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アラミド繊維シートで補強された組積体のせん断挙動

Shear Behavior of Masonry Specimens Strengthened with Aramid Fiber Reinforced Polymer Sheet

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It has been proved through past earthquake experiences that unreinforced masonry (URM) structures are not able to resist seismic loads and in order to reduce the serious damages caused by earthquakes, they should be considered for retrofitting. In-plane shear failure of load bearing walls is known as one of the dominant collapse causes of masonry structures. Fiber reinforced polymers (FRP) is known as the material with high tensile strength and light weight. Capability of FRP products for the retrofitting of different structure types is being investigated widely around world. In this study, application of aramid fiber reinforced polymer (AFRP) sheet on the unreinforced masonry specimens as a strengthening solution was examined and the impact on their shear behavior was investigated through a series of diagonal compression tests. It was found out that AFRP sheet has considerable beneficial effect on the shear strength and deformation capacity of URM specimens.

Keywords: *Unreinforced masonry, Seismic retrofitting, Aramid fiber sheet, Shear strength, Deformation capacity, Diagonal compression testing*
無補強組積造, 耐震補強, アラミド繊維シート, 剪断強度, 変形能力, 対角圧縮試験

1. INTRODUCTION

Masonry is known as a seismic vulnerable type of construction. Low lateral strength and brittle failure mode of unreinforced masonry (URM) structures have been the main cause of casualties in the earthquakes events around world.

Structural behavior of URM structures is complex. Material non-linearity along with geometrical non-linear behavior caused by progressive cracking is an inherent characteristic of unreinforced masonry. Experiences from the past earthquakes have been proved that the failure of load bearing walls is mostly responsible for damages and collapse of these structures.

There are two failure types for URM walls, in-plane and out of plane. As in-plane failure, the most brittle mode is the shear failure which represented by diagonal splitting and step-pattern sliding of brick and bed joint mortar. Shear failure mode dissipates very low seismic energy and occurs in a brittle manner.

In order to improve the in-plane behavior of URM walls, they should be considered for seismic retrofitting.

Due to the high dependency of the behavior of URM walls on the properties of the constitute materials and the geometry of wall, strengthening of them has been faced several difficulties.

There are some retrofitting strategies being applied to URM walls which are mainly categorized in the way they interact with the wall structure such as surface treatment, confinement, post tensioning, center core and so far. Among these approaches, surface treatment has been considered as the most applicable and economical one. This strategy has relatively low alteration to the structural and architectural characteristics of URM buildings.

Experimental investigations carried out on the last decade have been shown that fiber reinforced polymers (FRP) has a significant capability for the retrofitting purpose. FRP products are available mainly in the forms of sheet, mesh and rode. Based on the material used in the fiber, there are some types of FRP such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) and aramid fiber polymer (AFRP).

AFRP is characterized by light weight, high tensile strength, no corrosion and electrical non-conductivity[1]. In present study, an experimental work was carried out on the

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small-size masonry specimens to grasp the in-plane shear behavior of the AFRP-retrofitted specimens. Comparison between the results of retrofitted and bare specimens was used as a basis for the evaluation of the retrofit efficiency.

2. OUTLINE OF EXPERIMENT

In order to grasp the shear effect of AFRP sheet retrofitting on the URM wall specimens, diagonal compression tests were conducted on the small-size wall specimens. The results of this experimental study are useful for prediction of the shear behavior of the retrofitted masonry wall.

The test specimens were constructed and tested as unretrofitted and retrofitted ones. Comparison between these two test results was used as a basis for evaluation of the retrofit efficiency.

Two specimen types namely type A and type B – with different specifications - were constructed and tested which will be introduced in the following parts.

Mechanical characteristics of masonry unit bricks and bed joint mortar were obtained through testing and the properties of AFRP sheet were suggested by the producing company as it comes later.

3. PROPERTIES OF MATERIALS AND SPECIMENS

3.1 Material properties

The unit brick which was used in this study was a plain one (without holes) with average size of 210 mm x 110 mm x 60 mm. The average modulus of elasticity of it was 17.7 kN/mm^2. The average compressive and flexural strength of bricks were about 65.0 N/mm^2 and 9.0 N/mm^2, respectively.

In order to reach more realistic results from the study, bed joint mortar was prepared with a 28 days compressive strength as low as the one being used in common masonry construction in earthquake-prone regions.

Two types of bed joint mortar for specimens type A and B were prepared by mixing of cement, sand, light weight silica powder blended with proportions of 1:6.5:1 and 1:6.5:2, respectively. Also w/c ratio was chosen equal to 130%.

The compressive strength of the bed joint mortar used in the construction of specimens series A and B were measured as 14.6 N/mm^2 (63 days age) and 17.3 N/mm^2 (119 days age), respectively.

Table 1 Aramid sheet specifications

Sheet type	Material	Dimension (mm)	Thickness
A	AK-10/10	190 x 180	1 layer
B1	AK-10/10	310 x 250	1 layer
B2	AK-20/20	310 x 250	1 layer
Band A	AK-90	20 x (640 + 250 overlap)	3 layers
Band B	AK-90	20 x (900 + 250 overlap)	3 layers

The specifications of aramid sheet - which was suggested by producing company - are shown in Table 1 and Table 2.

3.2 Specimen specification

The masonry specimen types which tests were conducted on are shown in Figure 1 and Table 3. Two series of masonry specimens were constructed such as type A and type B. Each series was consisted of both unretrofitted and retrofitted specimens.

Six specimens of type A were constructed. Two out of them (namely A2) were retrofitted by one layer of AFRP sheet in both sides with sheet type AK-10/10 and other two ones (namely A3) were retrofitted in a similar way but with a confining band in order to eliminate the sheet debonding from masonry surface.

Two specimens (namely A1) were left unretrofitted as control ones.

Six masonry specimens of type B were made. Two of these specimens (namely B21 and B22) were retrofitted by one layer of AFRP sheet on both sides with sheet type AK-10/10 and other two ones (namely B31 and B32) were retrofitted using sheet type AK-20/20. Both types were confined by band. Two specimens (namely B11 and B12) were left bare.

In all masonry specimens, the thickness of bed joint mortar was kept about 10 mm. All specimens were cured after construction for at least 28 days. Then they were retrofitted in both sides using special adhesive.

Table 2 Aramid sheet material specifications[1]

Material	Weight (g/m^2)	Tensile capacity (KN/m)	Thickness (mm)	Tensile Strength (N/mm^2)	Young's Modulus (KN/mm^2)
AK- 10/10	180	98/98	0.048	2060	118
AK- 20/20	325	196/196	0.096		
AK-90	623	882	0.430		

Table 3 Specimen specifications

Specimen	Dimension (mm)			Retrofitting scheme
	Width (W)	Depth (D)	Height (H)	
A12	209.65	100.09	189.03	Unretrofitted
A21	209.01	102.08	192.59	Sheet A
A22	209.51	102.12	190.80	Sheet A
A31	209.64	102.58	191.34	Sheet A + Band A
A32	210.74	102.52	194.45	Sheet A + Band A
B11	331	99.4	271.5	Unretrofitted
B12	324	100.4	272.6	Unretrofitted
B21	328	103.3	298.4	Sheet B1 + Band B
B22	329	101.9	299.6	Sheet B1 + Band B
B31	329	103.9	274.1	Sheet B2 + Band B
B32	328	104.5	278.2	Sheet B2 + Band B

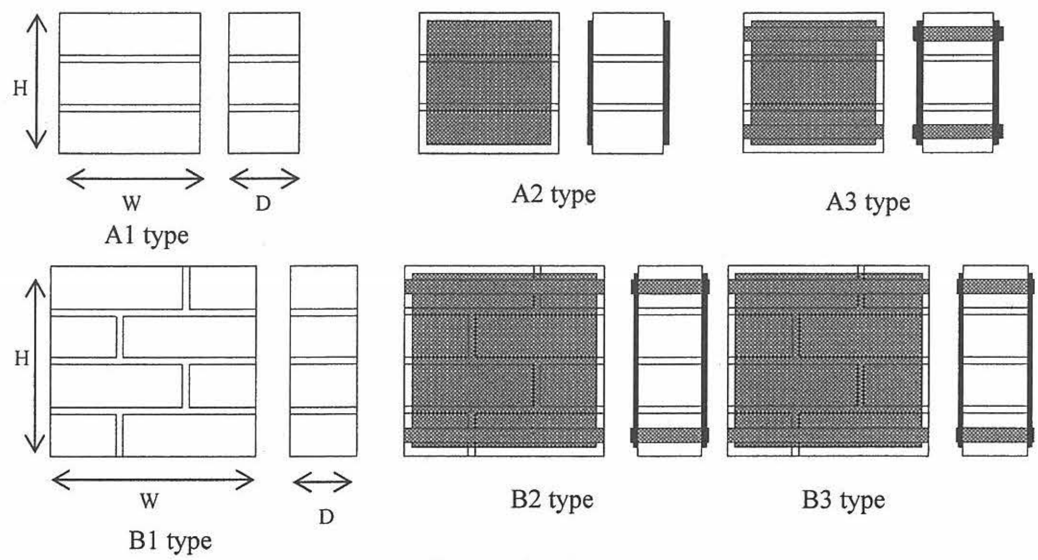

Figure 1 Specimen types

4. TEST CONFIGURATION

In the following parts procedure of the conducted tests on each series of specimens is described.

Average inclination degree (θ) of specimens was about 48° as shown in Figure 2.

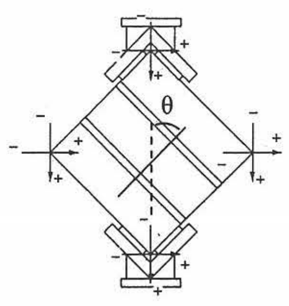

Figure 2 Schematic test configuration

4.1 Tests on specimens type A

Twelve displacement transducers were used to catch the deformational response of specimens type A under a force control loading manner. Two strong steel angles were used as load shoes for the force application

The arrangement of specimens is shown in the Figures 3-5.

4.2 Tests on specimens type B

Specimens type B were tested under compression in the same way as type A. To overcome the height of the specimen for setting of displacement transducers, a perimeter steel frame was utilized. The arrangement of specimens is shown in the Figures 6- 8.

The compressive load applied during tests was recorded. The shear strength of specimens was calculated as the maximum shear stress in specimens. The method of the calculation of shear stress and strain is explained in part 5.

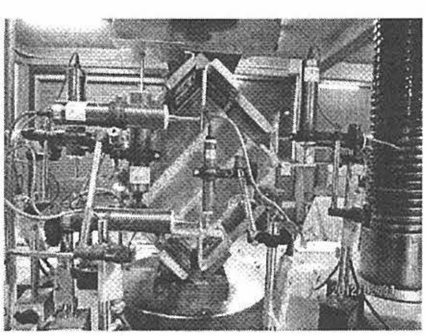

Figure 3 Specimen type A1

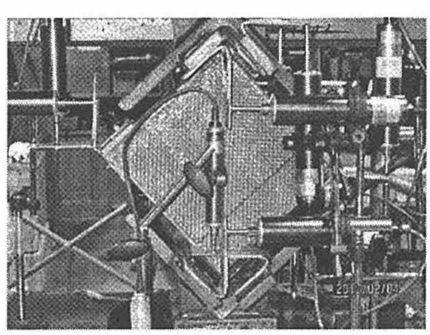

Figure 4 Specimen type A2

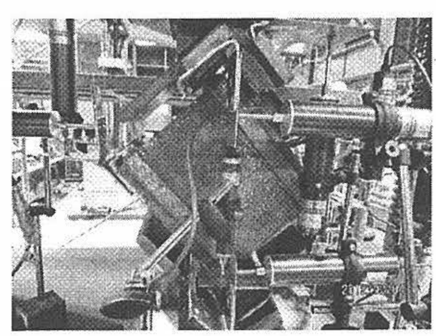

Figure 5 Specimen type A3

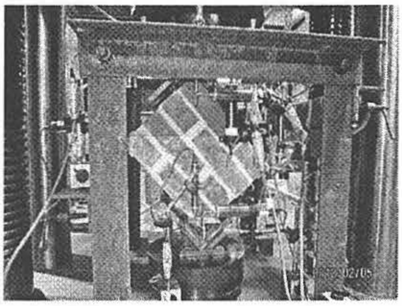

Figure 6 Specimen type B1

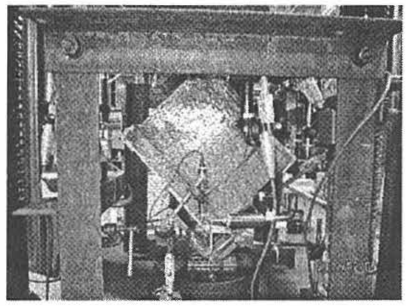

Figure 7 Specimen type B2

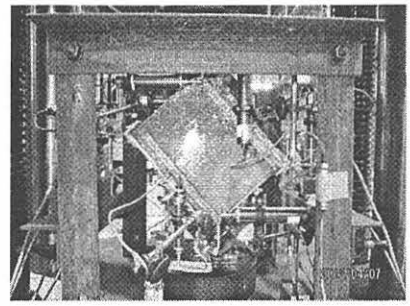

Figure 8 Specimen type B3

5. SHEAR STRESS AND STRAIN IN SPECIMENS

Shear strain induced by vertical compressive test load is shown by schematic drawings in Figure 9, where γ shear strain, δ displacement of the specimen edge, δH relative diagonal deformation of specimen in horizontal direction, δV relative diagonal deformation of specimen in vertical direction, L diagonal length, θ inclination degree and P is the compressive force. W, H and D are width, height and depth of specimen, respectively.

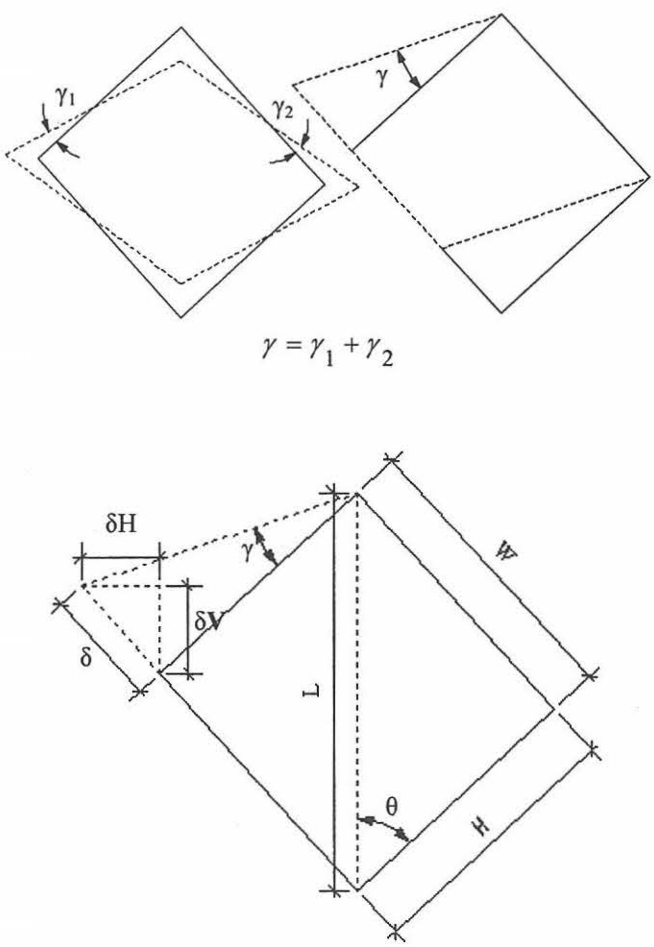

Figure 9 Shear strain in specimens

Shear strain is calculated based on the following relation,

$$\gamma \cong \tan\gamma = \frac{\delta}{H} \quad (1)$$

In which,

$$\delta = \delta H \cos\theta + \delta V \sin\theta \quad (2)$$

In the case of θ =45°, relation (1) can be written as:

$$\gamma = \frac{\delta H + \delta V}{L} \quad (3)$$

Which is recommended by ASTM (2002)[2].

Shear stress is simply calculated by the following relation,

$$\tau = \frac{P \sin\theta}{A} \quad (4)$$

In which, the cross sectional area A is:

$$A = W \times D \quad (5)$$

6. TEST RESULTS AND DISCUSSION

Failure of unretrofitted specimens (A1and B1 types) was represented by departing of brick and bed joint mortar in a very low displacement. In the case of specimens A2 type departing of aramid sheet from brick surface was followed by brick sliding and rupture of sheet along the adjacent bed joint. In the case of A3, B2 and B3 specimen types, failure was started by departing of sheet and its rupture at a place close to the confining band located in top and bottom of specimens and followed by diagonal cracks passing both brick and bed joint mortar (Figures 14-17).

Shear stress-strain diagram of specimens A and B are shown in Figures 10 and 12, respectively. As it is shown in Figure 11 shear strength of specimens A31 and A32 compare to specimen A12 were increased about 28% and 13%, respectively.

In case of series B, compare to specimen B1 type, shear strength of specimen types B2 and B3 were increased about 146% and 149%, respectively as shown in Figure 13.

High shear strength obtained from the retrofitted specimens with aramid sheet and band compare to ones retrofitted with sheet only shows the confining effect of it on specimen strength and ductility as observed during the failure of specimens.

In this study, deformation capacity (pseudo ductility) refers to the shear strain (reference strain) at 80% of the first stress peak in stress-strain graph. In case of unretrofitted specimens, this reference strain was considered at the maximum (100%) shear strength. The reference strains of specimens type A12, A21 and A22 were about 0.5%,0.56% and 0.5% respectively. So, A2 type showed an average deformability about 1.1 times bare A1 type. In case of B1, B2 and B3 types, the average reference strain were about 0.25%, 1% and 1.37%, respectively.

As a result B2 and B3 types were about 4 and 5.5 times more deformable than bare B1 type.

In retrofitted specimens, increase in shear stress was observed after reaching first stress peak. This was repeated frequently during the test as shown in Figure 10 and 12 which can be attributed to the hardening effect of retrofit overlay due to the redistribution of stress after each local debonding.

The final drop of graphs occurs when these small local debonding zones join together. In case of the specimens confined with band, this drop is attributed to the tearing of AFRP sheet.

According to the test data, it was revealed that AFRP retrofitting has the potential of enhancing both shear resistance and deformability of the URM specimens.

However it must be mentioned that since AFRP loses most of its efficiency after debonding, some preventive anchorages such as the band was utilized in this experimental study should be used in actual application.

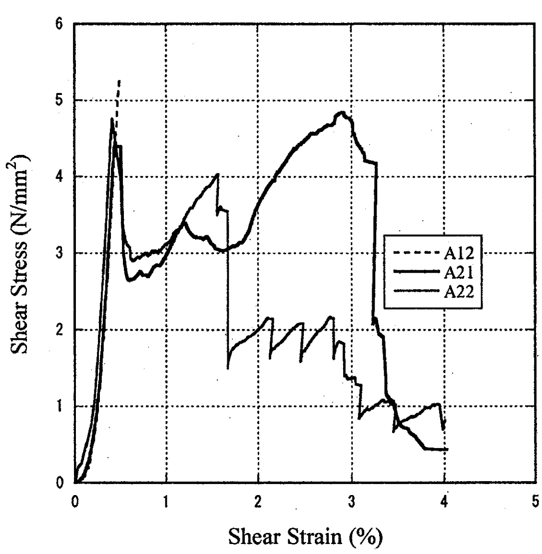

Figure 10 Shear stress-strain diagram of specimens type A

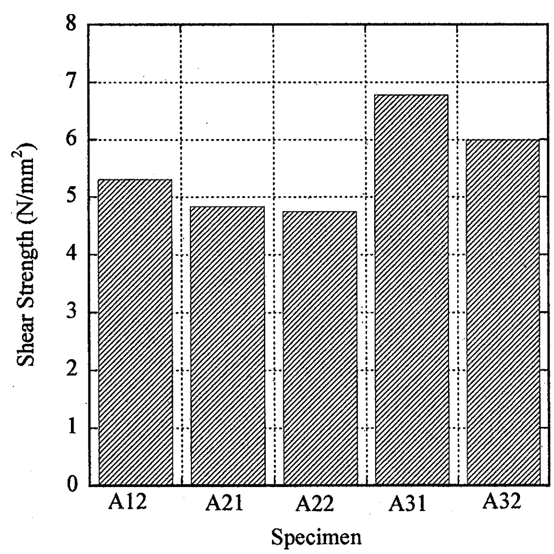

Figure 11 Shear strength of specimens series A

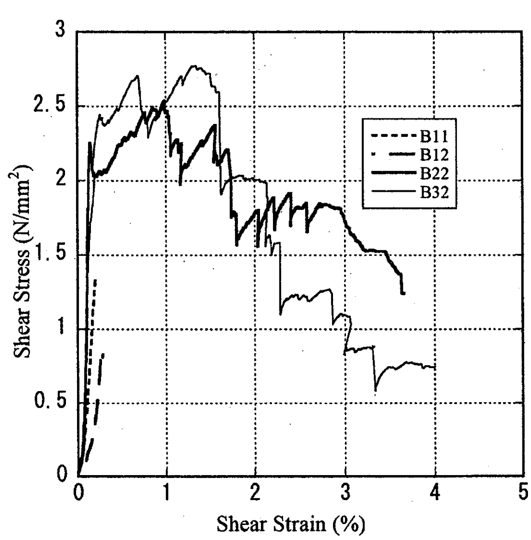

Figure 12 Shear stress-strain diagram of specimens type B

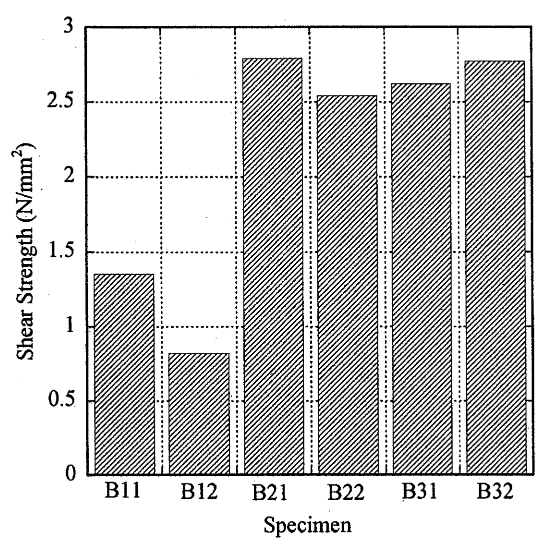

Figure 13 Shear strength of specimens series B

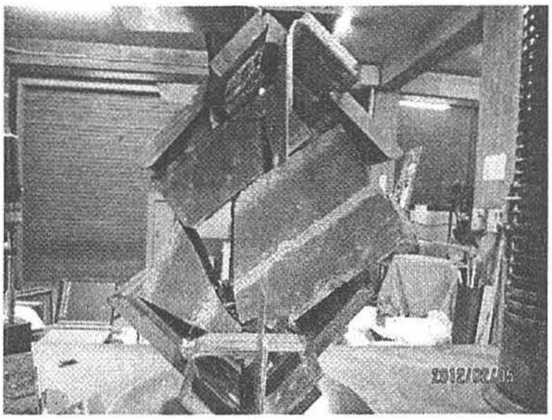

Figure 14 Failure mode of specimen type A1

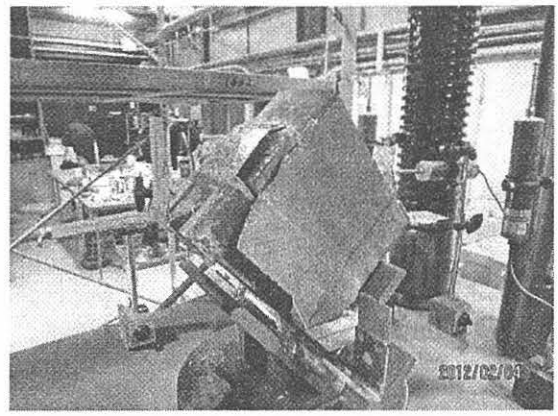

Figure 15 Failure mode of specimen type A2

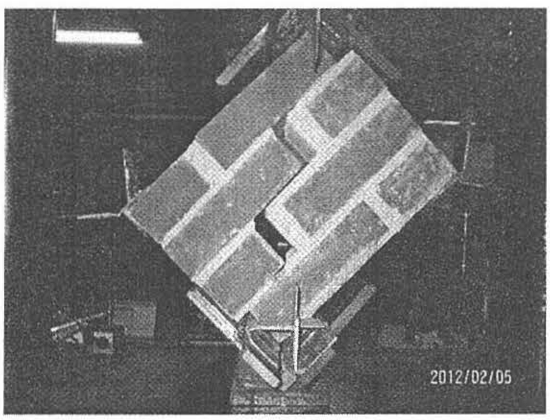

Figure 16 Failure mode of specimen type B1

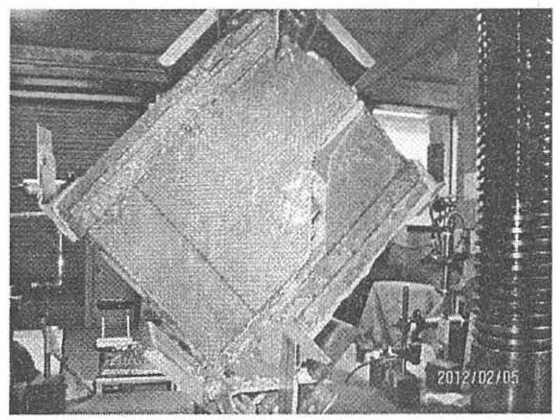

Figure 17 Failure mode of specimen type B2

7. COMPARISON TO OTHER RETROFITTING METHODS

In this part, results of this study in terms of shear capacity and deformation capacity were compared to some other retrofitting methods which are available in literature[3].

The comparison is shown in Table 4. V_{URM} and V_{RM} are referred to shear capacity of unreinforced and retrofitted masonry, respectively. Also D_{URM} and D_{RM} are the deformability of URM and retrofitted ones.

The average test results of specimens type B were shown in this table.

Table 4 Comparison of AFRP retrofitting to other methods

Retrofitting method	V_{RM}/V_{URM}	D_{RM}/D_{URM}
Shotecrete	3	1
Polymer band	1	2.5
Steel strip	1.9	–
Polymer grids	1.2	2
Ferrocement	1.5	1.7
AFRP (this study)	1.48	4.75

Comparison revealed that AFRP retrofitting compare to other methods shows a relatively fine balance between shear capacity and deformability enhancement.

Progressive cracking is mostly responsible for brittle in-plane failure which is originated from the low deformation capacity and leads to low energy dissipation capability of unreinforced masonry walls. In-plane failure mode is mainly governed by the first cracks generally occur in weak interface between brick and mortar during the application of lateral loads. Also the failure pattern and geometrical non linear behavior of the URM wall are greatly influenced by cracking. Therefore, although improving of the shear strength of the wall is vital, in order to avoid brittle failure and dissipating seismic energy, deformation capacity should be enhanced as well. In order to reach such deformability, the non-ductile debonding of AFRP overlay - in case of this study - must be prevented which was achieved by utilizing confining band.

Also it should be mentioned that some other factors influence the evaluation of the efficiency of strengthening techniques. Parameters such as added mass to structure, alteration to the shear stiffness, corrosion potential, anchorage problem to wall substrate, creation of zones with different stiffness.

AFRP sheet and FRP laminates in general have a very low alteration to the original mass and stiffness of the wall.

Moreover, there are some non-technical advantages and disadvantages of different retrofitting methods such as cost, space reduction and alteration to the original architectural features of URM structure[4].

Due to the numerous affecting parameters when it comes to the efficiency evaluation of a retrofit method, decisions should be made carefully.

8. CONCLUSION

Comparing the test results and the failure modes of unretrofitted and retrofitted masonry specimens, following conclusion remarks were found out:

(1) Shear strength of specimens A31 and A32 compare to bare specimen A12 were increased about 28% and 13%, respectively.

(2) Compare to bare specimen B1, shear strength of specimens B2 and B3 were increased about 146% and 149%, respectively.

(3) A2 type showed ductility about 1.1 times of bare A1type specimen.

(4) B2 and B3 types showed ductility about 4 and 5.5 times of bare B1type.

(5) Beneficial effect of confining band on strength and deformability - while most part of the shear strength is achievable - was observed.

Considering the beneficial effect of AFRP sheet on the shear strength and deformation capacity of URM specimens, it can be considered as an appropriate retrofitting method.

As a future research step, numerical analysis is being utilized to predict the behavior of masonry wall and the effect of retrofitting.

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