An Experimental Study on Shrinkage Strains of Normal-and High-Strength Concrete-Filled Frp Tubes

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Abstract. It is now well established that concrete-filled fiber reinforced polymer (FRP) tubes (CFFTs) are an attractive construction technique for new columns, however studies examining concrete shrinkage in CFFTs remain limited. Concrete shrinkage may pose a concern for CFFTs, as in these members the curing of concrete takes place inside the FRP tube. This paper reports the findings from an experimental study on concrete shrinkage strain measurements for CFFTs manufactured with normal- and high-strength concrete (NSC and HSC). A total of 6 aramid FRP (AFRP)-confined concrete specimens with circular cross-sections were manufactured, with 3 specimens each manufactured using NSC and HSC. The specimens were instrumented with surface and embedded strain gauges to monitor shrinkage development of exposed concrete and concrete sealed inside the CFFTs, respectively. All specimens were cylinders with a 152 mm diameter and 305 mm height, and their unconfined concrete strengths were 44.8 or 83.2 MPa. Analysis of the shrinkage measurements from concrete sealed inside the CFFTs revealed that embedment depth and concrete compressive strength only had minor influences on recorded shrinkage strains. However, an analysis of shrinkage measurements from the exposed concrete surface revealed that higher amounts of shrinkage can occur in HSC. Finally, it was observed that shrinkage strains are significantly higher for concrete exposed at the surface compared to concrete sealed inside the CFFTs.

1. Introduction

External confinement of concrete with fiber reinforced polymer (FRP) composites has become widely accepted as a technique for enhancing strength and ductility of normal- (e.g.,[1-3]) and high-strength (e.g., [4-9]) concretes (NSC and HSC). A large number of experimental studies into axial compressive behavior have been performed over the last two decades producing over 3000 test results, as discussed and assessed in the recent comprehensive review studies [10, 11]. The majority of early experimental studies focused on FRP-wrapped concrete columns (e.g., [12, 13]), with fewer studies reported on concrete-filled FRP tubes (CFFTs). Initial experimental studies on CFFTs (e.g., [14, 15]) along with more recent extensive studies on the axial compressive (e.g., [5, 16-20]) and seismic behavior of CFFT columns (e.g., [21-26]) have demonstrated the ability of CFFTs to develop very high inelastic deformation capacities, making them an attractive option for construction of new high-performance columns.

The use of higher strength concretes in the construction industry has been on a steady incline due to the superior performance and economy offered by HSC over NSC. These beneficial characteristics result in more cost-effective construction of bridges and multistory buildings. Recently, a significant amount of research has been performed on CFFTs manufactured with HSC (e.g., [6-9]) that has demonstrated the...
ability of these structural elements to display substantial strength and strain enhancements. However, the concrete shrinkage strain development for HSCFFTs is yet to be investigated. Concrete shrinkage may pose a concern for CFFT columns, as in these columns the curing of concrete takes place inside the FRP tube. This concrete shrinkage may influence the performance of the CFFT columns in the long term, and hence it is important to quantify and understand the shrinkage behavior 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 [27, 28].

Only two studies have been reported to date on concrete shrinkage in FRP-confined concrete, with both studies examining NSC specimens [29, 30]. Naguib and Mirmiran [29] monitored the concrete shrinkage development of a single CFFT specimen, with these strains monitored over a 12 month period. Karimi et al. [30] studied the compressive behavior of CFFT specimens with internal steel I-beams manufactured with and without a shrinkage reducing agent. However, to date, no experimental study has systematically investigated concrete shrinkage strain development within CFFTs.

To address this gap in the research, this paper presents an experimental investigation into concrete shrinkage measurements for normal- and high-strength CFFTs (NSCFFTs and HSCFFTs). The influence of strain measurement location and concrete compressive strength are examined. The results of the test program are first presented, followed by a detailed discussion on the observed influences.

2. Test database

2.1. Test specimens and materials

Six aramid FRP (AFRP)-confined cylindrical specimens, all with a 152 mm diameter and a 305 mm height, were prepared to monitor shrinkage development of the concrete in the CFFTs. Two different concrete mixes were used, with average compressive strengths of 44.8 and 83.2 MPa which are referred to as NSC and HSC, respectively. Three of the CFFTs were manufactured as NSC specimens, with the remaining three manufactured as HSC. The tubes of the CFFTs were made using two layers of AFRP, and the bottom and top surfaces of the specimens remained covered and uncovered respectively, for the entire duration of shrinkage strain measurements. Both the NSC and HSC were batched and mixed in the laboratory and consisted of crushed bluestone gravel as the coarse aggregate, with a 10 mm nominal maximum diameter. Superplasticiser was added to the HSC mix to ensure a workable concrete, which resulted in a measured slump of over 220 mm. The mix designs for the NSC and HSC mixes are reported in table 1.

| Concrete constituent     | NSC  | HSC  |
|-------------------------|------|------|
| Cement (kg/m$^3$)       | 380  | 506  |
| Silica fume (kg/m$^3$)  | 0    | 44   |
| Sand (kg/m$^3$)         | 700  | 700  |
| Coarse Aggregate (kg/m$^3$) | 1050 | 1050 |
| Water (kg/m$^3$)        | 220  | 172  |
| Superplasticiser (kg/m$^3$) | 0    | 12   |
| Water to cement ratio   | 0.58 | 0.33 |

The specimens were manufactured using a wet lay-up technique, which involved wrapping epoxy resin saturated aramid fiber sheets around Styrofoam templates. The FRP tubes were prepared using two layers of 0.2 mm thick fiber sheet with fibers oriented in the hoop direction, and they had a single overlap region of 150 mm length. The fibers used in the manufacture of the AFRP tubes had an elastic modulus of 128.5 GPa and ultimate tensile strength and strain of 2390 MPa and 1.86% respectively, determined by coupon tests.
2.2. Instrumentation
The six CFFTs were instrumented with strain gauges and placed in a temperature controlled room for 6 months to monitor the shrinkage strain development of concrete. Each specimen was instrumented to measure concrete shrinkage in the radial direction for the CFFTs at 4 locations. A single 20-mm strain gauge was bonded to the top concrete surface and an additional 3 embedded strain gauges with a gauge length of 20 mm were located within the concrete at depths \(d\) of 15, 75 and 150 mm from the top concrete surface. All four strain gauges were aligned horizontally along the diameter of CFFTs to record shrinkage of concrete only in the radial direction. Specimens were placed in a controlled environment, with the temperature maintained at 22 ± 2 °C and relative humidity at 55 ± 10%. An overview of this instrumentation set-up is presented in figure 1.

![Figure 1. Instrumentation of CFFTs: a) Typical surface strain gauge; b) Typical embedded strain gauges; c) AFRP tubes and data acquisition system prior to concrete pour](image)

3. Test Results
The concrete shrinkage strain measurements of the NSC and HSC specimens are presented in figures 2 and 3, respectively. Measurements of strains began immediately after strain gauges were mounted to the top surface of the hardened concrete, approximately 24 h after the concrete was cast into the FRP tubes.

![Figure 2. Shrinkage of concrete in NSCFFTs](image)

![Figure 3. Shrinkage of concrete in HSCFFTs](image)
It can be seen from the shrinkage strains of the NSCFFTs shown in figure 2 that NSC specimens recorded up to approximately 400 µε of radial shrinkage after six months, with over 85% of this occurring during the first two months. A similar shrinkage behavior was evident for the HSC specimens shown in figure 3, with a maximum of around 600 µε of shrinkage recorded at the end of the six-month period. As can be seen in figures 2 and 3, significant variations in shrinkage strain development can be seen when comparing values at the same locations from identically prepared specimens. A noticeable example of this is a comparison of surface measurements for HSCFFTs, where specimen 2 deviates from the general trend. These differences in measured shrinkage strains can be attributed to localized effects such as aggregate distribution.

3.1. Influence of strain measurement location
A comparison of the shrinkage strain development shown in figures 2 and 3 reveals that shrinkage strains recorded at the surface of the concrete are significantly higher than those recorded from embedment depths within the concrete of CFFTs. This experimental observation can be seen to be independent of concrete strength as it’s equally applicable to NSCFFTs and HSCFFTs. This outcome can be attributed to less water loss experienced by the concrete within the CFFT, resulting in lower shrinkage strains. In addition to this observation, a comparison of shrinkage strains monitored from embedded strain gauges reveals that embedment depth has little to no influence on amount of shrinkage with the majority of embedded gauges recording approximately 100 µε of shrinkage. Once again, this experimental observation can be seen to be equally applicable to NSCFFTs and HSCFFTs, and is in agreement with those presented in Naguib and Mirmiran [29] for the single NSCFFT examined.

3.2. Influence of concrete compressive strength
The influence of concrete compressive strength was examined through the comparison of shrinkage strain development at the same locations for NSCFFTs and HSCFFTs in figures 2 and 3, respectively. A comparison of the strains recorded at the top surface of the CFFTs reveals that shrinkage strain values are similar between NSC and HSC, except for one measurement that indicates that exposed concrete in HSCFFTs can develop significantly higher levels of shrinkage strains. A comparison of the shrinkage strains monitored from embedded strain gauges reveals that concrete compressive strength has little to no influence on development of shrinkage strains of concrete sealed inside CFFTs.

4. Conclusion
This paper has presented the results of an experimental study into the influence of strain measurement location and concrete compressive strength on concrete shrinkage strain measurements for CFFTs manufactured with normal- and high-strength concrete (NSC and HSC). Based on the results and discussion presented in this paper, the following conclusions can be drawn:

1. Shrinkage strains are significantly higher for concrete exposed at the surface compared to concrete sealed inside the CFFTs. It was found that these observations are equally applicable to NSCFFTs and HSCFFTs.
2. NSCFFTs and HSCFFTs typically develop comparable levels of concrete shrinkage strains, however HSCFFTs can develop significantly higher amounts. This observation of higher values was found to be limited to shrinkage strains measured on exposed concrete.

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