Recent contributions from UMinho and Empa on durability issues of flexural strengthening of RC slab with EB CFRP laminates

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ABSTRACT: Common research activities in the field of durability of prestressed externally bonded reinforcement (EBR) for reinforced concrete (RC) structures were carried out at both the University of Minho (UMinho) and the Swiss Federal Laboratories for Materials Science and Technology (Empa). The research includes the study of the durability of (i) the constituent materials (concrete, epoxy and CFRP laminate) and (ii) large-scale RC slabs strengthened with prestressed CFRP laminates with two different anchorage systems (mechanical anchorage and the gradient anchorage), when subjected to different environmental conditions. The main achievements for a better understanding of the durability of RC elements strengthened with prestressed EBR-FRPs are presented in this paper. Finally, the effect of polymer sealings and asphalt application at high temperatures on CFRP/epoxy/concrete connections is also briefly discussed.

1 INTRODUCTION

In particular situations, prestressed externally bonded (EB) carbon fiber reinforced polymer (CFRP) laminates are required for improving the performance of existing reinforced concrete (RC) structures. With this technique several benefits are obtained, such as reduction of crack width and deflection, increase of the ultimate capacity and of resistance to shear/fatigue brittle failure, among others.

The CFRP laminates can be directly prestressed (i) indirectly prestressed by cambering the structure upward, (ii) against an independent system or it can be (iii) against the structure itself. The latter option is typically selected due to its versatility and viability for *in situ* applications. Special anchorage systems for fixing the ends of the prestressed CFRP laminates are required. Two of the most used anchorage systems are: (i) the mechanical anchorage (MA), using metallic plates; and, (ii) the gradient anchorage (GA), which uses the ability of the epoxy to cure faster at higher temperatures, allowing to gradually reduce the prestressing force over several consecutive sectors at the strip end.

The experience of using prestressed EB CFRP laminates is still limited and, consequently, some concerns regarding the efficiency of the technique still exist, especially the durability, the long-term behavior and effect of elevated temperatures. The present paper gives recent deep insights in the context of these issues as a result of the research carried out at the UMinho and Empa.

2 MECHANICAL PERFORMANCE OF COLD-CURING EPOXY ADHESIVES

2.1 Effects of different environmental conditions (@UMinho)

2.1.1 Experimental program and test configurations

In order to assess the effects of different environmental conditions on the mechanical characteristics of a structural epoxy adhesive (S&P Resin 220), an experimental program composed of 78 epoxy specimens was carried out at UMinho. The specimens used were produced according to “type 1A” defined in EN ISO 527-2:2012. The following environmental conditions were studied, for a period of time that lasted up to 480 days: (i) immersion in plain water at 20 °C (PW); (ii) immersion in water with 3.5% chlorides at 20 °C (CW); (iii) specimens submitted to wet-dry cycles in water with 3.5% chlorides at 20 ºC (WD); (iv) specimens submitted to thermal (TC) and (v) freeze-thaw (FT) cycles. For series PW, CW and WD half the specimens were submitted to the action during 240 days (PW240, CW240 and WD240), whereas the other half continued up to 480 days (PW480, CW480 and WD480). Series TC was based on EN 13687-3:2002 standard and the applied temperatures ranged between -15 °C and +60 °C. Each cycle of series TC and FT lasted 24 hours of duration. In series FT, temperatures ranged from –18 °C to +20 °C according to CEN/TS 12390-9:2006 standard, and the specimens were immersed in water during the period of positive temperatures. In the case of series TC and FT half the specimens were submitted to the action during 120 days (TC120, FT120), whereas the other half continued in ageing conditions up to 240 days (TC240, FT240). Each series was composed of 6 specimens. Detailed information about the experimental program can be found in (Silva *et al.* 2016).

Dynamic mechanical analysis (DMA) and standard tensile test (STT) were used as methods of characterization of the epoxy. To determine the glass transition temperature (T_g), the specimens were subjected to a temperature ramp from room-temperature to 120 °C with a heating rate of 2 °C/min in an inert nitrogen atmosphere. The test was performed with the TA DMA Q-800 equipment, using a single-cantilever configuration, by the application of a constant amplitude (5 μm) with a frequency of 1 Hz. The T_g was calculated from two distinct methods: (i) the onset of the storage modulus curve drop; (ii) the peak value of loss modulus curves. The STT were performed according to EN ISO 527-1:2012. The epoxy samples were tested on universal testing machines under displacement control at a rate of 1 mm/min. In order to measure the longitudinal strain, a strain gauge (TML BFLA-5-3-3L) was installed at mid-length of the specimen.

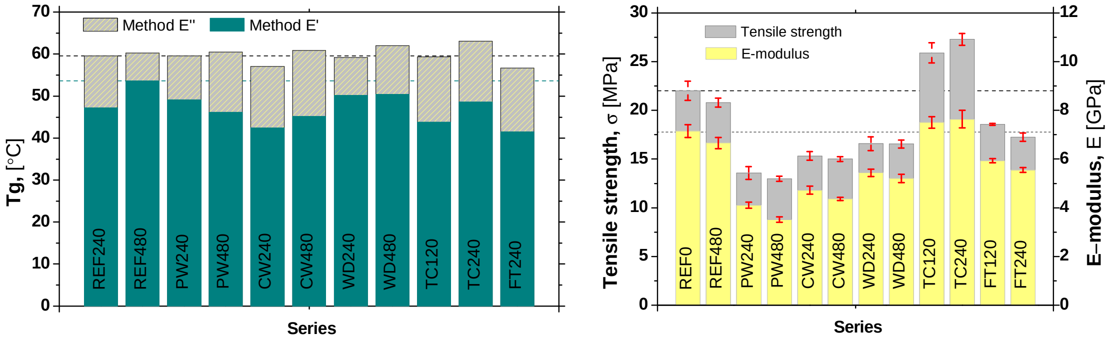
2.1.2 Results and main conclusions

Figure 1a includes the results of T_g calculated at the onset of the storage modulus curve drop (E') and the peak value of loss modulus curves (E''), whereas as Figure 1b shows the results of the tensile E-modulus and strength. The obtained results reveled the main following conclusions (Silva *et al.* 2016):

- In general, all the environmental conditions (PW, CW, WD and FT) negatively affected the values of T_g, mainly the specimens exposed to chlorides water and freeze/thaw cycles, with a relative decrease of about 21% and 23%, respectively. According to the literature, the exposure to wet environments may have as consequence the plasticization of adhesive and the negative temperatures might have interrupted the curing along time;
- From the tensile tests carried out, it was observed an increase up to 33% and 15% on the ultimate tensile stress and E-modulus, respectively, for the series submitted to thermal

cycles. The increase on strength and stiffness of the epoxy specimens is justified by the post-curing phase, as verified in dynamic thermomechanical analysis;

- A significant decrease on the ultimate tensile stress and E-modulus was observed for series PW, CW and WD up to 47% and 38%, respectively. These reductions of mechanical properties were observed due to the presence of water. This epoxy material seemed susceptible to the degradation mainly when it is immersed in plain water due to the occurrence of plasticization phenomena.



(a) (b)

Figure 1. Results of epoxy adhesive in terms of average values: (a) Glass transition temperature; and (b) tensile strength.

2.2 *Effects of curing at room and elevated temperature (@Empa)*

Earlier studies at Empa have focused on the effect of curing (room temperature curing or accelerated curing at elevated temperature) and mixing procedure (by hand of vacuum) on the mechanical performance of commercially available epoxy resins for civil engineering applications (Michels *et al.* 2016). It was demonstrated that porosity increases due to accelerated curing. However, it can be avoided when vacuum mixing is performed.

3 MA AND GA PRESTRESSING SYSTEMS: BEHAVIOR, DURABILITY AND ANALYTICAL SIMULATIONS

3.1 *Experiments at UMinho*

3.1.1 Test description and setup

An experimental program with RC slabs strengthened with prestressed CFRP laminate strips according to the EBR technique was carried out at UMinho for a better understanding of the short, durability and long-term structural behavior of such structural systems. Two anchorage systems were investigated: the mechanical anchorage (MA) system with metallic elements fixed to the ends of the FRP reinforcement and the gradient anchorage (GA). The long-term behavior of the slabs was assessed by their exposure to the following environments for approximately 8 months: (i) reference environment – specimens in climatic chamber at 20 ºC; (ii) water immersion in tank at 20 ºC of temperature; (iii) water immersion in tank with 3.5% of dissolved chlorides at 20 ºC of temperature; and (iv) wet/dry cycles in a tank with a water temperature of 20 ºC. Additionally, half of these specimens were also subjected to sustained loading (creep) of 20 kN (1/3 of their ultimate load), promoting the occurrence of cracking.

The experimental program was composed of 20 RC slabs: (i) 4 control specimens (series T0); (ii) 8 slabs subjected to distinct environmental conditions (labelled with the suffix _U); and, (iii) 8 slabs subjected to the combined effect of environmental and loading conditions (labelled with the suffix _C). As mentions previously, two anchorage systems were analyzed: MA and GA.

Figure 2 shows the specimens' geometry and the test configuration used in the experimental program. The slabs were 2600 mm × 600 mm × 120 mm (length × height × thickness). The upper and lower longitudinal inner reinforcement were composed of three steel bars with a diameter of 6 mm (3Ø6) and 5Ø8, respectively. Transverse reinforcement was composed of closed steel stirrups of Ø6 spaced of 300 mm. All strengthened slabs were strengthened with 2200 mm long CFRP laminates with a cross-section of 50×1.2 mm^2.

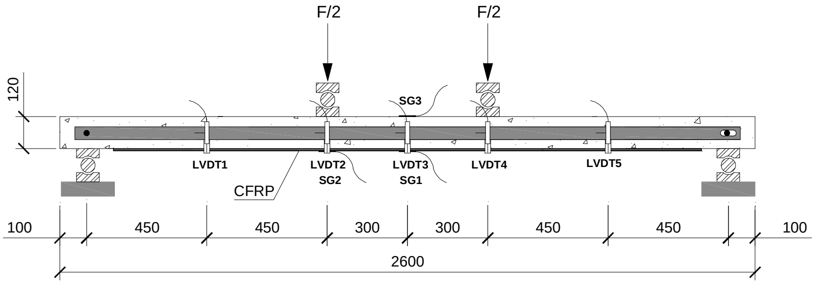


Figure 2. Specimen's geometry and test setup. Note: all units are in millimeters.

The slabs were loaded with a 4-point bending test configuration with a shear span of 900 mm. All tests were carried out with a servo-controlled equipment under displacement control at the rate of 1.2 mm/min at the actuator cross-head. During these tests five linear variable differential transducers (LVDTs) were used to record the deflection along the longitudinal axis of the slab and five strain gauges measured the strain variation in the CFRP laminate, concrete and steel reinforcement. The applied load (F) was also measured with a load cell (see Figure 2).

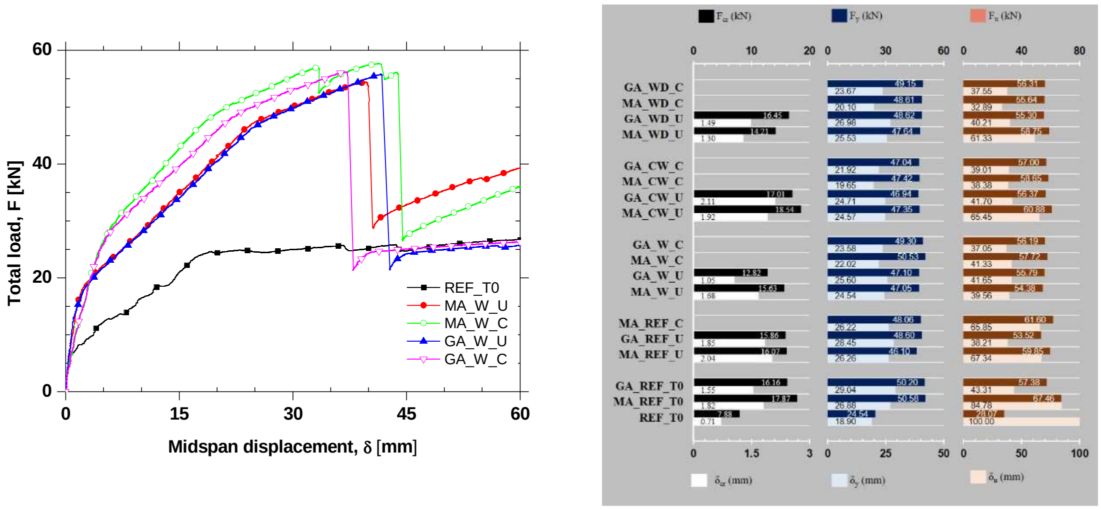
A concrete class C30/37 with a maximum aggregate size of 12.5 mm and no fly ash was used. The mean concrete compressive strength, assessed from cylinder specimens (150 mm/300 mm), was 40.2 MPa and its modulus of elasticity was of 30.0 GPa, at 28-days of age of concrete. The tensile properties of the CFRP laminate, steel reinforcement and epoxy adhesive were also assessed thought NP EN ISO 6892-1:2012, ISO 527-5:1997 and ISO 527-2:1993 recommendations, respectively.

3.1.2 Results and main conclusions

Typical results in terms of total load *versus* midspan displacement and key results obtained from the experimental program are presented in Figure 3. From this experimental program the following main results were obtained:

- A similar responses were observed for both anchorage techniques; however the mechanical plates of the MA system prevented a premature failure and, consequently, allowed the slabs to support greater ultimate loads and deflections;
- For the GA slabs, the initial debonding process was rapidly transformed into the complete strip detachment, resulting in a brittle failure, very similar to conventional EBR system without any end-anchorages;
- The MA_REF_T0 slab was the only that failed by CFRP rupture. In the remaining slabs seemed to have failed by strip intermediate debonding from the concrete;

- The slabs submitted to water immersion (series TW, CW and WD) improved the concrete modulus of elasticity and strength, which increased the initial slabs' stiffness and delayed the crack initiation;
- All tested environmental conditions led to a reduction of the yielding and the failure loads for both anchorage systems, nevertheless the influence of each environment was different on each anchorage system: TW and REF environment conditions seemed to have the highest degradation influence over the MA and GA slabs, respectively.



(a) (b)

Figure 3. (a) Typical total load *versus* midspan displacement (series of specimens immersed in water); (b) Key results obtained from the experimental program. Note: d=Midspan displacement;F=Force; CR=Cracking; Y=Yielding; U=Ultimate.

3.2 *Experiments at Empa*

3.2.1 Test description and setup

Recently, experimental investigations at Empa were performed on cantilever test setups (Figure 4, cantilever length=2.5 m) with an externally bonded CFRP reinforcement on the top surface, simulating the transverse direction in a box girder plate. The following two aspects of durability of CFRP strengthening systems were checked:

- Effect of polymer sealing layer and mastic asphalt application at elevated temperatures on the short-term stability of different CFRP/epoxy/concrete systems. Both slag applied and prestressed CFRP strips with GA were investigated;
- Long-term durability under sustained and fatigue loads (Figure 4). For instance, seasonal temperature peaks in summer can cause epoxy resin temperatures above 50 °C under direct sun exposure of the above lying asphalt layer.

Additionally, a Ph.D. thesis in collaboration with ETH Zürich focuses on the GA durability under freeze-thaw cycle (FTC) exposure. For this investigation, test samples with one gradient sector under shear stress were subjected to temperature changes between -15 °C and +25 °C and subjected afterwards to lap-shear loading up to failure in order to assess the residual anchorage resistance compared to the reference samples without ageing (Harmanci *et al.* 2017).

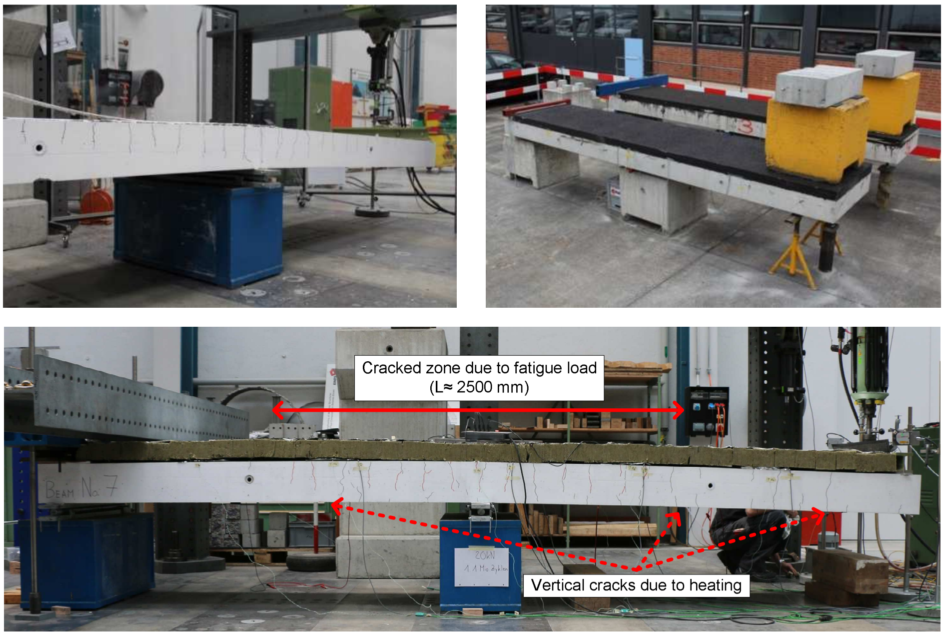


Figure 4. Cantilever static loading test to failure (upper left), cantilever test with asphalt under sustained load (upper right), cantilever fatigue test under elevated temperature (with heating mats) (bottom).

3.2.2 Results

The main findings of the experimental investigation were the following:

- Static loading tests to failure have shown that for slag applied CFRP strips, neither the high temperatures during polymer sealing nor the asphalt application have a negative effect on the load carrying capacity (Figure 5). Due to the post-curing of the epoxy resin, the CFRP/epoxy/concrete bond might even be slightly improved. However, a prestressed strip with a GA might undergo epoxy softening during the elevated temperatures, eventually resulting in a premature strip debonding already at construction phase;
- Cantilever tests with initially unstressed CFRP strips outside with a mastic asphalt layer and under sustained loading currently show a rather satisfying long-term behavior. As shown in Figure 6, strain at the maximum bending moment initially increases due to the application of the sustained load, followed by a slight increase due to most probably epoxy and concrete creep. Afterwards a more or less stable strain state is reached, subjected to the seasonal and daily temperature fluctuations;
- Fatigue tests at cracked state with a 50 °C epoxy temperature demonstrated that after 2 million cycles, no internal steel fracture occurred. This was the case for both unstressed and prestressed (GA) strips. Strip strains and tip displacement slightly increased during the loading cycles as a result of a gradual strip/epoxy or epoxy/concrete interface damage. Subsequent static loading at 50 °C exhibited even higher bearing capacity than the initial reference test Figure 5). The reason for this is believed to be a better shear stress distribution due to a slight reduced epoxy resin stiffness.

For an exposure of gradient anchorages to FTC exposure, the main finding was a reduced residual anchorage resistance after ageing by around 30% compared to the reference samples (uncarbonated or carbonated concrete (CC)). This lower force goes along with a shift of the debonding failure surface from the concrete substrate to the epoxy/concrete interface (Figure 7).

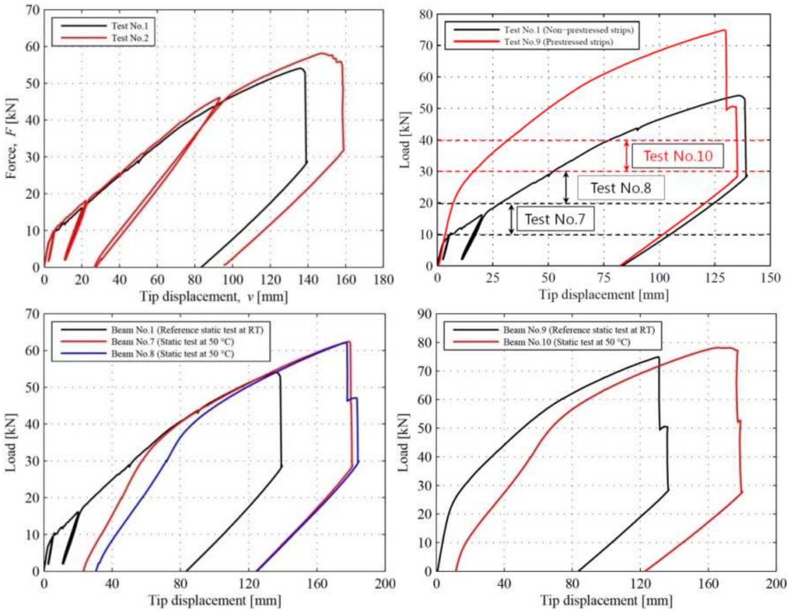


Figure 5. Force-tip deflection curves: unstressed CFRP strips, with and without asphalt application (upper left), unstressed and prestressed (GA) CFRP strips – reference tests (upper right), failure tests after fatigue and comparison to reference test, unstressed (lower left) and prestressed CFRP strips (lower right)

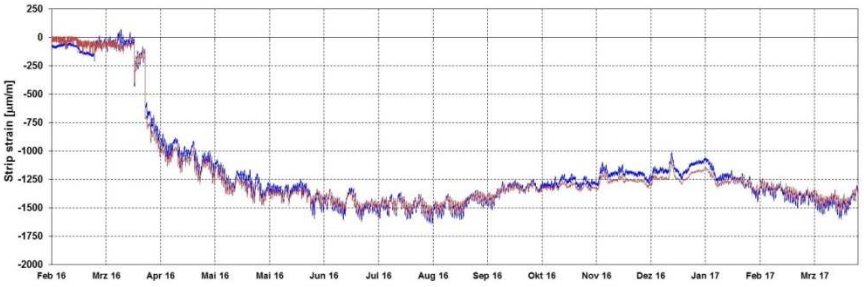


Figure 6. Strip strain (at maximum moment over the support) evolution in time under sustained load

4 CONCLUSIONS

The present paper summarized the main achievements on common research activities at UMinho and Empa on the durability and the long-term behavior prestressed EB CFRP laminates. From this research the following conclusions can be drawn:

- In general, at mesoscale level, important decreases on strength and stiffness are observed when the epoxy and lap shear (CFRP/epoxy/concrete) specimens are exposed to environments involving water;
- Prestressed EB CFRP laminates using the MA system prevents a premature failure and, consequently, allowed the slabs to support greater ultimate loads and deflections;
- In general, the durability of the strengthened slabs with EB CFRP laminates to different environmental conditions, is significantly higher when compared with the results obtained at material or bond levels.

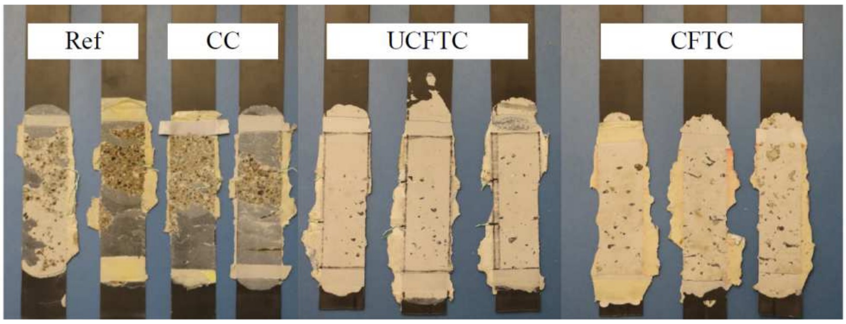


Figure 7. CFRP specimens after strip debonding (lap-shear): reference, carbonated concrete (CC), uncarbonated concrete & freeze-thaw (UCFTC), carbonated concrete & freeze-thaw (UCFTC)

5 ACKNOWLEDGEMENTS

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