An experimental study on the effect of concrete shrinkage on compressive behaviour of high-strength concrete-filled FRP tubes

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Publication details
AN EXPERIMENTAL STUDY ON THE EFFECT OF CONCRETE SHRINKAGE ON COMPRESSIVE BEHAVIOUR OF HIGH-STRENGTH CONCRETE-FILLED FRP TUBES

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ABSTRACT
Fibre reinforced polymer (FRP)-confined concrete has received significant research attention over the last two decades, with recent experimental studies identifying significant benefits offered by FRP-confined high-strength concrete (HSC). However, studies examining the influence of concrete shrinkage on the behaviour of FRP-confined concrete remain limited, with no reported study to date examining this influence on HSC specimens. Concrete shrinkage may pose a concern for concrete-filled FRP tubes (CFFTs), as in these members the curing of concrete takes place inside the FRP tube. This paper presents an experimental investigation on the influence of FRP-to-concrete interface gap, caused by concrete shrinkage, on axial compressive behaviour of FRP-confined HSC. A total of 18 aramid FRP (AFRP)-confined concrete specimens with circular cross-sections were manufactured. 3 of these specimens were instrumented to monitor long term shrinkage strain development and the remaining 15 were tested under monotonic axial compression. The influence of concrete shrinkage was examined by applying a gap of up to 0.12 mm thickness at the FRP-to-concrete interface, simulating 1600 microstrain of shrinkage in the radial direction. The results of this experimental study indicate that the influence of interface gap on axial strain enhancement is significant, with an increase observed as the gap increased. Conversely, the influence of interface gap on axial strength enhancement is found to be small with a slight reduction observed with increased gap. It was also observed that an increase in interface gap increases the tendency for a drop in axial stress at the transition region of axial stress-strain curves.

KEYWORDS
Fibre reinforced polymer (FRP), high-strength concrete (HSC), shrinkage, gap, CFFT, stress-strain.

INTRODUCTION
The use of fibre reinforced polymer (FRP) composites as a confining material for concrete has recently received significant research attention. A large number of experimental studies into the axial compressive behaviour have been performed over the last two decades producing over 3000 test results, as discussed and assessed in the recent comprehensive review studies reported in Ozbakkaloglu et al. (2013), Ozbakkaloglu and Lim (2013) and Lim and Ozbakkaloglu (2014). These studies revealed that the majority of early experimental studies focused on FRP-confined normal-strength concrete (NSC) (e.g., Karabinis and Rousakis 2002; Ilki and Kumbasar 2003; Smith et al. 2010) with studies on FRP-confined high-strength concrete (HSC) only recently gaining increased research attention. The extensive number of studies that have recently been undertaken on FRP-confined HSC that investigated the behaviour of HSC-filled FRP tube columns (e.g., Zohrevand and Mirmiran 2012; Idris and Ozbakkaloglu 2013; Ozbakkaloglu and Vincent 2013; Vincent and Ozbakkaloglu 2013a,b) and FRP-HSC-steel composite columns (e.g., Louk Fanggi and Ozbakkaloglu 2013; Ozbakkaloglu and Louk Fanggi 2013,2014;
Ozbaikkaloglu and Idris (2014) demonstrated the ability of these members to effectively combine the constitutive high-strength materials to exhibit a highly ductile behaviour under various loading conditions. However, the influence of long term concrete shrinkage on the axial compressive behaviour is yet to be investigated.

Concrete shrinkage may pose a concern for concrete-filled FRP tube (CFFT) columns, as in these columns the curing of concrete takes place inside the FRP tube. This concrete shrinkage may influence the compressive behaviour of the CFFT columns in the long term, and hence it is important to understand this influence for successful design and construction of these members. This is of particular importance for CFFTs manufactured with HSC due to the potential of higher levels of shrinkage associated with higher strength concretes (Bissonnette et al., 1999; Kwan et al., 2010). This important area of research has received very limited attention, with only two studies reported in the literature that experimentally investigated concrete shrinkage in FRP-confined concrete, with both studies examining NSC specimens (Naguib and Mirrman 2002; Karimi et al. 2011).

As part of a larger experimental program at The University of Adelaide on FRP-concrete composite columns, the experimental study reported in this paper was aimed at investigating the influence of concrete shrinkage on the compressive behaviour of HSC specimens. This original study examined test specimens manufactured with up to five different shrinkage levels in the radial direction. The radial shrinkage was simulated through predetermined gaps ranging from 0 to 0.12 mm supplied at the FRP-to-concrete interface, representing up to 1600 microstrain (µε) of concrete shrinkage. The results of the test program are first presented and followed by a detailed discussion on the observed influences of interface gap on specimen behaviour.

TEST PROGRAM

Test Specimens and Materials

A total of 18 aramid FRP (AFRP) confined cylindrical specimens, all with a 152 mm diameter and a 305 mm height, were prepared for the two phase experimental program. In the first phase three specimens were prepared to monitor long term shrinkage development of the concrete in CFFTs. These specimens were prepared as CFFTs to allow shrinkage measurements of FRP-confined concrete to be taken directly after the hardening of concrete. The tubes of the CFFT specimens were manufactured using two layers of AFRP, and the bottom surfaces of the specimens remained covered for the entire duration of shrinkage strain measurements.

In the second phase of the experimental program, 15 AFRP-confined cylindrical specimens were prepared using four layers of AFRP and tested under axial compression. The influence of concrete shrinkage on the axial behaviour was examined by preparing specimens with varying amount of gap at the FRP-to-concrete interface, simulating the change in interface conditions due to radial shrinkage of concrete. This gap was achieved by wrapping low strength polyethylene sheets around the concrete during the manual wet lay-up procedure of the aramid fibre sheets, to create a boundary gap between the concrete and FRP shell. The concrete specimens were 152 mm in diameter and the polyethylene sheets were 0.03 mm in thickness, resulting in a simulated nominal radial shrinkage of 400 µε per layer of polyethylene sheet. The test specimens were prepared with nominal shrinkage levels of 0, 400, 800, 1200 and 1600 µε. These shrinkage levels were selected to represent maximum possible shrinkage strains to be experienced by concrete in a CFFT column and are based on the results obtained from the first phase of the study, as discussed later in the paper. The details of the 3 CFFT specimens and 15 FRP-wrapped test specimens are given in Table 1, while the FRP-wrapping procedure is shown in Figure 1.

<table>
<thead>
<tr>
<th>Testing method</th>
<th>Average $f'_{con}$ (MPa)</th>
<th>Fibre thickness (mm)</th>
<th>Shrinkage gap (µε)</th>
<th>Number of specimens</th>
</tr>
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<tr>
<td>Axial compressive testing</td>
<td>83.4</td>
<td>0.8</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>83.4</td>
<td>0.8</td>
<td>400</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>83.4</td>
<td>0.8</td>
<td>800</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>83.4</td>
<td>0.8</td>
<td>1200</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>83.4</td>
<td>0.8</td>
<td>1600</td>
<td>3</td>
</tr>
<tr>
<td>Shrinkage monitoring</td>
<td>83.4</td>
<td>0.4</td>
<td>monitored</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1. Properties of test specimens
The concrete was batched and mixed in the laboratory and consisted of crushed limestone as the coarse aggregate, with a 10 mm nominal maximum diameter. The manufacturer supplied material properties of the unidirectional aramid fibre sheets are shown in Table 2. In addition to the manufacturer supplied properties, material properties of the FRP composites and polyethylene sheets determined from flat coupon tests are also provided in Table 2. The specimens were prepared using a manual wet lay-up process that involved wrapping epoxy resin impregnated fibre sheets around either Styrofoam templates or precast concrete cylinders for the CFFT and FRP-wrapped specimens, respectively.

Table 2. Material properties of fibre, FRP composite and polyethylene sheets

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal thickness (mm/ply)</th>
<th>Material properties</th>
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<tbody>
<tr>
<td>Aramid fibre</td>
<td>0.2</td>
<td>Provided by manufacturer</td>
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<tr>
<td></td>
<td></td>
<td>Ultimate Tensile stress (MPa)</td>
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<td></td>
<td></td>
<td>2600</td>
</tr>
<tr>
<td>Polyethylene sheet</td>
<td>0.03</td>
<td>Obtained from coupon tests</td>
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<tr>
<td></td>
<td></td>
<td>Ultimate tensile stress (MPa)</td>
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<tr>
<td></td>
<td></td>
<td>18.6</td>
</tr>
</tbody>
</table>

*calculated based on nominal thickness of fibres in FRP coupons

Instrumentation and Testing Procedure

The three CFFTs used in the first phase of the experimental program were instrumented with strain gauges and placed in a temperature controlled room to monitor the long-term shrinkage strain development of concrete. Each specimen was instrumented with a single 20-mm strain gauge bonded to the centre of the top concrete surface. Specimens were placed in a controlled environment, with the temperature maintained at 22 ± 2 degrees Celsius and relative humidity at 55 ± 10 %.

The axial compressive test specimens from Phase 2 were instrumented with four linear variable differential transformers (LVDTs), which were mounted at the corners between the loading and supporting steel plates of the test machine. The recorded deformations were used in the calculation of the average axial strains along the full height of the specimens. In addition to the four full-height LVDTs, four LVDTs were mounted on an aluminium cage attached to the mid-section of each specimen. This cage had an LVDT installed on each of its four sides and was designed to mount directly on the FRP shell via surface screws. The LVDT cage had a gauge length of 175 mm and it was placed at equal distance from each specimen end. These mid-section LVDT readings were used to correct the full-height LVDT records at the early stages of loading, where additional displacements due to closure of the gaps in the setup were also recorded by the full-height LVDTs. Hoop strains around the specimen perimeter were measured by 5 unidirectional strain gauges having a gauge length of 5 mm that were bonded horizontally on the FRP jacket outside the overlap region at specimen mid-height.

The specimens were tested under monotonic axial compression using a 5000-kN capacity universal testing machine. The loading was applied with load control at 3 kN per second, whereas displacement control was used at approximately 10 microstrain per second beyond the initial softening until specimen failure. To ensure an even loading surface, each specimen end was carefully levelled using a concrete grinding machine before testing. Precision cut steel discs, 15-mm thick and 150-mm in diameter, were installed at specimen ends to apply the load only to the concrete core. The experimental test setup used for axial compressive testing is shown in Figure 2.
TEST RESULTS AND DISCUSSIONS

Shrinkage Strain Measurements

It can be seen from the recorded shrinkage strains shown in Figure 3 that HSC specimens experienced a maximum of approximately 600 $\mu$e of shrinkage after six months with over 85% of this occurring during the first two months. Based on the shrinkage strain development trends observed in Figure 3, FRP-to-concrete interface gaps were selected for the second phase of the experimental program to represent the range of shrinkage expected over the full service life of a CFFT column made with HSC.

Axial Compression Tests

Observed failure modes

The observed failure mode of the specimens was rupture of the FRP tube accompanied by an instantaneous loss of applied load. Typical specimen failures are shown in Figure 4, where the observed FRP rupture was localized to specimen mid-section. Typical shear cone formations were evident in all failed specimens where FRP rupture allowed examination of the concrete core.
Axial stress to lateral- and axial-strain behaviour

It can be seen from the axial stress-strain relationships presented in Figure 5 that the curves of all specimens exhibited overall ascending second branches. However, it can be observed in these figures that as the interface gap increased so did the tendency for a slight loss in axial stress during the transition region between the first and second branches. This behaviour can be attributed to the increased interface gap causing a delayed activation of the confinement mechanism, during the rapid expansion of the concrete core. As can be seen in Figure 5, this behaviour was temporary and was followed by strength recovery and further performance gains. As evident from Figure 5, an increase in FRP-to-concrete interface gap lead to a slight decrease in ultimate strength, whereas an increase in interface gap resulted in a significant increase in ultimate strain enhancement.

Figure 5. Axial stress to lateral- and axial-strain behaviour of test specimens

In addition to axial stress-strain relationships, Figure 5 also presents the corresponding axial stress to lateral strain relationships. A close examination of these curves reveals that specimens with no interface gap started developing lateral strain in the FRP shell as soon as the axial load was applied. On the other hand, specimens with 400 µε or higher of interface gaps experienced a significant delay in lateral strain development as the interface gap was closed by the expanding concrete core. These observations suggest that a strong correlation exists between delay in FRP activation, as indicated by lateral strain development, and drop in axial stress near the transition region.
CONCLUSIONS

This paper has presented the results of an experimental investigation into the influence of concrete shrinkage on the axial compressive behaviour of FRP-confined HSC. Based on the results and discussion presented in this paper, the following conclusions can be drawn:

1. An increase in FRP-to-concrete interface gap results in a slight decrease in axial strength enhancement of FRP-confined HSC. On the other hand, an increase in interface gap leads to a significant increase in axial strain enhancement of FRP-confined HSC.

2. An increase in interface gap increases the tendency for a drop in axial strength at the transition point between the first and second branches of the stress-strain curve of FRP-confined HSC. This strength loss is caused by the delay in activation of the confinement mechanism in the presence of the interface gap.

REFERENCES


