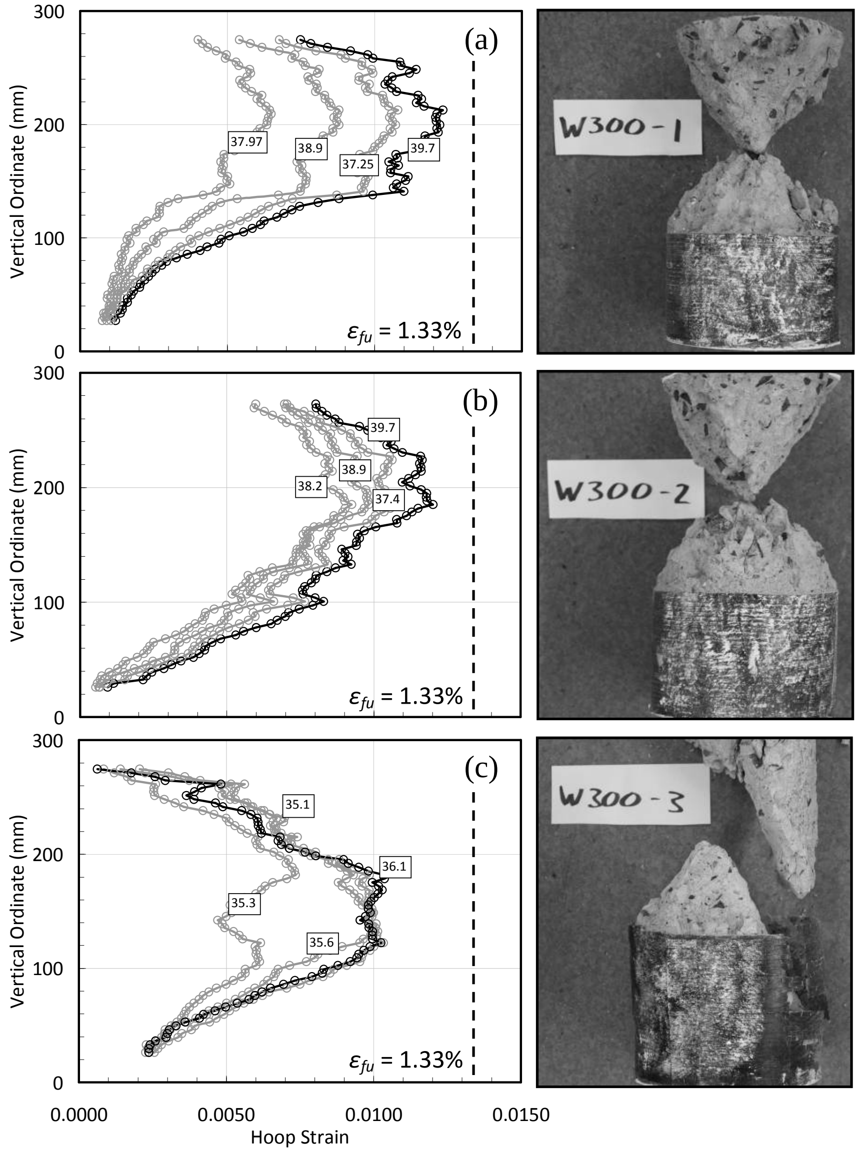

Figure 2. Vertical hoop strain profiles recorded during the 25 seconds prior to failure and post-failure photographs for FRP wrapped cylinders (a) W300-1, (b) W300-2, and (c) W300-3

Several features of Figures 2 through 5 are noteworthy:

- Considerable hoop strain variation and volatility was present in all tests. Both the shape of the hoop strain profiles and the degree of volatility appear to be random phenomena, such that it seems unlikely that generalizations can be made with respect to these issues.
- The evolution of hoop strain profiles occurs rapidly at loads near ultimate (recall that each of the strain profiles shown are five seconds apart), although 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 and Karam [7] hypothesis of shear failure planes mentioned above.
- For the 2:1 cylinders (W300s) hoop strains are generally 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 specimen. However, even within the middle 150 mm where frictional confinement is typically assumed to be absent, the hoop strain varies by up to 70% of the coupon failure strain.
- For 4:1 and 6:1 cylinders (W600s and W900s) the hoop strain variation outside the top and bottom 75 mm appears to be almost completely random, and no generalizations are possible. For the W600s up to 75% variability in hoop strain is observed within the middle 450 mm, and for the W900s this value is also about 75% within the middle 750 mm.
- As observed in previous tests on 2:1 FRP confined cylinders [1], the average manufacturer-specified coupon failure strains for the FRP sheet (ε_{fu} = 1.33%) are almost achieved in most cases (or exceeded in one case), albeit only locally. It should be noted that previous research [1] has shown that hoop strains also vary radially (by up to 50% of the average coupon failure strain) as well as vertically, so measuring hoop strains along a single vertical line provides no guarantee that the maximum hoop strain is observed.
- Visual comparison of the hoop strain profiles with images of the respective cylinders taken after failure shows a clear correlation between locations of maximum observed hoop strain and locations of failure initiation. The correlation is better in some cases than others (for Columns W600-2 and W900-1 for instance) but it is present in all cases.
- In cases where two cameras were used (i.e. for the W600s and W900s), the hoop strains from each camera agree well at the joint between the two images, thus providing additional confidence in the optical hoop strain measurement technique.

STATISICAL VARIABILITY POTENTIAL CONSEQUENCES

Given that is has now been convincingly proven that considerable hoop strain (and axial strain) variability exists in FRP confined concrete cylinders, both longitudinally and radially, an obvious next step is to determine the consequences of this for available empirical confinement models which have been calibrated (and validated) on the basis of incomplete, localized hoop (and axial) strain measurements. A first step in this direction can be taken by providing a quantified statistical description of the observed hoop strain variability; one such quantification based on the data presented in the current paper has been provided in Figure 6 and Table 2.

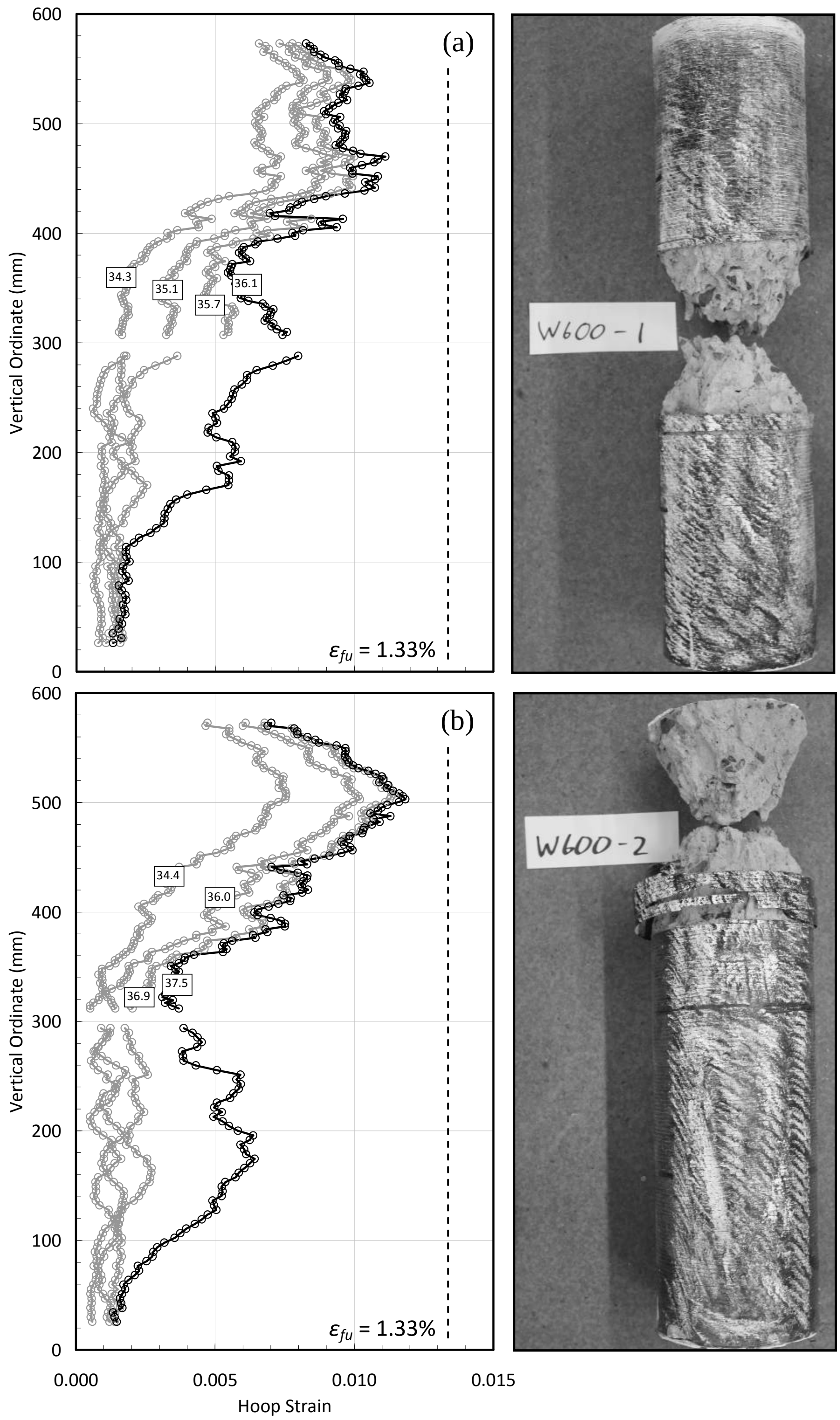

Figure 3. Vertical hoop strain profiles recorded during the 25 seconds prior to failure and post-failure photographs for FRP wrapped cylinders (a) W600-1 and (b) W600-2

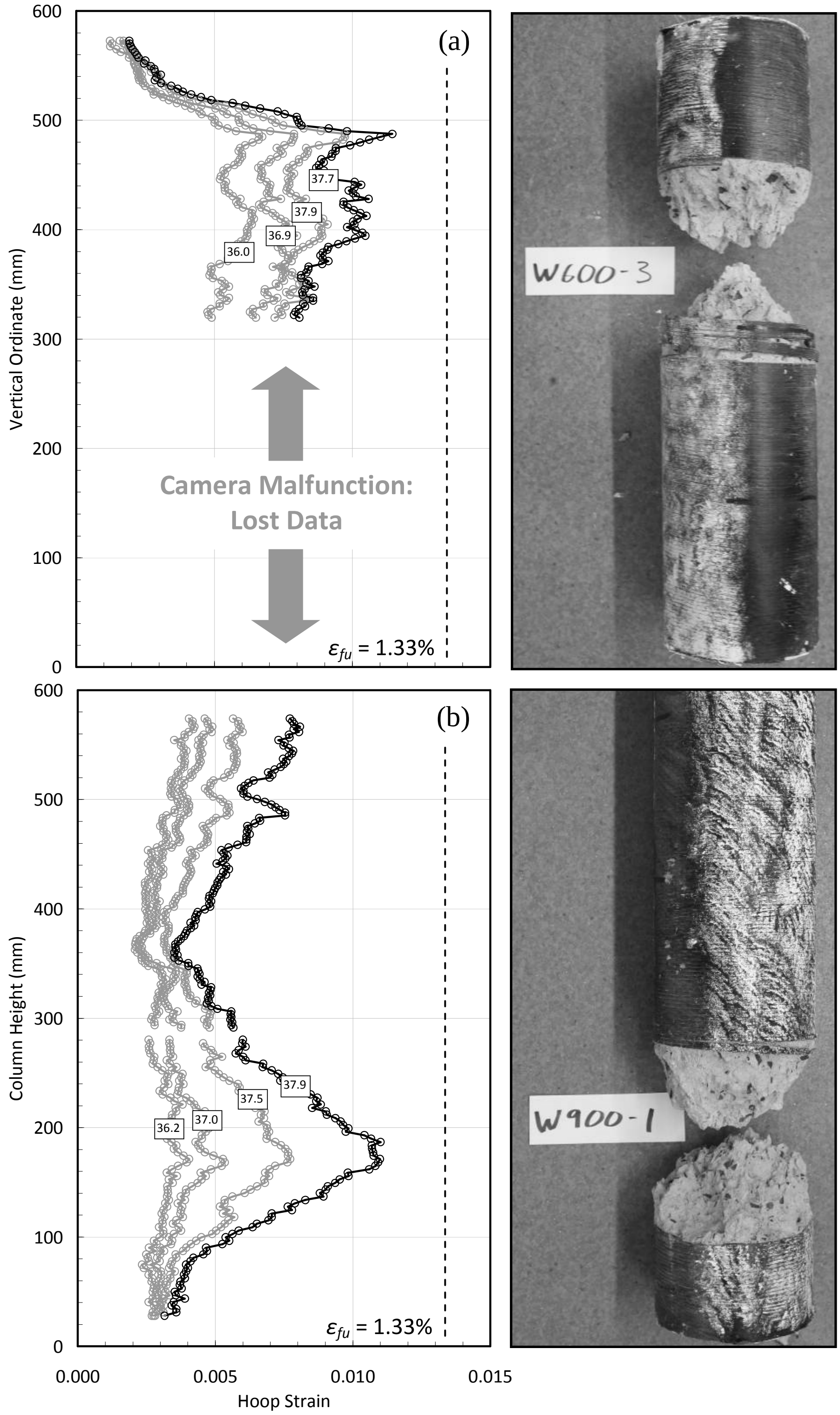

Figure 4. Vertical hoop strain profiles recorded during the 25 seconds prior to failure and post-failure photographs for FRP wrapped cylinders (a) W600-3 and (b) W900-1

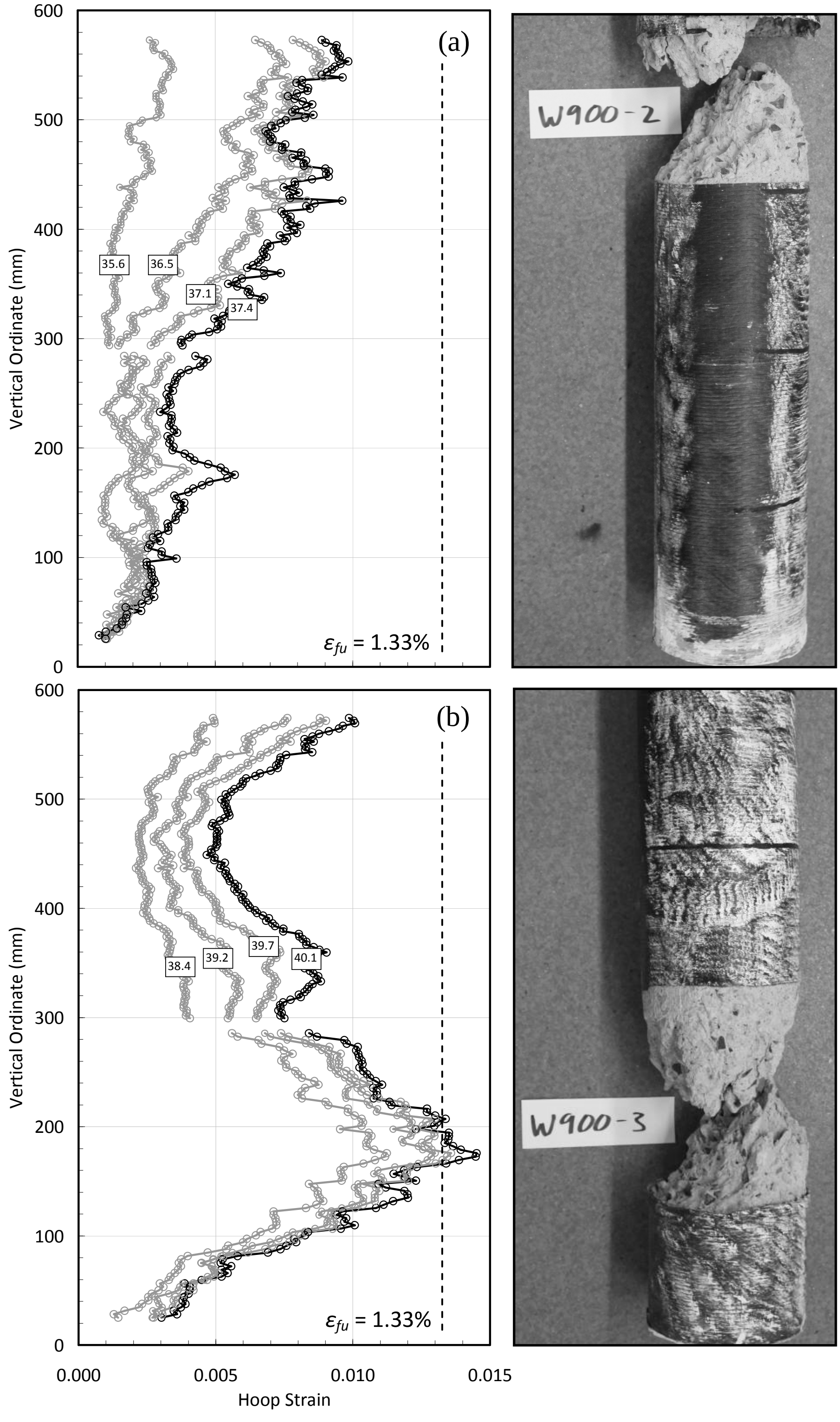

Figure 5. Vertical hoop strain profiles recorded during the 25 seconds prior to failure and post-failure photographs for FRP wrapped cylinders (a) W900-2 and (b) W900-3

Figure 6 shows a statistical summary of hoop strain efficiencies recorded for each individual FRP confined cylinder (only strains recorded outside the top and bottom 75 mm of the cylinders have been included). Table 2 provides a numerical summary of these data which may be helpful to others in performing reliability studies on empirical models for FRP confined concrete. These data represent by far the most detailed statistical descriptions of hoop strain variability ever presented. For the W300 specimens each population represents about 175 individual readings (≈ 525 in total), whereas the W600 and W900 populations contain about 200 individual readings for each cylinder (≈ 600 in total).

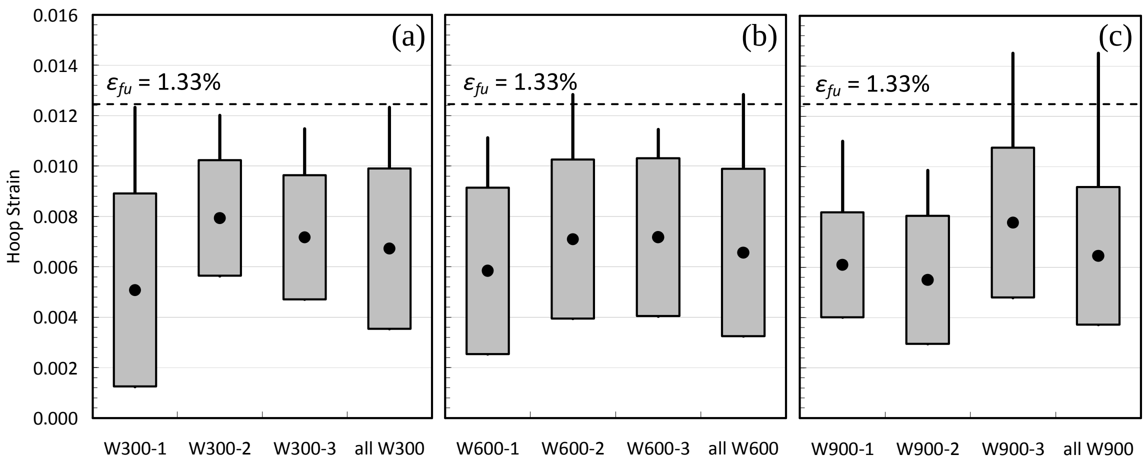

Figure 6. Statistical summary plots for observed hoop strains at failure for FRP wrapped cylinders (mean, mean plus/minus one standard deviation, and maximum value)

Table 2. Statistical summary for observed hoop strains at failure for FRP wrapped cylinders

ID	Specimen #	Mean value (%)	Std. dev. (%)	Max. value (%)	Mean strain efficiency[1]	Std. dev. of strain efficiency[1]	Max. strain efficiency[1]
W300	1	0.51	0.38	1.23	0.38	0.29	0.92
	2	0.79	0.41	1.20	0.59	0.31	0.90
	3	0.72	0.24	1.15	0.54	0.18	0.86
	All 300	0.67	0.32	1.23	0.50	0.24	0.92
W600	1	0.58	0.33	1.11	0.44	0.25	0.83
	2	0.71	0.32	1.28	0.53	0.24	0.96
	3	0.72	0.31	1.15	0.54	0.23	0.86
	All 600	0.66	0.32	1.28	0.50	0.24	0.96
W900	1	0.61	0.20	0.98	0.46	0.15	0.74
	2	0.55	0.25	1.10	0.41	0.19	0.83
	3	0.78	0.30	1.45	0.59	0.23	1.09
	All 900	0.65	0.27	1.45	0.49	0.20	1.09
All		0.66	0.30	1.45	0.50	0.23	1.09

[1] Based on supplier's specified average test value for tensile coupon failure strain (www.sikaconstruction.com)

Figure 6 shows that the distributions of hoop strains are reasonably similar from one cylinder to the next, and also between cylinders of different aspect ratios. The mean hoop strain varies between 0.51% and 0.78% (η = 0.38 and η = 0.59) for individual specimens, but is almost uniformly about 0.66 for each cylinder length group (η = 0.50). This agrees exactly with the value of η = 0.5 recommended by Jiang and Teng for carbon FRP wraps [4]. This makes sense given that even isolated strain gauges (as used by Jiang and Teng) on multiple columns should eventually yield the same statistical population of hoop strain data as those given above. On this preliminary basis it 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 reasonably consistent, with values ranging between 0.18 and 0.31. These data can be used to develop empirical FRP confinement models with a prescribed level of statistical confidence, and such an analysis is currently underway by the authors.

CONCLUSIONS

The data presented in this paper have shown that considerable hoop strain variability and volatility exist in FRP confined concrete at loads approaching failure. In combination with prior work by others [7], these data suggest that the observed strain localizations are caused at least in part by localization of shear failure planes within the concrete followed by movement of solid concrete wedges along those failure planes. 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 the coupon failure strain, albeit only locally. A statistical summary of the observed hoop strains has indicated that the hoop strain variability is similar for cylinders of aspect ratios 2:1, 4:1, and 6:1, so that empirical confinement models derived on the basis of localized strain measurement from 2:1 cylinders need not be called into question. Taking all hoop strain measurements from all cylinders presented herein (a total of 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 [4] for carbon FRP confined concrete and can be used in future reliability studies on empirical FRP confinement models.

ACKNOWLEDGEMENTS

The research presented herein was supported financially by The School of Engineering at The University of Edinburgh, Scotland.

REFERENCES

1. Bisby, L. A. and Take, W. A., Strain Localizations in FRP Confined Concrete: New Insights. *Structures and Buildings*, in press (2009).
2. Harries, K. A. and Carey, S. A., Shape and ‘‘gap’’ effects on the behavior of variably confined concrete. Cement and Concrete Research, **33**(6), 881-890 (2003).
3. Lam, L. and Teng, J. G., Ultimate condition of fiber reinforced polymer-confined concrete. *Journal of Composites for Construction*, **8**(6), 539-548 (2004).
4. Jiang, T. and Teng, J. G., Strengthening of short circular RC columns with FRP jackets: a design proposal. *3rd International Conference on FRP Composites in Civil Engineering*, Miami, USA, 2006.
5. ACI, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, *440.2R-08*. American Concrete Institute, USA, (2008).
6. White, D. J., Take, W. A. and Bolton, M. D., Soil Deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique*, **53**(7), 619-631 (2003).
7. Tabbara, M. and Karam, G., Numerical investigation of failure localization and stress concentrations in FRP wrapped concrete cylinders. *5th International Conference on Advanced Composite Materials in Bridges and Structures*, Winnipeg, Canada, 2008.
8. Bisby, L. A., Take, W. A. and Caspary, A., Quantifying strain variation in FRP confined concrete using digital image analysis. *1st Asia-Pacific Conference on FRP in Structures*, Hong Kong, 2007.