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Author(s):
Harmanci, Yunus E.; Michels, Julien; Chatz, Eleni N.

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RESIDUAL RESISTANCE OF NON-MECHANICAL PRESTRESSED CFRP ANCHORAGES SUBJECTED TO ENVIRONMENTAL CONDITIONS

Yunus Emre Harmanci
Inst. of Struct. Engineering, ETH Zurich / Empa
Stefano-Franscini-Platz 5
CH-8093 Zurich/Switzerland
harmanci@ibk.baug.ethz.ch

Julien Michels
Struct. Eng. Research Laboratory, Empa
Überlandstrasse 129
CH-8600 Dübendorf/Switzerland
julien.michels@empa.ch

Eleni Chatzi
Institute of Structural Engineering, ETH Zurich
chatzi@ibk.baug.ethz.ch

ABSTRACT: Flexural strengthening of reinforced concrete (RC) elements with prestressed Carbon Fiber Reinforced Polymers (CFRP) as an externally bonded reinforcement (EBR) has gained increasing popularity over the last years. Opposite to conventional mechanical anchorages, the gradient anchorage is a purely bond-based technique. It is achieved by utilizing the fast curing property of epoxy under high temperatures together with a segment-wise prestressing force release at both strip ends. The short-term performance of the gradient anchorage has been previously investigated and its underlying force transfer mechanisms have been explained. The current study focuses on the durability and long-term performance under the influence of varying environmental conditions as this occurs in real-world structures during service. For this purpose, a special experimental setup has been designed with the aim to ensure a constant interfacial shear force between CFRP-epoxy-concrete prior to accelerated ageing conditions. Special attention is put on freeze-thaw cycles in combination with carbonation as well as elevated temperature and high relative humidity. First results of reference and carbonation cases are reported and discussed in this paper.

1. Introduction

Externally bonded Carbon Fiber Reinforced Polymer (CFRP) strips have become a popular method to strengthen existing concrete structures such as buildings and bridges. The beneficial effect of prestressing the strips has been documented in several research activities (El-Hacha et al, 2003) (Michels et al, 2011). Regarding the required end-anchorage, mainly two different systems are currently available: a) mechanical anchorage - requiring anchor bolts and plates to be installed, and b) gradient anchorage - consecutive sector wise epoxy resin heating and partial prestress force release at the strip ends. The latter results in a pure strip-epoxy-concrete anchorage that requires less time compared to the conventional systems and is immune to corrosion due to the absence of any metallic plates (Michels et al, 2014) (Sena-Cruz et al, 2015).

Czaderski (2012) investigated the gradient anchorage in detail for its short-term behaviour both experimentally and analytically. Design equations based on the SIA 166 guideline for structural strengthening with FRP (SIA, 2004) were eventually presented. However, as aging and durability is not only an issue for the structure itself but also for the strengthening system, there is a need to investigate the long-term performance of repair methods in order to validate their performance and accelerate industry acceptance. The aim of the ongoing project is to extend the short-term findings of the gradient anchorage with the inclusion of long-term effects by both experimental investigations by means of accelerated ageing tests and numerical investigations by derivation of novel constitutive laws in the macro scale and simulation with Finite Element Analysis (FEA).

This work focuses on a first experimental part of this project, namely the experiments investigating the influence of carbonated concrete surface on the load carrying capacity of the gradient method end-anchorage. The experimental procedure and results are explained and commented in the following sections in detail.

2. Experimental Investigation

2.1. Material Properties

Pultruded S&P 150/2000 CFRP strips with a 50x1.2 mm^2 cross-section and the two-component S&P Resin 220 were used for this work. Concrete was casted in March 2015 and then stored in a 20°C, 90% RH climate chamber. The reference case specimens were taken out in October and subsequently tested until mid-November in order to assess the strength evolution.

The carbonated concrete (CC) samples were transferred to the carbonation chamber in July 2015, initially starting with a CO_2 content of 1%. It was later increased to 8% CO_2 to accelerate the carbonation process. The entire procedure took approximately 5 months, taking place between June and December 2015. Figure 1 shows the evolution of carbonated concrete depth at different ages. The purple color depicts non-carbonated and grey color depicts carbonated areas within a cross-section. This discoloration is achieved by spraying a 1% Phenolphthalein solution on a freshly split concrete surface taken from a regular 120x120x360 mm^3 prism.

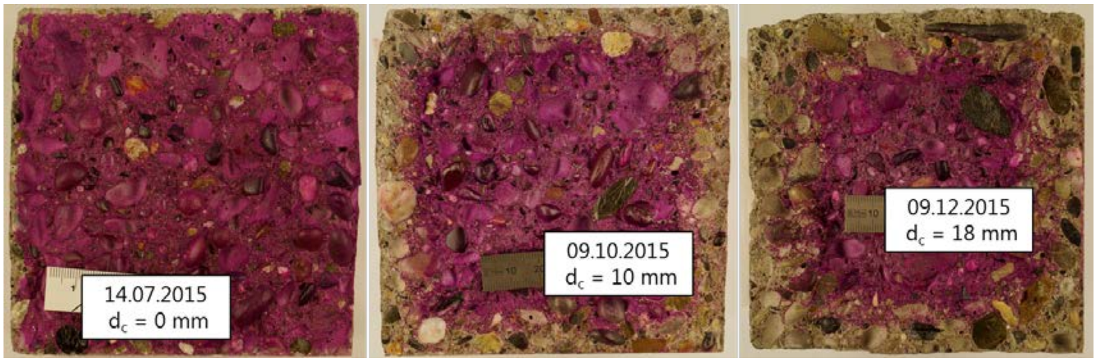

Figure 1: Concrete carbonation depth (d_c) evolution over time

The concrete compressive strength evolution for the reference case as well as the carbonated case samples is given in Figure 2. After an initial period of strength increase, the latter stabilizes and has reached 54.6 MPa after 266 days. The carbonated concrete has reached a far higher strength with 65.7 MPa at the same age.

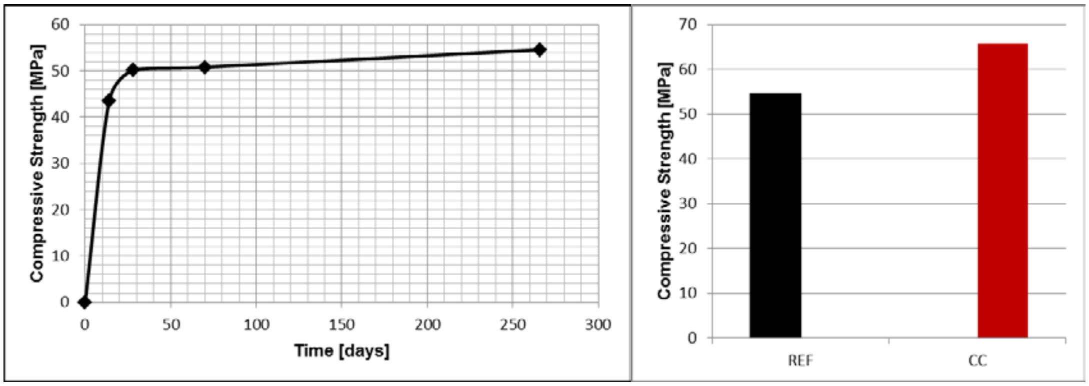

Figure 2 - Concrete compressive strength evolution. REF: Reference, CC: Carbonated Concrete

2.2. Test Setup

The tests are composed of two steps (see Figure 3):

a) CFRP strip anchoring (Prestress-Force Release)

- CFRP strip is prestressed and bonded to the concrete block.
- Epoxy is cured at high temperatures.
- Prestress force F_p is released on one end, leaving the system under constant average shear stress.

b) Lap-Shear Test

- The prestressed end is loaded up to failure load F_u (after ageing for the specimens with particular environmental exposure), determining the residual anchorage resistance.

For the presented tests, no system aging has been performed. Comparison is made between reference and carbonated concrete.

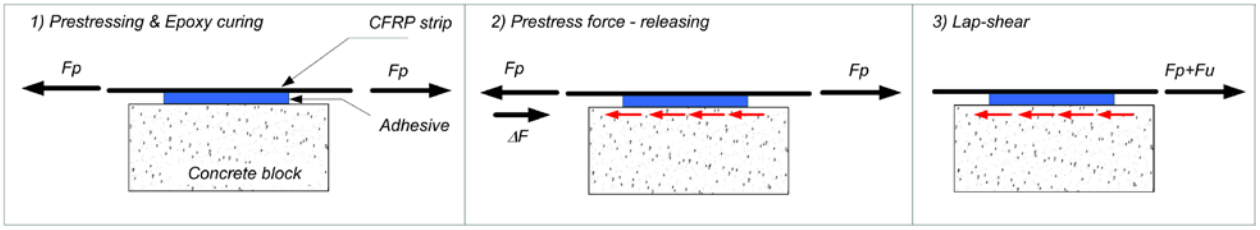

Figure 3: Test procedure: 1) CFRP Prestressing & Accelerated Epoxy Curing, 2) Prestress Force-Releasing, 3) Lap-Shear Testing

For this purpose a new experimental configuration has been designed. Several constraints such as the maximum size and weight that each ageing chamber can hold, as well as a robust anchorage that can keep the prestress forces during the entire testing period, were considered. Concrete blocks used for the tests are sized 250x200x150 mm^3 and the CFRP strip used for strengthening has a cross-section of 50x1.2 mm^2. The last constraint was ensured by developing a novel clamping system able to hold the prestressing force constant prior and presumably during to the temperature cycles and prolonged periods of testing. A clamp out of anodized aluminium and stainless steel is supported against two-adjustable screw jacks concentric with respect to the CFRP strip. These two screw jacks are supported by two stainless steel rails attached to the concrete block. The clamp is also supported and fixed horizontally to avoid the exertion of any moment on the strip. An illustration and application of such a sample is given in Figure 4.

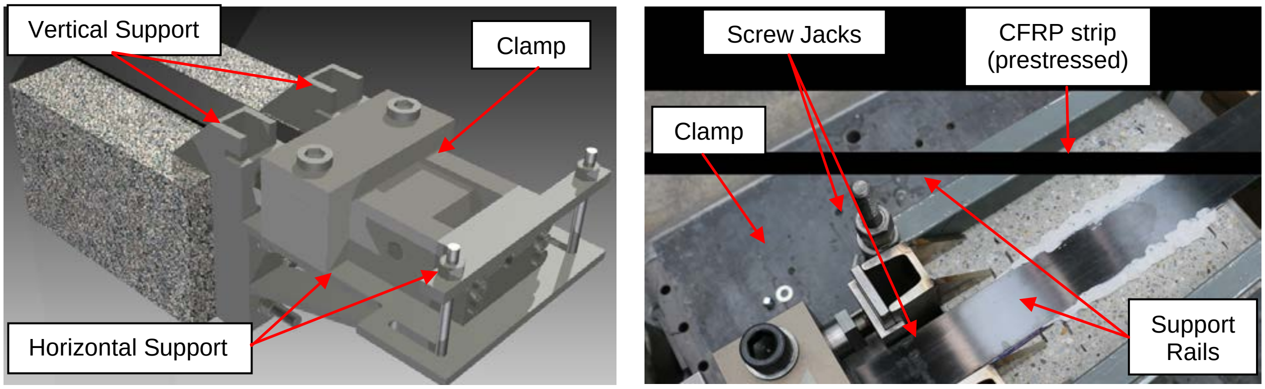

Figure 4: Novel Clamp and Specimen Design. (Left: Rendered Design, Right: Support Detail)

During both prestress-force release as well as lap-shear tests, forces are tracked by load cells attached to the hydraulic jacks. Displacements are measured with a 3D-Digital Image Correlation system. The entire test setup is shown in Figure 5.

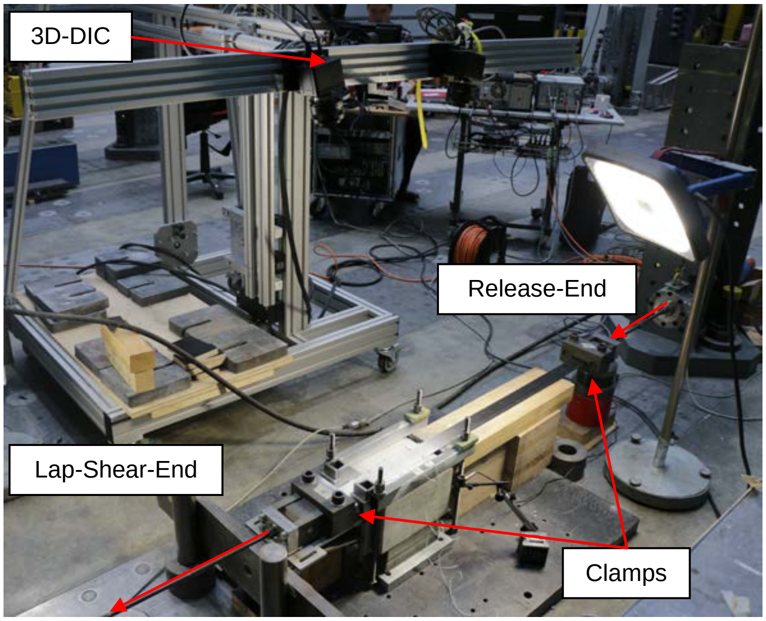

Figure 5: Testing setup together with the 3D-DIC measurement setup

Two cases have been tested to this end, namely the reference and the carbonated concrete (CC) cases. Each series had 3 specimen, further ageing scenarios are currently being prepared. Results are reported in the next section.

3. Results

With an attempt to reach an average interfacial shear stress of 1 MPa, the manually operated hydraulic pumps were aimed at 8 kN. The average ultimate residual load carrying capacity F_{ult} of the anchorage is summarized in Figure 6. It is evident that for similar releasing forces the residual load carrying capacity of the carbonated concrete case is about 15% higher. This can be attributed to the considerably higher compressive, hence higher tensile strength of concrete with a carbonated layer.

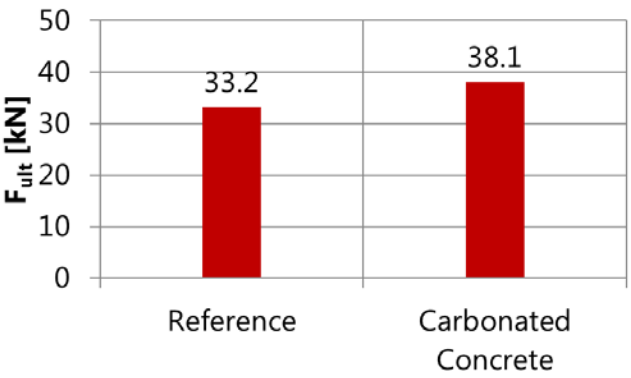

Figure 6: Average ultimate residual load carrying capacity F_{ult} for the final lap-shear tests

In both cases, failure occurs in a brittle manner, predominantly within the concrete layer and is comparable to the failure modes reported in (Czaderski-Forchmann, 2012). A typical failure surface mostly contains propagation into the concrete with visible large aggregates; however the failure surface also contains sections of epoxy as well as concrete-epoxy, CFRP-epoxy interfaces. An example image from such a failure surface is given in Figure 7 on the left side. Application of the 1% Phenolphthalein solution on the failure surface of the carbonated concrete case revealed no major discoloration, indicating that the failure surface is within the carbonated concrete layer and does not progress deeper into the non-carbonated core.

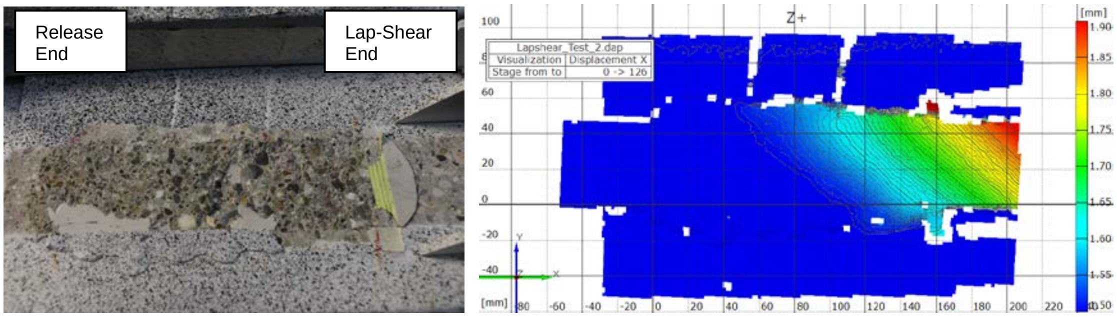

Figure 7: Concrete Failure Surface (Left), X-Displacements before failure (Right)

3D-DIC measurement results were used to deduce the slip behavior by taking three sections from the last image before failure in each experiment (Figure 7) and extracting the x-displacement along those sections. One section would be along the CFRP strip and two sections would be along the bare concrete on the left and right of the strip. By removing the average x-displacement of concrete from the x-displacement of CFRP, one can obtain the slip of the strip. The results for lap-shear tests are given in Figure 8. There was no significant difference between the slip profiles of the reference and carbonated concrete specimens. The maximum slip values were observed within the range of 0.17-0.24 mm.

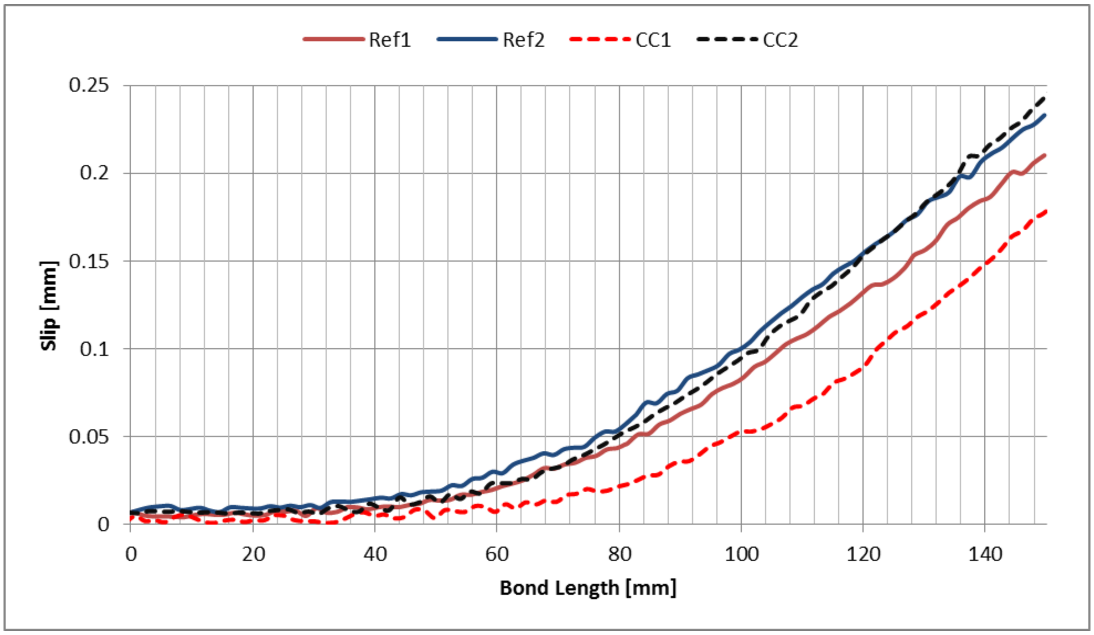

Figure 8: "Slip vs Bond Length" for the lap-shear tests

4. Conclusions and Outlook

Several conclusions can be drawn from the presented results:

- A new experimental setup was designed in order to understand the long-term performance of the Gradient Anchorage. This setup, so far used for reference and carbonated concrete (CC) cases, will be further used for ageing tests.
- First results indicate a higher residual load carrying capacity for the CC case, which can be linked to its higher compressive strength compared to the reference concrete. The average residual load carrying capacity was 33.2 kN for the reference and 38.1 kN for the carbonated concrete case.
- The failure occurs in both cases predominantly within the concrete layer even though small transitions to epoxy and interfaces have also been observed.
- There was no significant difference between the slip profiles of reference and carbonated concrete specimen for lap-shear tests.

Ongoing ageing cases focuses on the effect of temperature cycles (+25 to -15°C) with and without carbonation as well as higher temperature and humidity conditions (40°C with 90% RH). Additional material specimen will help explain the effect of ageing on various parameters, such as notched beams for the fracture energy of concrete and epoxy or dog bones for the tensile strength of epoxy. The compiled result of this experimental campaign will help explain the behaviour of prestressed CFRP on a long-term scale under environmental influence.

5. Acknowledgements

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