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COMBINED SEAWATER EXPOSURE AND AXIAL CYCLIC LOAD BEHAVIOR OF CONCRETE-FILLED FRP TUBE (CFFT)

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Abstract

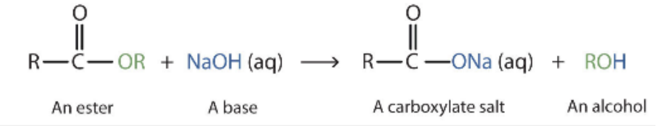
Concrete-filled fiber reinforced polymer tube (CFFT) columns, the new type of bridge columns as alternatives to conventional reinforced concrete columns, have demonstrated superior advantages on mechanical behavior and easy construction during the past few decades. A lot of researchers have investigated the behavior of CFFT cylinders under monotonic compression load, however, limited studies has been done on its performance under cyclic compression load, which reflects its earthquake resistant capacity in seismic region. Especially, the cyclic behavior of CFFT cylinders after long-term weather conditioning still faces uncertainties. In this study, CFFT cylinders were immersed into seawater solution with two different elevated temperatures for up to 450 days. Sustained axial load were applied to the cylinders during conditioning in order to simulate the real-life situation. Cylinders were taken out from the seawater solution periodically to conduct cyclic compression tests. It is observed from the test results that though the conditioned CFFT cylinders dissipated less energy than the unconditioned ones during the early stage, they can sustain larger strain and consume more energy in the large-strain stage.

Keywords: FRP; CFFT; seawater corrosion; cyclic compressive load; energy dissipation.

1. Introduction

Fiber reinforced polymer (FRP) has been widely used in bridge engineering during the past few decades due to its high strength-to-mass ratio and easy construction. FRP can be used for retrofitting and upgrading of existing bridge columns in the form of column wrapping or used for construction of new bridge columns in the form of concrete-filled FRP tubes (CFFT). The stress-stain behaviors of both FRP wrapped concrete cylinders and CFFT under monotonic compression load have been widely investigated [1-10]. However, only a few studies were carried out to investigate the cyclic loaded behavior of concrete cylinders confined by FRP jackets, and no researcher studied CFFT case ever before. Rodrigues and Silva [11] reported that the axial stress of FRP-confined concrete cylinder under monotonic loading is smaller than that of under cyclic loading for a given axial strain for the same cylinder. The ultimate strength and axial strain under cyclic compression loading were also higher than that of the monotonic loading curve [12-13]. It is also shown that the dissipated energy in each cycle increased with the axial plastic strain of the cylinder [14].

One potential application for CFFT is to be used in coastal and marine area. However, the performance of CFFT under seawater exposure has not been fully investigated yet. FRP tubes consist of fiber such as glass fiber imbedded into resin matrix such as polyester. When subjected to dilute alkali like sodium hydroxide [NaOH] in seawater, the ester group, which is the weakest bond in polyester matrix, is vulnerable to hydroxyl ions by hydrolysis process where the reaction equation is shown below [15]:



$$R-\overset{\displaystyle O}{\overset{\|}{C}}-OR + NaOH\,(aq) \longrightarrow R-\overset{\displaystyle O}{\overset{\|}{C}}-ONa\,(aq) + ROH \qquad (1)$$

The ester group is hydrolyzed into carboxylate salts and alcohols, which results in the breakdown of polyester molecure, and thus deteriorates FRP's properties. The reaction is catalyzed when the environment temperature increases. Moisture can reduce the glass transition temperature (Tg) of the resin due to plasticization effect. The performance of FRP would be dramatically deteriorated should the ambient temperature exceeds the Tg of the resin [16]. The Tg of the polyester resin would range between 40°C to 120°C depending on the curing process [17]. Bare glass fibers in the high pH cement environment are severely degraded due to a combination of pitting, hydroxylation, hydrolysis, and leaching [18-20]. Although resin can act as a protection layer to prevent fibers from direct contact to chemical solution, the solution that carries detrimental ions can still diffuse through the bulk resin, or wick along fiber-matrix interface, and eventually deteriorate the fibers [20].

To the best knowledge of the authors, only one study has been done to test the property changes of CFFT cylinders after long-term salt solution immersion. Robert and Fam [18] submerged the CFFT cylinders into salt solution at different elevated temperatures for up to 1 year, and tested the FRP rings cut from the outer FRP tube after certain periods. Though test results showed up to 21% degradation on the strength of the FRP rings, no compression tests on the CFFT cylinders had been conducted. Also, sustained axial load was not applied to the CFFT cylinder during conditioning in the experiment, which did not reflect the real-life scenario where bridge columns are always under axial service load in reality.

2. Research significance

Although researchers carried out investigation on the behavior of concrete cylinders wrapped with FRP jackets subjected to cyclic compression load and the durability of CFFT after long-term seawater exposure, the combined scenario, i.e., cyclic compression of CFFT after long-term seawater exposure, has not been investigated yet. This study evaluates the axial cyclic loaded behavior of CFFT cylinders after being exposed to seawater at two different elevated temperatures for 450 days. The FRP tubes consisted of glass fiber and polyester resin. Sustained axial load was also applied to the CFFT cylinders during the seawater exposure to simulate the service load effects during real-life situation.

3. Material Properties

The outer tubes used for the CFFT cylinders were fabricated by the filament winding process with a winding angle ± 37° and an isothalic polyester thermosetting resin impregnating strands of continuous glass fiber filaments (Table 1). Self-consolidating concrete (SCC) was used to cast all of the CFFT cylinders (Table 2). The average 28th day compressive strength from 4 in × 8 in cylinders was 7200 psi.

4. Experimental Program

4.1 specimen preparation

Two different groups of cylinders were investigated during the experimental work: the conditioned ones and the control ones. The conditioned cylinders were immersed into seawater tank and taken out at 4 different time periods for testing. The control cylinders were kept in the laboratory under ambient temperature and moisture. Each group had three 12-inch high CFFT cylinders: two would be tested under monotonic compression load and one with cyclic compression load. Only the cyclic loaded specimens will be discussed in this paper. In order to simulate the bridge columns in reality where concrete isn't exposed to outside environment, the top and bottom surfaces of the cylinders were coated with a thin layer of epoxy (Fig. 1b). An end grinder machine was used to grind both surfaces of each cylinder to be smooth and flat before coating (Fig. 1a).

Table 1 - Dimension and mechanical properties of the FRP tubes based on experimental data

OD (in)	**t (in)**	**f_L (ksi)**	**E_L (ksi)**	**ε_L (%)**	**f_H (ksi)**	**E_H (ksi)**	**ε_H (%)**
6.6	0.125	8.4	1523	0.71	21.4	2028	1.60

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 moduli in longitudinal and hoop directions, respectively; ε_L and ε_H = failure strain in longitudinal and hoop directions, respectively.

Table 2 - SCC mixture proportions

w/cm	**Cement (lb/cy)**	**Fly Ash (lb/cy)**	**Water (lb/cy)**	**Fine aggregate (lb/cy)**	**Coarse aggregate (lb/cy)**	**HRWRA (lb/cy)**	**VEA (lb/cy)**
0.38	590	295	336	1411	1411	3.6	1.2

(a) (b)

Fig. 1 - Specimen preparation: (a) CFFT cylinders; (b) epoxy coating on concrete surfaces

4.2 test setup for seawater tank

Four CFFT columns each consisted of three CFFT cylinders stacked on top of each other were immersed in a salt-water tank. Steel plates stiffened using HSS tubes were placed on top and underneath the tank. Four 1 inch diameter Dywidag bars were passed through the steel plates to post-tension the CFFT cylinders to the required stress. Heavy-duty steel springs were used to keep the applied load constant during the exposure period (Fig. 2). Hydraulic jacks were used to apply the required load and the applied force was measured by a load cell during loading process. The target axial pressure on each CFFT stack was 1000 psi, which was approximately 10% of the cylinder's design axial load capacity. This percentage is a typical value for bridge column where the service load is approximately 10% of the ultimate axial capacity. Strain gauges were instrumented on each Dywindag bar to monitor the load relaxation, and the setup was reloaded if necessary.

The salinity of the salt solution in the tank was 3.5% by mass. The pH of the seawater was adjusted to 8.2 with 0.1N sodium hydroxide solution [21]. Two identical tanks were used. The only difference between the two tanks was the temperature. Heating elements and temperature controllers were used to keep the temperature of the seawater at 23°C and 35°C for the first and second tank, respectively. In addition, a circulator pump was immersed into the bottom of each tank to circulate the solution in order to make the temperature and salinity of the seawater evenly distributed everywhere. Sample solution was taken out from the tank twice a week to test the salinity and pH. The fresh salt solution would be added if the concentration changed or the water level dropped below the top surface. The actual immersion days for cylinders at each time period are shown in Table 3.


(a) (b)

Fig. 2 - (a) loading setup for the tank; (b) post-tensioned tank setups

Table 3 - Immersion time for each period of cylinders

Days	1st period	2nd period	3rd period	4th period	Total
Tank 1 (23°C)	90	106	101	153	450
Tank 2 (35°C)	93	180	60	117	450

4.3 instrumentation and setup for the compression test

In order to reach the same stable conditions right before conducting mechanical tests, each group of the conditioned cylinders was kept in laboratory ambient conditions for at least one week after being taken out of the seawater. The control specimens were tested at the same time with the 1st period conditioned cylinders. An MTS 2550 loading frame was used to conduct the compression test on each cylinder (Fig. 3). Two linear variable displacement transformers (LVDTs) were anchored underneath the top loading plate to monitor the average vertical deformation along the height of each tested cylinder. Two strain gauges were bonded to the FRP tube surface at mid-height along the hoop direction to track the local hoop strains of the FRP. The loading regime was cyclic compressive loading with 0.02 in/min displacement rate, and three cycles at each target displacement level (Fig. 4).

Fig. 3 - Setup for the compression test on CFFT cylinders

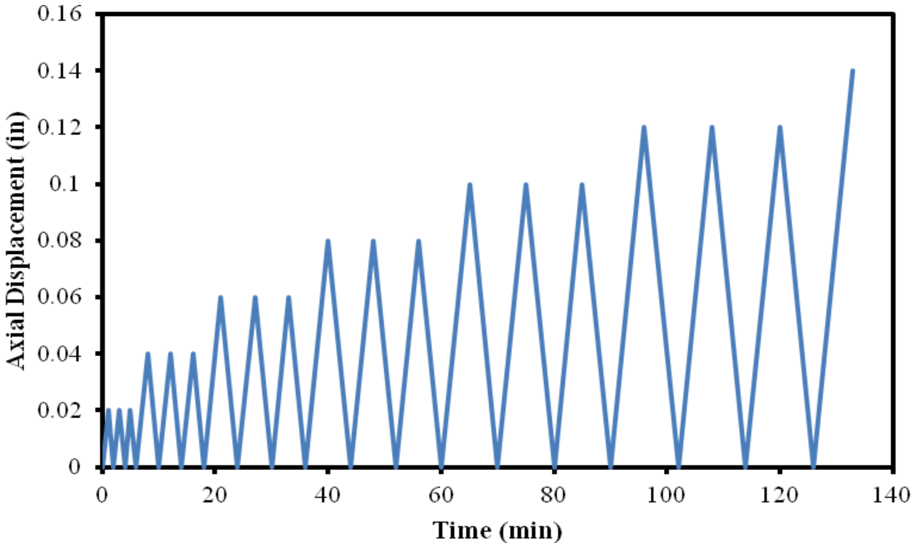
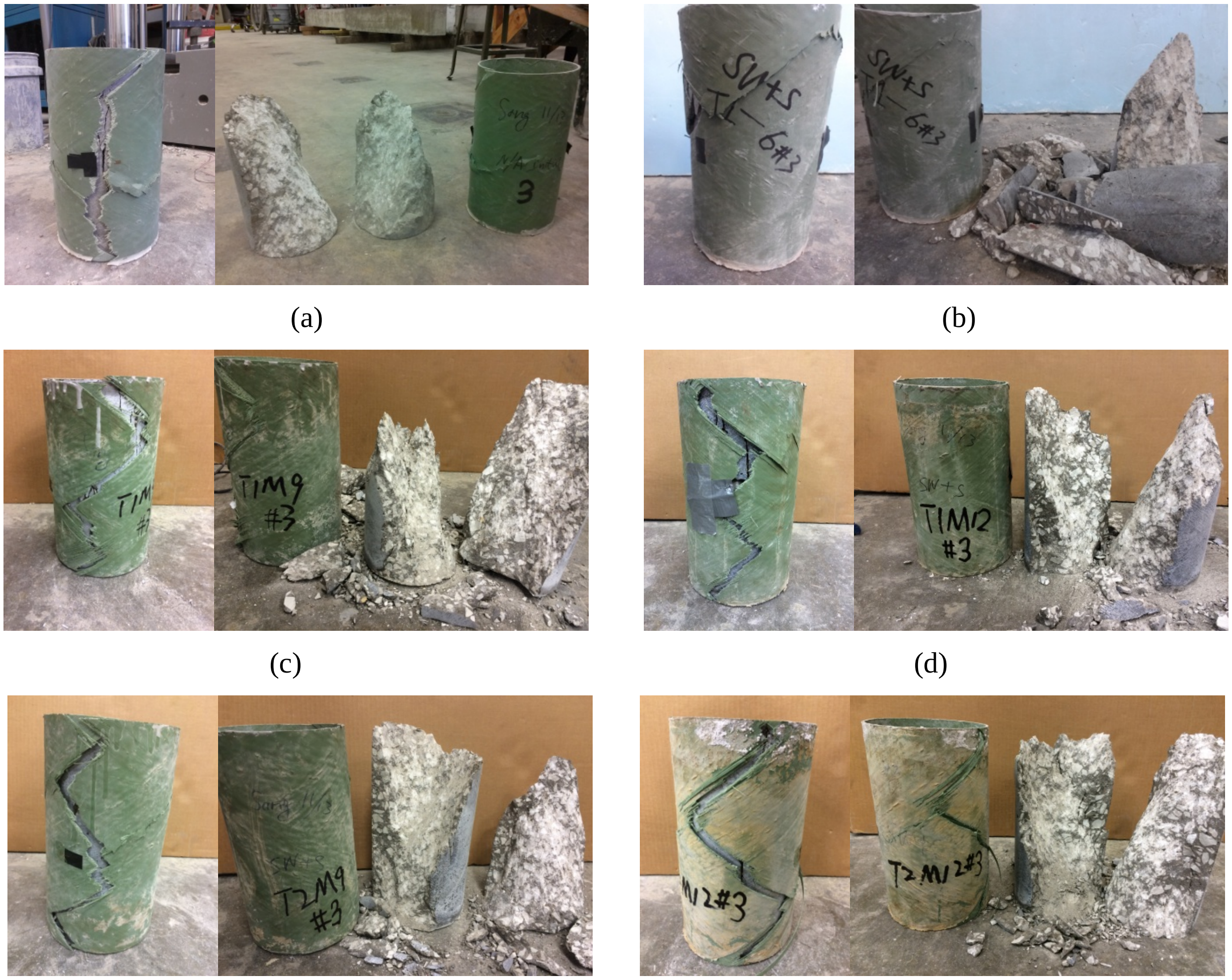


Fig. 4 - Loading regime for the cyclic compression load

5. Test Results and Discussion

5.1 Failure Modes

All the CFFT cylinders failed with FRP zig-zag rupture at approximately ±37°, i.e., following the winding angle followed by diagonal shear fracture of the concrete core (Fig. 5). The shear failure of the concrete core agreed well with what was found by Ozbakkaloglu and Akin [13] for the high-strength-concrete specimens. One interesting finding among the conditioned cylinders was that the FRP laminate delaminated at some spots due to plasticization effect on polyester resin, which led to debonding between FRP layers. This delamination phenomenon didn't happen to the control specimens. The nomination for each cylinder was in the format of "CFFT_XX#", where "XX" represents the conditioning situation (UC = Unconditioned; T1M3 = Tank 1 for 3 months; T2M6 = Tank 2 for 6 months), and "#" represents the sample number. Noted that the M3 or M6 doesn't mean the cylinders had been staying in the seawater tank for exactly 3 months or 6 months. Instead, the actual immersion time periods are listed in Table 3.



(a) (b)

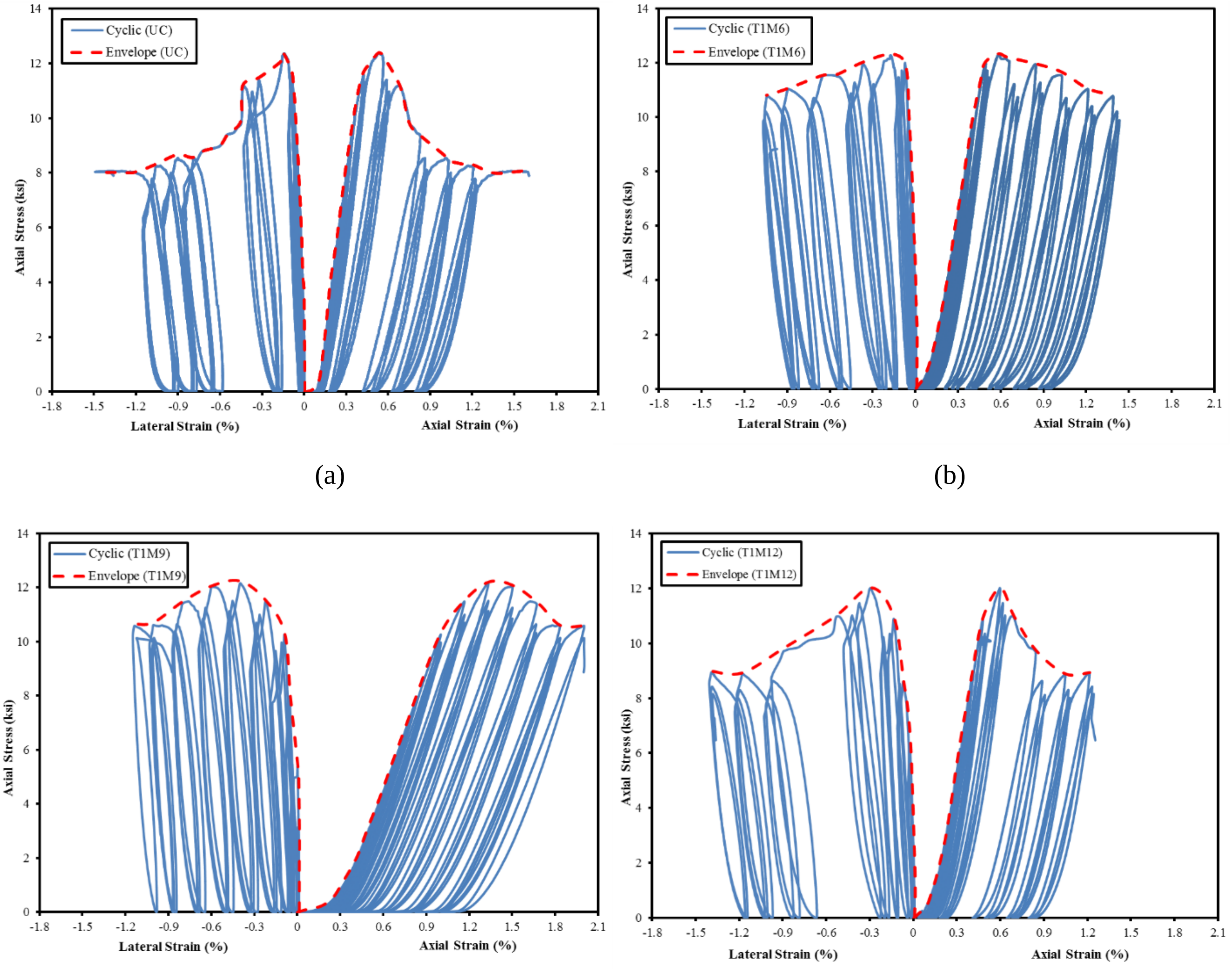
(c) (d)

(e) (f)

Fig. 5 - Failure modes of the outer FRP tubes and core concete for several CFFT specimens: (a) CFFT_UC#3; (b) CFFT_T1M6#3; (c) CFFT_T1M9#3; (d) CFFT_T1M12#3; (e) CFFT_T2M9#3; (f) CFFT_T2M12#3

5.2 Stress-Strain Curve

The cyclic stress-strain curves and the envelopes for the CFFT cylinders under cyclic compression load are depicted in Fig. 6. In those figures, the axial strains are defined as positive which took the average values from the two LVDTs, while the lateral strains are defined as negative which averaged from the two strain gauges on the FRP tube. Almost all of the cyclic curves exhibited strain-softening behavior instead of two ascending branches observed in other researchers' experiments [12-14]. It was probably due to the very low confinement ratio (confinement pressure over unconfined concrete strength), which was around 0.09 for the CFFT cylinders in this experiment, that led to inadequate confinement from the FRP tube when inner concrete core began to dilate. The confinement ratios for specimens in the referred studies were from 0.2 to 0.7.

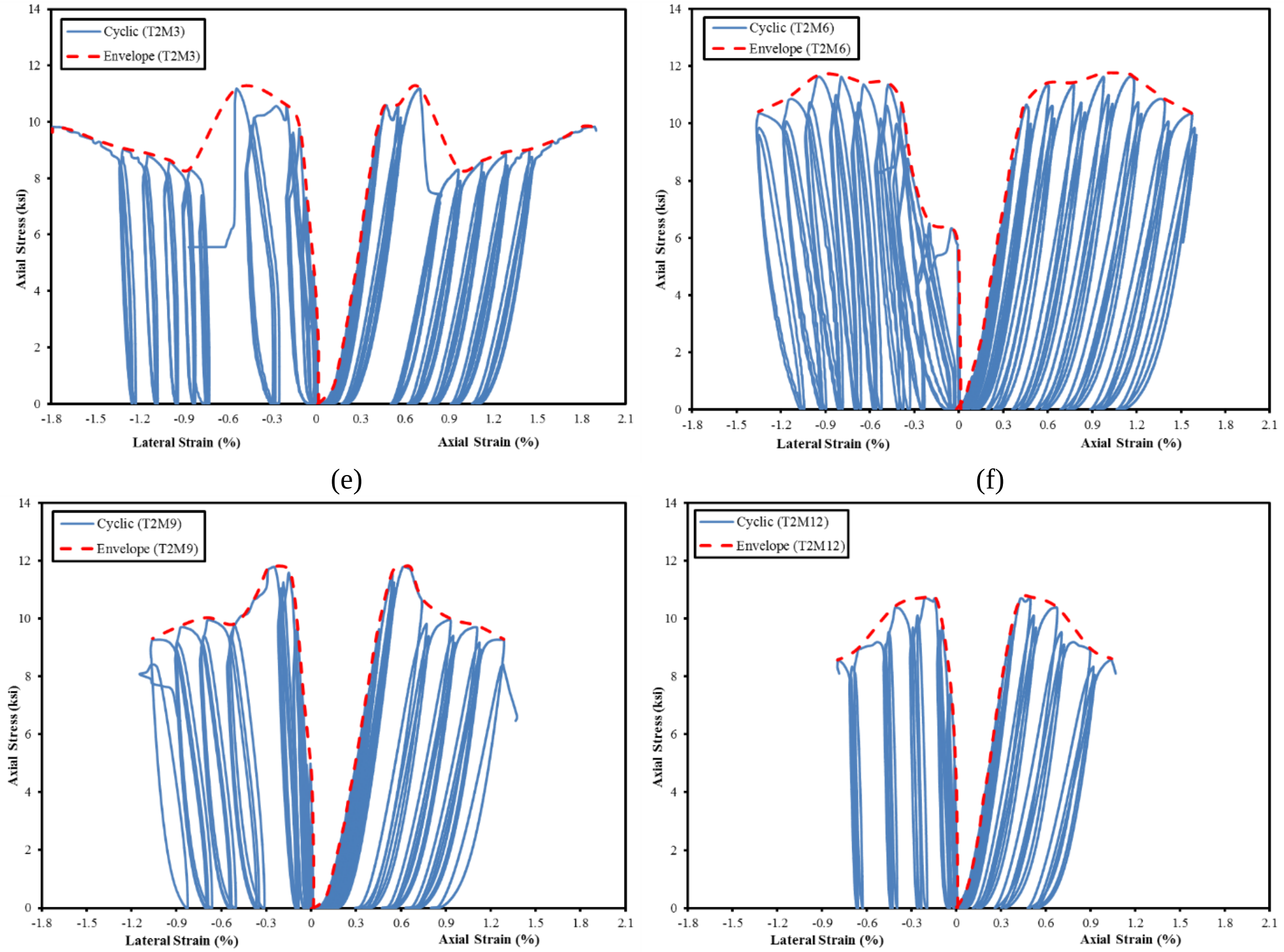


(a)

(b)

(c)

(d)



(e) (f)

(g) (h)

Fig. 6 - Stress-strain curves and envelopes for CFFT cylinders under cyclic compression test: (a) CFFT_UC; (b) CFFT_T1M6; (c) CFFT_T1M9; (d) CFFT_T1M12; (e) CFFT_T2M3; (f) CFFT_T2M6; (g) CFFT_T2M9; (h) CFFT_T2M12

Several key parameters of the test results, including maximum stress, ultimate axial strain and lateral strain, are summarized in Table 4. The data suggested that most conditioned cylinders were degraded in both strength and strain after seawater exposure, with more affect on strains than on strength. The strength loss for the last cylinder from Tank 2 (T2M12) was 13%, while the axial strain and lateral strain were degraded by almost 35% and 49%, respectively.

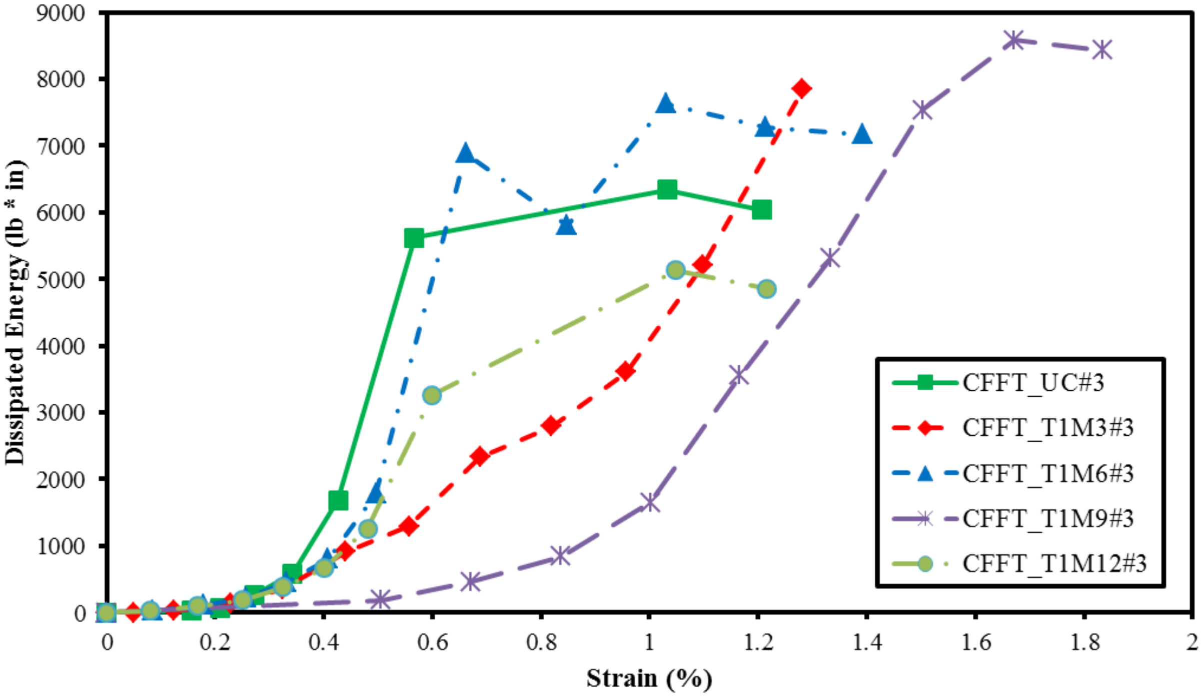
Table 4 - Key results for the CFFT cylinders under cyclic compression test

Properties	**UC**	**T1M3**	**T1M6**	**T1M9**	**T1M12**	**T2M3**	**T2M6**	**T2M9**	**T2M12**
max stress (ksi)	12.37	11.60	12.34	12.22	11.99	11.20	11.75	11.78	10.75
axial strain (%)	1.59	1.48	1.38	2.01	1.22	1.90	1.58	1.29	1.04
lateral strain (%)	1.49	- [a]	1.04	1.14	1.39	1.79	1.35	1.06	0.79

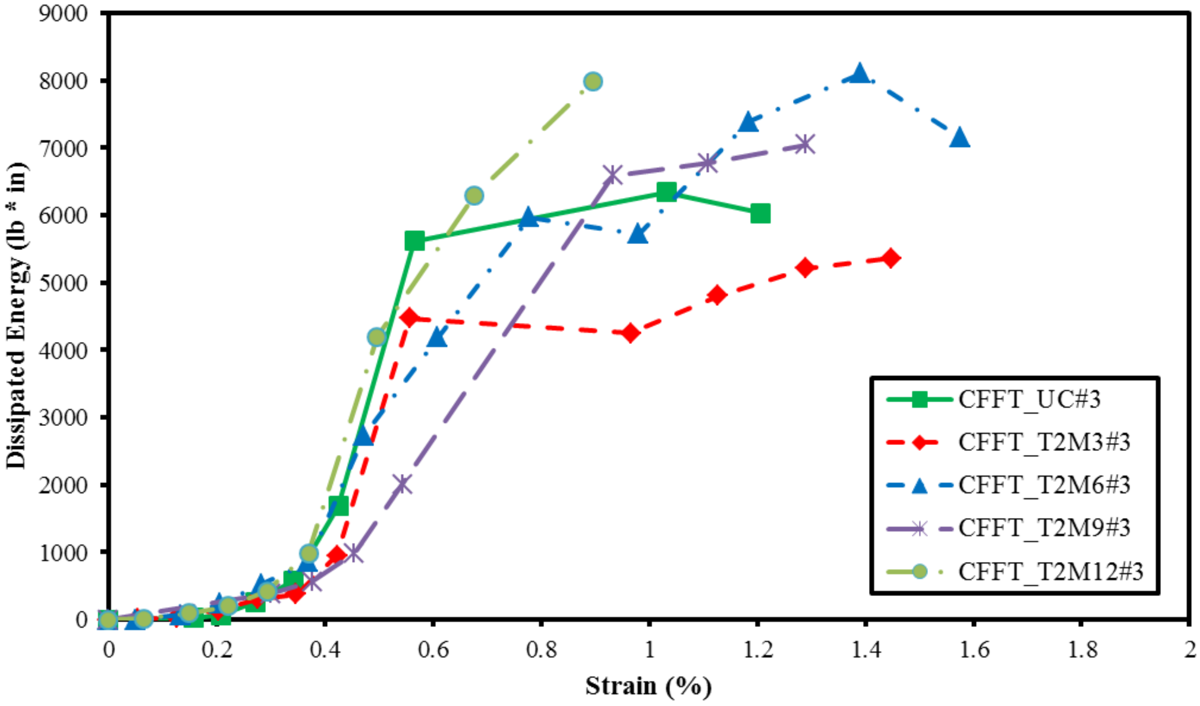
[a] The strain gauges data for specimen T1M3 were lost during the test.

5.3 Energy Dissipation Capacity

The dissipated energy curves for cylinders in each tank are shown in Fig. 7. The dissipated energy was calculated as the area enclosed in each loop cycle. There were three cycles per each displacement level and the energy from the first loop of each level was taken for consideration. The values of horizontal axis were the maximum vertical strains of the first loop of every level. The data points for the sudden falling branch were not added for comparison. It can be seen from the figures that the all of the conditioned cylinders dissipated less energy than the unconditioned specimens in small strain range, but most of them consumed more energy in large strain level. When polyester matrix was subjected to seawater conditioning, it is postulated that the hydrolysis effect resulted in reduced strength for the FRP tube, while the tube become softer and more ductile due to plasticization effect. The reduced strength made the conditioned cylinders dissipate less energy, while the softer tube could help dissipate more energy and the larger ductility could let the cylinder continue to consume energy at larger strain. There’s no clear trend about how the conditioning time affect the energy dissipation capacity, but one can generally see that the higher temperature in tank 2 led to higher dissipated energy when compared to that of tank 1 cylinders with lower temperature. It is probably because the higher temperature further soften the FRP tube, and improve the dissipated energy. .



(a)



(b)

Fig. 7. Energy dissipation history for CFFT cylinders under cyclic compression test: (a) Tank 1; (b) Tank 2

6. Summary and Conclusions

This study investigated the cyclically loaded behavior and energy dissipation capacity of CFFT cylinders after long-term seawater exposure with different elevated temperatures. Several conclusions can be drawn from the test results:

1. The influence of plasticization effect on polyester resin resulted in debonding and delamination on FRP laminates when the FRP tube ruptured.

2. Generally, the seawater exposure deteriorated the CFFT cylinders more on strain than on strength. The strength loss for cylinders immersed in 35°C for 450 days was 13%, while the axial strain and lateral strain were degraded up to 35% and 49%.

3. The FRP tube becomes softer due to the higher conditioning temperature, which helped dissipate more energy for the CFFT cylinder.

Future studies may use low-strength concrete instead of high-strength concrete to achieve better confinement effect by the FRP tube, which was beyond the scope of this study.

7. Acknowledgments

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