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THE GRADIENT ANCHORAGE METHOD FOR PRESTRESSED CFRP STRIPS: FROM THE DEVELOPMENT TO THE STRENGTHENING OF AN 18 M LONG BRIDGE GIRDER

Matteo BREVEGLIERI[1]*, Christoph CZADERSKI[1], Julien MICHELS[2]

Abstract

The external bonding of carbon fiber-reinforced polymer (CFRP) strips by two-component epoxy adhesive on the concrete surfaces of buildings and bridges is a retrofitting method accepted worldwide. The gradient anchorage (GA) is an anchoring method especially developed to anchor prestressed CFRP strips to concrete elements without a need for mechanical clamping after the installation phase. This method takes advantage of the adhesives property to undergo accelerated curing when heated. The results of more than fifteen years of research on the development of the gradient anchorage at the Swiss Federal Laboratories for Materials Science and Technology (Empa) are presented in this paper. The basic principles and application steps are explained, and the main results starting from the development of the technique up to the testing of real scale girders are described, and the new challenges posed by this innovative system are highlighted. The gradient anchorage is a valid alternative to a mechanically anchored system for prestressed FRP (P-FRP).

Address

[1] Empa – Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland
[2] re-fer AG, Brunnen, Switzerland

* ***Corresponding author:*** matteo.breveglieri@empa.ch

Key words

- CFRP,
- Concrete strengthening,
- Prestressed FRP,
- Gradient anchorage.

1 INTRODUCTION

The use of composite materials for structural strengthening is nowadays considered a practical and ordinary solution to increase load-carrying capacity and extend the life of reinforced concrete structures. As a result of more than two decades of international research and pioneering applications (Czaderski and Meier 2018), it is possible to deliver strengthening solutions based on the use of FRP with a good level of safety. The advantages are well known; composite materials used for structural strengthening, such as, for example, Carbon Fiber Reinforced Polymers (CFRP) have excellent mechanical properties, i.e., a high ultimate tensile strength and modulus of elasticity. Nevertheless, when unstressed CFRP is bonded to a concrete surface, the strengthening material has a tendency to debond at a relatively low-stress level, because of the concrete's low tensile strength. In order to reach high tensile stresses and hence better exploit the properties of the material, prestressing is recommended.

The first tests on prestressed CFRP strips date back to the early 1990s. (Triantafillou et al., 1992) established the maximum achievable prestressing force in FRP sheets without using end anchorages. In (Deuring, 1993), mechanical anchorages were used to transfer the prestressing forces from the composite to the concrete substrate. Subsequently, several researchers dedicated their work to develop applications of bonded prestressed FRP; more details can be found in (Motavalli et al., 2011; Michels et al., 2016a). The advantages of using prestressed FRP (P-FRP) can be compared to those of conventional prestressed concrete structures. The durability and serviceability of the structural elements are improved; the application of prestressing force can reduce the existing deflections and crack widths or even close existing cracks. The stiffness of the concrete element is significantly increased, unlike in the case of unstressed FRP. Fig.1 shows how the cracked phase initiation (M_{cr}) and the steel yielding (M_y) occurs at higher loads in case of the prestressed CFRP, which implies a significant reduction of the deflection in the serviceability limit state; the final strengthening effect is clearly greater

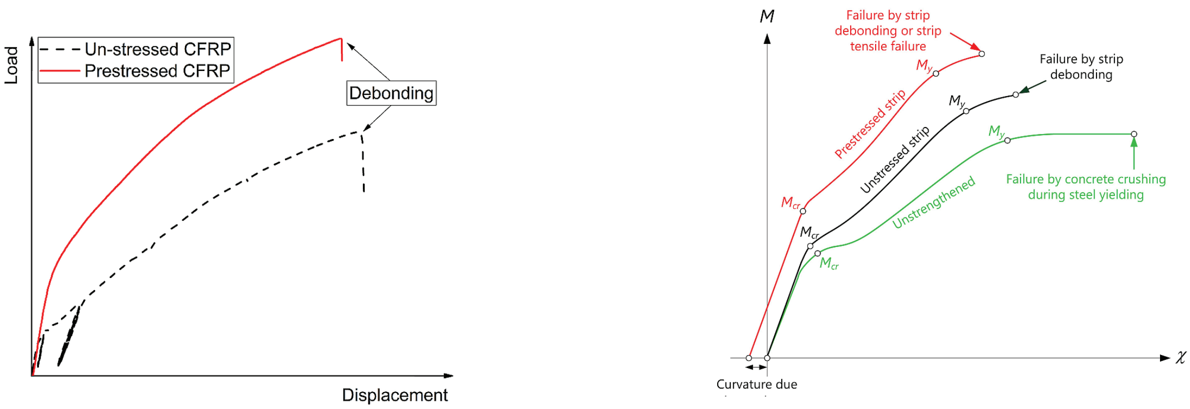


Fig. 1 *Advantages of using prestressed CFRP for flexural strengthening: (a)Load-displacement and (b) Moment curvature relationship*

(Fig.1a). (Meier, 2007) pointed out the importance of the stiffness of the strengthened member by affirming that one important reason for the poor efficiency is that many strengthening tasks are stiffness and not strength controlled. Fig.1b shows a moment-curvature comparison between un-stressed and prestressed sections; M_{cr}, M_y and M_u increase due to the effect of the prestressing. The higher ultimate moment M_u, lead to higher stress in the composite, which in the case of P-FRP, can also reach tensile failure. This consideration explains how it is possible to take advantage of the material's full strength, unlike the case of un-stressed FRP, where debonding occurs at 20-30% of the FRP's strength (Motavalli et al., 2011). The fatigue resistance is also increased since the stress range in the internal steel rebars decreases with the application of the prestressing.

In a similar way to non-prestressed systems, epoxy adhesives are used to bond the P-FRP to the concrete substrate. Nevertheless, at the strip ends, a special anchorage system is required to transfer the forces from the EBR to the concrete surface in order to avoid premature debonding during the release of the prestressing force (Triantafillou et al., 1992; Czaderski, 2012). Most of the available anchorage systems on the market make use of metallic elements; however, non-metallic anchors are also available. (Kim et al., 2008) present a study that considers the replacement of the steel parts with CFRP U-wraps. A recent review of the type of anchors for CFRP plates that contains information on their commercial availability can be found in (Mohee et at., 2016). One of the simplest metallic anchorages is represented in Fig. 2 and consists of a plate that applies compression to the strip surface. All the metallic mechanical systems must be permanently fixed to the concrete with screws or dowels. The anchorage system requires a minimum of adhesive curing, which implies that the prestress force at the ends is generally fully released one day after the installation (Michels et al., 2016a).

One possible existing drawback to the use of prestressed FRP is the reduction of ductility, which is directly related to the high increase in stiffness and to elastic behavior of the strengthening material (Fig. 1b). If the ductility demand surpasses the demand of the element's strength, this drawback can be overcome by adopting an unbonded strengthening solution. In a prestressed-unbonded system, the FRP is mechanically fixed only at the strip ends using mechanical anchorages. Due to the lack of bond along the FRP's length, higher deflection can be obtained at the ultimate load, but the increase in strength is lower when compared to the bonded P-FRP; wider cracks are also expected in the unbonded configuration. More information on unbonded P-FRP and the calculation strategy can be found in (Harmanci et al., 2016).

The prestressing procedure can be performed using indirect or direct prestressing methods (Michels et al., 2016a). In the indirect method (Fig. 3a), the FRP is bonded to a previously cambered element so as to induce a negative curvature. The release of the cambering action results in the loading of the FRP and the development of the pre-stressing effect on the structure. In the direct method, the strips or sheets are directly prestressed using an external reaction structure (Fig. 3b) or the structure itself (Fig. 3c) and are later bonded to the structure. The most advantageous method for an actual application is the direct method, which uses the structure itself as a reaction structure.

In this paper, the basic principles of the gradient anchorage and the different development steps from a small-scale up to real scale applications are explained. The gradient anchorage method is an anchoring technique for prestressed externally bonded CFRP strips. This technique is based on a sequential step-wise reduction of the stress at both ends of the CFRP strip. By following this procedure, the total prestressing force is distributed over several segments. This is made possible by exploiting the ability of the epoxy adhesive to undergo accelerated curing when heated (Czaderski et al., 2012).

Fig. 2 *Example of installed anchors for prestressed CFRP (Photo from S&P Clever Reinforcement Company AG)*

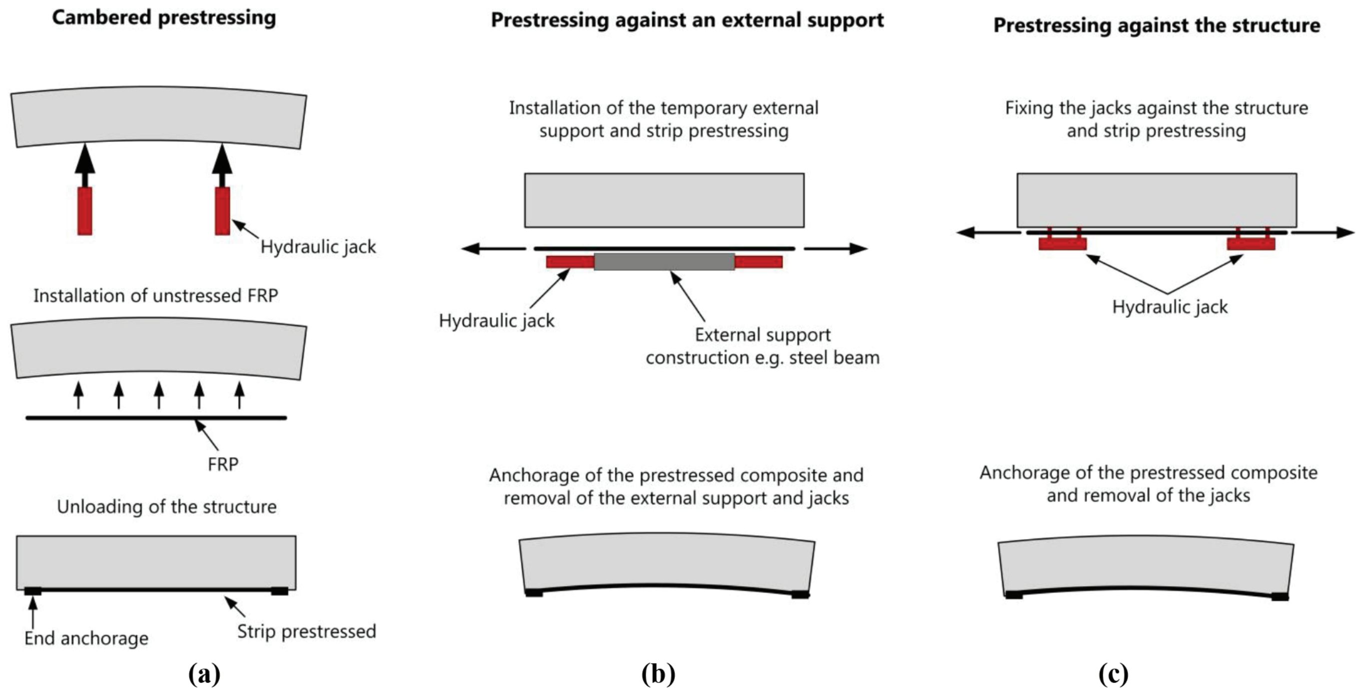


Fig. 3 *Type of prestressing strategies using FRP on existing RC structures (from (Michels et al., 2016a))*

2 THE GRADIENT ANCHORAGE (GA)

After the first tests on prestressed CFRP strips that were anchored using mechanically fastened plates (Deuring, 1993) at the Swiss Federal Laboratories for Materials Science and Technology (Empa) under the supervision of Prof. Urs Meier, an innovative idea to anchor prestressed CFRP laminates was developed, i.e., the Gradient Anchorage (GA) (Stöcklin and Meier, 2001, 2003; Meier and Stöcklin, 2005; Meier, U.S. Patent 6,464,811 B1). What differentiates the Gradient Anchorage from other anchorage systems is the absence of mechanical anchors after installation. The absence of mechanical parts eliminates the problem of corrosion in the anchorages, and it also has better aesthetics.

2.1 GA strengthening procedure

The surface preparation of the concrete substrate (surface grinding and cleaning) is required, as is done for the application of unstressed strips, before the different components of the anchorage devices are installed. The current version of the hardware for the GA installations has been significantly upgraded during a R&D project in collaboration with the Swiss company S&P Clever Reinforcement Company AG (Czaderski et al., 2012; Michels et al., 2012, 2013); unlike the first prototype, the system has become easier to install on site. The main parts of the GA are presented in Fig.4; additional information can be found in (Michels et al., 2013; Correia et al., 2015).

Once all the components are in place, the strips are pulled simultaneously at both ends using hydraulic jacks. The desired deformation (i.e. the prestressing force) can be measured by installing strain gauges, using deformeters or, on the construction site, by measuring the increase in length between predefined marks on concrete and the FRP. Fig. 5 displays the different phases and the basic concept of this anchorage system. After the CFRP has been loaded to the desired level of prestressing, the first sector of length Δl_1 is heated with a special device (Fig. 4). During this time period, the adhesive undergoes ac-

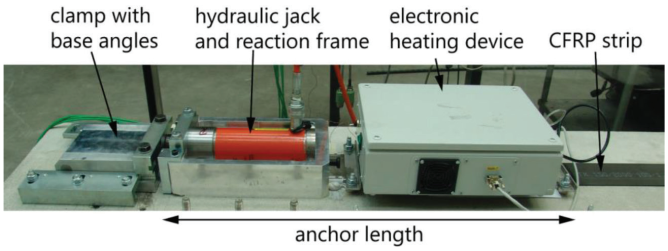


Fig. 4 *The main parts of the gradient anchorage (GA) for the installation of prestressed CFRP strips*

celerated curing up to the point where it reaches an adequate strength to endure the force ΔF_1, which is a part of the prestressed force F_P. At this stage, the force exerted by the jack can be reduced to the value F_P - ΔF_i. The procedure described has to be repeated for i_{th}-number of sectors until reaching zero force at the end of the strip. In Fig. 5, the shear stress in the gradient τ_p is also displayed; it represents the average shear stress and is calculated as the prestressing force divided by the area of the GA. Fig. 6 displays the heating and the prestress force release procedures for the application of a 4-segments gradient anchorage. The measured temperature reached in the epoxy adhesive approximately ranges between 90 and 110 °C. The time interval for each step is 35 minutes, and the entire phase takes approximately 3.5 hours. If the preparation of the strip, the installation of the prestressing device, and their removal are taken into account, it is possible to estimate the application time for one strip as taking approximately 5h. Due to the fact that only the strip ends undergo accelerated curing, it is necessary to allow the epoxy adhesive in the free length to cure at room temperature in order to reach an adequate strength before additional loading is applied. In the case of an incorrect design of the value ΔF_1 or the low strength of the epoxy adhesive due to an unsuccessful accelerated curing procedure, premature debonding of the strip might occur upon the release of force ΔF_i as explained in the following sections.

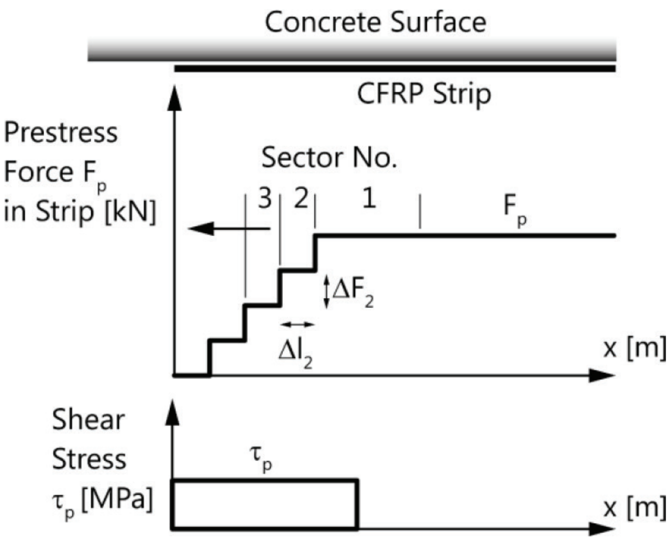


Fig. 5 *Gradient anchorage principle, and average shear stress τp*

3 ROOM TEMPERATURE AND ACCELERATED CURING OF THE EPOXY ADHESIVE FOR STRUCTURAL APPLICATIONS

To correctly design a Gradient Anchorage it is important to have a good knowledge of how adhesive properties develop over time at different temperatures. Several studies have been dedicated to understanding the adhesive behavior, the correct curing conditions, and the lap-shear strength of partially cured CFRP adhesives bonded to concrete (Michels et al., 2012; Czaderski et al., 2012; Czaderski 2012). Cold-cured (i.e., room temperature curing) epoxy-based adhesives used for FRP strengthening applications develop most of their strength during the first three days. It is known that the workability of this type of adhesive and its curing time is affected by the ambient temperature, so that relevant differences have to be expected in cases of winter or summer applications. Furthermore, the ability to cure under high temperatures of certain types of structural adhesives was known well before the first tests on the gradient anchorage took place (Matsui, 1990).

(Michels et al., 2013) evaluated the short-term tensile strength of epoxy adhesive by simulating the typical GA curing procedure. Dog-bone specimens were firstly heated and then tested at room temperature after 10 minutes of cooling. In comparison to reference specimens cured for 3 days at room temperature, the accelerated curing provided a lower tensile strength and modulus of elasticity. In addition to previous tests, an accurate comparative analysis of the tensile strength of commercially available cold-curing epoxy adhesive was performed by (Michels et al., 2016b). The results showed that the axial tensile strength and stiffness of specimens cured at high temperature and tested after 3 days were lower when compared to specimens cured at room temperature (3 days of curing). This was justified by the augmented material porosity developed during the accelerated curing process. The authors observed that the higher porosity could facilitate the penetration of deterioration agents and might affect the durability of strengthened structures. It was also demonstrated that the accelerated curing process has the ability to slightly increase the glass transition temperature (T_g) due to the higher cross-linking of the polymer chains (Michels et al., 2015). This observation can be slightly beneficial for FRP use at an elevated ambient temperature or when it is exposed to radiative heating (i.e., solar radiation). The heating procedure and the prestressing action had negligible effects on the mechanical properties on the CFRP strips (Michels et al., 2013).

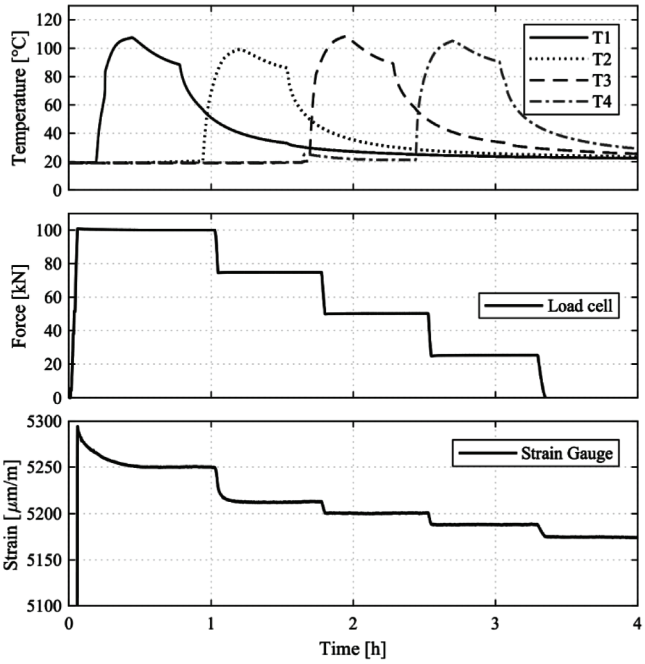


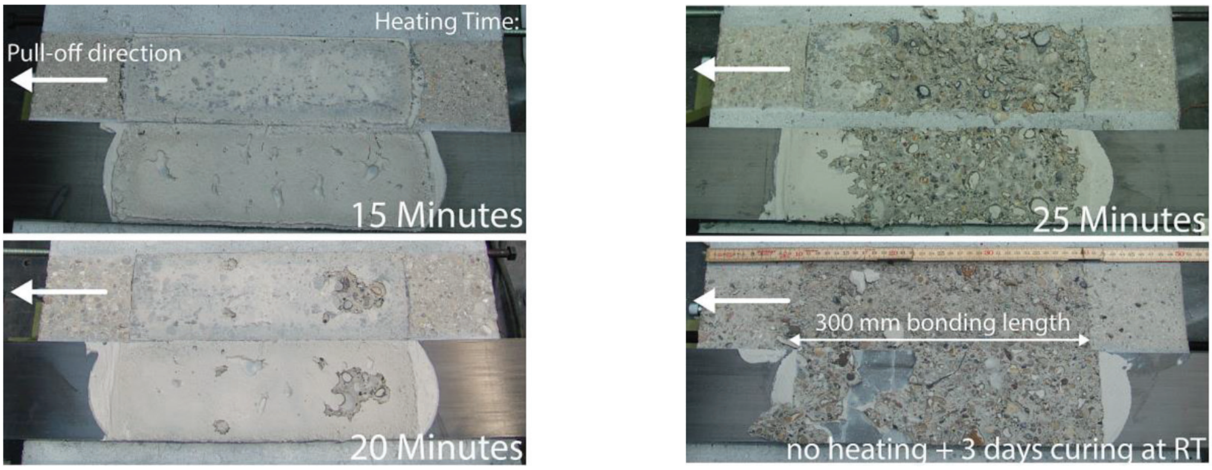
Fig. 6 *Development of the measured temperature of the epoxy adhesive in each sector; stepwise decrease of force at the strip end; loss of pre-strain during the GA application*

(Czaderski et al., 2012) showed how an accelerated curing time can affect the type of failure and consequently the strength of the lap-shear test (Fig. 7). Specimens heated for less than 25 minutes exhibited failure in the adhesive and a low bond strength. Meanwhile, for a curing time equal to 25 minutes, the failure occurred in concrete; this implies that an adequate bond strength capable of transferring the force to the concrete had been achieved. It was also highlighted that a partially cured adhesive (25 min); can lead to a temporary higher end-anchorage strength compared to the fully cured adhesive, this was justified by the lower degree of stiffness and the higher interfacial energy of partially cured adhesive (Fig. 7b).

4 LAP-SHEAR AND PRESTRESS FORCE RELEASE TESTS

A gradient anchorage has a complex behavior; its mechanical strength is a function of the level of pre-stress, temperature, curing time, bond length (l_i), and concrete strength. The GA optimization criteria are met when the anchorage capacity is maximized and the total time for the application is reduced as much as possible. In order to have a better understanding of the GA method and in view of optimizing its mechanical behavior, a single sector of length Δl_i has been studied. Two main aspects are of interest: (1) the anchorage resistance due to the release of the prestressing force, in order to estimate the maximum transferable release force to a bonded segment, and (2) the residual anchorage resistance in order to estimate the increase in maximum force in addition to the prestressing force F_p.

Similarly to (Czaderski el al., 2012), lap-shear tests have been performed by (Michels et al., 2012) to compare different designs of the heating devices. The results shown in Fig. 8a confirmed the previously presented findings, i.e., a higher anchorage strength, characterized by softer force-slip behavior, was obtained with a partially cured epoxy adhesive. In addition in (Michels et al., 2012; Czaderski, 2012), the debonding force during the releasing of the prestress force was evaluated during a so-called “prestress force release test” (Fig. 8b). In this test configuration (Fig. 9), the prestressing force is applied a)



b)

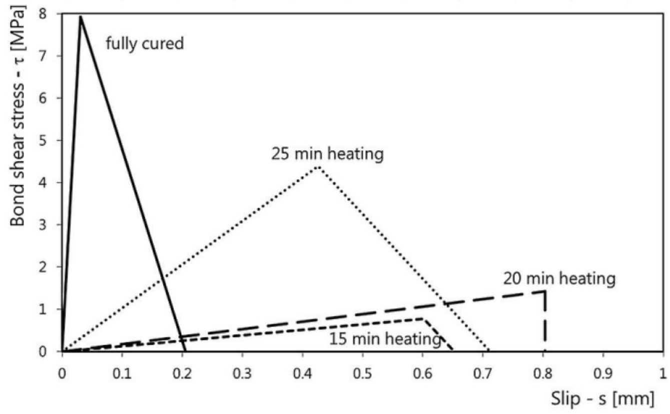


Fig. 7 *(a) Comparison of the failure mode of the lap-shear bond test for different curing procedures, (b) local bond shear-slip relationship calculated from the experimental results (adapted from (Czaderski el al., 2012))*

to both sides and the CFRP is bonded to the concrete (Step 1). Once the adhesive is cured (or partially cured using the accelerated heating), the force at one end is released up to the failure of the bonded system (Step 2); the difference between the initial prestressing force F_p and the F_1 force at which failure occurs, represents the force that is transferred to the concrete block, i.e., the debonding force. From this test, similar observations to the lap-shear test can be made. It has been observed that 25 min of curing time is a suitable time to develop sufficient shear strength to initiate a complete failure in the concrete substrate in both the lap-shear and prestress force-release tests. The higher bond strength showed by the lap-shear and the release tests in Fig. 8 is the result of higher interfacial energy and the higher effective length that characterizes the partially cured epoxy. In fact, as a consequence of the lower stiffness of the local bond-slip behavior (Fig. 7b), the effective bond length increases, which might allow the shear stress to transfer along the entire length of the bonded sector. During the prestress force release test, this observation represents an advantage since the redistribution of the bond stress maximizes the

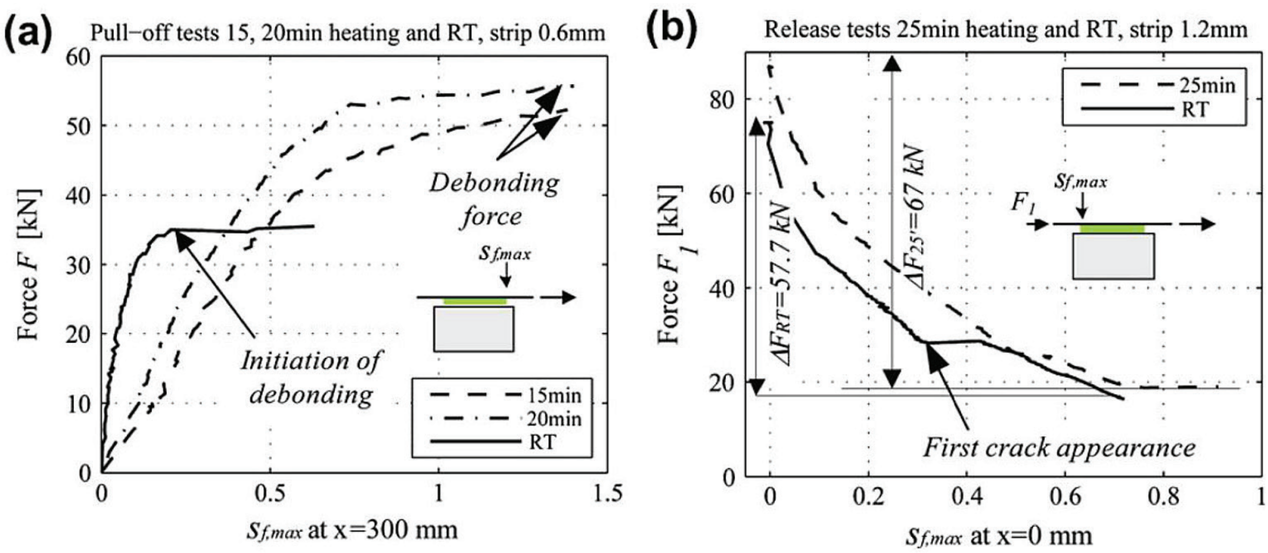


Fig. 8 *Force-slip comparison between a fully cured epoxy adhesive (room temperature - RT) and partially cured adhesive (15 min and 20 min). (a) Lap-shear tests, (b) Prestress Force release tests (from Michels et al., 2012)*

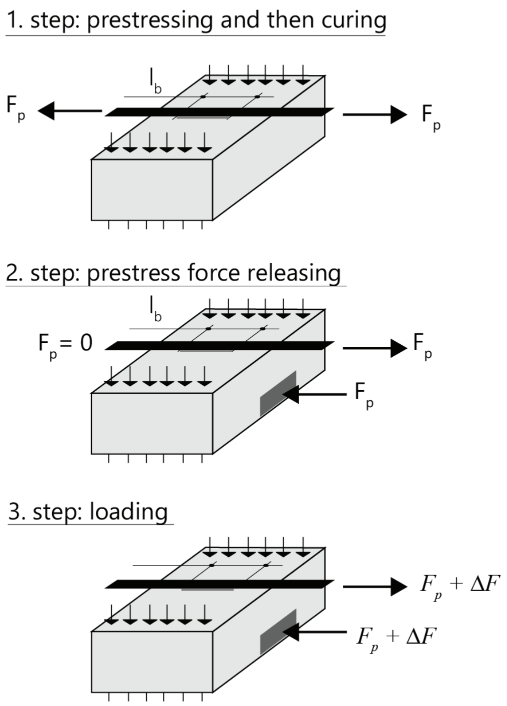


Fig. 9 *Test setup for the prestress force release test (Steps 1 and 2), Step 3 is carried out to evaluate the residual strength of the GA (from Motavalli et al., 2011)*

efficiency of the anchorage's resistance. It needs to be stressed that this temporary increase in strength is connected to the softer behavior of partially cured epoxies; after one hour the strength typically starts to decrease. For fully cured epoxies the stiffness and the anchorage strength of the bonded joints reach a similar value for both the accelerated and room temperature curing.

(Czaderski, 2012) evaluated the residual strength of a GA anchorage if Step 2 does not lead to failure. The tests were first carried out first by releasing the full force on one side without complete failure (Step 2) and then by increasing the force on the other side up to failure (Step 3 in Fig. 9). By adopting this mixed release/lap-shear test, it was possible to study the interaction between the two mechanisms. The test was monitored using a full-field 3D digital image correlation (DIC) measurement system, which was able to measure the in-plane and out of plane displacement of the strip. Fig 10 shows the bond mechanism for the pure prestress force release (a), mixed lap-shear/release (b), and simple lap-shear (c) tests from the side. By comparing the different crack patterns in Fig. 10, it is possible to see how the release mechanism affects the strength of the residual anchorage. The release of the prestressing might damage the bond interface and lead to the crack initiation in the concrete. Both shear and normal displacements occur at the interface. In a prestress force release test, the normal displacement (i.e., the separation) is crucial, whereas in a simple lap-shear test, the longitudinal displacement (i.e., the slip) is decisive. In general, it was observed that a large release of prestress force can be associated with a small lap-shear anchorage resistance. Similar observations have been confirmed in an experimental and numerical study performed by (Michels et al., 2014). (Czaderski, 2012) explained the reduction of the anchorage pulling resistance using a simplified fracture energy-based approach, founded on the idea that the available fracture energy is reduced by the release mechanism. Two cases can be discerned: (1) For long bond lengths, the release phase does not affect the residual pulling resistance, and the anchorage strength can be calculated as for unstressed CFRP; the total force at failure is the sum of the anchorage's pulling resistance and the prestressing force. (2) For short bond lengths, the release of the prestressing force interacts with the pulling on the other side, and the anchorage's strength is reduced (see Fig. 10b).

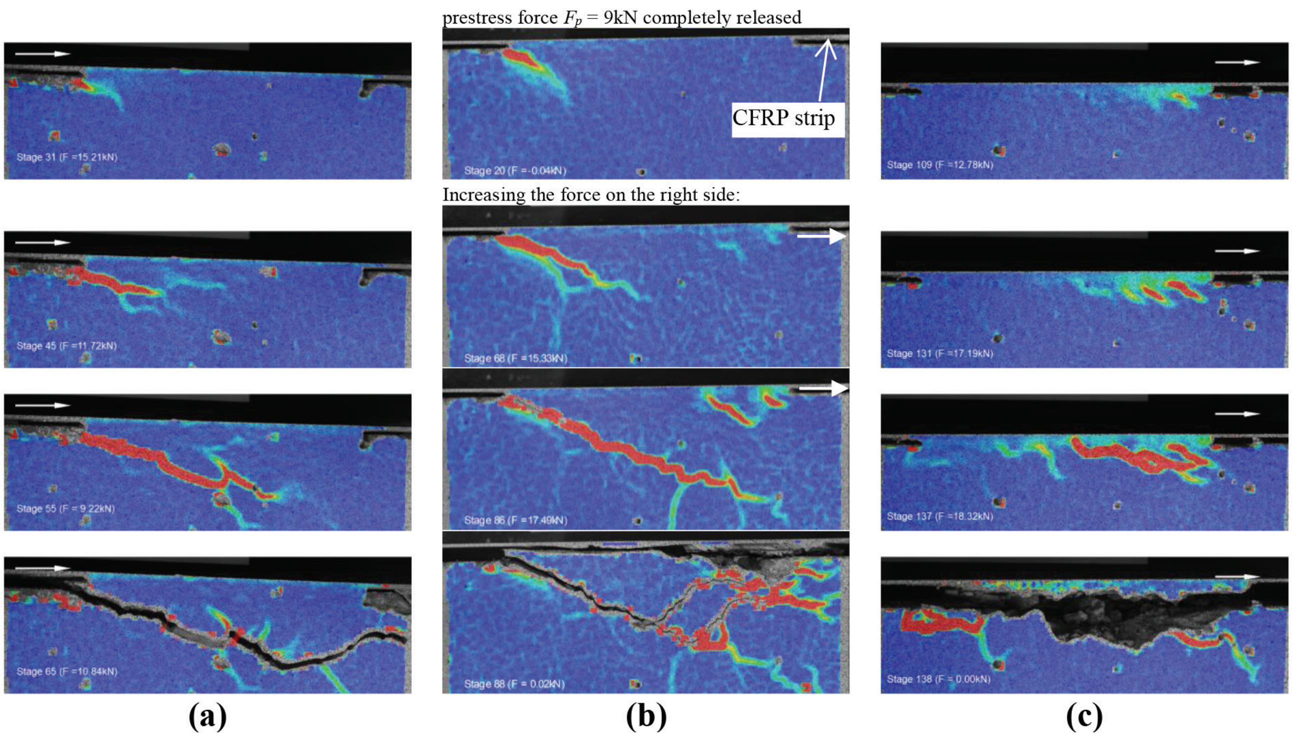


Fig. 10 *Bond mechanism measured with DIC from the side. a) A pure prestress force release test (prestress force on the left side decreases), b) a mixed lap-shear/ prestress force release test and, c) a simple lap-shear test (force on the right side increases), adapted from (Michels et al. 2014)*

5 BEAM TESTS

The experimental tests on RC beams that are strengthened using the gradient anchorage method have not been confined to the Empa laboratories; the research has been extended to collaborations with the University of Minho (Portugal) and the University of Lodz (Poland).

The first tests at Empa showed the effectiveness of the gradient anchorage on RC beams with spans of 2.1 m (Stöcklin and Meier, 2001, 2003) and 6.0 m (Meier and Stöcklin, 2005). In the latter work, it was possible to achieve the tensile failure of the CFRP when a CFRP thickness of 0.6 mm was used. Some critical aspects were later highlighted by (Aram et al., 2008); P-FRP strengthened beams presented a similar or even lower increase in the load-carrying capacity when compared to the unstressed CFRP. Due to the short shear span of the beams tested, flexural/shear cracks formed in the area of the gradient anchor's length. This result implies that in addition to the initial shear stress generated by GA method (τ_p, see Fig. 5), the shear stresses at the FRP-concrete interface resulting from the change in tensile force along the FRP due to the additional load need to be considered.

Subsequently, two reinforced concrete beams were strengthened using prestressed unbonded CFRP (Czaderski, 2012); the strip ends were anchored over a length of 300 mm using a gradient anchorage. At each step, the reduction in the prestressing force was 12 kN, the difference between the two beams was the level of prestressing, 36 and 24 kN. It was observed that for such configurations, premature debonding occurred as soon the resistance of the end anchorage was reached. The test purpose was to simulate a realistic end-anchorage strength testing of the GA. In term of the anchorage resistance, the beam test was in agreement with the lap shear test, showing lower resistance for the highest prestressing level.

(Kotynia, et al., 2011) proved that a gradient anchorage can withstand fatigue loading; FRP debonding was observed after the fracture in the steel longitudinal reinforcement. A fatigue loading test (Slab 10, Table 1) was also performed by (Gallego et al., 2018); unlike (Kotynia et al., 2011), the load was lower and a fracture of the internal rebars did not occur; nevertheless excellent fatigue resistance of the GA under the effect of the elevated operating adhesive temperature of 50°C was also highlighted. After the fatigue test, the residual bearing capacity was even higher than that of the reference slab (Slab 9). (Michels et al., 2013) presented test results on the efficiency of the GA method, which showed a strain in the CFRP at the ultimate load, near to the tensile failure.

(Correia et al., 2015) compared the performance of the GA and mechanical anchorage (MA) systems (similar, to that shown in Fig, 2) during static loading; the results showed that the ultimate load-carrying capacity of the GA beams was lower than when MA was used. Debonding failure occurred in most of the beams at one of the extremities and then propagated to the middle of the slab. Unlike in a GA, in an MA as debonding propagates and reaches the end anchors, the CFRP works as in an unbonded configuration, and the load-carrying capacity is determined by the loss of adhesion between the CFRP and the steel plates or the tensile strength of the laminate.

The relevant data on beams strengthened with GA available in the literature have been collected in Table 1. In this overview the following information is reported: beam length (L) and cross-section (b and h), number and diameters of the longitudinal bars, number and cross-section of the CFRP strip ($t_f b_f$), prestressing force (F_p), length of the GA ($l_{b,GA}$), average shear stress in the gradient (calculated as $\tau_p = Fp/l_{b,GA} \cdot b_f$), increase in the ultimate load in comparison to the unstrengthened reference specimen (ΔF), efficiency of the CFRP strengthening ($\epsilon_{f,max}/\epsilon_{fu}$), strain at debonding/failure ($\epsilon_{f,max}$), ultimate tensile strain (ϵ_{fu}) and type of failure. All the CFRP strips used had a modulus of elasticity in the range of 158-170 GPa; the concrete had moderately high compressive strength and an approximate range of 45-60 MPa, with the exception of (Correia et al., 2017), in which the concrete's compressive strength was lower (28 MPa). The two beams tested by Czaderski (2012) are not reported in the table, since they do not represent an actual strengthening application but the simulation of an end anchorage test. In a similar way since it was not possible to estimate the effectiveness of the GA in a fatigue test that failed due to the rupture of the longitudinal steel bars, the beams tested by (Kotynia et al., 2011) were not included in the table. In terms of efficiency, it has been demonstrated that a higher increase in cracking, yielding and ultimate load can be obtained. An average efficiency ratio ($\epsilon_{f,max}/\epsilon_{fu}$) of 0.67 demonstrates that the GA can be a reasonable alternative to the MA. It has been shown that the GA works well as an anchor method for prestressed strips. The design of a GA system, besides the curing condition and level of prestress, requires particular attention to the length and position of the GA sector. The latter should be located in an uncracked zone. However, this is not always possible due to specimen's geometry and the length of the GA itself. As previously explained for (Aram et al, 2008), additional shear stress limitations due to external loading are needed in such a case. It is less likely that the development of a crack pattern reaches the anchorage zone in slender beams in comparison to beams with a low span/depth ratio (Correia el al., 2015). As typically for bonded systems, the GA is sensitive to the concrete strength. Therefore, this parameter needs to be taken into account in the evaluation of the ultimate strength; it needs to be highlighted that the GA has been mainly tested on RC beams with high concrete compressive strength. More information on the design of the gradient anchorage can be found in (Czaderski, 2012). Furthermore, the service temperature of the strengthened structure is very critical as creep and subsequent failure can occur at elevated temperatures, what was observed at Empa in several experiments. Recommendations for limitations of the service temperature considering the sustained load and CFRP strip prestress are under preparation at Empa.

6 LARGE-SCALE BRIDGE GIRDER TESTS

The application of the gradient anchorage method was also tested on large-scale girders. In (Czaderski et al. 2007), 17-m-long prestressed bridge girders (Fig. 11a), taken from a 40-year-old Swiss bridge were tested at Empa. One girder was strengthened using the gradient anchorage method with six prestressed CFRP strips (1.2 x 50 mm²), which were prestressed with 1000 MPa (~ 60kN), as displayed in Fig. 11b. Fig. 11c shows one of the first prototypes of combined prestressing and heating devices developed in the year 2006. The gradient's total length was 0.8 m, and the average stress τ_p was equal to 1.5 MPa. The first and the following five heating sectors were 0.3 and 0.1 m long, respectively. The increase in load-carrying capacity compared with the unstrengthened girder was +45% and +24%, in the case of the P-EBR and non-prestressed CFRP, respectively. Concrete cover debonding occurred at the plate end at a strain value close to 1.4%, which corresponded to approximately 82% of the CFRP's tensile strength. A second experimental campaign on large bridge girders was carried out within the framework of a Polish-Swiss collaboration project (TULCOEMPA) between the Technical University of Lodz (Poland) and Empa. The main purpose of this work was to strengthen and refurbish the Szczercowska Wieś bridge (Łódź, Poland) (Kotynia et al., 2015; Michels et al., 2016c). Before applying the CFRP strengthening to the actual bridge using the Gradient Anchorage method, two exact replicas of the existing bridge girders (18.4 m long) were built at Empa and were strengthened with 2 CFRP strips (1.2 x 100 mm²), see Fig. 12. A CFRP strip strain level ε_p equal

Vol. 26, 2018, No. 3, 29 – 40

Tab. 1 *Results of experimental test on RC beams or one-way slabs strengthened with the Gradient Anchorage (GA) method*

	Specimens' name	L, b, h [m]	Steel (C) comp. (T) tens.	CFRP number, Cross section[mm]	F_P [kN] (ε_P[%])	τ_P [MPa]	$l_{b,GA}$ [m]	ΔF [%]	$\frac{\varepsilon_{f,max}}{\varepsilon_{fu}}$	$\varepsilon_{f,max}$ [%]	ε_{fu} [%]	Failure
Stöcklin and Meier 2001,2003	1	2.3,0.5,0.20	--	2 -1.15 x 50	~50 (0.55)	~1.25	0.8 (0.3/5 x 0.1)	135	--	--	--	PO
Meier and Stöcklin 2005	T3	6.5,1.0,0.22	7φ8 (C)	2 - 1.24 x50	61 (0.59)	1.5	0.8 (0.3/5 x 0.1)	86	0.48	0.82	1.7	PO
	T4		7 φ 12 (T)	4 - 0.6 x50	29 (0.65)	0.6		90	0.61	0.92	1.5	TF
Aram et al. 2008	Pb3	2.4,0.15,0.25	2 φ 12(C) 2φ12 (T) Strand φ 0.6"	1 - 1.2 x50	60 (0.60)	1.5	0.8 (0.3/5 x 0.1)	6	0.53	0.90	1.7	ED
	Pb4				30 (0.3)	0.6		17	0.46	0.79		IC/ED
Michels et al. 2013	1	6.5, 1.0, 0.22	7 φ 8 (C) 7φ 8 (T)	1 - 1.2 x 100	~120 (0.6)	~1.5	0.8 (0.3/0.2/0.2/0.1)	--	0.84	1.42	1.7	DE
	2								0.68	1.16		DE
	3								0.81	1.38		DE
	4								0.75	1.28		DE
Correia et al. 2015	S1_L50 1.4_GA	2.6, 0.6, 0.12	3 φ 6 (C) 5 φ 8 (T)	1 -1.4 x50	43.9 (0.41)	1.5	0.6 (0.2/0.2/0.2)	120	0.59	1.03	1.8	ED
	S1_L80 1.2_GA			1 - 1.2 x 80	64.1 (0.41)	1.3		160	0.60	0.90	1.5	ED
	S2_L50 1.2_GA			1 - 1.2 x 50	39.2 (0.4)	1.3		126	1.01	1.16	1.2	ED
Correia et al. 2017	GA_REF_T0[R]	2.6, 0.6, 0.12	3 φ 6 (C) 5 φ 8 (T)	1 - 1.2 x 50	39.6 (0.4)	~1.3	0.6 (0.2/0.2/0.2)	104	0.66	1.16	1.8	DE
	GA_REF_U				40.6 (0.41)			90	0.63	1.1		DE
	GA_TW_U				40.6 (0.41)			99	0.68	1.19		DE
	GA_TW_C				40.6 (0.41)			100	0.61	1.06		DE
	GA_CW_U				40.6 (0.41)			101	0.68	1.19		DE
	GA_CW_C				39.6 (0.4)			103	0.60	1.05		DE
	GA_WD_U				39.6 (0.4)			97	0.62	1.08		DE
	GA_WD_C				41.6 (0.42)			100	0.67	1.17		DE
Czaderski et al. 2017	Slab 5a	6.5, 1.0, 0.22	7 φ 8 (C) 7φ 8 (T)	2 - 1.2 x 100	120 (0.6)	1.5	0.8 (0.3/0.2/0.2/0.1)	35[S]	--	--	1.7	DE[A]
	Slab 5	5.0, 1.0, 0.22	7 φ 12 (C) 7 φ 12 (T)	2 - 1.2 x 100	100 (0.52)	0.8	1.2 (0.3/0.3/0.3/0.3)	--	--	--	1.7	DE[B]
	Slab 6							15[S]	--	--		DA[A]
	Slab 9[R]							91	--	--		DE
	Slab 10							99	0.88	1.45		DE

Legend:
PO- Peeling off
TF- CRP tensile failure
DE – Debonding
ED- Plate end debonding
IC- Intermediate crack debonding

[S] value of the sustained load
[A] Debonding after ~3 months and ~ 2 years, for Slab 5a and Slab 6, respectively.
[B] Debonding after asphalt temperature simulation
[R] Reference (time, t0)

(a) (b) (c)

Fig. 11 *Tests on the "Viadotto delle Cantine - in Capolago" (Switzerland): (a) original bridge (b) strengthened girders, (f) First prototype of the prestressing and heating GA device (Czaderski et al., 2007)*

Fig. 12 *Test on 18.4 m-long bridge girder (Michels et al., 2016c)*

to 0.58%, which corresponded to a force of 115 kN, was chosen. The gradient anchorage length adopted was equal to 0.8 m (0.3/0.2/0.2/0.1 m), with three release steps of 50, 35, and 35 kN, and τ_p=1.5 MPa. The full capacity of the CFRP was reached, i.e., the tensile failure (Fig. 12) occurred at a measured strain of 1.58%; the corresponding increase in the load-carrying capacity was equal to 24%. The CFRP sheets applied to strengthen the girder in shear had a beneficial effect on the bond, which might have helped the strips to reach the tensile failure.

The tests on large-scale girders demonstrated the feasibility and effectiveness of prestressed CFPR strips anchored using the gradient anchorage method. It was also observed that an acceptable reduction of ductility was obtained.

7 NEW CHALLENGES: LONG-TERM BEHAVIOR AND DURABILITY

The ongoing research on CFRP strengthening at Empa is focusing on the durability and long-term behavior of un-stressed and prestressed systems with particular attention on the GA method. For this latter type of application, durability is an important issue because in the anchoring zone, the total shear stress consists of the contributions caused by the external (additional) load and the initial shear stress required to anchor the prestressing force (τ_p). In addition, it was observed that accelerated curing under high temperatures increases the porosity of the adhesive, which might facilitate penetration of deterioration agents with possible implications for the long-term performance of the strengthening method (Michels et al., 2016b). An extensive study on a commercial structural epoxy was performed by (Silva et al., 2016; Silva 2017); the negative effect of wet environments (i.e., plain water or water with 3.5% chlorides) on tensile stress, E-modulus and glass transition temperature was highlighted. On the contrary, it was shown that material properties can benefit from thermal cycles due to the post-curing effects induced by the temperature. A 2.4 m long beam strengthened in the year 2000 (Stöcklin and Meier, 2001), is stored and not loaded at the Empa laboratory at room temperature. After 18 year, the pre-strain slightly reduced, most likely due to the concrete creep. However, this subsequent long-term test only provides general information and it is not representative of actual strengthening applications for which the effects of humidity, temperature, and environmental exposure need to be considered.

(Czaderski et al. 2017; Gallego et al. 2016, 2017, 2018) studied the temperature stability of the gradient method to increase the negative resisting moment of reinforced concrete bridge slabs. Tests were carried out on one-way cantilever slabs of lengths equal to 5m; parameters such as the effect of the mastic asphalt application (Slab 5, Table 1), fatigue resistance at an elevated ambient temperature (Slab 10, Table 1) and the slab's long-term durability under a sustained load and exposure to environmental conditions (Slabs 5a and 6, Table 1) were studied. The tests showed that the mastic asphalt application, due to the high temperatures generated in the adhesive, might result in the P-FRP debonding already in the construction phase. In order to avoid the occurrence of debonding, a layer of insulating material

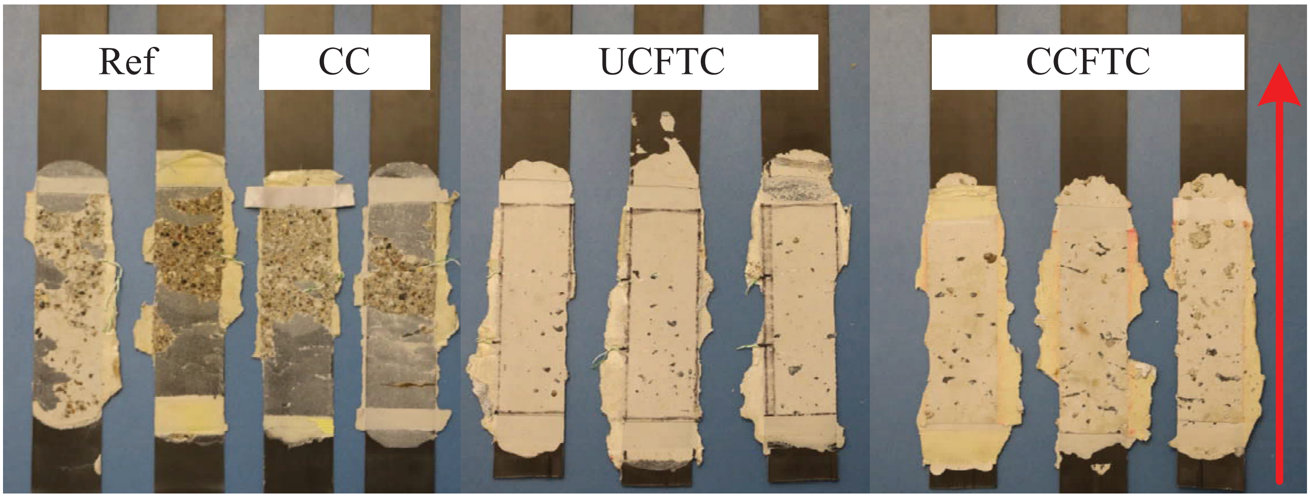


Fig. 13 *Type of failure: Reference (Ref), carbonated (CC), uncarbonated freeze-thaw cycles (UCFTC) and carbonated freeze-thaw cycles (CCFTC) specimens (from Harmanci et al., 2018a)*

needs to be applied for this type of application. It was also observed that the combination of high ambient temperatures, sustained load and high prestressing force can lead to the FRP debonding after a limited period. The time interval depends, besides the temperature reached in the adhesive, also from the prestressing force and gradient anchorage configuration. In Slab 6 (τ_p = 0.8 MPa), one FRP strips debonded after approximately 2 years. Meanwhile, in Slab 5a which was characterized by a higher prestressing force, different gradient anchorage configuration (τ_p = 1.5 MPa), a much higher value of the sustained load, and not any environmental protection, debonding occurred after approximately 3 months.

Correia et al. 2017, carried out tests on the long-term behavior of strengthened slabs exposed for approximately 8 months to different environments (climatic chamber at 20°C (REF), plain water (TW), chloride water (CW) and wet-dry cycle (WD)); half of them were subjected to a sustained load of 20 kN to consider the effects on cracked concrete (See Table 1). The failure tests showed that all the various environments led to debonding failure with a reduction of the yielding and failure loads, which was mainly related to the bond degradation caused by water or humidity. The highest reduction was obtained after the exposure in the climatic chamber (GA_REF_U) and to wet-dry cycles (GA_WD_U); both beams were uncracked during their exposure, nevertheless, the decrease in load-carrying capacity was limited.

(Harmanci et al., 2018a, 2018b) observed a deterioration mechanism at the concrete-adhesive interface by performing a lap shear test on a single GA segment subjected to freeze-thaw (FT) cycles; the effects of carbonation were also considered. It was observed that after the FT cycles, the predominant failure was at the concrete-epoxy interface (Fig. 13) and a decrease in the anchorage's resistance of approximately 30% for both un-carbonated and carbonated specimens was recorded. It was also highlighted that the strength reduction due to FT cycles of single system components (concrete, adhesive, CFRP) is significantly lower than the reduction of the total system. The results highlight the damage of the interface, which was probably ascribable to the moisture and additional stresses during the thermal cycles.

8 CONCLUSIONS

The present review illustrates the main findings with regards to the development of the gradient anchorage method for strengthening RC beams and slabs and sheds light on the unsolved problems in terms of long-term and durability.

- In general, it is possible to state that the GA method is an effective solution to anchor prestressed CFRP strips. The high-stress level on the FRP at debonding demonstrates that a high utilization factor can be obtained, which implies that the material properties are almost fully employed.
- The development of the bond strength of cold curing and accelerated curing of CFRP-concrete interfaces is explained. It was shown that accelerated curing, in addition to a reduction in the curing time, is able to increase the temporary strength of the bonded GA sector, which has a favorable effect during the release of the prestressing force.
- A feasible setup for on-site GA applications was developed in cooperation with the S&P Clever Reinforcement Company AG (Seewen, Switzerland) and Empa.
- It has been demonstrated that environmental conditions, such as humidity, temperature and FT cycle can affect the performance of the GA and, in combination with high CFRP prestresses and/or high sustained loading, are critical for their long-term behavior. Therefore, similar recommendations such as the one proposed by (Czaderski and Meier, 2018) for unstressed CFRP can be applied to RC elements strengthened using the GA method. The most important are:
  - FRPs should only be used for Exposition Classes X0, XC1(dry) and XC3,
  - Moderate sustained loading (prestressing and external loads),
  - Service temperatures ≤ 45 °C (ca. 15°C lower as T_g)
- The ongoing work is dedicated to studying, how the simultaneous effects of sustained loading, high prestressing forces, and elevated ambient temperatures can affect the long-term resistance of GA.

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