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Effect of partly cured adhesives on bond-slip relationship of FRP-concrete interface

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ABSTRACT: External prestressing of existing reinforced concrete (RC) beams by means of bonded fiber reinforced polymer (FRP) strips is getting more and more common as a possible strengthening technique for either underdesigned or damaged members. However, the current technical solutions for external prestressing with FRP require a mechanical anchorage system at the end of the strip, in order to react to the high interface stresses arising in that part of the FRP-to-concrete interface. An alternative solution based on a gradual reduction of the prestressing force in the end zone of the FRP strip which avoids any mechanical anchorages has been recently developed at Empa. Generally speaking, this solution, called “gradient method”, works on the accelerated curing of epoxy resins under heating exposure. Therefore, a better understanding of accelerated curing of adhesive by heating is necessary. The present paper describes some experimental results of pull-off tests carried out on FRP strips glued on concrete blocks and cured through heating with variable duration. The maximum force at debonding onset observed in the tests on specimens with different curing durations at elevated temperatures were compared with a reference test carried out on a specimen fully cured at room temperature for three days. Furthermore, the displacements measured by means of an optical image correlation system are presented with the aim of showing the effect of the heating duration. Moreover, a simple calibration procedure has been used for identifying the supposed bi-linear shear-stress-slip relationship describing the effect of partly cured adhesive on the behavior of the FRP-to-concrete adhesive interface.

1 INTRODUCTION

Strengthening existing structures is an important issue in structural engineering in the civil field. In the last twenty years, several possible applications of composite materials, such as fiber reinforced polymers (FRP) have been proposed for strengthening of both reinforced concrete (Teng et al., 2007) and masonry structures (Triantafillou T., 1998).

External prestressing of existing RC beams through FRP strips is one of the most recent advances in the possible application of composites for structural strengthening of civil constructions (Motavalli & Czaderski, 2007). Mechanical devices are generally required for anchoring those prestressed FRP strips, in order to absorb the high interface stresses arising at their ends (El-Hacha et al., 2003; Yu et al., 2008).

An alternative solution for anchoring prestressed CFRP strips without any mechanical device has been recently developed at Empa (Stöcklin & Meier, 2003). It is based on a progressive release of the prestressing force in the end part of the FRP strips, while the epoxy adhesive in the same zone undergoes a fast curing process due to heating exposure. Since the prestressing action in the FRP is released piece-wise in the end part of the strip and the prestressing action falls to zero at the end of the anchorage (Aram et al., 2008 and Czaderski & Motavalli, 2007), this anchoring procedure is called “Gradient Method”.

An in-depth knowledge of the evolution of the mechanical properties of the adhesive FRP-to-concrete interface depending on the curing process in terms of both heating exposure duration and temperature is of paramount importance for an effective and efficient implementation of the “Gradient method” in RC beams externally prestressed by FRP strips. Although several contributions can be found in the scientific literature about the evolution of the mechanical properties of epoxy adhesives depending on their curing conditions (see Czaderski et al., 2010 for a thorough report of the State-of-the-Art about this subject), specific studies dealing with the case of adhesive connecting FRP strips and concrete are still needed for understanding the influence of curing process on the mechanical behavior of FRP-concrete interface.

The present paper reports the results of a series of three pull-off tests carried out on FRP strips glued on concrete blocks and cured at the same temperature (namely approximately 90˚ C) and different duration, ranging from 15 to 25 minutes. A reference test is also carried out on a similar specimen cured at room temperature for three days.

The testing procedures and the measurement equipments are briefly described in the second section of the paper, along with the main mechanical properties of the materials utilized for the experimental specimens. In the third section, the results of the four above mentioned pull-off tests are reported and preliminarily discussed. An in-depth analysis of those results is then proposed in section four by identifying the shear-stress-slip interface relationships for all the tests with the aim of investigating how their key features depend on the heating duration. A more detailed description of the investigation including a further test series on axial tensile tests can be found in Czaderski et al., 2010.

2 EXPERIMENTAL TESTS

This section describes both the test layout and the measurement equipments. It finally reports the mechanical properties of the materials utilized for the tested specimens.

2.1 Test layout and devices

The layout of the pull-off tests reported in the present paper is represented in Figure 1, showing a 100-mm-wide and 1.2-mm-thick FRP strip glued to a concrete block and pulled-off.

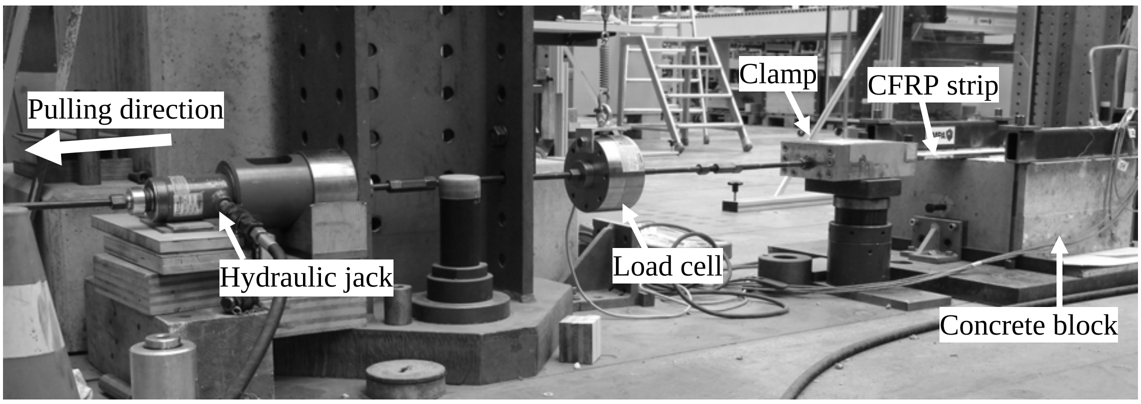

Figure 1: Test setup for pull-off bond tests.

Three out of the four tested specimens underwent an accelerated curing process, by means of heating through a purposely designed device. The heating duration ranged from 15 to 25 minutes and the pull-off test have been carried out after a cooling phase of 5 to 10 minutes after the end of the heat transfer. The pull-off force has been applied through a hydraulic jack in force control up to failure.

2.2 Testing and measurement equipments

Since the actual temperature developed inside the adhesive layer is a key parameter to be monitored during the curing phase and before and during the pull-off test, the tested specimens were equipped with sensors for measuring the temperature within both the adhesive layer and the heating elements. The measured average temperature inside the adhesive during the pull-off tests was in the range of 40 to 45°.

The full-field 3D displacements of the test specimen were measured during the experimental investigations with an optical image correlation measurement system (Gom, 2009). A description of the measurement system used can be found in Czaderski et al. (2010). The optical system has been also utilized for measuring the average thickness of adhesive for the four specimens. Due to the gluing process, the adhesive layer had not a uniform thickness but a “mountain” like shape. The mean thickness was between 3.65 and 3.8 mm. Finally, the force applied through the mentioned hydraulic jack has been measured by a load cell (Figure 1).

2.3 Mechanical properties of materials

Conventional concrete with an aggregate diameter ranging from 0 to 32 mm was used for all the specimens. At 28 days, a compressive cube strength $f_{c,cube}$ of 51.5 MPa was measured, whereas the splitting tensile strength f_{ct} was found to be 3.25 MPa. All the specimens were realized making use of a commercially available epoxy-based adhesive called S&P resin 220.

The carbon FRP strip had a thickness of 1.2 mm and a width of 100 mm with the mechanical properties listed in Table 1 according to the S&P declaration. The elasticity modulus was additionally determined before the bond tests in a loading test for each strip. The measured elasticity modulus of 174 GPa corresponded very well with the stated one, see Table 1.

Table 1: Mechanical properties of the CFRP strips according to the S&P certificate

Modulus of elasticity E_f [GPa]	**Tensile strength f_u** [MPa]	**Elongation at 2000 MPa ε_{2000}** [%]	**Width b_f** [mm]	**Thickness t_f** [mm]
173.9	2975	1.142	100	1.23

3 EXPERIMENTAL RESULTS

The results of the pull-off bond tests carried out on the four FRP-to-concrete specimens are given in Table 2 as a function of the heating duration before the test. In particular, the values of the maximum experimentally measured force F_u (or the force at initiation of debonding) are reported for the various tests along with the maximum interface slip and the observed failure mode. The characteristic stage “initiation of debonding” was defined as the decisive stage to determine the bond shear stress-slip relationship although the force can slightly increase afterwards. See the discussion on that topic in Czaderski et al. (2010). It can be observed that the specimens cured at an elevated temperature for 15 or 20 minutes exhibit significantly lower strengths and higher values of the maximum slip. Moreover, the specimens cured for 25 minutes had an even higher maximum force than the reference specimen cured at room temperature.

Table 2: Pull-off tests: results of the experiments (F_u=maximum force at failure or initiation of debonding, s_{max}=maximum slip at F_u at end of bond zone at loaded end)

Heating duration [min]	$\mathbf{F_u}$ [kN]	$\mathbf{s_{max}}$ [mm]	**Failure mode**
15	18.4	0.652	Adhesive
20	34.4	0.803	Mainly Adhesive
25	75.7	0.712	Concrete
3 days at room temp.	57.6	0.218	Concrete

Figure 2 shows the interfaces of the test specimens after failure. In the first two specimens (heated for 15 and 20 minutes, respectively) the failure was in the resin. In particular, only a very small part of concrete has been peeled away in the second test, while in the first one the failure did not involve at all the concrete substrate. On the contrary, the failure mode observed in the third specimen (i.e., cured for 25 minutes), was substantially similar to the one observed in the reference test. A significant layer of concrete has been peeled-off, meaning that the failure process completely developed within the concrete.

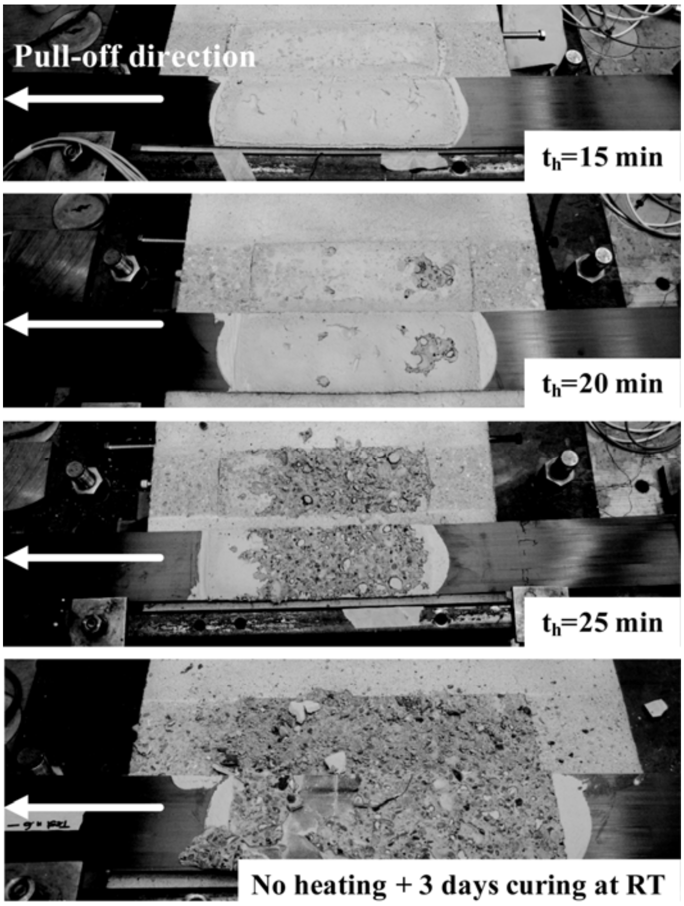

Figure 2: Pull-off tests at different curing durations: observed failure modes at the concrete-FRP interface

However, after 25 minutes curing at high temperature, the tested specimen did not completely behave like in the reference test. The pictures reported in Figure 2 show a deeper peeling phenomenon for the latter. Moreover, Figure 3 shows another behavioural difference between the two last specimens shown in Figure 2. It deals with the displacements measured at a given stage of the pull-off test and shows that the displacements observed on the specimen cured for 25 minute are, on the one hand, higher than those measured for the reference specimens.

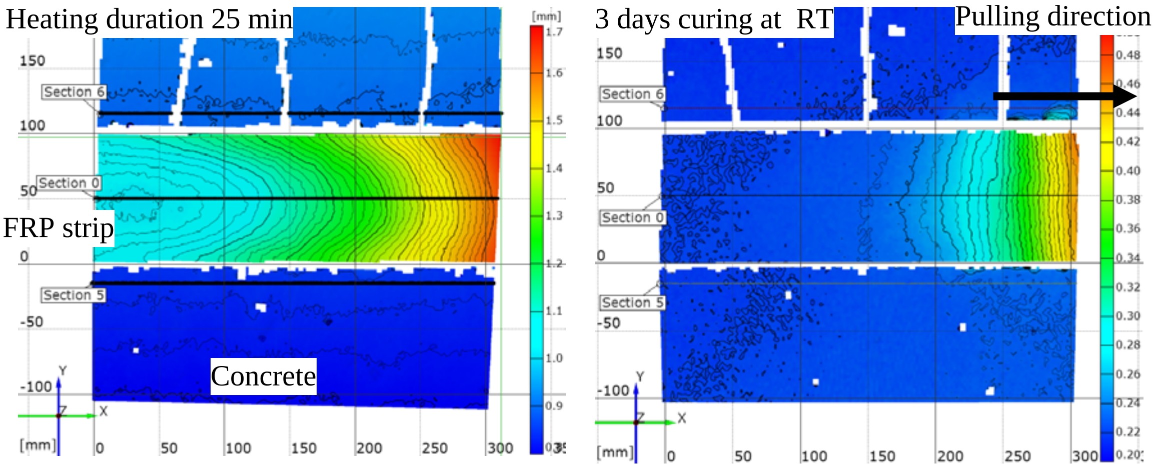

Figure 3: Measurement of displacements in x-direction of both the FRP strip and the concrete surface through the image correlation measurement system.

On the other hand, they are significantly non-uniform throughout the width of the strip (Figure 4), as a result of the differential level of curing actually achieved by the adhesive.

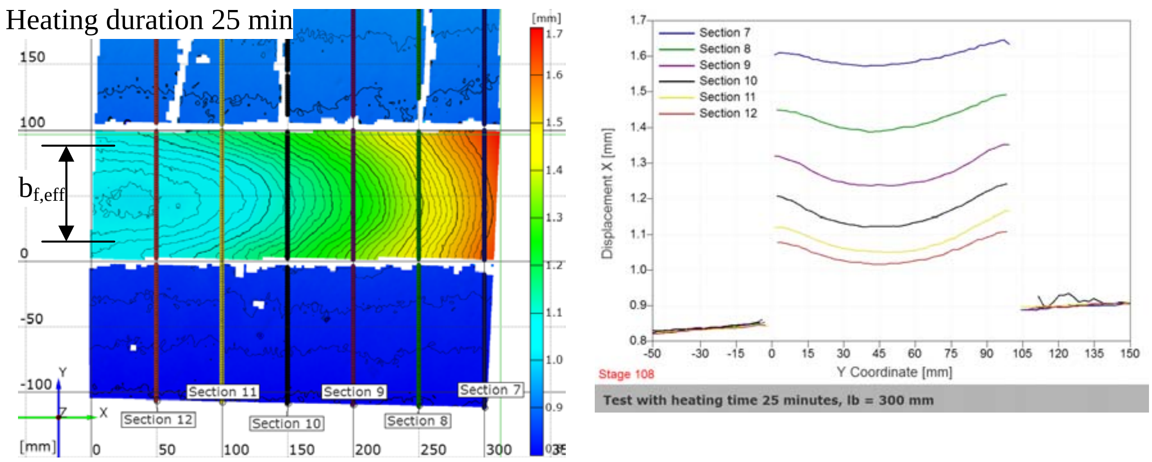

Figure 4: Displacements in x-direction, cross-section through the width of the strip at failure

4 ANALYSIS OF THE EXPERIMENTAL RESULTS

The results of the pull-out tests can be utilized for identifying the bilinear shear-stress-interface-slip relationship represented in Figure 5.

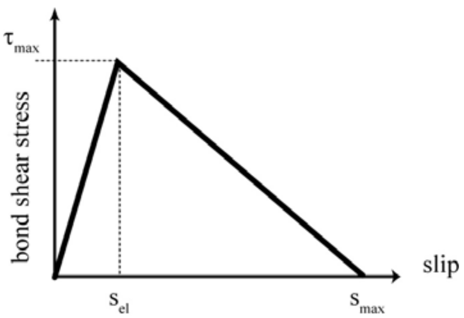

Figure 5: General bi-linear relationship for the FRP-to-concrete interface

Three mechanical parameters completely describe the above relationship between the shear stresses τ and the interface slips s:

- the maximum shear strength τ_{max};
- the interface slip s_{el} at the end of the elastic branch of the interface relationship;
- the interface slip s_{max} at debonding, which has been measured experimentally and reported in Table 2 for the four tests.

Since the displacement field of both the FRP strip and the concrete surface have been monitored during the tests, the corresponding experimental values of the interface slips can be evaluated by the difference between the displacements of the CFRP strip (sections 0 in Figure 3) and the concrete surface (sections 5 and 6 in Figure 3) beside the strip.

The maximum observed displacement at the last stage before failure or initiation of debonding can be assumed as s_{max}. In particular, three load stages were considered in the present study at three different load levels $F^{(i)}$ (i=1,2,3). The first force level $F^{(1)}$ was chosen for every test among the very first stages in the loading process. On the contrary, the third level $F^{(3)}$ was supposed to be the one at the onset of debonding. The force level $F^{(2)}$ was simply taken as an intermediate one, see Figure 7. A bilinear relationship like the one represented in Figure 5 has been identified for the four tests by means of an optimization procedure described in Czaderski et al. (2010), inspired at the so-called inverse identification method discussed in Faella et al. (2008). Figure 6 represents the four τ-s relationship identified for the various tests. In Figure 7, also a comparison between the measured and calibrated slips is given. Generally, a good agreement can be observed. Furthermore, in this figure, the effect of different curing durations on both the displacements and the transfer length can be clearly seen. The total bonding length has been used for transferring the load in the test with 25 minutes, while only approximately one half has been needed in the reference test. This can explain the fact that a larger failure load has been observed in the former test.

The bilinear interface relationships corresponding to the above calibrations have been represented in Figure 6 with the aim of demonstrating the effect of accelerated curing on the mechanical properties of the FRP-to-concrete interface. The relationships derived from the tests with 15 minutes heating duration and the test with 20 minutes heating duration are characterized by a very low stiffness and no decreasing branch, as the resin is not fully cured. On the contrary, a significantly higher value of the stiffness is observed in the tests with 25 minutes heating duration, but the stiffness is still clearly lower compared to the reference tests. Also the value of the strength τ_{max} is in this test lower compared to the reference tests. The lower stiffness, also testified by the higher values of interface slips represented in Figure 7 can be justified, on the one hand, by the incomplete curing and, on the other hand, by the fact that the temperature in the epoxy layer was still higher than the corresponding room one during the reference test.

Variable slips have been observed throughout the width of the strip for the bonded length. The 1D model utilized for identifying the interface relationship cannot simulate this effect. As a matter of fact, the resin cured more in the middle part than close to the lateral edges, Figure 4. Thus, a further identification has been carried out for the test specimen with 25 minutes heating duration by considering a reduced value $b_{f,eff}$ of the width of the strip for taking into account of the inhomogeneous curing of resin. The result is described by the dashed line in Figure 6 which is closer to the reference curve, especially in terms of shear strength.

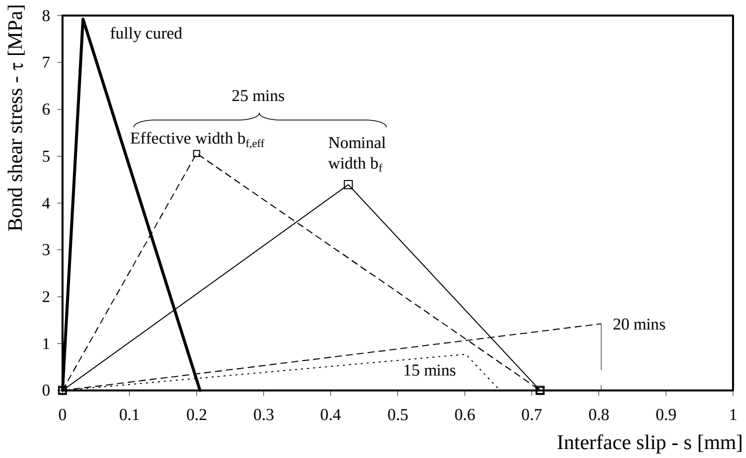

Figure 6: Pull-off bond tests: resulting interface relationships between shear stresses and slips

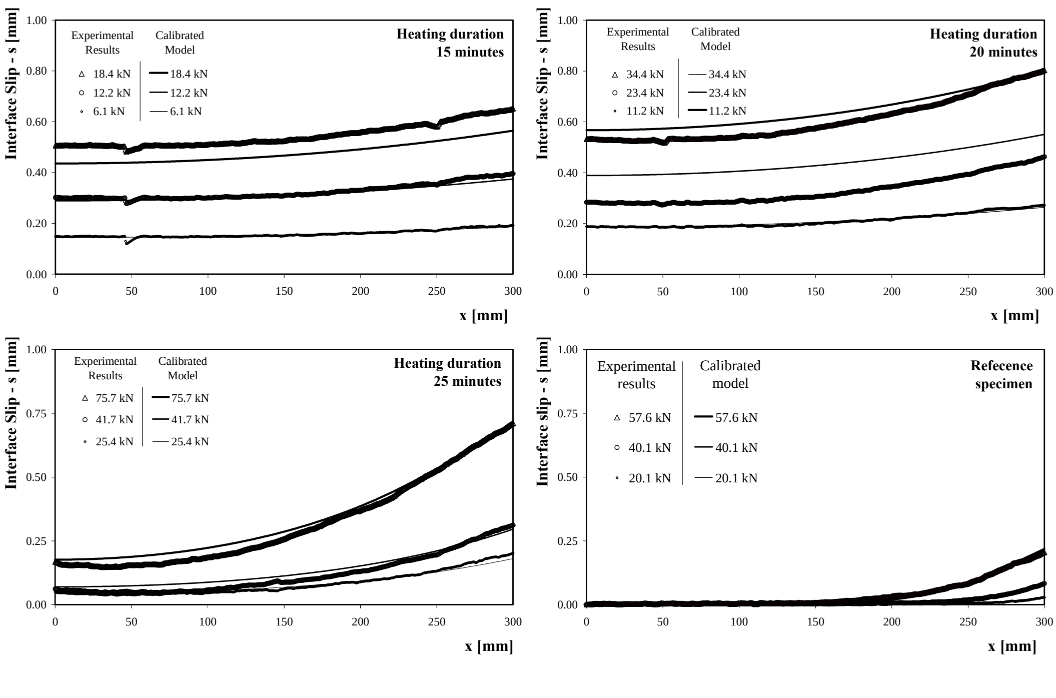

Figure 7: Interface slips at three different load levels: experimental measures and numerical simulation

5 CONCLUSIONS

The pull-off tests at 90°C curing temperature showed that 15 to 20 minutes of curing resulted in a failure mainly in the adhesive. At 25 minutes curing duration (at the same temperature) led to the same failure mode observed in the fully cured specimen. In both cases, failure developed throughout the concrete substrate. The displacements measured by using an optical image correlation system delivered the slips and transfer lengths. The test with 25 minutes heating duration used the total bond length for transferring the load compared to the reference test, which used only approximately the half of the bond length. This might explain the fact that the former specimen failed at a load larger than the one observed in the reference test. A bilinear shear-stress-interface-slip relationship has been analytically identified for each test with the aim of pointing out the influence of curing duration (and temperature) on the key mechanical properties of the FRP-to-concrete interface. Larger interface slips and, consequently, a significantly lower stiffness of the elastic branch of the interface relationship have been observed in the cases of short heating duration.

6 ACKNOWLEDGEMENTS

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