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Case study

Utilization of CFRP for strengthening RC columns in marine environment

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ABSTRACT

This paper reports the results of an experimental investigation of the utilization of carbon fiber reinforced polymer (CFRP) to concrete marine structures. The study involved testing reinforced concrete (RC) columns. A total of 32 specimens were grouped and investigated to evaluate the performance of CFRP wrapped RC circular columns in a marine environment. The specimens were immersed for different periods in crude oil or seawater, which are common conditions for marine structures. The specimens were identical and had a diameter of 150 mm and an overall height of 550 mm. Period of immersion was the main test parameter and the investigation focused on the performance of the columns wrapped with CFRP in terms of load capacity, deformation and ductility. The test results showed that the ultimate load capacity of the RC columns wrapped with CFRP was not noticeably affected by immersion in crude oil or seawater. However, there was a significant reduction in ultimate axial displacement and radial strain. Hence, there was a significant negative effect of immersion in crude oil or seawater on the ductility of RC columns confined with CFRP.

1. Introduction

In the past few decades, many types of materials have been developed for the repair or strengthening of reinforced concrete (RC) structures, driven by the demands of the construction industry arising from the existence of concrete problems, such as deterioration, and the need for post-strengthening of structures to ensure their safety and serviceability [1]. Among these materials, fiber reinforced polymer (FRP) has been widely used in construction engineering [2,3] because of its tensile strength, corrosion resistance, and easier handling, in addition to the economic advantages [4,5].

RC elements in marine structures are often exposed to an aggressive marine environment with high humidity and seawater attack in addition to the effects of materials like crude oil. The effects of the marine environment on RC, especially cracking and deterioration, are very harsh and more notable than in other environments [6,7].

Many studies have investigated RC strengthened using FRP. These studies have covered many aspects of FRP-wrapped RC columns, including mechanical properties like strength capacity and ductility [8,9] and durability [10–12]. Chastre and Silva [13] investigated the mechanical behavior of RC circular columns confined with CFRP to evaluate the effects of some parameters, including the diameter of the columns and the number of CFRP layers. They proposed an equation to predict the compressive strength capacity and deformation of circular RC columns wrapped with CFRP, based on their experimental data and the results of other researchers [14–16]. Toutanji [17] reported improvements in strength and ductility due to the confinement of RC columns with

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Table 1
Properties of CFRP and epoxy resin (as per manufacturer).

Material	Tensile E-modulus (MPa)	Tensile strength (MPa)	Ultimate elongation	Density (gm/cm^3)
CFRP	238000	4300	1.8%	1.76
Epoxy Resin	4500	30	0.9%	–

CFRP. The author also investigated the effects of exposure to wet/dry cycles using seawater, and the results exhibited no significant change in strength and only slight changes in ductility (5–15% in terms of ductility ratios).

The main goal of this paper is to investigate the effect of the marine environment on the behavior of RC strengthened with CFRP sheets in the short term. The purpose is to evaluate the aggressiveness of crude oil and seawater on the performance of RC columns wrapped with CFRP and those unwrapped for the same period of exposure. However, the main focus is on the effect of immersion in crude oil or seawater on CFRP-wrapped columns.

2. Experimental program

2.1. Materials

Portland cement concrete was produced in the laboratory according to the ratios of the adopted mix design and used for casting all specimens. Moist curing was used for at least 28 days. Two groups of RC columns were cast to study the effects of crude oil and seawater on the behavior of CFRP-wrapped columns. The average values of concrete compressive strengths at 28 days were 45 MPa and 41 MPa for Group A and B, respectively. The concrete mix proportions were 1:1.5:2 (cement: sand: gravel) by weight, with a water- cement ratio of 0.45. Crushed natural gravel with a maximum size of 10 mm and natural sand were used as coarse and fine aggregate, respectively.

A unidirectional carbon fiber reinforced polymer (CFRP) from the SIKA Company was used for the wrapping of column specimens, and ASIKAdu-330 adhesive was used in the wrapping process. Table 1 shows the properties of the composite materials according to the manufacturer.

The crude oil used in this investigation was Iraqi heavy type collected from the Tawka Station, while the seawater was collected from the Mediterranean Sea, Antalya, Turkey.

2.2. Specimen layout and test set-up

A total of 32 specimens were grouped and investigated to evaluate the performance of CFRP-wrapped RC circular columns in the marine environments explained in Table 2. All the specimens were identical. The diameter of the cross-section was 150 mm and the height of each column was 550 mm. Deformed steel bars with yield strength of 420 MPa were used for longitudinal and transverse reinforcing with nominal diameters of 10 mm and 5 mm, respectively. A schematic of an RC column specimen is shown in Fig. 1(a).

One layer of CFRP sheet was wrapped manually around the RC column with the fiber orientation around the circumferential direction and an overlap length of 100 mm. Additional 50 mm strips of CFRP sheet were installed at the ends of each specimen in order to prevent premature failure. Two weeks after wrapping, the specimens were immersed in crude oil or seawater for different periods, as per the experimental program.

Table 2
Details of tested specimens.

Group	Specimen	Strengthening	Immersion condition	Number of specimens
A1	O-CN-WO	Without	Control (no immersion)	2
	O-30d-WO	Without	30 days in crude oil	2
	O-60d-WO	Without	60 days in crude oil	2
	O-90d-WO	Without	90 days in crude oil	2
A2	O-CN-CFRP	With CFRP	Control (no immersion)	2
	O-30d-CFRP	With CFRP	30 days in crude oil	2
	O-60d-CFRP	With CFRP	60 days in crude oil	2
	O-90d-CFRP	With CFRP	90 days in crude oil	2
B1	S-CN-WO	Without	Control (no immersion)	2
	S-7d-WO	Without	7 days in seawater	2
	S-30d-WO	Without	30 days in seawater	2
	S-90d-WO	Without	90 days in seawater	2
B2	S-CN-CFRP	With CFRP	Control (no immersion)	2
	S-7d-CFRP	With CFRP	7 days in seawater	2
	S-30d-CFRP	With CFRP	30 days in seawater	2
	S-90d-CFRP	With CFRP	90 days in seawater	2

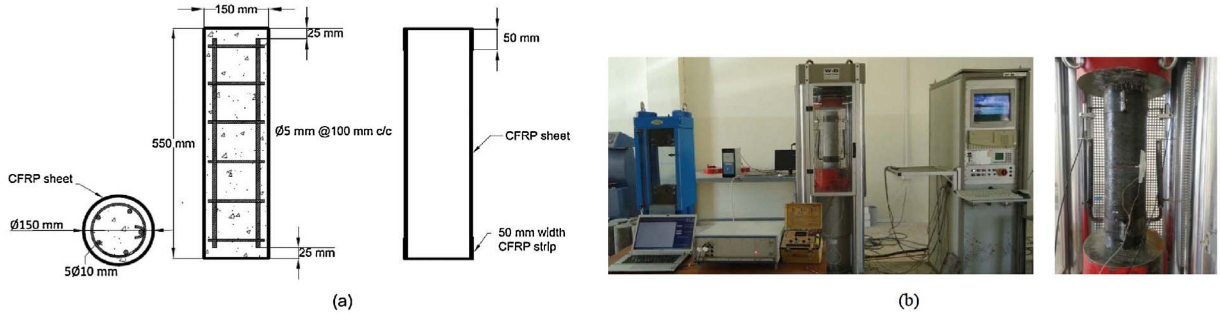

Fig. 1. (a) Steel reinforcement and CFRP wrapping details of RC specimens; (b) Test set-up.

A universal testing machine with a capacity of 3000 kn was used to load column specimens axially in compression until failure. All tests were carried out based on monotonic loading at a constant rate of 0.3 MPa/s. Longitudinal displacements were measured by using two linear variable differential transducers (LVDTs) with a range of 10 mm and accuracy of 0.01 mm over a length of approximately 420 mm. In addition, strain gauges 50 mm in length were placed at the mid-height of the specimens with the fiber direction of the CFRP sheet to measure the radial strain. Fig. 1(b) shows the test set-up.

3. Results and discussion

3.1. Effects of crude oil

Test results of the compressive load tests for all RC columns, with and without CFRP wrapping, that were immersed in crude oil for different periods are presented in Fig. 2. The ultimate load capacities and the comparisons between specimens with CFRP wrapping and control specimens are shown in this figure.

The ultimate load capacity of each column in Group A2 (CFRP-wrapped RC columns) was compared with the control specimen (without immersion in crude oil) and also with the ultimate load capacity of Group A1 (without CFRP), which were immersed for the same period in crude oil. Fig. 2(b) explains these comparisons in terms of strength capacity percentages. It can be seen that the capacity of CFRP- wrapped columns was not affected and there was a slight increase in capacity, which may be attributed to the ageing of the concrete. In contrast, the capacity of unwrapped columns was significantly affected by immersion in crude oil for 30, 60 and 90 days, and the negative changes in load capacity were 11%, 16% and 18%, respectively.

The ultimate deformations obtained for columns wrapped with CFRP are summarized in Table 3. The axial displacement against axial load for specimens wrapped with CFRP is plotted in Fig. 3(a). It is evident that the ultimate axial displacements decreased due to immersion in crude oil. The maximum reduction in ultimate axial displacement was about 37% after 90 days of immersion. The trends of the curves for different periods of immersion in crude oil also changed. These curves give an indication of the ductility of CFRP-wrapped RC columns after immersion in crude oil, and the ductility was clearly reduced with the period of immersion.

The radial stress-strain curves of the columns wrapped with CFRP are presented in Fig. 3(b). The ultimate radial strain decreased with the period of immersion in crude oil. The maximum reduction in ultimate radial strain was about 44% after 90 days of immersion. The trends of the radial stress-strain curves also enhanced the effect of crude oil immersion on the ductility of RC columns wrapped with CFRP.

3.2. Effects of seawater

The effect of immersion in seawater for different periods on the ultimate load capacity and the comparison between the specimens

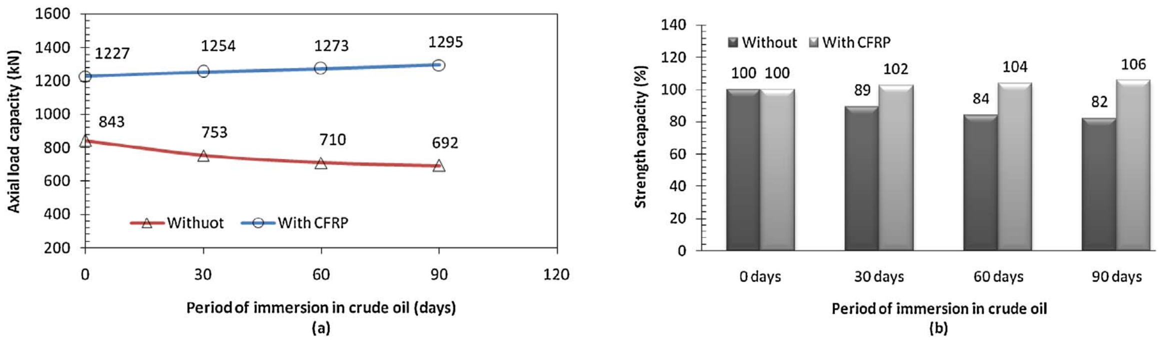

Fig. 2. (a) Ultimate axial load capacity of test specimens immersed in crude oil; (b) change in ultimate load capacity of test specimens immersed in crude oil.

Table 3
Summary of results of tested specimens immersed in crude oil.

Specimen	Ultimate load P_u (kN)	Ultimate axial displacement δ_a (mm)	Ultimate axial strain[*] ϵ_a (x10⁻6)	Ultimate radial strain ϵ_r (x10⁻6)	Ultimate stress σ_u (MPa)
O-CN-CFRP	1227	1.580	3807	8421	69.4
O-30d-CFRP	1254	1.083	2610	5821	71.0
O-60d-CFRP	1273	1.006	2424	5109	72.0
O-90d-CFRP	1295	0.997	2402	4742	73.3

* Based on average vertical distance of 420 mm.

with CFRP wrapping and the controls are presented in Fig. 4.

The comparisons in terms of strength capacity percentages after immersion in seawater for different periods are shown in Fig. 4(b). There was insignificant influence of seawater on the capacity of CFRP-wrapped columns. The capacity of unwrapped columns was also unaffected by immersion in seawater for 7 and 30 days, and there was a negative change in load capacity of about 8% after 90 days of immersion in seawater.

Table 4 summarizes the ultimate deformations of columns wrapped with CFRP and immersed in seawater for different periods. Fig. 5(a) shows the relationship between the axial displacement and axial load for specimens wrapped with CFRP. It can be seen that the ultimate axial displacements decreased due to immersion in seawater. The maximum reduction in ultimate axial displacement was about 53% after 90 days of immersion. Similar trends of curves to those due to immersion in crude oil were observed. These curves give an indication of the ductility of CFRP wrapped RC columns after immersion in seawater, and the ductility was clearly reduced with the period of immersion.

Fig. 5(b) shows the radial stress-strain curves of the tested columns wrapped with CFRP and immersed in seawater. It is clear that the ultimate radial strain decreased with the period of immersion in seawater. The maximum reduction in ultimate radial strain was about 38% after 90 days of immersion. The trends of the radial stress-strain curves give an indication of the significant reduction in ductility of RC columns wrapped with CFRP due to immersion in seawater .

3.3. Mode of failure

The failure pattern of all tested specimens wrapped with CFRP and immersed in crude oil for different periods was governed by an explosive and sudden type of failure. It is evident that failure occurred as the CFRP sheet reached its maximum tensile strength. The damage locations were at the upper third of the height for specimens O-CN-CFRP, O-30d-CFRP and O-90d-CFRP, while they were at the lower third for specimen O-60d-CFRP, as shown in Fig. 6(a).

The explosive and sudden failure type was also observed for all tested specimens wrapped with CFRP and immersed in seawater for different periods. The failure occurred as the CFRP sheet reached its maximum tensile strength. The damage after 90 days of immersion in seawater was aggressive and more than that which occurred due to immersion in crude oil. Fig. 6(b) shows the failure mode of CFRP-wrapped specimens after immersion in seawater. The damage locations of all specimens were within the upper third of the column height.

4. Conclusions

Based on the results obtained from experiments on RC columns wrapped with CFRP and immersed in crude oil or seawater for different periods, which are common conditions for marine structures, the following conclusions can be drawn:

- The ultimate load capacity of the RC columns wrapped with CFRP was not affected due to immersion in crude oil and seawater.

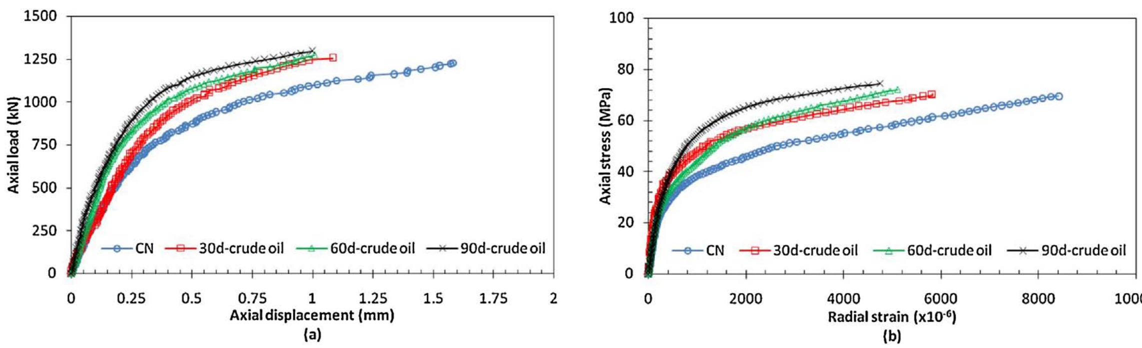

Fig. 3. (a) Axial load-displacement curves of CFRP-wrapped specimens immersed in crude oil; (b) radial stress-strain curves of CFRP-wrapped specimens immersed in crude oil.

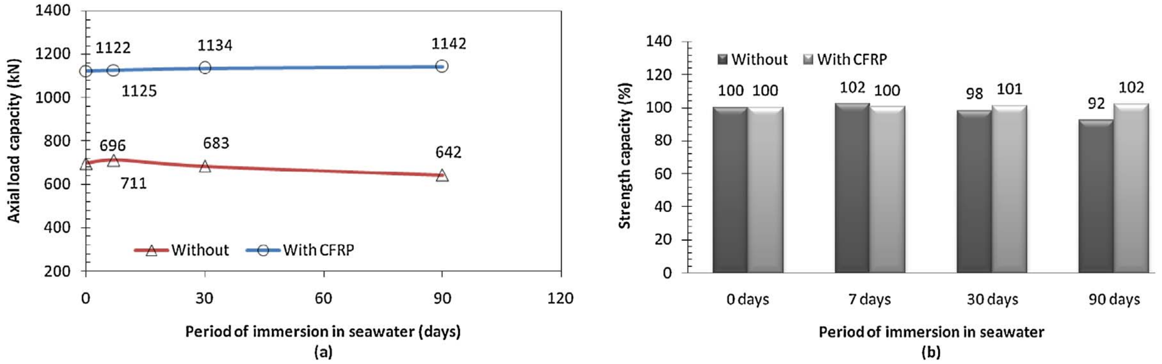

Fig. 4. (a) Ultimate axial load capacity of test specimens immersed in seawater; (b) change in ultimate load capacity of test specimens immersed in seawater.

Table 4
Summary of results of tested specimens immersed in seawater.

Specimen	Ultimate load P_u (kN)	Ultimate axial displacement δ_a (mm)	Ultimate axial strain* ϵ_a (x10^{-6})	Ultimate radial strain ϵ_r (x10^{-6})	Ultimate stress σ_u (MPa)
S-CN-CFRP	1122	1.336	3181	6571	63.5
S-7d-CFRP	1125	1.058	2519	6269	63.7
S-30d-CFRP	1134	0.871	2074	5527	64.2
S-90d-CFRP	1142	0.626	1490	4068	64.6

* Based on average vertical distance of 420 mm.

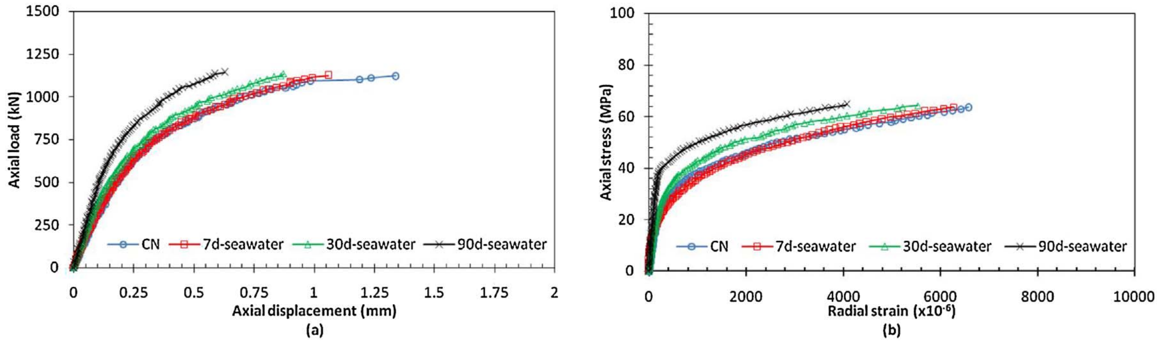

Fig. 5. (a) axial load-displacement curves of CFRP-wrapped specimens immersed in seawater; (b) radial stress-strain curves of CFRP-wrapped specimens immersed in seawater.

There was a significant reduction in the load capacity of the control columns (without CFRP) due to immersion in crude oil and less reduction in load capacity due to immersion in seawater.

- Noticeable decreases in the ultimate axial displacement of the CFRP-wrapped columns were observed after immersion in crude oil

Fig. 6. Failure mode of CFRP-wrapped specimens after (a) immersion in crude oil; (b) immersion in seawater.

and seawater. The maximum decreases in axial displacement were 37% and 53% after 90 days of immersion in crude oil and seawater, respectively.
- Noticeable decreases in the radial strain of CFRP-wrapped columns were observed after immersion in crude oil or seawater. The maximum decreases in axial displacement were 44% and 38% after 90 days of immersion in crude oil and seawater, respectively.
- A significant negative effect was observed on the ductility of RC columns confined with CFRP due to immersion in both crude oil and seawater.
- All tested specimens wrapped with CFRP and immersed in crude oil or seawater for different periods were governed by an explosive and sudden failure type after reaching the maximum tensile strength of the CFRP sheet.

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