Durability of HC-FCS cylinders subjected to hybrid environmental and mechanical loads

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ABSTRACT: Hollow-core fiber reinforced polymer-concrete-steel (HC-FCS) column system is relatively a new type of bridge column consisting of an external fiber reinforced polymer (FRP) tube, inner steel tube, and concrete shell in between. HC-FCS represents a promising alternative to conventional reinforced concrete columns with superior mechanical behavior and easy construction. However, one obstacle hindering greater acceptance of this type of columns in bridge construction application, especially in harsh environment area, is the lack of experimental data for the durability of HC-FCS columns subjected to long-term severe weather conditions. This study investigates the performance of HC-FCS cylinders exposed to combined freezing-thawing cycles, high temperature cycles and wet-dry cycles. Sustained axial load were also applied to the cylinders to simulate the service load in real life. Compression tests were conducted on the cylinders after the environmental conditioning finished. Test results indicate that the environmental exposures slightly reduced the strength of HC-FCS cylinders. Sustained axial load further deteriorated the strain capacity of the cylinders by causing micro-cracks on the FRP tube.

1 INTRODUCTION

Fiber-reinforced polymer (FRP) has been gaining increasing popularity in civil engineering market during the past few decades. Its high strength-to-mass ratio, ease of fabrication and relatively good corrosion resistance make it a good material for existing structures' retrofitting and new structures' construction (Hollaway 2010). However, the wider acceptance of FRP for infrastructure applications is being questioned because the rigorous durability performance of this material still faces uncertainties.

The hollow-core FRP-concrete-steel (HC-FCS) column, recently proposed by Teng et al. (2007), is one of the novel applications of FRP for new bridge construction. Several researchers have studied the mechanical behavior of this type of column (Abdelkarim and ElGawady 2016a, 2016b, 2016c; Anumolu et al. 2016) but no study has been done on its durability performance subjected to harsh weather conditions, such as freeze/thaw cycles in winter seasons, wet/dry cycles in rainy seasons and heating/cooling cycles in summer seasons (Micelli and Myers 2008).

Several researchers have investigated the durability capacities for different type of FRP specimens, including FRP rods, coupons, panels and FRP wrapped concrete cylinders. Wet/dry cycles using distilled water reduced the tensile strength of GFRP coupons by 11% after 10,000 hours' exposure (Silva et al. 2014). Dry freeze/thaw cycles barely affected the mechanical properties of FRP specimens, while wet freeze/thaw cycles cause moderate degradation on them. The extra moisture absorbed by the resin would expand in volume under freeze/thaw cycles, which resulted in initiation and propagation of microcracks in the resin. On the other hand, dry heat or heating/cooling cycles were shown to cause insignificant damage on FRP wrapped concrete cylinders (Kshirsagar et al. 2000; Karbhari et al. 2000 and 2002; Toutanji and Balaguru 1998; Silva et al. 2014).

This paper presents the durability evaluation of HC-FCS cylinders subjected to combined freeze/thaw cycles, wet/dry cycles, and heating/cooling cycles, while the cylinders were under sustained axial load. Prefabricated GFRP tubes made with polyester resin were used in this study. Compression tests were conducted on HC-FCS cylinders after the conditioning was completed, for both pre and post-conditioned specimens.

2 MATERIAL PROPERTIES

The FRP tube used as stay-in-place formwork in this experiment was manufactured through a filament winding process that utilized an isothalic polyester thermosetting resin to impregnate strands of continuous glass filaments. The winding angles of filaments were +35°. The detailed dimension and mechanical properties are listed in Table 1. Coupon tensile tests and split-disk tensile tests were conducted on samples cut from the tube in longitudinal and hoop directions, respectively, according to ASTM D3039 and ASTM D2290. Each test had at least three replicated samples and the average values were taken accordingly.

Table 1. Dimension and mechanical properties of the FRP tube

OD^*(mm)	t^*(mm)	f_L^*(MPa)	E_L^*(MPa)	ε_L^*(%)	f_H^*(MPa)	E_H^*(MPa)	ε_H^*(%)
214.6	3.2	58.1	10501	0.71	151.7	13348	1.73

Note: OD = outer diameter; t = wall thickness; f_L and f_H = ultimate tensile strength in longitudinal and hoop directions, respectively; E_L and E_H = elastic modulus in longitudinal and hoop directions, respectively; ε_L and ε_H = failure strain in longitudinal and hoop directions, respectively.

The outer diameter of the steel tube was 101.6 mm, and the wall thickness was 1.9 mm. Three 101.6 mm × 406.4 mm steel tubes were tested under a monotonic compressive load at a 0.5 mm/min displacement rate. Three coupons cut from the tube in the longitudinal direction were tested in tension based on ASTM A370. The mechanical properties of the steel tube are listed in Table 2.

Table 2. Mechanical properties of the steel tube

Compressive Strength (MPa)	Tensile Strength (MPa)	Tensile Strain (%)	Elastic Modulus (MPa)
500.6	620.5	0.4	200000

Self-Consolidating Concrete (SCC) was used to cast all of the HC-FCS cylinders. The mix design of the SCC is given in Table 3. Three 101.6 mm × 203.2 mm plain concrete cylinders were also casted to test the compressive strength on 28th day, and the average strength was 46.5 MPa.

Table 3. SCC mix proportions

w/cm	Cement (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	HRWRA (kg/m^3)	VEA (kg/m^3)
0.38	350	175	199	837	837	2.1	0.7

3 EXPERIMENTAL PROGRAM

3.1 Specimen Preparation

All of the cylinders were divided into three different sets: unconditioned unloaded (control), conditioned unloaded, and conditioned loaded. Each group had four specimens: three 304.8 mm high cylinders and one 228.6 mm high cylinder. This paper only focuses on the 304.8 high cylinders (Fig. 1a). In order to remove any unrelated moisture and temperature influence other than the environmental conditions on the GFRP tubes, all of the cylinders were cured in room temperature and covered with plastic cloth only. In addition, the top and bottom surfaces of the cylinders were coated with a thin layer of epoxy (Fig. 1b), for the purpose of simulating the actual scenario of HC-FCS bridge columns where the annular concrete and steel tube are not exposed to the outside environment.

(a) (b)

Figure. 1. Specimen preparation: (a) HC-FCS cylinder; (b) epoxy coating on concrete surfaces

3.2 Instrumentation and Test Setup in Environmental Chamber

In order to apply a sustained load on conditioned loaded specimens while they were experiencing environmental exposures, four cylinders in series were sandwiched between steel plates with post-tensioned Dywidag bars. Both a schematic and a picture of the setup are shown in Fig. 2. A hydraulic jack was used to apply the load and the load was monitored by a load cell. The target stress was 1 ksi, which is approximately 10% of the cylinder's design axial strength. This percentage is a typical value for bridges in the US where the service load ranges from 5% to 10% of the design axial capacity. Three nuts on top of the top steel plate were tightened after the target load was reached, followed by removing the hydraulic jack and the load cell. Three sets of washer springs were placed between the bottom two plates in an effort to sustain the load. Strain gauges were applied on each Dywidag bar to monitor the load relaxation, and the setup was reloaded if necessary. In addition, cylinders that were designed to undergo conditioning without loading were also placed on the floor of the environmental chamber.

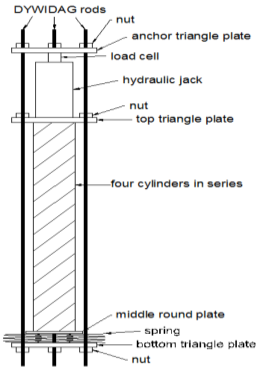


Figure. 2. Loading setup for environmental chamber

3.3 Environmental Exposure Regime

The complete environmental conditioning regime consisted of one set of freeze/thaw cycles, three sets of heating/cooling cycles, and three sets of wet/dry cycles alternatively. This regime was first proposed by Micelli and Nanni (2004) and has been adjusted in this study. A total of 50 cycles were applied for each set of conditions. The complete conditioning regime is illustrated in Fig. 3. The freeze/thaw, heating/cooling and wet/dry cycle conditions were aimed to simulate the winter, summer and rainy seasons over a 20-year period in American Midwest based on data from National Centers for Environmental Informaiton (NCEI) and National Weather Service. The total running time for the complete conditioning process was approximately 72 days.

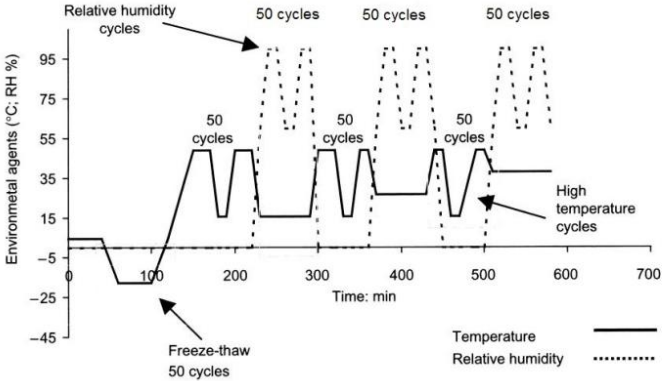


Figure. 3. Exposure regime used in the environmental chamber

3.4 Instrumentation and Setup for the Compression Test

All of the cylinders removed from the environmental chamber after the end of conditioning were kept in lab condition for at least one week before compression tests. Compression tests were conducted on a MTS 250 load frame with a capacity of 500 kip. Two linear variable displacement transformers (LVDTs) were instrumented underneath the top loading plate to monitor the vertical global deformation. Two strain gauges were applied to the FRP tube surface symmetrically at mid height along the hoop direction to track the hoop strain changes of the

FRP tube. A thin layer of hydro-stone was cast on top of the HC-FCS cylinders before compression test in order to distribute the vertical load uniformly. In the following sections, the nomination of the specimens are UC_#, FT_# and FT+S_# for control specimens, conditioned unloaded specimens, and conditioned loaded specimens, respectively, where the "#" sign represents the sample number.

Figure. 4. Setup for the compression test on HC-FCS cylinders

4 TEST RESULTS AND DISCUSSION

4.1 Failure Modes

All of the HC-FCS cylinders failed right after the rupture of the outer GFRP tube along the hoop direction. No obvious damage or buckling was observed on the inner steel tubes (Fig. 5), while similar observations for the inner steel tube were found on other researcher's experiment (Yu et al. 2012). The nearly intact mode of the inner steel tubes could be possibly due to the crack of the hydro-stone layer on top of the steel tube edge during loading, so not enough vertical pressure was transferred from the top loading plate to the top edge of the steel tube. In addition, the lower tendency to expand horizontally for the high-strength concrete shell could also result in no significant damage on steel tubes. The 28th day compressive strength for the concrete in referred research was 43.9 MPa while that value for this experiment was around 62 MPa in average. Much louder broken sound was heard for conditioned cylinders compared to the control specimens, suggesting that the environmental conditioning had probably embrittled the outer GFRP tube.

(a)

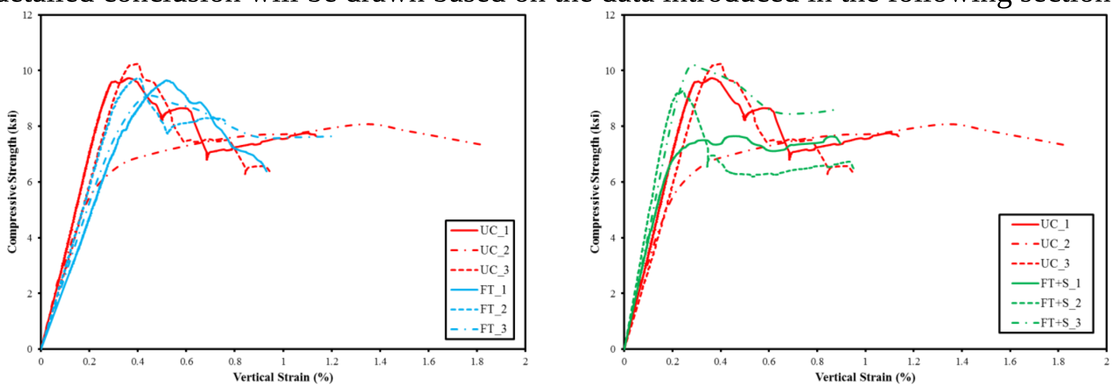
(b)

(c)

Figure 5. Failure modes of selected HC-FSC cylinders: (a) UC_1; (b) FT_1; (c) FT+S_1

4.2 Stress-Strain Curves

The stress-strain curves for most HC-FCS cylinders can be generally divided into three stages: starting with linearly increasing line representing the compression of concrete of inner steel tube in the elastic range, followed by the decreased slope indicating the crack of the concrete and the engagement of the confinement by the outer FRP tube and inner steel tube. The second stage was short and transited to the gradually decreasing line until sudden failure. This strain-softening behavior was also observed from other researchers' similar tests (Mandal et al. 2005; Cui and Sheikh 2010), which suggesting that high-strength concrete less benefited from confinement compared to low-strength concrete. As also seen from the curves, the conditioned specimens showed lower maximum strength and strain in average compared to control specimens, but more detailed conclusion will be drawn based on the data introduced in the following section.



(a) (b)

Figure. 6. Stress-strain curves in vertical direction for: (a) UC vs. FT; (b) UC vs. FT+S.

4.3 Maximum Strength and Strain

Generally, the conditioned cylinders demonstrated decreased maximum strength and strain compared to the control specimens (Fig. 7), indicating the GFRP tube was deteriorated during the environmental conditioning. The sustained load further degraded the properties of the cylinders, but affected more on the strain than on the strength. The hoop strains of the conditioned loaded specimens were deteriorated more severely than conditioned unloaded specimens. This is due to expanding pressure applied on the outer GFRP tube by the concrete shell resulted from the extra vertical load, which cause the generation and propagation of microcracks on the resin phase of the GFRP. Thus, the conditioned loaded cylinders showed more reduced hoop strain. More detailed data can be seen in Table 5, where strength reductions for FT and FT+S cylinders were 5% and 10%, respectively. FT cylinders were decreased by 7% and 12% on vertical strain and hoop strain, respectively, while the FT+S cylinders were reduced by 12% and 38% on vertical strain and hoop strain, respectively.

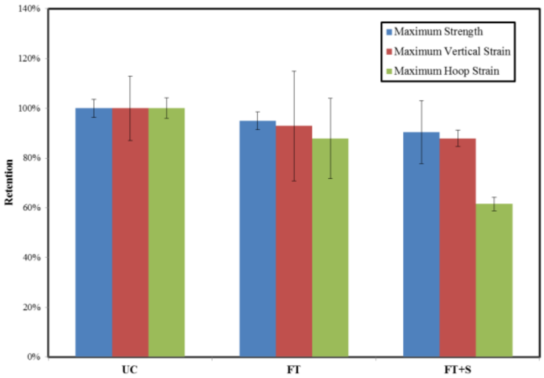


Figure. 7. Retention for maximum strength and strain of HC-FCS cylinders with ± one standard deviation

Table 4. Mechanical Properties in both vertical and hoop direction for HC-FCS cylinders

Cylinder		Maximum Strengh (MPa)	Maximum Vertical Strain (%)	Maximum Hoop Strain (%)
UC	Average	68.8	1.04	1.25
	Standard Deviation	2.48	0.13	0.05
	COV	4%	13%	4%
	Retention	100%	100%	100%
FT	AVERAGE	65.4	0.97	1.10
	Standard Deviation	2.48	0.23	0.20
	COV	4%	22%	16%
	Retention	95%	93%	88%
FT+S	AVERAGE	62.2	0.92	0.77
	Standard Deviation	8.69	0.03	0.03
	COV	13%	3%	3%
	Retention	90%	88%	62%

5 CONCLUSION

Experimental work has been done to investigate the combined freezing-thawing cycles, heating/cooling cycles, and wet/dry cycles on the performance of HC-FCS cylinders while under sustained axial loading. More parameters (e.g. tensile strenght of the FRP tube, SEM image of the FRP) should be investigated in futher studies to better understand the mechanisms. Several conclusions can be drawn from this paper and are shown as below:

1. The environmental conditioning caused slight degradation on the strength of the HC-FCS cylinders, and acceptable degradation on the hoop strain of the outer GFRP tube.

2. Even with the sustained load, the strength of the HC-FCS cylinders were only reduced by up to 10%, however, the sustained load caused more microcracks on the GFRP tube and decreased the hoop strain of the GFRP tube by up to 40%.

6 REFERENCE

Abdelkarim, O., and ElGawady, M., A., 2016a, Dynamic and static behavior of hollow-core FRP-concrete-steel and reinforced concrete bridge columns under vehicle collision. Polymers, Vol. 8 (12), 432 – 449.

Abdelkarim, O., and ElGawady, M., A., 2016b, Performance of hollow-core FRP-concrete-steel bridge columns subjected to vehicle collision. Engineering Structures, Vol. 123, 517-531.

Abdelkarim, O., and ElGawady, M. A., 2016c, Behavior of hollow FRP-concrete-steel columns under static cyclic axial compressive loading. Engineering Structures, Vol. 123, 77 – 88.

Anumolu, S., and Abdelkarim, O., and ElGawady, M., A., 2016. "Behavior of hollow-core steel-concrete-steel columns subjected to torsion loading" J. Bridge Engineering, ASCE, 21(10), 04016070-1:14.

Cui, C., and Sheikh, S., 2010, Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers, Journal of Composite for Construction, Vol. 14, Issue 5.

Hollaway, L.C., 2010, A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials*, Volume 24, Issue 12, Pages 2419–2445.

Karbhari, V. M., Rivera, J., and Dutta, P. K., 2000, Effect of short-term freeze-thaw cycling on composite confined concrete, *Journal of Composites for Construction*., 4(4), 191–197.

Karbhari, V. M., Rivera J., and Zhang, J., 2002, Low-temperature hygrothermal degradation of ambient cured E-glass/vinylester composites, *Journal of Applied Polymer Science,* Volume 86, Issue 9, pages 2255–2260.

Kshirsagar, S., Lopez-Anido, R., and Gupta, R., 2000, Environmental aging of fiber-reinforced polymer-wrapped concrete cylinders, *ACI Material Journal,* Volume 97, Issue 6, pp. 703-712.

Mandal, S., Hoskin, A., and Fam, A., 2005, Influence of concrete strength on confinement effectiveness of fiber-reinforced polymer circular jackets, *ACI Structural Journal*, 102(3), 383.

Micelli, F., and Nanni, A., 2004, Durability of FRP rods for concrete structures, *Construction and Building Materials*, 18 pp. 491–503.

Micelli, F. and Myers, J.J., 2008, Durability of FRP-confined concrete, *Proceedings of the ICE-Construction Materials*, Volume 161, Issue 4, pp. 173-185.

Silva, M., Cidade, M. T., Biscaia, H., and Marreiros, R., 2014, Composites and FRP-strengthened beams subjected to dry/wet and salt fog cycles, *Journal of Materials in Civil Engineering*, 26(12), 04014092.

Teng, J.G., Yu, T., Wong, Y.L., Dong, S.L., 2007, Hybrid FRP–concrete–steel tubular columns: Concept and behavior, *Construction and Building Materials*, Volume 21, Issue 4, Pages 846–854.

Toutanji, H. and Balaguru, P., 1998, Durability characteristics of concrete columns wrapped with FRP tow sheets." *Journal of Materials in Civil Engineering*, 10(1), 52–57.

Yu, T., Zhang, B., Cao, Y.B., Teng, J.G., Behavior of hybrid FRP-concrete-steel double-skin tubular columns subjected to cyclic axial compression, *Thin-Walled Structures*, Volume 61, Pages 196-203.