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FRP RETROFIT OF WALLS CONSTRUCTED WITH HISTORICAL BRICKS

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Summary. *Rehabilitation and seismic retrofitting of historical structures is a major concern for the engineering communities of countries in earthquake prone areas. In this study, bricks from a historical building, which is around 130 years old, were used for constructing wall specimens, which were tested under diagonal tension before and after retrofitting with glass FRP (fiber reinforced polymer) composite sheets. After experimental work on reference and FRP retrofitted specimens, it was shown that shear capacity and deformability of historical masonry walls can be increased significantly.*

1 INTRODUCTION

There are many historical structures all around Turkey, most of which are in danger of severe damage during potential earthquakes due to lack of adequate maintenance, existing structural damages and material deterioration. Particularly, in Istanbul, where seismologists report that the probability of an earthquake with a magnitude around seven is approximately 60 percent in 30 years, there are many invaluable historical structures, since Istanbul served as the capitals of Roman, Byzantine and Ottoman Empires for many years. Therefore, seismic rehabilitation and retrofitting of historical structures should be a major concern, in order to preserve these cultural heritages. A large portion of these historical structures are masonry structures constructed with solid brick walls. Seismic retrofit of historical structures using conventional approaches by using reinforced concrete is not adequate since the reversibility of these interventions is generally very limited, if not impossible. In recent years, several research projects on seismic analysis of historical masonry structures [1,2] and seismic retrofit of these structures or structural members using fiber reinforced polymer composites were carried out in different parts of the world. These studies were on the axial and/or shear behavior of masonry wall specimens retrofitted with FRP composites and the obtained results were promising in terms of remarkably better structural performance, [3-6]. The shaking table tests of three dimensional historical masonry structures retrofitted with FRP composites confirmed the experimental results obtained at the end of tests of single wall specimens subjected to static loads, [7]. The behavior of FRP retrofitted masonry walls were investigated using various approaches, [8-12]. Findings in these studies were generally in good agreement with experimental results.

In this study, bricks taken from a historical building, which is approximately 130 years old, were used to construct wall specimens, which were tested under diagonal tension either before or after retrofitting with repair mortar as plaster and glass FRP composite sheets over the plaster. A large number of mortar specimens were taken from the building for obtaining the average mechanical properties of the joint mortar. After several trial mortar mixtures, a mixture was obtained which can represent the compressive and tensile strengths of the existing joint mortar in-situ. This representative joint mortar was used for bonding historical brick units. The constructed wall specimens were tested without plaster as reference specimens, which represented the in-situ walls, with plaster to identify the contribution of plaster on the experimental results and with glass FRP sheets over plaster to determine the effect of FRP retrofit on the behavior. The details of this study can be found elsewhere [13].

2 TESTING PROGRAM

The test program included a reference specimen constructed only with bricks and mortar (type A), a specimen plastered with high performance repair mortar (type B), two specimens strengthened by using glass FRP sheets applied on the high performance repair mortar layers (type C), Fig. 1, and a specimen strengthened by using glass FRP sheets applied on the high performance repair mortar layers anchored into the bricks (type D), Fig. 2. During the retrofitting process, varying number of glass FRP layers (1 and 2) were applied. The specimens were tested under diagonal compression. The specimen characteristics are presented in Table 1.

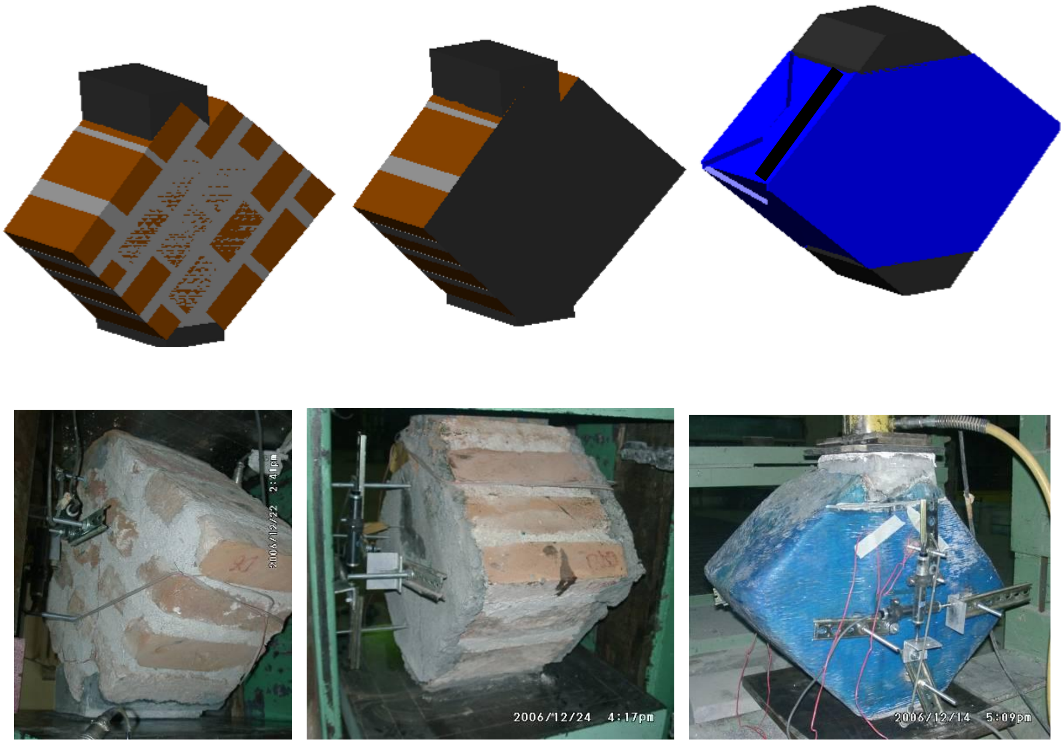

Figure 1: Reference (type A), plastered (type B) and retrofitted (type C) specimens

3 MATERIALS

The clay bricks, which were used during preparation of wall specimens, were collected from a historical building, which is around 130 years old, (Fig. 3). The dimensions of the bricks were approximately 60×110×230 mm^3. Before using as wall units, they were cleaned thoroughly and made free of mortar. The average compressive strength and elasticity modulus of these bricks were determined as 5.0 and 118 MPa at the end of single brick compression tests. These mechanical characteristics were determined as 2.1 and 192 MPa at the end of compression tests of prism specimens of three bricks.

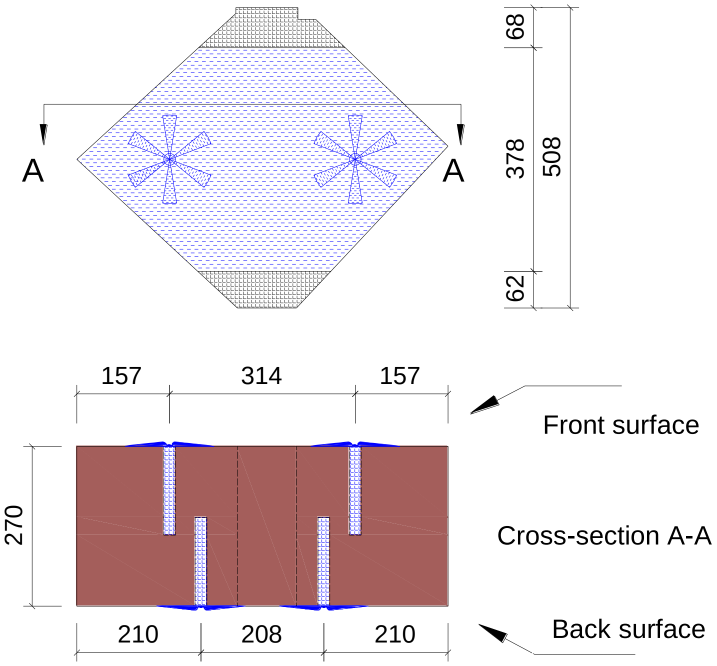

Figure 2: Type D specimen with FRP sheets anchored into the bricks, (units in mm)

Table 1: General characteristics of specimens

Specimen	Plaster	FRP	FRP plies on both surfaces	FRP anchors
A	No	No	0	No
B	Yes	No	0	No
C-1	Yes	Yes	1	No
C-2	Yes	Yes	2	No
D	Yes	Yes	2	Yes

For determining the appropriate joint mortar, which can represent the mortar characteristics in-situ, 6 different trial mixtures were prepared. All trial mixtures were composed of cement, hydraulic lime, sand and water. At the end, a mixture of cement, hydraulic lime, sand and water, with the respective ratios of 01: 02: 15: 2.6, by weight was shown to represent the existing mechanical characteristics of existing joint mortar in the historical building. The mechanical characteristics of original joint mortar and trial mortar mixtures were determined through three point bending tests and compression tests (Fig. 4). After these tests, average flexural tensile and compressive strengths of the joint mortar used in the construction of wall specimens were determined as 1.2 and 3.3 MPa at 28 days and 1.6 and 3.8 MPa at 90 days.

Before bonding the glass FRP sheets on the wall specimens, a plaster was necessary to obtain a flat surface on which FRP sheets could be bonded. Therefore, a ready-mixed cement based repair mortar was used for this purpose. The average flexural tensile and compressive strengths of the repair mortar were determined as 7.0 and 44.0 MPa, respectively.

Figure 3: Historical bricks

Figure 4: Tests for determination of mechanical characteristics of joint mortar

For retrofitting, EG-60AR glass FRP, with the elasticity modulus of 65.000 MPa and tensile strength of 1700 MPa was used, (Fig. 5). The effective thickness and maximum elongation of the material was given as 0.23 mm and 2.8% by the manufacturer. The glass FRP sheets were bonded on the plaster using an epoxy based adhesive, with the tensile elasticity modulus of 3000 MPa and tensile strength of 50 MPa.

Figure 5: Glass FRP sheets to be used for retrofit of walls

4 CONSTRUCTION OF SPECIMENS AND RETROFITTING

The dimensions of specimens were approximately 500×500×230 mm^3. While constructing the specimens, a special mortar mixture was used for the mortar to represent the mechanical characteristics of the mortar used in this historical building. The thicknesses of horizontal and vertical joint mortar were 20 and 10 mm, respectively. The construction phases of wall specimens are presented in Fig. 6. After walls were constructed, the surfaces of the specimens other than the reference specimen were covered with plaster of repair mortar, (Fig. 7). The thickness of the plaster was approximately 20 mm on both surfaces. After plastering, three specimens were retrofitted by bonding the glass FRP composites on two surfaces, (Fig. 8). Specimen C-1, C-2 and D were strengthened with one, two and two plies of glass FRP sheets on both surfaces, respectively. The application of glass FRP anchors into the bricks is presented in Fig. 9.

Figure 6: Construction of wall specimens

Figure 7: Plastered specimen

Figure 8: FRP application on specimens C-1 and C-2

Figure 9: Application of glass FRP anchors into the retrofitted specimen D

5 TESTING AND MEASURING SETUP

All the specimens were tested under diagonal tension using an Amsler Loading Machine. The average longitudinal and transverse deformations were measured on both surfaces of specimens by using displacement transducers and strain gages. The average longitudinal deformations were measured in the gage lengths of 270 and 500 mm by using displacement transducers and in the gage length of 60 mm by strain gages. The average transverse deformations were measured in the gage length of 250 mm by displacement transducers and in the gage length of 60 mm by strain gages. All data was collected by a data logger through a switch box. The testing setup is shown in Fig. 10.

Figure 10: Testing setup

6 EXPERIMENTAL RESULTS

6.1 Damage mechanism of specimens

The reference specimen A failed in a brittle manner at a very low level shear stress due to vertical separation of wall into two parts. The separation followed the boundaries of horizontal and vertical mortar joints and brick units had minor breakages. The maximum load and load corresponding to vertical crack formation were almost same. Vertical deformation was slightly higher at maximum load with respect to load at which vertical crack was formed. No compression failure of bricks or joint mortar was observed throughout the loading.

Specimen B with plaster on two surfaces also failed due to a vertical crack similar as specimen A, passing through the interface between bricks and joint mortar, with minor damage to brick units around the crack. However, the behavior was remarkably better in terms of both ductility and strength. The damage of specimen B is presented in Fig. 12.

Figure 11: Damage of reference specimen A

Figure 12: Damage of plastered specimen B

Specimen C-1 retrofitted with 1 ply of glass FRP sheets on two surfaces over plaster failed suddenly due to separation of FRP sheets, plaster and a thin layer of bricks from the brick wall. The failure phenomena showed that the weakest link was the brick itself. The resisted load by this specimen, as well as the average vertical deformation at peak load, were more than three times those of reference specimen and more than two times than those of the specimen with plaster. Although the failure occurred at a significantly higher deformation level, ductility was poor due to sudden loss of strength caused by peeling off the brick surface together with the plaster and glass FRP sheet on one surface of the specimen. After the test, it was observed that there was a vertical crack under the plaster and FRP sheet, which continued along the vertical and horizontal joint mortar. At the peak load, there were indications of local brick crushing around the loading points, while there was no crushing at the middle parts of the specimen.

Failure mechanism of specimen C-2 was similar as specimen C-1, Fig. 14. Since the tensile strength of bricks, whose average flexural tensile strength was defined as 1.4 MPa, was the weakest component, glass FRP sheets were never stressed near their tensile capacities. Therefore, increase in the thickness of FRP sheets did not positively affect the behavior. The capacity of this specimen was less than that of specimen C-1, while their deformability characteristics were similar. The difference in strengths of specimens C-1 and C-2 is attributed to the variation of brick quality, since the bricks were original 130 years old bricks, which were collected randomly. Unlike the reference (A) and plastered (B) specimens, whose capacities were governed by the strength of joint mortar, the capacities of these two specimens were governed by the tensile characteristics of bricks.

Figure 13: Damage of FRP retrofitted specimen C-1

Specimen D, which was identical to specimen C-2 with additional glass FRP anchors as shown in Fig. 2 and Fig. 9, failed in a similar manner as specimens C-1 and C-2 with two slight differences, which were provided by the additional anchors, Fig. 15. The separation of FRP sheet, plaster and a thin surface of brick wall initiated at around 60 kN load and average vertical strain of 2000 microstrain. However, in contrast to other specimens, the separation did not cause a sudden and significant drop in strength, but a small reduction in the resisted load, followed by an increase in the capacity up to 63 kN at up to the average vertical axial strain level of 3000 microstrain. After this point, the resisted load decreased gradually, exhibiting a better ductility than the other FRP retrofitted specimens.

Figure 14: Damage of FRP retrofitted specimen C-2

Figure 15: Damage of FRP retrofitted specimen D with FRP anchors

6.2 Strength and deformability characteristics

The test results in terms of strength and deformation characteristics are summarized in Table 2 and 3. In these tables, P_{cr} and P_{max} are the loads at the formation of vertical crack and maximum load, respectively, and ε_{cr} and ε_{max} are the average vertical axial strains corresponding to these loads. ε_{85}, ε_{50} and $A_{\varepsilon 0.85}$ are the average vertical strains at the 85% and 50% of the peak load on the descending branch of the load-average vertical deformation relationships, and areas under the same relationship up to the average vertical strain of ε_{85}, respectively. It should be noted that the given vertical deformations in these tables are taken from the measurements in the gage length of 500 mm, which was the full height of specimens.

Table 2: Strength and deformation characteristics of specimens (gage length: 500 mm)

Specimen	P_{cr} (kN)	ε_{cr}	P_{max} (kN)	ε_{max}	Enhancement in strength (%)	Enhancement in vertical deformation corresponding to strength (%)
A	23.0	0.0002	24.5	0.0008	-	-
B	32.0	0.0011	32.0	0.0011	31	38
C-1	82.0	0.0029	82.0	0.0029	234	263
C-2	67.0	0.0039	67.0	0.0039	173	388
D	58.0	0.0018	63.0	0.0033	157	313

Table 3: Toughness and deformability characteristics of specimens (gage length: 500 mm)

Specimen	$\varepsilon_{0.85}$	$\varepsilon_{0.50}$	Enhancement in $\varepsilon_{0.85}$ with respect to A (%)	Enhancement in $\varepsilon_{0.50}$ with respect to A (%)	Ductility $\varepsilon_{0.85}$ / ε_{max}	$A_{\varepsilon 0.85}$ normalized with respect to A
A	0.0012	0.0015	-	-	1.5	1.0
B	0.0035	0.0054	192	260	3.2	3.7
C-1	*	0.0078	-	420	-	5.1
C-2	*	0.0085	-	467	-	5.8
D	0.0038	0.0111	217	640	1.2	10.1

*Due to sudden loss of strength, strain at 85% of the strength could not be measured

6.3 Load-average vertical strain relationships

The load-average vertical strain relationships are presented for all specimens in Fig. 16. In this figure, vertical axis represents the compressive load applied in vertical direction and horizontal axis shows the average vertical deformation obtained in the gage length of 500 mm. As seen both plastering and retrofitting with glass FRP sheets enhanced the strength and deformability of masonry walls constructed with historical bricks. However, in the case of FRP retrofitted specimens, ductility was reduced due to a sharp reduction of strength upon initiation of separation of FRP sheets, plaster and a thin layer of bricks from the core of brick walls. However, as seen in Fig. 16, the areas under the load-deformation relationship are much higher in the case of FRP retrofitted specimens highlighting a better energy dissipation feature in case of seismic events. It is clear that using the applied load, geometry of the specimens, vertical and horizontal deformations and gage lengths utilized for the deformation measurements, shear stresses and strains can also be calculated using Eq. (1) and (2), [14], where τ, γ, P, b and t represent shear stress, shear strain, applied load, height and thickness of the section subjected to shear stresses, respectively. Δy_1, Δy_2, Δx_1 and Δx_2 are the measured displacements in vertical and horizontal directions and GL is the gage length for these measurements.

$$\tau = 0.707\ P / (bt) \quad (1)$$

$$\gamma = (\Delta y_1 + \Delta y_2 + \Delta x_1 + \Delta x_2) / GL \quad (2)$$

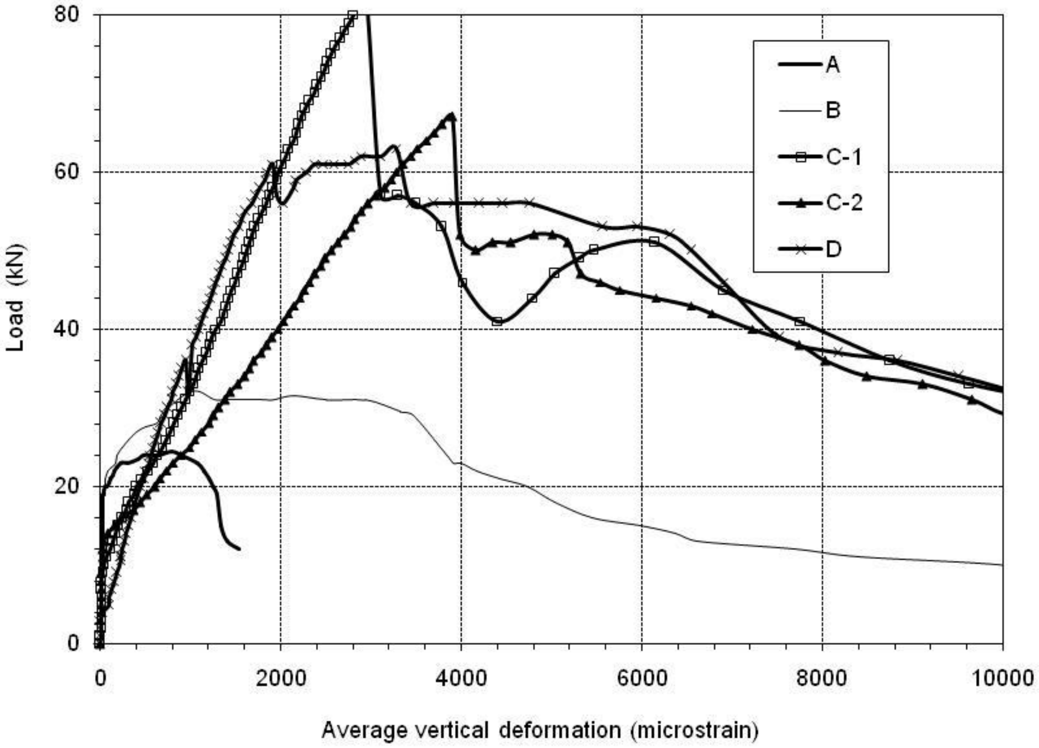

Figure 16: Load-average vertical strain relationships for all specimens (gage length: 500 mm)

7 CONCLUSIONS

At the end of the diagonal tension tests, basic experimental data was obtained on the current mechanical characteristics and failure mechanisms of historical brick walls and the effects of FRP retrofitting of these walls. Performances of the different retrofitting configurations were compared in terms of strength, deformability and mechanism of failure. As demonstrated, both application of a plaster of high strength repair mortar and glass FRP sheets enhanced the strength and deformability of masonry walls significantly. The plaster provided 31% enhancement in strength and 38% enhancement in corresponding vertical deformations, which provided significantly more ductile behavior. The failure modes of reference specimen and plastered specimen were similar due to vertical cracks in the direction of loading, which followed the interface between the bricks and joint mortar. Although the glass FRP sheets provided remarkable additional strength and further enhancement in the deformability, the FRP sheets were not efficiently utilized due to failure mode, which was separation of FRP sheets together with the plaster and a thin layer of bricks from the core of brick wall. Therefore, the capacity of the FRP retrofitted walls were governed by the tensile strength of bricks themselves rather than quality of FRP sheets, bonding adhesive or plaster. The enhancement in strength and corresponding vertical deformation was 157-234% and 263-388%, respectively. The anchors made from glass FRP rolls inserted into the brick wall to retard the separation of outer shell were successful for preventing sudden loss of strength, as well as providing significantly better ductility in the case of FRP retrofitted specimens. When the FRP sheets were removed, as expected the vertical cracks following the interface of the brick units and joint mortar were also formed in the case of FRP retrofitted specimens. In all cases, damage in the wall was concentrated to the joint mortar, with minor damage to the brick units.

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