Lim, Jian Chin; Ozbakkaloglu, Togay
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Factors influencing hoop rupture strains of FRP-confined concrete

Jian Chin Lim[1, a] and Togay Ozbakkaloglu[1,b]

[1]School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, Australia

[a]jlim@civeng.adelaide.edu.au, [b]togay.ozbakkaloglu@adelaide.edu.au

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Abstract. It is now well understood that the hoop rupture strain of fiber reinforced polymer (FRP) jackets confining concrete is often lower than the ultimate tensile strain of the component fibers. A number of reasons for the lower hoop rupture strains in FRP have been identified; however, the relationships between the material properties of FRP-confined concrete and hoop ruptures strains are yet to be established. This paper presents the results of an experimental study into the factors influencing the hoop strain efficiency of FRP jackets. 24 FRP-confined concrete specimens were tested under axial compression. The results indicate that the hoop rupture strains of FRP jackets decrease with either an increase in the strength of the unconfined concrete or the elastic modulus of the fiber material. These observations were verified by additional results from a large FRP-confined concrete test database assembled from the published literature.

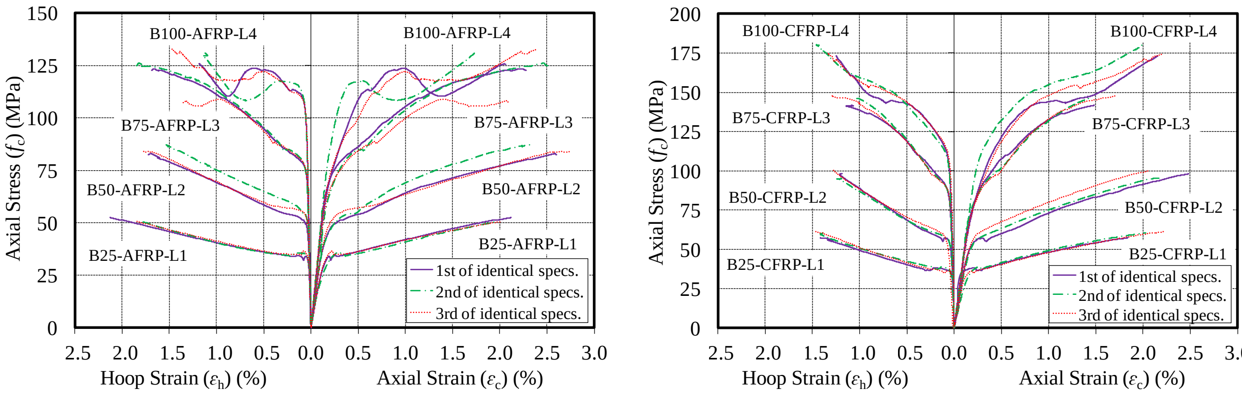
Introduction

The use of fiber reinforced polymer (FRP) composites as a confinement material for concrete has received a great deal of attention over the past two decades [1] and it has been demonstrated that FRP-confined concrete columns develop highly ductile behavior under simulated seismic loading [2-5]. The key requirement for the accurate prediction of the ultimate axial stress and strain of FRP-confined concrete is the accurate prediction of the hoop rupture strain developed by the confining FRP jacket. Research has shown that the ultimate material tensile strain of fibers is unachievable in the in-situ form of an FRP jacket, and the lower observed efficiency has led to the development of a range of strain reduction factors to establish the actual hoop rupture strain of the FRP jacket [6-9]. As was reported in Wu and Jiang [10], the strain reduction factors recommended in the past vary substantially from 0.274 to 1.133, indicating that additional studies are required for more accurate and reliable estimation of the strain reduction factor in FRP-confined concrete.

Factors reducing the efficiency of FRP jackets can be classified as either material dependent or material independent. A number of material independent factors contributing to lower efficiency in FRPs have been identified in previous studies [7, 9-15]. These factors include: (i) the differences in methods of measurement and test apparatus, and (ii) differences between FRP jackets and flat coupons caused by workmanship, geometric imperfections, residual strains, shrinkage incompatibility, non-uniform bond between concrete and FRP, curvature of the FRP jacket, multiaxial stress state in the FRP jacket. In addition to these, the strength of concrete and the elastic modulus of FRP material have recently been identified by the authors as two important material dependent factors [8, 12, 16-20]. However, additional targeted investigations are required to gain a clearer insight into the influence of these factors on the hoop rupture strains of FRP jackets. To this end, this paper reports on an experimental study that was designed specifically to closely examine the influence of the two aforementioned factors on the hoop strain efficiency of the FRP jackets.

Experimental Program

Twenty-four FRP-confined concrete specimens were manufactured and tested under monotonic axial compression. All of the specimens were 152 mm in diameter and 305 mm in height. To fabricate the specimens, FRP tubes were first manufactured from either aramid or carbon fiber sheets using manual wet-layup techniques, which involved wrapping epoxy resin impregnated fiber sheets around polystyrene forms in the hoop direction. The tubes were fabricated with 1 to 4 layers of fiber sheets, using a single continuous sheet which terminated with an overlap region of 150 mm. The top and bottom ends of the tubes were strengthened with one additional layer of 50 mm wide fiber sheets to constrain the location of FRP rupture to the middle section of the tubes. The pre-fabricated FRP tubes were filled with four different concrete mixtures having target strengths of 25, 50, 75, and 100 MPa. The specimens were tested under axial compression using a 5000-kN capacity universal testing machine. Prior to testing, the specimens were capped at both ends to ensure uniform distribution of the applied pressure, and the load was applied directly to the concrete core through the use of precision-cut high-strength steel discs. Axial deformations of the specimens were measured with four linear variable displacement transducers (LVDTs), which were mounted at the corners between the loading and supporting steel plates of the compression test machine. Figs. 1(a) and 1(b) show the axial stress-axial strain and axial stress-hoop strain curves of the AFRP and CFRP-confined specimens, respectively. All of the specimens failed due to the rupture of the FRP jackets at mid-height.



(a) (b)

Figure 1. Stress-strain curves of: (a) AFRP-confined specimens, and (b) CFRP-confined specimens

The properties of the unidirectional fiber sheets used for tube fabrications are provided in Table 1. Flat coupon tests were used to determine the tensile properties of the FRP composite jackets, where the loading was applied in accordance with ASTM D 3039 [21]. For each type of fiber, three 1 mm thick and 25 mm wide flat coupon specimens were made in a high-precision mould with three layers of fiber sheets using the wet layup technique. The coupons had a 138 mm clear span with each end bonded with two 0.5 mm by 85 mm long aluminum tabs for stress transfer during tensile tests. Each coupon was instrumented with a minimum of two 20 mm strain gauges for the measurement of the longitudinal strains and was tested using a screw-driven tensile test machine with a peak capacity of 200 kN. The test results from the flat coupon specimens, calculated based on nominal fiber thicknesses and actual coupon widths, are reported in Table 1, together with the manufacturer supplied properties of fibers. The average rupture strain obtained from the tensile coupon tests was slightly lower than that reported by the manufacturer.

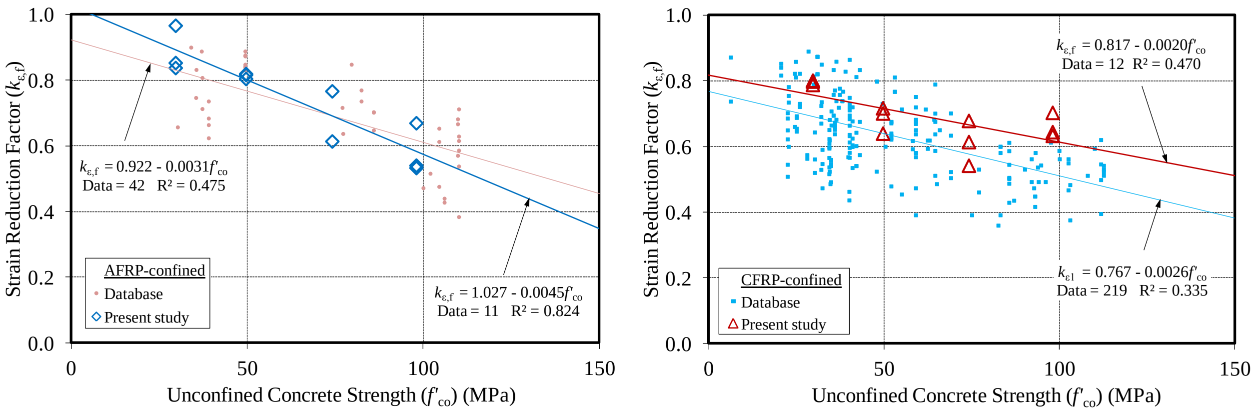
Table 1. Material properties of fibers, FRP composites and epoxy resin

Type	Nominal fiber thickness t_f (mm/ply)	Fiber/FRP properties					
		Provided by manufacturers			Obtained from coupon tests		
		Ultimate tensile stress f_f (MPa)	Ultimate tensile strain ε_f (%)	Elastic modulus E_f (GPa)	Ultimate tensile stress f_{frp} (MPa)	Ultimate tensile strain ε_{frp} (%)	Elastic modulus E_{frp} (GPa)
Carbon	0.167	4370	1.90	230.0	4152	1.76	236.0
Aramid	0.200	2600	2.20	118.2	2390	1.86	128.5

Hoop strain reduction factors. It is now understood that the hoop rupture strain of the FRP jacket is often smaller than the ultimate material tensile strain and that it can be estimated from the material properties using a strain reduction factor ($k_{\varepsilon,f}$). In this study, the strain reduction factors ($k_{\varepsilon,f}$) are calculated as the ratio of the average hoop rupture strain ($\varepsilon_{h,rup}$) in the FRP jacket to the material ultimate tensile strain (ε_f) specified by the manufacturer:

$$k_{\varepsilon,f} = \frac{\varepsilon_{h,rup}}{\varepsilon_f} \qquad (1)$$

Influence of unconfined concrete strength. Fig. 2 shows the variation of hoop strain reduction factors ($k_{\varepsilon,f}$) of different type of fibers with the unconfined concrete strengths (f'_{co}). As is illustrated in the figure, the fiber strain reduction factor ($k_{\varepsilon,f}$) values decrease with an increase in unconfined concrete strength (f'_{co}). This accords with Ozbakkaloglu and Akin [17], who observed that an increase in the compressive strength of concrete adversely affected the hoop rupture strain of FRP jackets. Furthermore, Fig. 2 illustrates that the trends established based on the results of the present study are consistent with the trends observed in the database of FRP-confined concrete [8, 22]. The reduction in FRP rupture strain with an increase in concrete strength can be explained by the increase in concrete brittleness, which alters the concrete crack patterns from heterogenic microcracks in normal-strength concrete (NSC) to localized macrocracks in high-strength concrete (HSC) [23, 24]. The changed cracking pattern reduces the in-situ capacity of the FRP jackets by causing localized stress concentrations.



(a) (b)

Figure 2. Variation of hoop strain reduction factors ($k_{\varepsilon,f}$) with concrete strength (f'_{co}): (a) AFRP-confined specimens, and (b) CFRP-confined specimens

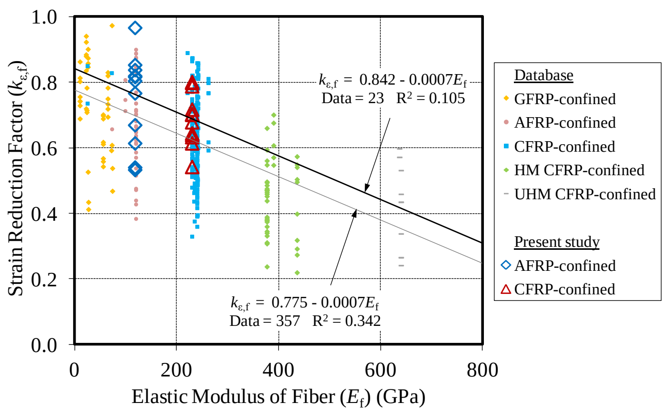


Figure 3. Variation of hoop strain reduction factors ($k_{\varepsilon,f}$) with elastic modulus of fibers (E_f)

Influence of type of FRP material. The observed dependence of the hoop rupture strain of the FRP jacket to the type of fiber materials was previously reported in Ozbakkaloglu and Akin [17] and Dai et al. [25]. To closely examine the material dependency of the hoop rupture strain of the FRP jacket, in the present study the relationship between the elastic modulus of the confining fibers (E_f) and the recorded hoop rupture strains ($\varepsilon_{h,rup}$) were investigated using the results of the present study and those from the aforementioned test databases. Fig. 3 shows the variation of hoop strain reduction factors ($k_{\varepsilon,f}$) with the elastic modulus of fibers (E_f). As evident from trendline of the figure, an increase in the elastic modulus of fibers (E_f) results in a decrease in the hoop strain reduction factor ($k_{\varepsilon,f}$). Consistent trends were found between the results of the present study and those from the test database [8, 22].

Strain Reduction Factor Predictions. Based on the analysis of a large database cataloguing 1063 test datasets, Eq. 2 was previously proposed in Lim and Ozbakkaloglu [8] to predict the strain reduction factor ($k_{\varepsilon,f}$) as a function of the unconfined concrete strengths (f'_{co}) and the elastic modulus of the fibers (E_f).

$$k_{\varepsilon,\mathrm{f}} = 0.9 - 2.3f'_{\mathrm{co}} \times 10^{-3} - 0.75E_{\mathrm{f}} \times 10^{-6} \quad (2)$$

where E_f is in MPa and $100{,}000\text{MPa} \leq E_f \leq 640{,}000\text{MPa}$.

Fig. 4 shows the comparison of the strain reduction factors ($k_{\varepsilon,f}$) predicted using Eq. 2 with the results of the present study. As evident from Fig. 4, Eq. 2 provides close and slightly conservative estimates of the experimentally obtained $k_{\varepsilon,f}$ values.

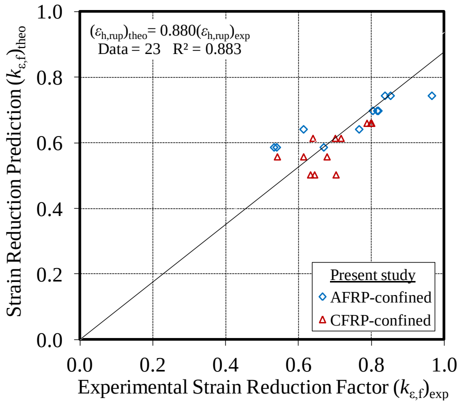


Figure 4. Comparison of predicted strain reduction factors ($k_{\varepsilon,f}$) with experimental results

Conclusions

This paper has presented the results of an experimental study on the factors influencing the hoop rupture strains in FRP-confined concrete. Based on the results and discussions presented in the paper the following conclusions can be drawn:

1. The average hoop rupture strains measured in the FRP-confined concrete, outside overlap regions, are affected by: (a) strength of concretes, and (b) type of FRP materials.
2. The hoop rupture strain reduction factor ($k_{\varepsilon,f}$) of FRP jackets decreases with an increase in the unconfined concrete strength (f'_{co}) and elastic modulus of fiber material (E_f). These finding are in agreement with those previously reported in Lim and Ozbakkaloglu [8].

The strain reduction factor expression previously proposed by Lim and Ozbakkaloglu [8] have been shown to be in good agreement with the results of the present study.

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