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Anchorage resistance of CFRP strips externally bonded to various cementitious substrates

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ABSTRACT

This paper presents a study on the anchorage capacity of Carbon Fiber Reinforced Polymer (CFRP) strips bonded to a cementitious substrate used for concrete surface reprofiling. The structural strengthening of a large-scale prestressed concrete girder in the framework of a bridge retrofitting project by means of prestressed CFRP strips required the levelling of an initial negative camber of about 2–4 cm. Both mid-span and girder end situations were investigated with lap-shear and prestress force-releasing tests. Four different solutions regarding the levelling material, i.e. three mortars applied by hand as well as dry shotcrete, were tested. The results in terms of strain, slip and total anchorage resistance are presented and compared. In the end, dry shotcrete is recommended for the girder application. In addition to a very convincing bond behavior, the application is, despite the necessity of involving a specialized company from the field, clearly less time-consuming and easier. The retained solution represents an interesting approach for future applications in bridge retrofitting when an even surface is necessary for bonding CFRP strips.

1. Introduction and background

Carbon Fiber Reinforced Polymer (CFRP) strips are known to be an efficient method for strengthening existing reinforced concrete (RC) structures. One possibility is to externally bond the strips to the concrete surface by means of an epoxy adhesive [1]. Bond strength of the system is generally tested with lap-shear tests, during which an externally bonded strip to a concrete block is loaded in tension up to delamination failure from the substrate. Concrete quality, aggregate size, surface preparation, quality of strip application, eopxy quality, curing degree, strip elastic modulus and strip thickness are among the most influencial factors of the total anchorage resistance. Literature in this field is extensive, the authors want to draw the attention to a few interesting experimental and theoretical works over the last years [2–13].

The fact of prestressing the externally bonded CFRP reinforcement allows a more efficient exploitation of the material's performances, mostly in terms of uniaxial tensile strength ($f_{f,u} >$ 2000 MPa). The background of the investigation is a larger bridge retrofitting project in Szczercowska Wieś (Poland) and a related research collaboration between Łódź University of Technology (Poland) and Empa (Switzerland). Structural upgrading of five 18.4 m-long prestressed concrete girders (cross-section is given in Fig. 1(a)) with prestressed CFRP strips requires a reprofiling layer in order to obtain an even surface along the lower flange bottom. For an adequate strip application, the initially negative cambering due to the internal steel cable prestressing has to be levelled by means of an additional cementitious substrate (see Fig. 1(b)).

Even though the ultimate load carrying capacity of a retrofitted structure can be reached by tensile failure of the composite reinforcement (see Meier and Stöcklin [14], Kotynia et al. [15]), strip debonding is most often the governing criterion. This manuscript presents a series of *lap-shear* as well as *prestress force-releasing* tests of CFRP strips externally bonded to a cementitious substrate used for concrete surface reprofiling. A first experimental series (lap-shear) presented in this paper deals with the anchorage resistances of CFRP strips bonded to an additional mortar layer, itself previously applied on a roughened concrete surface. The aim of this first experimental part was to obtain information about the location of failure in the substrate and the actual debonding loads at which strip delamination occurs in the area between the anchorage zones on the girder (see Fig. 1(b)).

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Nomenclature

α	reduction factor
ΔF_p	prestress force release
$\varepsilon_{f,u}$	maximum CFRP strain
AC	accelerated curing
b_f	CFRP strip width
$c1$	calibration factor
d_{max}	maximum aggregate size
DS	dry shotcrete
E_f	elastic modulus of CFRP strip
F	force
f_{ck}	characteristic compressive strength of concrete
$f_{cm,cube}$	average concrete compressive strength of on cube
f_{ctm}	unidirectional tensile strengh of concrete
$f_{f,u}$	CFRP uniaxial tensile strength
F_{p1}, F_{p2}	initial and final forces in the hydraulic jack
$F_{u,calc,a}, F_{u,calc,b}$	calculated anchorage resistance for lap-shear
$F_{u,exp}$	experimentally determined ultimate anchorage resistance for lap-shear or prestress force-releasing
FM	failure mode
G_f	fracture energy of mortar/shotcrete
k_b	geometry factor
k_c	compaction factor
l_b	bond length
$l_{b,a}$	active bond length
RT	room temperature curing
s_f	horizontal CFRP strip slip
t_f	CFRP strip thickness
t_l	mortar or shotcrete layer thickness
u_c	horizontal concrete displacement
u_f	horizontal strip displacement in central axis
w_f	vertical CFRP strip separation

A prestressed reinforcement always requires a specific anchorage system. Due to the particular geometry of the girder (limited flange width and the presence of prestressing steel cables in the flange, see Fig. 1(a)), a mechanical solution with anchor plates and dowels was not possible. Thus, the gradient anchorage was chosen (Meier and Stöcklin [14], Czaderski et al. [16], Kotynia et al. [15], Michels et al. [17,18]). This method, based on the accelerated adhesive curing (Czaderski et al. [19], Michels et al. [20,21]) and subsequent gradual prestress force release at both strip ends, leaves no remaining mechanical components on the structure. Therefore, the second test series (prestress force-releasing, see also Michels et al. [20]) was performed with the goal to determine the anchorage resistance and failure mode of two bond lengths, which are used in the gradient anchorage configuration. For this purpose, the strip is initially prestressed and subsequently bonded to the cementitious substrate, and finally, after accelerated curing, the prestress force is released from one side until failure occurs.

In this manuscript, both lap-shear and prestress force-releasing tests with their respective cementitious substrates are presented and discussed. As explained in the following paragraphs, four different cementitious solutions are investigated during both experimental campains. To summarize, with regard to Fig. 1, the following distinction is made:

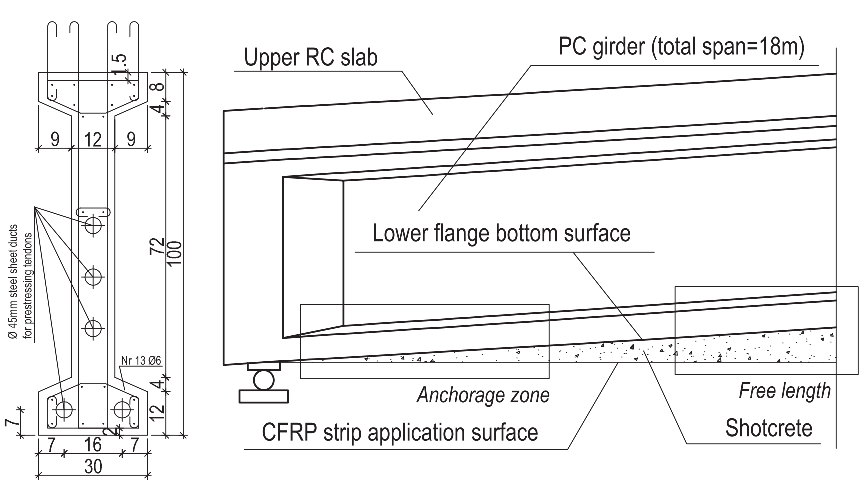
- *Lap-shear tests* for characterizing bond between the CFRP strip and the substrate and between the substrate and the concrete surface in the free length when the structure is under load.
- *Prestress force-releasing tests* for quantifying anchorage capacity and failure mode of a defined bond length l_b during the gradient anchorage application when a certain amount of the intial force F_p has to be released.

The lap-shear tests were almost entirely performed at Łódź University of Technology, whereas the prestress force-releasing tests were conducted at Empa. For comparison purposes, two lap-shear tests with a dry shotcrete layer were investigated at Empa.

In the end, a final suggestion for the girder levelling material for the bridge application is pronounced based on the presented experience and the resulting experimental observations. It is assumed that the deformability of the concrete/mortar or concrete/shotcrete system is small and that the obtained results are representative for the bond behavior on the large-scale girder.

2. Experimental investigation

In the following sections, the lap-shear tests performed at Łódź University of Technology will be denoted as *investigation 1*,



(a) Cross-section (b) Side-view at the girder end

Fig. 1. Cross-section of the prestressed concrete (PC) girder and side view including the upper RC slab with the levelling material of the prestressed concrete girder.

whereas the prestress force-releasing tests are described as *investigation 2*.

2.1. Materials

The different material names and characteristics are subsequently explained in the following two paragraphs. Their designations (*Mortar 1, 2 and 3 as well as dry shotcrete*) will be used throughout the whole manuscript.

For investigation 1 (Łódź University of Technology), the used concrete with a maximum aggregate size d_{max} of 16 mm had an average compressive strength on cube ($150 \times 150 \times 150\ mm^3$) $f_{cm,cube}$ of 50.6 MPa at 28 days. A commercially available epoxy resin [22] was used for bonding the strips to the respective substrates. The CFRP strips had a width b_f of 100 mm, a thickness t_f of 1.2 mm, and a nominal elastic modulus E_f above 165 GPa according to the distributor [23]. Two types of polymer cement concrete (PCC) mortars, denoted as *Mortar 1* [24] and *Mortar 2* [25], have been used for reprofiling (Kotynia et al. [26]). Detailed characteristics of both materials can be found in the referenced data sheets.

For investigation 2 (Empa), the basic structure used for the experimental investigation were old concrete blocks with an average compressive strength on cube $f_{cm,cube}$ in the range of 55 MPa after 28 days. Maximum aggregate size was 32 mm. Two different reprofiling mortar products were used. A hand-applied *Mortar 3* [27] with a maximum aggregate size of 4 mm is supposed to have a compressive strength after 7 days of 52.2 MPa according to the technical data sheet [27]. *Dry shotcrete* [28] with a maximum aggregate size of 8 mm was applied by the company Scheifele (CH). In this case, the distributor indicates a compressive strength of at least 50 MPa after 7 days. The same CFRP strip type as for investigation 1 with a width b_f was 100 mm, a thickness t_f of 1.2 mm, and a guaranteed elastic modulus E_f higher than 165 GPa [23] was used. Bond to the substrate was performed with the identical resin as for investigation 1 ([22]).

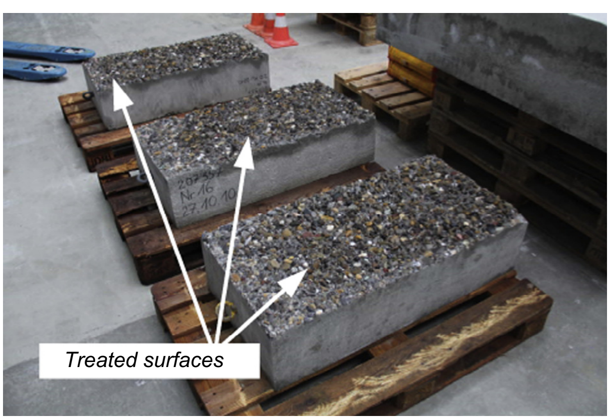


Fig. 2. Roughened surfaces after treatment with waterjet at high pressure.

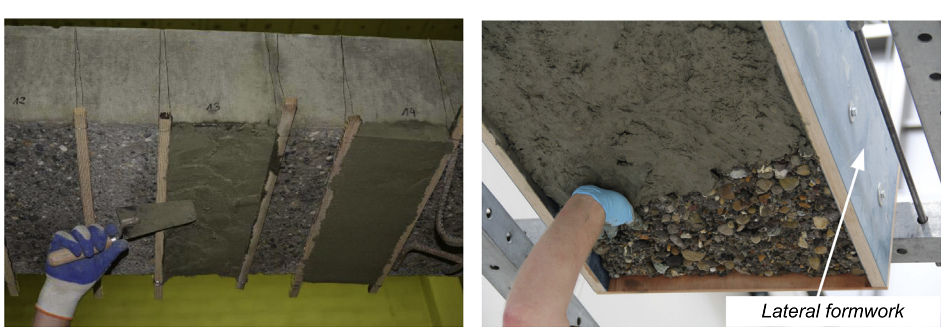
2.2. Waterjetting

The surface of the used concrete specimens was roughened by waterjet under high pressure, laitance was removed so that the aggregates are visible. An example of the treated blocks at Empa is given in Fig. 2. This approach will also be applied on the bridge girders. Both applications for the AP mortar and the dry shotcrete were performed overhead in order to work under the same conditions as for the future reprofiling on the bridge. A lateral formwork was placed in order to achieve the exact desired thickness t_l (see Fig. 3) listed in Tables 1 and 2.

2.3. Mortar application and configurations

The mortar layer configurations for investigation 1 were 1×15 mm (i.e. 1 layer with a thickness of 15 mm), 1×30 mm, 2×25 mm and 3×16 mm (see Table 1). An additional bond agent was applied on the concrete surface prior to the actual mortar. Mortars were applied manually by hand or with use of trowels and spatulas when the bonding agents were still wet. The application of thin layers (up to 25 mm) could be performed without any difficulty. However, thicker layers (30 mm) involved that the fresh mortar tended to fall off. Application of layers thicker than 30 mm was impossible as the fresh mortars were unable to resist gravity. For multi-layers, a waiting time of minimum 6 h between the application of two layers was considered. Bond agents were also used between the different mortar layers.

The additional mortar or shotcrete layer for investigation 2 had a total thickness t_l of either 20 or 50 mm (see Table 2). For Mortar 3, which was applied manually, the smaller layer with a thickness of 20 mm was performed by applying three consecutive layers of about 7–8 mm with intermediate curing durations of 3–4 h. The thicker layer of 50 mm was identically prepared, resulting eventually in a total duration for the application of 2 days with an overnight curing after the first 25 mm. In general, the application is judged rather difficult and exhausting, as at several occasions mortar was falling off and had to be replaced or reattached. The application of the dry shotcrete was easier. Both thicknesses could be achieved in one working stage shown in Fig. 4(a). The blocks were installed in a closed container, as dry shotcreting provokes a lot of dust and material rebound. After curing, all shotcrete surfaces (Fig. 4(b)) were ground prior to any strip application.



(a) Mortar application at Łódź University of Technology - Investigation 1

(b) Mortar application at Empa - Investigation 2

Fig. 3. Overhead mortar application by hand.

Table 1
Testing configurations and results of the lap-shear tests at Łódź University of Technology (∗ = CFRP strip bonded to the concrete substrate).

Test No.	Additional layer	$F_{u,exp}$ (kN)	$\varepsilon_{f,u}$ (‰)	FM
TUL-1	None*	75	3.2	–
TUL-2	None*	70	3.2	–
TUL-3	Mortar 1–1 × 15 mm	70	3.2	A
TUL-4	Mortar 1–1 × 15 mm	75	3.1	A
TUL-5	Mortar 2–1 × 15 mm	55	2.2	A
TUL-6	Mortar 2–1 × 15 mm	45	1.9	A
TUL-7	Mortar 1–1 × 30 mm	60	2.7	A
TUL-8	Mortar 1–1 × 30 mm	65	2.8	A
TUL-9	Mortar 2–1 × 30 mm	55	2.5	A
TUL-10	Mortar 2–1 × 30 mm	40	1.9	A
TUL-11	Mortar 1–2 × 25 mm	30	1.2	B
TUL-12	Mortar 1–2 × 25 mm	25	0.8	B
TUL-13	Mortar 2–2 × 25 mm	45	2.1	A
TUL-14	Mortar 2–2 × 25 mm	50	2.4	A
TUL-15	Mortar 1–3 × 16 mm	50	2.2	B
TUL-16	Mortar 2–3 × 16 mm	45	2.1	A

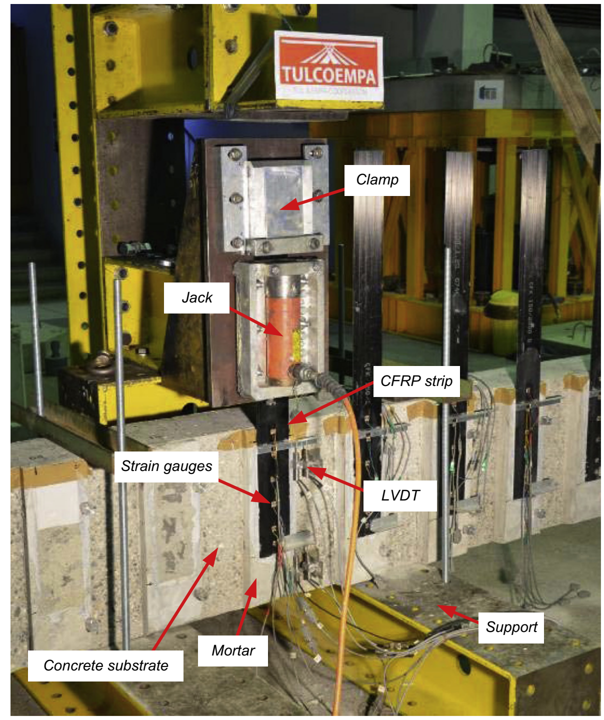


Fig. 5. Photo of the test setup at Łódź University of Technology.

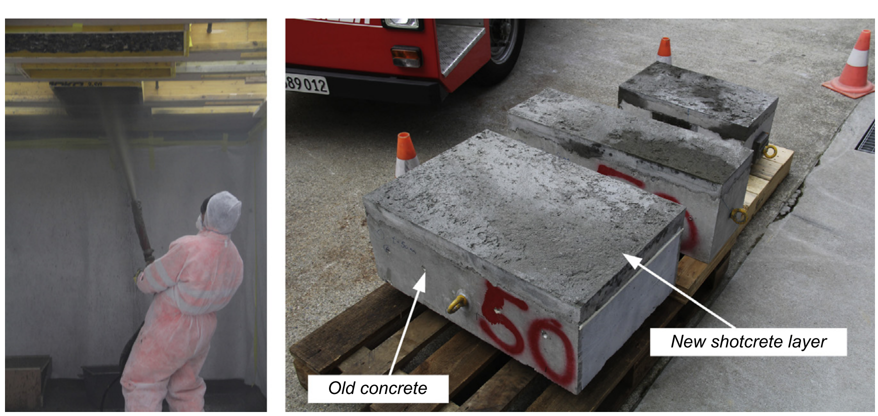
2.4. Test setups

2.4.1. Setup at Łódź University of Technology – investigation 1

A photo of the test setup for the lap-shear tests is given in Fig. 5. The concrete member was installed on a steel support and subsequently anchored with additional steel profiles. The free strip end was fixed in a aluminum clamp, on which load was applied by a hydraulic jack. The test was conducted under force control by manual increase of the oil pressive via a pump. Increase rate was not specifically fixed, attention was paid to a regular force increase up to failure. Six strain gauges (see Fig. 6) were applied on each CFRP laminate for the registration of CFRP strain. One

Table 2
Testing configurations and results of the tests performed at Empa (∗ = accelerated curing after approximately 3 h of waiting time due to technical problems with the heating device, RT = room temperature curing for 3 days, AC = accelerated curing for 25 min and approx. 15 min of cooling time).

Test No. -	Test type	Additional layer	t_l (mm)	l_b (mm)	Adhesive curing	Shotcrete age at testing day (days)	$F_{u,exp}$ (kN)
Empa-1	Releasing	None	/	300	AC	/	78.2
Empa-2	Releasing	Shotcrete	20	300	AC	14	81.8
Empa-3	Releasing	Shotcrete	20	200	AC	15	61.8
Empa-4	Lap-Shear	Shotcrete	50	300	RT	19	47.8
Empa-5	Releasing	Shotcrete	20	300	AC	20	72.6
Empa-6	Releasing	Shotcrete	20	200	AC	21	66.4
Empa-7	Lap-Shear	Mortar 3	50	300	RT	12	37.8
Empa-8	Releasing	Mortar 3	20	300	AC*	14	83.8*
Empa-9	Releasing	Mortar 3	20	200	AC	15	51.2
Empa-10	Releasing	Mortar 3	20	300	AC	15	74.7
Empa-11	Releasing	Mortar 3	20	200	AC	17	53.4



(a) Shotcrete application (b) Concrete blocks with additional shotcrete layer

Fig. 4. Dry shotcrete application and final blocks.

gauge was placed in the unbonded area of the laminate in the zone of pure tension (T1), while the remaining five were spread over the bonded length of the strip (T2–T6). Horizontal slips s_f were registered by four LVDT sensors P7–P10 mounted on the mortar and concrete surface.

2.4.2. Setup at Empa – investigation 2

In order to simulate the different anchoring steps during the application of the gradient anchorage, the test-setup for the prestress force-releasing tests follows the investigation presented in Michels et al. [20,21]. The test setup is presented in Figs. 7 and 8. In this configuration, the strip is initially prestressed by two hydraulic jacks. Forces are measured with two load cells behind each clamps. The strip is then bonded to the cementitious substrate by accelerated adhesive curing at high temperatures (about 100 °C for 25 min) using a special heating device. At the end, after a short cooling period of about 15 min, the initial prestress force is released by manually decreasing the oil pressure at a constant rate at one end in order to assess the total anchorage capacity for the defined bond length. This heating procedure is deducted from earlier investigations related to the mentioned gradient anchorage technique for prestressed CFRP laminates [17,19,20]. Full-field measurements (3D) with an Image Correlation System (ICS) were performed in order to obtain as much information as possible in terms of horizontal and vertical displacements of the strip during the debonding process as well as crack evolution in the concrete or mortar substrate. Horizontal slips s_f of the CFRP strips are always deducted in the central axis along the bond length by substracting the mortar's (or shotcrete) total horizontal displacement

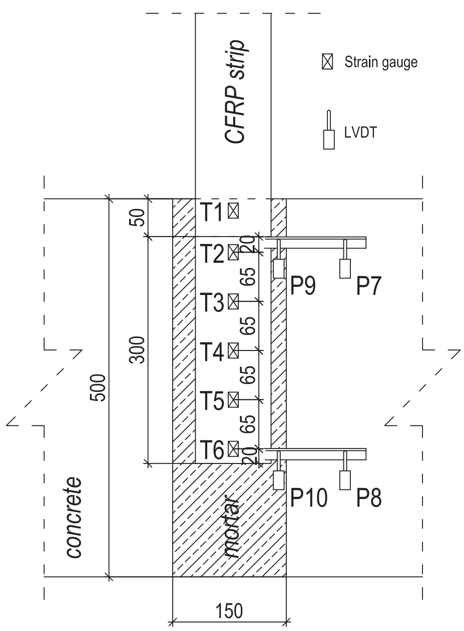


Fig. 6. Positions of the strain gauges T1–T6 and LVDTs P7-P10.

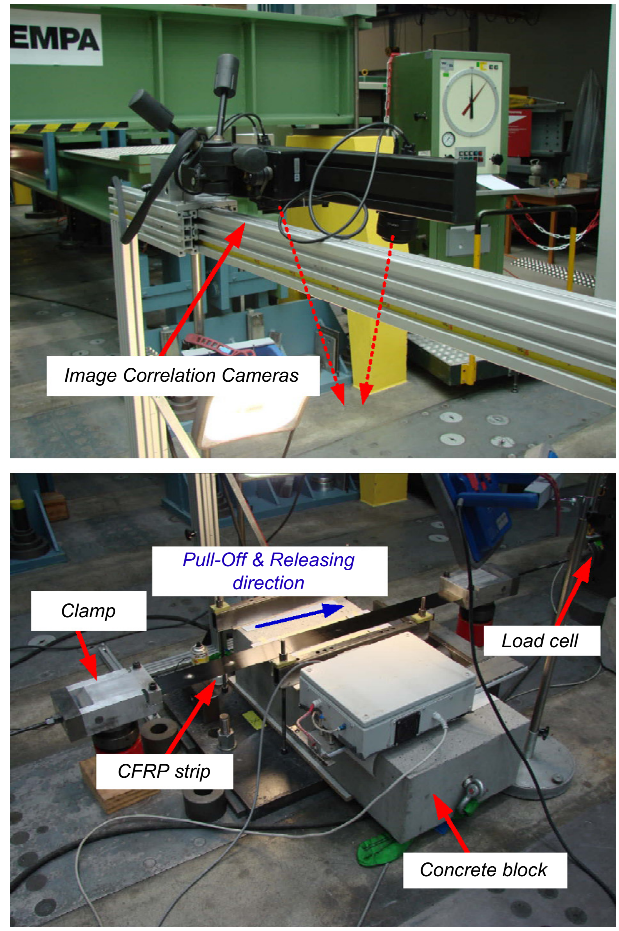


Fig. 8. Photo of the test setup at Empa.

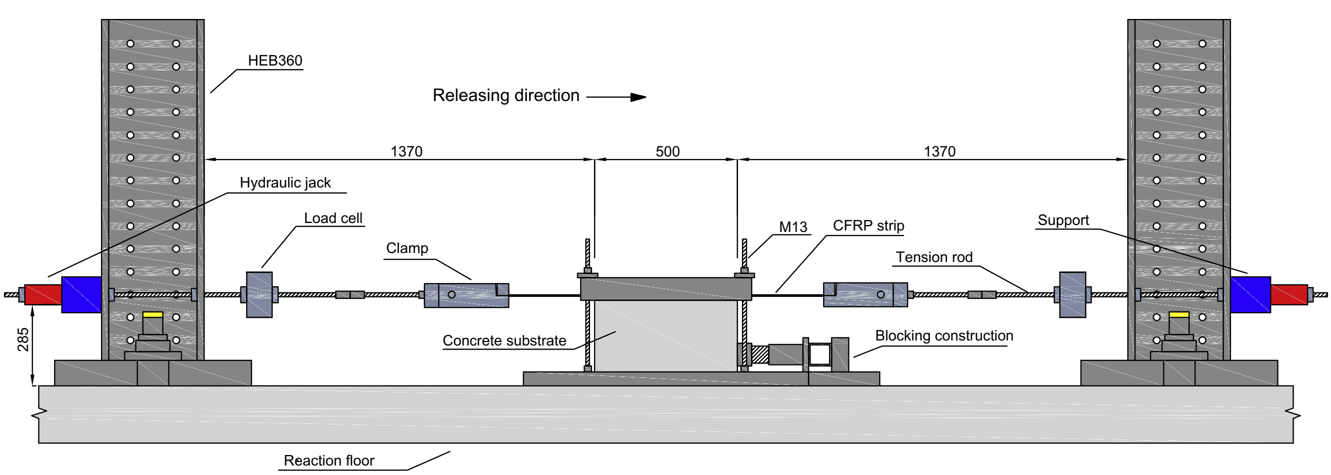


Fig. 7. Test setup of the releasing tests performed at Empa.

(average of Sections 0 and 2, see Fig. 9) from the total horizontal strip displacement (Section 1, see Fig. 9, Michels et al. [20]):

$$s_f = u_f - u_c \quad (1)$$

Additionally, two *lap-shear tests* were performed after externally bonding the CFRP strip to the mortar or shotcrete layer. In this case, the epoxy was cured at room temperature for 3 days. These tests can be compared with the previously mentioned lap-shear tests from investigation 1.

3. Results and discussion

3.1. Lap-shear tests

The reference tests for which the CFRP strip had been directly applied on the concrete substrate revealed anchorage resistances of 70 and 75 kN with a failure in the CFRP/epoxy interface, while the concrete surface remained undamaged. The experimental investigation of the tests with one or more additional mortar layers revealed either a bond failure in the substrate (denominated as failure mode 'A' in Table 1) or a possible bond failure between two mortar layers (failure mode 'B', in case a multi-layer application had been performed). A qualitative sketch is given in Fig. 10. All one-layer specimens, independently of the layer thickess t_l of 15 or 30 mm, exhibited failure mode A, as well as the multi-layer test performed with Mortar 2 (see Table 1). On the other hand, multi-layer tests with Mortar 1 led to failure mode B between two layers (see Table 1).

In terms of anchorage resistances, a direct comparison between the different mortar types and the different layer configurations is given in Fig. 11(a)–(c). A first observation is the fact that Mortar 2 substrate leads to anchorage resistances between 40 and 55 kN, independant of the layer configuration. This corresponds to maximum measured CFRP strains $\varepsilon_{f,u}$ in the range of 0.19–2.5‰. The magnitude of the anchorage resistances seems to be untouched by the layer configuration. In case of Mortar 1, a single layer application leads to high anchorage resistances of 60 and 75 kN ($\varepsilon_{f,u} = 2.7$ and 3.2‰, respectively). This one-layer load capacities are higher than the corresponding ones with Mortar 2. However, as stated in the previous paragraph, multi-layer configurations with Mortar 1 led to a failure between two layers. This resulted in lower total anchorage resistances as shown in Fig. 11(a), as in this case the material could not develop its full strength.

This leads to a first conclusion that, despite the higher resistances of a single-layer application, Mortar 2 is to be recommended over Mortar 1. The higher material strength of the latter, as indicated in Table 1, cannot be developed in multi-layer usage due to an premature failure between two mortar layers. The lap-shear tests performed at Empa with Mortar 3 (Table 2) shows an anchorage resistance of 37.8 kN. This represents only about 80% of the corresponding tests at TUL (Tests 13, 14 and 16, Table 1). Very similar resistances are obtained with dry shotcrete (47.8 kN, Table 2).

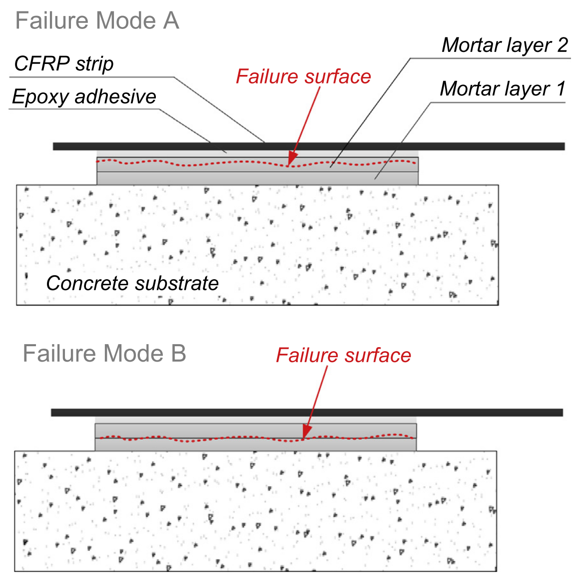


Fig. 10. Failures modes A and B for the lap-shear tests performed at Łódź University of Technology.

In Fig. 12(a), the strip strain ε_f of Test TUL-4 (Lap-Shear) is plotted in function of the location (T1–T6, see Fig. 6) for different load levels F. Fig. 12(b) also shows the strain evolution over the bond length for different load levels. Strain is initiated at the beginning of the bond length and propagates towards the end of the strip. Gauge T6 indicates almost no strain increase, showing that the provided bond length l_b of 300 mm can be considered as sufficient for the load transfer. Alternatively, one can say that the active bond length $l_{b,a}$, defined as the length over which the CFRP strip actively contributes to the load transfer with distinct slips (Michels et al. [20]), is shorter than the full bond length l_b.

For comparison purposes, the total anchorage resistance of a CFRP strip for a defined bond length on a cementitious substrate is estimated with Eq. 2 (Holzenkämpfer [29]) and Eq. 4 (fib-bulletin 14 [30]). Fracture energy G_f for Mode II is in the present case

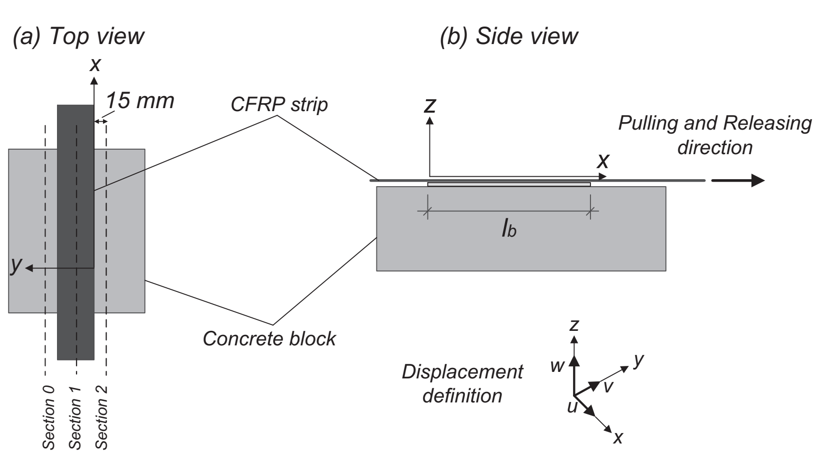
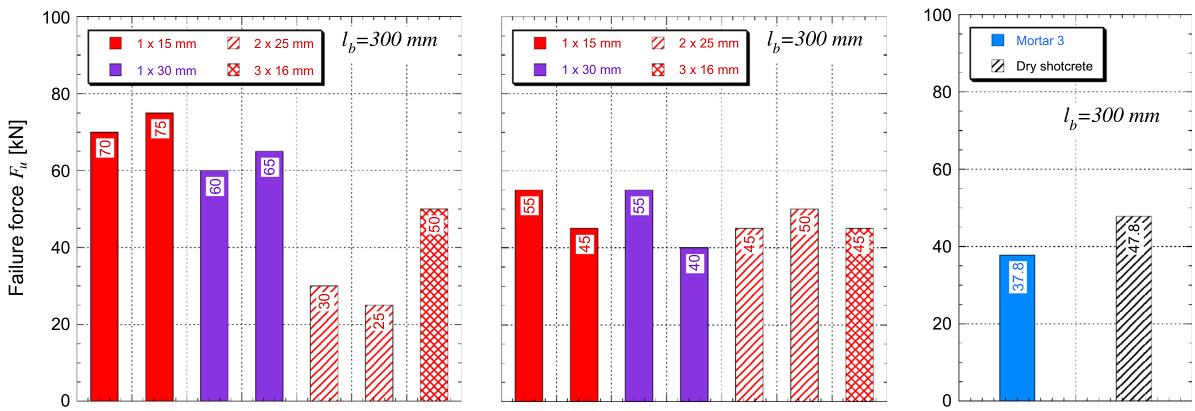
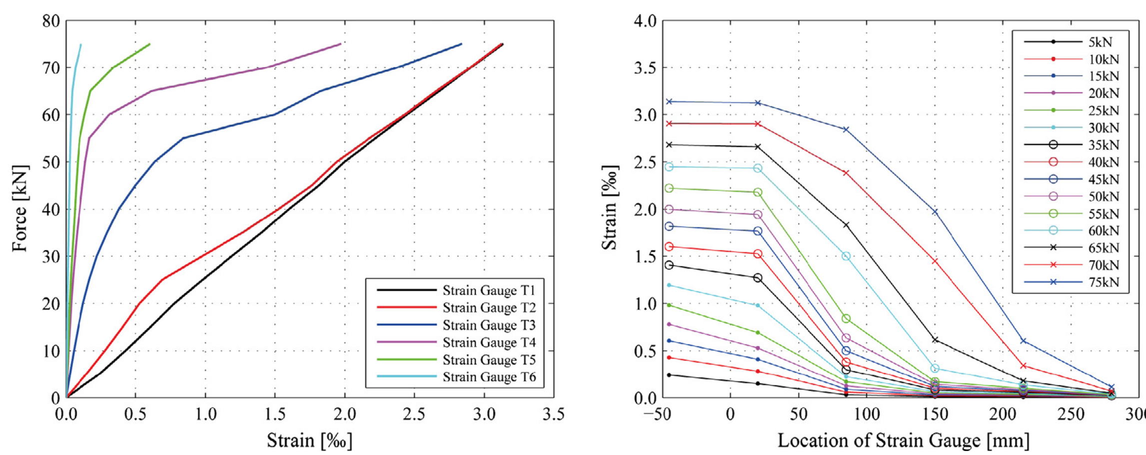


Fig. 9. Section and displacement definition for the slip s_f evaluation (investigation 2).



(a) Mortar 1 (b) Mortar 2 (c) Mortar 3 / Dry shotcrete

Fig. 11. Failure forces of the lap-shear tests with mortar types 1,2 (investigation 1) and 3 (investigation 2) substrate (bond lengths l_b = 300 mm) – tests TUL-3 to TUL16, Empa-4 and Empa-7.



(a) Force-strain at different locations x (b) Strain-location for different load levels F

Fig. 12. Force-strain evolution at different strip locations and strain evolution at different positions with growing force levels (lap-shear test TUL-4).

evaluated according to suggestions by Czaderski [31], see Eq. 3. Unidirectional tensile strength f_{ctm} was deducted from the characteristic compressive strength f_{ck} according to fib-bulletin 1 [32], see Eq. 5.

$$F_{u,calc,a} = b_f \cdot \sqrt{2 \cdot G_f \cdot E_f \cdot t_f} \quad (2)$$

$$G_f = 0.018 \cdot f_{ck}^{2/3} \cdot d_{max}^{1/4} \quad (3)$$

$$F_{u,calc,b} = \alpha \cdot c1 \cdot k_b \cdot k_c \cdot b_f \cdot \sqrt{E_f \cdot t_f \cdot f_{ctm}} \quad (4)$$

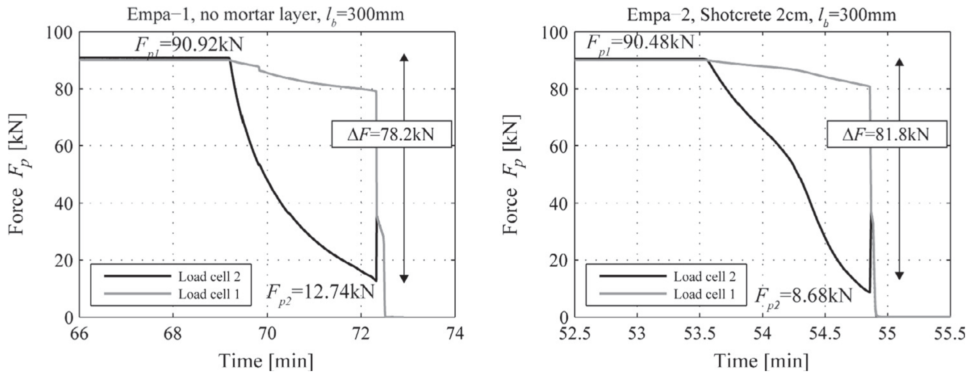
$$f_{ctm} = 0.3 \cdot f_{ck}^{2/3} \quad (5)$$

where f_{ck} = characteristic concrete compressive strength, α = reduction factor to account for the presence of inclined cracks, k_c = factor accounting for the state of concrete compaction, k_b = geometry factor taking into account a possible width effect, c1 = calibration factor (0.67 for CFRP strips according to the fib-bulletin 14 [30]).

The different influencial parameters are summarized in Table 3. Comparison values between experimental ($F_{u,exp}$) and numerical ($F_{u,calc,a}, F_{u,calc,b}$) values are given in Table 3. Please note that for Mortars 1 and 2, the anchorage resistances of 27.5 kN and 47.5 kN are mean values of two performed tests under the configuration 2 × 25 mm (see Table 1). The remaining values of 50 kN

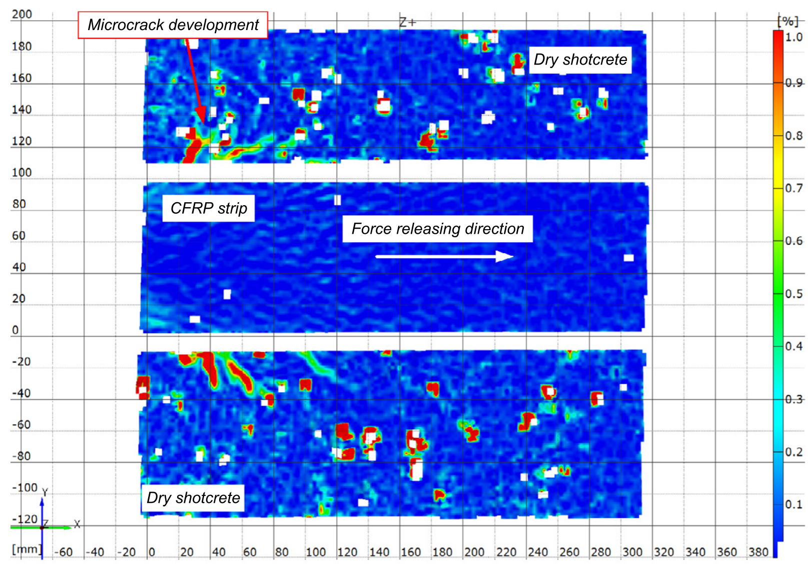
Table 3
Comparison between calculated and experimentally determined anchorage resistances for lap-shear tests with a mortar (shotcrete) thickness of 50 mm (* = average of 2 × 25 mm configuration, ** = 3 × 16 mm configuration, see Table 1, FM = failure mode (see Table 1).

	Mortar 1	Mortar 2	Mortar 3	Dry shotcrete
d_{max} (mm)	2	2	4	8
f_{ck} (MPa)	50	50	50	50
G_f (N/mm)	0.29	0.29	0.35	0.41
E_f (GPa)	165	165	165	165
t_f (mm)	1.2	1.2	1.2	1.2
b_f (mm)	100	100	100	100
α	0.9	0.9	0.9	0.9
c1	0.64	0.64	0.64	0.64
k_c	0.67	0.67	0.67	0.67
b (mm)	150	150	300	300
k_b	1.09	1.09	1.22	1.22
f_{ctm} (MPa)	4.1	4.1	4.1	4.1
Holzenkämpfer [29]/Czaderski [31]				
$F_{u,calc,a}$ (kN) (Eq. 2)	**33.9**	**33.9**	**37.0**	**40.3**
fib-bulletin 14 [30]				
$F_{u,calc,b}$ (kN) (Eq. 4)	**37.9**	**37.9**	**42.4**	**42.4**
$F_{u,exp}$ (kN)	27.5* (FM = B) 50** (FM = A)	47.5* (FM = A) 45** (FM = A)	37.8	47.8

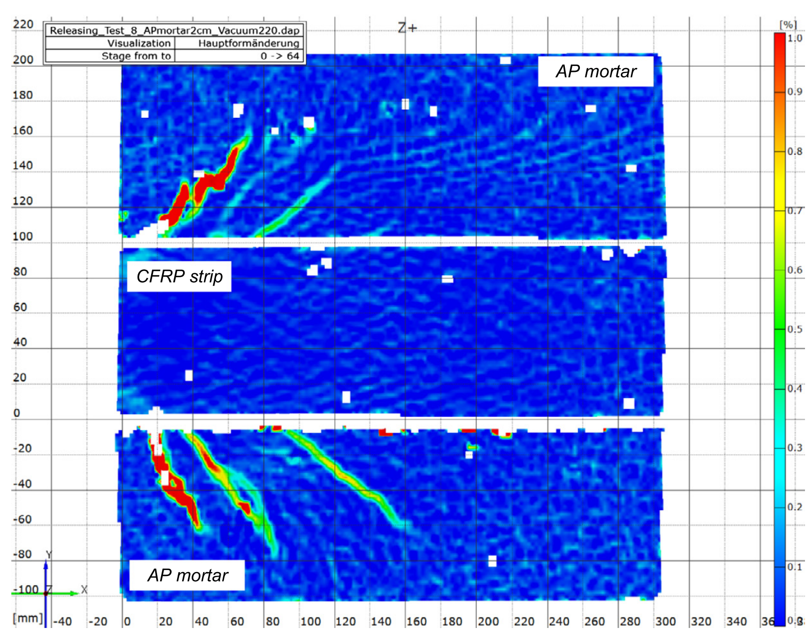


(a) 2 cm dry shotcrete - l_b=300 mm (b) 2 cm dry shotcrete - l_b=200 mm

Fig. 13. Force–time curves for the reference test (prestress force-releasing test Empa-1, Table 2) and with 2 cm of dry shotcrete (Empa-2).



(a) Dry shotcrete substrate - Empa-2



(b) AP mortar substrate - Empa-8

Fig. 14. Maximum principal strains at a releasing force level of 50 kN.

(a) Force-releasing (Test Empa-2)

(b) Lap-shear (Test Empa-4)

Fig. 15. Test specimens after test end.

and 45 kN, respectively, are the ones obtained with the configuration 3 × 16 mm for the mortar substrate. Regarding strength values, compressive strength of concrete as well as elastic modulus for the CFRP strip guaranteed guaranteed by the distributor were used to estimate the anchorage resistance. In general, the experimental results are higher than the expected calculated resistances in case the failure occurs in the mortar (or shotcrete) substrate, denoted as failure mode A (see Table 1 and Fig. 10). Both estimations $F_{u,calc,a}$ and $F_{u,calc,b}$ are on the safe side compared to the experiments, with the exception of Mortar 3. In case an interlaminar debonding in the cementitious substrate (failure mode B) occurs, such as for Mortar 1 in the 2 × 25 mm configuration, the estimations according to both Eqs. 2 and 4 are not applicable.

3.2. Releasing tests

3.2.1. Behavior during prestress force release

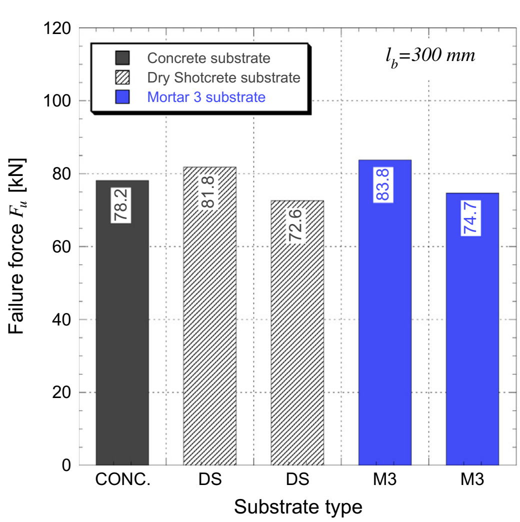
The force–time curve of the prestress force-releasing tests with a dry shotcrete layer and a bond length 300 mm is given in Fig. 13(b). In this case, the layer thickness was always 20 mm. For the practical application of the gradient anchorage on the large-scale girder, a total prestress force F_p of approximately 120 kN needs to be gradually anchored (see Michels et al. [17]). This configuration currently foresees three consecutive release steps of 50, 35 and 35 kN, with respective bond lengths of 300, 200, and 200 mm. Fig. 14(a) and (b) show maximum principal strains obtained by the ICS measurement system at a force release ΔF_p of 50 kN for both the dry shotcrete and the Mortar 3 reprofiling. In both cases, microcracks develop at the front part of the bond length at which the force is introduced in the system. Even though both configurations are far from debonding failure, crack development at this stage is more pronounced for the Mortar 3 substrate.

3.2.2. Behavior at failure

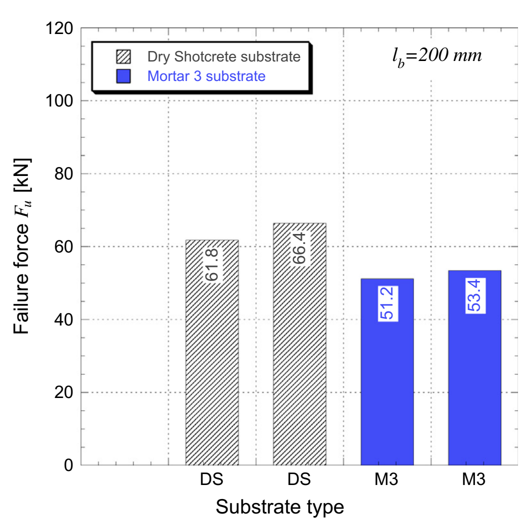
The ultimate load is deducted by substracting the final force value at the moment of failure F_{p2} from the initial total prestress force F_{p1} (Eq. 6 and Fig. 13(b)).

$$F_u = F_{p1} - F_{p2} \tag{6}$$

All the force-releasing tests exhibited a failure in the concrete (reference test for which the CFRP strip was directly bonded to the concrete subtrate), mortar or shotcrete. No failure in the adhesive or at any interface epoxy/concrete or epoxy/CFRP was observed. Similar to the tests documented in Michels et al. [20], failure with a dry shotcrete substrate occured by a deep penetration into the cementitious substrate with an additional lateral crack expansion (see Figs. 14(b) and 15(a)). This cracking behavior is in opposition to



(a) l_b=300 mm



(b) l_b=200 mm

Fig. 16. Failure forces of the releasing tests with bond lengths l_b of 300 and 200 mm, DS = dry shotcrete, M3 = Mortar 3.

failure modes known from lap-shear tests, which failed by an almost horizonzal sliding with a final failure in the very upper substrate layer (Fig. 15(b)).

In terms of forces, similar anchorage resistances for a bond length l_b of 300 mm are reached for both the hand-applied Mortar 3 and the dry shotcrete. The direct comparison is given in Table 2 and Fig. 16(a). A shorter bond length l_b of 200 mm, however, implicates slightly lower ultimate loads for Mortar 3 (see Fig. 16(b)). In this case, both tests revealed on average only 82% of the anchorage resistance than the ones with a dry shotcrete substrate.

3.2.3. Final recommendation

The aforementioned results with different cementitious substrates reveal a generally satisfactory behavior in terms of anchorage capacity and failure mode. All specimens clearly had enough resistance for the desired load levels of 50 and 35 kN due to the gradient anchorage. In terms of absolute force values, both methods give similar results with a slight superiority of the dry shotcrete when shorter bond length is applied. A significant advantage of the dry shotcrete though is the more appealing application procedure. The application is faster and the fact that specialized companies are at work leads to good quality of the substrate. However, due to the extreme dust release, certain precautions are necessary. The AP mortar application by hand is much more exhausting. Additionally, weak layer interfaces might decrease the overall anchorage resistances. Hence, for future applications in similar retrofitting projects, dry shotcrete is recommended.

4. Conclusions

The presented experimental results allow to draw a certain number of conclusions regarding practical applications in strengthening projects. As stated earlier, the aim of the investigation was to experimentally determine the most suitable solution for the reprofiling of the girder bottom surface in anticipation of a prestressed CFRP strip application.

- Roughening the initial concrete surface with waterjet under high pressure led to a satisfying bond behavior between the old concrete and new shotcrete/mortar layers. A failure between the two has not been observed in any test.
- Lap-shear tests, performed in order to study the bond behavior of the externally bonded reinforcement in the free length of the bridge girder, revealed the superiority of the mortar type 2 compared to type 1. Even though the latter exhibited higher anchorage resistance in one-layer applications (15 mm), its performance in terms of ultimate load was considerably reduced in multi-layer applications because of a debonding failure at the interface between two mortar layers. The first type on the other hand was able to offer more stable failure levels with each time a distinct failure not between the mortar layers but between the CFRP strip and the mortar.
- A direct comparison with lap-shear tests performed on concrete blocks with a dry shotcrete layer (layer thickness was in both cases 50 mm) did not reveal any considerable differences. This shows that both materials, dry shotcrete and the hand-applied mortar, are equivalent when it comes to a lap-shear bond behavior with a fully cured epoxy adhesive.
- The study on the behavior of dry shotcrete and a hand-applied mortar during the gradient anchorage application by means of the prestress force-releasing tests shows that both configurations are similar in terms of anchorage resistances. The dry shotcrete specimens, however, exhibited a clearer failure in the cementitious substrate, whereas the ones with a hand-mortar application showed a more ambiguous failure type possibly between two mortar layers. The first mode is in this case always preferred to a possible interface (between two mortar layers) delamination.
- At a load level of 50 kN for the gradient anchorage, both solutions were easily able to deliver the necessary anchorage resistance, with a less pronounced microcrack development in the dry shotcrete specimen (s).
- An application of a cementitious mortar by hand is not to be recommended. The spraying of dry shotcrete is more practical and faster than a mortar application by hand. Even thicknesses up to 50 mm could be handled in one working process, whereas a mortar application by hand was more difficult due to the fact that several layers had to be subsequently put in place.

The above listed conclusions result in the recommendation, that dry shotcrete is a very suitable technique for such levelling applications. Some preparations and precautions are certainly necessary, but the involvement of a specialized company led to an excellent quality of the performed work and subsequently very promising test results.

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