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S.T. Smith, T. Yu, D. Fernando and Z.Y. Wang (Eds.)

EXPERIMENTAL STUDY ON THE CONFINEMENT OF HIGH-STRENGTH CONCRETE COLUMNS WITH LARGE RUPTURE STRAIN FRP COMPOSITES

N. Sirach[1], S.T. Smith[2*], T. Yu[3], A. Mostafa[1] and Z.S. Tang[1]
[1] School of Environment, Science and Engineering, Southern Cross University
Lismore, NSW 2480, Australia
[2] School of Civil, Environmental and Mining Engineering, The University of Adelaide,
South Australia 5005, Australia
[3] School of Civil, Mining and Environmental Engineering, University of Wollongong
Wollongong, NSW 2522, Australia
Email: n.sirach.10@student.scu.edu.au, scott.smith@adelaide.edu.au, taoy@uow.edu.au,
ahmed.thabet@scu.edu.au, z.tang.11@student.scu.edu.au
* Corresponding Author

ABSTRACT
High-strength concrete (HSC) is finding increasing use in multi-storey construction in recent years. The performance of such structures can, however, be compromised by the high stiffness and low ductility of HSC. Confinement of HSC columns with fibre-reinforced polymers (FRP) can alleviate these shortcomings. To date, research attention on confinement is primarily focused on FRP composites with rupture strains up to approximately 3%, although recently introduced polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) fibres exhibit rupture strains of up to 10%. The use of HSC with large rupture strain (LRS) FRP composites in confinement applications is highly attractive because the efficient combination of these high-performance materials can lead to very high-performance columns. This paper presents an experimental study on the compressive behaviour of circular HSC columns confined with LRS FRP and traditional FRP composites. Results show that LRS FRP-confined columns exhibit similar strength enhancement to those traditional FRP-confined columns, however the ductility is significantly improved. In addition, the LRS FRP-confined HSC columns experience strength softening after concrete crushing.

KEYWORDS
FRP, large rupture strain, high strength concrete, confinement, experimental study.

INTRODUCTION
Throughout the past few decades, FRP composites have emerged as a viable means for the strengthening and retrofitting of RC columns (Teng et al. 2002). The behavior of these columns confined with carbon, glass and aramid FRP composites, which are herein referred to as *traditional FRP*, is now well-understood. In more recent years, a number of large rupture strain (LRS) FRP composites have emerged as viable solutions for the strengthening and repair of concrete, particularly for seismic retrofitting (Anggawidjaja et al. 2006; Dai et al. 2011; Ispir 2015; Saleem et al. 2017). These LRS FRP composites have high elongation capacities (typically >5%) and are more environmentally friendly in comparison to traditional FRPs as they are recycled from waste products such as plastic bottles. For these composites to be implemented in industry, a better understanding of their stress-strain behavior is needed.

High strength concrete (HSC) has become a widely used construction material in recent years due to the superior performance and economic benefits it provides. A shortcoming of HSC is that it is very stiff and has low ductility when compared to normal strength concrete. For this reason, the use of LRS FRP with HSC is highly attractive due to the possibility of developing a very high strength, highly ductile system. While many studies have assessed the behaviour of LRS FRP-confined normal strength concrete

(Dai et al. 2011; Bai et al. 2014; Pimanmas & Saleem 2018), no known studies to the author's knowledge have experimented with the use of LRS FRP and HSC. This knowledge gap is addressed herein via an experimental investigation on FRP-confined concrete cylinders.

EXPERIMENTAL PROGRAMME

Experimental Details

A total of 20 concrete cylinders confined with four different types of unidirectional FRP composites were tested under monotonic axial compression as summarised in Table 1. The specimen labelling convention adopted (see first column of Table 1) is based on FRP type (C = carbon, G = glass, PEN = polyethylene naphthalate, PET = polyethylene terephthalate), followed by the number of FRP layers (e.g. 1 = 1 layer, 2 = 2 layers), and then a letter to identify the two nominally identical specimens (a or b). For example, PET-3b refers to the second specimen of two nominally identical FRP-confined concrete specimens containing three layers of PET fibres.

In designing the test programme, careful consideration was given to the number of FRP layers applied to each specimen. It is well understood that the confinement pressure heavily influences the behaviour of FRP-confined concrete, thus this value was kept as consistent as possible across different FRP types. The confinement ratio, f_l/f'_{co}, calculated from Eq. (1), is used as the performance criterion in establishing relative confinement levels with different FRP materials. It is expressed as

$$\frac{f_l}{f'_{co}} = \frac{2E_f t_f \varepsilon_f}{D f'_{co}} \quad (1)$$

where f_l is the confining pressure, E_f is the modulus of elasticity, t_f is the total nominal thickness, ε_f is the ultimate tensile strain of the fibres, and D is the diameter of the concrete core. It should be noted that the second elastic modulus is used for the PEN and PET FRP samples.

All concrete specimens had a nominal diameter of 150mm and a height of 300mm. Each sample contained an overlapping zone of 150mm, which is approximately 1/3 of the circumference of each concrete cylinder. Four linear variable displacement transducers (LVDT's) were used during each test, with two LVDT's measuring the overall displacement between the platens on the universal test machine, while two LVDT's measured the axial strain within a 150 mm mid-height region of the column. The axial strain used in this study is taken from the mid-height region.

Material Properties

Flat coupon tests were conducted for each FRP composite on at least five specimens in accordance with ASTM D3039/D3039M. The carbon and glass FRP had an elastic modulus of 227 GPa and 86 GPa, respectively, and an ultimate strain of 0.013 and 0.022, respectively. The PEN and PET FRP have a first stage elastic modulus of 28.3 GPa and 18.9 GPa, respectively, and a second stage elastic modulus of 12.4 GPa and 6.2 GPa, respectively. The ultimate strains for each fibre type was 6.2% and 8.6%, respectively. At the time of testing and based on five cylinder tests, the concrete had an unconfined compressive strength of 110.6 MPa and a compressive strain capacity of 0.0026.

TEST RESULTS AND DISCUSSION

Stress-Strain Behaviour

Figure 1 illustrates the typical response of LRS FRP-confined HSC columns. Unlike traditional FRP confinement, a strength-softening region occurs after concrete crushing and before full FRP activation. This stress-strain response has previously been experienced for LRS FRP-confined square and rectangular normal-strength concrete columns (Saleem et al. 2017) and traditional FRP-confined square and rectangular HSC columns (Ozbakkaloglu 2013). Due to the nature of the HSC used in this study, the behaviour is due to the cracking pattern of HSC being localised macrocracks rather than radially distributed microcracks (Ozbakkaloglu 2013). As a result of this, full confinement is only activated after significant damage to the concrete has been sustained.

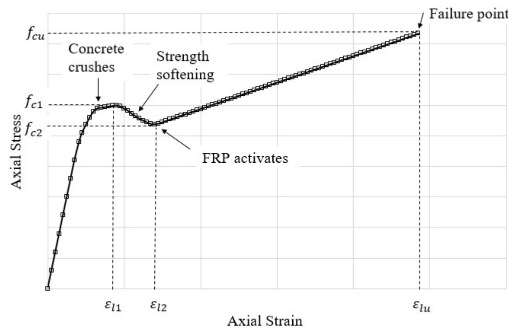
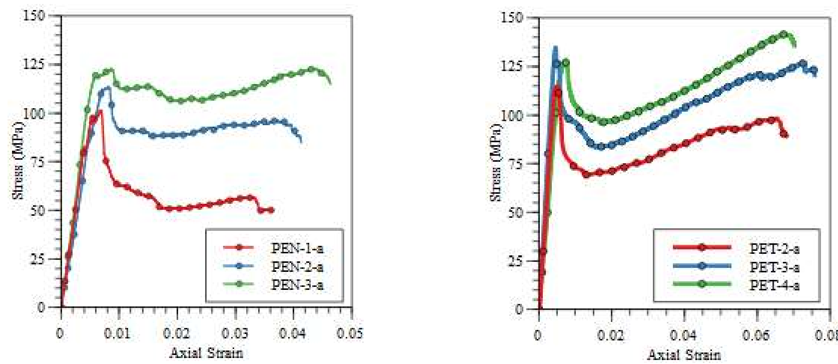


Figure 1. Typical axial stress-strain response of circular LRS FRP-confined HSC columns

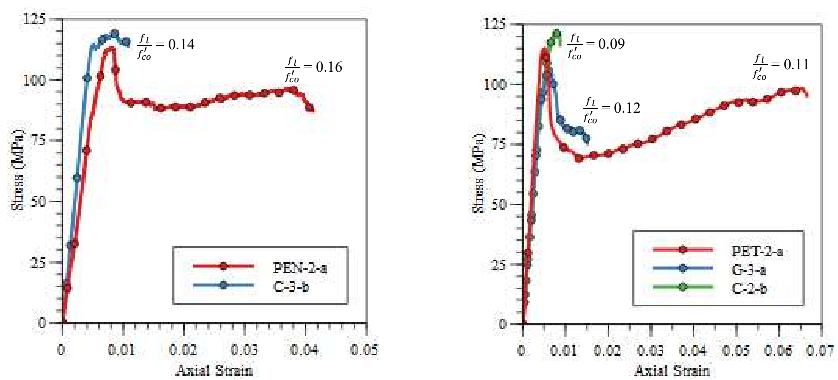
Figure 2 shows the influence the number of FRP layers has on the stress-strain response of PEN and PET FRP-confined concrete columns. Figure 2(a) demonstrates that the ultimate strength and ductility of the columns increases as the number of layers of PEN FRP increases. It is also evident that that the number of FRP layers influence the point of concrete crushing; as the number of layers increase, the concrete crushing occurs at a higher axial stress. Additionally, the extent of strength softening experienced after concrete crushing decreases as the number of FRP layers increases. Similar observations can be seen in Figure 2(b) for concrete confined with PET FRP.



(a) PEN FRP (b) PET FRP

Figure 2. Effect of FRP layers on the confinement of HSC

Figure *3*(a-b) shows comparisons of LRS FRP-confined HSC columns and traditional FRP-confined HSC columns with similar confining ratios. It shows that the columns achieve a similar ultimate strength at initial concrete crushing, however the traditional FRP composites rupture shortly after concrete crushing. It is also evident that the carbon FRP-confined column in Figure 3b does not experience any strength softening. However, failure occurs shortly after concrete crushing. For the glass FRP-confined sample, strength softening occurs after concrete crushing.



(a) PEN FRP (b) PET FRP

Figure 3. Effect of FRP type on the confinement of HSC

Table 1 presents the key results in this experimental programme, where f'_{c1}, f'_{c2}, and f'_{cu} refer to the axial stress and ε_{c1}, ε_{c1}, and ε_{c1} are the corresponding axial strains of the wrapped specimens at key locations on the stress-strain curve. Refer to Figure 1 for the location of these values on the stress-strain response.

Table 1. Test results

Test Specimen	f'_{c1} (MPa)	ε_{c1} (%)	f'_{c2} (MPa)	ε_{c2} (%)	f'_{cu} (MPa)	ε_{cu} (%)
PEN-1a(b)	101.1 (106.6)	0.69 (0.37)	51.0 (45.5)	1.71 (1.18)	55.6 (56.6)	3.35 (3.75)
PEN-2a(b)	113.1 (119.3)	0.81 (0.49)	88.3 (84.6)	1.51 (1.10)	93.7 (99.0)	3.95 (2.65)
PEN-3a(b)	122.2 (130.0)	0.82 (0.48)	106.7 (99.1)	1.89 (1.57)	122.7 (122.9)	4.40 (3.66)
PET-2a(b)	114.9 (118.2)	0.52 (0.51)	69.2 (63.9)	1.23 (1.23)	98.2 (96.5)	6.56 (6.37)
PET-3a(b)	134.7 (113.9)	0.46 (0.89)	83.9 (84.9)	1.65 (2.10)	126.9 (96.0)	7.28 (7.00)
PET-4a(b)	125.7 (122.2)	0.66 (1.00)	96.3 (91.7)	1.69 (2.18)	140.8 (133.3)	6.89 (7.90)
C-2a(b)	-	-	-	-	136.6 (121.5)	0.52 (1.02)
C-3a(b)	-	-	-	-	133.4 (119.1)	1.11 (0.85)
G-2a(b)	-	-	-	-	123.4 (113.2)	0.44 (0.46)
G-3a(b)	-	-	-	-	106.7 (110.0)	0.64 (0.69)

CONCLUSIONS

The performance of FRP-confined HSC columns subjected to concentric axial compression were investigated by considering the number of FRP layers and FRP type as variables. The results show that LRS FRP is capable of considerably improving the ductility of HSC. The stress-strain response of LRS FRP-confined HSC is different to that of its traditional FRP counterpart, with a strength-softening region occurring after concrete crushing and before full FRP activation. As the number of FRP layers increase, concrete crushing is delayed and the amount of strength softening is decreased. By drawing comparisons between LRS FRP-confined HSC and its traditional FRP counterpart using the confinement ratio, it is evident that LRS FRP provides a similar strength increase and a considerably greater ductility increase to that of traditional FRP.

ACKNOWLEDGEMENTS

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