

FLEXURAL STRENGTHENING OF MASONRY MEMBERS USING ADVANCED CEMENTITIOUS MATERIALS

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Abstract

Two different cement based fiber reinforced composites for the flexural strengthening of masonry beams under monotonic loading are studied. Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) with tensile strain-softening behavior, and PVA fiber reinforced cement based mortar (SHCC) with tensile Strain-Hardening were the developed composites. Both composites were applied on the tensile surface of masonry beams and the effectiveness of this technique for the flexural strengthening of these quasi-brittle structural elements was assessed by performing four point beam bending tests. Both materials contributed effectively to increase the load carrying capacity and ultimate deflection ductility of the tested masonry beams, but, higher average values were obtained for these two indicators of the strengthening effectiveness when using a layer thickness of SHCC that is 2/3 of the thickness of SFRSCC. Furthermore, much more homogenous results, in terms of force-deflection relationship, were obtained with masonry beams strengthened with SHCC than with SFRSCC.

1. INTRODUCTION

Masonry buildings are composed of quasi-brittle materials and, in general, have reduced resistance to seismic events. The detrimental ageing effects on the long term behavior of the materials composing these buildings, changes in their functionality requirements and in the applied load levels and the necessity to improve their behavior against seismic events are the sources of the extensive research carried out on the rehabilitation and strengthening of this type of structures. Surface treatment, grout and epoxy injection, external reinforcement, confinement methods, post tensioning and center core techniques are the most known conventional retrofitting techniques for masonry structures [1].

In the present paper the potentialities of a strain softening steel fiber reinforced self-compacting concrete (SFRSCC) and a SHCC are explored for the flexural strengthening of masonry elements, by applying a thin layer of these composites in the tensile face of these elements. Four point beam bending tests strengthened with these elements were executed to evaluate the increase of load and deformational capacities provided with this strengthening technique.

The SFRSCC developed in the scope of the present research program is reinforced with relatively low steel fiber content, presenting a tensile strain softening and deflection hardening [2, 3].

The SHCC developed in the present research program is reinforced with PVA fibers [4]. This type of cement composites present diffuse cracking patterns under tensile loading, and have high tensile strain ductility with a tensile strength in range of 3 to 6 MPa. Due to the relatively reduced crack width for serviceability limit state conditions (average values of about 60 μm [5]), these SHCCs have high durability and can develop self-healing performance [6]. They can be tailored to present self-consolidating requirement, which is a quite relevant property for the present application, since filling properly the spaces created in the joints between the clay bricks that compose the masonry elements is aimed due to the derived benefits of this strategy in terms of load carrying and energy dissipation capacities in real structural elements where this is possible to execute.

The development and the experimental characterization of the SFRSCC can be found elsewhere [2], while the detailed tailoring process of the SHCC can be in [4]. In the present work the main focus is placed on the mix design composition of the developed SHCCs, the tensile characterization of their behavior and on the assessment of the effectiveness of the flexural strengthening technique based on the use of these two types of fiber cement composites.

2. COMPOSITE DEVELOPMENT

2.1 Mix composition and fresh state properties

SFRSCC Mix Design: To produce SFRSCC, a concrete mix composed of Cement, Limestone filler, fine and coarse aggregates, water and superplasticizer with proportions presented in table 1 was prepared. Hooked end steel fibers of 35 mm in total length with an aspect ratio of 64 and tensile strength of 1100 MPa were mixed into the fresh matrix. The composition of this SFRSCC was formulated following the methodology mainly based on the three following steps: i) the proportions of the constituent materials of the binder paste are defined; ii) the proportions of each aggregate on the final granular skeleton are determined; iii) binder paste and granular skeleton are mixed in distinct proportions until self-compacting requirements in terms of spread ability, correct flow velocity, filling ability, blockage and segregation resistance are met, allowing the determination of the optimum paste content in concrete. A detailed description of the method can be found elsewhere [7]. To evaluate the self-consolidated requirements of the developed SFRSCC, the Slump-Flow, V-Funnel and L-Box tests were performed [8], having been obtained a slump flow of 760 mm with a T_{50} of 4 sec, a flow time of 9 sec in the V-Funnel and a H2/H1 ratio of 0.8 in the L-Box.

SHCC Mix Design: Based on previous research on the development of strain hardening cement composites [9], SHCCs were tailored to present rheological and mechanical properties suitable for the flexural strengthening of masonry elements. For this purpose three different

levels of water/binder (cement and fly ash) ratio, equal to 0.27, 0.30, and 0.35, were adopted, with the maximum allowable concentration of superplasticizer, having been attributed the designations of S27, S30 and S35 to these composites. Cement (C), Type “F” Fly Ash (FA), Fine Silica Sand (S) with maximum grain size of 0.5 mm, superplasticizer (SP), viscosity modifying agents (VMA), water (W) and Polyvinyl Alcohol fibers (PVA) were the main ingredients of cementitious mixes indicated in table 2. Two percent in volume of PVA fibers with 8 mm length, 40 μ m diameter, Young’s modulus of 40 GPa and tensile strength of 1600 MPa were used.

Mini slump flow test was used to measure the deformability of composite mix and the obtained results are reported in table 2. All composite mixes were examined by visual inspection and hand touching for a qualitative assessment of segregation of the mix constituents, bleeding water and fiber clumping. When necessary, the viscosity of the matrix was adjusted by changing the concentration of VMA, in order to obtain a more homogenous composite without clumped fibers. A detailed description of the rheological adjustment of SHCC can be found elsewhere [4].

Table 1: SFRSCC mixing composition per m³ of concrete

cement	water	SP	limestone	fine river sand	Coarse river sand	Crushed granite	Hooked end steel fiber
[kg]	[kg]	[dm ³]	[kg]	[kg]	[kg]	[kg]	[kg]
380.54	111.14	6.09	326.17	368.12	567.95	510.06	45.00

Table 2: SHCC mix proportions

Mix	SP/B	VMA/B	FA/C	W/B	S/B	PVA*	Mini-Slump
-	[%]	[%]	[%]	[%]	[%]	[%]	cm
S27	2	0.06	120	27	50	2	14.0
S30	2	0.10	120	30	50	2	18.5
S35	2	0.10	120	35	50	2	21.0

* Percent of total mix volume

2.2 Tensile behavior characterization

To determine the tensile strength of the SFRSCC, axial tensile tests were performed with specimens of 500 mm \times 100 mm \times 40 mm (L \times W \times T) dimensions. An LVDT was mounted on one side of the specimen to measure the deformation of the SFRSCC during the tensile test. The test was displacement controlled at a velocity of 1 μ m/s. From the results of these tests, the average value of 3.01 MPa for tensile strength was obtained.

For the determination of the fracture energy (G_f) of SFRSCC, the same dimensions for the specimens were used but a notch was applied at the intermediate length of the specimens in order to localize the fracture initiation and propagation at this fracture plane. This notch had a depth of approximately 20 mm and was made at each smaller side at the intermediate plane of the specimen. In each notch, two metal plates were glued for the installation of the LVDT to measure the crack opening. The test was performed under displacement control at a displacement rate of 1 μ m/s. The SFRSCC fracture energy was calculated from the stress-average crack width response. The average values for the fracture energy was 2.44 N/mm.

For the SHCC, three dog-bone type specimens were casted for each mix composition. The specimens were de-molded after 24 hours and cured for the rest of the age in a moisture room with temperature of 20⁰ C and 60% humidity. One specimen of each mix was tested by direct

tensile loading at 14 days, while the other two specimens were tested at the age of 28 days. The tensile tests were displacement controlled at a ratio of 5 $\mu\text{m}/\text{sec}$. Two LVDTs with a gauge length of 160 mm were placed on each side of the specimens to measure the tensile deformation that will be used to calculate average tensile strain. The stress-strain diagrams presented in Fig. 1a were obtained at 14 days. For more detail on test setup and 28 days results the reader should consult [4].

Specimens S30 and S35 developed diffuse crack patterns before failure crack localization, while S27 was failed by the formation of only three cracks, which justifies that this specimen did not exhibit a strain hardening character (Fig. 1b). In fact the low W/B ratio has increased significantly the energy required for crack initiation and propagation (higher crack tip toughness) in comparison with crack bridging toughness provided with PVA fibers in the S27 specimen. Therefore instead of forming a steady-state crack opening, as a required condition for strain hardening behavior, the crack opening was localized and the specimen failed following a softening post-cracking regime, similar to what is observed in ordinary fiber reinforced concretes.

Considering both rheological and mechanical characteristics, S30 had a relatively high strength with average strain ductility and an acceptable deformability. Therefore this mix composition was selected for the flexural strengthening of masonry beams of the second series of this research program. The fracture energy for S30 was evaluated by executing tensile tests with notched specimens subjected to direct tensile loading. The average value of 4.18 N/mm was obtained for fracture energy. The details of this experimental program could be found elsewhere [4].

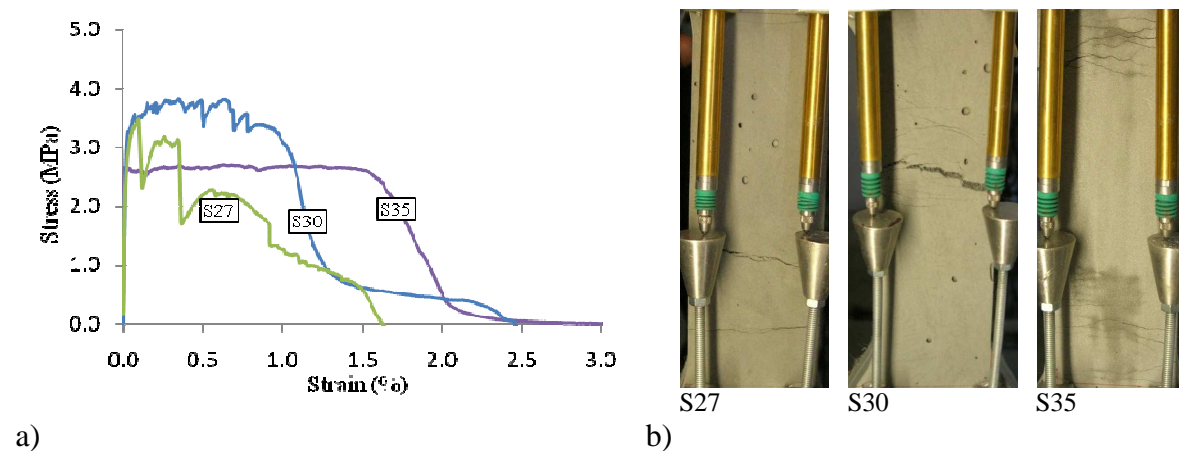


Figure 1: a) Direct tensile test results of SHCC specimens; b) SHCC specimens crack patterns

3. MASONRY BEAMS PREPARATION, STRENGTHENING AND TEST SETUP

Masonry beams composed of 11 handmade bricks bonded by low strength mortar (LSM: mortar without any compaction) were prepared. These LSM joints had a thickness of approximately 20 mm and depth of 105 mm. Bricks had dimensions of 205 mm \times 105 mm \times 55 mm (L \times W \times H) and were collected from six Portuguese monasteries [10].

A total number of 10 masonry beams was prepared in two different programs and categorized in four groups. The first two groups were composed of six beams for the

assessment of the effectiveness of SFRSCC for the flexural strengthening of this type of elements. Taking the results from the direct tensile tests and having performed preliminary numerical simulations with a cross section layer model it was verified that a significant increase in both the flexural resistance and stiffness could be achieved with a SFRSCC layer of 30 mm thick [2]. In the first group, composed of the beams designated T_01, T_02 and T_03, a layer of SFRSCC of constant thickness of 30 mm was applied in the face of the beams to be subjected to tension. In the second group, formed by the T_31, T_32 and T_33 beams, a SFRSCC layer thickness of 30 mm was guaranteed in the zones corresponding to the bricks, but 20 mm of the LSM mortar was also replaced with SFRSCC, forming a ribbed shape composite layer, in order to verify the possible contribution of these ribs for the flexural stiffness and load carrying capacity of this type of structural systems. Due to low cohesiveness of SFRSCC, a kind of adhesive was used in an attempt of improving the SFRSCC/Brick and SFRSCC/LSM interfaces for both groups of specimens. However, as explained elsewhere [3] the effectiveness of this bond agent was marginal.

To assess the advantages of using a layer of SHCC thinner than the thickness of the SFRSCC layer, for the flexural strengthening of this type of structural elements, the two other groups of masonry beams were strengthened with the developed S30 SHCC, one, group 3, where the thickness was 15 mm (B15_01, B15_02 beams) and the other, group 4, where the thickness was 20 mm (B20_01, B20_02 beams). For all SHCC strengthened beams also 20 mm of the LSM mortar was replaced with SHCC.

Four point beam bending tests were performed to assess the flexural behavior of strengthened masonry beams. The LVDT located at the mid-span section of the beam was used to control the test by imposing a displacement rate of 3 $\mu\text{m/sec}$. Detailed test setup is available at [2], [4].

4. STRENGTHENED BEAMS FLEXURAL TEST RESULTS AND DISCUSSION

SFRSCC strengthened beams: Flexural test results of SFRSCC reinforced beams presented a scattered range of results but still it could be mainly categorized in two distinct groups: specimens developing a multiple cracking in the constant bending moment region of the beam before failure (T_01 and T_33) and those failed with just a single crack (T_02, T_03, T_31 and T_32). These crack patterns are presented in Fig. 2. While the first group exhibited higher flexural ductility along with higher load carrying capacity (Fig. 3a), these flexurally strengthening performance indicators were much lower in the second group of masonry beams. Counting the population of discrete steel fibers crossing the failure section was a key point to reveal these distinct behaviors. While sufficient population of steel fibers provided enough crack bridging toughness, capable of forming several cracks in the specimens in the first group, the bridging toughness in the second group was not enough due to the much lower number of fibers in the fracture surface of the corresponding beams. Based on the results indicated in Fig. 3b, a minimum number of 75 steel fibers in the SFRSCC cross section (Specimen T_033) is required to have an effective contribution for the flexural strengthening of these masonry beams.

The force versus mid-span deflection, F-u, curves of Fig. 3a shows that replacing partially LSM joints by SFRSCC is effective, mainly in terms of flexural stiffness. The benefits in terms of deformational capacity of replacing partially LSM joints by SFRSCC are also appreciable when comparing the F-u curves of T_01 and T_33, since the deflection at peak

load of the T_33 was 1.5 times higher in the T_01. The benefits of the ribbed strengthening configuration is also visible when comparing T_32 and T_02 beams, since they had similar population of steel fibers in the fracture surface but the load carrying and deflection capacities of T_32 were higher than the corresponding ones of T_02. While the flexural crack formed in the SFRCC layer of T_02 continued directly through the brick/LSM interface, the favorable benefits of the SFRCC ribs in the joints of the T_32 beams, has contributed to the propagation of the crack through the brick, and then at the brick/LSM interface (Fig. 2d).

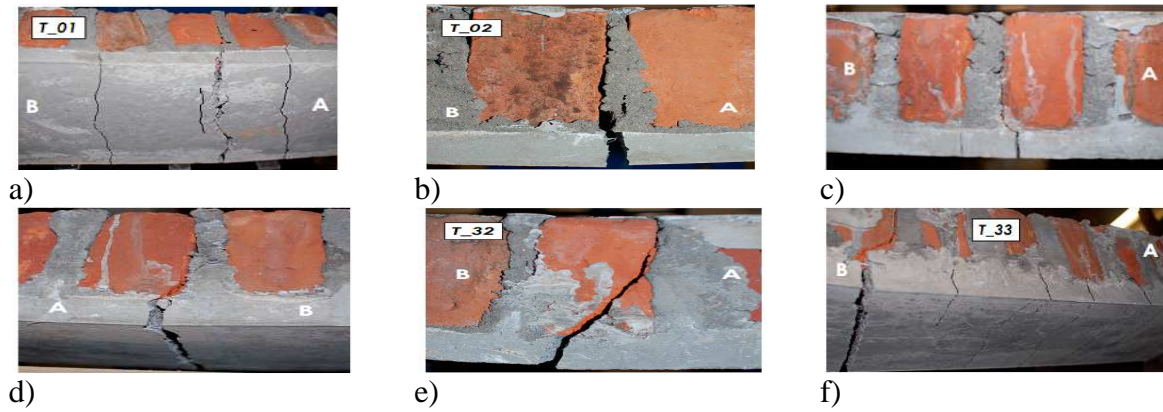


Figure 2: Flexural crack pattern for SFRCC strengthened specimens

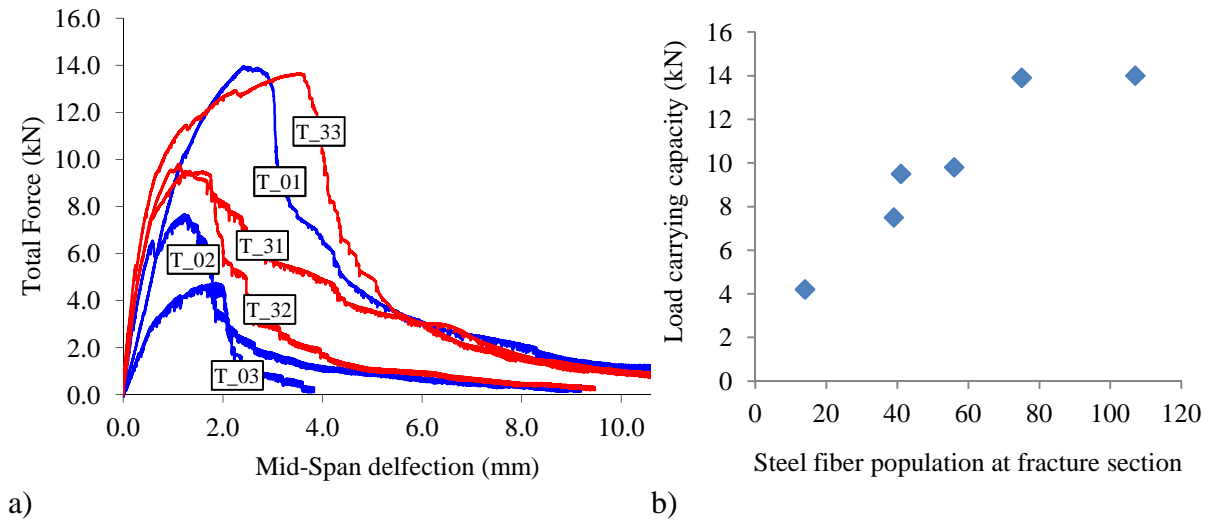


Figure 3: a) Load versus mid-span deflection for SFRCC strengthened specimens; b) Dependency of maximum bending load on the population of steel fibers at fracture surface

SHCC strengthened beams: All beams strengthened with SHCC exhibited sufficient deflection ductility before crack localization. In fact diffuse crack patterns were formed between and around the line loads (Fig. 6). The beams strengthened with a SHCC layer of 15 mm thickness (B15_01 and B15_02) had almost the same load-deflection and cracking behavior, and an average ultimate load and an average mid-span deflection of 9.6 kN and 5.5 mm, respectively, were recorded (Fig. 7). An increase of 5 mm in the thickness of the SHCC layer had a quite relevant increase in terms of load carrying and deflection capacities of the

masonry beams, as Fig. 7 evidence (B20_01 and B20_02 beams), since a load carrying and deflection capacities of 13.05 kN and 9.6 mm, and 12.83 kN and 6.4 mm were registered in B20_01 and B20_02, respectively. These values correspond to an increase of 35% in maximum load and 45% in ultimate deflection.

Except B20_02 beam, all the other beams had the same failure mode, with a first phase composed by the formation of a diffuse crack patten in the SHCC layer, followed by the failure crack localization and its propagation through the Brick/SHCC and Brick/LSM interfaces. In the B20_02 beam, the flexural failure crack formed in the SHCC near to one of the line load, has progressed through the brick unit with an inclined shear configuration, which finally followed at the Brick/LSM interface up to the collapse of the beam. Lower load carrying capacity and deflection ductility of B20_02 beam when compared to B20_01 could reasonably be justified because this shear deficiency of brick at that zone.

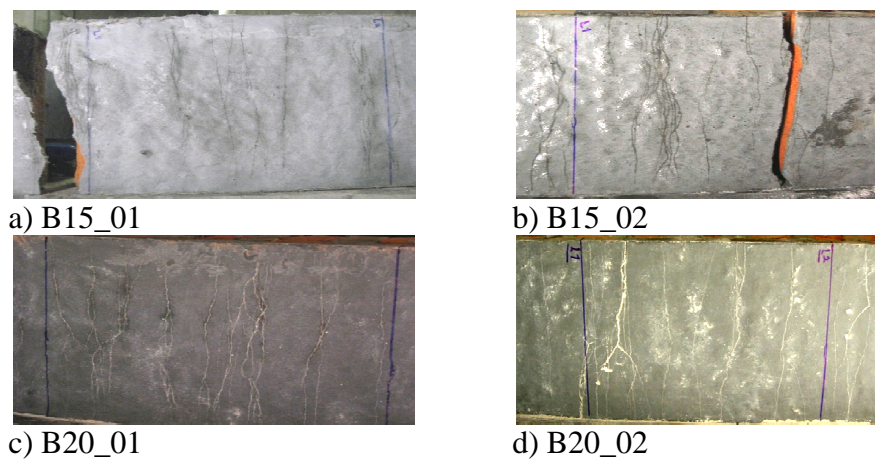


Figure 4: Flexural crack pattern for SFRCC strengthened specimens

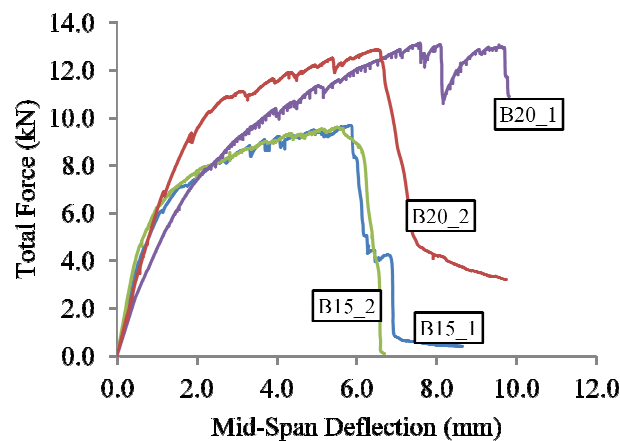


Figure 5: Load versus Mid-Span deflection for SHFRCC strengthened specimens

4.1 Comparing the effectiveness of SFRSCC and SHCC for the flexural strengthening of masonry beams

Two different composites as strengthening layer could be compared in terms of initial bending stiffness, maximum load carrying capacity and ultimate deflection. To this end, the

average results of B20_1 beam and B20_2 is compared with T_33, except for initial bending stiffness which was calculated based on average values of T3i (i=1 to 3) beams. Similar strengthening scheme (ribbed sections) along with multiple crack formation for T_33 is the reason to compare just this one with SHCC strengthened beams.

The slope of the Load-Deflection diagrams in linear stage is considered as the elastic bending stiffness of the strengthened beams. The average value of the beams strengthened with 20 mm SHCC is equal to 6017 kN/m, while the corresponding value of the SFRCC strengthened beams is 20200 kN/m. This higher flexural stiffness was expected due to both higher Young's modulus (E_c) and layer thickness of SFRCC when compared to SHCC layer. It should be noted that the E_c of the SFRCC was 32.2 GPa, which is 1.75 times higher than the E_c of SHCC (18.4 GPa). The SFRSCC with 10 mm thicker layer showed just 5% increase in maximum load carrying capacity. The B20 beams had an average value of the ultimate deflection of 8 mm, which is more than 2 times maximum deflection registered for T_33 beam (3.6 mm).

5. CONCLUSION

In the present work a strain softening steel fiber reinforced self-compacting concrete (SFRSCC) and a strain hardening PVA fiber reinforced cement composite (SHCC) were developed for the flexural strengthening of masonry beams. The material properties of both fiber cement composites (FCC) were determined and the effectiveness of both FCC was assessed by performing four point beam bending tests. For the SFRSCC a layer thickness of 30 mm was applied, while the potentialities of a thickness of 15 mm and 20 mm were explored in the beams strengthened with SHCC. Both FCCs were capable of increasing significantly the load carrying and the deflection capacities of the un-strengthened masonry beams (failed by each dead weight), but the increase level of these indicators when weighted in the volume of applied FCC are much higher when using SHCC. However a global cost analysis that takes into account the material costs and the durability performance of the FCCs, and the long term effectiveness of this technique when using these composite materials needs to be executed in order to have a more rational measure about their effectiveness.

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