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Influence of temperature on the CFRP/epoxy/concrete bond

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ABSTRACT: During the last decades, traffic loads by heavy vehicles have increased due to requirements of the current society and this fact has to be considered when the state of existing bridges is evaluated. Many concrete structures, for instance lateral cantilevers of highway box-girder bridges, can be strengthened on the upper side with externally bonded Carbon Fiber Reinforced Polymer strips in order to increase their load-bearing capacity in flexure. These additional reinforcements can be applied as an unstressed or prestressed system. The main goal of this paper is to analyze the effect of the temperature on the bond between the concrete substrate, the epoxy resin layer, and the externally bonded Carbon Fiber Reinforced Polymer strip. A literature review together with new experimental investigation performed at Empa will be used to summarize different influential parameters.

1 INTRODUCTION

Externally bonded (EB) prestressed Carbon Fiber Reinforced Polymer (CFRP) strips can be used as an additional reinforcement for strengthening reinforced concrete structures as for example the upper side of lateral cantilevers of highway concrete box-girder bridges. For this kind of application, CFRP strips, and hence the epoxy adhesive, can reach elevated temperatures mainly due to the sealing process and the subsequent application of the mastic asphalt layer during the construction or afterwards due to the sun heating. Despite of the large number of experimental works carried out concerning the long-term behavior of reinforced concrete elements strengthened with unstressed CFRP strips, very few experimental investigations have been done so far regarding the behavior of prestressed CFRP strips under more extreme temperature scenarios.

The main goal of this paper is to present the influence of temperature on the bond behavior of CFRP/epoxy/concrete systems. Firstly, a literature study will summarize performed experimental investigations on both unstressed and prestressed systems and their key results. Secondly, an own experimental campaign carried out at Empa with small concrete specimens to assess the temperature stability of the gradient anchorage (Michels et al. (2013)) for prestressed strips under a critical temperature scenario such as the application of mastic asphalt is introduced. Results from both the literature and experiments will be finally discussed and commented.

2 REVIEW OF EXISTING EXPERIMENTAL WORKS

This section summarizes the most important experimental campaigns carried out so far regarding the bond behavior of non-prestressed and prestressed EB CFRP subjected to different temperature scenarios. Special attention is attributed to details in temperature application (preheating of a climate chamber, exposure of the specimen prior to loading, etc) as well as the types of failure that have been observed.

2.1 Small scale elements strengthened with non-prestressed EB CFRP strips

These tests reproduce the local bond behavior of the interface concrete/epoxy/CFRP and can be classified in three point bending tests or double-lap shear tests according to Figure 1.

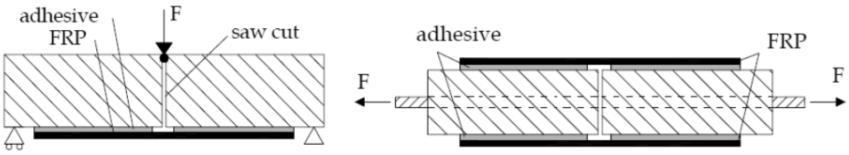

Figure 1. Typical test set-up in small scale specimens (Klamer et al. (2008)): (Left) Three point bending test; (Right) Double-lap shear test.

Tadeu et al. (2000) investigated the effect of temperature on reinforced concrete specimens strengthened with EB steel strips for three different concrete mixtures and four constant temperature levels (30°C, 60°C, 90°C and 120°C). The elements were placed in a furnace and the temperature inside was raised at a rate of 5 °C/min until the test temperature was reached. Then the temperature was kept constant before testing during three hours until a uniform temperature was obtained in the specimen. These tests showed a reduction of the failure load for high temperature values. Due to the similar coefficient of thermal expansion between the concrete and the steel plates, this strength reduction was related to the change in the mechanical properties of the adhesive at elevated temperatures. For the tests performed up to 30°C, failure was initiated in the concrete surface approximately at 30 mm from the surface. For the tests developed at elevated temperatures, failure of the adhesive took place. Those tests carried out at 120°C presented failures at the epoxy/strip interface.

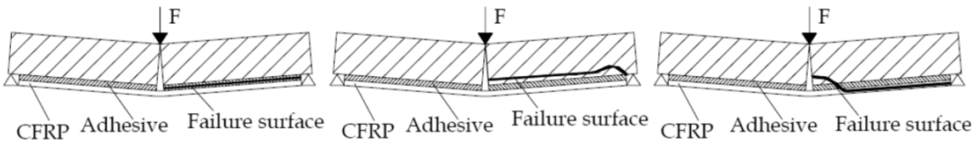

Figure 2. Failure modes observed for different temperature values (Di Tommaso et al. (2001)): (Left) Adhesive failure; (Middle) Concrete failure; (Right) Failure due to CFRP delamination.

Di Tommaso et al. (2001) carried out three point bending tests at very low (-100°C), low (-30°C), moderate (20°C) and high (40°C) temperatures. Depending on the test temperature, three different types of failure were observed. The specimens were strengthened at room temperature (20°C) and heated or cooled in a chamber in order to reach the aim temperature. The temperature was raised or lowered 1°C/min and the beams were tested after an approximately homogeneous temperature distribution was reached in the specimen. For high temperature values (40°C), failure was in the adhesive due to its softening while for moderate temperatures (20°C) failure was in the concrete near the interface with the adhesive. For low temperature values (-100°C and -30°C), beams collapsed due to delamination of the CFRP strip after the initiation of a crack in the concrete. The different failure modes are shown in Figure 2. The results showed that the load capacity decreased when the temperature increased from 20°C to 40°C. Besides, the failure mode changes with the temperature being more ductile at high temperature and more brittle at low temperature.

Double-lap shear tests were performed by Wu et al. (2005) with the configuration shown in Figure 1(Right). In this experimental campaign a cup oven was used to heat the specimens up to reach the aim temperature. Before the load application, each specimen was kept under the test temperature for at least six hours in order to assure a uniform temperature in the specimen. Each test was performed for a different temperature level (20°C, 30°C, 40°C, 50°C and 60°C) and the experimental results showed a reduction of the failure load with the increase of the temperature level.

A similar double-lap shear test setup was adopted by Leone et al. (2006). Twenty double-lap shear tests were performed at different constant temperature levels (20°C, 50°C, 65°C and 85°C). An electrical hollow furnace was used to heat the elements. The furnace was placed around the tested elements and the temperature was controlled by a thermocouple type K that measures the air temperature inside the furnace. Each specimen was heated during at least three hours before testing allowing the specimen to reach the uniform aim temperature. Generally, an increase of the failure load was observed up to temperatures of 50-60 °C. For tests carried out at higher temperatures, the failure load was significantly lower. Between room temperature and 50°C bond failure was typically characterized by a thin layer of concrete attached to the CFRP reinforcement. For higher temperature values (85 °C), debonding failure at the interface epoxy/strip happened. Failures at temperatures equal to 65 °C were intermediate between failure in the adhesive and failure in interface epoxy/strip.

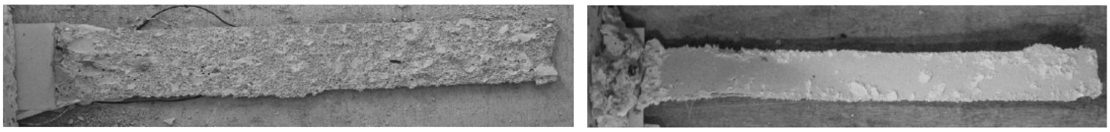

Figure 3. Different failures observed from Klamer et al. (2008): (Left) Concrete failure at epoxy temperatures between -20 °C and 50 °C; (Right) Adhesive failure at epoxy temperatures higher than the glass transition temperature.

More tests were developed by Klamer et al. (2006, 2007, 2008, 2009). Authors did double-lap shear and three point bending tests with EB CFRP strips for different concrete strengths (from 40 MPa to 70 MPa) and different temperature levels (from -20 °C to 60 °C). An isolated chamber was specially designed to test the specimens at elevated temperatures. This chamber was part of a closed air circuit and additionally several fans were placed inside the chamber to make sure that the heat was uniform along the elements. The specimens were heated or cooled down for approximately 16 hours before the load application. For the elements tested at low temperature levels a freezer was used. Those specimens tested at temperatures between -20°C and 50°C collapsed in an explosive way due to the failure of the concrete substrate (Figure 3(Left)). For moderate temperature scenarios, the increase of the temperature had a positive influence in the failure load. An increase of the failure load was observed until the glass transition temperature of the adhesive was approximately reached. Above this value the failure load started to decrease and a change of the type of failure, this time between concrete and epoxy, was observed (Figure 3(Right)). According to the authors, the difference in the coefficient of thermal expansion between the concrete and the strip, the reduction of the elastic modulus of the adhesive with the temperature increase and the change of the type of failure for high temperature levels are the three main causes that affect the capacity of such elements under elevated temperatures.

2.2 Large-scale beams strengthened with non-prestressed EB CFRP strips

Baumert et al. (1996) carried out four point bending tests on concrete beams built with and without longitudinal steel reinforcement at two different temperature levels (-27°C and 21°C). For the non-reinforced concrete beams, for both temperature levels, shear failure took place followed by debonding of the CFRP strip. For the reinforced concrete beams, debonding happened outside the constant moment region. Then, debonding extended towards the constant moment region along the level of the longitudinal reinforcement. In spite of the different failure modes observed in both cases depending on the longitudinal reinforcement ratio, the ultimate strength and the type of failure were not significantly affected by the temperature level.

Klamer et al. (2006, 2007, 2008, 2009) also developed tests for large scale beams strengthened with EB CFRP strips at different temperatures levels. Four different types of beams were designed in order to study the most important debonding mechanisms. These failure mechanisms are the following: Debonding due to high shear stresses (beams A), debonding at shear cracks (beams B), debonding at the end anchorage (beams C) and concrete cover rip-off (beams D). To have these failure modes, authors decided to vary the quality of the concrete and the dimensions of the strips. For each failure mechanism three similar beams were tested under four point bending at different constant temperatures (20°C, 50°C and 70°C) in order to study the effect of this variable. Again an isolated chamber was used to simulate the elevated temperature scenario. Beams A showed a similar behavior up to failure and similar failure loads for all the studied temperatures. Independently of the external temperature imposed, strip debonding started in a region away from the strip-end outside the constant moment region and was propagated towards the end of the strip. No significant differences were observed in the crack pattern of the beams at failure. At 20°C and 50°C, debonding propagated into the concrete leaving a small concrete layer attached to the adhesive after debonding. At 70°C, concrete also remained attached to the adhesive but in that case only in several zones. This fact indicates that there is a temperature value above which debonding changes from concrete failure to interfacial failure in the contact epoxy/concrete. Beams B presented a similar behavior for all the tested temperatures and only a slightly decrease in the stiffness was observed at elevated temperatures. This fact was related by the authors to the reduced elastic modulus of the concrete and the adhesive at elevated temperatures. For beams C (with shorter strips), as in the previous cases, the load-displacement curves at 50°C and 70°C showed a less stiff behavior compared to the beams tested at room temperature. In comparison with beams A and B, the crack patterns observed for such tests were different and the cracks were developed over the entire, but shorter bond length. For those tests carried out at 70°C, authors related the decrease in the load capacity to the reduction of the bond strength of the concrete/epoxy/strip joint at elevated temperatures. All the beams D failed due to concrete cover rip-off over the entire width and after failure the internal steel reinforcement was visible.

2.3 Strengthened elements with prestressed EB CFRP strips

El-Hacha et al. (2004) focused on the influence of the temperature on prestressed EB CFRP strips. In this experimental campaign five internally posttensioned concrete beams strengthened in flexure with prestressed EB CFRP strips were statically tested under different temperature levels. The beams were simply supported and tested under two concentrated loads applied at one-third of the span. Before the EB CFRP strips were placed, the beams were subjected to a preload in order to simulate the real conditions of cracked flexural concrete elements that require rehabilitation. Then, the beams were subjected to room (22 °C) or low temperature (-28 °C) for seven days and after this period they were tested under these temperatures. Tests at low temperatures did not show any significant damage in comparison with the beams tested at room temperatures and the crack patterns developed in both cases were similar to each other. In spite of this fact a slight increase of the ultimate load was observed in the beams tested at low temperature. These differences observed in the ultimate load were attributed by the authors to the change of the material properties at different temperature levels.

⇨ To summarize the three sections, one can state that the exposure temperature of a CFRP/epoxy/concrete system influences the failure mode when being loaded. Room temperature generally induces a failure in the concrete substrate, whereas often an interface failure concrete/epoxy is observed when higher temperatures occur.

3 PRESTRESS FORCE-RELEASE TESTS AT EMPA

3.1 Motivation

In the framework of a research project on the durability of EB CFRP reinforcements in bridge construction, an experimental campaign was performed to study the influence of elevated temperature of prestressed CFRP strips with the gradient anchorage (Michels et al. (2013)). Such elevated temperature scenarios can occur during the mastic asphalt application. The investigation included several tests on prestressed CFRP strips anchored to a concrete block and subsequently exposed to elevated temperature. This section will now present two of the performed tests and their key results in relation to the previously presented literature study.

3.2 Materials, test setup and procedure

Unidirectional CFRP strips by S&P Clever Reinforcement were used with a nominal width and thickness of 100 mm and 1.2 mm, respectively. Elastic modulus was about 165 GPa and tensile strength approximately 2900 MPa. A two-component cold-curing epoxy adhesive of type S&P Resin 220 has been used as bonding material. The concrete blocks were made using concrete with a maximum aggregate size of 32 mm and a water-cement ratio of 0.5. The concrete surface was ground before the strip application. Average concrete compressive strength on cube was 40 MPa.

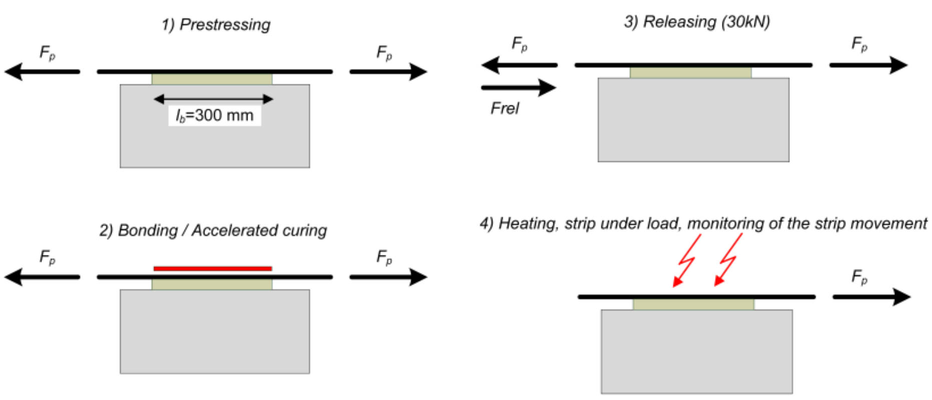

Figure 4. Anchoring and heating procedure for the temperature stability tests for prestressed CFRP strips.

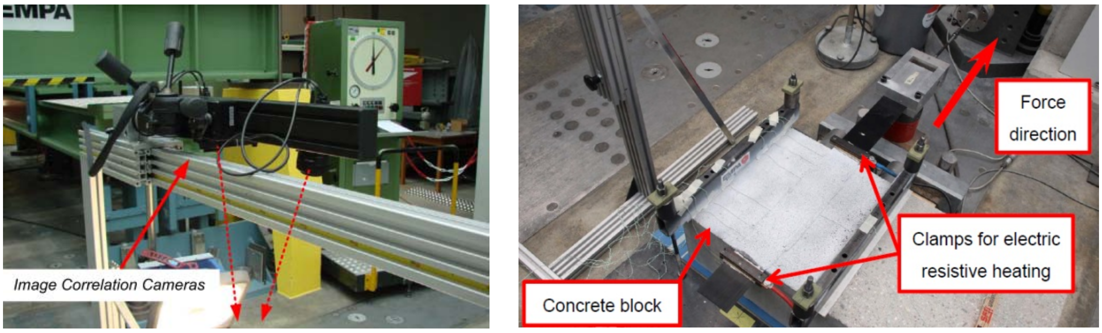

Figure 5. Setup for the temperature stability tests for prestressed CFRP strips.

The loading/heating procedure and test setup are shown in Figure 4 and Figure 5. The CFRP strip was initially prestressed and subsequently bonded over 300 mm with an accelerated epoxy resin cured at high temperature to the concrete substrate. Finally, the prestress force (F_p = 30 kN) was released on one side in order to simulate one gradient sector (Michels et al. (2013)) with a bonded length equal to 300 mm. In order to experimentally simulate the asphalt scenario, the CFRP strip was heated by electric current controlled by a thermocouple placed in the epoxy adhesive underneath. Measurements with thermocouples in the epoxy adhesive have shown that during the asphalt simulation the epoxy was subjected to the temperature profile shown in Figure 6(Left). An Image Correlation System (ICS) has been used to monitor the strip displacements.

3.3 *Experimental results*

The evolution of the prestress force in time for two tests (named No.3 and No.12) during the simulation of the asphalt scenario is shown in Figure 7. For both tests, it can be noticed that the prestress force remains more or less stable with a slight decrease during the complete exposure to elevated temperatures. Relative losses of the initial prestress force were only 5 % and 4 %, respectively.

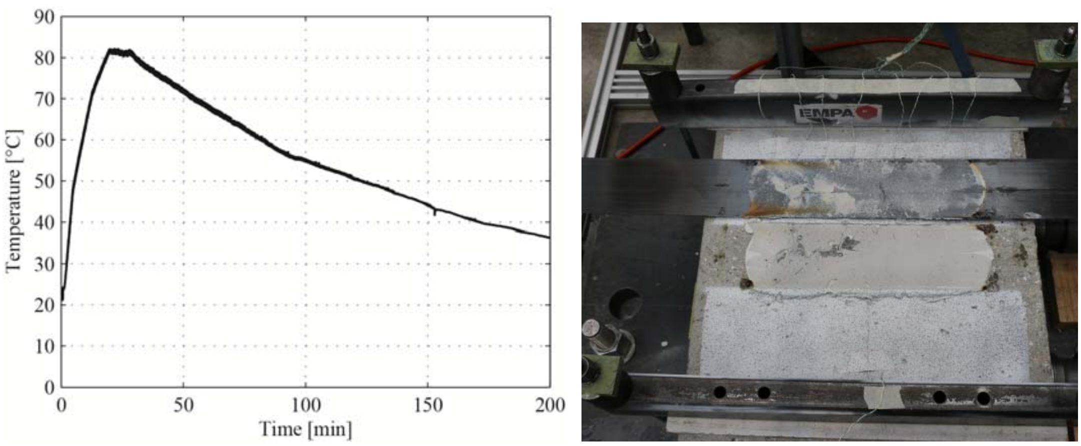

Figure 6. (Left) Epoxy temperature measured during the simulation of the asphalt scenario; (Right) Test No.12 after failure at a constant temperature of 80°C.

Some results for test No.12 obtained with the ICS during the simulation of the asphalt scenario are shown in Figure 8, in which the isolines of the longitudinal displacements are represented in the stage related to the beginning of the cooling down (80 °C). The relative slips between the CFRP strip and the concrete block at different points (points A, B and C) of the strip are shown in Figure 8(Right). The coordinate value x=0 mm corresponds to the end of the bonded length where the prestress force was released while the coordinate value x=300 mm is related to the other end. Results show that during the asphalt scenario, a significant slip of the strip due to creep deformation of the epoxy adhesive at elevated temperature happened. After the simulation of the asphalt scenario the strip displacement remained constant. The maximum slip values in the strip were measured in the zone of the bonded area where the shear stress level was among the highest, namely, near the zone where the prestress force was released (x=0 mm).

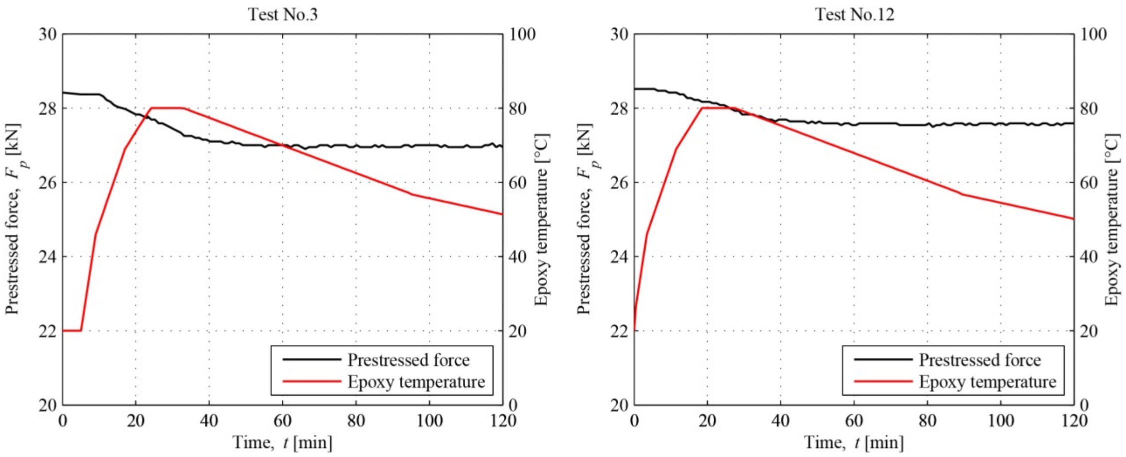

Figure 7. Evolution in time of the prestress force during the simulation of the asphalt scenario: (Left) Test No.3; (Right) Test No.12.

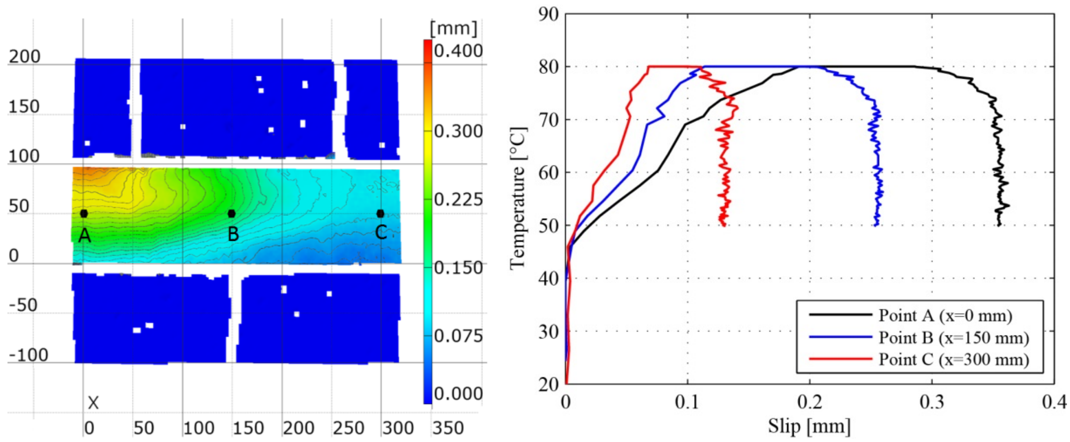

Figure 8. Measurements during the simulation of the asphalt scenario for test No.3: (Left) Longitudinal displacements at the beginning of the cooling down (80 °C); (Right) Relative strip displacements at three different points.

4 CONCLUSIONS

Several conclusions can be drawn from the presented literature study and experimental investigation:

- The surrounding testing temperature influences the bond strength of a CFRP/epoxy/concrete system. Different exposure temperatures generally lead to differences in anchorage resistances in lap-shear tests.
- Elevated temperatures lead in several cases to a change in failure type: under room temperature, concrete is generally the weakest link, in which cracking eventually leads to failure. At higher temperatures, however, a shift from the concrete substrate to an interface failure epoxy/concrete has been noticed in several research activities.
- The application of warm mastic asphalt can influence the behavior of an EB CFRP strip used for negative bending strengthening (i.e on the top side of the structure). In case of prestressed systems with the gradient anchorage, the loss in stiffness leads to a stress redistribution over the bond length. For the studied case, a prestress force of 30 kN anchored over 300 mm (average shear stress 1 MPa) remained stable with only a slight loss. Large-scale testing is necessary to give a final evaluation.

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