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Retrofitting masonry walls with carbon mesh

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ABSTRACT: Static-cyclic load tests and static tensile tests on retrofitted masonry were conducted at UAS Fribourg for a first evaluation of the S&P ARMO-system, a composite of carbon mesh embedded in high reactive mortar developed by S&P Clever Reinforcement Company. This system can be applied with established construction techniques using traditional construction materials.

The experimental study has shown that the ARMO-system provides a reasonable reinforcement of masonry walls. Retrofits by means of this system reach a similar strength and a higher ductility than retrofits by means of bonded CFRP sheets. Hence, the ARMO-system constitutes a good option for static or seismic retrofits. However, the experimental study also revealed that the mechanical anchorage of carbon mesh may be delicate depending on its design.

1 INTRODUCTION

Retrofitting of masonry walls has been a major research topic at UAS Fribourg since 2007. Theoretical and experimental studies have mainly focused on the use of high performance fibers (carbon, glass, aramid) in different applications.

This paper presents an experimental study of a newly developed retrofitting system (S&P ARMO-system). The system consists of a coated carbon mesh (unidirectional or bidirectional bundles of carbon fibers), which is embedded in specially adapted high resistant mortar: a one-component product based on inorganic binders, fibers, selected aggregates, and polymer. The bonding capacity between carbon fibers and mortar is achieved by amorphous silica coated on fibers and a reactive component added to the mortar, both reacting to a calcium-silicate-hydrate.

This system can be applied with established construction techniques using traditional construction materials. The retrofit of masonry walls by means of the ARMO-system is cost-efficient as the application of this reinforcement system can be carried out without experts, renouncing the usage of synthetic products, such as polymeric adhesive and leveling compound, and does not require extensive surface preparation.

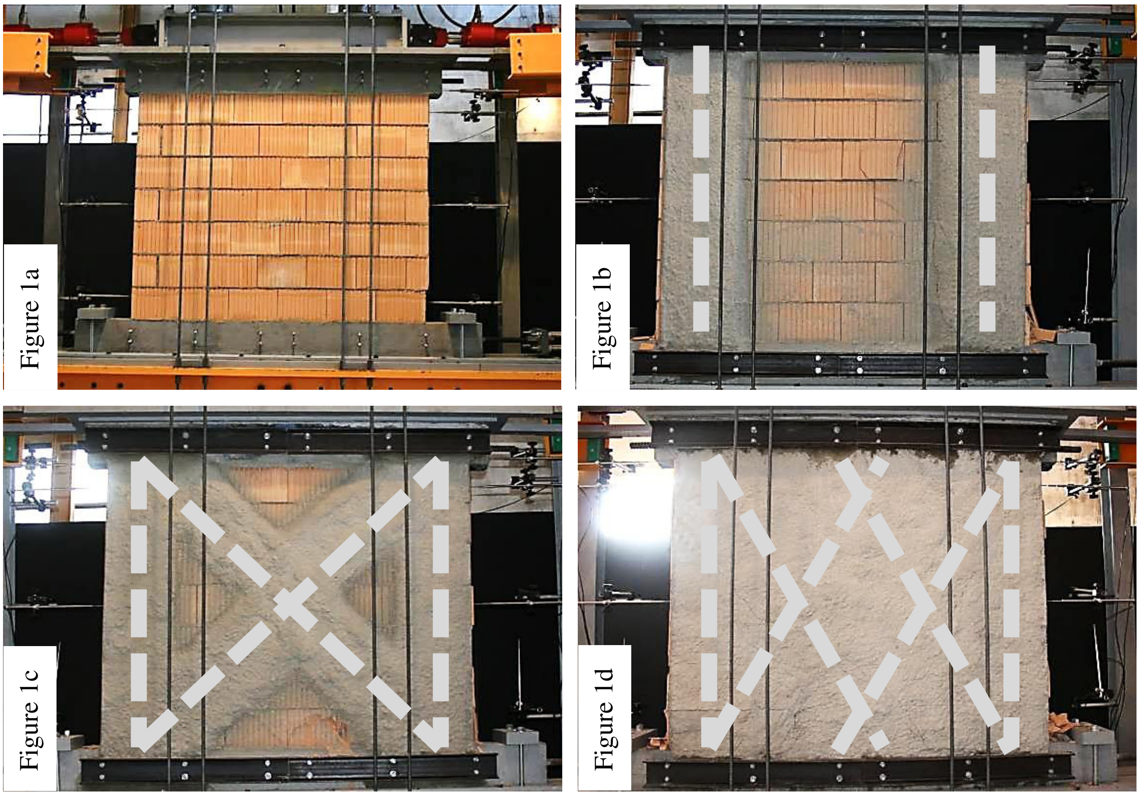
After cleaning masonry and concrete surfaces with a high pressure water gun, a first layer of mortar is applied. The carbon mesh is placed upon this layer whereby it is important to orientate and pre-stress all the carbon fibers of the mesh. Then, a second layer of mortar is applied. The whole retrofit results in a thickness between 15 mm and 25 mm. If necessary, two layers of carbon meshes can be used resulting in a thickness between 25 mm and 35 mm.

In order to study the S&P ARMO-system, three experimental series were conducted: The first series, Series MR-C, studied the behavior of retrofitted masonry walls under static-cyclic loading. In the second series, Series MT-A, static tensile tests were conducted on retrofitted masonry walls for studying the mechanical anchorage of carbon mesh embedded in different types of mortar. In the third series, Series AT-F, the mechanical anchorage of carbon mesh in adjacent concrete slabs or walls was analyzed. This report gives an overview of the first two experimental series, whereas the tests on the mechanical anchorage are described in Bischof & Suter (2013).

2 STATIC-CYCLIC TESTS ON RETROFITTED MASONRY WALLS

In Series MR-C, five masonry walls (height: 1,400 mm, length: 1,800 mm, thickness: 150 mm) were tested. Four were retrofitted by the S&P ARMO-system with the S&P ARMO-mesh L500 (200 g/m2, width: 300 mm), whereas one served as a reference wall without retrofit. The reinforcement was only applied on one face of each wall. Even though this creates a small eccentricity, the influence on the shear capacity and the deformability is negligible (Suter & Broye, 2009). The tested configurations are summarized in Table 1 and Figures 1a to 1d.

The masonry walls were built between two RC-beams (length: 2,000 mm, cross section: 150 x 200 mm), which represented RC-slabs below and above the masonry wall. The carbon mesh was mechanically anchored with U-formed steel profiles (UPN 120), which were themselves anchored in the RC-slabs. The vertical and the horizontal load were applied through the upper RC-beam.



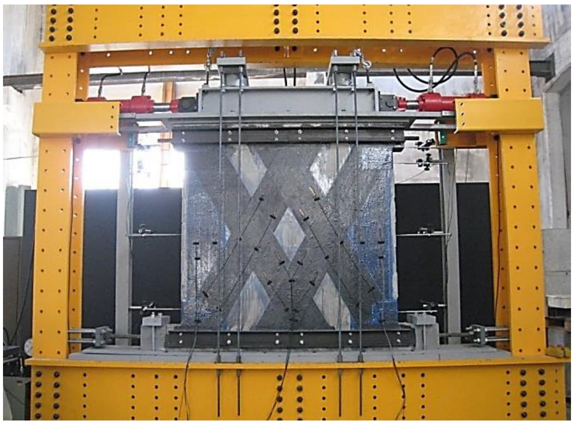
Figures 1a to 1d: Different configurations of carbon mesh for retrofitting masonry walls in Series MR-C. a: MR-C1, b: MR-C2, c: MR-C3 / MR-C4 (two layers), d: MR-C5

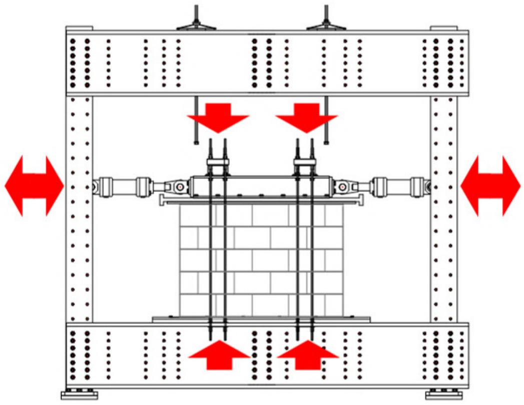
Table 1: Tested configurations of retrofitted masonry walls in Series MR-C

MR-C1	Reference wall, no retrofit
MR-C2	Two vertically applied carbon mesh strips
MR-C3	Two vertically and two diagonally (45°) applied carbon mesh strips
MR-C4	Two vertically and four diagonally (45°, two layers) applied carbon mesh strips
MR-C5	Two vertically and four diagonally (60°) applied carbon mesh strips

The static-cyclic load tests in Series MR-C were carried out on a set-up specifically designed for this research project (Figures 2a and 2b). This test set-up allowed for the application of normal and horizontal forces at the same time. The static-cyclic test process was performed as follows:

- Firstly, a vertical load corresponding to a distributed load of 0.5 N/mm^2 was applied by two hydraulic actuators with a capacity of 1,000 kN each. This vertical load was kept constant during the entire test.
- Secondly, a horizontal load was applied by two actuators with a capacity of +200/-300 kN each. Both were independently connected to an individual hydraulic system. The horizontal force was progressively and alternatively increased on each side, until the first crack occurred. The test was then driven by deformation until the ultimate limit state was reached and complete failure occurred.



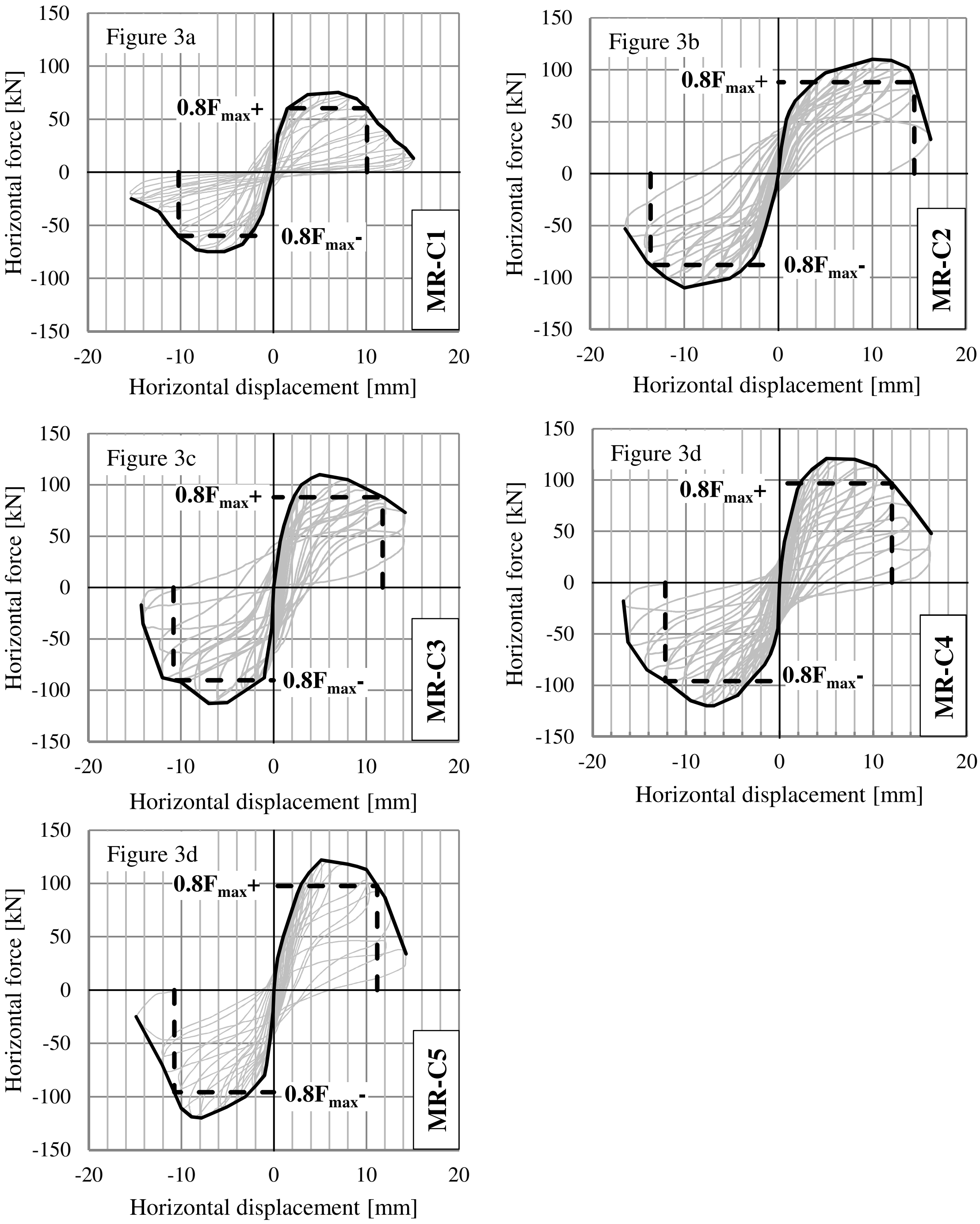


Figures 2a and 2b: Set-up for static-cyclic load tests

The load-displacement curves of the retrofitted masonry walls in Series MR-C are shown in Figures 3a to 3e. A summary of the maximum applied load and the maximum reached deformation at the top of the wall is given in Table 2.

Up to a horizontal load of 50 kN and a horizontal deformation of 1 mm, all five walls behaved very stiffly. For specimens MR-C1 and MR-C2, cracking then initiated with an angle of about 60° with respect to the horizontal, which corresponds to the inclination of the diagonal compression strut. For specimens MR-C3 to C5 with shear reinforcement, the masonry remained without cracks up to a horizontal force of about 80 kN. In all cases cracking initiated at the lower angles of the masonry wall due to the superposition of the diagonal compression strut and the axial normal force.

Compared to the reference wall (MR-C1), the ultimate load was increased by up to 61% (MR-C5), whereas the deformability was increased up to 38%. The maximum applied load and the deformation behavior in Series MR-C are mostly equivalent to the ones received in the experimental series with bonded CFRP sheets retrofitting masonry walls (Series MR-B, Suter & Grisanti, 2010). The vertical reinforcement inhibits rocking whereas the diagonally applied reinforcement strongly enhances the shear capacity. The closer the inclination angle of the diagonal carbon strips moves from 45° towards 90° with respect to the horizontal, the less the shear capacity is enhanced. Failure always happened when the masonry wall reached its compression capacity, either locally at the lower angles for specimens without shear reinforcement or over the whole length for specimens with shear reinforcement. The failed specimens are shown in Figures 4a to 4d.



Figures 3a to 3e: Load-displacement curves in series MR-C caused by horizontal loading at the top of the masonry wall

Table 2: Horizontal force and maximum displacement at the top of the wall in Series MR-C

	F_{max}^{+} [kN]	F_{max}^{-} [kN]	Comparison to reference wall	$0.8F_{max}^{+}$ [kN]	$0.8F_{max}^{-}$ [kN]	δ_u^{+} [mm]	δ_u^{-} [mm]	Comparison to reference wall
MR-C1	75.2	76.8	100%	60.2	61.4	10.1	10.2	100%
MR-C2	110.0	110.0	145%	88.0	88.0	14.5	13.6	138%
MR-C3	109.0	114.0	147%	87.2	91.2	11.8	10.8	111%
MR-C4	121.0	120.0	159%	96.8	96.0	12.0	12.2	119%
MR-C5	121.0	122.0	161%	96.8	97.6	10.8	11.2	108%

Figures 4a to 4d: Failed specimens in Series MR-C. a and b: MR-C2, c: MR-C3, d: MR-C5 (from left to right)

3 STATIC TENSILE TESTS ON RETROFITTED MASONRY WALLS

In Series MT-A, static tensile tests were carried out on masonry walls retrofitted with carbon mesh. The deformation and the cracking of tensile elements have been analyzed in detail. The tensile tests were conducted on a test setup which allowed for a uniform load application up to 1,000 kN and for deformations up to 160 mm (Figures 5a and 5b). The tests could either be carried out controlling the load application or controlling the deformations. Six masonry walls (height: 1,800 mm, width: 600 mm, thickness: 150 mm) were retrofitted by embedding coated carbon mesh into the mortar on both front and back sides. For the load application on the carbon fibers and their mechanical anchorage, concrete blocks were installed at the top and at the bottom (Figures 7a and 7b). The following parameters were varied throughout Series MT-A: quality of mortar, thickness of carbon mesh, and mechanical anchorage.

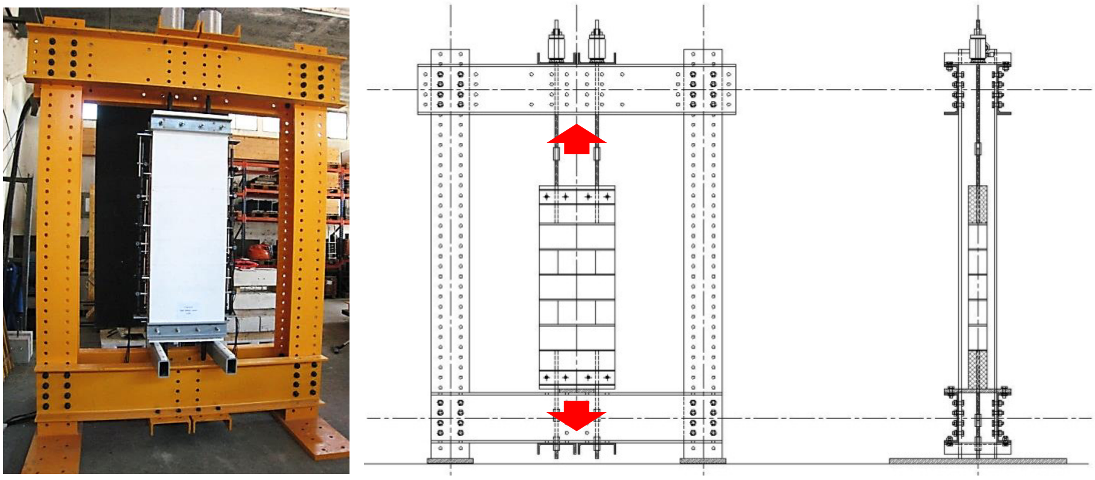
The S&P ARMO-system was principally developed for the reinforcement of existing structures. However, it may possibly be used for new masonry walls also. The tensile tests were not only carried out with the mortar S&P ARMO-crete, specifically developed for the S&P ARMO-system, but also with standard mortar used as exterior (Fixit 610, PC mortar) and interior plaster (Fixit 180, low resistant mortar). By embedding the carbon mesh in the mortar, “reinforced masonry walls” can be constructed. This should allow for enough resistance against medium seismic loading.

In specimens MT-A1/A2/A3/A4, the carbon mesh was mechanically anchored through U-formed steel profiles (UPN 120), which were fastened and pressed against the composite mesh-mortar. In specimens MT-A5 and MT-A6, the carbon mesh was mechanically anchored by being wrapped around aluminum profiles, which were fastened in the concrete blocks. These aluminum profiles were developed for the S&P ARMO-system.

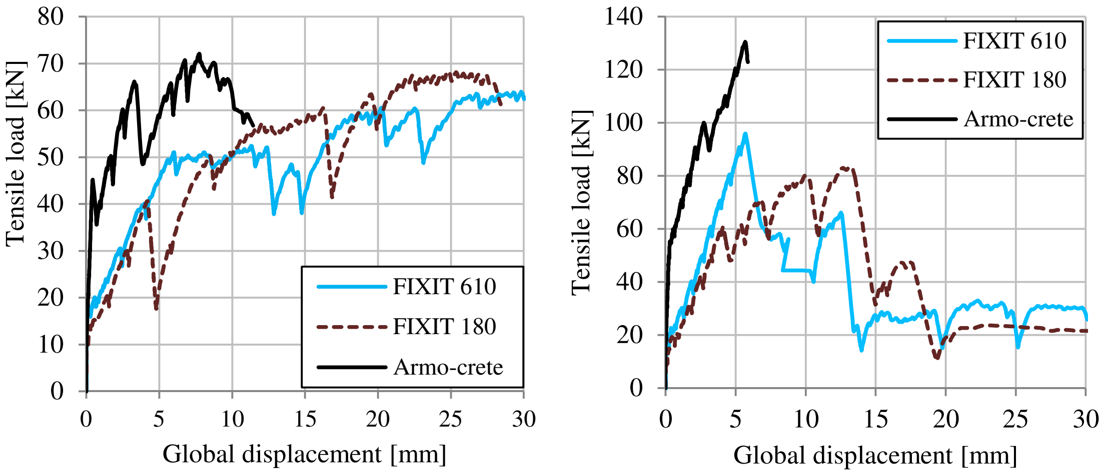
The resulting six configurations are summarized in Table 3 together with the maximum applied loads and their corresponding fiber stresses. The load-displacement curves of the static tensile tests with the lighter carbon mesh L200 and with the heavier carbon mesh L500 are shown in Figures 6a and 6b.

Table 3: Tested configurations of retrofitted masonry walls and test results of Series MT-A

	Configuration	F_{max} [kN]	σ_{max} [N/mm^2]
MT-A1	ARMO-mesh L500 (114 mm^2/m'), embedded in Fixit 610	95	677
MT-A2	ARMO-mesh L200 (46 mm^2/m'), embedded in Fixit 610	64	1,159
MT-A3	ARMO-mesh L500 (114 mm^2/m'), embedded in Fixit 180	84	598
MT-A4	ARMO-mesh L200 (46 mm^2/m'), embedded in Fixit 180	68	1,232
MT-A5	ARMO-mesh L500 (114 mm^2/m'), embedded in S&P ARMO-crete	132	940
MT-A6	ARMO-mesh L200 (46 mm^2/m'), embedded in S&P ARMO-crete	73	1,322



Figures 5a and 5b: Test set-up for static tensile tests on retrofitted masonry walls.



Figures 6a and 6b: Load-displacement curves of specimen MT-A2/A4/A6 (left) and MT-A1/A3/A5 (right)

The behavior of the masonry walls until first cracks occur depends on the mechanical properties of the mortar. For Fixit 610, the first cracks occur at an applied tensile load of approximately 20 kN corresponding to 0.2 N/mm^2 in the mortar. For Fixit 180, the first cracks occur at an applied tensile load of 10 kN. For S&P ARMO-crete, the first cracks occur at a considerably higher load of approximately 50 kN.

The carbon fibers cannot be sufficiently anchored by pressing the steel profile against the mortar, as the considerable difference of the maximum applied tensile load in MT-A1 and MT-A3 with carbon mesh L500 compared to the maximum applied tensile force in MT-A2 and MT-A4 with carbon mesh L200 shows. In MT-A5 and MT-A6, where the carbon mesh was wrapped around the mechanical anchorage, the maximum applied tensile loads were higher. Nonetheless, a different anchorage weakness occurred. The carbon mesh is prone to premature fiber rupture if stress concentrations occur due to non-uniform pre-stress conditions. These pre-stress conditions, however, are very difficult to control.

Figures 7a to 7c: Test specimen before retrofitting, after retrofitting, and after failure (from left to right)

4 CONCLUSION

Static-cyclic load tests as well as static tensile tests on retrofitted masonry have been conducted at UAS Fribourg for a first evaluation of the S&P ARMO-system.

The static-cyclic load tests have shown that masonry walls retrofitted by the S&P ARMO-system demonstrate practically identical behavior as masonry walls retrofitted by bonded CFRP sheets or plates and, hence, represent an equivalent alternative to these other retrofitting techniques of masonry. By applying CFRP sheets or carbon meshes as reinforcement to masonry walls, a new inner state of stress is generated. The reinforcement acts as a tension strut, whereas the masonry acts as a compression strut. The analysis of this tension and compression strut creates the possibility to design according to the truss analogy (Figure 8) or to stress fields. Obviously, the vertical component induced by the horizontal force due to seismic loading must be added to the vertical load acting on the wall without seismic loading.

The static tensile tests on the lighter S&P ARMO-mesh L200 (46 mm^2/m’) have shown that mean fiber stresses between 1,200 and 1,300 N/mm^2 can be reached. The static tensile tests on the heavier S&P ARMO-mesh L500 (117 mm^2/m’) lead to mean fiber stresses between 700 and 900 N/mm^2. However, it should be possible to increase this limit to a range between 1,000 and 1,200 N/mm^2 by improving the mechanical anchorage.

The results of the static tensile tests revealing the considerably lower performance of commercial mortar as opposed to S&P ARMO-crete for embedding the carbon mesh have proven the effectiveness of the latter.

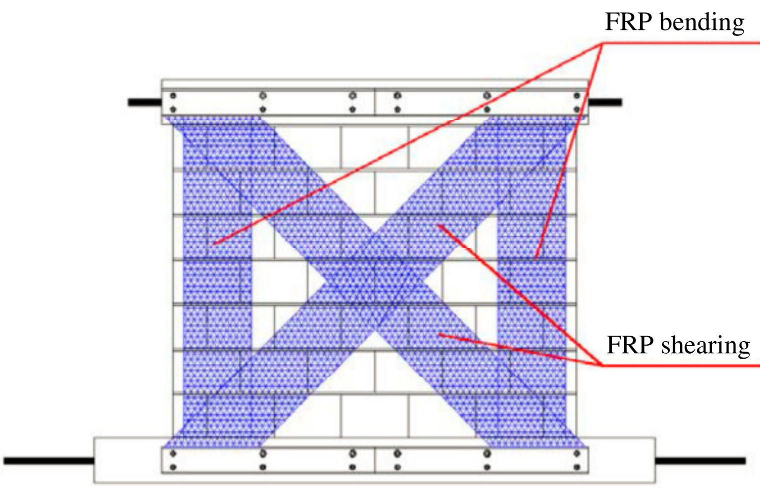


Figure 8: State of stress in retrofitted masonry wall

Overall, the various experiment series on masonry walls retrofitted with carbon mesh have brought about positive results and interesting findings. They confirmed the applicability of retrofits of masonry walls by means of the S&P ARMO-system. However, more studies are necessary for conclusive judgment.

A crucial detail for functioning retrofits of masonry walls by means of carbon meshes is the mechanical anchorage of the tensile loads in the adjacent concrete slab. Detailed studies on mechanical anchorages have been conducted at UAS Fribourg and are presented in Bischof (2013).

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