Modeling of the Shear Behavior of Unreinforced and Strengthened Masonry Walls

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SUMMARY
Masonry is a well-known composite material that is being extensively used throughout the world due to its accessibility, functionality and in many instances relatively low cost, but has low tensile and shear resistance. As a cultural heritage, there are a large number of historical masonry structures in Turkey and Mediterranean countries. Masonry structures are very reliable if they carry only gravity loads, but do not exhibit a good performance when subjected to lateral forces such as earthquake loadings. Therefore, it is important to understand the behavior of masonry structures under lateral loadings in order to take measures to protect historical monuments. Due to the high seismicity in Turkey and also many other countries, retrofitting of masonry structures with fiber polymers is getting more attention because of their high seismic performance. During the last ten years, there have been numerous experimental and numerical investigations and research work in literature on the strengthening technique of masonry structures wrapped with polymers. In this study, three-dimensional (3D) elastic-plastic micro modeling of unreinforced masonry (URM) and strengthened walls under compression and shear has been performed employing Drucker-Prager yield criterion. All the material parameters are expressed in terms of the compressive strength of masonry. In order to evaluate the accuracy of the proposed approach, experimental results of both unreinforced and strengthened masonry walls tested by Stratford et al. (2004) are employed. Shear behavior of walls is successfully predicted in terms of the horizontal load-displacement relations and the distribution patterns of the deformations over the wall.

Keywords: finite element analysis, masonry wall, fiber reinforced polymers, shear-compression behavior

1. INTRODUCTION

Many existing unreinforced masonry buildings as a significant portion of building stock in many countries are seismically vulnerable, and need to be retrofitted and strengthened. The worldwide engineering community has identified failures of unreinforced masonry (URM) walls as one of the major causes of material damage and loss of human life due to seismic events (CIES 2001). Therefore, the development of reasonable and practical retrofitting techniques for masonry members such as walls is an urgent need. In the literature, there are numerous experimental studies on retrofitting technique of masonry walls with FRP layers under monotonic or seismic loading. Those studies indicate that the external and near surface application of FRP composite laminates either on single or on both sides of masonry walls can remarkably enhance their in-plane and out-of plane shear carrying capacity (Mosallam, A and Banerjee, S., 2011). The application of FRP to improve the performance of masonry walls can primarily make considerable contribution to the shear strength of the wall.

Present study examines the mechanical behavior of URM and strengthened walls with glass-fiber reinforced polymers (GFRP) subjected to out-of-plane loading. In this context, two series of walls (unreinforced and strengthened) are considered. FRP composites in the form of strips, sheets and rods are used as strengthening materials. For this purpose, URM walls (clay 1 and concrete1) and strengthened walls (clay 2-3 and concrete 2-3) with GFRP sheets tested by Stratford et al. 2004 were numerically simulated and solutions were compared with the experimental ones.

Masonry walls are the main load bearing elements of masonry structures and the use of FRP composites, as mentioned above, enhances the strength and ductility of URM walls under earthquake loading. Therefore, attention should be primarily focused on the description of the wall behavior under shear and compression. The present study initially aims to model FRP-strengthened URM walls adopting a practical elasto-plastic approach previously applied to the FRP-confined masonry columns (Köksal et al. 2011). Thus, the mechanical properties of masonry materials such as brick and mortar, which exhibit much more complex behavior than those of other popular construction materials, are simply related with the compression strength. Adopting the analytical relations for cohesion and internal friction angle (Köksal et al. 2005, 2011), the material parameters of the yield criterion also account for the change of the linear part of the compressive meridian into a curve representing the nonlinear relationship between the shear strength and the normal stress at higher hydrostatic pressure values. In the application of the plasticity theory to FRP-strengthened masonry walls under vertical and lateral loading conditions, the constitutive behavior of masonry units such as mortar, brick and FRP composite material are considered separately. To validate the proposed methodology, two URM and two strengthened walls are analyzed using 3D finite element formulation. Strengthened walls externally bonded with one face of the walls (clay 2 and concrete 2) are successively simulated in LUSAS (Lusas 14.5-2) to predict the behavior of URM and strengthened walls. Predictions are compared with the experimental data from the study of Stratford et al. 2004.

2. MATERIAL MODELING

Numerical models applied to masonry structures involve mechanical parameters that are difficult to measure. Furthermore, masonry behavior generally requires complex theoretical modeling, which cannot be implemented practically into numerical analyses. Since the most common test preformed on concrete-like brittle materials is for the measurement of its uniaxial compressive strength, the most important mechanical properties of concrete can be assumed as directly related to its compressive strength. The authors have previously employed this approach in the elasto-plastic analysis of reinforced concrete (RC) elements successively (Köksal et al.2005, 2010, 2011, Doran et al. 2009). As in the case of RC members, the elasto-plastic analyses of masonry members refer to simple solutions rather than using complex theoretical models (Köksal et al. 2009). Accurate measurement of mechanical parameters for modeling interface behavior between the unit and mortar is very difficult and contingent upon local behavior containing many uncertainties. The nonlinear response of unit-mortar interface represents one of the most important features of masonry behavior (Marcari et al. 2007). Thus, the material parameters for mortar can be calibrated with the experimental results to reflect the effects of the interface behavior. The adoption of the perfect bond assumption between the masonry unit and mortar makes the analysis more robust. The following relation is employed for the mortar cohesion and friction angle (Köksal et al. 2004, Köksal et al. 2011):

$$c_{mr} = 1.55\sqrt[3]{f_{mr}} \tag{2.1}$$

$$\phi_{mr} = 1.519 f_{mr} \tag{2.2}$$

Higher hydrostatic pressure values exist and therefore a nonlinear relationship between the shear strength and hydrostatic pressure has been previously proposed for the case of FRP-confined masonry columns (Köksal et al. 2012):

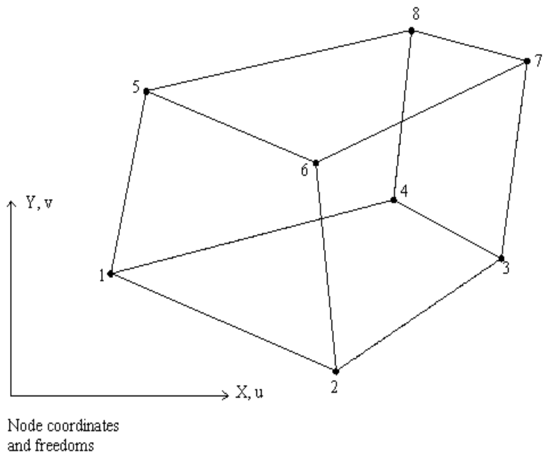
$$\frac{c_{mu}}{f_{mu}} = \frac{\tan\phi_{mu}}{3}\sqrt{\frac{\sigma_m}{f_{mu}}} \le \left.\frac{c_{mu}}{f_{mu}}\right|_{\frac{\sigma_m}{f_{mu}}=1}$$

$$\phi_{mu} = \phi_i - 0.75\frac{\sigma_m}{f_{mu}} \ge \phi_f = \left.\phi_{mu}\right|_{\frac{I_1}{f_{mu}}=1} \tag{2.3}$$

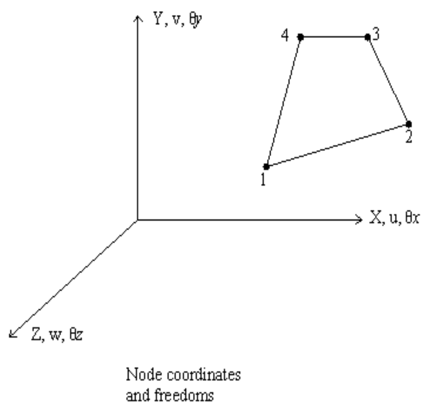
where σ_m is the mean stress (=$I_1/3$= $(\sigma_{xx}+\sigma_{yy}+\sigma_{zz})/3$); ϕ_i and ϕ_f are initial and final angle of internal friction in radians respectively. ϕ_i can be approximately equal to $\pi/3$ for brick. f_{mr} is the compressive strength of mortar, c_{mr} is the cohesion and ϕ_{mr} is he internal friction angles of mortar. f_{mu} is the compressive strength of the brick units, c_{mu} is the cohesion and ϕ_{mu} is the internal friction angles of brick units.

2. FINITE ELEMENT IMPLEMENTATION ON THE MASONRY WALLS

3D-finite element models for the walls tested by Stratford et al.(2004), including strengthened ones using FRP composites are developed in LUSAS (2011) and analyzed using 3D elasto-plastic analysis. Brick and mortar are modeled as separate elements with eight-nodded hexahedral element (HX8M) which is a solid element with an incompatible strain field (Figure2.1a). FRP composites are modeled via four-nodded thick shell element (QTS4) which has a thick and thin curved shell geometry including multiple branched junctions (Figure2.1b). Both the finite element (FE) formulations take account of membrane, shear and flexural deformations and are capable of modeling inelastic phenomenon.



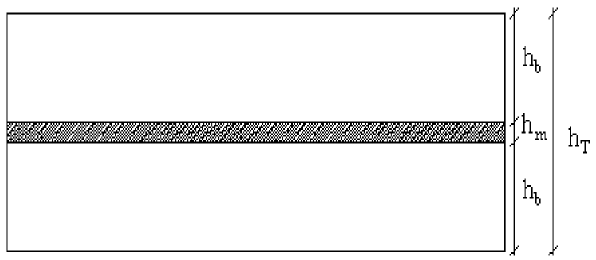
(a)



(b)

Figure 2.1 Types of finite elements for the constituents of a masonry wall:
(a) Brick and mortar; (b) FRP composites (Lusas 2011)

Elasto-plastic analyses require a definition for ending the nonlinear finite element analysis (NLFEA) when the stress-strain curve has a plastic plateau. For the case of URM wall, the end point for the analysis is determined by defining a discontinuity surface between two clay units along the thickness of the mortar which indicates a macro-crack on the wall (Figure 2.2). Dividing the mortar thickness by two block heights plus the mortar thickness, the maximum tensile strain ε_1 for clay 1 and concrete 1 walls can be found as: $10/(2x65+10)=0.071$ along this discontinuity surface. For the case of strengthened walls, FEA can be interrupted when the ultimate tensile strain of GFRP sheets reaches the rupture strain, $\varepsilon_{rup} = f_t / E_{FRP}$.



$$\varepsilon_{max} = \frac{h_m}{2h_b + h_m} \qquad h_T = 2h_b + h_m$$

Figure 2.2 Definition for the fracture of an interface and maximum tensile assumption (Jafarov and Köksal, 2011)

Stratford et al. (2004) tested six masonry panels under a combination of vertical preload and in-plane horizontal shear. Three of the tested panels were built with clay bricks (Clay 1,2,3) with the dimensions of 228x65x60 millimeters; others were built with concrete ones (Concrete 1,2,3) with the same dimensions and same mortar type with 10 mm thickness. One specimen of each material was left unreinforced, while the other two with whole surface were single-sided strengthened using GFRP. A sheet GFRP with a biaxial weave was applied to the masonry because single-sided strengthening could be more economic. GFRP had equal amounts of fibers in the horizontal and vertical directions (parallel to the mortar joints) and fibers were oriented at 45° to the joints. As shown in Figure 2.3, tested brick–masonry panels were based upon a 1200 mm square. A vertical load of N=100 kN (1.38 MPa) was first applied to the wall. The shear load was then applied to the wall by a horizontal hydraulic jack (P) and in order to evaluate the proportion of this load carried across the top surface of the wall bearing by friction, strain gauges were attached to the steel bars, giving the horizontal reaction force (H). Mechanical properties of the specimens (brick, mortar and GFRP) and its ingredients evaluated in this study are given in Tables 2.1 and 2.2 respectively.

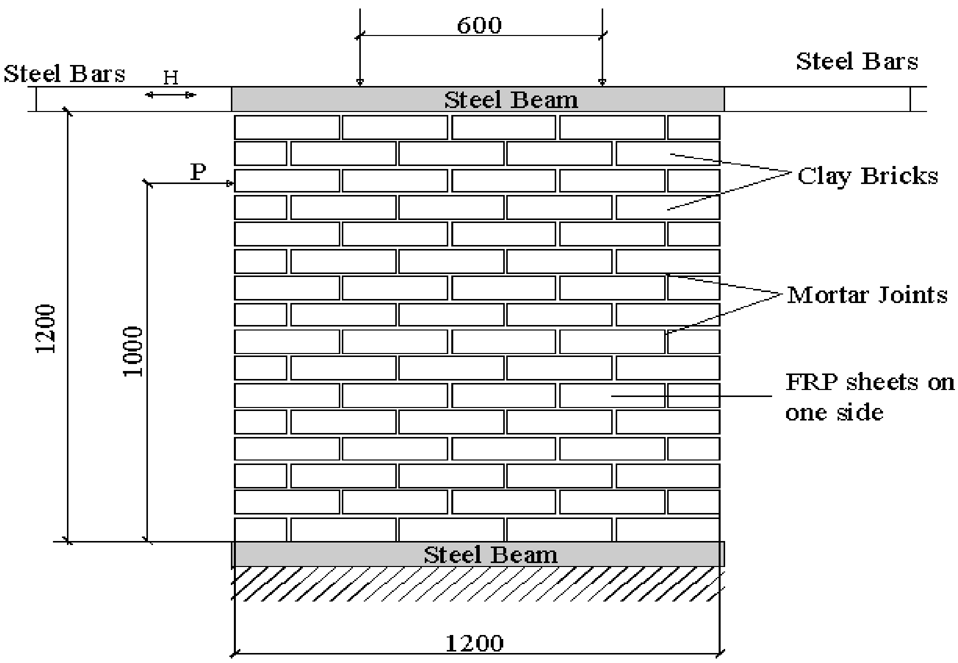


Figure 2.3 Experimental setup (Stratford et al., 2004)

Table 2.1 Mechanical properties of GFRP sheets

Wall Name	E_{frp} (MPa)	f_t (MPa)	t (mm)
Clay 2-3	73300	986	0,15
Concrete 2-3	73300	986	0,15

Table 2.2 Mechanical properties of masonry ingredients.

Brick							Mortar			
Wall Name	E_{mu} (MPa)	f_{mu} (MPa)	Poisson's Ratio	c_{mu} (MPa)	ϕ_{mu}	f_{mr} (MPa)	E_{mr} (MPa)	Poisson's Ratio	c_{mr} (MPa)	ϕ_{mr}
Clay 1-2-3	18600	62	0,2	3,04	59,68	11	3250	0,2	3,269	16,709
Concrete 1-2-3	29000	36	0,2	2,29	59,45	5,5	1500	0,2	2,736	8,354

Failure mechanism and crack patterns for URM and strengthened walls using GFRP have also been presented in the study by Stratford et al. URM clay specimens have failed along a near-horizontal crack at the base of the wall while the others failed by rapid propagation of a diagonal crack, which followed the mortar joints (Stratford et al., 2004). In this present study, FEA ends when the ultimate tensile strain at the wall reaches 0.071 value for URM walls (clay 1 and concrete 1). For strengthened walls using GFRP (clay 2-3 and concrete 2-3), FEA are interrupted when the ultimate tensile strain of GFRP sheets reaches the rupture strain value of 0.013. Both simulation model and laboratory test results for URM and strengthened ones are in very good agreement as shown in Figs 2.4 and 2.5.

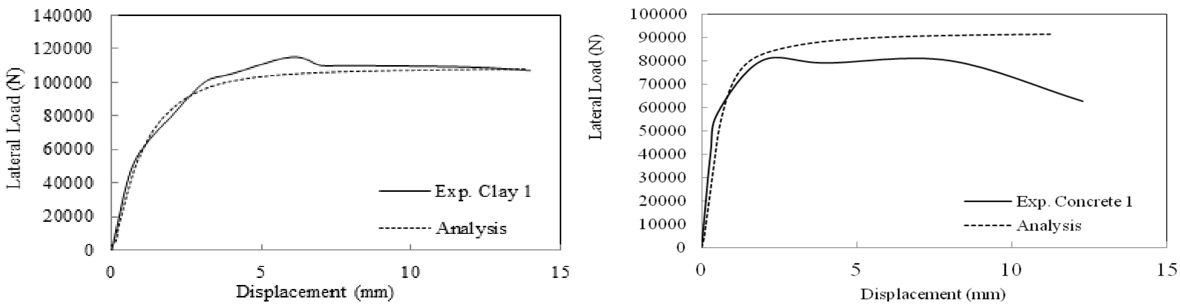


Figure 2.4 Load- displacement curves for URM walls

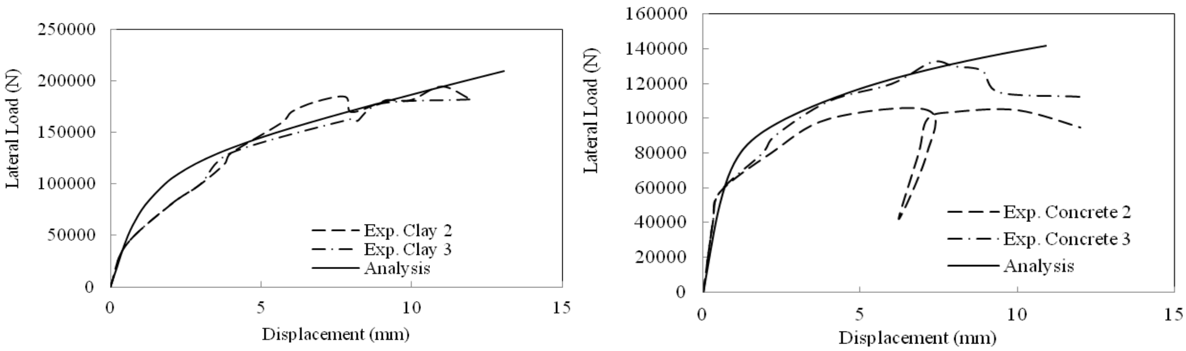


Figure 2.5 Load- displacement curves for strengethened walls with GFRP

Besides, failure mechanisms and crack patterns at this strain values seem reasonably similar as demonstrated in Figs 2.6. and 2.7.

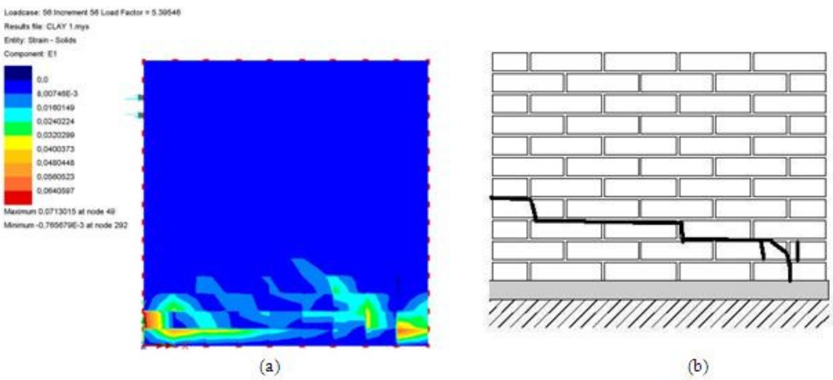


Figure 2.6 (a)Maximum stains over the URM wall (b) and crack patterns on clay1 wall (Stratford et.al 2004)

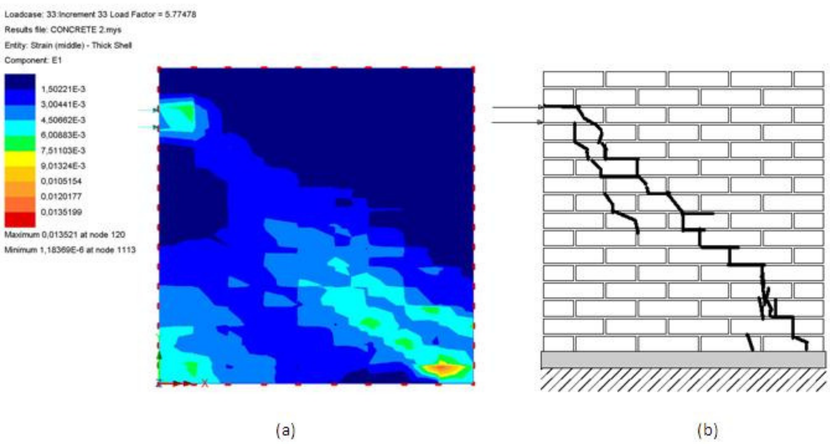


Figure 2.7 (a) Maximum stains over the strengthened wall with GFRP (b) and crack patterns on concrete 2 wall (Stratford et. al 2004)

CONCLUSIONS

This study is primarily concerned with 3D elastic-plastic analysis of URM and strengthened walls under compression and shear, using the Drucker-Prager yield criterion. In order to evaluate the accuracy of the proposed approach, experimental results of both unreinforced and strengthened masonry walls tested by Stratford et al. (2004). Based on the results of FEA, the following conclusions are obtained:

1. In 3D elasto-plastic analysis, the relations previously recommended by the authors for masonry columns for the cohesion and internal friction angle are updated for the analyses of masonry walls.

2. When the stress-strain curve has an ideal plastic plateau, it needs an end point definition to terminate the NLFEA. For the case of URM wall, the end point is determined defining the discontinuity surface between two clay units along the thickness of the mortar. It is possible to calculate the maximum strain ε_1 by dividing the mortar thickness by two block heights plus the mortar thickness. For the case of strengthened walls with GFRP, this point can be defined as rupture strain, $\varepsilon_{rup} = f_t / E_{FRP}$. Figs.4 and 5 support this definition.

3. In Figs.6 and 7, it can be concluded that URM walls generally fail along a near-horizontal crack at their base, and in most cases for the strengthened walls using GFRP, failure generally do not occur in the GFRP itself. They fail by rapid propagation of a diagonal crack along the mortar joints.

4. As can be seen in Figs. 4 and 5, strengthening with GFRP increases the load-capacity approximately by 65% in clay walls, %38 in concrete 2 wall and % 63 in concrete 3 wall respectively. However, it should be noted that the deformation capacities seem not to have changed with a single sided GFRP.

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