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EXPERIMENTAL INVESTIGATION ON SHEAR AND FLEXURE BEHAVIOR OF AAC MASONRY STRENGTHENED WITH FABRIC REINFORCED CEMENTITIOUS MATRIX

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ABSTRACT

In modern framed structures, AAC masonry is popularly used for the construction of infill and partition walls. The construction of walls with AAC blocks has been found to be more economical and less painstaking compared to other masonry units. However, researchers have highlighted that AAC masonry shows poor tensile capacity under in-plane and out-of-plane loads and may exhibit inferior performance during seismic events. In this study, the flexural and shear performance of AAC masonry was enhanced by using fabric-reinforced cementitious matrix (FRCM). This strengthening scheme was applied in two modes: direct and sandwich, which differ in the method of placing the fabric. In the sandwich method, the fabric was embedded between adhesive mortar and cement-sand mortar layers. In the direct method, the fabric was directly affixed to the masonry surface using anchors and then covered by a thick layer of cement-sand mortar.

The experimental results showed that the proposed strengthening methods could improve the strength and ductility of the masonry under shear and flexural loads. The test results showed comparable strengths for both types of strengthening methodologies. However, the direct mode of application, along with mechanical anchors, was found to be more helpful in attaining higher deformability. The superior performance of strengthened specimens suggests that either of these two methods of fabric application may be chosen for the strengthening of AAC masonry, depending on the availability of materials and ease in construction.

KEYWORDS: *AAC Masonry, Flexural and shear strength, FRCM strengthening, Seismic strengthening*

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INTRODUCTION

Masonry is generally used for the construction of load bearing walls, infill walls, external cladding, and so forth. Currently, autoclaved aerated concrete (AAC) masonry blocks are gaining popularity in the construction of masonry walls due to favorable properties such as lighter weight, speedy construction, and easier workability and workmanship. However, cracking of AAC masonry walls is a common problem due to the low compressive and tensile strength of AAC block. The cracking may be caused by shrinkage, creep, or moisture effects and are generally reported as small vertical cracks scattered into the wall [1]. Under slow cyclic and dynamic in-plane loads, ACC masonry wall showed a typical shear behaviour characterized by diagonal shear failure [2]. These problems require repair and maintenance work; hence, researchers are looking for the solutions to improve its cracking resistance.

Generally, fabric with high strength epoxy is used for strengthening the AAC masonry wallettes [3]. The studies performed by Kałuża, et. al. [1], Kubica and Kałuża [4], and Galman [5] showed that fiber-reinforced polymer was effective in enhancing the shear strength of AAC masonry wallettes. However, there is a scarcity of studies on evaluating the performance of AAC masonry strengthened with fabric reinforced cementitious matrix (FRCM). This study aims to enhance the flexural and shear strength of the AAC masonry wallettes using the glass FRCM.

In general, fabric can be placed either directly on the masonry substrate, which is then covered with thick layer of mortar (direct mode) or sandwiched between two thin layers of mortar (sandwich mode) [6-8]. In this study, either the direct or sandwich mode of strengthening was used to retrofit the masonry panels and the performance of the two methods was compared in terms of shear, flexure, and ductility mode.

EXPERIMENTAL PROGRAM

An experimental programme consisting of diagonal compression (shear) and four-point bending (flexure) tests was performed to evaluate the shear and out-of-plane flexural strength of AAC block masonry wallettes, respectively. The average dimensions used for the flexure tests were 777 mm × 390 mm and 810 mm × 410 mm for failure plane-parallel and perpendicular to the bed joint, respectively. The thickness was kept constant as 100-mm and 130-mm for control and strengthened wallettes, respectively. The dimensions used for the diagonal compression (shear) tests were 387 mm × 387 mm, keeping the thickness as similar to flexure specimens.

The experimental programme consisted of a total 45 wallettes among which 15 specimens were constructed for the diagonal compression test and 30 specimens were constructed for the flexure test. Of the 30 flexural test specimens, 15 each were made for determining flexural capacity parallel and perpendicular to the bed joint, respectively. In each set of 15 specimens, five were control specimens, and five each were strengthened with one of the two different modes of fabric application. The two different mode of fabric application were the direct method (D) and sandwich or the adhesive method (A). The test matrix is shown in the Table 1. All wallettes were prepared by an experienced mason with a joint adhesive mortar thickness of 3-mm.

Table 1: Details of tests specimens

Type of test	*Mode of fabric application*	*Nomenclature*	*Number of Specimens*
Flexure-Parallel to bed joint	Control	FL-C	5
	Direct	FL-D	5
	Sandwich	FL-A	5
Flexure-Perpendicular to bed joint	Control	FR-C	5
	Direct	FR-D	5
	Sandwich	FR-A	5
Diagonal Compression (Shear)	Control	DL-C	5
	Direct	DL-D	5
	Sandwich	DL-A	5

Fabric

Two types of fabrics, main fabric and edge fabric, were used in the study to strengthen the AAC masonry assemblages. The main fabric was placed over whole surface of the wallette, while the edge fabric was placed along the edges of the specimen. The grid sizes for main and edge fabric were 25 mm × 25 mm and 8.3 mm × 8.3 mm, respectively. The mechanical properties of both main and edge fabric are given in Table 2 [7].

Table 2: Specifications of fabric used

Characteristics	*Main fabric*		*Edge fabric*	
	Warp	*Weft*	*Warp*	*Weft*
Grid size (mm)	25		8	
Width of fabric roll (mm)	91		100	
Roll length (m)	45.7		50	
Fabric weight (g/m^2)	225		225	
Tensile strength (kN/m)	45		62	50
Elongation at break (%)	<3		3.5	

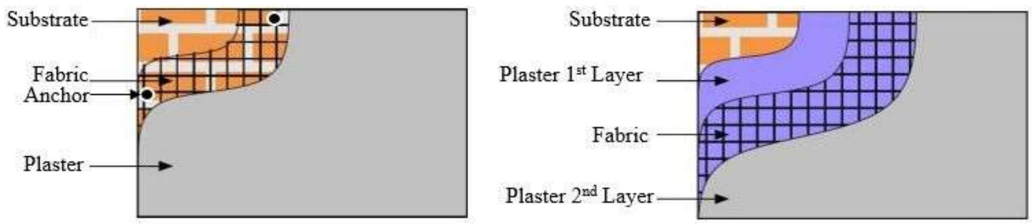
Mode of Application of Fabric

Two modes of fabric application were used (Figure 1). The steps involved are as follows:

Direct application: At first, the surface was brushed to remove any loose materials and then a thin coat of cement slurry was applied. The required sizes of fabrics were cut and held firmly using 3-mm diameter and 55-mm long anchors which were embedded up to a 35-mm depth. Lastly, a 15-mm thick mortar of mix proportion 1:4 (1-part cement and 4-part sand) was applied (Figure 1a).

Sandwich application: After cleaning the surface of the specimen, a 5-mm thin layer of block adhesive mortar was applied. The fabric was placed and, subsequently, it was covered with a 10-mm thick layer of 1:4 mortar. In this strengthening scheme, no mechanical anchors were used because the adhesion was provided by the block adhesive mortar (Figure 1b)

The past experimental studies have shown that the one-sided strengthening technique can efficiently improve the capacity of unreinforced masonry and help in achieving the ductility close to wallettes strengthened on both sides [8, 10]. Past experimental studies had also shown that one-sided strengthening scheme could even improve the performance of masonry walls under dynamic loads [10]. Thus, in the present study, the single-sided strengthening scheme was followed.



(a) (b)

Figure 1: Mode of fabric application; (a) direct, and (b) sandwich

MATERIAL PROPERTIES

AAC Blocks and Mortars

AAC blocks cut down into small sizes (200 mm × 100 mm × 75 mm) were used along with the adhesive mortar to prepare the AAC masonry specimens. The compression tests were conducted on the block units and the average strength was 3.74 MPa. Block joining adhesive mortar (manufactured by Sinha Engicon Pvt. Ltd., India) was used for AAC masonry and its average 3-days compressive strength of 50-mm was found to be 5.76 MPa. The 28-day compressive strength of 1:4 cement-sand mortar used for strengthening was 10.78 MPa [10].

AAC Masonry

Masonry prisms of five-block height were prepared and tested and the average compressive strength was 1.85 MPa. Further, Z-specimens were made to determine the tension bond strength of the AAC masonry [7, 11]. The average tension bond strength of AAC masonry was 0.11 MPa.

Bond Strength of FRCM

The bond test was performed as per ASTM C1583 [12] to determine the bond strength of the FRCM overlay with the masonry substrate. Five cores of 50-mm diameter were prepared for each type of strengthening. Two different failure modes were noticed during the tests: cohesive failure in masonry substrate and cohesive failure at cementitious matrix-fabric interface (Figure 2). However, only substrate failure was pre-dominant in most of the pull-off tests. Thus, the strength obtained for failure at cementitious matrix-fabric interface was not considered to calculate the average value. For sandwich technique, the average bond strength was found to be 0.41 MPa with a COV of 10%, whereas for direct technique it was 0.38 MPa with a COV of 21%.

(a) (b)

Figure 2: Bond failures; (a) cementitious matrix-fabric interface, and (b) in substrate

TEST SPECIMEN AND SETUP

Flexural Strength Test

To estimate the flexural strength, specimens were prepared in the laboratory in accordance with BS EN 1052-2 [13] (Figures 3a and 3b). The specimen was kept in the horizontal position and the four-point bending test was performed along the direction of failure plane-perpendicular and parallel to the bed joint (Figures 3c). The test was performed under displacement control at a loading rate of 0.6 mm/min. The flexural strength of masonry (f_f) was determined using:

$$f_f = \frac{3P_f(l_1 - l_2)}{2bw_b^2} \tag{1}$$

where, P_f is the maximum load reached (N), w_b and b are width of AAC block and width of masonry specimen in mm, respectively, and l_1 and l_2 are support span and loading span in mm.

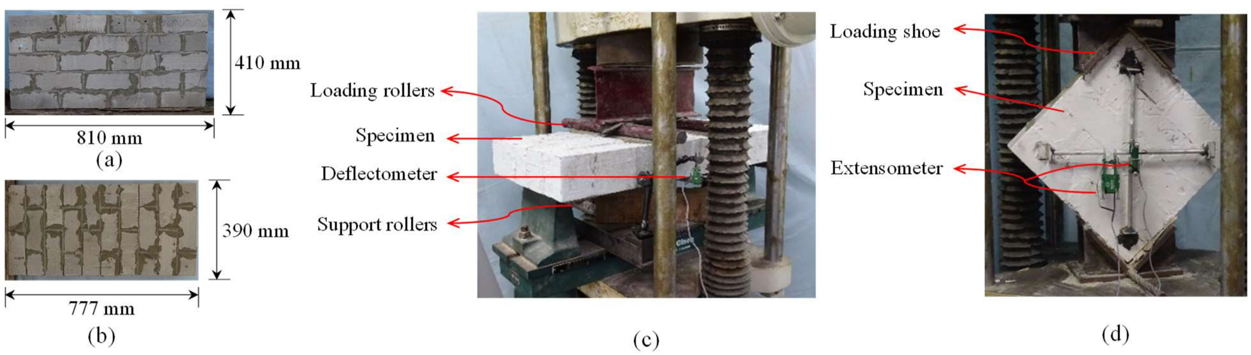


Figure 3: (a) Flexure test specimen for failure plane perpendicular to the bed joint, (b) Flexure test specimen for failure plane parallel to the bed joint, (c) Flexure test setup, and (d) Diagonal compression (shear) test setup

Diagonal Compression (Shear) Test

For the determination of masonry shear strength, diagonal compression (shear) test was performed in accordance with ASTM E519 [14]. The specimen was loaded in compression along the vertical diagonal to cause a diagonal tension failure (Figure 3d). This test was also performed at a rate of 0.6 mm/min. The shear strength, S_s, of the specimen was determined using:

$$S_s = \frac{0.707P}{A_n} \tag{2}$$

where, P is the applied load and A_n is the net area of the specimen.

TEST RESULTS AND DISCUSSIONS

Flexural Test

The flexural test results of masonry specimens along the direction of failure plane-parallel and perpendicular to the bed joint are summarized in Table 3 and the obtained load versus displacement plots for the control and strengthened specimens with failure plane parallel and perpendicular to bed joint are shown in Figure 4. The average flexural capacity of control specimens for the failure plane-parallel and perpendicular to the bed joint was found to be 0.18 kN-m (COV = 11%) and 0.26 kN-m (COV = 13%), respectively (Table 3). As expected brittle failure was observed for the control specimens after reaching their peak capacity.

Table 3: Flexure Test Results

Specimen Name	Average Peak Force (kN)	Average Peak Moment (kN-m)	Initial Ductility Index	Ultimate Ductility Index
FL-C	1.5	0.18 (11)	-	-
FL-D	10.7	1.25 (10)	1.19 (10)	5.37 (27)
FL-A	9.2	1.07 (8)	1.51 (18)	6.19 (10)
FR-C	2.3	0.26 (13)	-	-
FR-D	10.6	1.24 (10)	1.56 (6)	18.10 (20)
FR-A	14.1	1.65 (9)	1.73 (8)	14.62 (20)

Note: Values in parentheses indicate percentage coefficient of variation (COV)

A considerable increase in flexural capacity was observed when the specimens were strengthened with FRCM. The average flexural moment capacity of the specimens strengthened with direct and sandwich technique was found to be 1.25 kN-m (COV = 10%) and 1.07 kN-m (COV = 8%) for the failure-plane parallel to bed joint and 1.24 kN-m (COV = 10%) and 1.65 kN-m (COV = 9%) for the failure-plane perpendicular to bed joint, respectively. The flexural moment capacity of the strengthened specimen along the failure plane-parallel and perpendicular to the bed joint was enhanced by a factor of 5.9-6.9 and 4.7-6.35, respectively when compared to the control specimen.

The ductility or deformability of the specimens was compared using a factor called ductility index, λ. The value of ductility index, λ, was estimated as the ratio of displacement in the post-peak region corresponding to 80% of peak load to the yield displacement [15]. During the tests, multiple drops in the load-displacement curves were observed (Figure 4c-4f). The probable reason may be due to the slippage of fabric at the interface of cementitious matrix and substrate. Thus, ductility index at two points were considered, one at the first drop in the force and other in the region wherein no further increase in the force was recorded. The average values for ductility of parallel and perpendicular flexure specimens are given in Table 3.

The control specimens failed suddenly at the peak load after forming a crack at the weakest section of the specimen either along the mortar joint or in AAC blocks, as shown in Figures 5a and 5d. The strengthened specimens were able to sustain loads even at larger out-of-plane displacement when compared to the control specimens. In these specimens, one or more cracks were observed in the constant moment region before the failure (Figures 5b and 5e). For the specimens strengthened using direct mode of fabric application along with anchors, the rupture of fabric was also observed during the test. However, for specimens strengthened with sandwich mode of fabric application, debonding of the cementitious matrix was observed, which further contributed to the failure of the specimens (Figure 5c).

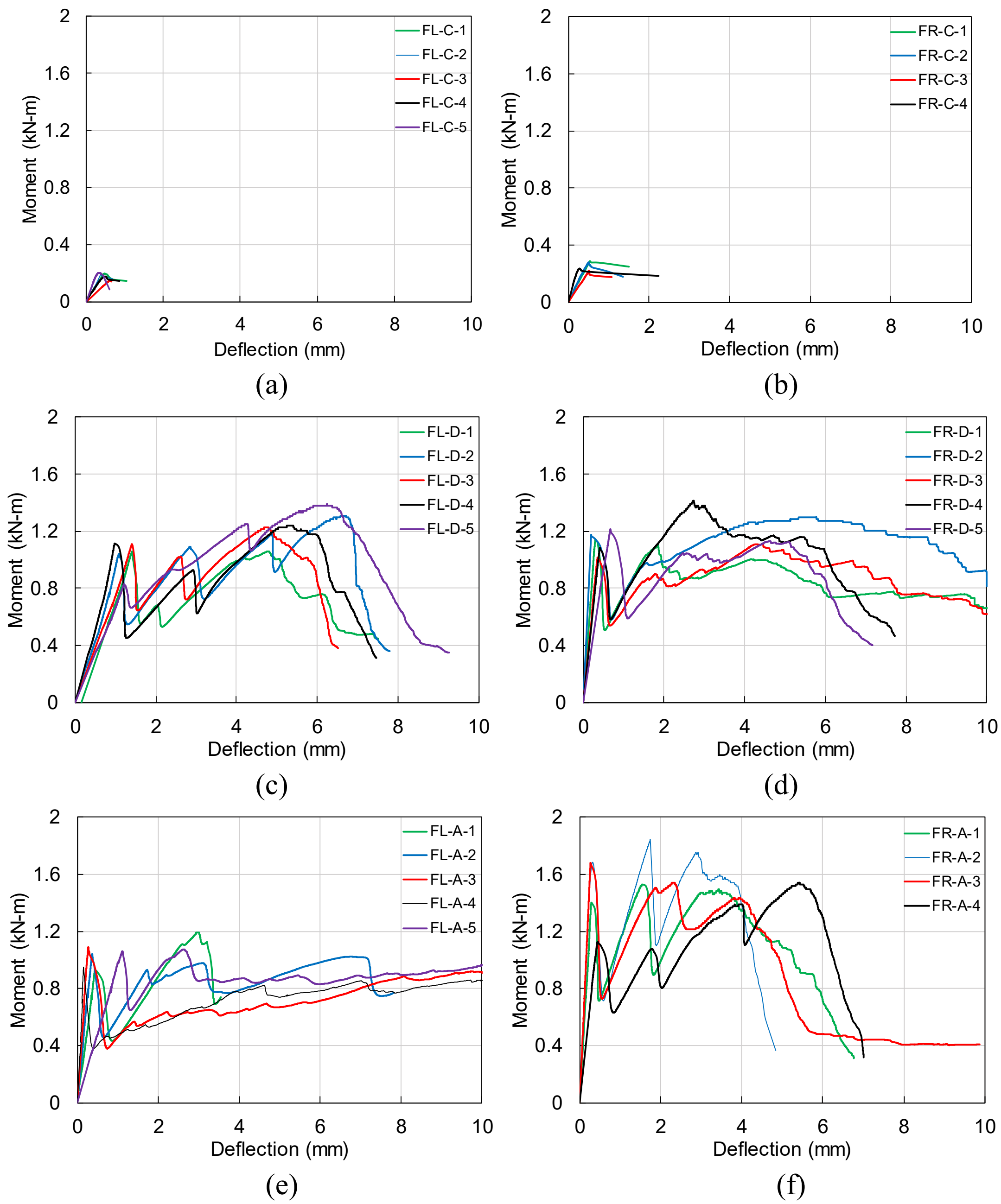


Figure 4: Moment-Deflection response; (a) FL-C specimens, (b) FR-C specimens, (c) FL-D specimens, (d) FR-D specimens, (e) FL-A specimens, and (f) FR-A specimens

Diagonal Compression (Shear) Test

The average shear strength and ductility values obtained for specimens are given in Table 4. The shear capacity versus displacement plots for the control and strengthened specimens are shown in Figure 6. The control specimens showed brittle response with little deformation before failure and a sudden drop in strength was observed after the peak load. The average peak shear strength of the control specimens was 0.69 MPa (COV = 17%). Different modes of fabric application showed a

(a) (b) (c) (d) (e)

Figure 5: Typical crack patterns observed in flexural test; (a) FL-C specimen, (b) FL-D specimen, (c) FL-A specimen, (d) FR-C specimen, and (e) FR-D specimen

considerable enhancement in the shear strength of the specimens. A higher ductility index value was also observed for all strengthened specimens. The average strengths of the specimens strengthened using direct and sandwich modes of fabric application were 1.18 MPa and 1.28 MPa respectively. The study showed that the average shear strength of the strengthened specimens was enhanced by a factor of 1.7-1.8 times compared to the control specimen.

Table 4: Shear Test Results

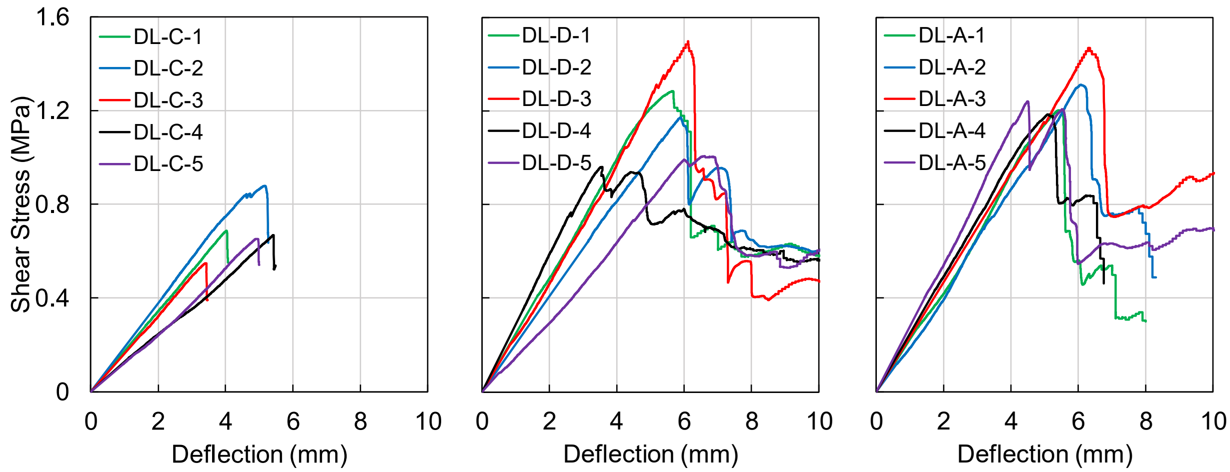
Specimen Name	Force (kN)	Average Strength (MPa)	Ductility Index
DL-C	37.8	0.69 (17)	-
DL-D	84.5	1.18 (18)	1.40 (11)
DL-A	92.0	1.28 (9)	1.19 (4)

Note: Values in parentheses indicate percentage coefficient of variation (COV)

Shear cracking in the diagonal specimens was observed when the principal tensile stress exceeded the tensile stress of the AAC masonry. The typical crack patterns for diagonal shear failure are depicted in Figures 7a-7c for control and strengthened specimens. Figure 7a illustrates the brittle failure of an unstrengthened specimen; these specimens were disintegrated in two to three fragments. In case of direct mode of fabric application, minor cracking formed within the middle third of the diagonal and subsequently propagated towards the loading shoes on both corners. However, in case of sandwich mode of fabric application, the cementitious matrix was damaged, which led to a debonding failure.

Comparison of Mode of Fabric Application

To understand the performance of both modes of fabric application, a normalized flexural and shear strength was calculated by taking the ratio of flexural or shear strength of strengthened specimens with their corresponding control specimens. The normalized strength and ductility values are shown in Figure 8. Figure 8a illustrates that the specimens strengthened using sandwich mode of fabric application provided slightly better results for the failure plane perpendicular to the bed joint, whereas direct mode of fabric application showed better result in case of failure plane-parallel to the bed joint. However, in case of diagonal specimens, performance of both mode of fabric application was comparable. Similarly, Figure 8b highlights that deformation capacities obtained for both modes of fabric application were approximately similar. Further, it was observed that masonry specimens with the sandwich mode of FRCM application experienced multiple drops in force under flexural loads and significant debonding at fabric and matrix interface.



(a) (b) (c)

Figure 6: Shear stress-deflection response; (a) DL-C specimens, (b) DL-D specimens, and (c) DL-A specimens

(a) (b) (c)

Figure 7: Typical crack patterns for diagonal (a) control (b) strengthened with the direct method (c) strengthened sandwich method

A one-way analysis of variance (ANOVA) was performed to analyze the statistical difference between strengthening schemes. The probability level used to analyze statistical significance was $P < 0.05$ for the tests. The ANOVA test on strength values indicated that there was no statistically significant ($P < 0.05$) difference in flexure ($P = 0.437$) and shear capacity ($P = 0.282$) obtained for both strengthening schemes. Further, the P values for ductility were found to be 0.580 and 0.004 for flexure and diagonal specimens, respectively. Thus, statistically there was no significant effect of mode of strengthening on ductility under flexure loads. However, ductility values obtained from shear test were statistically significantly different ($P < 0.05$) and therefore, based on ductility direct strengthening technique may always performed better than the adhesive technique.

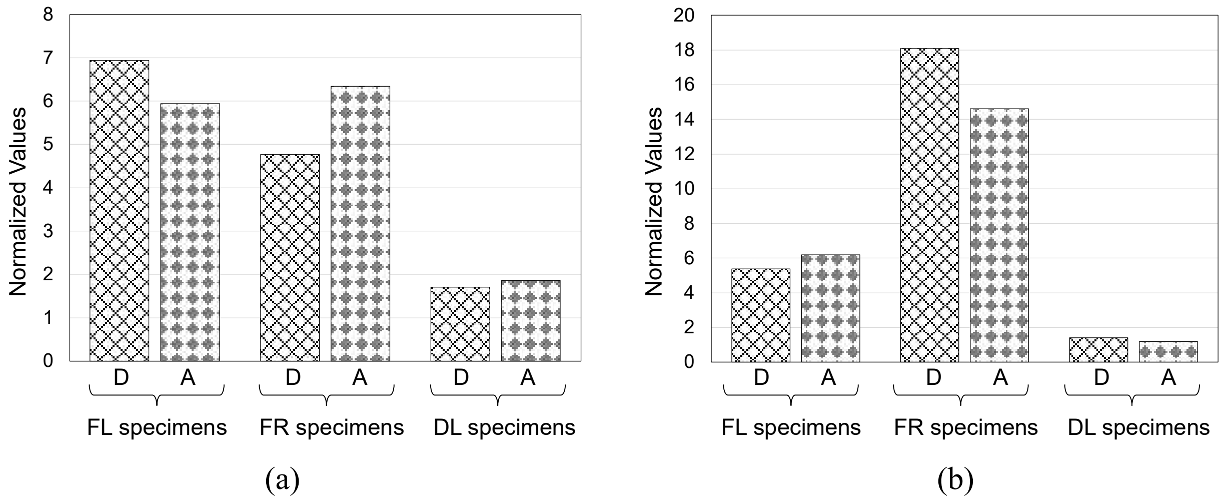


Figure 8: Comparison of normalized values for different strengthening schemes; (a) strength, and (b) ductility index

CONCLUSIONS

An experimental programme consisting of flexural and shear testing was performed on AAC masonry strengthened with two methods of FRCM application: sandwich and direct mode. The following key observations were made from this study:

1. A comparable improvement in flexure and shear strength was observed in both types of strengthening schemes. However, the sandwich technique showed slightly better results except in case of specimens with failure plane-parallel to the bed joint.
2. For the flexure specimens strengthened with the sandwich method, multiple drops in the moment capacity were observed due to the slippage of fabric at its interface with cementitious matrix. Further, significant debonding at the interface of cement-sand mortar and fabric was noticed for sandwich method of FRCM application.
3. The ultimate ductility index was observed to be higher in the case of the direct strengthening method with mechanical anchors when compared to the sandwich (adhesive) method.

The superior performance of strengthened specimens indicated that either of the two methods of fabric application may be chosen for the strengthening of AAC masonry, depending on the availability of materials and ease in construction. Further, the role of additional parameters, such as, multiple layers of fabric, both side strengthening, loading direction, and durability of FRCM should be investigated to gain a better understanding and development of design guidelines.

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