Mechanical anchorage of CFRP sheets retrofitting masonry walls

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ABSTRACT: An extensive experimental campaign on mechanical anchorages in different configurations for anchoring carbon fiber reinforced polymer (CFRP) sheets has been carried out at UAS Fribourg. Static tensile tests have been conducted to enhance the understanding of the anchorage's behavior and identify the associated limits.

The experimental results show that the tested materials and configurations rely immensely upon details. The sensitivity of the CFRP sheet to edges, non-uniformities on any adherend, and bonding defects can cause premature CFRP failure and, hence, pose problems for the design of a retrofit. In many configurations, these problems cannot be satisfactorily controlled. Nevertheless, tests also showed that effective anchorage can be achieved if the configuration of the mechanical anchorage is kept sufficiently simple and if appropriate materials are used.

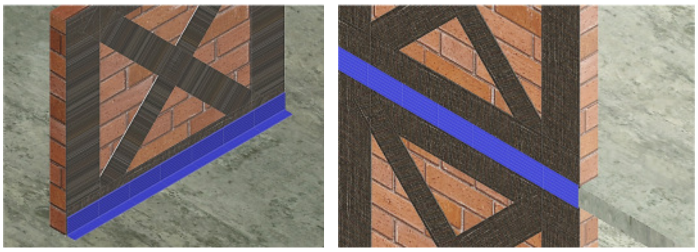
1 INTRODUCTION

A retrofit of unreinforced masonry (URM) walls using carbon fiber reinforced polymer (CFRP) sheets can be performed swiftly and without deep intervention in the load carrying structure of the building. Furthermore, CFRP is resistant to corrosion. Nevertheless, an efficient retrofitting of URM walls by means of composite material is only possible if the component strength can be exploited. The anchorage of the high tensile stresses in composite materials to adjacent concrete is therefore crucial. In tests on retrofitted URM walls conducted by Suter & Grisanti 2010, fiber stresses up to 950 N/mm^2 occurred and, hence, had to be anchored. However, the mechanical anchorages for composite materials retrofitting URM walls have often been neglected which lead to highly over dimensioned steel profiles (e.g. ElGawady 2004).

The mechanical anchorage of CFRP sheets was studied in detail at UAS Fribourg in three series of experiments, namely Series C, H and F. Studies on masonry reinforcement by carbon nets embedded in reactive mortar were also conducted but are not presented in this paper.

2 EXPERIMENTAL PROGRAM

Generally, two different implementations of mechanical anchorages are possible, depending on the location of URM walls in buildings to be retrofitted. For interior walls, the CFRP sheets have to be anchored in the slab perpendicular to the wall, whereas for exterior walls, the CFRP sheets can be anchored in the slab edge (Figures 1a and 1b). Series C was conducted to study the former problem whereas Series F was conducted to study the latter problem. Series H was carried out in order to understand the bonding behavior of CFRP sheets on metallic adherends.

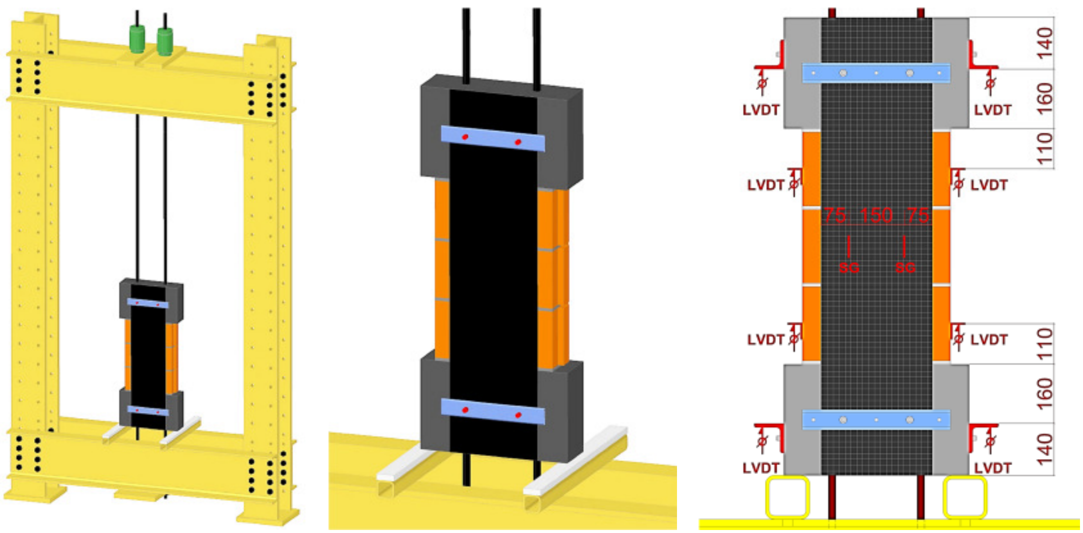


Figures 1a and 1b: Implementation of anchorage for interior walls (left) and for exterior walls (right)

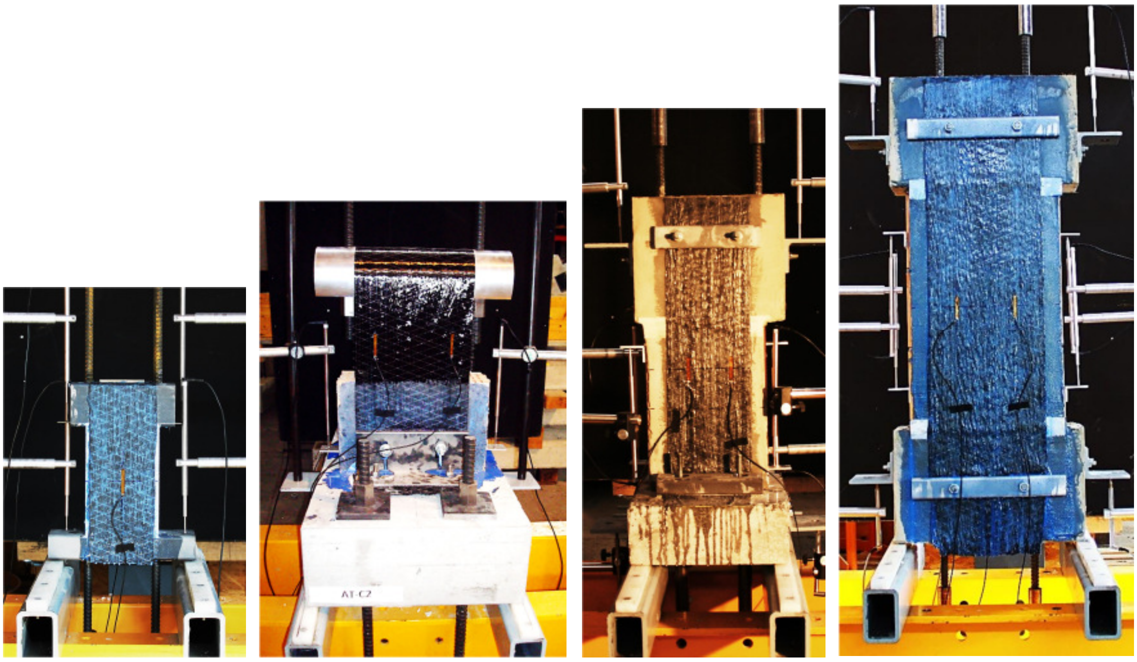
Two different CFRP sheets were used in the presented experiments: the S&P C-Sheet 240 200 g/m^2 and the S&P C-Sheet 240 400 g/m^2. For the mechanical anchorage, either steel or aluminum profiles were used as adherends. To assure intimate contact between adherend and adhesive, the adherend was grit-blasted and cleaned before bonding. The material properties of the CFRP sheets and the adhesive used in the experiments are given in Table 1. The test set-up and four typical specimens of all experimental series are shown in Figures 2a to 2c and Figures 3a to 3d, respectively.

Table 1: Properties of CFRP sheets (linear-elastic range) and adhesive given by manufacturer

CFRP sheets		S&P C-Sheet 240 200 g/m^2	S&P C-Sheet 240 400 g/m^2
	Elastic modulus E [N/mm^2]	240,000	240,000
	Theoretical tensile strength per fiber f_u [N/mm^2]	3,800	3,800
	Theoretical design cross section 1 m width [mm/m]	117	234
Adhesive		S&P Resicem	
	Elastic modulus E at +20°C. [N/mm^2]	4,820	
	Tensile strength after 14 days f_u [N/mm^2]	22	
	Pull off strength on concrete [N/mm^2]	> 4 (failure in concrete)	
	Pull off strength on steel [N/mm^2]	> 10.6	



Figures 2a to 2c: Overview of test set-up (left); Detail of test set-up in Series F (middle); Measurements in Series F with SG = strain gauge and LVDT = Linear variable differential transformer (right)



Figures 3a to 3d: Test specimen in Series H, Series C (C2 and C9), and Series F (from left to right)

3 EXPERIMENTAL SERIES H

The test specimens in Series H were made of two steel rectangular hollow section (RHS) profiles with a polystyrene cuboid in-between, bonded with 150 mm wide CFRP sheets at the front and back side (Figure 3a). The lower RHS profile was anchored while the upper RHS profile was pulled. The CFRP sheets, thus, transferred the pulling force from one RHS profile to the other. The upper RHS profile was longer than the lower one so as to assure a longer bond length at the upper profile. Therefore, failure would occur at the lower RHS profile if the bonded length was smaller than the effective bond length, beyond which the adhesive joint load capacity does not increase. The curvature of the RHS profiles was filled with Silicone in tests H1 to H4 and with Sikaflex®-11 FC in tests H9 to H12 in order to guarantee a smooth bonding surface. The characteristics and test results of Series H are given in Table 2.

Table 2: Characteristics and results (maximum applied load and tensile stress) of Series H

Specimen	Type of S&P C-Sheet	Anchorage profile (lower RHS profile)	Bonded length [mm]	F_{max} [kN]	σ_{max} [N/mm^2]
H1	240 200 g/m^2	RHS 100/60/5	45.0	51	1,442
H2	240 200 g/m^2	RHS 100/60/5	45.0	71	2,022
H3	240 200 g/m^2	RHS 100/100/5	85.0	62	1,772
H4	240 200 g/m^2	RHS 100/100/5	85.0	70	2,002
H9	240 400 g/m^2	RHS 100/60/6.3	41.1	120	1,715
H10	240 400 g/m^2	RHS 100/60/6.3	41.1	138	1,972
H11	240 400 g/m^2	RHS 100/100/6.3	81.1	137	1,956
H12	240 400 g/m^2	RHS 100/100/6.3	81.1	110	1,572

If shear bond stress is assumed to be uniformly distributed over the whole bonded surface, the maximum load of 138 kN in test H10 corresponds to a shear bond stress of 11.2 N/mm^2. Considering the actual shear bond transfer over the effective bond length described by a hyperbolic behavior up to the maximum bond shear stress and a harmonic behavior subsequently, when assuming a bilinear bond-slip-model (according to Fernando 2010 for linear adhesives), the maximum bond shear stress has to be significantly higher.

Given the rather high maximum applied fiber tensile stresses reached in Series H, the bonded length of 40 mm for S&P aluminum profiles, used as mechanical anchorage in Series C and F, can be considered as sufficiently long for both S&P C-Sheet 240 200 g/m^2 and S&P C-Sheet 240 400 g/m^2.

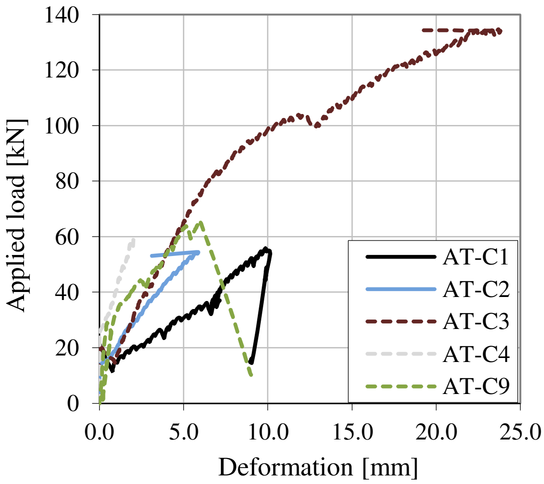
4 EXPERIMENTAL SERIES C

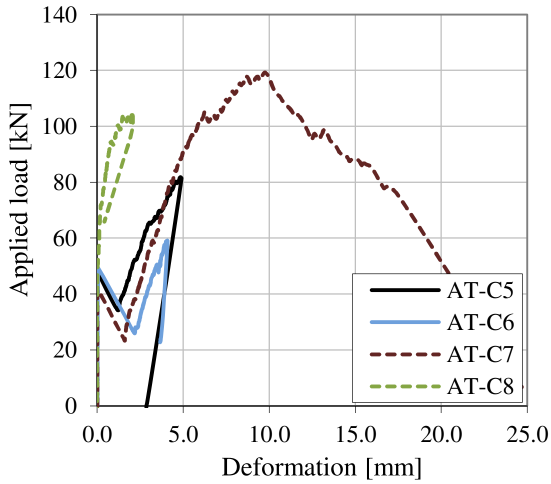
For test specimens C1 to C8, a masonry brick was placed on an anchored reinforced concrete block (Figure 3b). For test specimen C9, two masonry bricks were placed between an upper, vertical concrete block and an anchored lower, horizontal concrete block (Figure 3c). The configuration in test C9 allowed for a uniformly bonded surface between the CFRP sheet and the concrete blocks as well as between the CFRP sheet and the masonry bricks. The masonry and concrete surfaces were leveled and uniformed by applying a leveling compound. For specimens C1 to C8, a 300 mm wide carbon fiber sheet was applied whereas for specimen C9, a 200 mm wide carbon fiber sheet was applied.

In tests C1 to C4 and C9, RHS steel profiles were used whereas in tests C5 to C8, L-formed steel profiles were used for the mechanical anchorage. When using RHS profiles, the CFRP sheet is bonded to two sides of these profiles and, hence, undergoes a change of direction. In order to study the consequences caused by different magnitudes of diverting stresses in the curvature of the mechanical anchorage, the curvature radius was varied between set-ups.

The steel profile was vertically anchored in the concrete block with mechanical fasteners for tests C1 to C8 and with steel rods encased in the concrete block for test C9. For tests C2 to C8, horizontal anchors were applied to avoid the turning effect brought about by the eccentricity of the loaded carbon fibers with respect to the vertical fasteners. In tests C1 to C8, the CFRP sheets were pulled by an aluminum cylinder. In test C9, S&P aluminum profiles bonded to the CFRP sheets and anchored in the upper, vertical concrete block with encased steel rods were used for pulling the CFRP sheets.

The characteristics and test results of Series C are summarized in Table 3 and the corresponding load-displacement curves are given in Figures 4a and 4b (displacement between concrete block and aluminum cylinder for C1 to C8 and between concrete blocks for C9).





Figures 4a and 4b: Load-displacement curve of Series C (left: RHS profiles, right: L-profiles)

Table 3: Characteristics and results (maximum applied load and tensile stress) of Series C

Specimen	Type of S&P C-Sheet	Anchorage profile	Curvature radius [mm]	Anchorage in slab	Anchorage in brick	F_{max} [kN]	σ_{max} [N/mm^2]
C1	240 200 g/m^2	RHS 60/60/5	10.0	2xM12	-	56	795
C2	240 200 g/m^2	RHS 120/120/5	10.0	2xM12	2xM12	54	775
C3	240 400 g/m^2	RHS 120/120/5	10.0	2xM16	2xM12	136	968
C4	240 400 g/m^2	RHS 120/120/8	16.0	2xM16	2xM12	59	423
C5	240 200 g/m^2	LNP 150/100/10	-	2xM12	2xM12	82	1,166
C6	240 200 g/m^2	LNP 200/100/10	-	2xM12	2xM12	59	842
C7	240 400 g/m^2	LNP 150/100/10	-	3xM12	2xM12	119	849
C8	240 400 g/m^2	LNP 200/100/10	-	3xM12	2xM12	108	741
C9	240 200 g/m^2	RHS 80/40/8	16.0	2xM12 encased	-	82	1,407

As can be observed, the mechanical anchorage behaved very stiffly at the beginning of the loading process. This is owed to the tensile strength and the stiffness of the mortar connecting the anchored concrete block with the masonry brick. After the mortar's tensile failure, the system's stiffness highly depends on the presence of horizontal fasteners and the stiffness of the vertical anchorage (mechanical fastener for specimens C1 to C8 or encased by steel rods for C9). This is due to the different behavior of the mechanical anchorage under the bending moment, which is provoked by the eccentricity of the loading with respect to the vertical anchorage. If the rotation of the steel profile is not inhibited, failure always occurs in the curvature of the mechanical anchorage and concrete failure is the limiting factor. Horizontal fasteners can possibly increase the load that can be anchored. However, they raise new system weaknesses and therefore result in a number of different failure types.

In Series C, three different failure types occurred:

1. Rupture of CFRP sheet due to stress concentrations at the curvature (C1), at the edge of the steel profile (C2, C6, C9), or at the edge of the masonry brick (C4, C5):
   Changes of the fiber direction, edges, or bonding defects (e.g. by adhesive accumulation) causing stress concentrations or non-uniform stress distribution along the CFRP sheet lead to highly loaded fibers and, in most cases, subsequently to premature failure. In specimen C1, failure happened in the curvature of the steel profile caused by diverting stresses perpendicular to the fiber direction. Already little deformation of the mechanical fasteners caused a rotation of the anchoring steel profile. This rotation triggered immediate debonding due to peeling. Numerical analyses on mixed-mode bond behavior in Bischof (2011) have shown that bond shear capacity already drops drastically with small inclinations. Only the bonded joint between the CFRP sheet and the lower horizontal part of the steel profile allowed a further increase of the applied load. In specimens C2, C4, C5, C6, and C9, edges or bonding defects caused premature CFRP failure.
2. Anchorage failure with fracture cone in concrete due to fastener load (specimens C3, C7):
   As the anchorage strength in the concrete can only be enhanced to limited extents, the limited anchorage capacity in the concrete can significantly diminish the performance of slender mechanical anchorages for retrofitted masonry walls.
3. Debonding at vertical part of steel profile (C8):
   This failure occurred unexpectedly early, compared to the experiment results in Series H. Stress concentrations highly influence the bonding behavior and might therefore be the reason for this premature failure.

The failed specimens C1, C2, C3, and C8 are shown in Figures 5a to 5d.

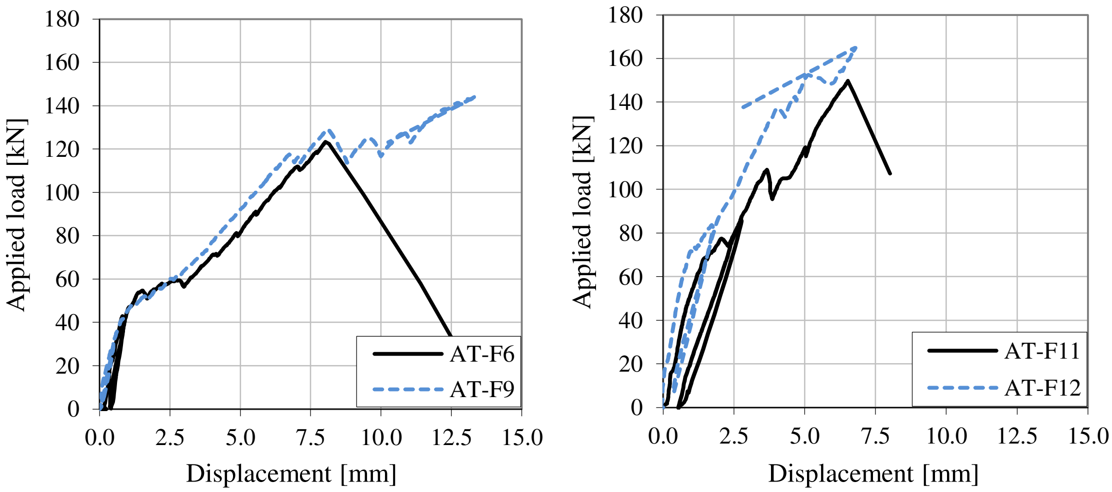
Figures 5a to 5d: Failed specimens C1, C2, C3, and C9 (from left to right)

It has been shown in Series C that detail effects enormously influence the behavior of the mechanical anchorage of CFRP sheets. By impeding anchorage failure of mechanical fasteners in the concrete in test C9, higher fiber tensile stresses could be reached. No conclusions can be drawn from Series C concerning the influence of the curvature radius of the profile incorporating the mechanical anchorage.

5 EXPERIMENTAL SERIES F

For the specimens of Series F, three masonry bricks were placed between two concrete blocks with encased threaded steel rods; two vertical rods for applying the test load and two horizontal rods for fastening the mechanical anchorage (S&P aluminum profiles). The masonry and concrete surface was leveled and uniformed by applying a leveling compound. After adding adhesive to the surface, 300 mm wide carbon fiber sheets were applied on front and back side and the aluminum profiles were fastened (Figure 3d).

Table 4 summarizes the characteristics and test results of Series F and Figures 6a and 6b show the associated load-displacement curves (displacement between two concrete blocks). In Figure 7, the fiber stress, measured by strain gauges, and total stress are compared. In Figures 8a to 8d, specimens F6, F11, and F12 are shown after complete failure and specimen F9 is shown after bonding failure of the interface concrete-CFRP.



Figures 6a and b: Load-displacement curve of Series F (left: C-Sheet 200 g/m^2, right: C-Sheet 400 g/m^2)

Table 4: Characteristics and results (maximum applied load and tensile stress) of Series F

Specimen	Type of S&P C-Sheet	Anchorage profile	Anchorage length [mm]	F_{max} [kN]	σ_{max} [N/mm^2]
F6	240 200 g/m^2	S&P Aluminum profile	40.0	123	1,757
F9	240 200 g/m^2	S&P Aluminum profile	40.0	145	2,059
F11	240 400 g/m^2	S&P Aluminum profile	40.0	150	1,066
F12	240 400 g/m^2	S&P Aluminum profile	40.0	165	1,174

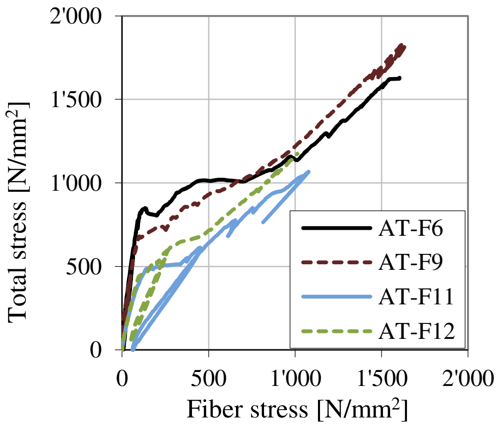


Figure 7: Comparison of measured fiber stress (strain gauges) and total stress (F/A_{Fiber}) in Series F

Figures 8a to 8d: Failed specimens F6, F11, and F12 and specimen F9 before failure (from left to right)

As in Series C, the anchorage system is initially very stiff due to the tensile strength of the mortar that connects the concrete blocks and the masonry bricks. Obviously, the mortar's tensile failure occurs at approximately the double fiber stress for the S&P C-Sheet 240 200 g/m^2 with respect to the S&P C-Sheet 240 400 g/m^2 (see Figure 7). After the mortar's failure, the load is completely transferred to the CFRP sheet. Fibers which are not perfectly arranged in the load direction either fail or orientate towards the load direction in a "transition phase" before all fibers are fully loaded (the curve in Figure 7 approaches a 45°-angle). In tests F9, F11 und F12, the CFRP sheet peeled from the concrete block. Both the joint between CFRP sheets and metallic mechanical anchorage as well as between CFRP sheets and concrete interact until the abrupt failure of the latter (Figure 8d). Afterwards, further load increase was possible. Consequentially, the tensile strength of CFRP sheets can better be exploited by metallic mechanical anchorage than by anchorage on concrete or masonry only. Debonding only occurred in test F11, most probably because adhesive leaked from under the S&P aluminum profile before curing and left about a third of the contact surface between CFRP sheet and mechanical anchorage unbonded on both the front and the back side. Interestingly, experiment specimen F9 showed a "quasi-ductile" behavior by repeated failure of fibers at an applied load around 120 kN.

In Series H, the magnitude of applied fiber stresses, which could be mechanically anchored on steel profiles, was similar for both S&P C-Sheets 240 200 g/m^2 and S&P C-Sheets 240 400 g/m^2. In Series F, however, the specimens retrofitted with S&P C-Sheets 240 400 g/m^2 did not reach the expected level of load application. Small irregularities, e.g. adhesive bonding problems in specimen F11, weaken the anchorage system and, usually, cause premature failure.

6 CONCLUSION

The static tensile tests conducted on the mechanical anchorage of CFRP sheets show that the tested materials and configurations depend immensely on details. The sensitivity of the CFRP sheet to edges, non-uniformities on any adherend, and bonding defects can cause premature CFRP failure and, hence, pose problems for the design of a retrofit. Especially for the configuration tested in Series C, these problems cannot be satisfactorily controlled. Nevertheless, the results in Series H and Series F show that effective anchorage can be reached if the configuration of the mechanical anchorage is kept simple and if appropriate materials are used. From Series H, it can be concluded that the bonded length of 40 mm is sufficiently long for both CFRP sheets used.

In Series F, anchorage was reliably achieved. It was established that the mortar between concrete and masonry influences the system's stiffness up to its failure. Bonded joints between CFRP sheets and metallic mechanical anchorage as well as between CFRP sheets and concrete interact until the latter fails. Consequentially, the tensile strength of CFRP sheets can be better exploited by metallic mechanical anchorage than by anchorage on concrete or masonry only.

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