pressure, and using a rotating nozzle with five jets. Both sides of the specimens were treated. The resulting surface roughness (Figure 4a) corresponded to a concrete surface profile number 5, as defined by the International Concrete Repair Institute [8]. The specimens were then wetted to saturate concrete substrate without leaving standing water on the surface. For convenience and a good control of the thickness of each mortar layer, the composites were applied with specimens resting on the ground and 4 mm thick steel plates were used for guidance, although the consistency of both mortars permitted rendering on vertical surfaces.

Test Setup

The experimental setup was designed to replicate structural walls subjected to gravitational loads and supported on each side by walls in the transversal direction. An eccentricity *e*=10mm (1/6 of the solid panels thickness) was provided at the top side, through a steel rod welded to the loading beam and in contact with the top side of the wall through a steel plate. A similar detail was used for the reaction beam. The compression load was applied vertically in displacement control at a rate of 0.003 mm/s using two linear variable displacement transducers (LVDTs) placed between the reaction frame (assumed rigid) and the loading beam. Additional measurements were acquired using two image correlation systems (ICS), and electric resistance strain gages.

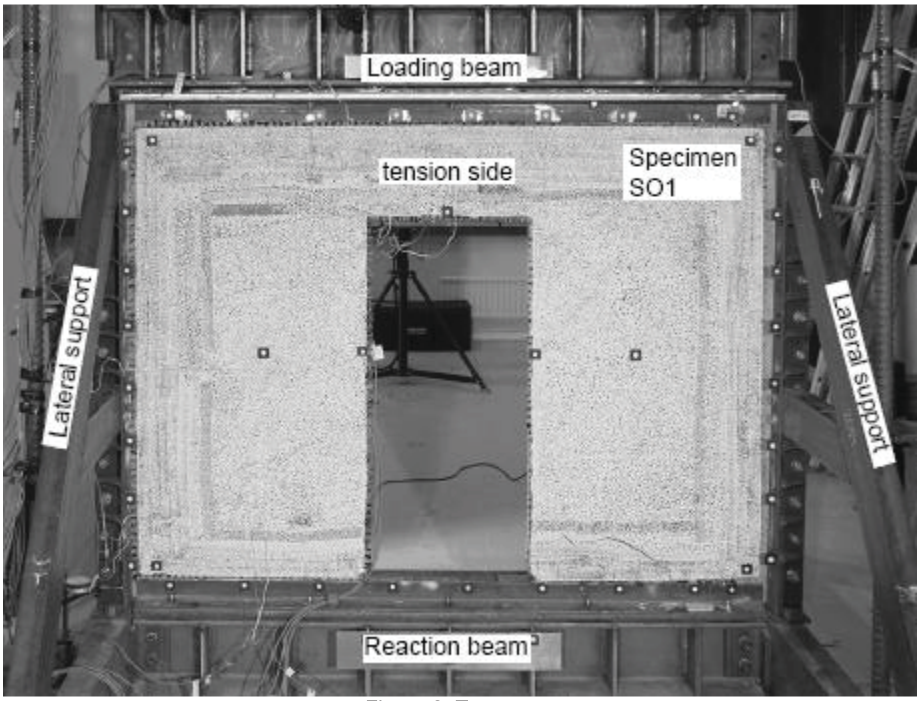

Figure 2. Test setup

RESULTS

Solid Wall

The maximum load bearing capacity of the solid wall was 1800 kN (Figure 3), this represent the control value or the target load with respect to which the efficiency of the strengthening solutions will be evaluated. The specimen presented out of plane deflections because of the eccentrically applied axial load. The specimen also exhibited double-curvature deformation due to the presence of the lateral supports. The failure mode of the solid wall was similar to that of a two way RC slab subjected to transversal loads, with cracks forming on the tension of the panel starting from the corners and progressing towards the middle of the panel. Along the largest cracks on the tension side, concrete crushing was observed on the compression side of the panel.

Walls with Openings

The capacity of all strengthened panels with openings are given in Figure 3. The capacity of the strengthened panels with small openings was above the capacity of the SW, which represented the target capacity. However, the capacity of the strengthened panels with large openings was below that of SW, therefore in this case the target capacity was not achieved. Both FRCM strengthening systems showed similar levels of effectiveness for panels with the same type of openings. For panels with small openings the C-FRCM and PBO-FRCM systems increased the capacity of the panels by 18% and 3% above that of the solid wall, respectively. For panels with large openings the C-FRCM and PBO-FRCM systems increased the capacity of the panels to 74% and 75% of the solid wall, respectively.

In addition, Figure 3 shows the maximum equivalent stress achieved for each specimen. The equivalent stress is calculated as the maximum capacity of each panel divided by its respective cross-section area. The equivalent stress for all strengthened panels with openings was approximately 25 MPa compared to 16.7 MPa obtained for the solid wall. Which suggests a roughly 50% increase in equivalent stress brought by the FRCM strengthening systems.

All specimen presented out of plane deflections and double-curvature deformations. In all cases the strengthened panels failed by crushing of the concrete at the bottom of one pier. The FRCM composites did not reach their tensile strength as concrete crushing led to a rapid decrease in the applied load. No FRCM debonding was observed up the failure. The FRCM partially detached in the area where the concrete was observed to be crushed.

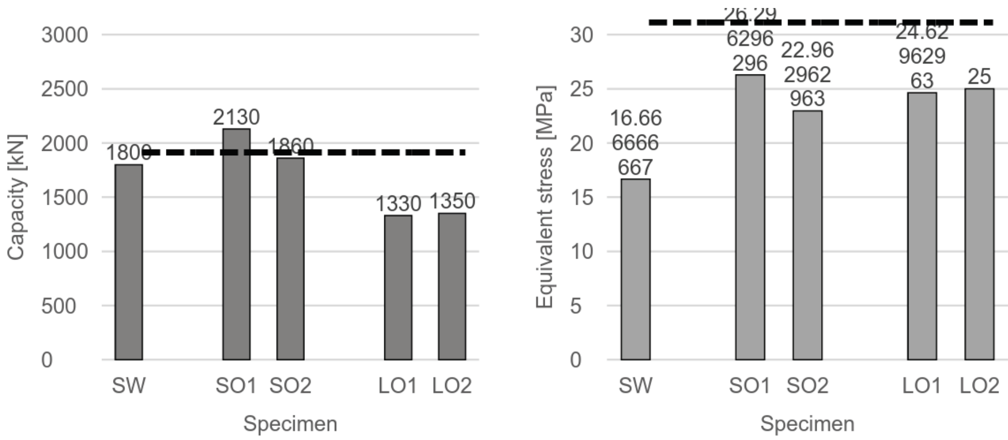

Figure 3. Experimentally obtained capacity of tested specimens (left) and equivalent stress (right)

CONCLUSIONS

This paper reports the results of an experimental study conducted on reinforced concrete walls with openings acting as compression, members strengthened with FRCM composites. Very few studies on FRCM strengthened concrete walls have yet to be reported. The present work is a first step in establishing FRCM systems as reliable solutions for strengthening concrete walls with cut-out openings acting as compression members. Four FRCM strengthened panels with openings and one solid panel without strengthening were tested to failure under eccentric compression. The following conclusions are made based on the findings of this study:

- The FRCM strengthening restored the capacity of the control wall for panels with small openings; however, for panels with large openings the capacity was not fully restored.

- Debonding of the externally bonded composites did not occur in any of the tested panels prior to the failure.
- The FRCM strengthening solution changed the failure mode of all strengthened panels from concrete cracking on the tension side and concrete crushing on the compression side along yield lines to concrete crushing at the bottom of one pier.

The findings of this study indicate that FRCM strengthening solution can be used for the repair and strengthening of RC walls with cut-out openings and provides foundations for future research. The proposed strengthening solution can appeal to practical applications, because it does not requires neither special works nor intensive man labour such as rounding of corners and introduction of anchors. However, a drawback can be considered the fact that special care needs to be given to the preparation of the old concrete surface, where water-jetting might not always be applicable. Future studies should address the combined action of axial loads, lateral loads and out-of-plane loads.

ACKNOWLEDGEMENTS

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Effectiveness of TRM Versus FRP in Flexural Strengthening of RC Beams

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ABSTRACT

This aim of this paper is to compare experimentally the performance of two strengthening systems; namely textile reinforced mortar (TRM) and fibre reinforced polymer (FRP) in flexural strengthening of reinforced concrete (RC) beams. The investigated parameters were: (a) the number of strengthening layers (1, 3, 5, and 7), (b) the textile surface condition (dry or coated fibres), and (c) the textile materials (carbon, basalt or glass fibres). For this purpose, 11 RC beams were fabricated, strengthened and tested in four-point bending. One beam was left unretrofitted (control specimen), four beams were strengthened with FRP materials and six beams were retrofitted with TRM materials. The results showed that, generally, TRM is less effective in increasing the flexural capacity of RC beams than FRP. However, the effectiveness of TRM in increasing the flexural capacity was very sensitive to the parameters under investigation. For example, by increasing the number of strengthening layers from 1 to 3, the TRM-to-FRP effectiveness ratio increased from 0.47 to 0.80. Coating the dry carbon textile resulted in considerable enhancement (52%) in the flexural capacity compared the dry carbon textile strengthened beam. Finally, different textile materials resulted in different flexural capacity increases of the strengthened beams, the coated basalt textile recorded the heights flexural capacity enhancement among the other types of textiles.

INTRODUCTION AND BACKGROUND

Over the last decade, a new composite material, known as textile-reinforced mortar (TRM), has been suggested for external strengthening of structures [1] as an alternative to FRP. A TRM composite comprises high-strength fibres (such as carbon, basalt or glass fibres) in form of textiles embedded into cement-based mortars. TRM is a relatively low cost material, resistant to high temperatures [2], compatible with the concrete substrate, can be applied in low temperature environments or on wet surfaces. Selected case studies on retrofitting applications of TRM in the construction field worldwide, can be found in [3]. Research on the flexural performance of RC beams strengthened with TRM has been reported in [4-9]. Parameters investigated in these studies, were; the textile-fibre materials, namely, carbon-fibre textiles in [4, 6, 9], polyparaphenylene benzobisoxazole (PBO)-fibre textiles in [5-6, 9], and basalt-fibre textile [7]; the number of layers [5-9]; the strengthening configuration [6]; the compressive strength of concrete [8]; and the type of textile-fibre materials [9]. Research on comparison between the effectiveness of TRM versus FRP in flexural strengthening of RC beams has only been reported in [4, 7]. This paper investigates the effectiveness of TRM versus FRP in flexural strengthening of RC beams, taking into account several parameters including; number of layers (1, 3, 5, and 7), the surface condition of the textile (dry or coated), and textile materials (carbon, basalt and glass).

EXPERIMENTAL PROGRAMME

Test Specimens and Investigated Parameters

A total of eleven beams with dimensions of 101 mm width and 202 mm depth were fabricated, strengthened and tested. The total length of the beams was 1675 mm, whereas the clear flexural and shear span were 1500 mm and 580 mm, respectively (Figure 1). The beams were intentionally designed with a low reinforcement ratio (ρ_s = 0.56%) in order to simulate flexure-deficient beams. The steel reinforcement comprised two 8 mm-diameter deformed bars in tension and two 12 mm deformed bars in compression (Figure 1). The shear reinforcement comprised 8 mm-diameter steel stirrups at a distance of 80 mm along the two shear spans. The concrete cover for all tested beams was equal to 15 mm. Table 1 provides a description of the tested specimens. The notation of the strengthened specimens is BN_F, where B represents the type of binder (R for epoxy resin, and M for cement mortar), N refers to the number layers, and F denotes the type of textile fibres (C for dry carbon fibres, CO for coated carbon fibres, CB for coated basalt fibres and G for glass fibres). The investigated parameters were: (a) the strengthening materials (TRM vs FRP), (b) the number of TRM/FRP layers, (c) the textile surface condition (coated vs dry), and (d) the material of the textile-fibres (carbon, glass and basalt).

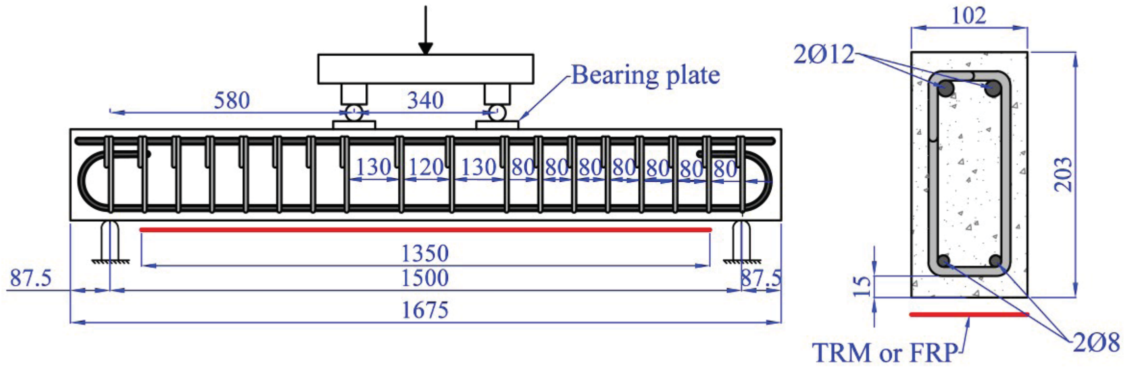

Figure 1. Details of test beams (all dimensions in mm)

Table 1. Strengthening configuration and materials properties of test specimens

Specimen	Thickness (mm)	No. of layers	ρ_f (%)	Concrete Strength (MPa)	
				Compressive strength	Tensile splitting strength
CON	-	-	-	19.9	2.1
M1_C	0.095	1	0.0475	19.9	2.1
M1_CO	0.095	1	0.0475	19.9	2.1
M3_C	0.095	3	0.1425	19.9	2.1
M5_C	0.095	5	0.2375	19.9	2.1
M7_CB	0.0371	7	0.1299	19.9	2.1
M7_G	0.044	7	0.1540	19.9	2.1
R1_C	0.095	1	0.0475	21.7	2.4
R3_C	0.095	3	0.1425	21.7	2.4
R7_CB	0.0371	7	0.1299	21.7	2.4
R7_G	0.044	7	0.1540	21.7	2.4

Materials Properties, Strengthening Procedure, and Experimental Set-up

The specimens were cast on two different dates using the same concrete mix design. The compressive and tensile splitting strength of the concrete were determined on the day of beams testing by conducting standard tests on concrete cylinders with dimensions of 150 mm-diameter and 300 mm-height. The corresponding results are presented in Table 1 (average from three specimens). Three different textiles (Figure 2) were used as external reinforcement, namely carbon-fibre textile (dry and coated), glass-fibre textile (dry) and basalt fibre-textile (coated). Details of the textiles, such as weight, mesh size and equivalent thickness (calculated based on the equivalent smeared distribution of fibres), are presented in Figure 2. It is noted that seven layers of glass-fibre or coated basalt-fibre textile have approximately the same axial stiffness with one dry carbon textile layer.

The binder of the TRM composite was cement-based with added polymers at a ratio of 8:1 by weight. The water to binder ratio was 0.23, resulting in a good workability and plastic consistency. The compressive and flexural strength of the mortar were 39.2 MPa, and 9.8 MPa (obtained on the day of testing). The binder used for FRP composite was an epoxy resin consisted of two parts with a mixing ratio of 4:1 by weight. For the specimen strengthened with coated carbon fibre textile (M1_CO), prior to strengthening the textile was impregnated with a low viscosity, two-part epoxy resin. The tensile strength and the elastic modulus of this adhesive were 72.4 MPa and 3.18 GPa, respectively (according to the material data sheets).