International Journal of Civil Engineering

Structure-Earthquake

Experimental in-plane behavior and retrofitting method of mud-brick walls

F. Tootoonchy, B. Asgarian*, F. Danesh
Received: July 2013, Revised: March 2014, Accepted: September 2014

Abstract

Despite the rapid growth of engineering science especially in the modern structural engineering and application of new materials in civil engineering, a significant percentage of world population in different countries are living in adobe buildings made from mud-bricks. In this paper, by performing experimental study on scaled mud-brick walls under monotonic load, in-plane behavior of the walls have been investigated for different levels of vertical load. After recognizing damage mechanisms from experiment, a simple retrofitting method has been presented to upgrade wall performance. Experimental behavior of retrofitted walls was also studied. The proposed retrofitting method consists of using polypropylene lace and tarpaulin belts. As a result, a better performance of the walls in terms of shear capacity, ductility and energy absorption are observed by using proposed retrofitting method. Meanwhile, Proposed retrofitting method has significant effect in rocking mechanism delay and prevention of wall sudden collapse.

Keywords: *Mud-brick Wall, Retrofit, Ductility, Energy absorption, Polypropylene lace, Tarpaulin belt*.

1. Introduction

A mud-brick is a fire free or sun-dried brick which is made from a stiff mixture of highly content of clay, sand, water and an organic material such as straw. Mud-bricks are one of the oldest and most widely used construction materials.

Adobe building made from mud-brick is a construction system that uses mud-brick to form bearing or non-bearing walls. It is estimated that about 30% of world's population lives in adobe and mud-brick buildings. In addition a number of historical and archeological building made from mud-brick. A lot of mud-brick buildings are in seismic active areas. As mud-brick is very brittle and low-strength material with heavy mass. Building made from this type of material are highly vulnerable in seismic active areas. A sample of destroyed adobe house after Bam earthquake is shown in Fig. 1.

The largest mud-brick structure is the Bam citadel which has been suffered serious damages during 2003 Bam earthquake. During Bam 2003 earthquake, most of the adobe buildings were destroyed, more than 26,000 people were died and over 60,000 were left without shelter [1]. Fig. 2 shows Bam citadel before and after 2003 earthquake.

** Corresponding author: asgarian@kntu.ac.ir*
1 M. S. in Structural Engineering, Faculty of Civil Engineering, K.N.Toosi University of Technology, Tehran, Iran
2 Associate Professor, Civil Engineering Faculty, K.N.Toosi University of Technology, Tehran, Iran
3 Associate Professor, Civil Engineering Faculty , K.N.Toosi University of Technology, Tehran, Iran

Fig. 1 A view of one sample destroyed adobe house after Bam earthquake

(before)

[DOI: 10.22068/IJCE.13.2.191]

(after)

Fig. 2 View of Bam Citadel before and after Bam earthquake

This research aims to study the in-plane behavior of mud-brick walls subjected to lateral loads, specifying their weakness and presenting solutions to upgrade their performance.

Previous study (Silveira et al., 2007) has tried to overcome lack of information about mud-brick and masonry structures[2]. The Civil Engineering Department of Aveiro University, in Portugal, has recently carried out a number of studies on the behavior of adobe structures in Aveiro district. This research mainly focused on constitution materials, their composition, adobe blocks/walls strength, stiffness, ductility and energy dissipation capacity. However, a meticulous evaluation of frequent occurrences of structural and non-structural damage in adobe structures is currently under investigation. In addition, the structural tests on adobe walls (Varum et al.; 2007) provided important future guidelines for developing reinforcement as well as rehabilitation solutions for seismic resistant adobe structures [3]. E. Quagliarini et al. performed experimental tests on four adobe walls subjected to compression and shear force. [4]. Another research has been carried out by L.Turanli & A.Saritasat in 2011 shows that the performance characteristic of the wall panels increases obviously through the use of plaster reinforcement mesh along the horizontal mortar joints between the adobe blocks [5]. D.M. Herbert et al. developed a new experimental method for testing the lateral load capacity of small-scaled masonry walls using a centrifuge and digital image correlation on 2011 [6]. A.A.Tasnimi & M.A.Rezazadeh conducted experimental and numerical study on two full scale one story brick buildings under torsional moment [7]. In-plane behavior of confined masonry walls- with and without opening was studied by S. Eshghi & K.Pourazin [8]. Previous researches on mud brick buildings behavior and their observation during earthquake show that there is several known damage mechanism in adobe buildings [9-11]. These studies have focused on joint slippage between ceiling and walls, out of plane damage, in-plane diagonal crack of wall, corner damage, cracks at openings, continuous spillage of material, damage at anchorage and cross- ties, damage in intersection of perpendicular walls and roof collapse. In FEMA 306 , the four damage mechanisms of rocking movement, bed joint sliding, diagonal tension and toe-crashing are mentioned [12].

Lateral resistance of the adobe structures made from mud brick are provided from in shear strength of the structural walls. This paper, through the experimental study of adobe walls made from mud-bricks, in-plane behavior of this type of walls is studied. In this regards, some mud bricks similar to those in historical building of Abyaneh are reproduced by using the soil directly collected from Abyaneh . Then, experimental study on walls made from produced mud-bricks and retrofitted walls has been carried out.

2. Sample Description

This paper investigates in-plane behavior of mud-brick walls made from Abyaneh red clay through experimental study. Abyaneh is a village of living traditions with architectural styles and historical buildings constructed using mud-brick. A sample of mud-brick historical building in Abyaneh village is shown in Fig. 3.

Fig. 3 A view of a three story historical building in Abyaneh

In this regards, some mud-bricks similar to original ones were reproduced from red clay of Abyaneh. Six scaled walls with the dimension of about 1m× 1m were constructed by using same red clay mortar. After about one month from the construction time, scaled walls were tested against horizontal loads applied at top of them in the presence of vertical load as shown in Table 1. In the first four samples (MW1 through MW4), the walls were subjected to lateral loads in presence of different amount of vertical stress as shown in Table 1. Meanwhile, no retrofitting was considered for these walls. Tested samples No. 5 and No. 6 (RMW1 & RMW2) had the same dimensions and vertical stress as sample No. 3, but these walls were retrofitted with propylene laces and tarpaulin belts as shown in Fig. 4. Polypropylene laces and tarpaulin belts (with 50 mm wide) were used to improve the performance of these walls (RMW1 and RMW2). Propylene lace which in 10^{mm} mesh (Fig. 4) is strong enough to environmental conditions and has ductile behavior.

[DOI: 10.22068/IJCE.13.2.191]

Table 1 Tested Wall Properties

No.	Experiment Name	Dimensions (cm)			Horizontal Displacement Rate ($^{cm}/_{s}$)	Vertical Load ($^{KN}/_{cm^2}$)
		Length	Height	Thickness		
1	MW 1	105	94	25	0.03	0
2	MW 2	107	102	25	0.03	0.0097
3	MW 3	105	94	25	0.03	0.0215
4	MW 4	108	100	25	0.03	0.0357
5	RMW 1	108	98	25	0.03	0.0215
6	RMW 2	108	97	25	0.03	0.0215

(a) (b)

Fig. 4 (a) Tarpaulin belt, (b) Polypropylene lace

3. Test Setup

In order to investigate the effect of vertical loads on lateral behavior of the walls, a loading system including loading frame, hydraulic unit, hydraulic jacks, and measuring and data acquisition systems have been used (Fig. 5).

To impose uniform vertical stress on the walls, a hydraulic jack and stiff beam have been used in which stiff beam was directly placed on the wall (Fig. 6 and) distributed uniform pressure during test. For imposing horizontal loads to the walls, hydraulic jack connected directly to the loading frame has been used. To avoid undesirable extra loads, due to top rigid beam movement during experiments, two rollers have been provided in both sides of vertical hydraulic jack, one between vertical jack and loading frame top beam and other between jack and rigid beam as shown in Fig. 7. To measure deformation of the wall, two transducers (LVDTs) were installed on the wall crown and toe.

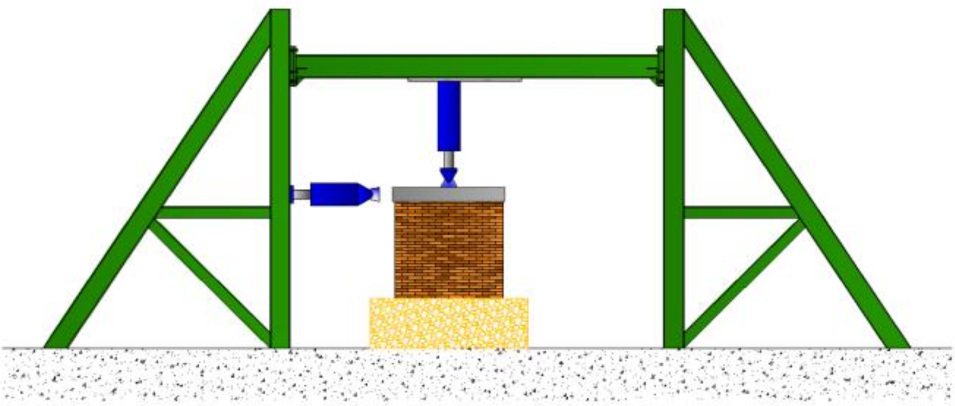
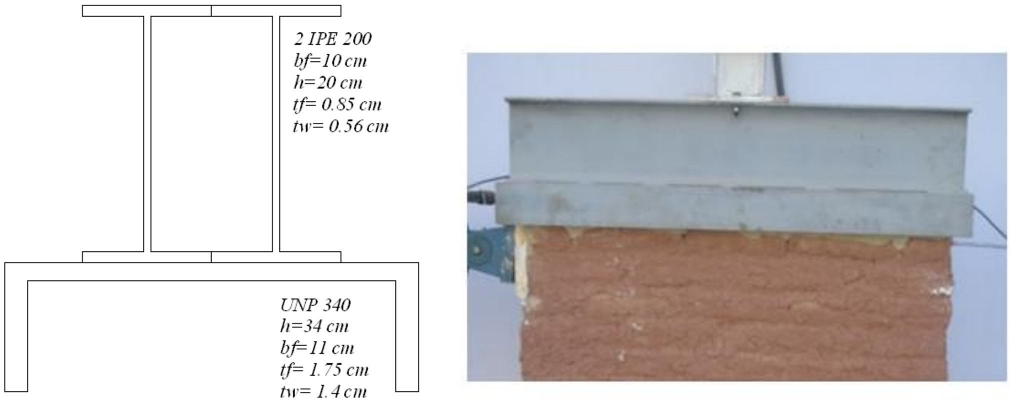


Fig. 5 Loading system



(a) (b)

Fig. 6 (a) Beam section, (b) Load distribution beam

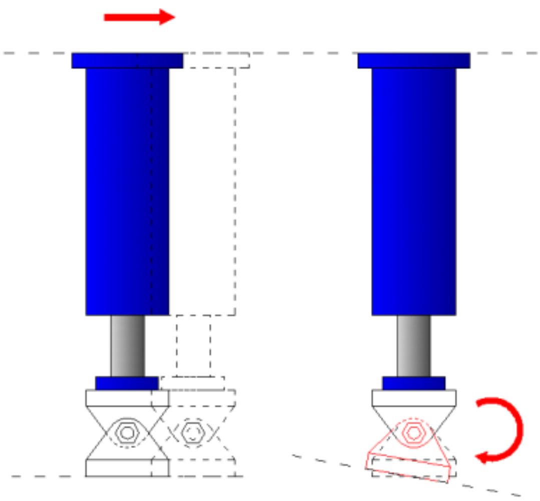


Fig. 7 Rolling and pin connections of vertical jack

During test, vertical load as per table 1 was imposed on the walls first. Then the lateral displacement with a uniform rate (as shown in Table 1) is applied using horizontal jack. Finally, behavior of the walls was measured for each test in terms of lateral load-lateral displacement. Energy dissipation and walls ductility, as the key parameters for comparison of walls behavior against lateral loads, were investigated from experiments. Wall ductility was defined through equation 1.

$$\mu_Y = \frac{\Delta_{85\%}}{\Delta_{yield}} \quad (1)$$

Where:

μ_Y: Ductility of the wall

Δ_{yield} : Lateral displacement of wall at yield point

F_Y : Load at yield point

$F_{\max}$:Maximum imposed load to wall

$\Delta_{\max}$: Displacement of wall correspond to $F_{\max}$

$F_{85\%}$: 85 % of maximum imposed load to wall

$\Delta_{85\%}$: Displacement of wall correspond to $F_{85\%}$ in degrading branch

Above parameters are shown in Fig. 8.

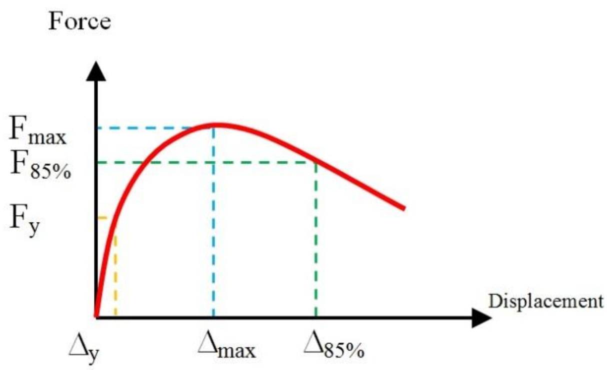


Fig. 8 Effective parameter in explaining ductility of behavior of a structure on its behavior curve

4. Experimental Results

Experimental observation of the behavior of tested walls with and without proposed retrofit method is presented in this section.

[DOI: 10.22068/IJCE.13.2.191]

4.1. Loading tests on unreinforced wall

MW1 wall was tested without any vertical load. Fig. 9 shows MW1 before and after the test. It can be seen that rocking damage mechanism has been occurred during the test.

Shear force-lateral displacement curve of MW1 is shown in Fig. 10. Short initial elastic behavior can be observed at the start of the test which was then adjusted by forming a crack in the bed joint. Then, a sudden strength fall was observed during rocking motion mechanism.

In MW2, MW3 and MW4 walls, in order to study the effect of vertical load in lateral behavior of samples, vertical distributed load is applied (as shown in Table 1) prior to imposing monotonic horizontal displacement. It can be seen from Fig. 11 that a combination of vertical and horizontal stresses in wall causes different stress distribution in different location of the wall. In MW2, MW3, and MW4 tests, first a linear elastic behavior is observed in the walls. Then by forming cracks around the wall diagonal (Fig. 12), a reduction in wall stiffness was observed. Loading is continued until reaching maximum capacity of the wall. The wall toe started crushing and its volume was increased. After a destruction of the wall toe and increase in the cracks depth and length, it leaded to reduce the walls strength.

Fig. 12 shows stages of formation of damage mechanism of MW2, MW3 and MW4 walls which was a combination of shear sliding mechanism in the wall diagonal and crushing of the wall at toe. It is noted that MW4 wall was suddenly damaged due to exceeding high vertical stress.

Fig. 13 compares shear force-lateral displacement curves of MW1, MW2, MW3 and MW4 in which effect of compressive stress and friction between joints caused improvement of strength and ductility. Sudden break of MW4 wall compared to the first three walls was observed since this wall has suddenly lost its load bearing capacity due to high vertical stress in wall.

Fig. 9 Damage mechanism of MW1 wall

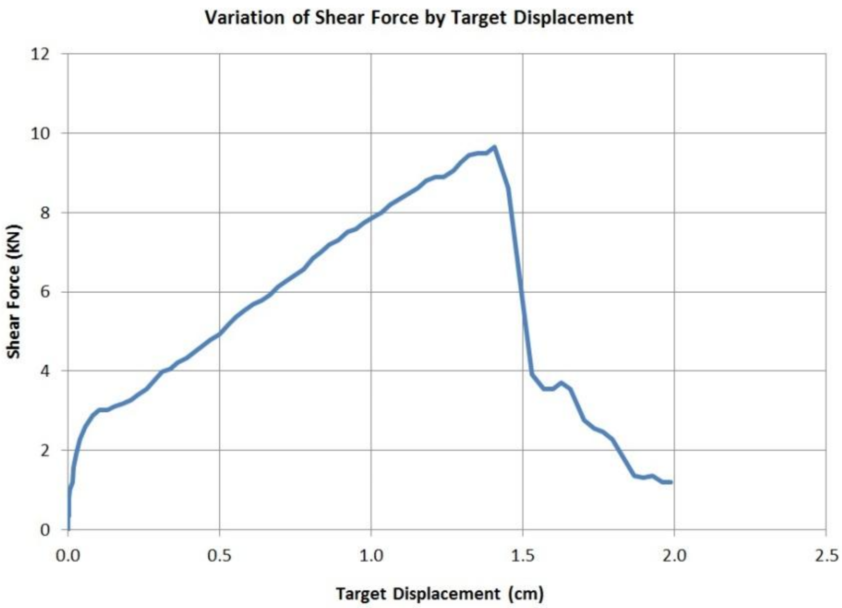


Fig. 10 Curve of shear force against sliding displacement of wall crown MW1

[DOI: 10.22068/IJCE.13.2.191]

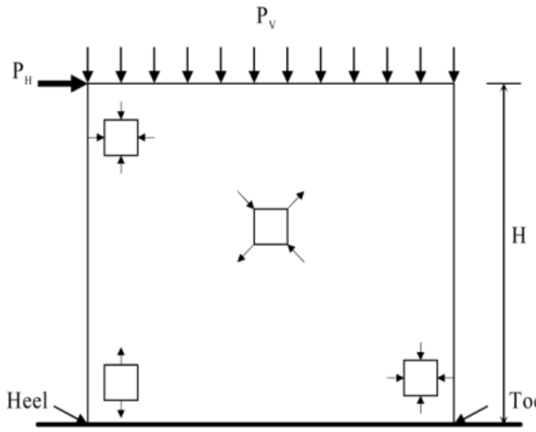


Fig. 11 Stress condition in the wall

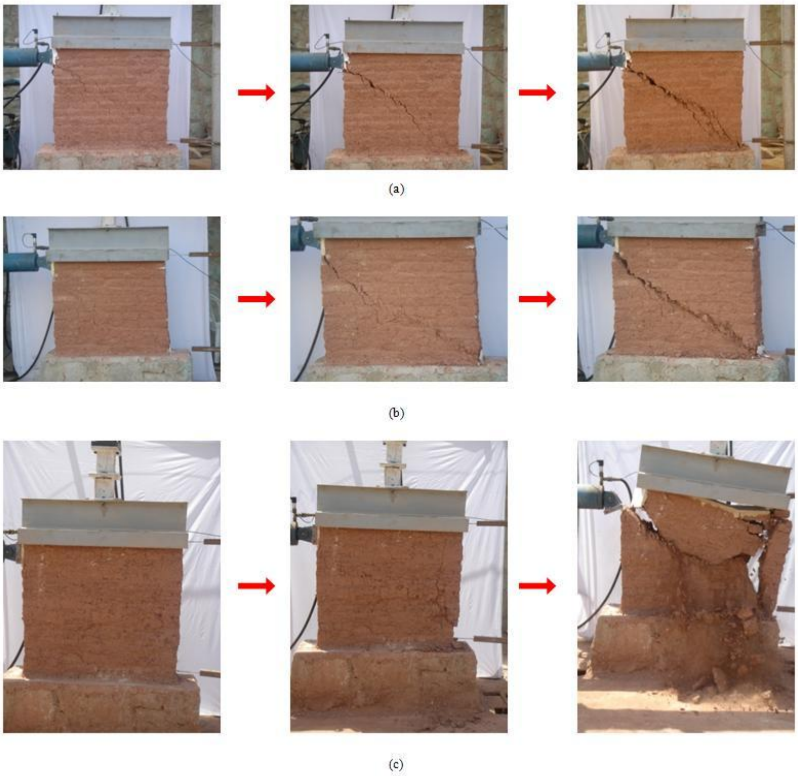


Fig. 12 Damage process: (a) MW2 wall, (b) MW3 wall, (c) MW4 wall

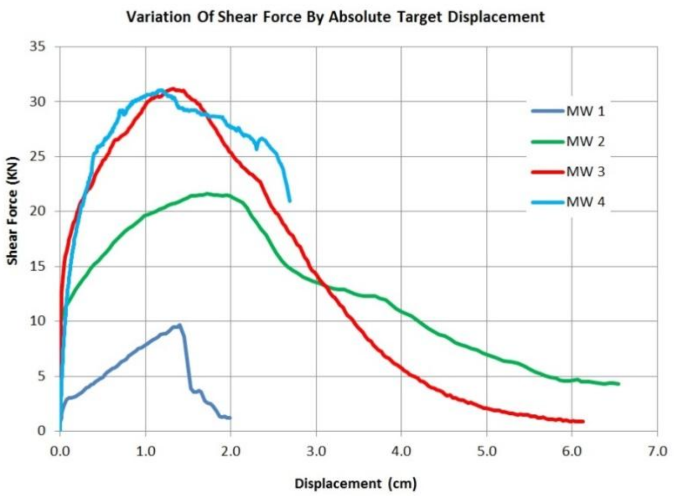


Fig. 13 Comparison of shear curve of MW1, MW2, MW3, MW4 walls

[DOI: 10.22068/IJCE.13.2.191]

Shear capacity $(F_{\max})$ and displacement of walls correspond to $F_{85\%}$ in degrading branch $(\Delta_{85\%})$ is presented in Table 2. As the significant point for the yield of the walls cannot be introduced from Fig. 13, ductility of the walls is not presented directly. However, ductility of the walls without and with proposed retrofitting method can be screened by observation of the walls behavior. It can be seen that the shear capacity of the walls was increased in presence of vertical stress. Meanwhile, ductility of the walls was also increased as the vertical stress was increased except sample No. 4 which has failed due to high vertical load.

Table 2 Quantities of the maximum shear capacity of wall, crown displacement

No.	F_{max} KN	$\Delta_{0.85}$ cm
MW1	9.65	-
MW2	21.61	2.37
MW3	31.16	1.89
MW4	31.06	2.27
RMW1	33.82	3.24
RMW2	33.93	5.31

4.2. Loading tests on retrofitted wall

By considering the experimental results of the four tested specimens, a retrofit method to upgrade the in-plane behavior and to prevent the wall uplift and rocking motion mechanism was proposed. For this purpose, RMW1 is surrounded only by polypropylene lace. After installing twisted wires in the wall at a distance of about 0.2^{m}, this net is fixed to the wall and then it is filled with clay mortar. The proposed method is a simple and cheap way which can be executed by an un-skilled labor. In the proposed method, when the wall is subjected to lateral loads, a tension force occurs in membrane net of polypropylene lace; by increasing the wall volume, its reaction is imposed on the wall in the form of a pressure confining force. It causes an increase in the shear capacity, ductility and energy absorption of the retrofitted wall compared to original ones. Fig. 14 shows the installation stages of the proposed method. Table 1 also shows the details of a test performed on a reinforced wall with polypropylene lace.

To compare the results, a vertical uniform load same as MW3 was applied to retrofitted walls and then the lateral displacement was applied to walls. Fig. 15 shows the views of the RMW1 during the test. It can be seen that the volume of the wall toe was increased during test and the surrounding net was stretched. Then, the volume of the wall was increased around the wall diagonal. Moreover, diagonal cracks were formed without any collapse despite the fact that wall underwent a considerable deformation. Ultimately, rocking motion mechanism was formed following appearance of diagonal cracks. Fig. 16 presents variation of shear force against lateral displacement of RMW1 wall.

Fig. 14 Installation process of polypropylene lace on adobe walls

Fig. 15 Damage mechanism of *RMW1* wall

[DOI: 10.22068/IJCE.13.2.191]

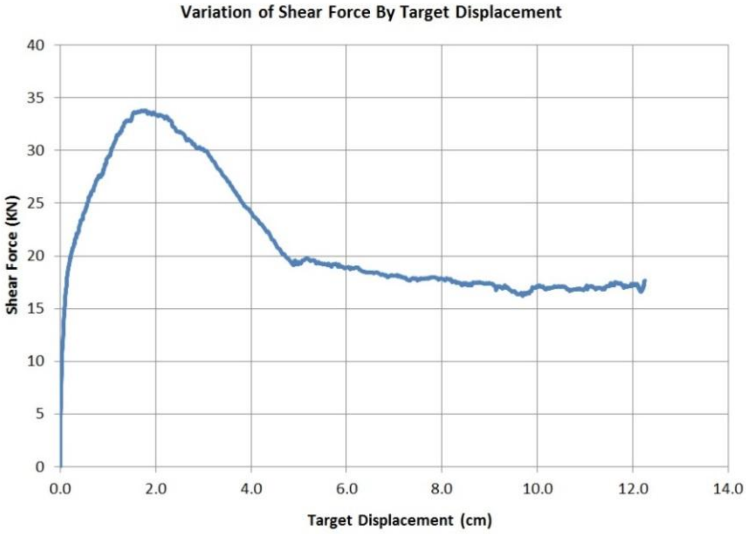


Fig. 16 Experimental behavior of RMW1 wall

It was observed that the application of polypropylene lace caused suitable cohesiveness of the wall compared to the behavior of the similar wall without proposed retrofit method (MW3). It can also be seen that using polypropylene lace resulted proper integrity of the wall. Actually, better performance of the wall was observed by postponing the occurrence of rocking motion mechanism. The sample RMW2 was connected to its foundation by tarpaulin belts (Fig. 17) in addition to using the polypropylene lace same as RMW1 sample. Adding tarpaulin belts helps the wall to postpone or even prevent rocking motion mechanism. Table 1 also shows the details of a test performed on RMW2.

Fig. 18 shows the damage mechanism of RMW2 wall. It was observed that with starting the load and upon completion of initial stages, volume of the wall toe was increased. Since, there was no possibility of occurrence of rocking motion mechanism, the wall begins forming diagonal cracks and ultimately the test is stopped by tearing of the net from the overlapping point in the wall toe.

Fig. 17 Use of tarpaulin belts to prevent rocking motion mechanism

Fig. 18 Damage mechanism of RMW2 wall

Shear force-lateral displacement curve of RMW2 is shown in Fig. 19. Fig. 20 compares shear force-lateral displacement of MW3, RMW1 and RMW2. This Fig. shows that proposed retrofitting method increases shear capacity and energy absorption of the mud-brick wall significantly.

[DOI: 10.22068/IJCE.13.2.191]

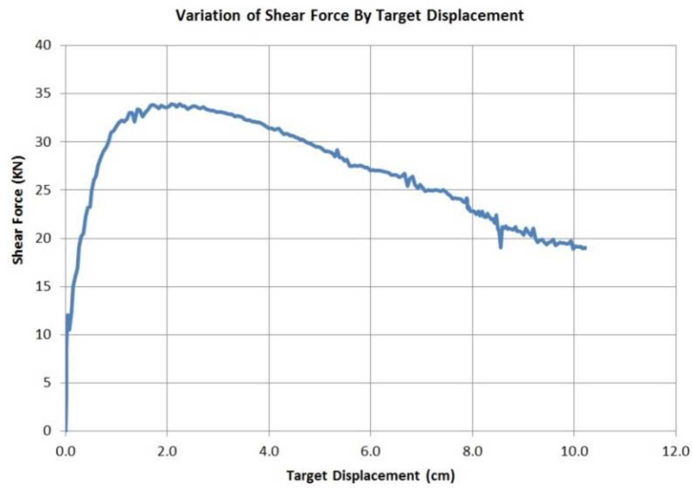


Fig. 19 Experimental behavior of RMW2 wall

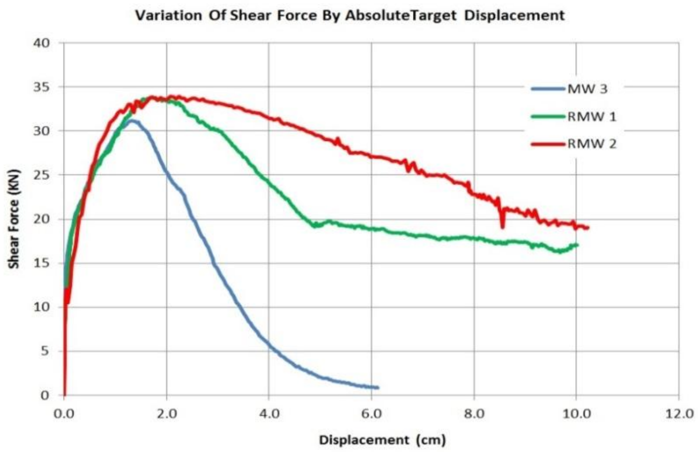


Fig. 20 Comparison of experimental behavior of MW3, RMW1, RMW2 walls

The shear capacity of the wall and its lateral displacement corresponded to 85% of the shear capacity are also shown in Table 2. It can be seen that by retrofitting the wall in addition to increasing shear capacity of the wall, its ductility and energy absorption were increased significantly. The energy deformation curves of the walls without and with proposed retrofitting method are presented in Figs. 21 and 22. It can be seen that the energy absorption of the walls in large deformation area increased significantly for retrofitted walls. The results for the energy absorption until failure and maximum displacement of the walls are also presented in Table 3. It can be seen that by using proposed retrofitting method, a better performance can be achieved compared to the walls without retrofit.

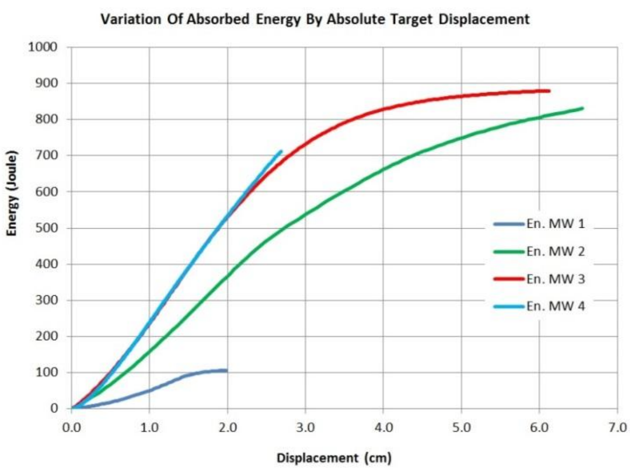


Fig. 21 Comparison of energy-displacement curve for sample walls without retrofit

[DOI: 10.22068/IJCE.13.2.191]

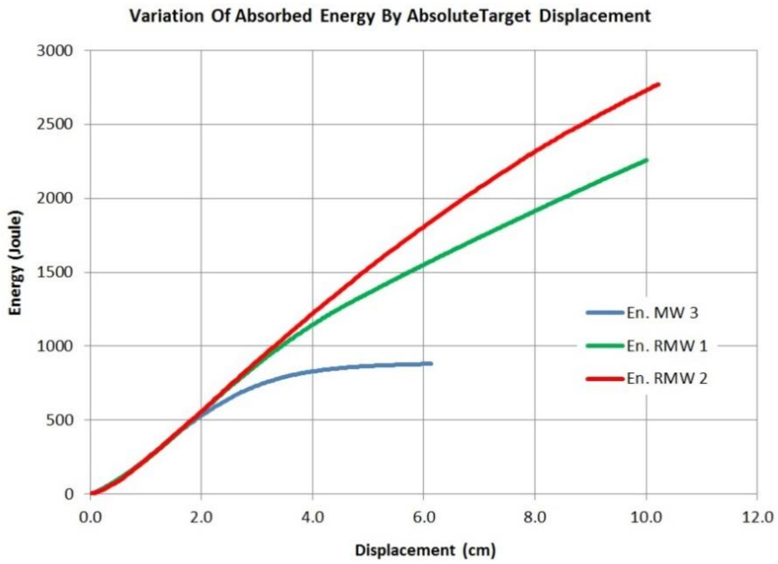


Fig. 22 Energy-displacement curve for retrofitted sample walls compared to non-retrofitted wall

Table 3 Tested Wall Energy Absorption Details

No.	$\text{Displacement}_{max}^{cm}$	$\text{Energy}_{Absorption}^{J}$
MW1	1.99	106.1
MW2	6.55	830.4
MW3	6.13	879.7
MW4	2.69	712.8
RMW1	10.01	2257.9
RMW2	10.22	2771.3

5. Conclusion

Based on the result of the experiments, it can be concluded that the vertical load is considerably effective on the behavior of adobe walls. It is seen that for the tested walls, the shear capacity of the walls is increased significantly by adding vertical loads in average range of intensity. However, by imposing high vertical loads, the wall behavior leads to a brittle failure.

It is also observed that by using polypropylene lace, falling of the tested walls is prevented during the experiment. Also, due to surrounding the wall by using the proposed method, a confinement action is created and wall shear capacity, ductility and energy absorption is increased significantly. Application of tarpaulin belts controls and postpones rotation of the wall around its toe and prevents uplift of the wall from its bed. By using tarpaulin belt and polypropylene lace in tested samples, wall ductility and energy absorption are increased significantly. In addition, it is observed that using tarpaulin belts and polypropylene lace together increases wall ductility and energy absorption compared to retrofitted wall with polypropylene lace.

References

[1] EERI, 2004, ES 21:S1, 2003. Bam, Iran, Earthquake Reconnaissance Report.

[2] Silveira D,Varum H, Costa A. Rehabilitation of an important cultural and architectural heritage: the traditional adobe constructions in Aveiro district, Sustainable Development III; Editors A. Kungolas, CA. Brebbia, E. Beriatos, WITPress, ISBN: 978-1-84564-103-0, Carvoeiro, Portugal, 2007, Vols 1-2, pp. 705-714.

[3] Varum H, Costa A, Silveira D, Pereira H, Almeida J, Martins Tiago. Structural behaviour assessment and material characterization of traditional adobe constructions, Adobe USA, NNMC and Adobe Association of the Southwest, El Rito, NM, USA, 2007.

[4] Quagliarini E, Lenci S, Iorio M. Mechanical properties of adobe walls in a Roman Republican domus at Suasa; Journal of Cultural Heritage, 2010, Vol. 11, pp. 130-137.

[5] Turanli L, Saritas A. Strengthening the structural behavior of adobe walls through the use of plaster reinforcement mesh; Construction and Building Materials, 2011, Vol. 25, pp. 1747-1752.

[6] Herbert DM, Gardner DR, Harbottle M, Thomas J, Hughes TG. The development of a new method for testing the lateral load capacity of small-scale masonry walls using a centrifuge and digital image correlation, Construction and Building Materials, 2011, Vol. 25; pp. 4465-4476.

[7] Tasnimi AA, Rezazadeh MA. Experimental and numerical study of strengthened single storey brick building under torsional moment, International Journal of Civil Engineering, 2012, No. 3, Vol. 10, pp. 7-7.

[8] Eshghi S, Pourazin Kh. In-plane behavior of confined masonrywallswith and without opening, International Journal of Civil Engineering, 2009, No. 1, Vol. 7, pp. 49-60.

[9] Celik OC, Sesigur H. Performance of historic masonry buildings during the April 6, 2009 L'Aquila Earthquake, Proceeding of 14th ECEE;Ohrid, Republic of Macedonia, 2010.

[10] Dhanasekar M. The Performance of Brick Masonry Subjected to In-Plane Loading; PhD Thesis, University of Newcastle, Australia, 1985.

[11] Vicente R, Rodrigues H, Costa A, Varum H, Mendes da Silva JAR. Masonry enclosure walls: lessons learnt from the recent abruzzo earthquake, Proceeding of 14th ECEE, Ohrid, Republic of Macedonia, 2010.

[12] Federal Emergency Management Agency. FEMA 306, Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Washington, D.C, 1998.

[13] Oliveira C, Varum H, Figueiredo A, Silveira D, Costa A. Experimental tests for seismic assessment and strengthening of adobe structures, Proceeding of 14th ECEE, Ohrid, Republic of Macedonia, 2010.

[14] Ousalem H, Miyauchi Y, Masato Y, Kibayashi M. Experimental investigation of post-tensioned brick masonry bearingwalls, Proceeding of 14th ECEE, Ohrid, Republic of Macedonia, 2010.