

EXPERIMENTAL STUDY ON OUT-OF-PLANE BEHAVIOUR OF MASONRY WALLS STRENGTHENING WITH CARBON FIBER REINFORCED POLYMER SHEETS

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Abstract. In this study, the out-of-plane failure mechanism of medium-sized masonry panels, which is frequently encountered during earthquakes, is discussed. Four of 100 mm x 410 mm x 1200 mm masonry panels were fabricated for the experimental study. Solid brick with dimensions of 50 mm x 100 mm x 200 mm was used in the production of the masonry panels. For mortar, repair mortar was used for ease of production. Three of the test specimens were strengthened with carbon fiber reinforced polymer (CFRP). The number of strips and the way of applying strips were adopted as test parameters. Panel specimens were tested under the effect of bending, applying three- point loading. During the experiments the measurements of load, displacement and strain were taken. Behaviour of the masonry panels were assessed in terms of ultimate load, the displacement corresponding to the ultimate load, stiffness and energy dissipation capacity. According to the results obtained, it is concluded that the strengthened masonry panels are quite successful against the out-of-plane failure mechanism.

Keywords: masonry panel, out-of-plane, CFRP

Introduction. It is known that most of the studies on earthquake resistant building design are on reinforced concrete and steel structure systems. For many western countries this makes sense because the usual building type in those countries is usually reinforced concrete or steel structures [1]. However, brick, adobe and stone masonry walls constitute the traditional building type in the Middle East and Eastern countries as well as in Turkey. Earthquakes cause collapse and loss of life in masonry buildings as well as reinforced concrete and steel structures. For this reason, it is extremely important to understand the earthquake behaviour of masonry structures and to make such structures safe against earthquakes. During an earthquake, masonry structures can have different failure modes. A masonry wall that can carry and transfer vertical and horizontal loads without collapsing must have geometric and physical properties that allow a monolithic behaviour [2]. It is thought that such a masonry wall could theoretically have two type of failure modes, in-plane, and out-of-plane, without any deterioration between brick and mortar [3-4]. Out of plane behaviour includes the collapse mechanism based on arch effect classified as horizontal and vertical bending mechanisms as well as the overturning mechanism shown in Figure-1. In-plane mechanisms, on the other hand, are the mechanisms in which each wall works individually and consists of various crack patterns such as crushing, tension, bending, diagonal shear and shear cracks, as seen in Fig.2.

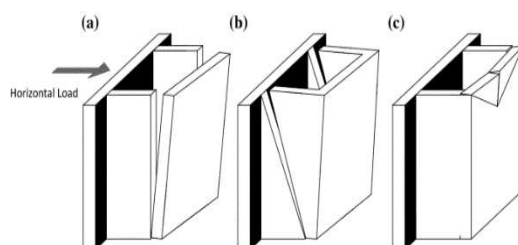


Figure 1. Out of plane mechanisms [4]

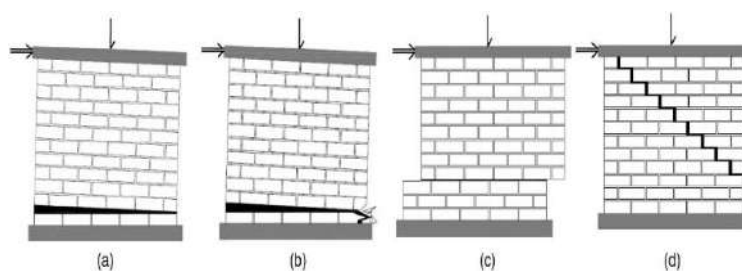


Figure 2. In-plane mechanisms [4]

When the literature is reviewed, it is seen that the main purpose of strengthening methods is to ensure sustainability and cost-effectiveness, and researchers have gradually turned to the use of structural materials with advanced technological properties. In some of the studies, jacketing was applied to the reinforced concrete structural elements by using concrete and steel reinforcement with higher strength than the material strength of the existing structure, and the bearing capacity of the structural element was tried to be increased [5-10]. Although good results were obtained in terms of bearing capacity, the difficulties encountered during the jacketing application caused a decrease in the use of this technique. Instead, strengthening of the structural elements with steel elements against shear and bending forces has come to the fore [11-13]. In this strengthening method, cost and architectural concerns and risks caused by negative environmental effects such as fire or corrosion were encountered. In the last 20 years, fiber reinforced polymers (FRP) have been widely used instead of these strengthening methods and many structures have been strengthened with this method. Also, many scientific studies have been carried out on the subject and FRP has become one of the most preferred materials in the strengthening-retrofitting literature [14-25]. Strengthening with FRP has also been applied to masonry structures and very successful results have been obtained [26-31].

From these studies, it was concluded that the strengthened method applied with epoxy bonded FRP systems gave very positive results in terms of bearing capacity, displacement capacity, stiffness, and energy consumption for masonry walls under the effect of different loadings. In the studies reviewed, it was seen that the strengthening made by bonding the textile material to cover the entire surface of the test specimen is quite limited. Within the scope of this study, four medium-sized masonry wall specimens were constructed and three of them were strengthened with CFRP strips. Two of the walls were strengthened with CFRP strips and one of the walls was strengthened by bonding CFRP to cover the entire surface of it. Behaviour of the masonry panels/walls were assessed in terms of ultimate load, the displacement corresponding to the ultimate load, stiffness, and energy dissipation capacity.

Experimental study. Test Specimens and Materials. Properties of the test specimens were given in Table-1. In the name of the specimens, the first letter “S” refers to “strengthened”, the second letter “S” refers to “strip”, the number written near the second letter S refers to the number of strips, the letter “L” refers to “layer”, the number written near the letter L refers to the number of layers. For example, the specimen named as S-S2-L1 was strengthened with 2 strips and the number of layers was 1. Dimensions of the bricks and the wall specimens were shown in Fig.3.

Table 1. Properties of test specimens [29]

Specimen	Dimensions	Number of strips	Number of layers
Control	100 mm x 410 mm x 1200mm	without strengthening	
S-S1-L1		1	1
S-S2-L1		2	1
S-F-L1		Full	1

Properties of the CFRP	Value	Picture
Specific Weight (g/m ²)	300 ± 10	
Thickness (mm)	0,12	
Tensile Strength (MPa)	4100	
Modulus of Elasticity (MPa)	231000	
Maximum Tensile Strain (%)	1,7 %	

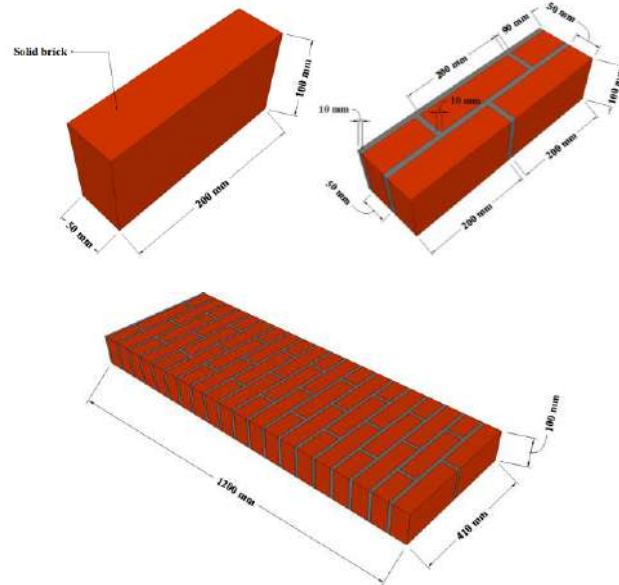


Figure 3. Geometric dimensions and some details of the test specimens [29]

Masonry blocks of 50 mm x 100 mm x 200 mm were characterized by compression following [30]. A cement-based mortar was used in the bed joints (10 mm wide). It is classified as M5 according to and was fully characterized on bending and compression, and elastic modulus, according to [31] and respectively.

Table 2. Average mechanical properties of masonry materials and assemblages [30]

Material	Compressive strength (N/mm ²)	Flexural strength (N/mm ²)	Elastic Modulus(N/mm ²)
Solid brick	3.15	-	-
Mortar	9.23	2.08	7.12

Strengthening details of the test specimens were shown in Figure-4 The properties of CFRP and two-component epoxy used for strengthening were given in Table 3. Strengthening stages were shown in Fig. 5. The surface on which the strip would be bonded was smoothed by a machine to remove protrusions. Then, compressed air was applied to the surface and dust was completely removed from the surface with a wet cloth. After the position of the strip was marked, the two-component epoxy was applied to the wall surface and the CFRP strip was placed onto the epoxy by hand pressing. Finally, another layer of epoxy was applied on the strip.

Table 3. CFRP Sikawrap 300-C and Sikadur 330 [30]

Properties of the Epoxy	Value	Picture
Tensile Strength (MPa)	30	
Modulus of Elasticity (MPa) (Bending)	3800	
Modulus of Elasticity (MPa) (Tensile)	4500	
Maximum Tensile Strain (%)	0,9 %	

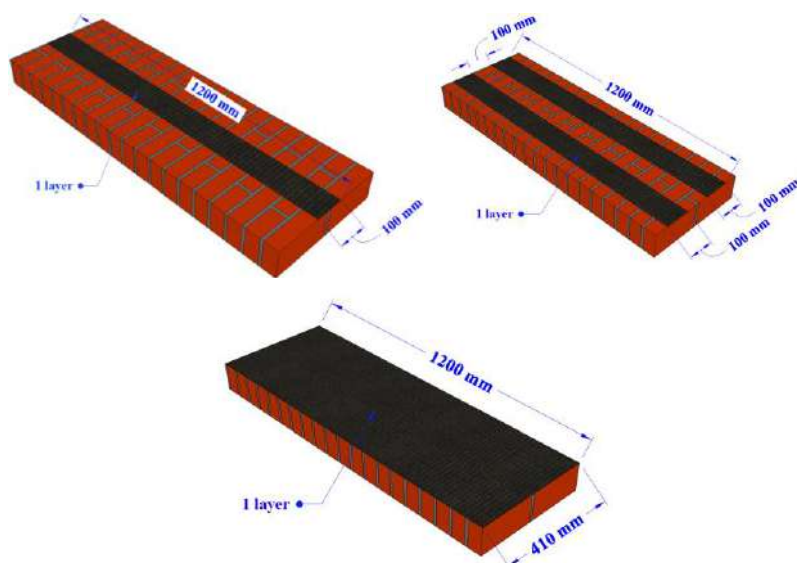
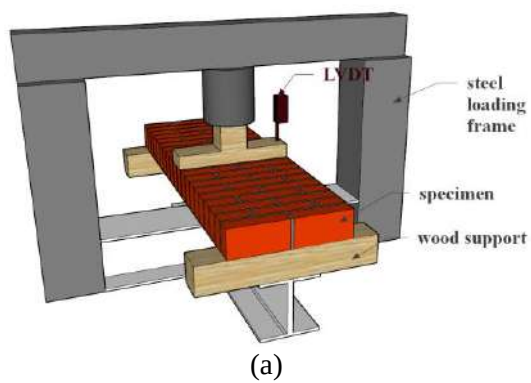


Figure 4. Strengthening details of specimens [30]



Figure 5. Strengthening processes of masonry panels [30]



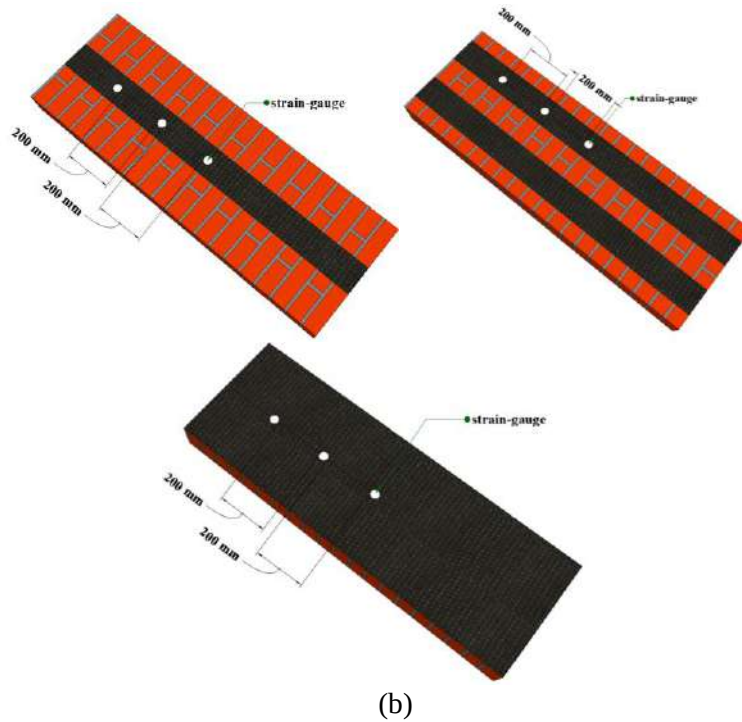


Figure 6. (a) Test setup and instrumentations and (b) strain-guage locations [30]

Test Setup and Instrumentation. The illustration showing the test and measurement setup in which the study was carried out was given in Figure 6. The axial load capacity of the test setup is 200 kN. The concentrated bending load was applied to the masonry panel specimens via a motor-controlled hydraulic system. The test specimens were loaded until collapse under the effect of monotonically increased loading and the experiments were followed simultaneously by the drawing of the load-displacement curves. The axial load applied to the masonry panel specimens was measured with a load cell having a capacity of 200 kN. The displacement values occurred in the test specimens due to the applied load were measured with a linear variable differential transformer (LVDT) having a capacity of 100 mm placed in the test setup. In addition, three strain measurements were taken on the strengthened masonry panel walls. All data were evaluated by transferring them to a computer with a data collection system.

Experimental results and discussion. The load-displacement curves obtained from the experiments were given in Figure 7. By using load displacement curves, values such as maximum bearing capacity, stiffness and energy dissipation capacity were determined for the assessment and comparison of the behaviour and performance of the test specimens. Comparisons and comments were made by considering the variables in the experimental program. The results obtained from the experimental study were given in Table 4. Ultimate load capacities of the masonry panel walls were obtained by reading the maximum load value reached in the load-displacement curves. Value of stiffness of the test specimens was obtained via dividing the ultimate load by deflection corresponding to the ultimate load. The energy dissipation capacities of the test specimens were obtained by calculating the area under the load-displacement curves. Energy dissipation capacities were calculated using the parts of the load-displacement curves up to the ultimate load. Failure modes of the specimens (control specimen, S-S1-L1, S-S2-L1 and S-F-L1) were shown in Figures 8-11.

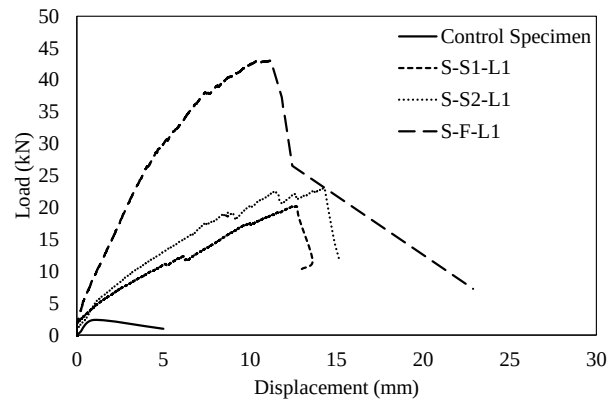


Figure 7. Load- displacement graphs [31]

Table 3. Experimental Results [30]

Spec. #	Ultimate Load (kN)	Disp. At Ultimate Load (mm)	Stiffness (kN/mm)	Energy Dissipation Capacity (kN-mm)	Max. strain (mm/mm)
Control	2.39	0.95	2.52	1.14	
S-S1-L1	20.09	12.71	1.58	155.87	0.01125
S-S2-L1	22.81	14.33	1.59	220.26	0.00875
S-F-L1	43.04	14.04	3.07	322.91	0.00747



Figure 8. Failure mode of control specimen [31]

The control specimen reached/achieved a load of 2.39 kN with a displacement of 0.95 mm and collapsed with a brittle manner. As seen in Figure 8, the collapse occurred at the mortar interface. There was no damage to the solid bricks forming the masonry panel walls.



Figure 9. Failure mode of S-S1-L1 [31]

The specimen S-S1-L1 reached/achieved a load of 20.09 kN with a displacement of 12.71 mm, and because of debonding of the CFRP strip from the masonry surface, the specimen suddenly lost its bearing capacity and

collapsed. In the middle part of the masonry wall, it was observed that the solid bricks were crushed because of compression (Fig.9).



Fig 10. Failure mode of S-S2-L1 [31]

The specimen S-S2-L1 reached a load of 22.81 kN with a displacement of 14.33 mm. The specimen suddenly lost its bearing capacity and collapsed because of debonding of the CFRP strip from the masonry surface. One of the strips deboned from the surface and the other one continued to contribute to the bearing capacity despite locally debonding of it. It is thought that the reason why these two strips do not collapse at the same time is a workmanship fault. Because the behavior of the strips was not identical even though there were identical loads on both strips.



Figure 11. Failure mode of S-F-L1 [31]

The specimen S-F-L1 reached a load of 43.04 kN with a displacement of 14.04 mm. Although the failure mode of the test specimen is similar with the other strengthened test specimens, the increase in the bearing capacity is quite remarkable.

As shown in Figure 11, solid bricks had large cracks and damage unlike other specimens. In other words, the specimen did not collapse due to the damages at the mortar interface. It determined that the solid bricks that make up the specimen reached the bearing capacity and were failure to compression and shear (complex) collapse.

The bearing capacity of S-S1-L1, S-S2-L1 and S-F-L1 is 8.41, 9.54 and 18.0 times greater than the reference specimen, respectively. The displacement capacities of the strengthened specimens have also increased. The displacements at maximum load are 13.38, 15.08 and 14.78 times greater than the reference specimen,

respectively. Significant improvements have been achieved in energy dissipation capacity. Compared to the reference specimen, an increase of approximately 280 times has been achieved.

Conclusion. Within the scope of this study, three of the four masonry panels produced were strengthened with CFRP strips. It was aimed to determine the out-of-plane behavior of specimens under quasi-static three-point bending and the following results were obtained;

- It has been demonstrated once again that masonry walls are extremely weak in out-of-plane behavior.
- The reference specimen carried a load of approximately 3 kN and had an extremely limited displacement (0.95 mm).
- When the strengthened specimens are taken into account, the maximum carrying capacity has increased by at least 8.41 and at most 18.00 times.
- Significant increases were also obtained in the displacement capacities of the strengthened specimens.
- Considering the reference specimen in terms of energy consumption, which is one of the most important parameters during an earthquake, an increase of up to 280 times has been achieved.
- This study has shown that masonry walls can be strengthened simply and the out-of-plane collapse mechanism that occurs during earthquakes can be prevented.

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