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Hussamaldeen GOAIZ

University of Wollongong, hagao106@uowmail.edu.au

Tao Yu

University of Wollongong, taoy@uow.edu.au

Muhammad N. S Hadi

University of Wollongong, mhadi@uow.edu.au

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Behaviour of CFRP-Confined Hollow Circular Concrete Columns with Inner PVC Tube

Hussam A. Goaiz¹

¹ Ph.D. Candidate, School of CME Engineering, University of Wollongong, Australia.

Email: hagao106@uowmail.edu.au

Tao Yu²

² Senior Lecturer, School of CME Engineering, University of Wollongong, Australia.

Email: taoy@uow.edu.au

Muhammad N.S. Hadi^{3,*}

³ Associate Professor, School of CME Engineering, University of Wollongong,
Australia.

Email: mhadi@uow.edu.au , *Corresponding author

Abstract

Existing studies have shown that the use of an inner tube can significantly enhance the effectiveness of confinement in fibre-reinforced polymer (FRP)-confined hollow columns. The inner tube used in the existing studies, however, generally had a large stiffness and also served as longitudinal reinforcement. The use of a stiff inner tube is inefficient in resisting bending for hollow columns with a relatively small void, and may be unnecessary for constraining the inner surface of concrete. Against this background, this paper presents the first experimental study on FRP-confined hollow columns with an inner PVC tube. The experimental program included a total of 18 specimens which were tested under axial compression. The test variables included the section configuration (i.e. solid specimens, hollow specimens and hollow specimens with a PVC tube) and the thickness of FRP. The test results showed that due to the beneficial

effect of the PVC tube which provided constraints/confinement from inside, FRP-confined hollow columns with an inner PVC tube generally possessed good strength and ductility compared to their counterparts without a PVC tube.

Keywords: CFRP; confinement; concrete; hollow columns; PVC tube.

1. Introduction

Fibre-Reinforced Polymer (FRP) composites have emerged rapidly as durable structural materials in recent years (Teng et al. 2002). One of the most important applications of FRP is as a confining material for concrete (e.g. Fam and Rizkalla (2001); Lam and Teng (2003); Li and Hadi (2003); Hadi (2006); Yu et al. (2013)). Because of the FRP confinement, both the strength and ductility of concrete can be significantly enhanced (Lam and Teng 2003).

Extensive studies have been conducted on FRP-confined solid circular concrete columns (e.g. Lam and Teng 2003), and the test results of such confined concrete can now be closely predicted by some of the existing stress-strain models (e.g. Lam and Teng 2003; Teng et al. 2007). By contrast, the behaviour of FRP-confined concrete in hollow circular columns is not yet well understood. In hollow circular columns, the annular concrete section is subjected to non-uniform confining pressure over its radius, and its behaviour can be much different from FRP-confined concrete in a solid circular column where the confinement is generally uniform over the cross-section.

A number of studies (Modarelli et al. 2005; Lignola et al. 2008; Yazici and Hadi 2009; Kusumawardaningsih and Hadi 2010; Yazici and Hadi 2012) have been conducted on FRP-confined hollow concrete columns. These studies suggested that the effectiveness

of FRP confinement is much reduced because of the existence of an inner void. In a hollow column, due to the lack of constraints from inside, the concrete near the inner edge suffers from early loss of load resistance as a result of local spalling failure (Wong et al. 2008). In addition, the absence of inner pressure to the annular concrete section leads to unequal lateral confining stresses in the radial and hoop directions, further reducing the effectiveness of confinement (Yu et al. 2010a).

To minimize the detrimental effects of the inner void, existing studies have explored the use of an additional inner tube, leading to the so-called double-skin tubular columns (DSTCs) (e.g. Fam and Rizkalla 2001; Teng et al. 2007; Yu et al. 2010b). Among these studies, Fam and Rizkalla (2001) reported tests on FRP-concrete DSTCs with an inner tube made of FRP; Teng et al. (2007) and Yu et al. (2010b), among others, reported tests on FRP-concrete-steel DSTCs with an inner tube made of steel. These studies generally demonstrated that with the additional inner tube, both the performance of the column and the effectiveness of confinement can be significantly improved.

In the existing studies on FRP-confined DSTCs, the inner tubes used were typically stiff and also served as longitudinal reinforcement. However, for hollow columns with a small- or medium-size void, the use of a stiff inner tube is inefficient in resisting bending. In such cases, the main longitudinal reinforcement should be placed away from the inner edge of the concrete section, while the function of the inner tube should be mainly to restrain the inner surface of concrete for effective confinement. As a result, the inner tube could be made of a less stiff material (e.g. PVC) and be more cost-effective than existing solutions. The permanent inner PVC tube has also many other advantages in construction industry besides the low cost such as; excellent durability, ease of fabrication and handling. Against this background, this paper presents an

experimental study on FRP-confined DSTCs with a PVC inner tube (i.e. FRP-PVC DSTCs) (Figure 1a). It is worth noting that FRP-PVC DSTCs can also be a preferred solution in applications where steel should be avoided (e.g. mining applications involving cutting), considering the much lower material cost of PVC compared with FRP. In the present study, the experimental program also included tests on FRP-confined hollow columns (FHCs) (Figure 1b) and FRP-confined solid cylinder (FCSCs) (Figure 1c) for comparison.

2. Experimental program

2.1 Specimens details

In total, 18 specimens were prepared and tested under concentric axial compression. All the specimens had an outer diameter of 150 mm and a height of 300 mm. These specimens were divided into three groups according to the section configuration. Specimens in the first group had an inner PVC tube (Figure 1a), specimens in the second group were hollow cylinders with an inner void of 90 mm (Figure 1b), while specimens in the third group were solid cylinders (Figure 1c). The PVC tube had an outer diameter of 90 mm and a thickness of 1.5 mm. Each group consisted of two control specimens without FRP and two pairs of FRP-confined specimens wrapped with one and two layers of carbon FRP (CFRP) sheet, respectively. The details of all the specimens are summarized in Table 1.

Each specimen is identified with an acronym (Table 1), which starts with a letter “HC” to represent hollow core specimens or “S” to represent solid specimens. For FRP-confined specimens, this is then followed by “1F” or “2F” to represent one or two layers of CFRP sheet. The letter “T” for some specimens is used to indicate that the specimens had an inner PVC tube. The number “1” or “2” at the end is used to differentiate two

108 nominally identical specimens. For example, specimen “HC1FT-1” was the first of two
109 nominally identical hollow core specimens with an inner PVC tube and a one-layer
110 CFRP wrap.

112 **2.2 Material properties**

113 Three concrete cylinders (100 mm × 200 mm) were tested during the test period
114 following AS 1012.9 (1999) and the average compressive strength was found to be 52.5
115 MPa.

116 Three coupons were cut from the PVC tube and tested under tension according to
117 ASTM D638 (2014). The typical tensile stress-strain curve obtained from these tests is
118 shown in Figure 2, where the tensile strains were obtained from a clip-on extensometer
119 attached to the specimen. The ultimate tensile stress, the ultimate tensile strain and the
120 elastic modulus were found to be 44.47 MPa, 54% and 3.6 GPa, respectively. In
121 addition, two PVC tubes with a length of 300 mm were tested under axial compression
122 and the test results are shown in Figure 3.

123 Tensile tests on CFRP coupons were conducted according to ASTM D7565 (2010)
124 standard. The test results showed that the average tensile force per unit width of one-
125 layer CFRP (0.35 mm thickness) and two-layer CFRP (0.7 mm thickness) were 593.7
126 N/mm and 1262.5 N/mm, respectively.

128 **2.3 Test set-up and instrumentation**

129 All compression tests were carried out using a Denison universal testing machine with a
130 loading capacity of 5000 kN (see Figure 4). One LVDT was used to measure the axial

strain of the mid-height region of 115 mm. In addition, two strain gauges with a gauge length of 5 mm were attached at the mid-height of the CFRP wrap to measure the hoop strains. All specimens were axially loaded up to failure with a displacement rate of 0.5 mm/minute.

3. Experimental results and discussions

3.1 Failure modes

All unconfined specimens failed by the crushing and spalling of concrete at the mid-height of the specimens. For hollow specimens without a PVC tube, damage on the inner surface was found after test. All CFRP-confined specimens failed by the rupture of CFRP due to hoop tension, except for Specimens S1F-2, HC1F-2 and HC1FT-2. For these three specimens, premature failure occurred near one end; the results of these specimens were thus excluded from the discussions below. This premature failure had been caused by the non-uniform distribution of the load on the capped surface of the specimen due to lack of squareness of the capping surface.

3.2 Axial stress-strain behaviour

The key test results are summarized in Table 2. The axial stress-strain curves of concrete in solid specimens are compared with those of concrete in hollow specimens without a PVC tube in Figure 5. For clarity of presentation, the stress-strain curves of confined specimens are all terminated at a point corresponding to the rupture of CFRP.

Figure 5a shows that the unconfined strength of hollow specimens was slightly lower than that of solid specimens (see also Table 2). In addition, the hollow specimens generally had a steeper descending branch than the solid specimens, suggesting that the inner void had a negative effect on both the strength and ductility of the specimen. Figures 5b and 5c show that the behaviour of CFRP-confined hollow specimens is quite different from that of the corresponding solid specimens. The latter generally had a bilinear stress-strain curve while the curves of the former typically had a descending branch. As a result, the CFRP-confined hollow specimens generally had a much lower peak stress than the corresponding solid specimens, although the ultimate axial strains of the former were comparable to or even larger than the latter. For hollow specimens, the stress decreased more rapidly after the peak value for specimens with a weaker CFRP wrap (see Figures 5b and 5c).

Figure 6 shows a comparison between the stress-strain curves of concrete in hollow specimens and those of concrete in the corresponding specimens with a PVC tube. When calculating the axial stress of concrete in the latter, the load contribution of the PVC tube was ignored as it was generally rather small (peak load = 22 kN) compared with that of the concrete (peak load of unconfined concrete = 522 kN).

Figure 6a shows that the presence of an inner PVC tube had a marginal effect on the behaviour of the unconfined concrete. Figure 6b, however, shows that the additional PVC tube reduced the decrease in stress in the descending second branch of the stress-strain curves of one-layer CFRP-confined specimens. For the specimen without a PVC tube (i.e. HC1F-1), the stress decrease in the second branch was 33% of the peak stress,

while for the specimen with a PVC tube (i.e. HC1FT-1) the stress decrease was only 9% of the peak stress. For two-layer CFRP-confined specimens, Figure 6c shows that the effect of PVC tube was even more obvious: Specimens HC2FT-1, 2 had a bilinear stress-strain curve with two ascending branches. By contrast, the curves of the two specimens without a PVC tube both had a clear descending second branch which was lower than that of their counterparts with a PVC tube. This is believed to be due to two important functions of the inner PVC tube: (1) preventing local spalling failure of concrete near the inner edge; and (2) providing inner pressure to the annular concrete section.

While Figures 6b and 6c clearly show the beneficial effect of the inner PVC tube, it may be noted that such effect does not seem to be significant. This was due to the use of a thin PVC tube in the present study whose stiffness was rather small. The PVC tube had a thickness of 1.5 mm and an elastic modulus of 3.6 GPa, so in terms of axial stiffness it was only equivalent to a steel tube of the same diameter and a thickness of around 0.03 mm. When a thicker PVC tube is used, it can be expected that the beneficial effect of the inner tube would be more pronounced.

3.2.1 Comparison between inner tube of PVC and steel

To compare the behaviour of PVC tube and steel tube, the results of four FRP-confined DSTC specimens with inner steel tube (2.1 mm thickness) were selected from a previous study that was conducted by Wong et al. (2008). The four FRP-confined DSTC specimens (D37-C1-I, D37-C1-II, D37-C2-I and D37-C1-II) were selected for the comparison among other specimens because they had relatively similar dimensions

(152.5 mm diameter $\times$ 305 mm height $\times$ 88 mm inner void) to the specimens with inner PVC tubes presented in this study. In addition, these specimens had nearly the same strength of the FRP confinement (average tensile strength of 1825.5 MPa).

Table 3 shows the results of the axial stress and axial strain of the four DSTC specimens and Specimens HC1FT-1, HC2FT-1 and HC2FT-2, in which $\sigma_{\max}$ is the maximum axial stress, and ϵ_u is the ultimate strain at the rupture of FRP confinement. The results presented in Table 3 showed that the axial stress increase ($\sigma_{\max}/f'_c$) of Specimens D37-C1-I, II was 10.7% higher than Specimen HC1FT-1. Also, the stress increase of Specimens D37-C2-I, II was 19.4% higher than Specimens HC2FT-1, 2. Whereas, the strain increase (ϵ_u/ϵ_{co}) of Specimens HC1FT-1 and HC2FT-1, 2 were 71.9% and 17.3% higher than Specimens D37-C1-I, II and D37-C2-I, II, respectively. Thus, using an internal steel tube in FRP-confined DSTC specimen has the advantage of increasing the axial stress capacity. The using of an internal PVC tube however, has the advantage of increasing the axial strain. In addition, the PVC tube has the advantages of low cost, low self-weight and ease of fabrication over the steel tube.

3.3 Axial-hoop strain behaviour

Figures 7 and 8 show the axial-hoop strain curves of one-layer and two-layer CFRP-confined specimens, respectively. In the two figures, the axial strains were obtained from readings of the LVDT while the hoop strains were averaged from two strain gauges attached at the mid-height of the CFRP wrap.

It is evident from both figures that the lateral expansion behaviour of hollow specimens was quite different from that of the corresponding solid specimens. Such difference became significant after an axial strain of around 0.0025, when the lateral expansion of

concrete started to increase rapidly. In hollow specimens, the concrete could move towards the inner void because of the absence of constraints from inside, leading to a reduced outward expansion as measured by the hoop strain gauges on the outer CFRP wrap (Figures 7 and 8). It is easy to understand that the curves of the specimens with a PVC tube generally lie between those of the corresponding solid and hollow specimens, due to the inner constraint/confinement provided by the PVC tube. It should also be noted that the effect of PVC tube on the outward expansion of concrete appeared to be more obvious for two-layer specimens (Figure 8) than one-layer specimens. This was probably due to the stronger confinement provided by the two-layer CFRP, which led to more significant inward movement of the inner surface and in turn activated the PVC tube more effectively. Figure 9 shows the shape of two PVC tubes after test in Specimens HC1FT-1 and HC2FT-1, respectively. It is evident that the deformation of the latter was much more significant than the former. The inward buckling that was observed in the mid-height region of the PVC tube of Specimen HC2FT-1 (Figure 9b) can be attributed to the local stress concentration on the FRP confinement of this specimen.

3.4 Effect of CFRP confinement

The effect of CFRP confinement is illustrated in Figure 10. Figure 10a shows the effect of CFRP confinement for hollow specimens with a PVC tube. The shape of the curves was found to be significantly affected by the FRP confinement: the curves of the two unconfined specimens (i.e. HCT-1, 2) both had a descend branch, the one-layer specimen (i.e. HC1FT-1) had an approximately elastic-perfectly plastic curve, while the two-layer specimens (i.e. H2FT-1, 2) had a hardened bilinear curve. Besides, the superior performance of two-layer specimens was believed to be also partially due to

the more effective confinement provided by the PVC tube from inside as discussed above.

Figure 10b shows the effect of CFRP confinement for hollow specimens, where all the curves had a descending branch. Again, the behaviour of the specimens depended on the amount of confining CFRP, and the two-layer specimens (i.e. HC2F-1, 2) are shown to have the largest strength. It may be noted that the stress decrease in the descending branch became less when a stronger CFRP wrap was used.

As expected, for solid specimens, both the strength and the ductility of concrete was much enhanced because of the confinement of CFRP, and such enhancement was more pronounced for specimens with a two-layer CFRP than those with a one-layer CFRP (Figure 10c).

3.5 Ductility of specimens

The ductility of concrete columns is considered as one of the structural design aspects that need to be taken into account, particularly when concrete columns are resisting a high axial load. Ductility can be improved by using CFRP sheets to confine concrete columns. In this study, the calculation of the ductility depends on the axial stress-strain behaviour of the confined concrete which is the main component taking axial loads. The calculation method used is according to GangaRao et al. (2007) which is suitable for concrete with softened and hardened axial stress-strain behaviour, as shown in Eqn 1 below:

$$\mu_{\varepsilon} = \frac{\varepsilon_u}{\varepsilon_y} \quad (1)$$

where μ_ε is the specimen's ductility, ε_u is the specimen's strain at 85% of the maximum stress at post-yielding (for unconfined specimens) or is equal to the **specimen's strain at rupture of FRP confinement** (for FRP-confined specimens) and ε_y is the strain at yield stress.

The method of defining the yield point is based on the equivalent elasto-plastic method that was suggested by Park (1989). In this study, three different types of stress-strain curves were observed. Figure 11 shows how yield stresses and yield strains are determined.

The results of ductility in this study are summarized in Table 4. In general, test results indicate that the ductility of concrete specimens can be significantly improved by applying CFRP confinement. Applying **two-layer of CFRP-confinement** shows an outstanding improvement in term of the specimens' ductility. The highest average value of ductility 15.5 was achieved by Specimens HC2FT (Hollow specimen with an inner PVC tube and two layers of CFRP confinement), while the lowest average value of ductility 2.25 was obtained by Specimens HC (unconfined hollow specimen). Table 4 presents the ductility values of the specimens and shows the comparative results of the ductility of **CFRP confined specimens** and unconfined ones. According to the results presented in Table 4, the ductility of hollow specimens can be enhanced to be of **close values** to those of the FRP-confined solid specimens by using PVC tube for internal confinement. Figure 12 presents a comparison between the normalized average maximum stress and the normalized average ductility for all specimens.

4. Conclusions

This paper has presented and interpreted the results of a series of compression tests on CFRP-confined hollow concrete specimens with and without an inner PVC tube. The failure mode, axial stress-strain behaviour and axial-hoop strain behaviour of the test specimens have been discussed. Based on the test results and discussions presented above, the following conclusions can be drawn:

1. The inner void in a concrete cylinder led to a slight decrease in the strength and ductility of unconfined concrete.
2. CFRP-confined hollow specimens with an inner PVC tube generally possessed good ductility and were **higher than** their counterparts without a PVC tube. This was due to the beneficial effect of the PVC tube which provided constraints/confinement from the inside.
3. Under the same axial strain, the outward lateral expansion of CFRP-confined hollow specimens was generally lower than the corresponding solid specimens. This suggests that the ultimate axial strain of the former may be larger than the latter for the same confining material.
4. Compared with hollow specimens without an inner tube, the presence of an inner PVC tube led to an increased outward expansion of the CFRP-confined specimens, but this effect was only obvious when the CFRP confinement was strong (i.e. by using a two-layer wrap).
5. For unconfined specimens, solid specimens exhibited higher ductility than hollow specimens. **For confined specimens, however, the ductility of hollow specimens with an internal PVC tube can be enhanced to show close values of ductility compared to those of the solid specimens.**

It should also be noted that the PVC tube used in the present study had only a small stiffness. Further studies are needed to investigate the effect of thickness of PVC tube. It can be expected the beneficial effects are even more pronounced than those presented in this paper if a thicker PVC tube was used.

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Figure 12. Normalized maximum stress and normalized average ductility

Table 1 Details of test specimens

Specimen		Inner Hole Diameter (mm)	Number of CFRP Layers	Inner PVC tube thickness (mm)
Type	Label			
Hollow core with inner PVC tube	HCT-1	87	----	1.5
	HCT-2	87	----	1.5
	HC1FT-1	87	1	1.5
	HC1FT-2	87	1	1.5
	HC2FT-1	87	2	1.5
	HC2FT-2	87	2	1.5
Hollow core	HC-1	90	----	----
	HC-2	90	----	----
	HC1F-1	90	1	----
	HC1F-2	90	1	----
	HC2F-1	90	2	----
	HC2F-2	90	2	----
Solid	S-1	Solid	----	----
	S-2	Solid	----	----
	S1F-1	Solid	1	----
	S1F-2	Solid	1	----
	S2F-1	Solid	2	----
	S2F-2	Solid	2	----

Table 2 Key test results

Specimens Label	Maximum Stress $\sigma_{\max}$ (MPa)		Strain at Maximum Stress $\epsilon_{\max}$		Strain at Rupture of FRP ϵ_u		Hoop Rupture Strain $\epsilon_{h, \text{rup}}$	
	$\sigma_{\max}$	Average $\sigma_{\max}$	$\epsilon_{\max}$	Average $\epsilon_{\max}$	ϵ_{cu}	Average ϵ_{cu}	$\epsilon_{h, \text{rup}}$	Average $\epsilon_{h, \text{rup}}$
HCT-1	46.7	46.2	0.0028	0.0028	---	---	---	---
HCT-2	45.7		0.0027		---		---	
HC1FT-1	54.1	54.1	0.0053	0.0053	0.0295	0.0295	0.0086	0.0086
HC2FT-1	66.5	65.0	0.0281	0.0199	0.0281	0.0287	0.0113	0.0122
HC2FT-2	63.5		0.0116		0.0293		0.0130	
HC-1	46.8	46.9	0.0023	0.0024	---	---	---	---
HC-2	46.9		0.0025		---		---	
HC1F-1	54.5	54.5	0.0048	0.0048	0.0298	0.0298	0.0091	0.0091
HC2F-1	60.9	62.8	0.006	0.0065	0.0274	0.0268	0.0101	0.0104
HC2F-2	64.7		0.007		0.0261		0.0106	
S-1	49.6	48.9	0.0028	0.0030	---	---	---	---
S-2	48.13		0.0032		---		---	
S1F-1	70.3	70.3	0.0316	0.0316	0.0316	0.0316	0.0098	0.0098
S2F-1	104.6	101.8	0.0214	0.0233	0.0214	0.0233	0.0129	0.0133
S2F-2	98.9		0.0251		0.0251		0.0137	

Table 3 Comparison between inner tubes of PVC and steel

Specimens Label	Maximum Stress $\sigma_{\max}$ (MPa)		Stress Enhancement	Strain at Rupture of FRP Tube ϵ_{cu}		Strain Enhancement
	$\sigma_{\max}$	Average $\sigma_{\max}$	$\sigma_{\max}/f'_c$	ϵ_{cu}	Average ϵ_{cu}	$\epsilon_{cu}/\epsilon_{co}$
HC1FT-1	54.1	54.1	1.03	0.0295	0.0295	9.8
HC2FT-1	66.5	65.0	1.24	0.0281	0.0287	9.5
HC2FT-2	63.5			0.0293		
D37-C1-I	42.9	42.2	1.14	0.0166	0.0150	5.7
D37-C1-II	41.4			0.0133		
D37-C2-I	55.9	54.4	1.48	0.0235	0.0212	8.1
D37-C2-II	52.9			0.0188		

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Table 4 Axial strain and ductility test results

Specimen Label	Strain ϵ			Ductility μ_{ϵ}	Average Ductility	Normalized average ductility
	Strain at Yield stress σ_y	Strain at Rupture stress ϵ_u	Strain at 85% of σ_{max}			
HCT-1	0.0018	---	0.0046	2.5	2.4	1.00
HCT-2	0.0018	---	0.0042	2.3		
HC1FT-1	0.0020	0.0295	----	14.8	14.8	6.17
HC2FT-1	0.0018	0.0281	----	15.6	15.5	6.46
HC2FT-2	0.0019	0.0293	----	15.4		
HC-1	0.0016	---	0.0033	2.1	2.25	1.00
HC-2	0.0016	---	0.0038	2.4		
HC1F-1	0.0021	0.0267	----	12.7	12.7	5.64
HC2F-1	0.0020	0.0274	----	13.7	13.4	5.96
HC2F-2	0.0020	0.0261	----	13.1		
S-1	0.0018	---	0.0056	3.3	3.15	1.00
S-2	0.0017	---	0.0048	3.0		
S1F-1	0.0019	0.0243	----	12.7	12.7	4.03
S2F-1	0.0015	0.0214	----	14.2	15.45	4.90
S2F-2	0.0015	0.0251	----	16.7		

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(a) Hollow Core Concrete Specimens with inner PVC tube

(b) Hollow Core Concrete Specimens

(c) Solid Concrete Specimens

Figure 1 Details of test specimens

Figure 2 Typical tensile stress-strain behaviour of PVC coupon

Figure 3 Axial compressive load-deformation behaviour of PVC tube

Figure 4 Instrumentation of compression test

(a) Unconfined solid and hollow specimens

(b) Solid and hollow specimens with one layer of CFRP

(c) Solid and hollow specimens with two layers of CFRP

Figure 5 Axial stress-strain curves of solid and hollow specimens

(a) Unconfined Hollow and hollow with inner PVC tube specimens

(b) Hollow and hollow with inner PVC tube specimens confined with one layer of CFRP

(c) Hollow and hollow with inner PVC tube specimens confined with two layers of CFRP

Figure 6 Axial stress-strain curves of hollow with and without PVC tube specimens

Figure 7 Axial-hoop strain response of one layer of CFRP confinement

Figure 8 Axial-hoop strain responses of two layers of CFRP confinement

Figure 9 PVC tube deformations of Specimens HC1FT-1 and HC2FT-1

(a) Hollow specimens with PVC tube

(b) Hollow specimens

(c) Solid specimens

Figure 10 Effect of CFRP confinements on stress-strain response

Figure 11 Definitions for yield stress and yield strain (a) unconfined specimens; (b) confined specimens with softening behaviour; (c) confined specimens with hardening behaviour (Park, 1989).

Figure 12 Normalized maximum stress and normalized average ductility