Long-Term Performance of Seawater Sea-sand Concrete (SSC) Columns Wrapped with CFRP Strips Under Simulated Marine Environment

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Abstract. This article presents a durability study of carbon fiber-reinforced polymer (CFRP) partially wrapped seawater sea-sand concrete (SSC) columns exposed to natural seawater to explore the effect of exposure duration on the long-term performance of the specimens. Thirty-two cylinders were wrapped with CFRP jackets and exposed to different times of wet-dry cycles (up to 360 days) in an outdoor simulated marine environment. Test results indicate that exposure has no obvious influence on the failure process and ultimate strains of specimens, but the compressive strengths of confined columns ($f_{cu}$) increase with the increment of exposure time, especially for the partially confined concrete specimens. Moreover, due to the significant variation of unconfined concrete strength ($f_{cc}$), the retentions of $f_{cu}$ and $f_{cc}/f_{cu}$ exhibit an opposite trend. Therefore, the increase of $f_{cu}$ should be considered when using the parameter of the confined-to-unconfined ratio of strength to evaluate the long-term performance of the specimens.

Keywords. Partial wrapping; Durability; Seawater sea-sand concrete; Natural exposure; Ultimate condition.

1. Introduction
In recent years, fiber-reinforced polymer (FRP) composites have been widely used in strengthening existing concrete structures and new constructions due to their extraordinary properties of high strength-to-weight ratio and excellent corrosion resistance [1,2]. On the other hand, to develop more environmental-friendly construction in coastal regions, attempts of the direct use of seawater and sea-sand for concrete mixing have been made by many studies [3,4] and the usage of seawater sea-sand concrete (SSC) can significantly alleviate the resource shortage problems and reduce the material transportation costs. However, considering the high chloride contents in seawater and sea-sand, the conventional steel reinforcement cannot be employed, and the FRP can be taken as an attractive replacement of steel, leading to the innovative combination of FRP and SSC, i.e., FRP-SSC structures [5,6]. As the FRP is effective when it is acted as the confinement for concrete members, many investigations have been conducted on the performance of the FRP confined SSC columns [7-9]. In the above-mentioned studies, most of them are only focused on the short-term structural behavior of the columns, but the long-term performance may seem more important for the practical applications for FRP-SSC structures. More importantly, only the mechanical properties of FRP fully wrapped SSC columns have been discussed without considering other FRP wrapping schemes. According to the study by Hollaway and Teng [10], it is crucial to choose the suitable wrapping strategy for the structural members based on their specific locations in the marine environment to improve their long-
term behavior. So the usage of partial wrapping is more reasonable for the columns not submerged in seawater since the evaporation of the moisture can be available in the unwrapped regions [11].

In addition, it is common to use the accelerated degradation tests by increasing the exposure temperature or (and) salt concentration of the solution to examine the durability of the FRP confined concrete columns. However, Li et al. [12] investigated the mechanical performance degradation of the SSC-filled FRP tubular columns under the natural indoor environment for up to 2.5 years. The results reveal that the natural environment may not be as severe as the accelerated test environment, which may result in the failure of the existing degradation models obtained by accelerated tests in predicting the real performance of the columns in a natural environment.

Against this background, this paper presents an experimental study of the durability of carbon fiber-reinforced polymer (CFRP) partially wrapped SSC columns under a wet-dry condition in a natural seawater environment. The effects of clear spacing ratios and conditioned time on the long-term behavior of the specimens were investigated through the test. The experimental program and the test results are presented and discussed in the following sections.

2. Experimental Program

2.1. Specimens Preparation

A total of 44 standard seawater sea-sand concrete cylinders were fabricated in this research, including 12 unconfined control specimens, 24 partially CFRP confined SSC columns and 8 fully CFRP confined SSC columns. The main test parameters are listed in Table 1, and figure 1 shows the wrapping schemes of CFRP wrapped specimens. Besides, five conditioned ages (0, 60 days, 120 days, 180 days, 360 days) were set to explore the exposure time on the mechanical performance of the specimens. It should be noted that the unconditioned specimens were derived from the authors’ previous study [13].

| Specimen ID | s/D | Wrapping schemes | Control a | Aging time (Days) 60 | 120 | 180 | 360 |
|-------------|-----|------------------|-----------|----------------------|-----|-----|-----|
| R           | /   | /                | 3         | 3                    | 3   | 3   | 3   |
| W4A2        | 0.6 | Partial          | 2         | 2                    | 2   | 2   | 2   |
| W5A2        | 0.5 | Partial          | 2         | 2                    | 2   | 2   | 2   |
| W6A2        | 0.4 | Partial          | 2         | 2                    | 2   | 2   | 2   |
| F1          | 0   | Full             | 2         | 2                    | 2   | 2   | 2   |

Note: (a) The control specimens were derived from the existing studies conducted by the authors’ group [13].

![Figure 1](image.png)

Figure 1. Wrapping schemes of the tested specimens (unit: mm).

The same concrete mix proportion was used for all specimens in this study. In addition, the unidirectional CFRP sheets were wrapped in the circumferential direction by the traditional wet-layup
technique. To prevent the premature debonding failure, an additional 150-mm overlap zone was provided. For ease of the following discussions, each specimen was given a name. R represents the control specimens. W4A2, W5A2 and W6A2 stand for the CFRP partially wrapped columns with the width of the FRP strips equal to 40 mm, 50 mm and 60 mm, respectively. F1 means the one-layer CFRP fully wrapped SSC columns.

2.2. Exposure Conditions
As shown in figure 2, a simulation tank was constructed in the outdoor environment in Dalian, China to simulate the natural marine environment. The sea tidal regime was simulated by the wet-dry cycling condition, which was achieved by 12 h of immersion in natural seawater and 12 h of drying with the help of the water pump in each chamber (figure 2). Each complete wet-dry cycle consisted of 24 h and the conditioned specimens were tested after 60, 120, 180 and 360 days, respectively.

![Figure 2. Simulation tank for seawater wet-dry cycling.](image)

2.3. Material Properties and Test Setup
The same raw materials of concrete, CFRP, test setup and instrumentations adopted in the previous study [13] were also used in this test, and both the unconditioned and conditioned specimens were fabricated at the same time to make the results more reliable. The readers may refer to the literature [13] for more details.

3. Results and Discussions

3.1. Failure Modes
Figure 3 shows the failure modes of some typical specimens at different aging times. It can be found that the surfaces of unconfined specimens and the unwrapped regions of partially wrapped specimens exhibited more obvious color change from whitish gray to dark gray with the increase of the aging time, which may result from the salt deposition on the surfaces after exposure in seawater. Besides, salt crystallization was also observed on the surfaces of CFRP jackets as shown in figure 3.
However, apart from the above-mentioned visual changes, the conditioned ages had no significant influence on the final failure modes of specimens. The unconfined specimens failed in a classic manner with the crushing of SSC, and the interior part of the specimens retained their original color. It is indicated that only the outer side of the unwrapped regions of the columns was affected by the seawater action, which is consistent with the observation from the study conducted by Islam et al. [14].

For the unconditioned CFRP confined specimens, the fully wrapped specimens showed no changes before the applied load reached the ultimate load of unconfined specimens, while some slight vertical cracks were observed in the unwrapped regions of the partially wrapped columns. Then, with the increase of the applied load, the number and the width of the cracks increased, and the sporadic popping sounds could be heard when the load was approaching the ultimate value. Finally, the fully and partially wrapped specimens failed by the rupture of the CFRP jackets and the CFRP strips at the midheight, respectively. A similar failure process was detected for the conditioned columns, but their failure became more brittle, which may result from the embrittlement of the CFRP system after the wet-dry cycles. Moreover, less concrete debris was found on the internal surface of the CFRP jackets after the test, so the concrete-resin interface was also degraded to some extent.

3.2. Stress-Strain Relationships

Figure 4 shows the axial stress-axial (lateral) strain relationships of the confined specimens. It should be noted that both the stress and strain in figure 4 are normalized by the unconfined strength $f_{\text{cu}}$ and peak strain $\varepsilon_{\text{pe}}$ at the corresponding aging time to exclude the effect of material properties of concrete.
As depicted in Figure 4, the natural wet-dry cycles have various impacts on the shape and key points of the normalized stress-strain curves for the specimens with different wrapping schemes. In specific, the slope of the post-peak segment on stress-strain curves of the partially wrapped specimens gradually degrades with the increase of the aging time, especially for the specimen W4A2 with the largest clear spacing ratio, which may be attributed to the plasticization of the resin matrix and the fiber-resin interface damage induced by the seawater action during wet-dry cycles, leading to the degradation of the confinement stiffness of CFRP strips. However, it is noteworthy that the locations of the transition points on the curves of the partially wrapped specimens are almost unchanged under different exposure times, illustrating that the exposure may have a similar degradation effect on the unconfined and partially confined cylinders. On the other hand, for the fully wrapped specimens, although the slope of the second linear portion decreases as a result of the wet-dry cycles, all columns possess a typical bi-linear stress-strain response regardless of the aging time. Moreover, the normalized stress-strain curves of unconditioned specimens are obviously higher than that of the conditioned columns, which manifests that the effect of the $f_{co}^*$ on the fully wrapped specimens is more significant compared to the columns wrapped with CFRP strips.

3.3. Effects of Conditioned Ages on Compressive Strength

3.3.1. Unconfined Specimens. It is worth mentioning that the average strength and strain of the nominally identical specimens will be used in the following discussions unless otherwise specified. It can be seen from Figure 5 that the ultimate strains of the unconfined specimens only fluctuate slightly during the aging period, while more obvious enhancement is detected for the compressive strength with the increase of aging time, especially in the early stage, which is consistent with the observations found by Li et al. [12]. This may result from the following two reasons. Firstly, the seawater in the tank can promote further hydration of the unhydrated cement, leading to the increase of the compactness of the concrete. Besides, the ettringite and Friedel salt produced from the reactions of the ions (e.g., chloride and sulphate ions) in the seawater, calcium hydroxide, unhydrated and hydrated calcium aluminate can improve the pore structure of concrete, which is also beneficial to the compressive strength development of SSC.
3.3.2. Confined Specimens. Figure 6 (a) presents the variations of the compressive strength $f_{cc}$ of confined specimens during the aging period. The overall ascending trend is detected with the increase of the aging time for a single column. Furthermore, due to the difference in FRP volumetric ratio, specimen F1 possesses the highest compressive strength at each conditioned time among all specimens. To exclude the influence of volumetric ratio on the compressive strength, the retentions of $f_{cc}$ and $f_{cc}/f_{co}^*$ are given in figure 6, where the retention of unconfined compressive strength $f_{co}^*$ is also depicted for comparison.

![Figure 5](image)

**Figure 5.** Effect of exposure duration on the material properties of SSC.

![Figure 6](image)

**Figure 6.** Variation of compressive strength with the increase of aging time.

As shown in figure 6 (b), although the $f_{cc}$ retentions of all confined specimens increase with the aging time, the retention of $f_{co}^*$ is still larger than that of $f_{cc}$ at every conditioned age. This is because apart from the SSC, both the fiber and resin matrix may also be degraded during the conditioned period. Moreover, due to the different thermal coefficients of fibers and matrix, the thermal variation may also cause the interface damage between fibers and matrix. However, the above-mentioned speculation needs further verification at the microscopic level in the future. Thus, the degradation mechanism seems more complicated for CFRP confined SSC compared to the unconfined specimens, leading to the more obvious decrease of $f_{cc}$ retentions. Nevertheless, it should be noted that the partially wrapped concrete specimens exhibit larger $f_{cc}$ retentions, which may result from the higher compactness of concrete since the aforementioned ettringite and Friedel salt can be produced more effectively due to the existence of unconfined regions in the partially wrapped columns. Besides, the possibility of matrix degradation and interface damage is also reduced because of the less usage of CFRP materials and smaller contact interface between CFRP and SSC.

However, the retention of the normalized $f_{cc}/f_{co}^*$ shows a completely different trend as depicted in figure 6 (c). The $f_{cc}/f_{co}^*$ retentions of all specimens are smaller than 100% and decrease with the increment of aging time, especially for the fully wrapped columns. This is because that the effect of
improved pore structures of concrete on the compressive strength of $f_{cc}^*$ is more significant than the influence of the conditioned ages on the strength $f_{cc}$, which is consistent with the observations as shown in figure 6 (b).

3.4. Effects of Conditioned Ages on Ultimate Strain

It should be noted that the ultimate strain of specimen W5A2 is much smaller than the other partially wrapped specimens due to the abnormal value of W5A2-2. Thus, to make the comparisons more reasonable, the ultimate strain of W5A2-1 instead of the average value will be used in the following discussions.

As shown in figure 7 (a), the variations of ultimate strains are more scattered compared with those of the compressive strengths and similar results were also detected by Xie et al. [15], which means that the ultimate strain is more sensitive to the conditioned environment. Moreover, the variations seem to have no relationship with the wrapping schemes. On the other hand, since the peak strain of unconfined concrete exhibits insignificant changes with the aging time, a similar trend of $\varepsilon_{cu}$ and $\varepsilon_{cu}/\varepsilon_{co}^*$ retentions is observed as depicted in figure 7 (b) and figure 7 (c). In specific, in the later stage of the conditioned period (180 days), the retention of $\varepsilon_{cu}/\varepsilon_{co}^*$ shows an obvious descending trend.

Figure 7. Variation of ultimate strain with the increase of aging time.

4. Conclusions

(1) Due to the seawater wet-dry cycling effect, the surfaces of concrete change into dark surfaces because of the salt deposits and the salt crystallization is also observed on the CFRP surfaces. However, the conditioned environment has little impact on the failure modes of the confined specimens, which is still controlled by the rupture of the CFRP jackets.

(2) The post-peak behavior of the CFRP partially wrapped specimens is significantly influenced by the aging time, while all fully wrapped columns possess typical bi-linear stress-strain responses regardless of the exposure duration. But the slope of the second linear segment is degraded to some extent.

(3) Under the conditioned environment in the present study, the compressive strength of unconfined specimens increases with the aging time, which leads to the different trend of the variations of $f_{cc}$ and $f_{cc}/f_{co}^*$ retentions.

(4) Compared to the compressive strength, the conditioned environment has no clear effect on the ultimate strain of confined specimens. Besides, the strain variations seem to have no relationship with the wrapping schemes.

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