Structural performance of FRP confined seawater concrete columns under chloride environment

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ABSTRACT

To alleviate resource shortage and environmental problems, a combination of fiber reinforced polymer (FRP) and seawater concrete is an attractive option for replacing conventional reinforced concrete in marine structures. The chloride ions in concrete structures increase with extension of service time due to penetration from the marine environment, resulting in serious deterioration of concrete structures. In order to apply such a material combination to civil infrastructure safely, the performance of FRP confined concrete with different chloride concentrations has been experimentally studied. The results show that a 23% reduction in strength is observed in 1-ply FRP confined concrete column when chloride ion concentration increases from 0% to 1.57% (saturated water level). Furthermore, a design-oriented model is proposed to evaluate the stress-strain behavior of FRP confined seawater concrete, as well as concrete with elevated chloride concentrations due to prolonged service time in the marine environment. The experimental findings and the proposed design-oriented model can promote the wide usage of FRP confined seawater concrete in offshore structures and artificial islands.

1. Introduction

In 2016, cement production has reached 4.2 billion tonnes across the world, and most of it is used to produce concrete and mortar [1]. In particular, more than half of this huge amount of concrete is produced and consumed in mainland China. Such a tremendous amount of cement and concrete production requires consumption of a huge amount of constituent materials, especially freshwater and river sand, raising serious resource shortage, ecological and environmental problems. Intensified exploitation of river sand possess a negative effect on river ecosystems and flood control. The consumption of a huge amount of fresh water poses a great threat to water shortage. As a result, some regulations have been issued by the Chinese government because of environmental and resource consideration, such as banning sand mining from the Yangtze River.

In order to avoid the overexploitation of freshwater and river sand and to reduce the financial expenses, the usage of seawater and sea sand is an attractive alternative for the construction industry, especially for the offshore structures and artificial islands in the marine environment [2–5]. Construction of offshore structures and artificial islands has become essential nowadays for the exploitation of oil and gas, as well as the infrastructure development of airports and ports. However, the high chloride content of seawater can greatly accelerate the corrosion of steel reinforcements and deteriorate the mechanical properties of traditional reinforced concrete [6,7]. To address this critical problem, fiber reinforced polymer (FRP) is an increasingly popular material for externally reinforcing marine concrete structures due to its superior electro-chemical corrosion resistance and high strength to weight ratio [8–12]. The FRP applications in seawater concrete columns in marine structures can be classified into internal reinforcements (FRP rebar) and external bonding (FRP wrap). As the chloride ion is an critical factor in the deterioration of the entire material system in the seawater environment, its effect on FRP strengthened concrete should be comprehensively studied [13–15]. Recently, the long-term performance of FRP rebar internally reinforced concrete with various chloride ion concentrations has been reported [16,17]. However, the structural properties and stress-strain behaviors of externally FRP wrapped concrete columns with different chloride ion concentrations are still not fully understood, hindering the application of the FRP wrapped seawater concrete system in engineering practice.

A number of studies have been conducted to investigate the structural behavior and durability of seawater concrete, FRP sheets and FRP wrapped concrete columns [18–27]. Seawater and sea sand concrete possess some different properties compared to normal concrete, mainly...
due to the chloride ions [28]. The chloride ions can accelerate the hydration process of concrete, resulting in a shortened setting time and accelerated strength gain at early stages. However, the seawater concrete may suffer a lower strength growth speed at later stages. As the mix proportion of concrete is varied, the compressive strength of seawater concrete may be similar to or slightly lower than that of normal concrete depending on the design mix [4]. For both seawater and sand concrete and normal concrete, FRP wrapping can provide confinement for concrete and such confinement is generally of the passive type, which can be interpreted as the lateral confinement pressure from FRP due to the lateral expansion of the concrete column under axial compression [29]. The effectiveness of FRP confinement has been studied by various researchers [30–32]. Most studies on the FRP confinement effect are focused on circular shape. Experimental studies have shown that the FRP wrapping technique can enhance the axial load carrying capacity of columns, and the enhancement effect depends on the FRP configuration (mechanical properties, layers and disposition), cross-section shape and column strength [33]. Based on previous studies, the deterioration of FRP sheets, especially for GFRP, is mainly caused by salt water and alkaline environment exposure compared to other environmental conditions [23]. Meanwhile, humidity has been demonstrated to cause the primary detrimental effect; salt ions and crystals then diffuse and expand into microcracks with time, exacerbating the deteriorating effect on FRP [34]. In an accelerated environmental condition test, GFRP sheets were immersed in 5% NaCl solution and a significant reduction on the tensile strength of GFRP was observed [35]. An experimental program was conducted to determine the strength of concrete columns wrapped by different FRP sheets subjected to salt solution. It was observed that both concrete columns wrapped by carbon FRP (CFRP) and those wrapped by glass FRP (GFRP) showed a reduction in ultimate strength after exposure to salt solution for four months [36]. The deterioration from salt water is more serious in GFRP wrapped concrete than that in CFRP wrapped concrete. Although wrapping with FRP sheets has been recognized as an effective strengthening technique and durability of single FRP material under chloride ions has been studied, the structural behaviors of the entire system, i.e. FRP wrapped seawater concrete, and its feasibility to marine structures are still unknown. Moreover, when FRP wrapped seawater concrete serves in the marine environment for a prolonged time, its chloride ion concentration would keep increasing due to the chemical potential energy difference between marine environment and concrete. Currently, there is no model that can accurately describe the stress-strain behavior of FRP wrapped seawater concrete being reported, not to mention the stress-strain behavior of FRP wrapped seawater concrete developing increased chloride ion concentrations with service time. This knowledge gap hinders the application of FRP wrapped seawater concrete to offshore structures and artificial islands and needs to be studied with more experimental data.

The objectives of this research are to experimentally investigate the structural performance of FRP wrapped seawater concrete and to propose a design-oriented model that can predict the stress-axial strain behavior of FRP wrapped seawater concrete columns with different chloride ion concentrations. Such different chloride ion concentrations may be encountered during the prolonged service life of structures in the marine environment. In this paper, FRP wrapped concrete with three chloride ion concentrations, i.e. fresh water level, seawater level and saturated water level, has been prepared and tested. The fresh water level acts as a benchmark, and the seawater level is used to evaluate the structural behavior of FRP wrapped seawater concrete. For the chloride concentration of saturated water, it is designed at a level that seawater concrete can reach after serving in the seawater environment for more than ten years [37]. The structural behaviors of FRP wrapped concrete specimens are determined by compressive test. In addition, based on experimental results, a modified design-oriented model that can depict the stress-strain responses of FRP confined concrete columns with different chloride ion concentrations is proposed. The experimental findings provide a comprehensive understanding on the structural behavior of FRP confined seawater concrete. Furthermore, the proposed model can be used to evaluate the behavior of FRP confined seawater concrete and to demonstrate its feasibility in constructing more durable and economical offshore structures and artificial islands.

2. Experimental program

The experimental tests were performed in this study to investigate the structural behavior of FRP confined seawater concrete columns and its performance under chloride ingress. The details of the materials, design and preparation of specimens and test instrumentation are introduced below.

2.1. Materials and specimens

In this work, test variables include chloride ion concentrations of mixing water used for preparing concrete and number of layers of FRP sheet. The dimensions of the concrete cylinder were 300 mm in height and 150 mm in diameter. Previous research has clarified that the size effect of columns is not significant until the diameter of the column is smaller than 50 mm [38]. Although the size of such a concrete column is small compared to that of columns in practical structures, the test results and stress-strain relations from such columns can still be adopted. Three kinds of mixing water with different salinities, 0%, 3.5% and 26.5%, were used to prepare the concrete cylinders. The 0% batch stands for distilled water for control group, and the 3.5% batch corresponds to the salinity of seawater. In order to simulate the chloride concentration of concrete structure after prolonged service in marine environment and evaluate its durability, a much higher salinity of water is adopted to cast concrete. The 26.5% salinity of casting water is selected because it is the saturated state for chloride ions that can be dissolved in water at 20°C [39]. It should be noticed that the chloride concentration of entire concrete system is only 1.7% when it is casted with 26.5% salinity of water, which is still much lower than that of seawater. It has been estimated that the chloride concentration of concrete structure may reach 1.7% level after serving in seawater environment for more than 10 years [37]. The salt water was prepared using NaCl solution because a latest research has demonstrated that seawater can be replaced by NaCl solution when evaluating the performance of concrete in marine [40]. Carbon FRP (CFRP) is used to wrap concrete columns to provide confinement. The FRP wrapping layers varied from 1-ply to 3-ply for concrete columns, and the concrete columns with no FRP wrapping were also prepared and tested as a benchmark. Through this design, the axial compressive behavior of FRP confined concrete columns affected by chloride ions, which is considered as the most important property of column components towards its real application, can be comprehensively studied. The nomenclature of specimens in this study can be described in the form of variables, for example FCC/PC-W-X, demonstrating condition of FRP confinement, chloride ion concentrations of mixing water and number of FRP layers in sequence. FCC represents carbon FRP confined concrete column, and PC stands for plain concrete without FRP confinement. The letter ‘W’ donates the chloride ion concentrations of mixing water, and the distilled water, seawater and fully saturated water used in this study are represented by ‘d’, ‘s’ and ‘f’, separately. The letter ‘X’ symbolizes the number of FRP layers for the concrete columns. For example, FCC-s-3 stands for the FRP confined concrete column in which seawater is used for casting concrete and three layers of FRP are wrapped for confinement.

Normal concrete was used in this work. The river sand, coarse aggregate and different chloride ion concentrations of mixing water were used to cast concrete cylinders. All sands and aggregates were put into an oven for complete drying before casting in order to minimize the water content. The concrete was mixed uniformly in a mixer. After one
day of casting, the specimens were demolded and put into a curing room at 25°C for 28 days. The detailed concrete design mix can be found in Refs. [41,42]. There are micropores and capillaries in the matrix of concrete, and such micropores act as important transportation channels for chloride ions. After curing, a gypsum capping was made to the top surface of concrete cylinder to achieve a smooth contact surface. Concrete cylinders were wrapped with a CFRP jacket through the wet layup method according to the specimen design. The nominal thickness of one-layer CFRP is 0.167 mm. A two-part epoxy was used as adhesive in the wrapping process. The fibers oriented in the hoop direction of circular concrete cylinder. An overlapping zone between starting point and finishing point was allowed in each FRP layer, and its length was 150 mm. The purpose of overlapping zone was to make sure the tensile strength of FRP jacket was fully developed. The FRP wrapped concrete specimens were kept in a dry environment at 25°C for two weeks of curing before the compressive test.

The tensile test of FRP was conducted to evaluate the mechanical properties of the FRP jacket. Three unidirectional single layer CFRP sheets were tested following the American Society for Testing and Materials (ASTM) standard D3039. The average tensile strength and elastic modulus of CFRP are 3.66 GPa and 232 GPa, separately. The average rupture strain of CFRP is 1.58%.

2.2. Test instrumentation

The vertical displacement of concrete column was measured through 25 mm linear variable differential transformers (LVDTs). Four LVDTs were evenly distributed around the circular cylinder and mounted on the aluminum frame that was fixed on the concrete. The gauge length of aluminum frame is 180 mm. Meanwhile, four strain gauges were horizontally bonded to the surface of FRP at the middle height of cylinder to measure the lateral strain. A schematic diagram of the distribution of LVDTs and strain gauges is shown in Fig. 1. All concrete specimens were tested under compression through a 3000 kN Material Test System (MTS) in displacement control mode. The load was applied monotonically until failure and the loading rate was selected as 0.4 mm/min according to ASTM standard. During compressive test, the centering of specimens was conducted through loading to 10% of loading capacity of the unconfined concrete column to verify test alignment. All test data, including load, displacement and strain variations were recorded simultaneously through a TDS 530 data logger.

3. Test results

3.1. Plain concrete

The effect of chloride ions is characterized by the mechanical properties of plain concrete and FRP confined concrete columns. The stress-strain relationships of plain concrete mixed with different water are shown in Fig. 2. It should be noted that the stress-strain relations in this paper only represent axial stress-axial strain relations and axial stress-lateral strain relations. For concrete, the compressive stress and strain is defined as positive. From Fig. 2, a slight decrease of peak strength ($f_{co}$) and elastic modulus ($E_c$) occurs from distilled water scenario to seawater scenario. This decreasing trend becomes more obvious with the increase of chloride ion concentration. The compressive properties of all concrete columns are shown in Table 1. When saturated water is used, the peak strength reduces to 29.05 MPa, showing a 40% reduction compared to that of PC-d-0. In fact, this saturated water
level of chloride ions in a concrete structure can be encountered after the structure has served in seawater for more than ten years [37]. However, contrary to peak strength, the corresponding axial strain (ε_{co}) of unconfined concrete at peak strength presents an increasing trend with an increase of chloride ion concentrations. The corresponding axial strains (ε_{co}) at peak strength of PC-s-0 and PC-f-0 are 0.23% and 0.30%, which are 9% and 43% larger than that of PC-d-0, respectively. Furthermore, the post peak response of PC-f-0 exhibits some different behavior. The post peak response of PC-f-0 is more smooth and gentle than that of PC-d-0, for which a quick drop can be found in the stress-axial strain curve. The end point of each stress-strain curve of plain concrete is defined when the stress reaches 20% of peak stress. For plain concrete specimens, the damage initiates with inclined cracking of concrete, and the specimens fail due to concrete crushing. The failure modes of plain concrete mixed with different water are similar.

### 3.2. FRP confined concrete

Axial compressive behavior of FRP confined seawater concrete column is analyzed based on key properties, including the ultimate strength, ultimate axial strain of FRP confined concrete columns and hoop strain in FRP. These properties cover important categories concerned in the existing design code, i.e. American Concrete Institute (ACI) 440.2R-17, to design and evaluate the compression behavior of FRP confined concrete columns [43]. The stress-strain responses of 1-ply and 3-ply FRP confined concrete columns are described in Fig. 3. The axial stress-axial strain curves are shown on the right, while the axial stress-lateral strain curves are shown on the left. The axial strain is the average value from readings of four LVDTs, as the data from LVDTs are more accurate than those from vertical strain gauges and they are not easily affected by localized post cracking of concrete. The lateral strain is the average value from the lateral strain gauges at the FRP surface at mid-height area. From Fig. 3, the axial stress-axial strain relationships of both 1-ply and 3-ply FRP confined concrete can typically be divided into three segments. The first segment is the first linear ascending segment where concrete specimen is in elastic stage and stress increases with strain linearly. Then, a transition segment follows. The microcracks in concrete come out and propagate with the increasing load, the FRP jackets start to carry load gradually and a smooth inflection comes out in the axial stress-axial strain curves. The third segment is the second ascending segment in which the hoop dilation of concrete due to increasing load is carried by FRP jackets. The slope of this ascending segment is determined by the FRP confinement stiffness. The termination of the third segment stands for the end point of stress-strain curve, as well as the failure of FRP confined concrete column. The stress-axial strain curves of FRP confined concrete with salt water, including seawater and saturated water, show different behaviors in the transition segment and the third segment compared to those of FRP confined concrete with distilled water. This difference mainly lies in the starting point of the transition segment and the slope of the second ascending segment. The different stress-strain behaviors may be attributed to the difference in concrete dilation properties, deteriorated peak axial strength and enhanced axial strain at peak strength. Similarly to plain concrete, chloride ions have a detrimental effect on the ultimate strength of FRP confined concrete. The peak strength of FCC-s-1 and FCC-f-1 possesses 14% and 23% of reduction compared to that of FCC-d-1, respectively. A similar behavior, 14% and 24% reduction of peak strength, is observed in FCC-s-3 and FCC-f-3 compared to FCC-d-3. Contrary to the deterioration of peak strength, the axial strain shows a growing trend with the higher concentration of chloride ions. The ultimate axial strain increases from 1.54% (FCC-d-1) to 2.30% (FCC-f-1) for 1-ply scenario and from 2.09% (FCC-d-3) to 2.82% (FCC-f-3) for 3-ply scenario. These phenomena are caused by the strain enhancement occurring in the plain concrete, which is discussed in Section 3.1.

For the axial stress-lateral strain behavior shown in Fig. 3, the effect of chloride ions on ultimate lateral strain is negative. In 1-ply FRP confined scenario, the ultimate lateral strain decreases slightly from 1.51% to 1.41% corresponding to FCC-d-1 and FCC-f-1, separately. This effect becomes more significant in 3-ply scenario, resulting in a reduction of ultimate lateral strain from 1.76% (FCC-d-3) to 1.39% (FCC-f-3). Such a large reduction may be attributed to the deterioration effect of chloride ions on the epoxy adhesive and concrete-epoxy interface. Previous molecular dynamics and experimental tests have demonstrated that chloride ions can significantly weaken the adhesion energy, by up to 57%, of concrete-epoxy system [44]. The deteriorated adhesion energy results in insufficient stress transfer from concrete to FRP jacket.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>FRP layer</th>
<th>Ultimate strength (MPa)</th>
<th>Ultimate axial strain</th>
<th>Ultimate lateral strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-d-0</td>
<td>none</td>
<td>48.44</td>
<td>0.21%</td>
<td>–</td>
</tr>
<tr>
<td>PC-s-0</td>
<td></td>
<td>41.94</td>
<td>0.23%</td>
<td></td>
</tr>
<tr>
<td>PC-f-0</td>
<td></td>
<td>29.05</td>
<td>0.25%</td>
<td></td>
</tr>
<tr>
<td>FCC-d-1</td>
<td>1-ply</td>
<td>73.43</td>
<td>1.54%</td>
<td>1.51%</td>
</tr>
<tr>
<td>FCC-s-1</td>
<td>3-ply</td>
<td>63.12</td>
<td>1.93%</td>
<td>1.48%</td>
</tr>
<tr>
<td>FCC-f-1</td>
<td></td>
<td>56.39</td>
<td>2.30%</td>
<td>1.41%</td>
</tr>
<tr>
<td>FCC-d-3</td>
<td></td>
<td>143.82</td>
<td>2.09%</td>
<td>1.76%</td>
</tr>
<tr>
<td>FCC-s-3</td>
<td></td>
<td>123.78</td>
<td>2.46%</td>
<td>1.57%</td>
</tr>
<tr>
<td>FCC-f-3</td>
<td></td>
<td>109.12</td>
<td>2.82%</td>
<td>1.39%</td>
</tr>
</tbody>
</table>

### Table 1
Experimental results of concrete column specimens.
3.3. Failure modes

The failure modes of FRP-confined concrete columns with different chloride ion concentrations and FRP layers are shown in Fig. 4. The failure of FRP confined concrete columns is mainly constituted by rupture of FRP jacket and concrete crushing. For the failure process of these specimens, a clicking sound first occurs due to rupture of epoxy. Then, an explosive sound is heard, representing the rupture of FRP. The FRP rupture is often accompanied by concrete crushing and sudden loss of load carrying capacity for the entire specimen. The rupture of FRP usually occurs near the mid-height region and outside of overlapping zone. Moreover, since the displacement control method was adopted for the entire loading process, the stiffness of the equipment plays an important role in the post-peak behavior and failure mode of FRP confined concrete specimens. If the stiffness of the equipment is comparable to the stiffness of the concrete sample with FRP confinement, the explosive failure mode can be remediated and a pseudo-ductile behavior can be observed. Due to the fact that the stiffness of equipment (made by stainless steel with the elastic modulus of 200 GPa) is much higher than that of FRP confined concrete samples, which is around 30 GPa, the explosive failure mode is observed in the experiment accordingly with the rupture of FRP jacket at the end of test. Such explosive failure is also widely reported for FRP confined concrete column [45-47]. As shown in Fig. 4, the crushing of concrete in specimen FCC-f-1 is much more intense than that of FCC-d-1. The reason behind this observation is that the ultimate axial strain of FCC-f-1 is much larger than that of FCC-d-1. Under a large axial deformation, the axial stress of concrete increases significantly, resulting in substantial crushing of concrete. Similar phenomena are also observed in the 3-ply scenario of FCC-d-3 and FCC-f-3. The damage to concrete in 3-ply scenario is more violent, and a large amount of concrete is broken into small pieces and even ashes, which can be seen in the FCC-f-3 specimens.

4. Discussion

4.1. Effect of ultimate behavior of FRP-confined concrete

The ultimate strength ($f_{cu}$) of FRP-confined concrete column and the corresponding axial strain ($\varepsilon_{cu}$) play an important role in determining stress-strain model of FRP confined concrete. According to the experimental results from FRP confined concrete columns, the ultimate strength and the corresponding axial strain vary with different chloride ion concentrations. The values of $f_{cu}$ and $\varepsilon_{cu}$ for all tested specimens are listed in Table 1.

In order to predict $f_{cu}$, most of the existing models are developed based on Richart’s model [48], which is shown as:

$$\frac{f_{cu}}{f_{co}} = 1 + k_1 \frac{f_{frp}}{f_{co}}$$

(1)

where $f_{co}$ is the confining pressure expressed as

$$f_{co} = \frac{2E_{s}\varepsilon_{s} \nu_{s} t_{s}}{D}$$

(2)

in which $E_{s}$, $\varepsilon_{s}$, and $t_{s}$ are the elastic modulus, rupture strain and nominal thickness of FRP, respectively; and $D$ is the diameter of the column. The model for $f_{cu}$ can be derived from the test data. A clear linear relationship between $f_{cu}/f_{co}$ and $f_{frp}/f_{co}$ can be correlated. The slope of the trend line is expressed as factor $k_1$ in Eq. (1). Through regression analysis of the test data in Table 1, the values of $k_1$ are obtained. It is noted that the regressed model (dashed line in Fig. 5) must pass through the point (0,1) because $f_{cu} = f_{co}$ or $f_{frp}/f_{co} = 1$ when confinement $f_{frp}$ is zero. It can be found that the value of $k_1$ varies from 3 to 3.6 with the increase of chloride ion concentrations. According to the analyses of the experimental results and recommendations from different studies, the confinement effectiveness coefficient, $k_1$, could be taken as 3.6 to calculate the ultimate strength of the FRP confined concrete with different chloride ion concentrations. The performance of calibrated Richart’s model and experimental results are shown in Fig. 5. A good agreement between values from calibrated Richart’s model and experimental values can be found, with the square deviation ($R^2$) equaling 0.97.

The effect of chloride ion concentration on the ultimate axial strain of FRP confined concrete has been demonstrated with experimental results in Fig. 3. With the increase of chloride ion concentrations, the ultimate axial strain of FRP confined concrete varies from 1.54% to 2.30% for 1-ply FRP confinement, and from 2.09% to 2.82% for 3-ply FRP confinement. Since the same FRP material was used for confinement, such ultimate strain variations could be related to the different stress-strain behavior of concrete with different chloride ion concentrations. Based on the stress-strain curves of unconfined plain concrete samples, although the compressive strength of concrete columns cast with distilled water and seawater is close to each other, the
corresponding axial strains at peak strength of unconfined concrete are different. For the concrete cast with saturated water, both the ultimate strength and the corresponding strain show significant variations. Such stress-strain behaviors of unconfined concrete result in different secant values of elastic modulus, $E_{sec}$, of concrete cast with different chloride ion contents. The dependence of the ultimate strain of FRP confined concrete on the secant values of elastic modulus and Poisson’s ratio can be demonstrated in the existing literature and experimental results of this study [8,18].

The general form of ultimate strain models is expressed as [18]:

$$\frac{\varepsilon_{ru}}{\varepsilon_c} = C + k_2 \left(\frac{E_{frp} t_f}{E_{sec} R}\right) \frac{\varepsilon_{rup}}{\varepsilon_c}$$

where $C$ is calibration constant, and $k_2$ is strain enhancement coefficients for FRP confined concrete. Considering the secant values of elastic modulus, the equation can be expressed as:

$$\frac{\varepsilon_{ru}}{\varepsilon_c} = C + k_2 \left(\frac{E_{frp} t_f}{E_{sec} R}\right) \frac{\varepsilon_{rup}}{\varepsilon_c}$$

Thus, the following expression is suggested for FRP-wrapped concrete based on the general form from literature and test data and [49]:

$$\frac{\varepsilon_{ru}}{\varepsilon_c} = 1.75 + k_2 \left(\frac{E_{frp} t_f}{E_{sec} R}\right) \frac{\varepsilon_{rup}}{\varepsilon_c}$$

where the strain enhancement coefficient, $k_2$, is taken as 9 for concrete cast with distilled water and seawater, and 6 for saturated water according to the analyses of experimental results. Fig. 6 shows that the regression lines of the test data are similar to both FRP confined concrete cast with distilled water and seawater, while for concrete cast with saturated water, the slope of the regression line decreases compared to those of other two groups. Fig. 6 shows a good agreement between experimental results and values obtained by proposed equations.

### 4.2. Stress-strain model of confined concrete considering effect of chloride ions

After careful observation of the stress-strain behavior of FRP confined concrete, the stress-strain curves can be described as an initial ascending region as a parabola, followed by a second region that is approximately linear. Such stress-strain behavior is of the typical form that has been reported in literature. The slope of strain hardening part reduces with the increase of chloride ion concentrations while the initial stiffness of the FRP confined concrete samples is similar. Therefore, a stress-strain model with a clear definition of the strain hardening slope that considers the effect of chloride ion concentration can be used to describe the structural behavior under compression.

Among various stress-strain models, a design-oriented model that has a clear definition of slope for the strain hardening portion and consider the ultimate behavior is chosen and modified to predict the stress-strain behavior of FRP confined concrete under the effect of different chloride ion concentrations [50,51]. Moreover, the design-oriented model offers an approach that is familiar to engineers for determining the strength and ductility of FRP-confined RC structural members with clearly defined parameters and forms. The stress-strain model for FRP-confined concrete is given as [52,53]:

$$\varepsilon_c = \frac{E_c \varepsilon_c - (E_c - E_f) \varepsilon_f^2}{4E_f}$$

when $0 \leq \varepsilon_c \leq \varepsilon_t$

and

$$\varepsilon_c = \varepsilon_t + E_2 \varepsilon_c$$

when $\varepsilon_t \leq \varepsilon_c \leq \varepsilon_{rup}$

where $f_o$ is the intercept of the stress axis by the linear second portion, $\varepsilon_t$ is the transition point connecting the parabolic first portion and linear second portion, and $E_2$ is the slope of the strain hardening portion, which could be expressed as:

$$\varepsilon_t = \frac{2f_o}{(E_c - E_2)}$$

$$E_2 = \frac{f_{rup} - f_o}{\varepsilon_{rup}}$$

The ultimate strength and strain of FRP confined concrete can be calculated according to Eqs. (1) and (5) in the corresponding scenario of chloride ion concentrations. The elastic modulus of unconfined concrete, $E_c$, can be taken as 47300 $f_{cu}$ (in MPa) according to the recommendation of design code [54]. Fig. 7 illustrates the meanings of the parameters in stress-strain model.

In order to determine the intercept of the stress axis by the linear second portion, $f_o$, different equations have been proposed [55]. After the calibration of these equations determining the intercept with the experimental results, $f_o$ is taken as the ultimate strength of unconfined concrete to predict the stress-strain behavior of FRP confined concrete. From the schematic diagram of the stress-strain model, with a lower slope of strain hardening portion, $E_f$, the intercept of the stress axis for concrete cast by seawater is close to the intercept of the stress axis for concrete cast by distilled water, $f_o$. When taking the compressive strength of unconfined concrete as $f_{cu}$, the $f_o$ and $f_o$ are close to each other.
other, echoing the experimental findings that the chloride ion concentrations at seawater level have a limited effect on the compressive strength of concrete compared to that of concrete cast with distilled water. This result further indicates that the proposed model is suitable for evaluating the stress-strain behavior of FRP confined concrete with different chloride ion concentrations.

After the determination of the corresponding parameters, a comparison between the predicted stress-strain model and experimental results of FRP confined concrete under different chloride ion concentrations is shown in Fig. 8. The predicted stress-strain curves agree well with the stress-strain relationships captured in the experiment of FRP confined concrete columns with 1-ply and 3-ply confinement, validating the effectiveness and accuracy of the proposed ultimate condition model and stress-strain model. Overall, the results and analyses in this study have covered important parameters mentioned in the design code, and the axial compressive behavior of FRP confined concrete columns with different chloride concentrations are comprehensively evaluated. According to the experimental findings and analytical results, it is recommended that for FRP confined concrete with chloride ion concentration at seawater level or below, the ultimate condition model with the same parameters can be used to predict its stress-strain behavior. When the chloride ion concentration is higher than seawater level, the compressive strength and strain enhancement ratio may reduce. From the viewpoint of safety concerns, it is recommended that the model with the parameters of concrete with saturated water should be used to predict the stress-strain behavior of FRP confined concrete when the FRP confined concrete serves in the marine environment for a prolonged duration. In the meantime, more complicated situation may be encountered when FRP confined seawater concrete columns are under various service conditions, such as different mechanical loadings including eccentric loading, fatigue loading or cyclic loading, and environmental conditions including moisture and temperature variations. More insights upon the effect of complicated service conditions on FRP confined seawater concrete are recommended for future work.

5. Conclusions

This paper presented the results of an experimental study on the structural behavior of FRP confined seawater concrete columns and explored their performance under chloride ingress. Based on the experimental results, a revised design-oriented model describing stress-axial strain behavior is proposed. The conclusions can be drawn as follows:

1. The compressive strength of plain concrete with seawater is only slightly lower than that of normal concrete. When saturated water is used, the deterioration of compressive strength is serious, up to 40%, compared to that of plain concrete with distilled water. Meanwhile, the axial strain corresponding to peak stress showed an increasing trend with the increase of chloride ion concentrations.
2. One layer FRP confined concrete with saturated water possesses a 23% reduction in ultimate strength, but a 49% enhancement in ultimate axial strain compared to those of 1-ply FRP confined concrete with distilled water. All FRP confined concrete specimens with different chloride ion concentrations failed due to rupture of FRP jacket.
3. Ultimate strength and strain calculated from proposed model agree well with the experimental results, demonstrating that the modified model is capable of evaluating the structural behavior of FRP confined concrete with different chloride ion concentrations.
4. The effect of chloride ion concentration at seawater level on the stress-strain behavior of FRP confined concrete is limited compared to that of FRP confined concrete cast by distilled water, and the same model could be used to predict their ultimate behaviors. When the chloride ion concentration increases to the saturated level, the

Fig. 7. Schematic diagram showing the general form of used stress strain model with a parabola followed by a linear second strain hardening portion.

Fig. 8. Performance of stress-strain model in predicting FRP confined concrete with different chloride ion concentrations. The analytical model agrees well with experimental results in terms of the ultimate strength and strain of FRP confined concrete as well as the stress-strain behavior under compression.
compressive strength and ultimate strain vary significantly. Due to safety concerns, it is recommended that when the FRP confined seawater concrete serves in the marine environment for a prolonged duration, the proposed model for FRP confined concrete with saturated water could be used to predict its ultimate condition and stress-strain behavior.

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Declarations of interest

None.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

References