Behaviour of Prestressed CFRP Anchorages under Freeze-Thaw Cycle Exposure

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ABSTRACT: The long-term behaviour of structures strengthened with prestressed carbon fiber reinforced polymers (CFRP) under varying environmental conditions is critical to ensure a safe performance. An end-anchorage is needed for prestressed systems to inhibit delamination. This work focuses on the gradient anchorage, which relies on segment-wise heating and prestress-force-releasing at strip-ends to distribute the prestressing force over multiple segments. To assess the effect of freeze-thaw-cycles (FTC) on the gradient anchorage, uncarbonated and carbonated concrete blocks were strengthened with prestressed CFRP and bonded with a single-segment gradient anchorage. Afterwards specimens were loaded until failure by lap-shear testing both before and after FTC exposure. Blocks were monitored during FTC by fiber optic sensors (FOS) and a 3D-DIC system during gradient application and lap-shear testing. Results indicate that residual anchorage resistance, stiffness and deformation capacity of the system is reduced after FTC and the failure mode switched from concrete substrate to epoxy-concrete interface failure.

1 INTRODUCTION

The use of CFRP strips as an externally bonded reinforcement (EBR) for reinforced concrete (RC) flexural members has been widely adopted by the industry owing to extensive research that resulted in numerous methods and guidelines for analysis as well as design purposes (Bakis et al. (2002)). Prestressed CFRP, due to its higher utilization of the materials strength as well as providing improved structural performance, has similarly received widespread attention, with the first field applications already surpassing a decade of their operational lifetime (Michels et al. (2016)). Although most prestressed EBR (PEBR) techniques share conceptually similar traits, the major difference lies within their way of implementing the end-anchorage. Arguably, the most important part of such systems, end-anchorages can be of various mechanical or non-mechanical techniques (Sena-Cruz et al. (2015)). Out of the many methods, the so called gradient anchorage (Michels et al. (2013)) a non-mechanical technique relying on section-wise accelerated curing of the epoxy adhesive and partial prestress force releasing at the strip ends (Figure 1), is being investigated in this work. Short-term behaviour of the gradient anchorage was studied both in lap-shear and full-scale beam tests (Czaderski (2012)) and proven to be a valid method of anchoring prestressed CFRP strips.

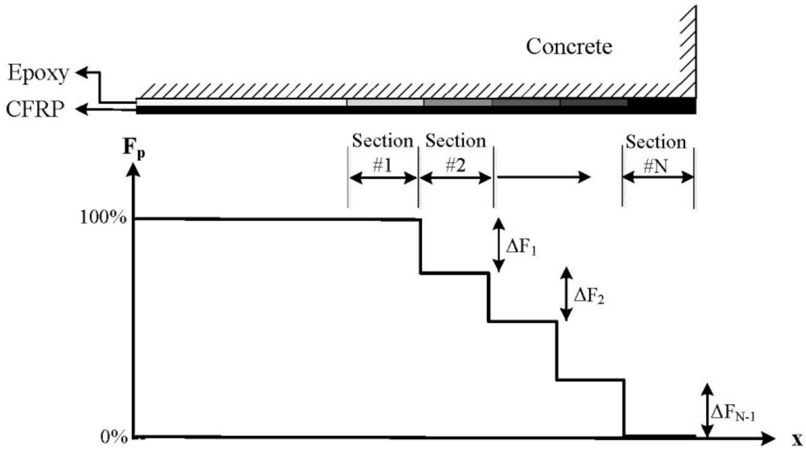

Figure 1: Schematic description of the gradient anchorage.

Considering the fact that the operational lifetime of every structure comprises exposure to various environmental conditions, experimental and theoretical conclusions on the long-term performance are absolutely necessary. Such conclusions are not common for PEBR and do not yet exist for the gradient anchorage. Thereupon, this work aims to provide such conclusions for PEBR systems and the aforementioned anchoring technique, mainly focusing on the experimental evaluation during and after FTC exposure. For this purpose, uncarbonated and carbonated concrete blocks were strengthened with prestressed CFRP and subsequently anchored with a single-section gradient anchorage. The residual anchorage resistance of these blocks were then tested in a lap-shear test setup before and after FTC and compared. Strains experienced by the CFRP strip during FTC was measured by Fabry-Pérot white-light interferometry based FOS.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

For the concrete mix, a Portland-limestone cement (CEM II/A-LL 42.5 N) was used with a water-cement ratio of 0.48, which is within the defined range for exposure classes XC4 and XF3 in EN 206-1 (2002). No air entraining admixture was used and well-rounded alluvial gravel was used with a maximum aggregate size of 16 mm to minimize size-effect based variations.

The commercially available thixotropic two-component epoxy S&P 220 was used to bond the CFRP to concrete. CFRP strips used for this study come from the identical batch of unidirectional pultruded S&P 150/2000 with width b_f of 50 mm and a thickness t_f of 1.2 mm.

2.2 Prestress-Force-Release and Lap-Shear Tests: Principles and Procedure

The aim of prestress-force-release test is to simulate an isolated section of the whole gradient anchorage, which is visualized in Figure 1. The conventional lap-shear tests at the end of the prestressing procedure provide the remaining residual anchorage resistance. The procedure is illustrated in Figure 2, where F_p denotes the prestressing and releasing force and F_u the ultimate load which is considered as the anchorage resistance.

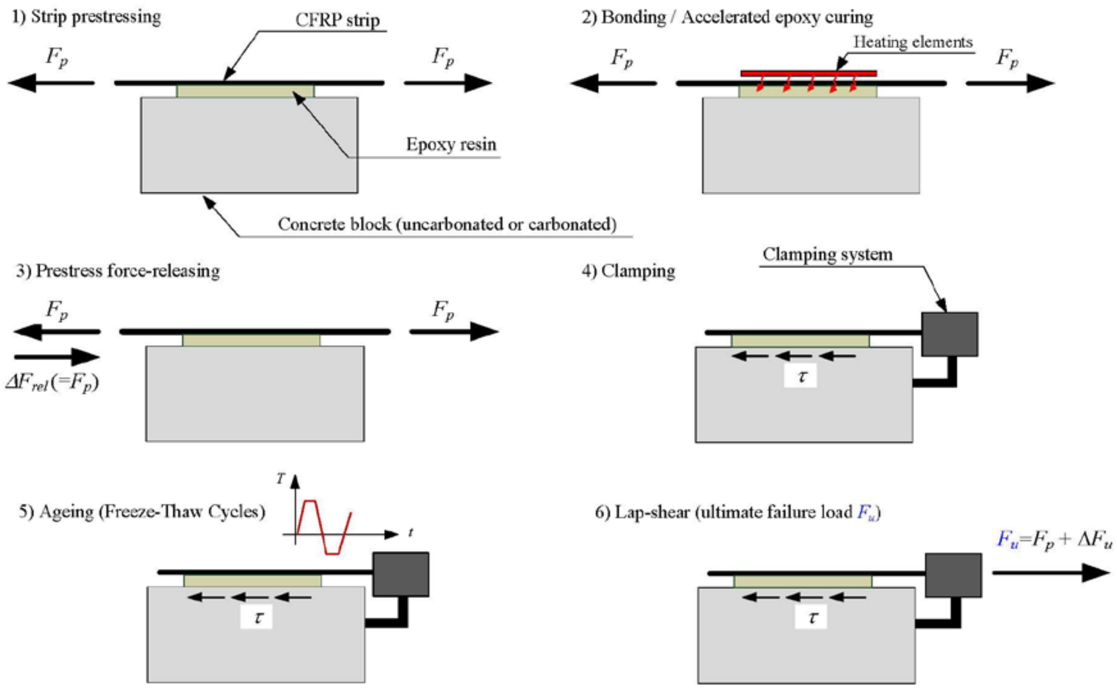

Figure 2: Schematic overview of the experimental procedure.

The prestressed blocks are produced by adopting the following procedure.

- Fixing a concrete block with a grinded surface (H=150, W=200, L=250 mm) to the strong floor.
- Marking the bond length (w=50, l_b=150 mm) and applying epoxy on the marked surface as well as on the CFRP strip.
- Clamping the CFRP at its ends, fixing the lap-shear side by means of a custom designed system (schematically visualized by the rectangle in Figure 2) and prestressing to approximately 8 kN (Figure 2-1).
- Applying a predefined heating curve for 35 minutes via a heating device placed on top of the CFRP strip (Figure 2-2). After completion of the heating procedure, the device is removed and the system is left to cool until the epoxy temperature reaches 25-30°C (30-60 minutes).
- Releasing the prestressing force gradually to zero, which allows the load to be transferred onto the epoxy and concrete as shear stresses (Figure 2-3 & 2-4).

Henceforth, the prestressed system can be transferred to the ageing chamber for subsequent FTC (Figure 2-5). Lastly, the blocks are transported back to the same setup and loaded from the fixed end until failure (Figure 2-6). For a more in-depth description of the experimental procedure, interested readers are referred to Harmanci et al. (2017). The resulting test specimen is presented in Figure 3.

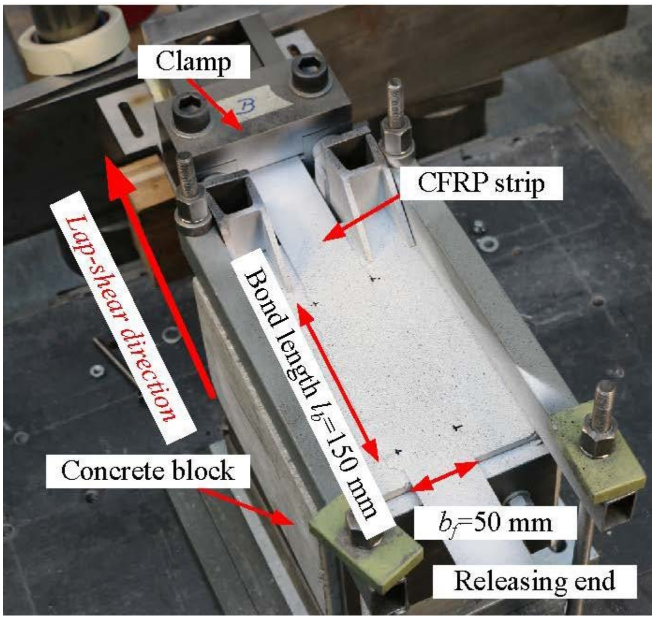

Figure 3: Concrete block with prestressed CFRP anchored with a single section gradient anchorage and painted with a speckle pattern for 3D-DIC measurements.

2.3 Ageing Procedure

Four scenarios were considered for this study: reference tests (REF), carbonated concrete (CC), freeze-thaw cycles with an uncarbonated concrete (UCFTC) and freeze-thaw cycles with a carbonated concrete (CCFTC). Reference tests do not undergo any ageing procedure after prestress-force-releasing and prior to lap-shear testing.

Concrete is carbonated in an accelerated manner by following SN505262/1 (2003), in a chamber constituting 57% RH and 4% CO_2 until a carbonation depth between 15-20 mm is achieved, which in this case took 5 months. Both REF and CC cases are left for 2 days after prestress-force-releasing in laboratory environment (20°C) prior to lap-shear testing.

After the prestress-force-release procedure, strengthened blocks are transferred into the climate chamber and 120 freeze-thaw cycles are applied. Each cycle lasts 12 hours, with the maximum and minimum temperatures of +25°C and -15°C, respectively. The maximum and minimum temperatures are kept constant for 5 hours and the transition from one temperature to the other takes 1 hour. The cycles are carried out in a dry state, yet some condensation during thawing occurred due to humidity that was trapped within the system. The exact relative humidity (RH) and temperature profiles during one cycle within the chamber are presented in Figure 4. Following the completion of FTC exposure, blocks are taken out and brought back to the aforementioned setup to be tested in a lap-shear configuration at ambient temperature to determine their residual anchorage resistance.

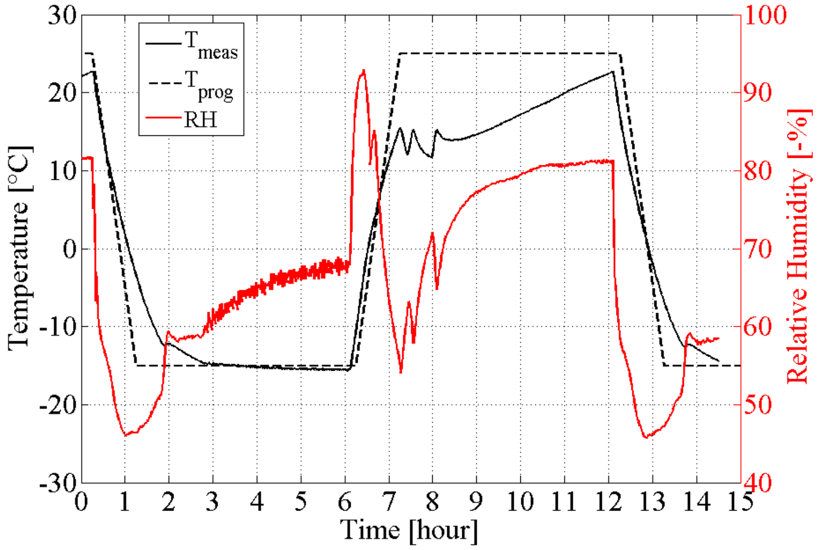

Figure 4: Programmed temperature curve and measured temperatures and RH during a single FTC.

2.4 Instrumentation

As previously mentioned, a 3D-DIC system (ARAMIS, gom Gmbh) was employed both during the prestress-force-releasing as well as lap-shear tests to obtain the full field displacements of the bonded surface. A white-over-black speckle pattern is required for these measurements, which can be observed in Figure 3. Eventually the full-field displacements are used to calculate slips s_f in the loading direction along the bond length by subtracting displacements along section $u_{f,1}$ from the average of $u_{c,0}$ and $u_{c,2}$. The aforementioned sections are shown in Figure 5 and mathematical expression of slips given in Equation 1.

$$s_f = u_{f,1} - (u_{c,0} + u_{c,2})/2 \quad (1)$$

Strains experienced by the CFRP strip during FTC were measured by installing Fabry-Pérot based FOS (FOS-N, Smartec SA). These sensors rely on white light interferometry to measure the Fabry-Pérot cavity length using white light interferometry. Their main advantages over conventional strain sensors are high sensitivity, EMI immunity, as well as temperature independency (no need for temperature compensation) (Belleville & Duplain (1993)). For every specimen undergoing FTC exposure, 5 FOS were installed, 4 of which are within the bond and 1 at the free length (Figure 5).

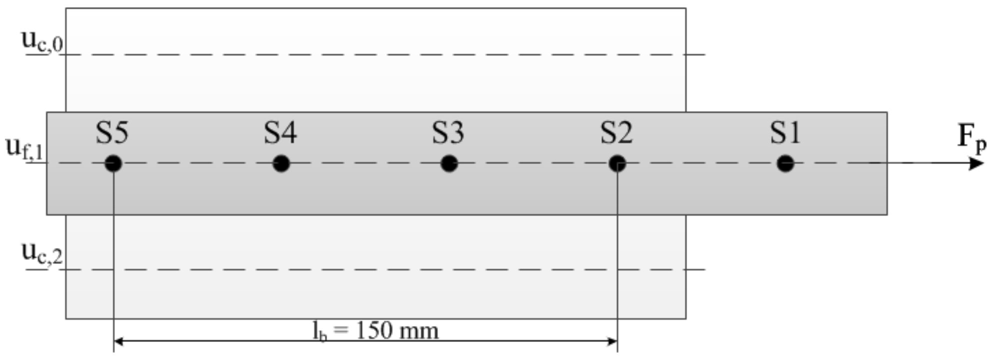

Figure 5: Top view of specimens, with markers denoting FOS locations and sections for 3D-DIC

3 RESULTS AND DISCUSSION

Concrete cubes and epoxy dog-bones, exposed to the same conditions as explained in Section 2.3, were tested to quantify the effect of such exposures to the individual materials. It was observed that carbonated concrete exhibited an increase in compressive strength by about 20%. Both uncarbonated and carbonated concrete cubes were not affected by FTC exposure. Similarly, epoxy dog-bones, before and after FTC, did not undergo any significant change in their elastic modulus and tensile strength. Based on these results, it can be concluded that FTC does not induce any deterioration to the measured individual material properties.

Results from lap-shear tests are summarized in Figure 6 by their force – slip relationship. A beneficial increase of 15% in the residual anchorage resistance ($F_{u,avg}$) is observed for the CC case, analogue to cube compression tests. Aside from F_u, maximum slips as well as the initial stiffness until initial crack initiation ($s_{f,el}$ = 0.02 mm, Czaderski (2012) seems to remain within the same magnitude. Discordantly, every metric discussed herein experiences a considerable reduction after FTC exposure, both for carbonated and uncarbonated specimens. The residual anchorage resistance and initial stiffness is reduced by roughly 30% for UCFTC and CCFTC, compared to reference and CC cases, respectively. Maximum slips at failure are half the amount of specimen which did not undergo FTC.

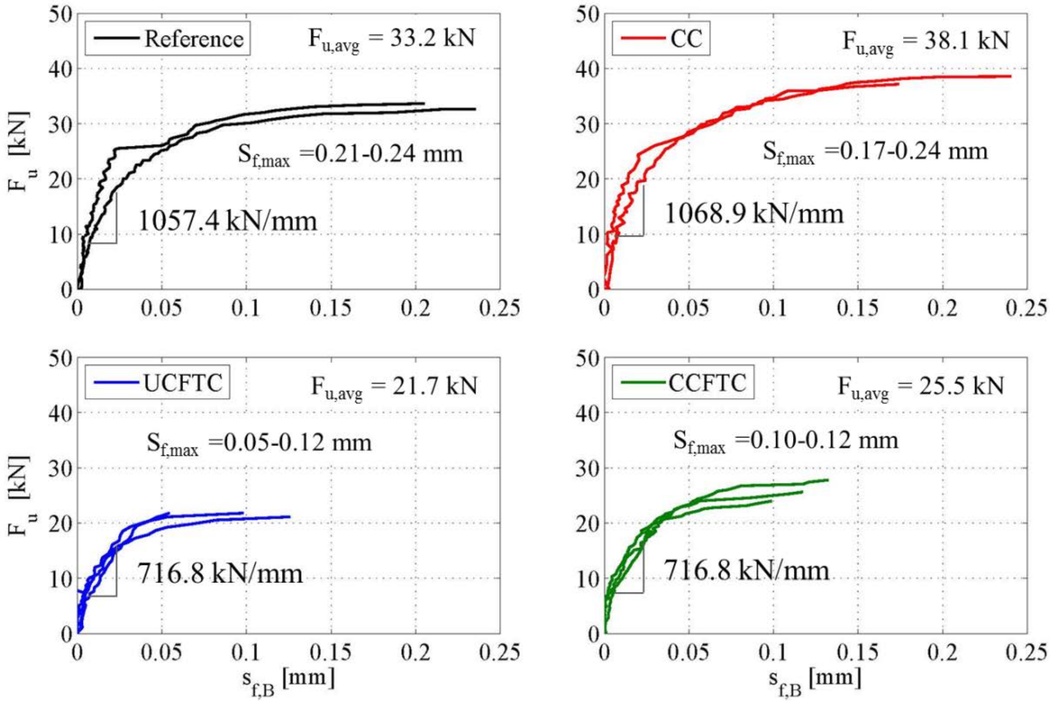

Figure 6: Force-slip relationship for every lap-shear test.

Another interesting effect observed after exposure to FTC is the change in failure mode, which shifted from a concrete substrate to an epoxy-concrete interface failure, as shown in Figure 7. This shift indicates that the epoxy-concrete interface becomes the weakest component of the bond after FTC exposure, likely due to the inherent humidity within the system (Figure 4) and mechanical loads induced due to the change in temperature and differing thermal expansion coefficients. This weakening is also manifested by the systems stiffness as well as deformation and load carrying capacity.

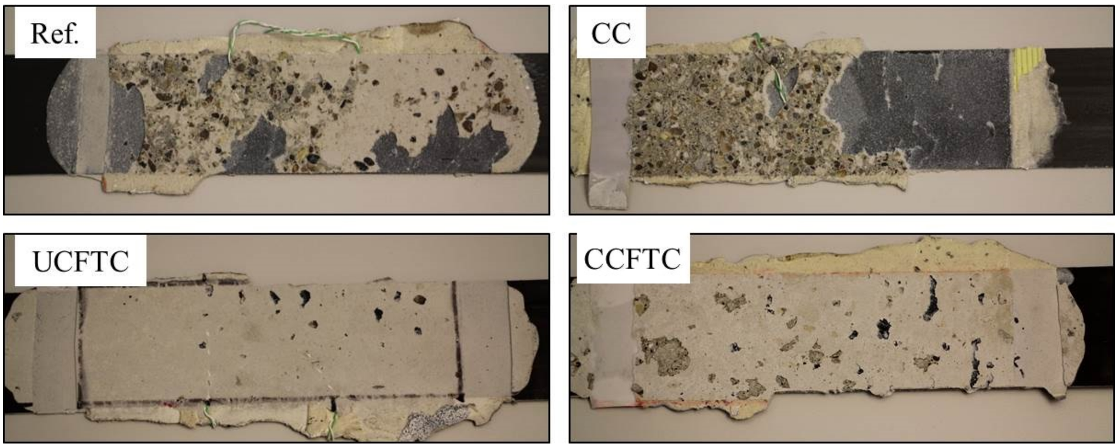

Figure 7: Typical failure surface for every exposure case.

The underlying mechanisms behind the change in structural behavior after FTC exposure can potentially be better explained with the aid of strains measured during freeze-thaw cycling using FOS installed on top of the CFRP strip. The maximum (at 25°C) and minimum (at -15°C) strains recorded during each cycle for a selected specimen are plotted in Figure 8a & b. It is evident from these figures that with each cycle, a residual strain is present along the strip. Sensor positions 1 and 5, which correspond to the lap-shear and prestress-force-releasing ends of the bond respectively, experience higher strain differentials as expected from conventional theory of bonding. In terms of maximum strains, this residual strain has a positive value, meaning that the strip is actually being tensioned with each cycle. This strain evolution seems to slow down and eventually stop between cycles 50-75. The exact reason behind this progressive tensioning is outside the scope of this study, yet it seems highly probable that concrete swelling due to ambient moisture is creating this additional prestressing. Following the recent FIB bulletin for concrete structures (FI du Béton, 2013), concrete swelling occurring during FTC was calculated to be around 60 με, and its effect on CFRP is derived to about 20 με in the free length. The maximum CFRP strain observed in Figure 8-a at sensor position 1 (in the free length) matches the theoretically calculated value accurately.

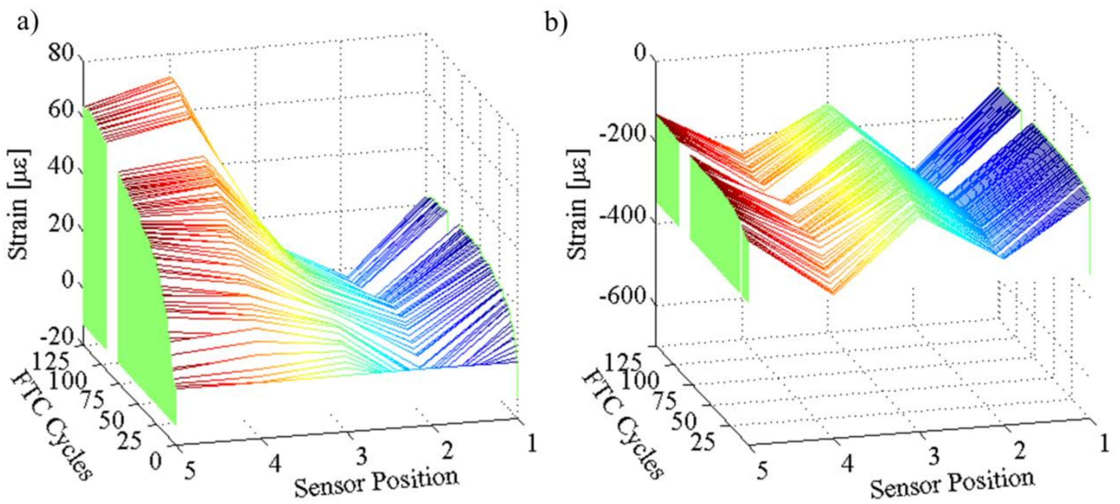

Figure 8: Maximum (a) and minimum (b) strains observed during FTC.

4 CONCLUSIONS

A rigorous experimental study on the long-term behaviour and residual anchorage resistance of a prestressed CFRP strip with a gradient anchorage was described and its results presented. Findings show that carbonation does not induce a shift in failure mode, and increases the residual anchorage resistance by approximately 15%. On the other hand, exposure to FTC promotes a shift in the failure mode from concrete substrate to a concrete-epoxy interface failure, and reduces the residual anchorage resistance by approximately 30% both for uncarbonated and carbonated specimens. Initial stiffness as well as maximum slips are analogously reduced after FTC exposure. Contrastingly, individual material tests reveal no significant increase or reduction in the material parameters after freeze-thaw cycles for both concrete and epoxy specimens. These conclusions strengthen the theory that the deterioration mechanism along the interface is the most important factor to consider in durability aspects. It is speculated that the chemical component of the bond suffer by ingress of moisture and differing thermal expansion coefficients of epoxy and concrete could cause significant stresses during thermal cycling.

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