2018

Behaviour of carbon fibre-reinforced polymer-confined hollow circular concrete columns with inner polyvinyl chloride tube

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*

---

**Publication Details**

Behaviour of carbon fibre-reinforced polymer-confined hollow circular concrete columns with inner polyvinyl chloride tube

Abstract
Existing studies have shown that the use of an inner tube can significantly enhance the effectiveness of confinement in fibre-reinforced polymer-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 article presents the first experimental study on fibre-reinforced polymer-confined hollow columns with an inner polyvinyl chloride 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 polyvinyl chloride tube) and the thickness of fibre-reinforced polymer. The test results showed that due to the beneficial effect of the polyvinyl chloride tube which provided constraints/confinement from inside, fibre-reinforced polymer-confined hollow columns with an inner polyvinyl chloride tube generally possessed good strength and ductility compared to their counterparts without a polyvinyl chloride tube.

Disciplines
Engineering | Science and Technology Studies

Publication Details
Behaviour of CFRP-Confined Hollow Circular Concrete Columns

with Inner PVC Tube

Hussam A. Goaiz

1 Ph.D. Candidate, School of CME Engineering, University of Wollongong, Australia.
Email: hagao106@uowmail.edu.au

Tao Yu

2 Senior Lecturer, School of CME Engineering, University of Wollongong, Australia.
Email: taoy@uow.edu.au

Muhammad N.S. Hadi

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/confine ment 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 (FCHCs) (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
nominally identical specimens. For example, specimen “HC1FT-1” was the first of two nominally identical hollow core specimens with an inner PVC tube and a one-layer CFRP wrap.

2.2 Material properties

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

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

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

2.3 Test set-up and instrumentation

All compression tests were carried out using a Denison universal testing machine with a 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 × 305 mm height × 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 \( \sigma_{\text{max}} \) is the maximum axial stress, and \( \varepsilon_u \) is the ultimate strain at the rupture of FRP confinement. The results presented in Table 3 showed that the axial stress increase \( (\sigma_{\text{max}}/f'_c) \) 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 \( (\varepsilon_u/\varepsilon_{\text{co}}) \) 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:

\[
\mu_\varepsilon = \frac{\varepsilon_u}{\varepsilon_y}
\]
where $\mu$ is the specimen’s ductility, $\varepsilon_u$ 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 $\varepsilon_y$ 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.

Acknowledgement

The authors are grateful for the financial supports received from the Australian Research Council through a Discovery Early Career Researcher Award (Project ID: DE140101349) for the second author. The authors would like to thank Messers Fernando Escribano, Cameron Neilson and Ritchie Mclean from the high bay laboratory of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia for their technical supports during the tests. The first author is grateful for the financial supports received from the Higher Committee for Education Development in Iraq.

References


List of Tables

Table 1. Details of test specimens.
Table 2. Key test results.
Table 3. Comparison between inner tubes of PVC and steel
Table 4. Axial strain and ductility test results
List of Figures

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.

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

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.

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
### Table 1 Details of test specimens

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Label</th>
<th>Inner Hole Diameter (mm)</th>
<th>Number of CFRP Layers</th>
<th>Inner PVC tube thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow core with inner PVC tube</td>
<td>HCT-1</td>
<td>87</td>
<td>----</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>HCT-2</td>
<td>87</td>
<td>----</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>HC1FT-1</td>
<td>87</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>HC1FT-2</td>
<td>87</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>HC2FT-1</td>
<td>87</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>HC2FT-2</td>
<td>87</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Hollow core</td>
<td>HC-1</td>
<td>90</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>HC-2</td>
<td>90</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>HC1F-1</td>
<td>90</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>HC1F-2</td>
<td>90</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>HC2F-1</td>
<td>90</td>
<td>2</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>HC2F-2</td>
<td>90</td>
<td>2</td>
<td>----</td>
</tr>
<tr>
<td>Solid</td>
<td>S-1</td>
<td>Solid</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>S-2</td>
<td>Solid</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>S1F-1</td>
<td>Solid</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>S1F-2</td>
<td>Solid</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>S2F-1</td>
<td>Solid</td>
<td>2</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>S2F-2</td>
<td>Solid</td>
<td>2</td>
<td>----</td>
</tr>
</tbody>
</table>
Table 2 Key test results

<table>
<thead>
<tr>
<th>Specimens Label</th>
<th>Maximum Stress $\sigma_{\text{max}}$ (MPa)</th>
<th>Strain at Maximum Stress $\varepsilon_{\text{max}}$</th>
<th>Strain at Rupture of FRP $\varepsilon_{u}$</th>
<th>Hoop Rupture Strain $\varepsilon_{h,rup}$</th>
<th>Average $\sigma_{\text{max}}$</th>
<th>Average $\varepsilon_{\text{max}}$</th>
<th>Average $\varepsilon_{u}$</th>
<th>Average $\varepsilon_{h,rup}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCT-1</td>
<td>46.7</td>
<td>46.2</td>
<td>0.0028</td>
<td>---</td>
<td>46.2</td>
<td>0.0028</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>HCT-2</td>
<td>45.7</td>
<td>46.2</td>
<td>0.0027</td>
<td>---</td>
<td>45.7</td>
<td>0.0027</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>HC1FT-1</td>
<td>54.1</td>
<td>54.1</td>
<td>0.0053</td>
<td>0.0295</td>
<td>54.1</td>
<td>0.0053</td>
<td>0.0295</td>
<td>0.0086</td>
</tr>
<tr>
<td>HC2FT-1</td>
<td>66.5</td>
<td>65.0</td>
<td>0.0281</td>
<td>0.0199</td>
<td>66.5</td>
<td>0.0281</td>
<td>0.0199</td>
<td>0.0113</td>
</tr>
<tr>
<td>HC2FT-2</td>
<td>63.5</td>
<td>65.0</td>
<td>0.0116</td>
<td>0.0199</td>
<td>63.5</td>
<td>0.0116</td>
<td>0.0199</td>
<td>0.0113</td>
</tr>
<tr>
<td>HC-1</td>
<td>46.8</td>
<td>46.9</td>
<td>0.0023</td>
<td>0.0024</td>
<td>46.8</td>
<td>0.0023</td>
<td>0.0024</td>
<td>---</td>
</tr>
<tr>
<td>HC-2</td>
<td>46.9</td>
<td>46.9</td>
<td>0.0023</td>
<td>0.0024</td>
<td>46.9</td>
<td>0.0023</td>
<td>0.0024</td>
<td>---</td>
</tr>
<tr>
<td>HC1F-1</td>
<td>54.5</td>
<td>54.5</td>
<td>0.0048</td>
<td>0.0048</td>
<td>54.5</td>
<td>0.0048</td>
<td>0.0048</td>
<td>0.0091</td>
</tr>
<tr>
<td>HC2F-1</td>
<td>60.9</td>
<td>62.8</td>
<td>0.006</td>
<td>0.0065</td>
<td>60.9</td>
<td>0.0065</td>
<td>0.0065</td>
<td>0.0101</td>
</tr>
<tr>
<td>HC2F-2</td>
<td>64.7</td>
<td>62.8</td>
<td>0.007</td>
<td>0.0065</td>
<td>64.7</td>
<td>0.0065</td>
<td>0.0065</td>
<td>0.0104</td>
</tr>
<tr>
<td>S-1</td>
<td>49.6</td>
<td>48.9</td>
<td>0.0028</td>
<td>0.0030</td>
<td>49.6</td>
<td>0.0028</td>
<td>0.0030</td>
<td>---</td>
</tr>
<tr>
<td>S-2</td>
<td>48.13</td>
<td>48.9</td>
<td>0.0032</td>
<td>---</td>
<td>48.13</td>
<td>0.0032</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>S1F-1</td>
<td>70.3</td>
<td>70.3</td>
<td>0.0316</td>
<td>0.0316</td>
<td>70.3</td>
<td>0.0316</td>
<td>0.0316</td>
<td>0.0098</td>
</tr>
<tr>
<td>S2F-1</td>
<td>104.6</td>
<td>101.8</td>
<td>0.0214</td>
<td>0.0233</td>
<td>104.6</td>
<td>0.0214</td>
<td>0.0233</td>
<td>0.0129</td>
</tr>
<tr>
<td>S2F-2</td>
<td>98.9</td>
<td>101.8</td>
<td>0.0251</td>
<td>0.0233</td>
<td>98.9</td>
<td>0.0251</td>
<td>0.0233</td>
<td>0.0137</td>
</tr>
</tbody>
</table>
Table 3 Comparison between inner tubes of PVC and steel

<table>
<thead>
<tr>
<th>Specimens Label</th>
<th>Maximum Stress $\sigma_{\text{max}}$ (MPa)</th>
<th>Stress Enhancement $\sigma_{\text{max}}/f'_c$</th>
<th>Strain at Rupture of FRP Tube $\varepsilon_{\text{cu}}$</th>
<th>Average $\varepsilon_{\text{cu}}$</th>
<th>Strain Enhancement $\varepsilon_{\text{cu}}/\varepsilon_{\text{co}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC1FT-1</td>
<td>54.1</td>
<td>54.1</td>
<td>1.03</td>
<td>0.0295</td>
<td>9.8</td>
</tr>
<tr>
<td>HC2FT-1</td>
<td>66.5</td>
<td>65.0</td>
<td>1.24</td>
<td>0.0281</td>
<td>9.5</td>
</tr>
<tr>
<td>HC2FT-2</td>
<td>63.5</td>
<td></td>
<td>0.0293</td>
<td>0.0287</td>
<td></td>
</tr>
<tr>
<td>D37-C1-I</td>
<td>42.9</td>
<td>42.2</td>
<td>1.14</td>
<td>0.0166</td>
<td>5.7</td>
</tr>
<tr>
<td>D37-C1-II</td>
<td>41.4</td>
<td></td>
<td>0.0133</td>
<td>0.0150</td>
<td></td>
</tr>
<tr>
<td>D37-C2-I</td>
<td>55.9</td>
<td>54.4</td>
<td>1.48</td>
<td>0.0235</td>
<td>8.1</td>
</tr>
<tr>
<td>D37-C2-II</td>
<td>52.9</td>
<td></td>
<td>0.0188</td>
<td>0.0212</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 Axial strain and ductility test results

<table>
<thead>
<tr>
<th>Specimen Label</th>
<th>Strain ε</th>
<th>Strain at Yield stress $\sigma_y$</th>
<th>Strain at Rupture stress $\varepsilon_u$</th>
<th>Strain at 85% of $\sigma_{\text{max}}$</th>
<th>Ductility $\mu_\varepsilon$</th>
<th>Average Ductility</th>
<th>Normalized average ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCT-1</td>
<td>0.0018</td>
<td>---</td>
<td>0.0046</td>
<td>2.5</td>
<td>2.4</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>HCT-2</td>
<td>0.0018</td>
<td>---</td>
<td>0.0042</td>
<td>2.3</td>
<td>14.8</td>
<td>6.17</td>
<td></td>
</tr>
<tr>
<td>HC1FT-1</td>
<td>0.0020</td>
<td>0.0295</td>
<td>---</td>
<td>14.8</td>
<td>15.5</td>
<td>6.46</td>
<td></td>
</tr>
<tr>
<td>HC2FT-1</td>
<td>0.0018</td>
<td>0.0281</td>
<td>---</td>
<td>15.6</td>
<td>15.5</td>
<td>6.46</td>
<td></td>
</tr>
<tr>
<td>HC2FT-2</td>
<td>0.0019</td>
<td>0.0293</td>
<td>---</td>
<td>15.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC-1</td>
<td>0.0016</td>
<td>---</td>
<td>0.0033</td>
<td>2.1</td>
<td>2.25</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>HC-2</td>
<td>0.0016</td>
<td>---</td>
<td>0.0038</td>
<td>2.4</td>
<td>12.7</td>
<td>5.64</td>
<td></td>
</tr>
<tr>
<td>HC1F-1</td>
<td>0.0021</td>
<td>0.0267</td>
<td>---</td>
<td>12.7</td>
<td>13.4</td>
<td>5.96</td>
<td></td>
</tr>
<tr>
<td>HC2F-1</td>
<td>0.0020</td>
<td>0.0274</td>
<td>---</td>
<td>13.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC2F-2</td>
<td>0.0020</td>
<td>0.0261</td>
<td>---</td>
<td>13.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-1</td>
<td>0.0018</td>
<td>---</td>
<td>0.0056</td>
<td>3.3</td>
<td>3.15</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>S-2</td>
<td>0.0017</td>
<td>---</td>
<td>0.0048</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1F-1</td>
<td>0.0019</td>
<td>0.0243</td>
<td>---</td>
<td>12.7</td>
<td>12.7</td>
<td>4.03</td>
<td></td>
</tr>
<tr>
<td>S2F-1</td>
<td>0.0015</td>
<td>0.0214</td>
<td>---</td>
<td>14.2</td>
<td>15.45</td>
<td>4.90</td>
<td></td>
</tr>
<tr>
<td>S2F-2</td>
<td>0.0015</td>
<td>0.0251</td>
<td>---</td>
<td>16.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Figure 5  Axial stress-strain curves of solid and hollow specimens
Figure 6 Axial stress-strain curves of hollow with and without PVC tube 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 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
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