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Experimental study on durability of strengthened corroded RC columns with FRP sheets in tidal zone of marine environment

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Abstract. The main objective of this paper was to illuminate the effect of marine environmental condition on durability of reinforced concrete (RC)-corroded columns strengthened with carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) layers. Small-scale columns were prepared and corroded by an accelerated corrosion process. After strengthening, compressive strength tests were carried out on control and weathered specimens. In this research, a marine simulator was designed and constructed similar to the tidal zone of marine environment in south of Iran which was selected as a case study in this research. Mechanical properties of wrapped specimens were studied after placing them inside the simulator for 3000 hours. Marine environment decreased ultimate strength by 4.5% and 26.3% in CFRP and GFRP-wrapped columns, respectively. In some corroded-columns, strengthening was carried out after replacing damaged cover by self-compacted mortar. In this method, by confining with one layer of CFRP and GFRP, 4.2% and 22.4% reduction in ultimate strength was observed, respectively, after exposure. Furthermore, the elastic-brittle behavior has been verified in this retrofit method. Also results of tension tests revealed, the ultimate tensile strength was degraded by 2% and 28.8% in CFRP and GFRP sheets, respectively, after applying marine exposure.

Keywords: FRP sheets; marine exposure; corroded columns; strengthening; durability

1. Introduction

Corrosion of steel bars has been known as the predominant factor causing widespread deterioration of reinforced concrete (RC) structures, especially when they are located in coastal marine environments. It can lead to structural defeat due to the expansion of corrosion products and also loss of the reinforcing steel cross-sectional area (Costa and Appleton 2002, Pech-Canul and Castro 2002, Shi *et al.* 2012, Safehian and Ramezanianpour 2015, Otieno *et al.* 2016). There are many solutions to rehabilitation of corrosion-damaged RC columns, such as steel or concrete jacketing and fibre reinforced polymer (FRP) confining. In recent years, FRPs have been cumulatively used to strengthen corroded columns, as they provide high tensile strength, non-corrosiveness, and lightness, and can be easily applied (Bank 2006). While wrapping by FRP sheets is known as an effective rehabilitation technique, the durability of this method especially in harsh environmental conditions such as marine environment is still under investigation (ACI 440.2R-08 2008, Böer *et al.* 2014). There have been various studies on durability of FRP sheets and also corroded columns which confined by FRP layers in aggressive environments similar to marine conditions presented in the following:

Having put GFRP coupons in synthetic sea water at ambient temperature, Karbhari and Zhao (1998) found that sea water exposure caused maximum degradation in mechanical properties of FRP sheets, especially in GFRP, in comparison to other environmental conditions such as fresh water and freeze-thaw cycles. Micelli *et al.* (2002) placed some concrete columns wrapped with FRP sheets in 15% saline solution for 120 days and observed an ultimate strength reduction of 27% and 10%, respectively, for GFRP and CFRP-wrapped columns. In a study by Tastani and Pantazopoulou (2004) concrete columns were strengthened by FRP sheets after being conditioned to accelerated corrosion, and an enhanced compressive strength and ductility was observed after confinement. Pantazopoulou *et al.* (2001) found that confining corroded columns with FRP sheets could change the process of corrosion by slowing down the rate of it, and also could improve ductility and strength of corroded columns. In a study conducted by Bae and Belarbi (2007) on RC columns confined by FRP sheets, a significant reduction in the ultimate load and ductility of the GFRP-wrapped columns was observed after maintaining them in saline solution. Additionally, confining corroded columns by one layer of CFRP caused 145.5% increase in ultimate strength. Degradation in the tensile properties of FRP sheets were examined by Cromwell *et al.* (2011). After 10,000 hours of immersion in saline solution, 6% and 3% reduction in ultimate strength was observed in GFRP and CFRP sheets, respectively. Gharachorlu and Ramezanianpour (2010) proceeded to investigate the effect of marine environmental condition on confined concretes

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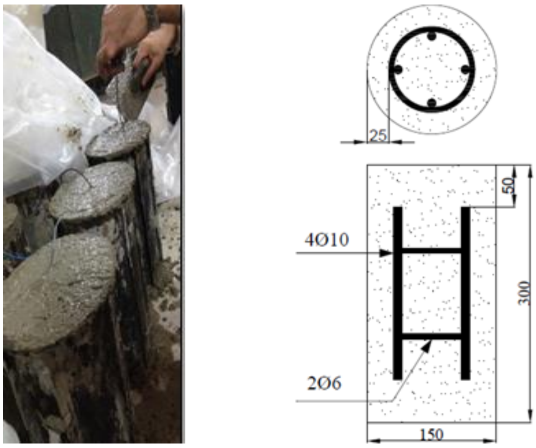


(a) Preparing RC columns (b) RC columns-geometry and reinforcement details (dimension in mm)

Fig. 1 Reinforced concrete specimens

Table 1 Mix properties of the concrete

W/C	Cement (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)	Compressive strength (MPa)
0.51	341	804	974	29.8

Table 2 Mix properties of self-compacted mortar

W/C	Cement (kg/m³)	Sand (kg/m³)	limestone powder (kg/m³)	Superplasticizer by weight of cement (%)	Slump flow (cm)	Compressive strength (MPa)*
0.45	450	1469	130	0.8	26	60

*Compressive strength test was carried out on 5×5×5 cm cubic specimens

Table 3 Mechanical properties of FRP sheets

FRP type	Fibre volume ratio (%)	Tensile strength (MPa)	Ultimate strain (%)	Tensile modulus of elasticity (GPa)
GFRP	35	190	1.21	15.6
CFRP	30	342	0.76	44.7

by CFRP and GFRP sheets. Highest reduction in strength was observed in GFRP-wrapped specimens. Furthermore, in comparison between confining by CFRP and GFRP sheets, Böer *et al.* (2013) found that the exposure to saltwater caused a sharp decrease in the strength and ductility of the columns wrapped by GFRP sheets. In a study on the durability of FRP materials by Silva *et al.* (2014), it was found that ultimate strength of GFPR sheets have been affected by saline water, and more destructive effect was observed as the temperature increased. Nossoni *et al.* (2015) in a study observed that after confining corroded columns by FRP sheets, the mass loss of steel bars reduced 33-46% after 130 days of testing, and also both types of CFRP and GFRP sheets reduced corrosion rate of steel bars equally. Joshi *et al.* (2015) investigated the structural behavior of differently wrapped corroding columns. They concluded that confining by GFRP sheets provided adequate enhancement in the strength and ductility of the corroded columns irrespective of the amount of the mass loss of steel bars.

These studies indicate that wrapping by FRP sheets could be an excellent solution for the rehabilitation and strengthening of corroded RC columns. On the other hand, the durability of FRP sheets has been found to be affected by exposure to aggressive environments, such as high humidity, saline solution and high temperature. Therefore, in a harsh environmental condition, the performance of corroded columns after confining is under question. The main objective of this paper is to survey the performance of corroded RC columns after strengthening by FRP sheets, in the tidal zone of marine environment in the southern of Iran, which is known to have extraordinarily harsh conditions due to the presence of chloride ions in seawater, high temperature and humidity, tidal phenomena, and solar UV radiations. Also, the effect of replacing corroded cover on mechanical properties and durability of wrapped columns is investigated.

2. Experimental program

2.1 Material properties

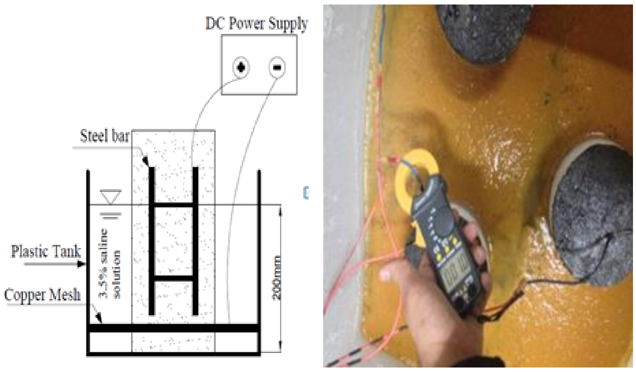
In this study, 30 RC columns were prepared with dimensions 150 mm in diameter by 300 mm in height and reinforced with four Φ10 longitudinal steel bars at 25 mm cover. The rational for the cross section of the steel bars as a fraction of the gross sectional of the specimen was 1.7%. Also, two Φ6 circular hoops at the top and bottom of specimens supported the longitudinal reinforcement. Columns preparation, typical geometry and reinforcement are shown in Fig. 1. In some cases, corroded cover was replaced by self-compacted mortar before strengthening. Mix properties of the concrete and self-compacted mortar are summarized in Tables 1-2, respectively. Slump flow test was carried out on the self-compacted mortar according to the EFNARC guideline (EFNARC 2005).

FRP sheets were fabricated in type of Glass/Epoxy and Carbon/Epoxy which installed with the wet lay-up technique. Tensile strength parallel to the fiber was determined in accordance with the ASTM D3039 standard (ASTM D3039/D3039M 2008). Mechanical properties of the FRP sheets are shown in Table 3.

2.2 Accelerated corrosion

Since the main objective of this paper was to investigate the effectiveness of strengthening RC-corroded columns by FRP sheets in coastal areas, firstly 27 RC columns were corroded by rapid corrosion process and other specimens remained un-corroded for comparison purposes. In many researches, accelerated corrosion process and calculation of the mass loss of steel bars were carried out according to Faraday's law (Otieno *et al.* 2016, Tastani and Pantazopoulou 2004, Pantazopoulou *et al.* 2001, Bae and Belarbi 2007, Nossoni *et al.* 2015, Joshi *et al.* 2015, Xie and Hu 2013, Guneyisi *et al.* 2013, Sun *et al.* 2015), which is expressed by the following equation

$$t = \frac{m \times n \times F}{a \times I} \quad (1)$$



(a) Schematic presentation of the accelerated corrosion process

(b) Accelerated corrosion process in the laboratory

Fig. 2 Accelerated corrosion

Where t=time of the corrosion process (s); m=mass loss of iron (gr); n=valence of the reacting electrode for the material (n_{steel}=2); F=Faraday's constant (96500 A.s); a=atomic mass of iron (55. 85 gr); I=corrosion current (A).

In this study, the specimens were placed in a plastic container which contained industrial salt solution of 3.5% concentration and was filled up to 2/3 of the height of the columns. Specimens were subjected to 1(A) external current which continued up to 15% mass loss of steel bars. Schematic representation of the experimental set up for the rapid corrosion process and specimens under accelerated corrosion in laboratory are shown in Fig. 2.

2.3 Strengthening methods

Two types of FRP-strengthening methods were examined in this research. In method 1, FRP sheets were applied directly on the corrosion-damaged concrete while in method 2 wrapping was carried out after replacing corroded cover by self-compacted mortar. Strengthening by method 1 is easier and faster than method 2. In contrast, although replacing the corroded concrete may appear to be difficult and costly in method 2, further steel corrosion will be prevented.

The procedure of preparing corroded columns before wrapping in method 1 is shown in Fig. 3. In this method, corroded surface was polished and cleaned, then primer was applied on cracked surface for smoothening.

Fig. 4 shows preparing specimens before confining in method 2. In this method, first the corroded surface was cut to the level of steel bars and then it was removed and replaced with self-compacted mortar. Cutting corroded cover before removing caused less destructive effect on sound concrete.

After surface preparation, one layer of CFRP and GFRP sheets applied on specimens and then epoxy resin was applied on the unwrapped portions of the columns. So, moisture and chloride ions couldn't ingress through the top and bottom of the wrapped specimens. Finally, wrapped columns were placed in two different environmental conditions.

(a) Cleaned specimens

(b) Applying primer

Fig. 3 Preparing specimens for strengthening in method 1

(a) Cutting corroded concrete

(b) Removing corroded concrete

(c) Replacing corroded concrete by self-compacted mortar

Fig. 4 Preparing specimens for strengthening in method 2

2.4 Environmental conditions

After strengthening, specimens were placed in two different environmental conditions. First one was normal condition in laboratory and second one was tidal zone of marine environment in the south of Iran which was selected as the environment condition to be simulated as a case study in this research. Many RC structures show signs of deterioration, mainly due to the chloride-induced corrosion of steel bars in this area. Environmental factors such as chloride ions in seawater, high temperature and humidity, tidal effects and UV radiations have degraded the durability of materials to a serious danger level.

(a) Exterior view of the marine simulator

(b) Specimens placed in tidal pool

Fig. 5 Marine simulator

Investigation on the durability of confined RC columns would take a very long time; therefore a marine simulator was constructed in the Concrete Technology and Durability Research Center (CTDRC) at Amirkabir University of Technology to apply accelerated marine condition on the specimens. The simulator was designed to allow researchers to control and monitor the air temperature and humidity, and water temperature, and programming tidal and UV radiation cycles.

The exterior view of the simulator and also the specimens which were placed in the tidal pool are shown in Fig. 5. In order to simulate the coastal region in the south of Iran, the temperature of the interior simulator was set to 40℃, its humidity to 68%, and the salt concentration of water to 36.6 grams per liter. Also, the temperature and humidity of the normal condition in laboratory was 20℃ and 40%, respectively. The specimens were placed in the simulator environment for 3,000 hours and experienced 125 cycles of 24 hour. One cycle consisted of 12 hours Immersion in salt water (when the tidal pool was full of salt water) and 12 hours exposure to UV radiation under dry condition (when the tidal pool was empty).

2.5 Test methods

Two test methods were used to evaluate the effects of marine environment on durability of specimens. Direct tension tests were carried out on FRP sheets according to ASTM D3039 Standard (ASTM D3039/D3039M 2008) and also uni-axial compression failure tests were carried out on columns. By comparison the result between control and marine simulator specimens, durability assessment will be determined.

The type of the specimens, FRP sheets, retrofit methods, environmental conditions imposed to each one and test methods are summarized in Table 4. As shown in Table 4, SG-C and SC-C are the control GFRP and CFRP sheets, respectively. SG-M and SC-M are the GFRP and CFRP sheets, respectively, which were placed in marine simulator. C-C and CA-C are non-corroded and corroded columns, respectively, without any exposure. Columns CGA-C and CCA-C are the control columns wrapped with GFRP and CFRP, respectively, in method 1. CGA-M and CCA-M are weathered columns which wrapped by GFRP and CFRP sheets, respectively, in method 1. Also, columns CGAR-C and CCAR-C are the control columns wrapped with GFRP and CFRP, respectively, in method 2. Columns CGAR-M and CCAR-M are weathered columns which wrapped by GFRP and CFRP sheets, respectively, in method 2.

Table 4 Test specimens (dimension in cm)

Specimen ID	Specimen shape	FRP type	Accelerated Corrosion	Retrofit Method	Environmental conditioning	Test method
SG-C	sheet	GFRP	-	-	Control	Tension (D3039)
SC-C	sheet	CFRP	-	-	Control	Tension (D3039)
SG-M	sheet	GFRP	-	-	Marine Simulator	Tension (D3039)
SC-M	sheet	CFRP	-	-	Marine Simulator	Tension (D3039)
C-C	cylinder 15×30	-	No	-	Control	Compressive Strength
CA-C	cylinder 15×30	-	Yes	-	Control	Compressive Strength
CGA-C	cylinder 15×30	GFRP	Yes	1	Control	Compressive Strength
CCA-C	cylinder 15×30	CFRP	Yes	1	Control	Compressive Strength
CGAR-C	cylinder 15×30	GFRP	Yes	2	Control	Compressive Strength
CCAR-C	cylinder 15×30	CFRP	Yes	2	Control	Compressive Strength
CGA-M	cylinder 15×30	GFRP	Yes	1	Marine Simulator	Compressive Strength
CCA-M	cylinder 15×30	CFRP	Yes	1	Marine Simulator	Compressive Strength
CGAR-M	cylinder 15×30	GFRP	Yes	2	Marine Simulator	Compressive Strength
CCAR-M	cylinder 15×30	CFRP	Yes	2	Marine Simulator	Compressive Strength

3. Experimental results and discussion

3.1 Tensile strength test

The results of tensile strength test after exposure are summarized in Table 5 for CFRP and GFRP sheets. It was found that durability of CFRP sheets was more than GFRP in marine environment. The ultimate tensile strength for CFRP and GFRP was reduced by 2% and 28.8%, respectively, after exposure. Also, 18% and 17% reduction in tensile modulus was observed in CFRP and GFRP sheets, respectively. Marine environment caused 19.5% increase and 14.2% decrease in ultimate strain of CFRP and GFRP, respectively, as well. Increasing ultimate strain after exposure in CFRP sheets was probably due to the negative coefficient of thermal expansion (ACI 440.2R-08 2008) which caused residual strain.

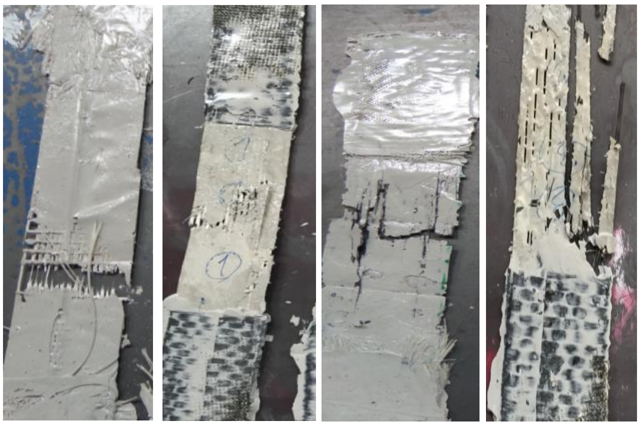
Fig. 6 shows tensile failure mode of GFRP and CFRP sheets before and after marine exposure. Before exposure, cracks appeared transverse to the fibers direction in both GFRP and CFRP sheets. This failure mode was due to the fiber and matrix fracture together. (See Figs. 6(a) and 6(c)). In CFRP layers, exposure caused mainly matrix degradation, hence carbon fibers pull out were observed after fracture (Fig. 6(d)). Exposure caused more destructive effect on GFRP sheets and fracture occurred transverse to the glass fibers. Therefore it was concluded that in marine

Table 5 Mechanical properties of FRP sheets after exposure*

Specimen	Tensile strength (MPa)	Ultimate strain (%)	Tensile modulus of elasticity (GPa)
SG-M	135.3 (-28.8%**)	1.04 (-14.2%)	12.9 (-17%)
SC-M	335.1 (-2%)	0.91 (19.5%)	36.7 (-18%)

*The values in the table are the average of three similar sheets

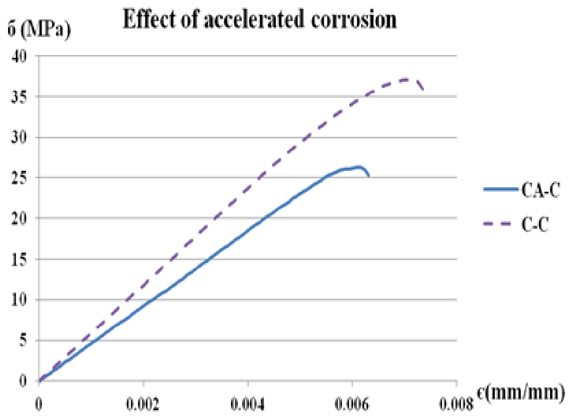
**The values in the parenthesis are the percentile ratio of increase/decrease of the FRP properties when compared to the results of the control specimens



(a) SG-C (b) SG-M (c) SC-C (d) SC-M

Fig. 6 Failure mode of FRP sheets

environmental condition, both fiber and matrix were degraded in GFRP sheets (Fig. 6(b)).



(a) Axial stress-strain curves of non-corroded and corroded RC columns before exposure

(b) Failure mode of non-corroded RC columns (c) Failure mode of corroded RC columns

Fig. 7 Effect of accelerated corrosion

3.2 Compressive strength test

3.2.1 Effect of accelerated corrosion on compressive behavior

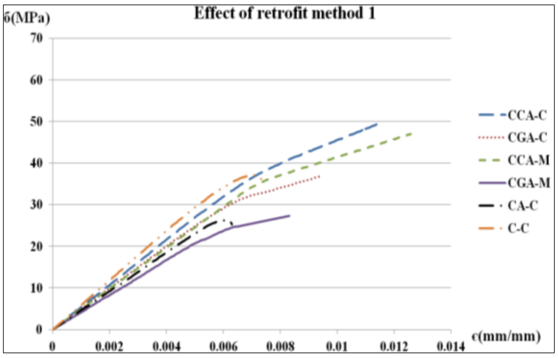
By comparing the axial stress-strain curves for non-corroded (C-C) and corroded RC columns (CA-C), it was found that the ultimate strength, ultimate strain and the modulus of elasticity were decreased by 29%, 14.5% and 22.1%, respectively, after accelerated corrosion process. Degradation in mechanical properties was due to the corrosion of steel bars and consequently propagation of the internal cracks. Fig. 7(a) shows axial stress-strain diagram of non-corroded and corroded RC columns before exposure. Also failure modes of C-C and CA-C columns are shown in Figs. 7(b) and 7(c), respectively. Failure mode of corrosion damaged RC columns was more brittle than non-corroded RC column.

3.2.2 Effect of retrofit method 1 on compressive behavior

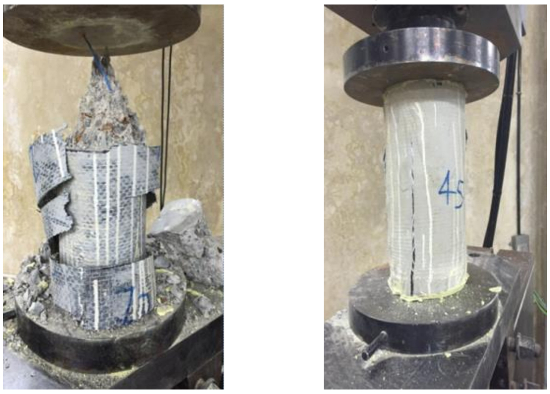
Fig. 8(a) shows axial stress-strain curves for retrofitted specimens without repairing corroded cover (method 1). Parameters obtained from these graphs are summarized in Table 6. Before exposure, wrapping by one layer of GFRP and CFRP caused 40.3% and 87% increasing in ultimate strength, respectively, and consequently destructive effects of corrosion was compensated. Also, ultimate axial strain was increased by 49.7% and 80.1% after strengthening with one layer of GFRP and CFRP, respectively. In marine condition, wrapping with one layer of GFRP and CFRP increased ultimate strength by 3.4% and 78.7% and also improved ultimate strain by 31.7% and 99.5%, respectively. Marine environment degraded compressive strength in wrapped columns. In GFRP-wrapped columns, exposure caused 26.3% and 12% reduction in ultimate strength and strain, respectively. Confining by CFRP sheets showed better performance in marine environment, only 4.5% reduction in ultimate strength was observed after exposure. Also, CFRP-wrapped columns showed 10.7% increasing in ultimate strain.

The second slope of the curves in the plastic region (E2), called the axial modulus of plastic, is an important indicator in the design of columns wrapped by FRP sheets (see Fig. 8(a)). After marine exposure, E2 was decreased by 31.3% and 20.7% in wrapped columns by GFRP and CFRP sheets, respectively. The more reduction in the axial modulus in the plastic region was observed in GFRP-wrapped columns.

Failure mode of confined columns after exposure revealed that CFRP-wrapped columns mostly collapsed because of matrix degradation. Therefore failure occurred parallel to the fibers orientation (Fig. 8(b)). On the other



(a) Axial stress-strain curves of strengthened specimens



(b) Failure mode of CCA-M (c) Failure mode of CGA-M

Fig. 8 Effect of retrofit method 1

hand failure of GFRP-wrapped columns was mainly due to the glass fibers degradation; hence GFRP was ruptured perpendicular to fibers orientation (Fig. 8(c)).

3.2.3 Effect of retrofit method 2 on compressive behavior

Fig. 9(a) shows axial stress-strain curves for retrofitted specimens after replacing corroded cover by self-compacted mortar (method 2). Parameters obtained from these graphs are summarized in Table 6. Generally, brittle behavior was observed after replacing damaged cover. Probably, this behavior was because of brittle behavior of mortar under compression. Test results in control specimens showed 108% and 152% increase in ultimate strength and 43.5% and 70.4% increase in ultimate strain, after strengthening with one layer of GFRP and CFRP, respectively.

In marine condition, confining with one layer of GFRP and CFRP after cover replacement, increased ultimate strength by 61.2% and 142.2%, respectively. Also, 45.6% increase and 8.4% decrease in ultimate strain of CFRP and GFRP-wrapped columns were observed, respectively. Furthermore, exposure in marine environment caused 22.4% and 4.2% decrease in ultimate strength and 36.2% and 14.5% decrease in ultimate strain in wrapped columns by GFRP and CFRP, respectively.

The failure modes of columns retrofitted by method 2, after marine exposure, are shown in Figs. 9(b) and 9(c). Similar to strengthening by method 1, CFRP-wrapped columns were ruptured mainly due to the matrix degradation. Also, fibers degradation was more evident in GFRP-wrapped columns.

Table 6 Mechanical properties of the strengthened specimens in methods 1 and 2 for both control and marine conditions*

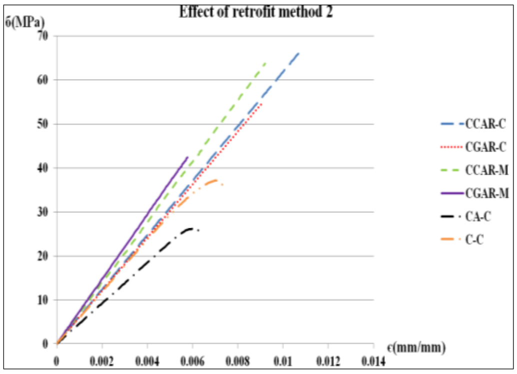
Environmental condition	Specimen ID	$\acute{o}u$ (MPa)**	ϵu (%)**	E_2 (GPa)**
Control	C-C	37.1	0.738	-
	CA-C	26.3	0.631	-
	CGA-C	36.9 (40.3%)†	0.945 (49.7%)†	1.98
	CCA-C	49.2 (87%)†	1.137 (80.1%)†	2.72
	CGAR-C	54.7 (108%)†	0.906 (43.5%)†	-
	CCAR-C	66.5 (152.8%)†	1.075 (70.4%)†	-
Marine Simulator	CGA-M	27.2 (3.4%)† (-26.3%)‡	0.831 (31.7%)† (-12%)‡	1.36 (-31.3)‡
	CCA-M	47 (78.7%)† (-4.5%)‡	1.259 (99.5%)† (10.7%)‡	2.16 (-20.7%)‡
	CGAR-M	42.4 (61.2%)† (-22.4%)‡	0.578 (-8.4%)† (-36.2%)‡	-
	CCAR-M	63.7 (142.2%)† (-4.2%)‡	0.919 (45.6%)† (-14.5%)‡	-

*The values in the table are the average of three similar columns

**$\acute{o}u$: The ultimate compressive stress at failure, ϵu: The ultimate axial strain at failure, E_2: Axial modulus in the plastic region (the 2nd part of the curves)

†Values in parentheses show the increase/decrease percentage compared to CA-C

‡Values in parentheses show the increase/decrease percentage compared to similar specimens before exposure



(a) Axial stress-strain curves of strengthened specimens

(b) Failure mode of CCAR-M (c) Failure mode of CGAR-M

Fig. 9 Effect of retrofit method 2

3.2.4 Comparing retrofit methods

Lower strength in cracked concrete cover caused significant degradation in ultimate strength of wrapped columns. By comparing the incremental percentages presented in Table 6, it was found that, in term of strength, replacing corroded cover was efficient in both CFRP and GFRP-wrapped columns. In control condition, increasing by 40.3% in ultimate strength of GFRP-wrapped columns, reached up to 108% after replacement of corroded cover. These values were 87% increasing which reached up to 152.8% in CFRP-wrapped columns. In marine environmental condition, because of more curing time for repair mortar, the improvement in ultimate strength was more than that for the control condition. Replacing corroded cover, increased ultimate strength enhancement of 3.4% up to 61.2% and 78.7% up to 142.2% in GFRP and CFRP-wrapped columns, respectively, in marine condition.

Regarding to durability, in retrofit method 1, 26.3% and 4.5% reduction in ultimate strength was observed in strengthened columns by GFRP and CFRP sheets, respectively, after marine exposure. Also in retrofit method 2, exposure caused 22.4% and 4.2% reduction in ultimate strength, in GFRP and CFRP-wrapped columns, respectively. Thus, it can be concluded that although replacing corroded concrete cover by self-compacted mortar caused higher strength in confined columns, the durability of wrapped columns in method 2 was not significantly changed when compared to the corresponding confined columns in method 1. It was due to the similar exposure condition. In both retrofit methods, FRP sheets were exposed to the marine environment.

A few durability enhancements in retrofit method 2 were due to the prevention of internal cracks propagation because of replacing damaged concrete. In retrofit method 1 internal crack probably was developed because of entrapped moisture and chloride ions. Also, because of lower strength and durability of GFRP sheets, in comparison with CFRP, cracks expansion had more destructive effect in GFRP layers.

4. Conclusions

In this study, an extensive experimental program was carried out to evaluate the durability of RC corroded columns strengthened by FRP sheets in the marine environment. Effect of replacing corroded cover was pointed out throughout the test results. The following conclusions are drawn from this study:

• The marine environment had the most deteriorate effect on GFRP sheets. Based on the tensile tests outcomes, the decrease in ultimate tensile strength was 28.8% and 2% for GFRP and CFRP sheets, respectively, after marine exposure. Investigation on failure modes revealed that, exposure mostly caused matrix degradation in CFRP. In GFRP sheets both fiber and matrix were degraded.

• Propagation of internal cracks after accelerated corrosion process caused 29% reduction in compressive strength. Wrapping corroded columns by GFRP and CFRP sheets increased ultimate strength by 40.3% and 87%, respectively, in the retrofit method 1. On the other hand marine environment caused 26.3% and 4.5% reduction, respectively, in GFRP and CFRP-wrapped columns in this retrofit method. It was concluded that although GFRP sheets improved ultimate strength up to un-corroded specimens, marine exposure had a destructive effect on wrapped columns, hence the environmental condition after strengthening RC-corroded columns should be considered.

• In term of strength, replacing corroded cover by self-compacted mortar was efficient in strengthening of RC corroded columns, however the brittle failure was observed. After replacing corroded cover and confining by GFRP and CFRP layers, 108% and 152.8% increase in ultimate strength was observed, respectively, in control condition. In term of durability, marine exposure caused 22.4% and 4.2% reduction in ultimate strength, respectively, in GFRP and CFRP-wrapped column. Because of similar exposure condition in different retrofit methods, retrofit method 2 was not significantly more durable than the retrofit method 1 in marine environmental condition.

• In both retrofit methods, columns were collapsed by FRP breaking. After exposure, CFRP and GFRP mostly ruptured parallel and perpendicular to the fibers orientation, respectively. Therefore it could be concluded that durability of glass fibers was dramatically lower than that for carbon fibers in marine environments.

Acknowledgments

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