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EXTERNAL CONFINEMENT OF BRICK MASONRY COLUMNS WITH OPEN-GRID BASALT REINFORCED MORTAR

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ABSTRACT

A large portion of existing unreinforced masonry buildings in earthquake regions is in urgent need of retrofitting. Masonry brick columns are frequently used as load-bearing elements in such buildings. In this paper, the efficiency of historical masonry column confinement externally with open-grid basalt fiber reinforced mortar, as a strengthening method, is investigated experimentally. A total of 5 masonry column specimens are produced with solid bricks, which have been collected from a historical building constructed around the 1930s, and a local mortar with sub-standard mechanical characteristics to simulate existing historical mortar. The columns with 900 mm height and cross-sectional dimensions of 360 mm x 360 mm are constructed in running bond. All column specimens are tested under concentric compressive loads and the outcomes of the column tests are evaluated in terms of strength, deformability and failure characteristics. A comparison is also made between the experimental results and theoretical predictions made using available analytical models.

KEYWORDS

Basalt fiber reinforced mortar, compression strength, confinement, masonry, stress-strain.

INTRODUCTION

There are many historical structures which are the remains of Byzantium and Ottoman periods in Istanbul, Turkey. In order to provide their existence in future, these structures need to be analyzed and strengthened if required. In recent years, the efficiency of fiber-reinforced polymer (FRP) sheets and textile reinforced mortar (TRM) used for masonry structures as strengthening materials has been investigated. It should be noted that the number of studies related to the application of FRP for masonry elements is less than that for concrete structures.
The masonry elements confined with FRP were studied by Krevaikas and Triantafillou (2005), Corradi et al (2006), Aiello et al (2007), Balsamo et al (2009), Aiello et al (2009) and Ludovico et al (2010). It was observed that the response and failure of axially loaded masonry confined with FRP was similar to that of concrete. The studies show that the confinement of structural members with FRP provides significant improvements in strength and ductility. Additionally, based on the experimental data of the masonry elements confined with FRP, several analytical models were suggested by Krevaikas and Triantafillou (2005), Corradi et al (2006), and Ludovico et al (2010).
In consideration of studies related to FRP, there are fewer researches on the masonry structures using textile reinforced mortar (TRM) as strengthening materials which are presented in the following paragraphs.
The masonry columns confined with an alkali-resistant fiber glass open-grid bonded with cement based mortar were tested under axial compressive loading by Balsamo et al (2009). They reported that confinement systems based on the use of glass grid and cement based mortar allowed significant stiffness gains but reduced the global ductility.
Papanicolaou et al (2006) performed a study about the application of externally bonded textile reinforced mortar as an alternative method to the application of fiber reinforced polymer (FRP) for shear walls, beam-column type walls and beam type walls subjected to cyclic in-plane loading. It was observed that the application of TRM jacketing reduced strength but in terms of deformability it was much more effective compared with resin-based system.

Harajli et al (2010) evaluated different strengthening systems using textile mesh and mortar for strengthening historical wall specimens and tested them to find out their out-of-plane flexural behavior under static and cyclic loadings. The use of a coated basalt textile with a lime mortar for strengthening masonry walls resulted in the least stiffness and strength degradation, the highest energy absorption and dissipation capacities, and the best combination of wall strength and ductility possible.
As outlined above, according to the literature survey of the authors, while there are limited studies on the axial behavior of masonry confined with textile reinforced mortar, there is no information on the behavior of brick masonry columns externally confined with basalt fiber reinforced mortar. The objective of the study is to investigate the efficiency of external confinement with open-grid basalt reinforced mortar on the axial behavior of masonry columns. Axial compression tests are conducted on confined and unconfined masonry columns. It should be emphasized that in this study, instead of polymer materials, local mortar is used as plaster because of having effective adherence, low cost and coordination between mortar and fiber materials.

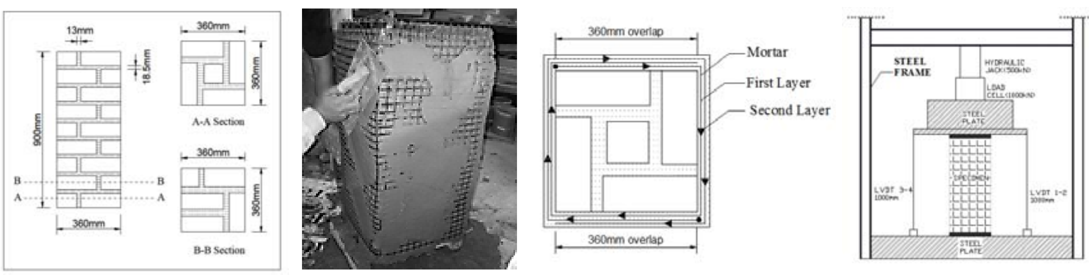
EXPERIMENTAL PROGRAM

Specimen Construction

A total of five masonry column specimens with square cross-section are constructed using bricks taken from a historical building built in the 1930s century and mortar with sub-standard mechanical characteristics to represent mortar characteristics of the masonry buildings of that period. The dimensions of the bricks are in a range of 110-120 mm width, 230-240 mm length and 60-70 mm height. The local mortar using for joints was designed to simulate historical mortar. The mortar contains cement and lime as binder, (cement: lime: sand: water 1: 2: 15: 2.9 by weight). Local mortar used for surface plastering and for bonding basalt grids on the surface of each specimen had different mixture ratios than mortar used for joints. This mortar contained cement: lime: sand: water ratio equal to 1: 2: 15: 3.72 by weight. The reason for increasing water ratio in this mortar was to attain a more plastic mixture for making the fibers were well impregnated.
Each masonry column includes nine rows bonded with eight bed and several head mortar joints, Figure 1(a). The nominal height of each column was 900 mm, with nominal cross-sectional dimensions of 360x360 mm (b x d) without plaster. The masonry columns were constructed in running bond. The nominal thickness of mortar was 18.5 mm for bed joints and 13 mm for head joints, Figure 1(a).

Strengthening Procedure

Two of the specimens were confined externally with 2 layers of open-grid basalt reinforcement, (S-2B-L (1)-(2)). For bonding basalt grids on the specimens, local mortar is used as plaster and open-grid basalt fibers were embedded in the plaster. Two other masonry columns were plastered with local mortar without any basalt grids, (S-0B-L(1)-(2)). The remaining specimen was the reference specimen without plaster and open-grid material, (S-0B-0). The thickness of the open-grid basalt fibers reinforced mortar applied was 15 mm for specimens S-2B-L (1) and (2).
The steps followed for the external confinement process of the masonry columns are: (1) the corners of each column were rounded at an average radius (r_c) of 12 mm using a grinding machine, (2) the surfaces of the columns were soaked with water properly, (3) the surfaces were plastered with local mortar at a nominal thickness of 2 mm for bonding basalt grid, (4) the first layer of basalt grid was placed on the mortar by hand pressure without damaging the grid, (5) the first basalt grid was covered using local mortar with a nominal thickness of 3 mm, (6) the second basalt grid was placed over the mortar, and (7) the last layer of local mortar with a nominal thickness of 3 mm was applied by trowel to fully cover the second layer of basalt grid.
It should be mentioned that each layer of basalt grid had a single overlap of 360 mm length. The confinement syste



(a) (b)

Figure 1. Masonry column and confinement system (a), test setup (b)

Material Characterization and Test Setup

The historical bricks used for the construction of the masonry columns were characterized with their compressive and flexural strengths. The average compressive strength of the solid bricks obtained through testing fourteen half bricks was 9.0 MPa with 2.3 MPa standard deviation thus 0.26 coefficient of variation. The average flexural strength of the solid bricks obtained through testing six bricks was 1.7 MPa with 0.7 MPa standard deviation. The coefficient of variation was 0.42.

The average flexural strengths at 28 and 90 days of the mortar samples (160x40x40 mm) used for the joints between bricks were determined as 0.46 and 0.56 MPa, respectively. The compression tests were performed on half specimens obtained after the bending tests. The average compressive strengths at 28 and 90 days are determined as 1.40 and 1.53 MPa, respectively. Due to the problems taking place during the tests of the plaster mortar, the mechanical properties of the plaster could not be obtained. However, as the water used for the plaster mixture was higher than that for the joint mortar, it may be expected that the mechanical characteristics of the plaster mortar were lower than those of the joint mortar.

The material properties of unidirectional open-grid basalt reinforced with mortar are provided by the supplier. The basalt fabric with 25x25 mm open grid has 170 gr/m^2 nominal weight. Basic mechanical properties of open-grid basalt reinforced mortar are given as 6.0 MPa ultimate tensile strength (f_f), 370 MPa tensile modulus (E_f) and 1.62 % ultimate tensile strain (ε_{fu}). These values are defined as typical test values by the supplier

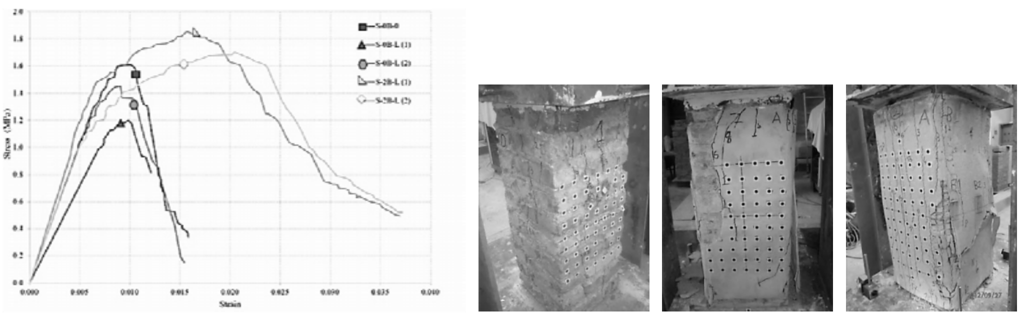
All specimens were tested under axial compression load. The load was applied by means of a hydraulic jack with the load capacity of 500 kN. The applied load was recorded by means of a 1000 kN load cell. In all tests, four linear variable differential transducers (LVDTs) with 1000 mm capacity were used in order to measure axial deformation. LVDTs were installed at each four corners of the specimens. Test setup is shown in Figure 1(b).

TEST RESULTS

The responses of the masonry columns to the compression loads are characterized with axial stress - average strain relationships. These relationships are plotted using the average measurements of four LVDTs, Figure 2(a). Numerical values of the test results are summarized with unconfined strength (f_{mo}), confined strength (f_{mc}), axial deformation at maximum strength (ε_{mc} for confined, ε_{mo} for unconfined), elastic modulus (E), energy dissipation (A) and ductility (μ), Table 3. Young's modulus, which is determined using the least squares method defined in ASTM E 111-04 (2004), is the slope of the linear branch of stress-strain relationship below the proportional limit. In accordance with this statement, Young's modulus is computed based on the higher linear least square regression coefficient computed in a stress range of 30-60%. Energy dissipation is defined as the area under the stress-strain curve enclosed by the strain corresponding to 50% of the strength in the post-peak region. Ductility ratio was calculated as the ratio of strain values at the crossing points of 85 percent of the strength at stress-strain relationship.

As seen in Figure 2(a) and Table 1, the strengths and corresponding axial strains of the reference (S-0B-0) and plastered specimens (S-0B-L (1) and S-0B-L (2)) are close to each other. It is considered that the contribution of the local mortar used for the plaster may be ignorable. The differences between strength and strain values of these specimens are due to highly-scattering characteristics of historical bricks.

As expected, the open-grid basalt reinforced mortar was effective in confining the brick masonry columns. The average increments are 25% for compressive strength and 86% for axial strain at peak stress with respect to the corresponding average values of S-0B-0, S-0B-L(1), and S-0B-L(2) specimens.



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

Figure 2. Stress – Average strain curves (a), appearances of (b) reference, (c) plastered and (d) confined specimens after tests

Table 1. Test results

Specimen notation	f_{mo}-f_{mc} (MPa)	ε_{mo}-ε_{mc}	E (MPa)	A ($x10^{-2}$)	μ
S-0B-0	1.61	0.0102	204	1.32	1.09
S-0B-L (1)	1.20	0.0099	144	0.86	1.10
S-0B-L (2)	1.45	0.0091	204	1.26	1.21
S-0B-L*	1.33	0.0095	174	1.06	1.16
S-2B-L (1)	1.85	0.0159	231	3.80	1.35
S-2B-L (2)	1.70	0.0200	202	3.80	1.19
S-2B-L*	1.78	0.0180	217	3.80	1.27

*Mean values of similar specimens

A specific trend is not found between the elastic moduli of the unconfined and confined specimens. It can be concluded that there is not a significant influence of the masonry confinement on the elastic modulus similar to the case of concrete confinement. Generally, elastic modulus of masonry is defined as a function of its compressive strength. According to the test results obtained in this study, the elastic modulus varies between 120-140 times the axial strength. These values are notably lower than the elastic moduli coefficient of 1000 given in EN 1996-1-1 (Eurocode 6) (2005) and are close to the coefficient of 200 given in TSDC (2007). This constant was also reported as 200 by Ispir and Ilki (2013), based on the compression tests of historical masonry wall specimens taken from the load-bearing walls of another historical structure in Istanbul, Turkey. The average gains in the ductility ratio and energy dissipation are determined as about 12% and 230%, respectively.
The appearances of specimens after their experiments are shown in Figure 2(b, c, d). The reference specimen failed in a brittle manner with vertical cracks through the head joints firstly and then through the bricks, Figure 2b.The failure of plastered specimens (crushing of mortar) was observed after separation of the plaster, Figure 2c. The failure modes of the two confined specimens were identical. Separation of the basalt grid reinforced mortar plaster from the masonry column was followed by the vertical cracks over the plaster. By means of expanding crack widths, basalt fibers on the surfaces and corners started to separate. Then the specimens experienced strength degradation after the rupture of the basalt fibers at the corners, Figure 2d.

ANALYTICAL PREDICTIONS

In order to predict the compressive strengths of unconfined and FRP-confined masonry, analytical models are available in the literature. In this part, the unconfined and confined masonry strengths (f_{mo}, f_{mc}) calculated using several models are compared with the strengths obtained through the tests.
The predictions for the unconfined compressive strength can be made using the relationship given by Eurocode 6 (2005) and Turkish Seismic Design Code (TSDC) (2007).
Eurocode 6 (2005) gives Eq. (1) for the determination of unconfined masonry compressive strength. As seen in this expression, the masonry strength is calculated depending on the compressive strengths of masonry block and mortar, and the constants of K, α, and β. These constants reflect the influences of masonry block, whole ratio in the block, and mortar joint thickness. If masonry has a longitudinal joint through all or a part of the length of the masonry, the value of the constant (K) is multiplied by 0.8.

$$f_{mo,c} = K f_{uc,n}^{\alpha} f_{mc}^{\beta} \tag{1}$$

In this equation, $f_{mo,c}$is the characteristic compressive strength of the masonry, $f_{uc,n}$is the normalized compressive strength of the block and f_{mc} is the compressive strength of the mortar. It should be noted that in order to transform the characteristic compressive strength to the mean compressive strength, the characteristic strength is multiplied by 1.2 as suggested by Eurocode 6 (2005). Constant K takes the value of 0.55 for masonry built with clay block and general purpose mortar which is without any special characteristics in terms of joint thickness and density. For masonry formed with a general purpose mortar, α and β constants are equal to 0.7 and 0.3, respectively. The normalized compressive strength of the block is the strength converted to the air dried compressive strength of an equivalent 100 mm wide x 100 mm high masonry block. For this, the compressive strength of each brick tested was converted to the normalized compressive strength and the average value of the normalized compressive strengths was calculated as 7.8 MPa. Substituting these numerical values into Eq. (1), the mean compressive strength of the unconfined masonry was computed as 2.5 MPa.
According to TSDC (2007), the mean compressive strength of the unconfined masonry is taken as 50% of the block compressive strength if masonry wall tests cannot be performed. In accordance with TSDC (2007), the mean compressive strength of the unconfined masonry is determined as 4.5 MPa.
As seen, Eurocode 6 (2005) and TSDC (2007) overestimate the mean compressive strength of the unconfined masonry with respect to the compressive strength obtained from the tests. This may be resulting from the large dimensions of the specimens tested (nominal 360x360x900 mm) with respect to the dimensions suggested by the codes, namely, these differences may be explained with size effect.

CNR-DT200 (Italian Guideline) (2004), Krevaikas and Triantafillou (2005) and Ludovico et al (2010) propose expressions for the determination of the compressive strength of FRP-confined masonry. Comparing the test results presented in this paper with the predictions of the models presented in these references, the appropriateness of these models for masonry confined with open-grid basalt reinforced mortar is investigated. These models are summarized in the following paragraphs. It should be noted that partial and environmental factors given in Italian Guideline (2004) is not taken into account to make a direct comparison with the test results.

Italian Guideline (2004) proposes an equation similar to the equations proposed for FRP-confined concrete, Eq. (2).In this equation, k is a coefficient defined by Eq. (3) and f_{leff} is the effective confining pressure defined by Eq. (4).In these equations, g_m is masonry mass-density (kg/m^3), k_e is ratio of the effectively confined area (Eq. (5)) and f_l is confining pressure (Eq. (6)). In Eqs.(5) and (6), A_g is the cross-sectional area of masonry column, ρ_f is FRP reinforcement ratio given with Eq. (7), and r_c is the corner radius.

$$f_{mc} = f_{mo} + k f_{leff} \tag{2}$$

$$k = \frac{g_m}{1000} \tag{3}$$

$$f_{leff} = k_e f_l \tag{4}$$

$$k_e = 1 - \frac{(b-2r_c)^2 + (d-2r_c)^2}{3A_g} \tag{5}$$

$$f_l = \frac{1}{2}\rho_f E_f \varepsilon_{fu} \tag{6}$$

$$\rho_f = \frac{4n_f t_f}{\max(b,d)} \tag{7}$$

Krevaikas and Triantafillou (2005) proposed a model based on the compression test results of 42 masonry prismatic specimens constructed with clay bricks. Masonry specimens were confined with CFRP or GFRP sheets. The model expressions are given in Eq. (8):

$$\frac{f_{leff}}{f_{mo}} \le 0.24 \Rightarrow \; f_{mc} = f_{mo} \tag{8a}$$

$$\frac{f_{leff}}{f_{mo}} \ge 0.24 \Rightarrow \; f_{mc} = f_{mo}\left[0.6 + 1.65\frac{fl_{eff}}{f_{mo}}\right] \tag{8b}$$

In this model, f_{leff} is calculated using with Eq. (4). However, the definition of ρ_f is different. The expression used by Krevaikas and Triantafillou (2005) model is given in Eq. (9). It should be noted that while Eqs. (7) and (9) give the same numerical value for a square specimen, these equations give different numerical value for a rectangular specimen. Additionally, this model is based on f_{fe} instead of $E_f\varepsilon_{fu}$. f_{fe} is the effective tensile strength of FRP in hoop direction, which is generally less than f_{fu}. However, for the numerical predictions given in the study of Krevaikas and Triantafillou (2005), the ultimate tensile strength of FRP was used. Therefore, in this study, for the prediction of the compressive strength masonry columns, the tensile strength of open-grid basalt reinforced mortar provided by manufacturer (defined as typical test value) is taken into account.

$$\rho_f = \frac{2(b+d)n_f t_f}{bd} \tag{9}$$

Another important issue with the Krevaikas & Triantafillou model is that, since the limits are defined based on the tests done on epoxy based FRP, Eq, (8a) tends to govern always, and thus an adjustment in the limit of 0.24 would be needed for application in TRM system.

Ludovico et al (2010) proposed an analytical model using the test results conducted on 18 square masonry columns confined with CFRP, GFRP or BFRP. The model includes different relationships for masonry columns constructed with tuff or clay bricks. In this paper, the relationship given for the masonry with clay bricks is taken into account. While the structure of the equation that they proposed for strength is same as the equation given in the Italian Guideline (2004), the definitions of the coefficient ρ_f and k are different (Eq. (9) and (10)). In addition, this model is based on ε_{fe} instead of ε_{fu}. However, for the numerical predictions given in the study of Ludovico et al (2010), the ultimate tensile strain of FRP was used. Therefore, in this study, for the predictions of the strength of masonry columns, the ultimate tensile strain of open-grid basalt reinforced mortar provided by manufacturer is taken into account.

$$k = 1.53\left(\frac{f_{leff}}{f_{mo}}\right)^{-0.10} \tag{10}$$

The confined masonry compressive strengths computed using the models are presented in Table 2 together with the ratios of predicted (P) to measured (M) compressive strengths. As seen in Table 2, while the compressive strengths calculated using the models of Italian Guideline (2004) and Ludovico et al (2010) are in good agreement with the average of the test results, the model of Krevaikas&Triantafillou (2005)underestimates the corresponding average of the test results. As a result, the models of Italian Guideline (2004) and Ludovico et al (2010) can be used to predict the compressive strength of the masonry column, although the experimental data on which these models were established did not include the masonry columns confined with the open-grid basalt reinforced mortar.

Table 2. Model predictions

Model	f_{mc} (MPa)	f_{mc} (P) / f_{mc} (M)
Italian Guideline(2004)	1.84	1.04
Krevaikas&Triantafillou (2005)	1.61	0.91
Ludovico et al (2010)	1.89	1.07

CONCLUSIONS

The experimental studies showed that the reference specimen and specimens confined with only local mortar exhibited a similar behavior. Beside this, the open-grid basalt reinforced mortar provided a fairly small compressive strength gain of the historical brick masonry column with respect to the reference specimen and the specimens confined with only local mortar. On the other hand basalt jackets reinforced mortar improves energy dissipation of the masonry columns notably. The two available models can be used to predict the compressive strength of the masonry column confined with the open-grid basalt reinforced mortar, although these models are suggested for FRP confined masonry.

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