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Behavior of Heritage Masonry Walls Retrofitted With CFRP Sheets

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ABSTRACT: In this paper, the seismic vulnerability of heritage masonry walls is assessed by conducting a numerical study on both unreinforced and reinforced masonry walls originally considered by Demir (2012) at Istanbul Technical University (ITU). The wall is representative of the heritage form of construction used in Ottoman Empire Classical Period monumental structures constructed in and around Istanbul. The wall has two leaves, with a shear key of rubble stone mortar bonding the two leaves together. Finite element analysis of the heritage wall under cyclic loads was carried out and the results were compared with the experimental response. The effects of strengthening of these walls with carbon fibre reinforced plastics (CFRP) sheets was investigated numerically and the increase in strength recorded. The wall retrofitted with CFRP was modelled in an ABAQUS environment. The numerical model for the CFRP reinforced heritage wall shows that with proper configuration of the CFRP the failure mode of the unreinforced wall can be modified so as to enhance the strength and integrity of the wall.

1 INTRODUCTION

Masonry wall as a building block of masonry structures has attracted tremendous attention from several research directions. It has been studied extensively for architectural features, structural aspects and properties of materials utilized for construction. Taking the structural point of view, masonry structures have been studied extensively for better understanding of its behavior. One of the greatest motivations for this direction of research is that historical structures represent valuable treasures for the countries culturally and economically. Attempts are being exerted for preserving, maintaining and strengthening historical structures so that they can still be in good conditions for longer periods of time.

In this study, masonry walls are modeled using elastoplastic-damage model as originally developed by Lubliner et al (1989) and further extended by Lee and Fenves (1998). The masonry blocks and rubble were modeled using solid elements whereas CFRP laminate was modeled using an orthotropic shell element. The wall units, rubble and mortar are modeled as elastoplastic material with scalar damage using yield surfaces that are generalization of the Drucker-Prager model. In this model, new terms account for hardening and softening in compression and softening in tension, with parameters calibrated to the experimentally measured stress-plastic strain data from uniaxial compressive and tensile tests for both the blocks and the rubble stone mortar. Scalar form of damage is built into the model to account for stiffness degradation. Modes of failure of the unreinforced wall observed in the simulation are compared with the experimentally determined failure modes of Demir (2012).

Demir (2012) conducted a study to examine the response of walls representing the monumental structures in Istanbul subjected to cyclic loading. In his study, Demir investigated the effect of cyclic loading on a multi-leaf masonry wall used in the ancient heritage mosque. As shown in Fig 1, dimensions of the walls were 1.2 by 1.2 m with thickness of 30 cm. Each leaf was built with stone, using dry jointing system.

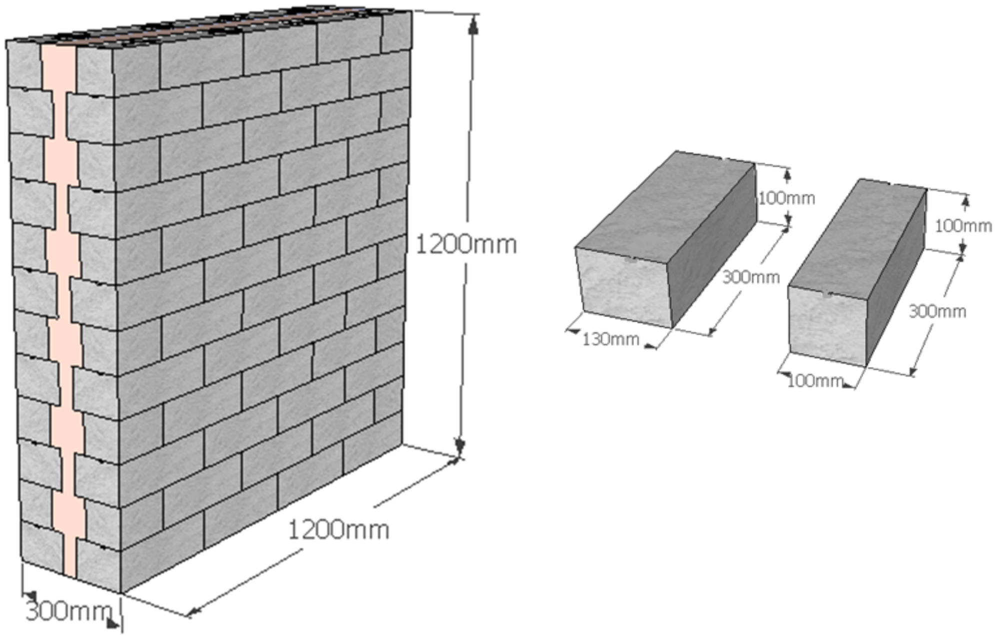


Fig 1. Geometric Details of Walls (Demir 2012)

The walls were subjected to varying pre-compression axial force prior to the application of cyclic lateral load. Some of the variables are summarized in Table 1.

Table 1 Variables in Demir's (2012) Experiments

Wall Sample	Axial Stress Magnitude (MPa)
M-25-C	0.25
M-50-C	0.5
M-75-C	0.75
M-100-C	1

Demir (2012) has reported different modes of failure of the walls according to the level of axial force. He observed that the walls tend to be stiffer when the axial stress was higher. In the work presented here, two different finite element simulations, using micro-analysis approach, have been conducted for the walls under consideration. The first simulation was conducted for the case of wall without reinforcement (URM) and the second simulation was conducted for the wall reinforced with CFRP (RM). In the FEM simulations, fixed support (Ux=0, Uy=0, and Uz=0) were assumed at the base of the walls. Monotonic loading type was adopted in this study and a comparison made between numerical and experimental results where available.

2 FINITE ELEMENT MODEL IN ABAQUS ENVIRONMENT

Only one axial load case in which the wall is subjected to 0.5 MPa axial loading was studied. Uniaxial stress-plastic strain data for both bricks and rubble in uniaxial compression and tension have been used in the plastic damage model incorporated in an ABAQUS environment. Figs 2 and 3 show this data as based on actual testing carried out by Demir (2012).

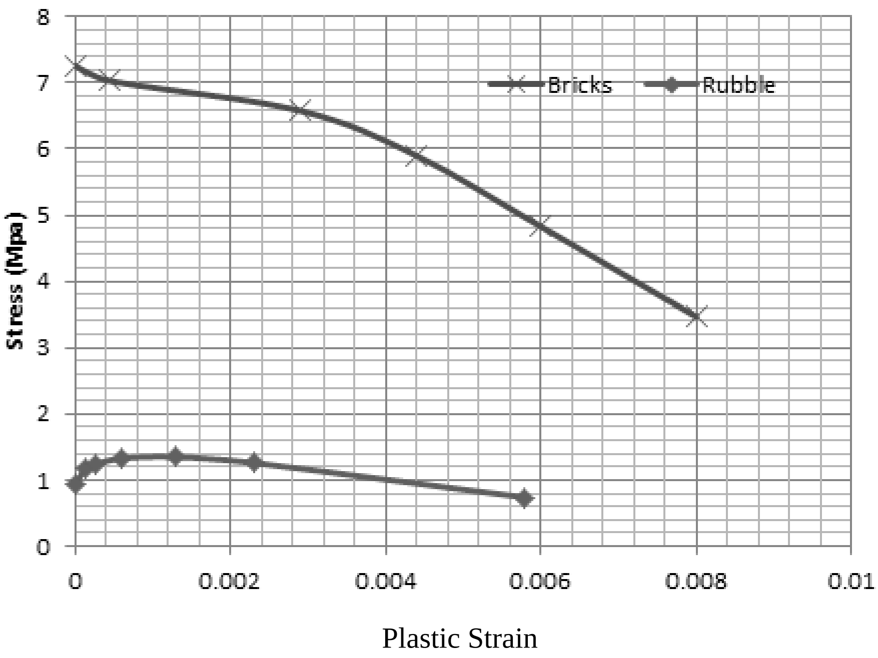


Figure 2. Plastic Strain vs Stress in Compression

Plastic damage model, developed by Lubliner et al. (1989) and adopted in the commercial software ABAQUS, needs certain material parameters to be input in carrying out the simulations. Some of these parameters were assumed to be the default values and some others were based on actual experiments. These parameters are shown in Table 2. The CFRP properties adopted in this study are shown in Table 3.

The CFRP sheet used in this study is a SikaWrap-230C, which is a woven carbon fiber fabric recommended for structural strengthening and improved seismic performance of masonry walls. The SikaWrap-230C uses mid-strength unidirectional carbon fibers. The laminate itself is of thickness 1 mm impregnated with Sikadur-330 epoxy. In this study, only one CFRP laminate of thickness 1.0 mm and the width was 50 mm are used. The CFRP laminate stripes were placed in both sides of the wall and extended vertical and horizontal though the whole dimensions of the wall. It should be mentioned that, the subscripts in Table 3 represent the principal material directions of the CFRP lamina. The wall reinforced with CFRP is shown in Fig 4.

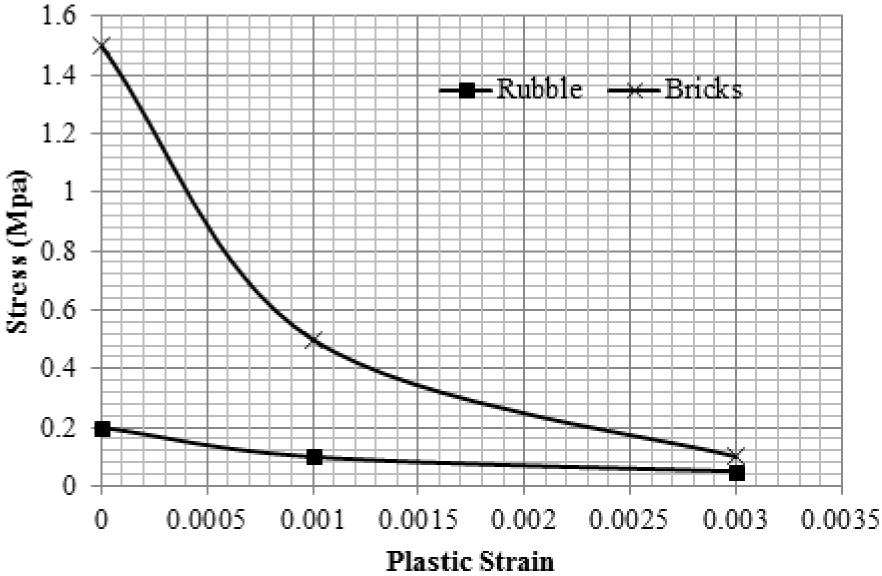


Figure 3. Plastic Strain vs Stress in Tension

Table 2. Parameters Used in Plastic Damage Model.

Mass Density (Tone/mm^3)	Young's Modulus (MPa)	Poisson's Ratio	Dilation Angle ψ (Degree)	Eccentricity ϵ	f_{b0}/f_{c0}	K
2.4E-009	3200	0.18	36	0.1	1.16	0.67

Table 3. Proprieties of CFRP lamina.

E_1 (MPa)	E_2 (MPa)	ν_{12}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	σ_u (MPa)
28000	2800	0.25	5000	5000	5000	350

3 MESHING PROCEDURE.

Dynamic explicit analysis was used in this simulation. The element used for each part of the mode and description of the element is shown in Table 4:

Table 4. Element Properties

Part	Element	Element description
Stone brick	C3D8R	8 node linear brick, reduced integration
Rubble	C3D8R	8 node linear brick, reduced integration
CFRP	S4R	A 4-node doubly curved thin or thick shell, reduced integration,

The interaction between the wall stone bricks themselves and between the wall stone bricks and the rubble was assumed to be only through friction with coefficient of friction of 0.7 whereas the interaction between the wall and the CFRP was assumed to be perfect bond.

4 DISCUSSION OF RESULTS

The lateral loading was a displacement control type. This maximum transverse displacement specified in the simulation was 10 mm. Experimental and numerical results for lateral load-displacement are shown in Fig 5. It can be seen that the wall lateral load response was enhanced 16% as a result of reinforcing with CFRP. A comparison of stress and deformation patterns (at drift=10 mm) between unreinforced and reinforced masonry walls is shown in Figs. 6(a) to 6(f).

It can be seen from Figs 6(a) to 6(f) that the failure mode of the wall has changed. In the URM case, failure resulted due to rocking and separation at lower base course levels driven by peeling tensile stress on one side, whereas the other side exhibited high compression/shear driven damage at the lower base course levels.

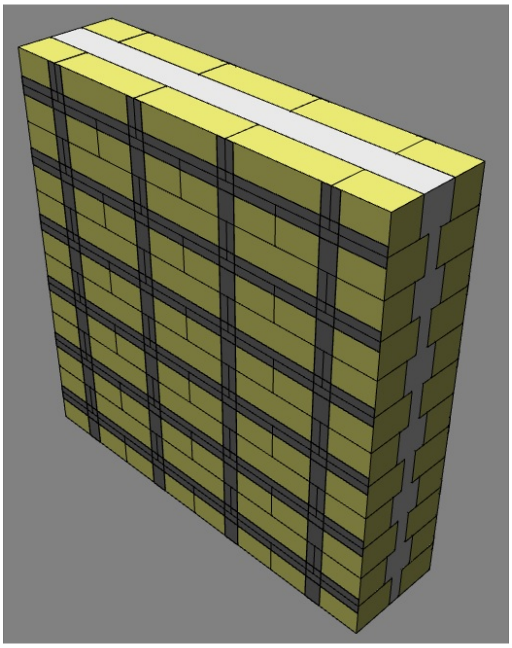


Figure 4. Pattern of CFRP lamina on both sides of the wall

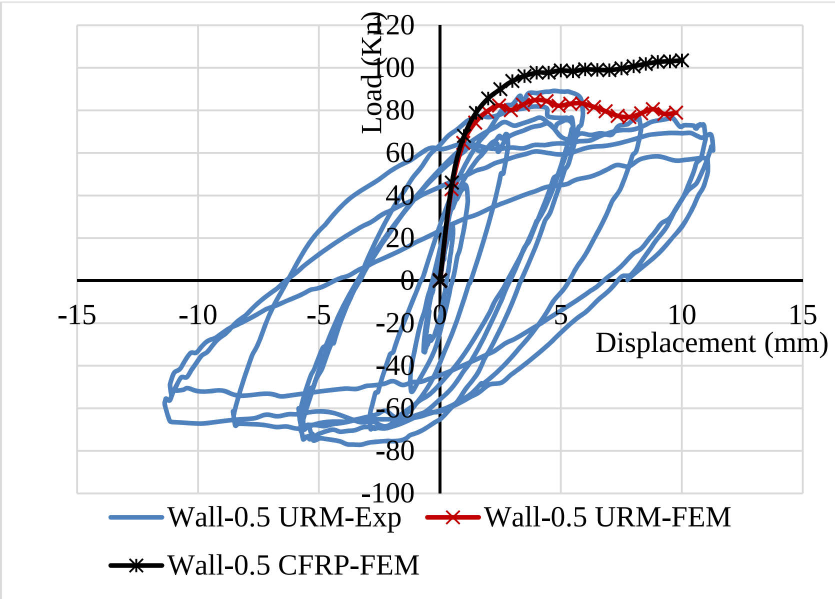


Figure 5. Lateral Response of the Wall with Axial Stress of 0.5 Mpa

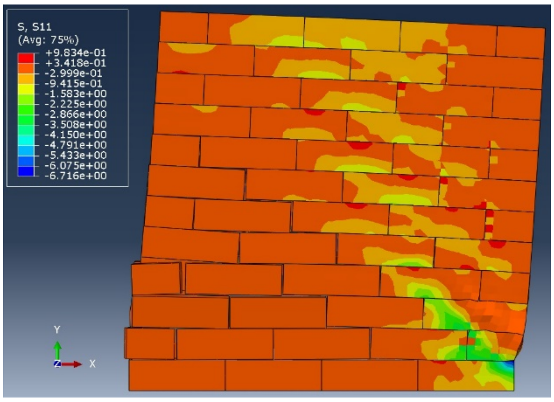


Fig 6(a). Stress (S11) in the Bricks (URM)

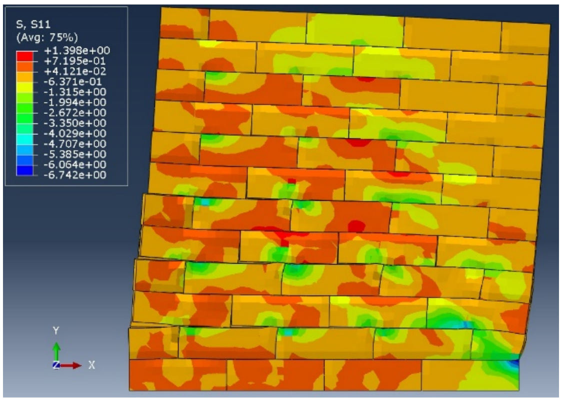


Fig 6(b). Stress (S11) in the Bricks (RM)

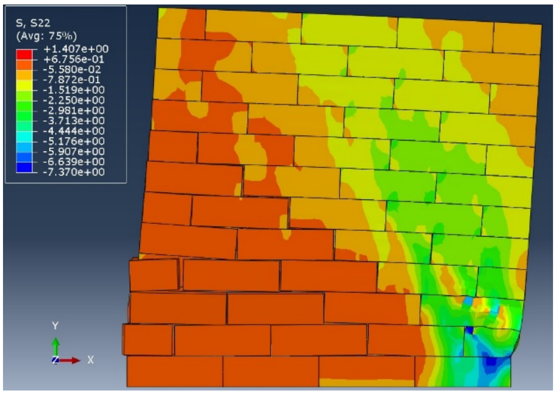


Fig 6(c). Stress (S22) in the Bricks (URM)

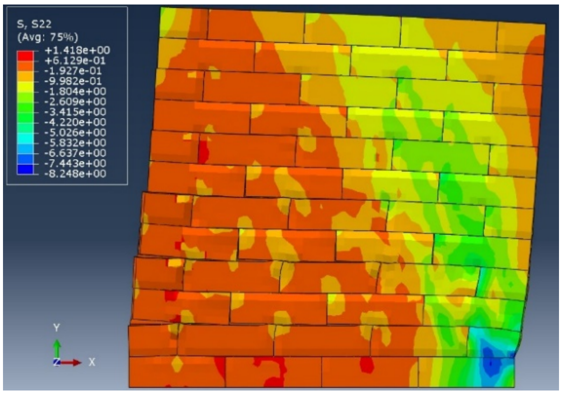
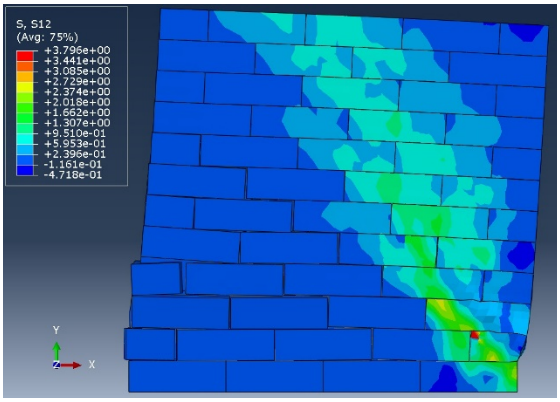


Fig 6(d). Stress (S22) in the Bricks (RM)



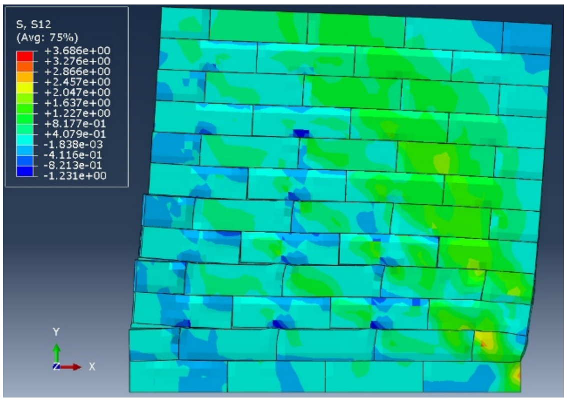
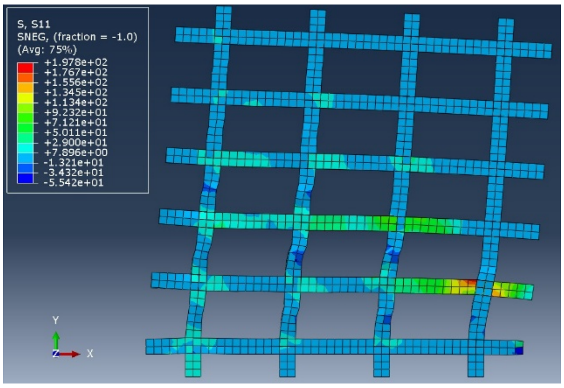


Fig 6(e). Stress (S12) in the Bricks (URM)

Fig 6(f). Stress (S12) in the Bricks (RM)

For the CFRP reinforced wall, it can be seen that the left side of the wall was prevented from excessive rocking and bed course separation was minimized. Head joint separation was also reduced significantly. The reinforced wall retained the integrity up to the maximum drift level. The stress distribution in CFRP in reinforced masonry wall (RM) is shown in Figs. 7(a) to 7(c). It can be seen that the CFRP effectively holds the wall together as one unit. The stress in y-direction (S22) in the left side of the wall is high which means that the CFRP is acting to reduce the phenomenon of the bed rocking.



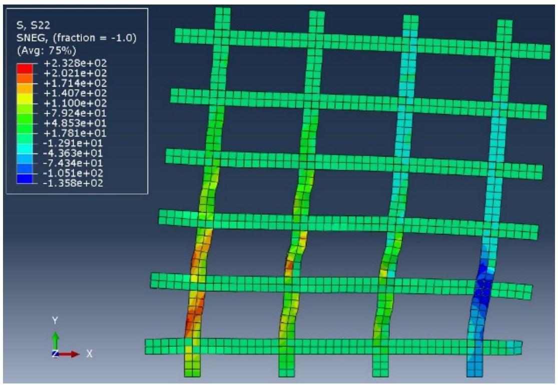


Fig 7(a). Stress (S11) in the CFRP lamina.

Fig 7(b). Stress (S22) in the CFRP lamina.

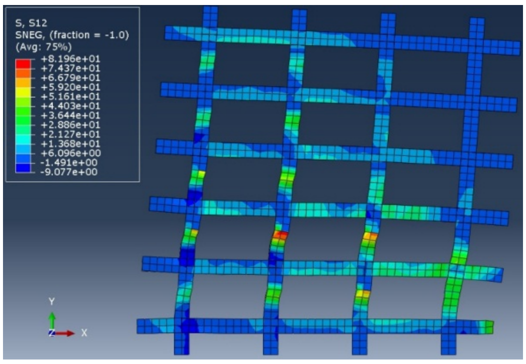


Fig 7(c). Stress (S12) in the CFRP lamina.

5 CONCLUSIONS

Finite element simulation was carried out for the double-leaf heritage wall, with a shear key of rubble stone mortar and which was tested at ITU. The wall was retrofitted using vertical and horizontal CRFP sheets and the numerical simulation was carried out in the ABAQUS environment using damage-plasticity model. It can be concluded that the CFRP sheets have a pronounced effect in enhancing the strength and integrity of the wall. The lateral strength capacity is increased and also the failure mode changes. Adoption of suitable configuration of the CFRP has been shown to reduce premature failure driven by rocking and separation at lower base course levels, and allows for greater mobilization and participation of the entire wall in resisting the applied lateral load.

6 REFERENCES

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