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C-FRCM Jacket Confinement for RC Columns under Impressed Current Cathodic Protection

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Abstract: In coastal regions, chloride penetration causes steel reinforcing bar (rebar) corrosion in reinforced concrete (RC) structures, leading to durability problems in existing structures. A new intervention method, impressed current cathodic protection and structural strengthening (ICCP-SS), was adopted to rehabilitate sea-sand concrete columns. A carbon fiber-reinforced cementitious matrix (C-FRCM) was used as a dual-functional material in the ICCP-SS system, wherein the C-FRCM served as both an anode and a strengthening material. This study aimed to consider the effects of the total charge density on the confinement effect of C-FRCM jackets and the compressive strength of columns under ICCP-SS intervention to demonstrate the long-term effectiveness of the ICCP-SS intervention method for sea-sand RC columns and to investigate the appropriateness of existing strength models for RC columns strengthened by C-FRCM jackets under ICCP. The experimental program included a total of nine reinforced concrete stub columns. Prior to the compression tests, the columns were subjected to 270 days of accelerated corrosion and 250 days of cathodic protection under protective cathodic current densities of 20 mA/m^2 and 60 mA/m^2. This paper presented an experimental program, a comparison between short-term and long-term test results of ICCP-SS, a comparison of existing strength models and a discussion on the appropriateness of the existing models for C-FRCM jackets subjected to an applied current.

Keywords： C-FRCM; carbon fiber mesh; column; corrosion; impressed current cathodic protection; reinforced concrete; structural strengthening

Introduction

Concrete is the most widely used building material in the world. However, reinforced concrete (RC) structures might face durability problems (Zhang et al. 2017a; Li et al. 2019), most of which are caused by the corrosion of steel rebars induced by chloride ions (Mehta 1991). The influence of steel corrosion on an RC structure has the following aspects: First, rusting causes the steel volume to expand, causing the concrete to crack (Rodriguez et al. 1994); Second, when a rebar is corroded, the cross-sectional area of the rebar is reduced (Ahmad 2003); Third, the bonding performance of rebar and concrete is decreased by the corrosion (Fang et al. 2006).

Impressed current cathodic protection (ICCP) has been found to be one of the most effective technologies to prevent steel corrosion in RC structures (Lambert and Paul 1995; Pedeferri 1996). The ICCP utilizes an electric field that makes the negatively charged chloride ions in the concrete move away from the surface of the rebar to the anode, thereby inhibiting the corrosion of the rebars (Chess and Broomfield 2003). A typical ICCP system for RC structures consists of an external power supply, a cathode (i.e., the steel rebars), an anode and a complete circuit system. An ideal anode should have a low consumption rate, good electrical conductivity, easy construction and simple installation. Currently, the most popular anode materials include coated titanium anodes (Lassali et al. 1998), conductive coating anodes (Clemeña and Jackson 1998), and thermal-sprayed zinc anodes (Bullard et al. 1996). However, these conventional anodes are rather expensive. Recently, Zhu et al. (2016, 2017, 2018) proposed using carbon fiber (CF) mesh as the anode material, which utilized the good electrical conductivity and stable electrochemical properties of the CF mesh. Moreover, to ensure good electrical conduction between the CF mesh and the rebars, the bonding material is also important. A new electrically conductive cementitious matrix (Su et al. 2019a) was used in this study. By embedding a CF mesh inside a cementitious matrix, a carbon fiber-reinforced cementitious matrix (C-FRCM) composite is obtained (D’Ambrisi and

Focacci 2011).

The confinement jackets in most previous studies were steel jackets (Susantha et al. 2001; Kwan et al. 2016) and fiber reinforced polymer (FRP) - epoxy resin jacket (Lam and Teng 2003; Teng et al. 2007; Zhang et al. 2017b). With the study of FRCM jackets, their advantages have gradually emerged. Peled (2007) compared FRCM jackets and FRP jackets for repairing damaged concrete columns and their corresponding failure modes and mechanical responses; they found that FRCM jackets were a better choice than FRP jackets in terms of compatibility. Furthermore, a cementitious matrix can be used to fill the damaged area of a component surface. Basalo et al. (2012) used scanning electron microscopy (SEM) to study the influence of the infiltration of inorganic cementitious materials on the stress transfer, and their experimental results showed that cementitious matrix fails to effectively penetrate into the fiber bundle, but the inorganic matrix and the concrete member have good compatibility. In addition, the strength of the FRCM-confined columns increased linearly as the number of fiber layers increased, indicating that FRCM has a good confinement effect on concrete columns. Ombres (2014) investigated the influence of fiber mesh winding angles and fiber layers on the compression performance of confined concrete columns. Their experimental results showed that a winding angle of 90° was the most effective among the tested angles. They introduced a winding angle reduction factor into the confining pressure prediction formula. Ludovico et al. (2010) compared four different confinement schemes on concrete cylinders: uniaxial glass FRP (GFRP) laminates, alkali-resistant fiberglass grids bonded with cement-based mortar, bidirectional basalt laminates preimpregnated with epoxy resin or latex and bonded with cement-based mortar, and cement-based mortar jackets. Their experimental results showed that the basalt-reinforced mortar (BRM) confinement system provided concrete columns significantly better compression capacity and ductility than GFRP jackets. In addition to research at ambient temperature, Trapko (2013) studied the effects of temperature on FRCM/carbon FRP (CFRP) confinement. The failure stresses of the CFRP-confined columns decreased with increasing temperature, and the load-bearing capacity decreased by 10% for every 20 °C increase in temperature. However, the failure stress change in the FRCM-confined columns was negligible. Trapko (2013) also found that the FRCM-confined columns exhibited greater ductility than the CFRP-confined columns. In addition, there are a number of existing design standards for the capacity prediction of confined RC columns (Fib 2001; ISIS 2001; ACI 2017; GB 2013). Most of these standards (Fib 2001; ISIS 2001; ACI 2017; GB 2013) were developed based on FRP-epoxy resin jackets, whereas ACI 549.4R-13 (ACI 2013) was specifically proposed for FRCM confinement jackets. Although there are many similarities between the FRP-epoxy resin system and the FRCM system, they could have different mechanical behaviors and confinement models. Furthermore, if a C-FRCM jacket was used as the confinement material and the anode simultaneously, as proposed by Zhu et al. (2018), the long-term effects of ICCP on the C-FRCM jacket have not been studied.

Therefore, the key objectives of this study are to consider the effect of the total charge density on the confinement provided by C-FRCM jackets and the compressive strength of columns under ICCP and structural strengthening (ICCP-SS) intervention to prove the long-term effectiveness of the ICCP-SS intervention method for sea-sand RC columns and to investigate the appropriateness of existing strength models for RC columns strengthened by C-FRCM jackets under ICCP. First, this paper extracted the short-term behavior of RC columns subjected to ICCP-SS from the literature (Zhu et al. 2018). Please note that the ICCP-SS intervention method uses a dual-functional material (CF mesh) to combine cathodic protection and structural strengthening as an integrated retrofitting technique (Su et al. 2019b). Second, a new experimental program on the relatively long-term performance of RC columns subjected to ICCP-SS intervention is presented. The electrochemical and mechanical properties of C-FRCM should be considered because the C-FRCM composite serves as a dual-functional material. The experimental results of both the short-term and long-term performance are compared and discussed. The effects of the applied current density and total charge quantity on the C-FRCM confinement can be subsequently analyzed. Third, the experimental results were compared with the results from existing FRCM confinement models. The accuracy of the existing models for C-FRCM jackets without applied current, with short-term cathodic protection and with long-term cathodic protection were assessed. Finally, to improve the design accuracy and simplify the design procedure, suggestions were proposed to modify the existing models.

Data collection

Zhu et al. (2018) conducted the first series of short-term experiments as part of the overall research project. A total of nine reinforced concrete columns were prepared with a diameter of 200 mm and a height of 750 mm. The specimens experienced a 90-day accelerated corrosion process and a 90-day cathodic protection process. The protective cathodic current densities adopted in the study were 26 mA/m^2 and 80 mA/m^2. Zhu et al. (2018) compared the performance of the newly proposed ICCP-SS intervention method with two conventional intervention methods: ICCP and C-FRCM strengthening. Their results showed that by using C-FRCM as a dual-functional material, ICCP-SS can inhibit steel rebar corrosion and improve the loading capacities of RC columns. However, the relatively short-term experimental program (Zhu et al. 2018) cannot reflect the long-term performance of the ICCP-SS intervention method. The long-term ICCP operation leads to polarization on the anode, which might have effects on the confinement. Therefore, this study conducts relatively long-term studies and identifies the effects of applied current on C-FRCM confinement.

Experimental program

Test specimens

A total of nine RC columns with a diameter of 220 mm and a height of 660 mm were cast from a single batch of concrete. The nominal diameter of the longitudinal rebars was 10 mm, whereas that of the stirrup was 8 mm. The details of the internal reinforcement and the dimensions of the column specimens are shown in Fig. 1.

The nine specimens were divided into five groups: (1) two reference specimens without any NaCl (C2-RF and C2-RF-R), (2) one specimen with NaCl but without any repair (C2-F0-I0), (3) two specimens with NaCl repaired by the ICCP technique (C2-F0-I20-D250 and C2-F0-I60-D250), (4) one specimen with NaCl repaired by the SS technique (C2-F1-I0), and (5) three specimens with NaCl repaired by the ICCP-SS technique (C2-F1-I20-D250, C2-F1-I20-D250-R and C2-F1I60-D250). The labeling system of the specimens is given in Table 1. The NaCl content in the concrete mix was 3% of the cement mass. After the curing period, some specimens were exposed to 270-day accelerated corrosion, followed by 250-day cathodic protection as designed. The protective cathodic current densities were 20 mA/m^2 and 60 mA/m^2.

Material properties

The material properties of the concrete, steel rebars, CF mesh, cementitious matrix and C-FRCM composite were measured in this study. The 28-day compressive strength of concrete was found to be 42 MPa, which was determined in accordance with a standard cylinder test ASTM C39 (ASTM 2012); the cylinder had a diameter of 150 mm and a height of 300 mm. Two sizes of rebars—8 and 10 mm—were used in the specimens as stirrups and longitudinal bars, respectively. The tensile strengths of the rebars were measured by tensile tests in accordance with ASTM A370 (ASTM 2017a), and the gauge length of the rebars was 400 mm. The mechanical properties of a bundle of CF meshes (12k fiber filaments for one bundle) were measured based on ASTM D4018 (ASTM 2017b), and the gauge length of the tested specimens was 150 mm. The compression and flexural strengths of the proposed cementitious matrix were measured in accordance with the European Committee for Standardization EN1015-11 (EN 1993). Please note that the cementitious matrix used in this study is different from that in the short-term study (Zhu et al. 2018). The average material properties obtained from the aforementioned tests are presented in Table 2. Three repeated tests were conducted to obtain each material property.

The C-FRCM composite considered in this study comprised two layers of mortar and an internal layer of CF mesh. The mechanical properties of the C-FRCM composite were tested in accordance with ACI 549.4R-13 (ACI 2013) using a 10 kN electric-control universal testing machine. The dimensions of the C-FRCM coupons were 400 mm × 50 mm × 10 mm (length × width × thickness) (see Fig. 2(a)), and the gauge length of the coupons was 200 mm. Previous studies (Bisby et al. 2009; Bilotta et al. 2017) found that the cracking position of FRCM composite materials was highly discrete, so conventional techniques were not appropriate for the strain measurement of C-FRCM composites. Strain gauges attached to the specimen can measure only the local strain and might not be able to capture the strain field in the cracking region, and data measured by an extensometer could be affected by the energy released during the occurrence of cracks. Therefore, in this study, in addition to an extensometer, a noncontact measurement technology—digital image correlation (DIC)—was also used to obtain the strain field of the C-FRCM coupons during loading. The images from DIC can output the visual crack development and the overall failure mode of the specimens.

The strain field of C-FRCM at ultimate tensile strength is shown in Fig. 2(b). Two through cracks appeared on the surface of the specimen. The failure mode of the C-FRCM composite was slippage between the CF mesh and the cementitious matrix, as shown in Fig. 3. Fig. 4 shows the stress-strain curves of the C-FRCM composite; three parallel tests were carried out for each type of C-FRCM composite. Fig. 4(a) is the C-FRCM used in the short-term tests (Zhu et al. 2018), and Fig. 4(b) is the C-FRCM used in this study. The curve was obtained with tests conducted in accordance with Annex A of AC434 (AC 2016) using the clevis-type grips prescribed in its provisions. Note that the tensile stress of C-FRCM is the ratio of the tensile load to the cross-sectional area of the CF. The typical stress-strain curves of an FRCM composite are generally bilinear. The initial linear segment of the curve corresponds to the FRCM uncracked linear behavior and is characterized by the uncracked tensile modulus of elasticity E_{frcm}^{*}. The second linear segment, which corresponds to the FRCM cracked linear behavior, is characterized by the cracked tensile modulus of elasticity E_{frcm}. According to AC434 (AC 2016), the cracked tensile modulus was derived based on two points in the second part of the curve. These two points correspond to stress levels of $0.6f_{fu}$ and $0.9f_{fu}$ (f_{fu} is the ultimate tensile strength of FRCM). The results derived from C-FRCM stress-strain curves are shown in Table 3.

Experimental program

An accelerated corrosion process was used to induce corrosion in the test specimens within a reasonable period. A certain amount of NaCl (3% chloride by weight of the cement) was added to the concrete mix to simulate sea-sand concrete. This amount of sodium chloride should be sufficient to initiate corrosion (Zhu et al. 2017). Please note that no sodium chloride was added to the control specimens (C2-RF and C2-RF-R). Afterwards, all of the specimens were placed outdoors to cure for 28 days. The specimens were subjected to a wet-dry cycle twice per week (each cycle consisting of two-and-a-half wetting days and one drying day). The accelerated corrosion process lasted for 270 days.

After the accelerated corrosion procedure, the C-FRCM jacket was bonded to columns. For each confined specimen, the CF meshes have an overlap length of 200 mm (i.e., approximately D/4, where *D* is the diameter of the specimens) (Nguyen et al. 2016) to prevent premature failure of the fabric due to debonding. The C-FRCM strengthening process following the same steps as that used in Zhu et al. (2018): (1) sandblast the concrete surface to remove any surface grease, laitance and heterogeneous parts, (2) apply a layer of cement-based mortar with a thickness of 3 mm, (3) wrap one layer of CF mesh around the column, and (4) apply a second layer of cement-based mortar with a nominal thickness of 3 mm on top of the CF mesh (see Fig. 5(a)). Afterwards, a ribbed roller was used in both the hoop and longitudinal directions to facilitate impregnation. Specimens were cured for 28 days before the application of ICCP. The ICCP was applied to columns by connecting the steel rebars to the negative terminal and the CF mesh anode to the positive terminal of a direct current (DC) power supply. The ICCP systems were operated in an open area for 250 days (Fig. 5(b)).

Compression tests

All specimens were powered down and the wet-dry cycle was simultaneously stopped before testing. All specimens were tested under uniaxial compression at a controlled displacement rate of 0.3 mm/min in accordance with ASTM C39 (ASTM 2012). Axial deformation was measured with three linear variable differential transducers (LVDTs) located between the upper and lower end plates. Transverse deformation was measured with LVDTs mounted on two opposite sides of the specimen. A total of nine strain gauges were attached to the CF mesh to measure the strain of the CF mesh (Fig. 6).

Experimental results

Results of ICCP

By measuring the open circuit potential, corrosion rate and corrosion current density of the rebars, the corrosion status of the rebars in the columns could be evaluated. ASTM C876 (ASTM 2015) classifies the corrosion state of rebars according to their measured open circuit potentials (see Table 4). In addition, Grantham et al. (1997) also proposed classifying the corrosion state of rebars based on the measured corrosion current density and corrosion rate (see Table 4).

The open circuit potentials of the rebars were measured and recorded, as shown in Fig. 7. The open circuit potentials of the rebars in the reference columns (C2-RF and C2-RF-R) were found to be approximately -100 mV, which indicated that the probability of corrosion was less than 10% and able to be ignored. The open circuit potentials of the rebars in the corroded specimens without any treatment (C2-F0-I0 and C2-F1-I0) were found to be approximately -270 mV, which meant that the probability of corrosion was approximately 50% and that the rebars were moderately corroded. In contrast, the open circuit potentials of the rebars from the ICCP-protected columns (C2-F0-I20-D250, C2-F1-I20-D250, C2-F1-I20-D250-R, C2-F0-I60-D250 and C2-F1-I60-D250) were approximately -270 mV before the ICCP application and rose to -170 mV after the ICCP application. This finding indicates that the application of ICCP reduced the possibility of rebar corrosion.

The corrosion rates of the rebars were measured and recorded, as shown in Fig. 8. The corrosion rates of the rebars in the reference columns were found to be approximately 5.5

μm/year. The corrosion rates of the rebars in the corroded specimens without any treatment were 23 μm/year. In contrast, for other columns, the corrosion rates of the rebars were found to be approximately 23 μm/year before the application of ICCP and 5.5 μm/year after the application of ICCP, which clearly indicates the effectiveness of ICCP on the protection of steel reinforcement.

The corrosion current densities of the rebars were also measured and recorded, as shown in Fig. 9. The corrosion current densities of the rebars in the reference columns were found to be approximately 0.5-1.0 μA/cm^2, which indicates slightly corrosive conditions. The corrosion current densities of the rebars in the corroded specimens without any treatment were approximately 4.0 μA/cm^2. After the application of ICCP, the corrosion current densities of those protected columns decreased to less than 1.0 μA/cm^2. Similarly, the measured results of corrosion current densities also demonstrated that ICCP can successfully protect the rebars in columns under corrosive environments.

After compression testing, the rebars were removed from the tested columns to measure the linear density reduction due to corrosion. The rebars were cleaned and weighed in accordance with ASTM G1 (ASTM 2011) (Fig. 10). The rebar mass loss results are shown in Table 5. For the specimens containing NaCl and protected by ICCP, the mass loss in the rebar was less than 2%, whereas for specimens containing NaCl without ICCP, the mass loss was between 3.5% and 4%. In conclusion, when C-FRCM composite is used as the anode material, ICCP can effectively prevent further corrosion of the rebars even in corrosive environments.

Results of compression tests

For the unconfined columns, sudden failure occurred due to concrete crushing (Fig. 11(a)). Regarding C-FRCM-confined columns, the failure of the columns occurred in a more gradual manner. Initially, a main vertical crack in the cementitious material propagated slowly on the column surface. The confined column failed when the crack widened and the CF mesh ruptured in the hoop direction (Fig. 11(b)). This failure mode is similar to that in the observations reported by Zhu et al. (2018) and Ombres and Mazzuca (2017).

The load-deformation curves of all specimens are plotted in Fig. 12, and the experimental results are summarized in Table 6. The initial part of the load-deformation curves at low strains were similar among the reference columns and strengthened columns because the compression loads were mainly resisted by the concrete cores and the C-FRCM jacket did not effectively work yet. As the loads approaching the ultimate strength, the load-deformation curves of the ICCP-SS strengthened columns departed from those of the unconfined columns, and the C-FRCM jacket gradually developed its confinement effect. For the reference columns (C2-RF and C2-RF-R), the load capacities were found to be 1804 kN and 1771 kN (average load = 1787 kN), respectively. The capacity of the corroded specimen without any treatment (C2-F0-I0) was 1746 kN, which was 2.32% lower than that of the reference column, attributing to the reduction in the rebar cross section. For specimens that were protected only by ICCP (C2-F0-I20-D250 and C2-F0-I60-D250), the compression load capacities were 7.42% higher than that of the corroded specimen C2-F0-I0, which demonstrates that ICCP can effectively impede further corrosion in the rebars. The load capacity of the column strengthened only by C-FRCM (C2-F1-I0) was 2069 kN, which was 15.75% higher than that of the reference columns (C2-RF and C2-RF-R). The results showed that the C-FRCM jacket could effectively improve the loading capacity of degraded columns. The three columns retrofitted by the ICCP-SS method (C2-F1-I20-D250, C2-F1-I20-D250-R, and C2-F1-I60-D250) exhibited 24-37% greater loading capacities than the reference columns (C2-RF and C2-RF-R).

Comparison between short-term and long-term performance of the ICCP-SS intervention method

Ultimate strength improvement

To compare the effect of ICCP on C-FRCM confinement, the relationships between the applied current density, protection duration and charge quantity and the ultimate strength increase percentage (compared to reference column) were studied and are plotted in Fig. 13, which included both the short-term and long-term test results. The ultimate capacity enhancement increases as the current density and protection time increase. Fig. 13(a) shows that a larger current density leads to greater capacity enhancement, especially for confined columns; for unconfined columns, the capacity enhancements were generally the same. Table 7 shows that for the C-FRCM confined column, the ultimate strength increase rate increases with increasing charge density. This finding indicated that the larger charge density can lead to a lower corrosion rate of the steel rebars and less stress concentration on the C-FRCM interface, thereby achieving better mechanical properties with the C-FRCM. The application of ICCP technology may cause degradation in the C-FRCM interface of the anode material, which will result in a more uniform stress distribution and less stress concentration of the C-FRCM jacket during the loading process. Therefore, the effect of premature failure of the fiber mesh could be reduced, indirectly improving the confinement effect. Fig. 13(b) shows that a longer protection duration leads to greater capacity enhancement: the capacity enhancement of the confined columns in this study was higher than that of the confined columns in the short-term tests (Zhu et al. 2018). The results indicate that the cementitious matrix in this study might have positive effects on the C-FRCM confinement. To make the comparison more straightforward, Fig. 13(c) displays the compression capacity improvement with respect to the charge density applied to the C-FRCM jacket. For ICCP-protected columns, the capacity enhancements were mainly due to the successful protection of the steel rebars and were found to be slightly improved as the charge density increased. The compression resistance enhancement when the charge density increased was more pronounced in the ICCP-SS-protected columns than in the ICCP-protected columns, which is indicated by the different slopes of the hollow dots (ICCP specimens) and solid dots (ICCP-SS specimens) in Fig. 13(c), which again revealed that larger charge density not only prevents the steel rebars from corroding but also leads to better confinement effects of the C-FRCM jacket.

Effective strain of CFs

For C-FRCM jackets, the measured ultimate strain of the CF wrapped on the column was lower than the ultimate strain measured from the tensile tests due to different loading configurations, which leads to an analysis of the efficiency of the C-FRCM jacket. The efficiency of the FRCM composite is an indicator of the confinement effect of the FRCM jacket. This study defines the FRCM strain efficiency factor (k_e) as the ratio of the ultimate hoop strain of the FRCM jacket (ε_{fl}) to the ultimate tensile strain of the FRCM coupon (ε_{fu}), i.e., $k_e = \varepsilon_{fl}/\varepsilon_{fu}$. The hoop strain and strain efficiency factor of both short-term and long-term specimens are presented in Table 8. The efficiency of the C-FRCM jacket after long-term cathodic protection is greater than that in the short-term condition. In addition, the C-FRCM tensile test results show that the performance of the second series of C-FRCM composites is better than the first series of C-FRCM composites, wherein the former has greater ultimate strength and strain (see Table 3 and Fig. 4). Note that since the fracture location of CFs is unknown, it is difficult to accurately capture the ultimate strain of CFs via strain gauges. However, this conclusion can be generally validated by the better C-FRCM confinement with larger charge density, for which a detailed explanation is given as follows. The manual implementation of the C-FRCM jacket might cause imperfections in the bonding interface due to poor workmanship, which resulted in localized stress concentration. The applied currents during ICCP might cause the degradation of the anodic surface (i.e., C-FRCM jacket), which could release the stress concentration and lead to more uniform strain development in the confining jacket. Thus, the degraded bonding after ICCP may delay the fiber fracture, resulting in a better confinement effect.

Existing prediction models of confined strength

The confined concrete column expands under axial loads. On the one hand, the C-FRCM jacket deforms circumferentially and generates tensile stress in the hoop direction; on the other hand, the C-FRCM jacket limits the expansion of the core concrete column, so that the core concrete is subjected to a three-direction loading state, thereby improving the axial loading capacity. The compressive strength of confined concrete (f_{cc}) under active confinement can be expressed in a nondimensional form, as given by Eq. 1 (Thériault et al. 2004). Fig. 14 shows that the theoretical confining pressure exerted by a jacket can be calculated with Eq. 2.

$$\frac{f_{cc}}{f_{co}} = 1 + k\left(\frac{f_{lu}}{f_{co}}\right)^{\alpha} \qquad \text{Eq. 1}$$

$$f_{lu} = \frac{2ntf_t}{D} \qquad \text{Eq. 2}$$

where f_{cc} is the compressive strength of the confined concrete, f_{co} is the compressive strength of the concrete, f_{lu} is the confining pressure exerted by the confinement material, k and α are empirical constants to be calibrated through a best-fit analysis to minimize the difference between the predicted and experimental strength capacities, n is the number of layers of the confinement material, t is the thickness of the confinement material, f_t is the tensile strength of the confinement material, and D is the diameter of the specimens.

Existing models

The confinement models are different for different confining materials, such as steel jackets (Susantha et al. 2001; Kwan et al. 2016), FRP-epoxy jackets (Lam and Teng 2003; Teng et al. 2007) and FRCM jackets (Peled 2007). Since this study focused on C-FRCM jackets, only the existing confinement models developed for FRCM jackets are considered herein, including the ACI model codified in ACI 549.4R-13 (ACI 2013), the OM model proposed by Ombres and Mazzuca (2017) and the TR model proposed by Triantafillou et al. (2006).

The ACI confinement model is codified in Chapter 11 of ACI 549.4R-13 (ACI 2013), as shown in Eqs. 3-4.

$$\frac{f_{cc}}{f_{co}} = 1 + 3.1\frac{f_{lu}}{f_{co}} \qquad \text{Eq. 3}$$

$$f_{lu} = \frac{2nA_f E_{frcm}\varepsilon_{fe}}{D} \qquad \text{Eq. 4}$$

where A_f is the area of the mesh reinforcement by unit width; E_{frcm} is the tensile modulus of elasticity of the cracked FRCM; ε_{fe} is the effective strain of the FRCM composite material at failure, which is taken as $\varepsilon_{fe} = \varepsilon_{fd} \leq 0.012$ in ACI 549.4R-13 (ACI 2013); and ε_{fd} is the design tensile strain of the FRCM.

Recently, Ombres and Mazzuca (2017) extracted a total of 152 experimental results on FRCM-confined concrete cylinders from the literature. Moreover, they proposed a prediction model for FRCM jackets, term herein as the OM model, based on the collected experimental data. An efficiency factor accounting for the reduction in the effective strain of the CF in the hoop direction was adopted in this model, as shown in Eqs. 5-7.

$$\frac{f_{cc}}{f_{co}} = 1 + 0.913\left(\frac{f_{lu}}{f_{co}}\right)^{0.5} \qquad \text{Eq. 5}$$

$$f_{lu} = \frac{2ntE_f k_e \varepsilon_f}{D} \qquad \text{Eq. 6}$$

$$k_e = 0.25\left[\left(\frac{\rho_f E_f}{f_{co}}\right)^{0.3} - 1\right] \qquad \text{Eq. 7}$$

where E_f is the longitudinal elastic modulus of the fiber reinforcement, ε_f is the ultimate tensile strain of the fiber, and ρ_f is the FRCM reinforcement ratio ($\rho_f = 4nt/D$). In addition, *ke'* is 0.335 in the first series of tests (Zhu et al. 2018), whereas *ke'* is 0.320 in this study.

Triantafillou et al. (2006) investigated the response of cylinders and short rectangular columns confined by FRCM jackets and reported a substantial increase in compressive strength and deformability provided by the confinement jacket. Based on the experimental results, a semiempirical prediction model on the compressive strength of concrete confined by FRCM jackets was proposed by Triantafillou et al. (2006), termed herein as the TR model. The TR model is depicted in Eqs. 8-9.

$$\frac{f_{cc}}{f_{co}} = 1 + 1.9\left(\frac{f_{lu}}{f_{co}}\right)^{1.27} \qquad \text{Eq. 8}$$

$$f_{lu} = \frac{2ntf_{fu}}{D} \qquad \text{Eq. 9}$$

where f_{fu} is the ultimate tensile strength of the FRCM.

Result comparisons

The three considered models are used to predict the confined concrete strengths of the tested columns considered in this paper. Note that the experimental ultimate stress f_{cc} is calculated by Eq. 10 in this paper.

$$N = f_{cc}(A_g - A_s) + f_y A_s \qquad \text{Eq. 10}$$

where N is the axial bearing capacity of the RC columns, A_g is the gross cross-sectional area of the compression column, A_s is the total area of the longitudinal steel bars, and f_y is the tensile yield strength of the steel.

Based on Eq. 10, the contribution of the longitudinal steel bars has been excluded in the calculation process. After compression testing, the corroded steel rebars were removed from the columns for weighing and tensile tests so that the corrosion rate of the steel rebars was measured and the material properties of corroded rebars could be obtained and used in Eq. 10. The measured material properties and dimensions are used in the calculation. The predicted confined concrete strengths are compared with the test results in Fig. 15. This comparison revealed that all three models underestimated the confinement strengths provided by the C-FRCM jacket; note that the OM model (Ombres and Mazzuca 2017) seems to be slightly more accurate than the other two models (Triantafillou et al. 2006; ACI 2013). Moreover, the conservatism of the three models is more pronounced when the specimen is subjected to larger charge density during ICCP. The results of the confined columns without ICCP protection are closest to the prediction curve. The results show that within the scope of this study (applied cathodic current densities ranging from 20 mA/m^2 to 60 mA/m^2), the application of a protective current further improves the carrying capacity of C-FRCM-confined concrete columns, and the loading capacity improved as the protective current increased. Therefore, the existing models cannot accurately capture the improved confinement in the presence of ICCP. Hence, modifications are needed to extend the existing models for the prediction of the C-FRCM jacket after ICCP.

Suggestion for model modification

Fig. 4 shows that the bilinear stress-strain response of the C-FRCM composite is different from the elastic stress-strain curves of CF bundles (Arboleda 2014). The behavior of the C-FRCM jacket not only relates to the embedded CF mesh but also the bonding interface between the CF mesh and the cementitious matrix. The experimental program showed that the failure mode of the C-FRCM composite plate is not a complete fracture of the embedded

CF; instead, the failure mode is a combination of CF rupture and slippage between CF mesh and cementitious matrix. The results showed that the measured strains (ε_{fe}) of the embedded CF at ultimate loads in the column tests were generally lower than those from the tensile tests (ε_{fu}) because it is difficult to precisely capture the strain of embedded CF meshes at the critical locations (Bilotta et al. 2017) even using strain gauges, extensometers and DIC techniques. In addition, given that the effective strain is obtained, the modulus of the material is also needed. Currently, some models suggested using the modulus of the embedded CF, whereas others suggested using the modulus of the C-FRCM composite. Therefore, to avoid the inaccurate estimation of the C-FRCM strain distribution and the unclear selection of the modulus, it is suggested to use the C-FRCM ultimate strength in the confining pressure prediction, as shown in Eq. 11. Please note that the ultimate strength of C-FRCM herein is defined as the strength obtained by the tension tests of the C-FRCM composite coupons, where $f_{c\text{-}frcm}$ is the ultimate tensile strength of the C-FRCM composite coupons.

$$f_{lu} = \frac{2ntf_{c-frcm}}{D} \qquad \text{Eq. 11}$$

Additionally, in this study, the results revealed that ICCP has positive effects on C-FRCM confinement since the C-FRCM also serves as the anode. The reasons for the positive effects are related to the more uniform stress distribution in the C-FRCM jacket, which leads to better utilization efficiency of the embedded CF mesh. To include this effect in the confinement model, it is suggested to adjust the k value in Eq. 1 when considering the C-FRCM jacket under different anodic polarization, i.e., different charge densities during cathodic protection. Based on Eq. 11 for calculating confining pressures f_{lu} and different exponents suggested in different models (α = 0.5 (Ombres and Mazzuca 2017), 1.0 (ACI 2013) and 1.27 (Triantafillou et al. 2006), the k value is derived for each column, as shown in Table 9 and Fig. 16. By observation, it is found that there is a linear relationship between the k value and the total charge density (Q). Equations showing the relationship between the k value and the total charge density (Q) were obtained by regression fitting, as shown in Fig. 16 and given in Eqs. 12, 13 and 14 for exponents (α) equal to 0.5, 1.0 and 1.27, respectively.

When $\alpha = 0.5$, $k=0.11Q+0.77$ Eq. 12

When $\alpha = 1.0$, $k=0.55Q+4.00$ Eq. 13

When $\alpha = 1.27$, $k=1.35Q+9.70$ Eq. 14

The proposed confinement models using Eq. 11 to calculate the confining pressures f_{lu} and Eqs. 12-14 to calculate the k values are compared with the experimental results in Fig. 17. The experimental data points are much closer to the proposed models in Fig. 17 than to the existing models in Fig. 15. Hence, it is suggested to use the proposed confinement model for the design of C-FRCM-confined columns under cathodic protection.

Conclusions

A dual-functional intervention method, ICCP-SS, has been applied to a series of RC columns in a chloride-induced corrosive environment. This study includes an experimental program to validate the effectiveness of this new intervention method on steel reinforcement protection and loading capacity improvement. The behaviors of these columns were obtained after 250 days of cathodic protection. Moreover, experimental data of RC columns protected by the ICCP-SS method in a short-term timeframe were extracted from the literature and used in this study for comparison purposes. By comparison, the potential effects of applied current on the confinement of C-FRCM jackets have been investigated. Compression test results showed that the loading capacities of the columns retrofitted by the ICCP-SS method were up to 40% greater than those of the corroded columns without any protection. In addition, a comparison of the experimental results with the predictions by different C-FRCM confinement models shows that the three considered models underestimated the confinement effects provided by the C-FRCM jacket. This paper proposes to use the C-FRCM ultimate strength instead of the CF ultimate strength in the confining pressure calculation. Herein, the confinement model estimating the confined concrete strength is modified based on the ultimate strength of the C-FRCM, which is obtained from tensile tests of composite coupons. For the three exponents used in the existing confinement models, corresponding k values are derived. The results show that there is a linear relationship between the k value and the electric charge from the ICCP system: the greater the charge density is, the better confinement enhancement. Therefore, it is suggested to consider the effects of applied currents in the k value. The newly modified confinement models were compared to the experimental results, and the predictions made by the modified models were closer to the experimental results than the predictions made by the existing models. The relationships between the k value and the charge density for the confinement model obtained herein can be used for the design of ICCP-SS-protected columns in future engineering applications.

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Notations

A_f = area of mesh reinforcement by unit width

A_g = the gross cross-sectional area of compression column

A_s = the total area of longitudinal steel bars

D = diameter of compression member

E_f = longitudinal elastic modulus of fiber reinforcement

E_{frcm} = tensile modulus of elasticity of cracked FRCM

E_{frcm}^* = tensile modulus of elasticity of uncracked FRCM

f_{cc} = maximum compressive strength of confined concrete

f_{co} = specified compressive strength of concrete

$f_{c\text{-}frcm}$ = ultimate tensile strength of C-FRCM composite coupons

f_{fu} = ultimate tensile strength of FRCM

f_{lu} = confining pressure exerted by FRCM jacket at maximum axial stress

f_t = the tensile strength of the confinement material

f_y = the steel tensile yield strength

k = empirical constants to be calibrated through a best-fit analysis

k_e = the strain efficiency factor

k_e'= the calculated value of the strain efficiency factor proposed by the OM model

n = number of layers of mesh reinforcement

N = the axial bearing capacity of reinforced concrete columns

Q = charge density

t = thickness of the fabric mesh

α = empirical constants to be calibrated through a best-fit analysis

ε_f = ultimate tensile strain of fiber

ε_{fe} = effective tensile strain level in FRCM composite material attained at failure

ε_{fd} = design tensile strain of FRCM

ε_{fu} = ultimate tensile strain of FRCM coupon

ρ_f = the FRCM reinforcement ratio ($=4nt/D$)

References

AC (Acceptance Criteria). (2016). *Acceptance criteria for masonry and concrete strengthening using fabric-reinforced cementitious matrix (FRCM) and steel reinforced grout (SRG) composite systems*. AC434. Brea, CA: ICC Evaluation Service.

ACI (American Concrete Institute). (2013). *Guide to design and construction of externally bonded fabric-reinforced cementitious matrix systems for repair and strengthening concrete and masonry structures*. ACI 549.4 R-13. ACI Committee 549, Farmington, MI.

ACI (American Concrete Institute). (2017). *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*. ACI 440.2R-02. Farmington, MI.

Ahmad, S. (2003). “Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review.” *Cem. Concr. Compos.* 25(4): 459-471.

Arboleda, D. (2014). “Fabric reinforced cementitious matrix (FRCM) composites for infrastructure strengthening and rehabilitation: Characterization methods.” PhD thesis, University of Miami.

ASTM (2011). *Standard Practice for preparing, cleaning, and evaluating corrosion test specimens*. ASTM G1-03. United States.

ASTM (2012). *Standard test method for compressive strength of cylindrical concrete specimens*. ASTM C39-12. United States.

ASTM (2015). *Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*. ASTM C876-15. United States.

ASTM (2017a). *Standard test methods and definitions for mechanical testing of steel products*. ASTM A370-17. United States.

ASTM (2017b). *Standard test methods for properties of continuous filament carbon and graphite fiber tows*. ASTM D4018-17. United States.

Basalo, F. J. D. C., Matta, F., and Nanni, A. (2012). “Fiber reinforced cement-based composite system for concrete confinement.” *Constr. Build. Mater*. 32(7): 55-65.

Bilotta, A., Ceroni, F., Lignola, G. P., and Prota, A. (2017). “Use of DIC technique for investigating the behaviour of FRCM materials for strengthening masonry elements.” *Composites Part B*. 129: 251-270.

Bisby, L. A., Roy, E. C., Ward M, and Stratford, T. J. (2009). “Fibre Reinforced Cementitious Matrix Systems for Fire-Safe Flexural Strengthening of Concrete: Pilot Testing at Ambient Temperatures.” *Proceedings advanced composites in construction*. Edinburgh, UK.

Bullard, S. J., Covino Jr, B. S., Cramer, S. D., McGill, G. E. (1996). *Thermal-Sprayed Zinc Anodes for Cathodic Protection of Steel-Reinforced Concrete Bridges*. No. DOE/ARC-1996-004. Albany Research Center (ARC), Albany, OR; Oregon Department of Transportation, Salem, OR.

Chess, P. M., and Broomfield, J. P. (2003). *Cathodic Protection of Steel in Concrete*. CRC Press

Clemeña, G., and Jackson, D. (1998). “Long-Term Performance of Conductive-Paint Anodes in Cathodic Protection Systems for Inland Concrete Piers in Virginia.” *Transport. Res. Rec*. 1642(1): 43-50.

D’Ambrisi, A., and F. Focacci. (2011). “Flexural strengthening of RC beams with cement-based composites.” *J. Compos. Constr*. 15(5): 707–720.

EN (1993). *Methods of Test for Mortar for Masonry–Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar*. EN1015-11. Brussels, European Committee for Standardization.

Fang, C., Lundgren, K., Plos, M., and Gylltoft, K. (2006). “Bond behaviour of corroded reinforcing steel bars in concrete.” *Cem. Concr. Res*. 36(10): 1931-1938.

Fib (2001). *Externally bonded FRP reinforcement for RC structures*. Technical report bulletin 14, the International Federation for Structural Concrete, Switzerland.

GB (2013). *Code for design of strengthening concrete structures*. GB50367-2013. China.

Grantham, M. G., Herts, B., and Broomfield, D. J. (1997). “The use of linear polarisation corrosion rate measurements in aiding rehabilitation options for the deck slabs of a reinforced concrete underground car park.” *Constr. Build. Mater*. 11(4): 215-224.

ISIS (2001). *ISIS Canada Design Manual No. 4: Strengthening reinforced concrete structures* *with externally-bonded fiber reinforced polymers*. Winnipeg, Canada.

Kwan, A. K. H., Dong, C. X., and Ho, J. C. M. (2016). “Axial and lateral stress–strain model for concrete-filled steel tubes.” *J. Constr. Steel. Res,* 122: 421-433.

Lambert and Paul (1995). “Cathodic protection of reinforced concrete” *Anti-Corros. Method. M.* 42(4): 4-5.

Lam, L., and Teng, J. G. (2003). “Design-oriented stress–strain model for FRP-confined concrete.” *Constr. Build. Mater*. 17(6–7): 471-489.

Lassali, T. A. F. Castro, S. C. D., and Boodts, J. F. C. (1998). “Structural, morphological and surface properties as a function of composition of Ru+Ti+Pt mixed-oxide electrodes.” *Electrochim. Acta*. 43(16–17): 2515-2525.

Li, L.Z., Liu, X., Yu, J.T., Lu, Z.D., Su, M.N., Liao, J.H., and Xia, M. (2019). “Experimental study on seismic performance of post-fire reinforced concrete frames.” *Eng. Struct.* 179(1): 161-173.

Ludovico, M. D., Prota, A., and Manfredi, G. (2010). “Structural Upgrade Using Basalt Fibers for Concrete Confinement.” *Journal of Composites for Construction J. Compos. Constr*. 14(5): 541-552.

Mehta, P. K. (1991). “Durability of concrete-fifty years of progress.” *NISP. S P*. 126: 1-32.

Nguyen, C. V., Lambert, P., Mangat, P. S., O’Flaherty, F. J., and Jones, G. (2016). “Near-surface mounted carbon fibre rod used for combined strengthening and cathodic protection for reinforced concrete structures.” *Struct. Infrastruct. E.* 12(3), 356-365.

Ombres, L. (2014). “Concrete confinement with a cement based high strength composite material.” *Compos. Struc*. 109(6): 294-304.

Ombres, L., and Mazzuca, S. (2017). “Confined Concrete Elements with Cement-Based Composites: Confinement Effectiveness and Prediction Models.” *J. Compos. Constr*. 21(3): 04016103.

Pedeferri, P. (1996). “Cathodic protection and cathodic prevention.” *Constr. Build. Mater*. 10(5): 391-402.

Peled, A. (2007). “Confinement of Damaged and Nondamaged Structural Concrete with FRP and TRC Sleeves.” *J. Compos. Constr*. 11(5): 514-522.

Rodriguez, J., Ortega, L. M., and Casal, J. (1994), “Corrosion of reinforcing bars and service life of reinforced concrete structures: Corrosion and bond deterioration." *International conference on concrete across borders,* Odense, Denmark. Vol. 2.

Su, M., Wei, L. L., Zeng, Z. W., Ueda, T., Xing, F., and Zhu, J. H. (2019a). "A solution for sea-sand reinforced concrete beams." *Constr. Build. Mater*. 204 (2019): 586-596.

Su, M., Wei, L, Zhu, J.H., Ueda T., Guo G. and Xing, F. (2019b), "Combined Impressed Current Cathodic Protection and FRCM Strengthening for Corrosion-Prone Concrete Structures." *J. Compos. Constr*. 23(4): 04019021.

Susantha, K. A. S., Ge, H., and Usami, T. (2001), "Uniaxial stress–strain relationship of concrete confined by various shaped steel tubes." *Eng. Struct*. 23(10): 1331-1347.

Teng, J. G., Huang, Y. L., Lam, L., and Ye, L. P. (2007). "Theoretical Model for Fiber-Reinforced Polymer-Confined Concrete." *J. Compos. Constr*. 11(2): 201-210.

Thériault, M., Neale, K. W., and Claude, S. (2004). "Fiber-Reinforced Polymer-Confined Circular Concrete Columns: Investigation of Size and Slenderness Effects." *J. Compos. Constr*. 8(4): 323-331.

Trapko, T. (2013). "The effect of high temperature on the performance of CFRP and FRCM confined concrete elements." *Composites Part B*. 54(1): 138-145.

Triantafillou, T. C., Papanicolaou, C. G., Zissimopoulos, P., and Laourdekis, T. (2006). "Concrete Confinement with Textile-Reinforced Mortar Jackets." *ACI Struct. J.* 103(1): 28-37.

Zhang, D., Rashid, K., Wang B，Ueda, T. (2017a). "Experimental and analytical investigation of crack spacing and width for overlaid RC beams at elevated temperatures." *J. Struct. Eng.* 143(12): 04017168.

Zhang, D., Zhao, Y., Jin, W., Ueda, T., Nakai, H. (2017b). "Shear strengthening of corroded reinforced concrete columns using pet fiber based composites." *Eng. Struct*. 153: 757-765.

Zhu, J. H., Wei, L., Guo, G., and Zhu, A. (2016). "Mechanical and Electrochemical Performance of Carbon Fiber Reinforced Polymer in Oxygen Evolution Environment." *Polymers*. 8(11): 393.

Zhu, J. H., Wei, L., Moahmoud, H., Redaelli, E., Feng, X., and Bertolini, L. (2017). "Investigation on CFRP as dual-functional material in chloride-contaminated solutions." *Constr. Build. Mater*. 151: 127-137.

Zhu, J. H, Su, M., Huang, J., Ueda, T., and Xing, F. (2018), “The ICCP-SS technique for retrofitting reinforced concrete compressive members subjected to corrosion.” *Constr. Build. Mater*. 167: 669-679.