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CONFINEMENT OF CONCRETE COLUMNS WITH LARGE RUPTURE STRAIN FRP COMPOSITES

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ABSTRACT

Fibre-reinforced polymer (FRP) composites can be used as a confinement mechanism to improve the strength and ductility of concrete columns. In recent years, a number of large rupture strain (LRS) FRP composites have emerged, namely polyethylene naphthalate (PEN) and polyethylene terephthalate (PET), and they are a promising solution for the seismic retrofitting of reinforced concrete (RC) columns. These composites are desirable as they are made from recycled plastic bottles, making them a cheaper and more environmentally friendly alternative to traditional FRPs (i.e. carbon FRP and glass FRP). This paper presents an experimental study on the axial compressive behavior of LRS FRP-confined normal-strength concrete columns. The effect of FRP layers on the stress-strain behavior of these columns is investigated. Furthermore, several tests on traditional FRP-confined columns were tested in parallel and these results are used to make comparisons to those LRS FRP-confined columns. Results show that LRS FRP-confined columns achieve a similar ultimate strength and significantly higher ultimate strains to their traditional FRP counterpart when the confining ratio is similar.

KEYWORDS

FRP, large rupture strain, concrete, confinement, experimental study.

INTRODUCTION

The confinement of concrete with fibre-reinforced polymer (FRP) composites is a well-recognised solution for strengthening and retrofitting columns (Teng et al. 2002). Research attention on FRP confinement has predominately been focused on carbon, glass and aramid FRP composites, which are herein referred to as *traditional FRPs*. In more recent years, several large rupture strain (LRS) FRP composites have emerged as a viable alternative to traditional FRPs for confinement applications (Dai et al. 2011; Bai et al. 2014; Ispir 2014; Saleem et al. 2017). These LRS composites have high elongation capacities (typically greater than 5%) and are more environmentally friendly in comparison to traditional FRPs since they are recycled from waste products such as plastic bottles. To facilitate the use of LRS FRP composites in practical confinement applications, a thorough understanding of the stress-strain behaviour of FRP-confined concrete is essential. To achieve a better understanding of the stress-strain response of LRS FRP-confined concrete columns, this paper presents experimental results for both traditional FRP and LRS FRP-confined columns, using the confinement ratio as a means for comparison.

EXPERIMENTAL PROGRAMME

Experimental Details

A total of 16 FRP-confined concrete cylinders covering four FRP types were tested under monotonic axial compression. All specimens had a nominal diameter of 150mm (diameter of concrete core) and a height of 300mm. The specimen labelling adopted is based on FRP type (C = carbon, G = glass, PEN = polyethylene naphthalate, PET = polyethylene terephthalate), followed by the number of FRP layers (i.e. 2 = 2 layers), and then a letter to differentiate two nominally identical specimens (a or b). For example, PET-3-b refers to the second specimen of two nominally identical three-layer PET FRP-confined specimens. Two LVDT's were used to measure the axial displacement of the 150 mm mid-height region of the column.

Flat coupon tests were undertaken on at least five samples of each FRP composite in accordance with ASTM D3039/D3039M and the results are shown in Table 1. The concrete used in this study was cast and tested in accordance with AS1012. At the time of testing and based on five cylinder tests, the concrete had an unconfined compressive strength of 20.9 MPa.

Sample Preparation

The FRP composites were applied to the surface of the cured concrete using the wet lay-up approach. Regardless of the number of plies used for each sample, a single continuous FRP sheet, with the main fibres in the hoop direction, was used to wrap the samples. Each sample had an overlapping zone of 150mm, which is approximately 1/3 of the circumference of the concrete cylinder.

In designing the test programme, careful consideration was given to the number of FRP layers applied to each specimen. The confinement pressure heavily influences the behaviour of FRP-confined concrete, thus this value was kept as consistent as possible across different FRP types to enable direct comparison. 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

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

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.

TEST RESULTS AND DISCUSSION

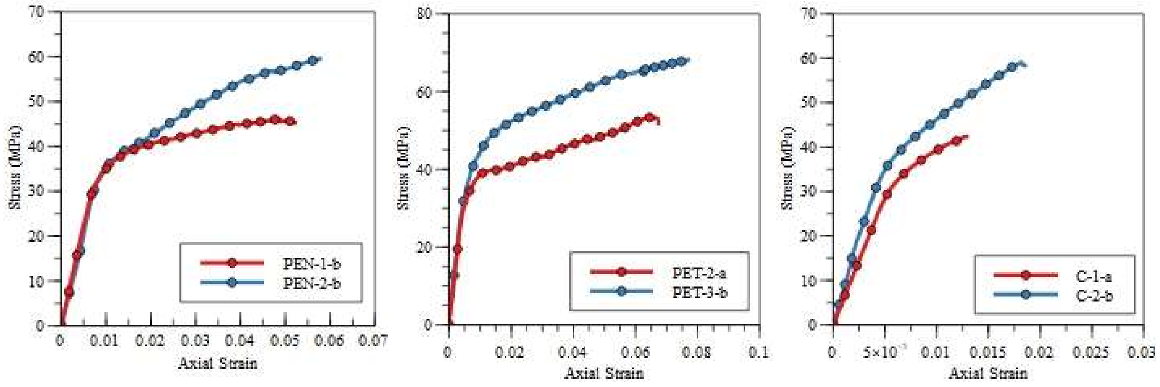
Failure Mode

Figure 1 displays the typical failure mode of specimens confined with different FRP types. It can be observed in Figure 1(a-b) that the failure mode of PEN and PET FRP is concentrated to a small vertical portion near the midspan of the sample. Once the FRP ruptures, a horizontal break occurs around the circumference of the sample at either the top or bottom of the vertical FRP rupture. As seen in Figure 1(c-d), a large number of carbon and glass FRP fibres in the midspan region rupture simultaneously and there is not a distinct vertical region where the failure occurred. A general observation was that the PEN and PET FRP had a gradual failure, where the carbon and glass FRP had a sudden explosive failure.

(a) PEN (b) PET (c) Carbon (d) Glass

Figure 1. Typical Failure Modes of FRP-Confined Concrete with Different FRP Wraps

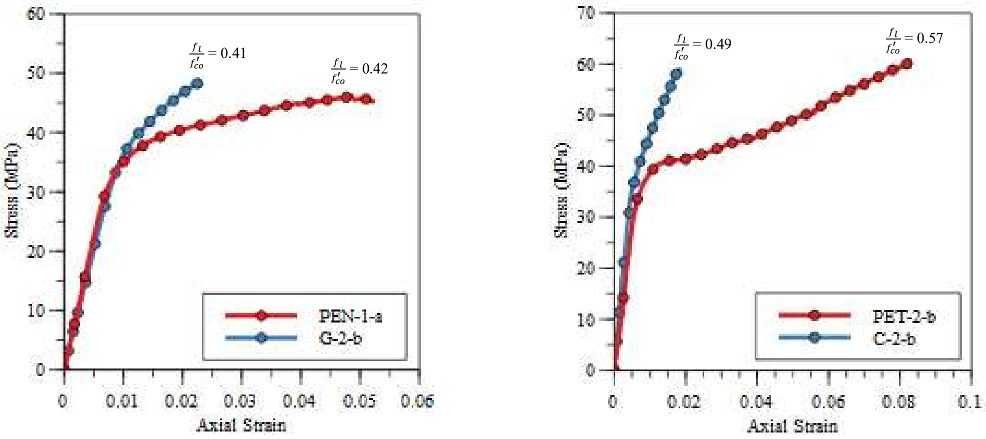
Figure 2 shows the effect of FRP layers on the axial performance of columns confined with PEN, PET and carbon FRP. Figure 2(a-b) shows that as the number of LRS FRP layers increase, the ductility and strength of the columns significantly increase. It is evident in Figure 2(c) that carbon FRP has a similar trend when the number of FRP layers are increased. This attests to the reliable and predictable confinement qualities of LRS FRP composites for strengthening and retrofitting concrete columns.



(a) PEN (b) PET (c) Carbon

Figure 2. Effect of FRP Layers on the Confinement of Concrete Columns

Figure 3 shows comparisons of LRS FRP-confined columns to traditional FRP-confined columns with similar confining ratios. It is evident that the LRS and traditional FRP-confined columns achieve a similar ultimate strength, however the ultimate strain is considerably higher for those LRS FRP-confined columns. The curves of all FRP-confined samples in this study have three distinct portions, with an initial linear branch, a curved transition zone, and then a final linear branch until failure. Regardless of FRP type, the initial linear branch is similar since this portion is predominantly controlled by the unconfined strength of concrete. The transition zone is much tighter and longer for the LRS FRP-confined columns, showing that the activation of FRP confinement is more gradual than that of traditional FRP with the same confining ratio. A final linear branch is evident for all samples, where the traditional FRP-confined columns have a steeper but shorter branch.



(a) PEN (b) PET

Figure 3. Effect of FRP Type on the Behaviour of FRP-Confined Concrete Columns

Table 1 presents the key results in this experimental programme, where E_{frp1} and E_{frp2} refer to the first and second elastic modulus, respectively; t_{frp} refers to the thickness of the FRP wrap; ε_{rup} refers to the rupture strain of the FRP; f'_{cu} and ε_{cu} refer to the ultimate compression strength and corresponding axial strain of the wrapped specimens.

Table 1. Test Results

Test Specimen	E_{frp1} (GPa)	E_{frp2} (GPa)	t_{frp} (mm)	$\varepsilon_{h,rup}$ (%)	f'_{cu} (MPa)	ε_{cu} (%)
PEN-1-a	28.3	12.4	0.848	6.2	-	-
PEN-1-b	28.3	12.4	0.848	6.2	46.2	5.13
PEN-2-a	28.3	12.4	1.696	6.2	65.5	5.71
PEN-2-b	28.3	12.4	1.696	6.2	59.5	5.76
PET-2-a	19.0	6.2	1.682	8.6	53.3	6.45
PET-2-b	19.0	6.2	1.682	8.6	60.8	8.24
PET-3-a	19.0	6.2	2.523	8.6	65.2	6.22
PET-3-b	19.0	6.2	2.523	8.6	68.1	7.70
C-1-a	227.0	-	0.13	1.3	42.3	1.28
C-1-b	227.0	-	0.13	1.3	43.4	1.40
C-2-a	227.0	-	0.26	1.3	63.5	2.06
C-2-b	227.0	-	0.26	1.3	59.0	1.82
G-1-a	85.9	-	0.17	2.2	31.6	1.09
G-1-b	85.9	-	0.17	2.2	32.1	1.39
G-2-a	85.9	-	0.34	2.2	49.8	2.38
G-2-b	85.9	-	0.34	2.2	48.5	2.27

CONCLUSIONS

FRP-confined concrete columns subjected to axial compression were investigated by taking the number of FRP layers and FRP type as variables. The results show that LRS FRP is capable of considerably improving the ductility and ultimate strength of concrete. The generalised shape of the stress-strain response for LRS FRP-confined columns and traditional FRP-confined columns are similar. Through comparing LRS FRP-confined concrete and traditional FRP-confined concrete, it is apparent that the LRS FRP system experiences a similar strength enhancement and a significantly greater ductility enhancement. Furthermore, an increase in the number of FRP layers has the same effect on LRS FRP-confined concrete as it does with traditional FRP-confined concrete, namely, strength and ductility increasing as the number of FRP layers increases.

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REFERENCES

ASTM. (2008) “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials”, *D 3039/D 3039M*, West Conshohoken, PA.

Bai, Y. L., Dai, J. G. and Teng, J. G. (2014) “Cyclic compressive behavior of concrete confined with large rupture strain FRP composites”, *Journal of Composites for Construction,* ASCE, Vol. 18, No. 1, pp. 1-12.

Dai, J. G., Bai, Y. L. and Teng, J. G. (2011) “Behavior and modeling of concrete confined with FRP composites of large deformability”, *Journal of Composites for Construction,* ASCE, Vol. 15, No. 6, pp. 963-973.

Ispir, M. (2014) “Monotonic and cyclic compression tests on concrete confined with PET-FRP”, *Journal of Composites for Construction*, ASCE, Vol. 19, No.1, pp. 04014034.

Saleem, S., Hussain, Q. and Pimanmas, A. (2017) “Compressive behavior of PET FRP-confined circular, square, and rectangular concrete columns”, *Journal of Composites for Construction,* ASCE, Vol. 21, No. 3, 04016097.

Standards Australia. (2014) “Methods of testing concrete – Method 2: Preparing concrete mixes in the laboratory”, *AS 1012.2*.

Standards Australia. (2014) “Methods of testing concrete – Method 9: Compressive strength tests – Concrete, mortar and grout specimens”, *AS 1012.9*.

Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L. (2002) *FRP-Strengthened RC Structures*, John Wiley & Sons, West Sussex, U.K.