Asia-Pacific Conference on FRP in Structures (APFIS 2007)
S.T. Smith (ed)

QUANTIFYING STRAIN VARIATION IN FRP CONFINED CONCRETE USING DIGITAL IMAGE CORRELATION: PROOF-OF-CONCEPT AND INITIAL RESULTS

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ABSTRACT

Circumferential (hoop) wrapping with externally bonded (EB) fibre reinforced polymer (FRP) sheets is now a method of choice for strengthening and axial deformability enhancement of reinforced concrete columns. The mechanics of FRP confinement and the development of predictive models for axial strength and strain enhancement have received significant research attention over the past two decades, such that design codes and guidelines for these types of members are now available. However, one fundamentally important factor that remains incompletely understood is the *Strain Efficiency* of the FRP wraps – the ratio of the tensile hoop strain in EB FRP wraps at failure (member failure is typically initiated by hoop failure of the FRP wraps in tension) to the failure strain observed in tensile tests on FRP coupons. Research on these types of members using conventional instrumentation (i.e., discrete foil strain gauges) has shown that the measured hoop strain at failure may lie anywhere in the range of 50% to 110% of coupon test values, although typically it is considerably less than 100%. These limited data provide little insight, however, into the variation of hoop strain over the surface of FRP wraps, the factors influencing *Strain Efficiency*, or even whether the true failure strains are accurately captured by localized conventional strain instrumentation. This paper presents the initial results of a study aimed at quantifying the axial and hoop strain variation over the surface of FRP confined concrete cylinders using a novel digital image correlation technique. Included are a proof of concept for the new technique, initial results, and comparisons with data obtained using conventional instrumentation. Implications for future testing and a more complete understanding of FRP confined concrete are discussed.

KEYWORDS

FRP, reinforced concrete columns, strengthening, confinement, strain efficiency, image correlation.

INTRODUCTION & BACKGROUND

Confinement of circular reinforced concrete (RC) columns with circumferential (hoop) fibre reinforced polymer (FRP) wraps is widely recognized as an efficient and effective means of increasing both their axial compressive strength and their axial and flexural deformability (De Lorenzis and Tepfers 2003, ACI 2004, Lam and Teng 2004, Bisby *et al.* 2005, Jiang and Teng 2006). Various models now exist which can reasonably accurately predict the effects of FRP confinement on the axial compressive strength and stress-strain behaviour of unreinforced short concrete cylinders (Jiang and Teng 2006). However, even the most accurate existing FRP confinement models are relatively poor at predicting the ultimate axial strain of FRP confined concrete, ε_{ccu} (De Lorenzis and Tepfers 2003, Bisby *et al.* 2005). This poor predictive ability with respect to axial strain at failure is partly a consequence of the large variability observed in measured hoop strains in FRP wraps at failure. Because member failure is typically initiated by tensile failure of the FRP wraps in the hoop direction, poor predictions of hoop strain at failure result in poor predictions of axial strain at failure. The ratio of hoop strain in the FRP wraps at failure to the failure strain observed in direct tensile tests on FRP coupons, referred to hereafter as the *Strain Efficiency*, η, may be anywhere in the range of 0.58 to 0.91 (Lam and Teng 2004).

Based on the large volume of available test data on these types of members, Jiang and Teng (2006) have recently suggested η = 0.5 for carbon FRP wraps and η = 0.7 for glass FRP wraps for design of FRP confined concrete (in the absence of test data on a specific FRP system), and Committee 440 of the American Concrete Institute (ACI 2007) will soon suggest η = 0.55 for any circular FRP wrapped column. However, this (conservative) approach provides little insight into the factors influencing the variation of hoop strain at failure (i.e., the *Strain Efficiency*). Furthermore, it remains unclear from the available data whether the true failure strains in FRP wraps were accurately captured by localized foil strain gauges (used almost exclusively in the available literature).

This paper presents the initial results of a study aimed at directly observing and quantifying both the axial and hoop strain variation over the surface of FRP confined concrete cylinders, with a view to developing a more rational understanding of the factors involved in initiating failure of these types of members. These goals are accomplished using a digital image correlation code, *geoPIV*, designed specifically for measuring solid deformations by White *et al.* 2003. The current paper includes a proof-of-concept for the novel measurement technique when used in structural testing, initial results from tests on carbon FRP confined concrete cylinders, and comparisons against test data obtained using conventional foil strain gauges.

TEST SETUP & EXPERIMENTAL PROCEDURES

Geometry and Loading

Table 1 provides details of the testing program. The goal of this initial program was to enable direct comparison between axial and hoop strains measured using conventional foil strain gauges and those obtained using digital image correlation. The test program consisted of concentric, monotonic, uniaxial compression tests on three unwrapped and three FRP confined standard (150 mm diameter × 300 mm tall) unreinforced normal strength concrete cylinders. The FRP confined cylinders were wrapped in the hoop direction with a single layer of a commercially available hand lay-up CFRP strengthening system. A hoop overlap of 100 mm was provided in all cases, as recommended by the FRP system supplier.

Table 1. Details and results of preliminary testing program

Name	FRP[a]	Axial strength (MPa)	Strengthening ratio[b]	Ult. axial strain (foil) (%)[c]	Ult. axial strain (photo) (%)[c]	Ult. hoop strain (foil) (%)[d]	Ult. hoop strain (photo) (%)[c]	*Strain Efficiency* (foil)[e]	*Strain Efficiency* (photo)[e]
0-1	None	33.3	0.96	--	0.36	--	-0.28	--	--
0-2	None	35.5	1.02	--	0.30	--	-0.15	--	--
0-3	None	34.4	0.99	--	0.33	--	-0.25	--	--
1-1	1-ply	44.1	1.27	0.82	0.80	-0.98	-0.93	0.76	0.72
1-2	1-ply	44.1	1.27	0.93	0.87	-1.04	-1.10	0.81	0.85
1-3	1-ply	43.0	1.24	0.91	0.90	-0.95	-1.21	0.74	0.94

[a] All FRP wrapped cylinders were strengthened with the SikaWrap Hex 230C carbon/epoxy FRP system
[b] Ratio of specimen strength to average unwrapped compressive strength
[c] Maximum value as measured using digital image correlation
[d] Maximum value as measured using foil strain gauges
[e] Based on FRP coupon properties determined by the Authors ($\varepsilon_{fu,ave}$ = 1.29% and $\sigma_{\varepsilon fu}$ = ± 0.10%) in accordance with ACI 440.3R-04 (ACI 2004)

Conventional Instrumentation

Conventional instrumentation was used to measure and record axial and hoop strains, as well as the applied load on the cylinders during testing. Each FRP confined cylinder was instrumented with six foil strain gauges – three in the hoop direction and three in the axial direction as shown in Fig. 1(a). These were bonded to the exterior of the FRP wraps along a vertical line on the side of the cylinder directly opposite the centreline of the overlapping zone (the effect of the overlapping zone on η will be studied in future tests). The strain gauges used were 120 Ω, 10 mm gauge length, adhesively-bonded uniaxial foil strain gauges by Kyowa Inc., Japan. The unwrapped cylinders were not provided with conventional strain instrumentation.

Strain Measurement by Digital Image Correlation

Digital images of the cylinder (with the field of view shown in Fig. 1) were taken every five seconds during testing using an 8 Megapixel resolution Canon Digital Rebel camera as each cylinder was loaded until failure. The image processing technique of normalised cross-correlation (as implemented in the *geoPIV* code) was then used to define particular regions of interest in the first image and then track each of these regions in each subsequent image. As shown in Figs. 1(b), the regions of interest were chosen as square patches of 64x64 pixels along the centreline of the specimen. In order for these patches to be tracked through subsequent images using normalised cross-correlation, each patch was required to contain sufficient image texture to be visually unique. In other words, the patches were required to contain sufficient variation in the intensity and distribution of pixel colours to be unmistakable in subsequent images. As the carbon FRP by itself was pure black, a white paint texturizing effect was applied to the surface of each of the cylinders to impart a random, high-contrast, image texture. The resulting texture of the two enlarged patches shown in Fig. 1(b) is therefore clearly unique.

Validation experiments using the *geoPIV* code reported by White et al. (2003) have demonstrated that the precision of this measurement technique is typically better than $1/10^{th}$ of a pixel. The choice of the vertical distribution of tracked patches in Fig. 1(b) has been made to enable the direct measurement of the axial strain profile between each of these deformation nodes. It should be noted that the gauge length of these "virtual strain" gauges was approximately 27mm; almost three times larger than the 10mm gauge length of the foil gauges.

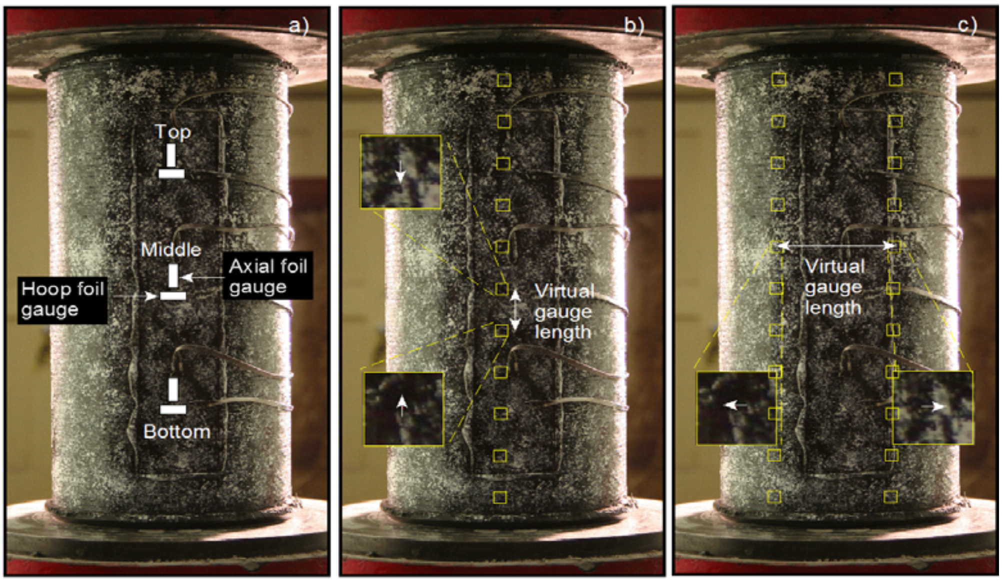

Figure 1. Typical FRP confined specimen showing (a) conventional strain instrumentation, (b) virtual axial strain patches, and (c) virtual hoop strain patches

The calculation of hoop strain using the optical technique is slightly more complex. As discussed in detail by Take and Kemp (2006), horizontally placed patches (as in Fig. 1(c)) can be used to track radial strain in cylindrical samples under concentric uniaxial load. By making the assumption that radial strain is radially symmetric around the sample, the radial strain can be taken as equivalent to the hoop strain. In this case the gauge length of the virtual strain gauges was approximately 73mm, more than seven times larger than the 10mm gauge length of the conventional foil gauges.

RESULTS

Validation of the Technique

Figs. 2(a) to 2(c) show typical results of validation studies for the specific case of FRP confined Specimen 1-1 by presenting a comparison of axial and hoop strains measured at the (a) top, (b) middle, and (c) bottom of the cylinder (refer to Fig. 1(a) for strain gauge locations) using both foil and virtual strain gauges. In general, the agreement between conventional and virtual strain gauges is excellent at all locations, and the virtual strain gauges appear to accurately capture both trends in and magnitudes of strain over the full range of loading. The reader will note that the hoop strains appear to be considerably larger at the middle of the specimen, according to both the conventional and virtual strain gauges (discussed further below). Furthermore, in most cases the maximum strains (both axial and hoop) were not precisely captured by the virtual strain gauges. This is due to the fact that photos were taken at five second intervals during testing, so in some cases the cylinders failed almost five seconds from the most recent photo. Conventional strain readings were recorded at 10 Hz, so that the localized failure strains were more accurately captured by the foil gauges in same cases (at the end of the test the strain rates are high, causing large differences in measured strain values over the five second interval between photos). As shown in Fig. 2(d), the correlation between both hoop and axial strains at the elevation of the conventional foil gauges is very good, with a coefficient of determination, r^2, of 0.98 for Specimen 1-1. These data suggest that while the technique may require refinement and further validation (currently underway), the errors associated with the assumption of a radially symmetric strain field required for the hoop strain calculation are sufficiently small for this technique to be used in quantifying strain variation over the height of an FRP confined concrete cylinder.

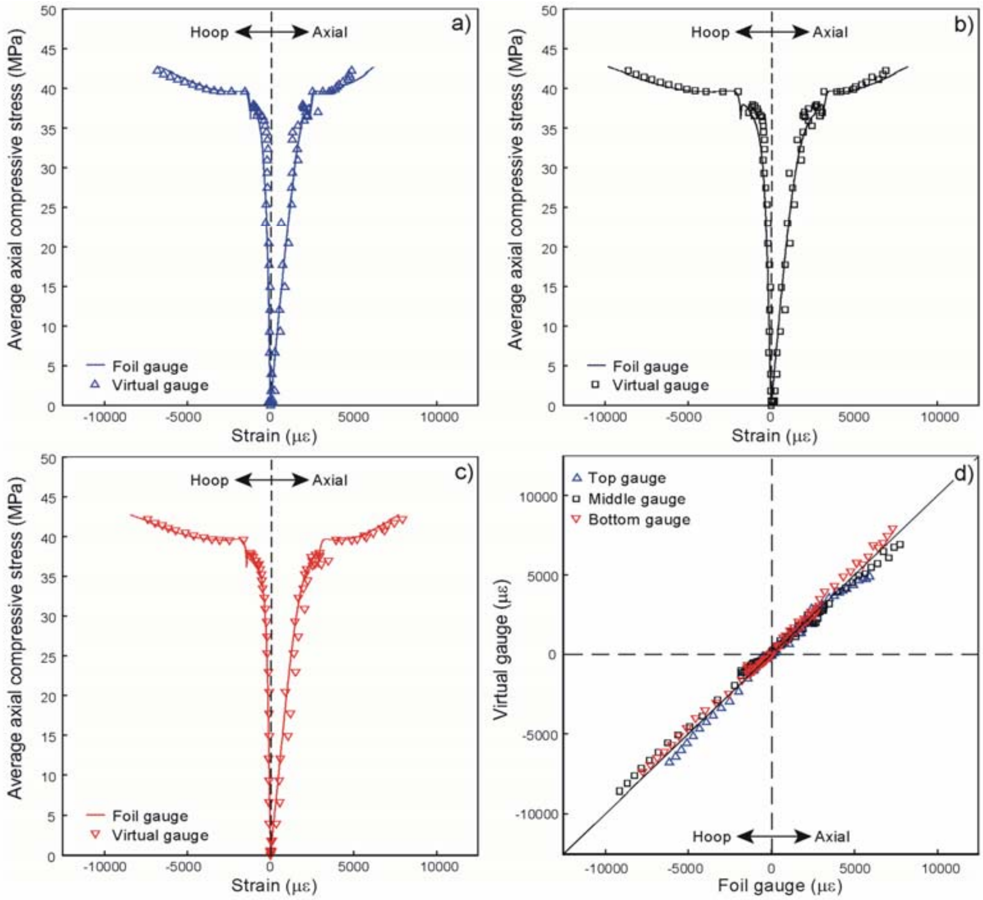

Figure 2. Comparison of foil and virtual gauges located at the (a) top, (b) middle, (c) bottom of Specimen 1-1, and (d) their resulting degree of agreement

Strain Variation in FRP Confined Specimens

Assuming that the optical technique to measure virtual strains provides accurate strain data (as is suggested by Fig. 2 and the preceding discussion), it is instructive to use the technique to study the variation in both hoop and axial strain over the height of FRP confined concrete cylinders; this has been done in Figs. 3 and 4, respectively, for FRP confined Specimens (a) 1-1, (b) 1-2, and (c) 1-3.

Figs. 3(a) through 3(c) show the variation in virtual hoop strain with vertical location for all three wrapped cylinders at both 35 MPa (the average compressive strength of the unconfined concrete cylinders) and at ultimate load (or as close to ultimate load as possible given the five second interval between photos). Also included in Fig. 3 are the strains measured by the foil strain gauges at the same load levels. Hoop strains measured by both foil and virtual strain gauges are small (<1000 με) at an axial stress of 35 MPa, which is as expected since it is well known that lateral dilation is minimal until the unconfined peak strength is reached but accelerates rapidly thereafter. It is clear from these plots that there is good agreement between the conventional and virtual strain gauges (both at 35 MPa and at ultimate). Most interestingly, there is significant variation (>10000 με in some cases) in virtual strain over the height of the cylinders. To put this observation into perspective, this means that, depending on the location of a conventional foil strain gauge installed to measure hoop strain on an FRP confined concrete cylinder, it is entirely possible that the maximum recorded hoop strain at failure could result in apparent η values varying well within the range exhibited by test data available in the literature. It is important to note, in the case of the current tests, that much of the strain variation observed in the top and bottom regions (about 75 mm from the top and bottom) of the cylinders is due to an additional artificial confinement arising from frictional lateral restraint by the loading platens. However, even within the 150 mm long central region of the cylinders, the virtual hoop strain varies by up to 4500 με at failure (about 35% of the coupon failure strain).

Fig. 4 provides similar plots showing the variation in both conventional and virtual axial strain with vertical location. These plots show similar trends as for Fig. 3, with axial strain variation also seen to vary by several thousand microstrain, although in this case the variation trends are less apparent (in any case the trends are considerably less important in terms of understanding and modelling FRP confinement of concrete).

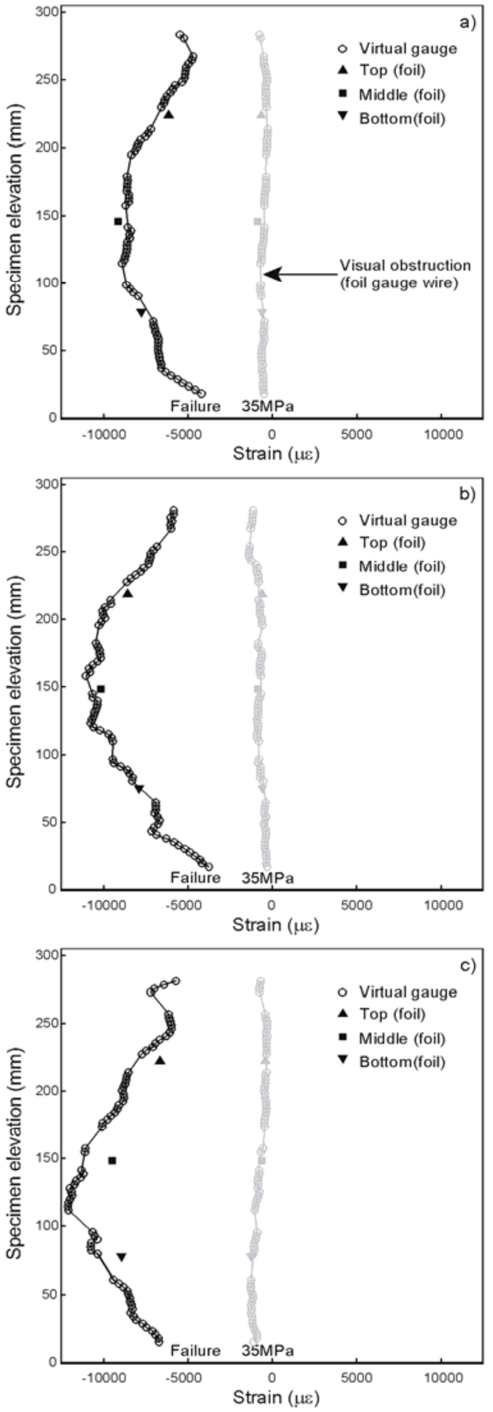

Figure 3. Distribution of hoop strain for (a) Specimen 1-1, (b) Specimen 1-2, and (c) Specimen 1-3

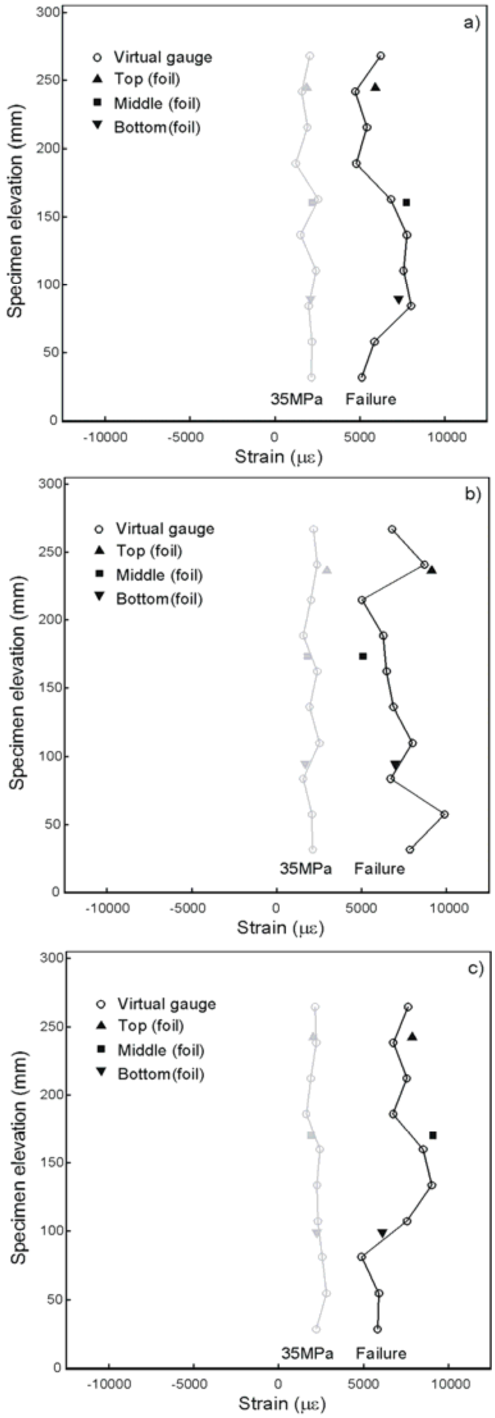

Figure 4. Distribution of axial strain for (a) Specimen 1-1, (b) Specimen 1-2, and (c) Specimen 1-3

DISCUSSION

Table 1 and Figs. 2, 3, and 4 provide selected data recorded using conventional and virtual instrumentation during testing. Table 1 indicates that the maximum axial and hoop strains recorded by any of the three foil strain gauges were reasonably consistent, with an average *Strain Efficiency,* η of 0.77 for the confined concrete (based on the maximum foil gauge hoop strain readings at failure for each specimen). However, Figs. 3 and 4 show that there was considerable variability in the conventional strain gauge data within the middle 150 mm of the FRP wrapped cylinders (i.e., away from frictional confinement effects arising near the testing platens). For instance, hoop and axial strains measured at failure by conventional foil gauges varied by up to about 3000 με (25% of $\varepsilon_{fu, ave}$) and 4000 με (45% of $\varepsilon_{ccu, \text{ave}}$), respectively. The result of this variation is that the conventionally-measured η (i.e. obtained from each individual conventional foil hoop gauge on each of the three specimens at failure) varied between a minimum of 0.52 and a maximum of 0.81, with an average of 0.67 and a standard deviation 0.10. These data clearly show that measurements obtained using isolated foil strain gauges cannot be relied on to provide a complete picture of hoop strain in FRP wraps at failure. It is thus not surprising that η values suggested in the literature vary in the range of 0.5 to 0.9 (Jiang and Teng 2006, ACI 2007), nor is it surprising that no empirically derived models exist which can predict FRP confined ultimate axial strain in concrete with a mean error of less than about 50% (De Lorenzis and Tepfers 2003, Bisby *et al.* 2005).

Again, the above points highlight the need for a better understanding of the various factors influencing the hoop strain in the FRP wraps at failure. The reader is reminded that virtually all available models for FRP confinement have been derived empirically using hoop strain data measured by isolated foil strain gauges (or not measured at all). The experimental methodology suggested herein provides a means by which the true behaviour of these types of members can be rationally understood and subsequently accurately predicted.

CONCLUSIONS AND FUTURE WORK

Based on the testing described in this paper, the following primary conclusions can be drawn:

- It is possible to accurately measure both hoop and axial strains (and strain variation) in FRP confined concrete cylinders using digital image correlation implemented using *geoPIV*. There is good correlation between strains measured using the new technique and those measured with conventional foil strain gauges.
- Optical (virtual) strain measurements can provide badly needed information regarding the axial and hoop strain variation over the height of an FRP confined concrete member, and initial data presented herein show that significant strain variation (greater than 2500 με or up to 35% of the coupon failure strain) is observed at ultimate conditions (consistent with the hoop *Strain Efficiencies* quoted in the available literature).
- Most available confinement models have been developed empirically on the basis of (apparently) incomplete hoop strain data, and additional research in this area is thus badly needed to formulate a rational understanding of the true mechanics of confinement and the factors influencing hoop *Strain Efficiency* and subsequent model predictions.
- Future testing should be performed: (1) using multiple cameras to validate the assumption of uniform hoop strain; (2) using higher frame rates to capture strains at the instant of failure; and (3) to refine the technique and study additional factors such as the length of the hoop overlap, concrete strength, bond (or lack thereof) between the concrete and the FRP, concrete mix characteristics (i.e. aggregate type and gradation), the presence if internal steel reinforcement, FRP type, scale effects, etc. Much of this testing is currently underway by the Authors.

ACKNOWLEDGMENTS

The Authors would like to acknowledge the financial support of Queen's University, the Natural Sciences and Engineering Research Council of Canada, and the Intelligent Sensing for Innovative Structures Network (ISIS Canada) of the Networks of Centres of Excellence Program of the Government of Canada. The Authors would also like to thank Mr. Jeff Kemp for his assistance in performing the tests described herein.

REFERENCES

ACI (2007). *ACI 440.2R-XX: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (DRAFT)*, American Concrete Institute, Farmington Hills, USA.

ACI (2004). *ACI 440.3R-04: Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, USA.

Bisby, L.A., Dent, A.J.S and Green, M.F. (2005). "Comparison of confinement models for fiber-reinforced-polymer-wrapped concrete", *ACI Structural Journal*, 102(1), 62-72.

De Lorenzis, L. and Tepfers, R. (2003). "Comparative study of models on confinement of concrete cylinders with fiber-reinforced polymer composites", *Journal of Composites for Construction*, ASCE, 7(3), 219-237.

Jiang, T. and Teng, J.G. (2006). "Strengthening of short circular RC columns with FRP jackets: a design proposal", *Proceedings of the Third International Conference on FRP Composites in Civil Engineering*, A. Mirmiran and A. Nanni, eds., Miami, USA, December, 187-192.

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

Take, W.A., and Kemp, J. (2006). Application of digital image-based deformation measurements to geotechnical testing. 59th Canadian Geotechnical Conference, Vancouver, 313-318.

White, D.J., Take, W.A. and Bolton, M.D. (2003). "Soil Deformation measurement using particle image velocimetry (PIV) and photogrammetry", *Géotechnique*, 53(7), 619-631.