Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23

STM JOURNALS

Experimental Investigation on the Seismic Disaster Mitigation of Unreinforced Brick Masonry Buildings

Mohammad Javed*, Bashir Alam, Ali M. Syed, Khan Shahzada, Naveed Ahmed
Department of Civil Engineering, University of Engineering & Technology, Peshawar, Pakistan

ABSTRACT

The Himalayan region is considered to have the potential to produce earthquakes of magnitude 8.0 or greater once every 100 years. Since the occurrence of an earthquake cannot be prevented; therefore, seismic disaster mitigation remains the only option for the civil society. Unreinforced masonry (URM) buildings, constructed with stone or brick, are very common in Northern Pakistan part of Himalayan belt. The seismic performance of stone masonry was found very poor in October 2005 Kashmir earthquake and was the main source of fatalities as most of the collapsed buildings in the area were constructed with stone masonry. Unreinforced brick masonry (URBM) buildings, however, performed much better than stone masonry buildings and survived collapse in most of the highly affected areas except Balakot town and in some parts of Muzzafarabad. The performance of URBM would have been much better if buildings were designed and constructed using engineering principles of earthquake disaster mitigation instead of experience based thumbs rules developed by the masons. Taking the lessons from the earthquake disasters of October 2005, an experimental investigation was carried out to evaluate and quantify the seismic performance of unreinforced brick masonry (URBM) shear walls constructed in stone dust mortar being widely used in Northern Pakistan and thus to further promote the research and development for earthquake disaster prevention. In-plane shear-compression tests were carried out on twelve walls, using quasi-static cyclic loading. The effect of geometry and extent of gravity load (as measured by pre-compression level) on various parameters used to quantify seismic performance such as ductility, ultimate drift ratio and equivalent viscous damping for evaluating energy dissipation capacity, of the walls is also examined and discussed.

Keywords: *Unreinforced masonry, Shear strength, Ductility, Drift, Energy dissipation.*

****Author for Correspondence:*** E-mail mjaved@nwfpuet.edu.pk

1. INTRODUCTION

An earthquake jolted Kashmir and the Northern Areas of Pakistan on October 8, 2005. It was one of the deadliest earthquakes (with M_w = 7.6) considering the number of fatalities in the history of indo-Pakistan subcontinent. As a consequence of earthquake, more than 70,000 people died; 80,000 left injured, 2.5 million people were displaced and 3.3 to 3.5 million people were affected. The resulting total economic loss was estimated US$5.2 billion. According to the Asian Development Bank and the World Bank, 4,55,000 buildings were partially or fully damaged. Most of these damaged and collapsed buildings had been constructed with unreinforced stone and brick masonry. Most of the typical damages observed in the URM buildings are shown in Figure 1.

Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23

(a) (b) (c)

(d) (e) (f)

Fig. 1: (a) Toe-crushing Failure in a Slender Wall (b) Diagonal Shear Failure (c) Disintegration of Double Leaf Wall (d) Wall Collapsed in out-of-plane Direction; (e) Cracks Originated from Opening's Corner (f) Separation of Orthogonally Connected Walls at Corners [1,2].

The performance of unreinforced brick masonry (URBM) was, however, found to be much better than unreinforced stone masonry [1]. However, the seismic disaster due to URBM buildings could have been much mitigated if engineering principles, instead of thumb rules used by local masons, would have been followed in the design and construction of URBM buildings. In order to reduce potential damage to URBM buildings in future earthquakes, an experimental study was needed to evaluate seismic disaster mitigation of URBM buildings based on the results of experimental work.

It is important to note that the research work on unreinforced brick masonry has led to the development of preliminary analytical tools for the seismic design and assessment of unreinforced masonry (URM) structures (such as FEMA 356 [3] and the subsequent ASCE/SEI 41-06 [4], or Eurocode 8 [5]) but still more work needs to be done towards the full understanding of the seismic behaviour of URBM structures. Similarly, it is a known fact that one of the most important factors that influence the behaviour of URBM is mortar. A change in either the constituents and/or proportions of the cementitious material and fine aggregate can induce appreciable changes in the failure mode, lateral load capacity, and deformability of the masonry systems [6]. Thus it is essential to study the behaviour of URBM, made with specific types of mortar. A type of mortar, using stone dust as partial replacement of sand, is widely used in URBM construction throughout Northern Pakistan, however, very little information is available on its behaviour when used in URBM. Therefore, in this work a detailed experimental study was carried out to investigate the seismic performance and thus to help in mitigating the seismic disaster of URBM construction using stone dust mortar, under the action of in-plane lateral quasi-static cyclic loading [2]. The stone dust is obtained from the crushing industry plants producing coarse aggregates. The stone dust is locally known as '*khaka*'. The name seems to be derived from the word *'khak'*, which means clay.

The entire experimental work was carried out in two phases. In the first phase, tests were conducted to determine the physical and mechanical properties of masonry and its constituents. In the second phase, shear-compression tests were carried out on URBM walls to determine their seismic performance. Aspect ratios and pre-compression levels were varied to observe their effect on the seismic performance of the URBM. Lateral force-displacement hysteresis diagram of eight walls are presented along with discussion on the failure modes. In addition, experimental results regarding displacement ductility and drift capacity, modulus of elasticity, energy dissipation characteristics of the tested walls are also discussed and presented in a quantifiable way. The influence of pre-compression level on displacement ductility factor, ultimate drift ratio and energy dissipation characteristics is also investigated.

2. EXPERIMENTAL WORK

The experimental work comprised of two phases, the first being testing masonry constituent and masonry assemblages to find their mechanical and physical properties. In the second phase, shear-compression tests were carried out on URBM walls having different aspect ratios and pre-compression levels to observe their effect on the seismic performance of the URBM.

2.1 Properties of Masonry and its Constituents.

The experimental work was carried out on the masonry constituents (bricks and mortar) as well as masonry assemblage (masonry prisms, triplets). The standard testing protocols for each type of testing were followed [7–10]. The results of experiments carried out in this phase along with the number of tested samples are given in Table I.

Table I: *Mechanical Properties of Masonry and its Constituents used in the Experimental Work.*

	Mean value	No of tested specimens	C.O.V (%)
Compressive strength of brick units perpendicular to the bed joint (MPa), f_b	22.5	12	23.4
Tensile strength of the brick units (MPa), f_{bt}	2.67	8	22.2
28 days Compressive strength of the mortar cubes (MPa), f_{mo}	5.05	24	10.3
Compressive strength of the masonry (MPa), f_m	4.53	9	14.2
Principal Tensile strength of the masonry (MPa), f_{tu}	0.24	4	16.7
Coefficient of friction of masonry, μ	0.59	11	-
Cohesion of masonry (MPa), c	0.39	11	-
Modulus of elasticity of the masonry (MPa) , E_m	1300	9	17

2.2 In-plane Quasi-static Cyclic Tests on URBM Walls

One of the important objectives of the experimental work was to evaluate the mitigation of seismic disaster due to unreinforced brick masonry construction by quantifying its seismic performance through experimental investigation of brick masonry shear walls constructed in stone dust mortar. To accomplish this, shear-compression tests were carried out using quasi-static cyclic loading on four series of walls. The details of testing are given in the following sub-sections.

2.2.1 Geometry of the Walls

Walls with three different geometries were tested during experimental work. The walls had the aspect ratios (i.e., height-to-length ratio) of 0.66, 0.93 and 1.22. Three walls each were cast with aspect ratios of 0.66 and 1.22, and the remaining six walls were cast with aspect ratio of 0.93. Keeping in view the capacity of the actuator, the length of each wall was limited to 1360 mm. All walls were constructed using English bond, which is commonly used in Northern Pakistan. Walls with the aspect ratios of 0.66 and 0.93 were cast to simulate the geometry of typical walls in rooms with a door opening at the end. The walls with an aspect ratio of 1.22 were cast to simulate the geometry of a typical slender pier between door and window openings.

2.2.2. Pre-compression Levels

Pre-compression levels on the walls were 0.42, 0.64 and 0.71 MPa. These values of pre-compression simulated the vertical load on walls supporting two to three stories. A total of four series of walls, with three walls in each series, were tested.

Based on the aspect ratio and pre-compression level, walls were divided into four categories, namely WI, WII, WIII and WIV. Each wall in a given series was designated with a lower case alphabet at the end of the category designation. e.g., the first wall of the WI category was designated as WIa. Similarly, the second and the third wall of same category were designated as WIb and WIc, respectively. The details of the dimensions (length, l; thickness, t; height, h), aspect ratios (h/l), and pre-compression levels (σ_o) are given in Table II.

Table II: *Characteristics of tested walls*

Wall Series	h (mm)	l (mm)	t (mm)	$A.R = h/l$	σ_o (MPa)	σ_o/f_m
WI	1660	1360	236	1.22	0.71	0.153
WII	1280	1360	236	0.93	0.42	0.091
WIII	1280	1360	236	0.93	0.64	0.138
WIV	900	1360	236	0.66	0.64	0.138

2.3. Testing Setup

Quasi-static cyclic tests were carried out for three different levels of pre-compression (σ_o/f_m=0.091, 0.138 and 0.153 corresponding to σ_o= 0.42 MPa, 0.64 MPa and 0.71 MPa, respectively) by using the testing setup shown in Figure 2. This testing setup developed double bending curvature in a wall since top beam of testing setup was forced to translate horizontally, creating a double-fixed condition. Experimental work on URBM walls, loaded in double bending curvature, is scarce as compared to cantilever walls since the experimental setup is somewhat more complex.

The lateral seismic forces were simulated by step wise linearly increasing static lateral displacements. The typical lateral displacement history is shown in Figure 3. The testing process consisted of two phases. The first phase of experimental work on walls was carried out with force controlled testing. This phase consisted of a total of four linearly increasing force cycles of different magnitudes. Objective of the force controlled testing phase was to have a well defined lateral load-displacement curve before the occurrence of diagonal tension shear cracking. The second phase of experimental work on walls was carried out with displacement controlled testing.

Deformations in the walls were recorded by means of the LVDTs shown in Figure 2. LVDT1 was used to measure the lateral displacement at the top of a wall. LVDT2 was used to monitor possible slippage of a wall with respect to the R.C. beam anchored to the testing floor. LVDT3 was used to check the possibility of rocking, especially in slender walls. LVDT4 and 5 were used to record the diagonal deformations in a wall.

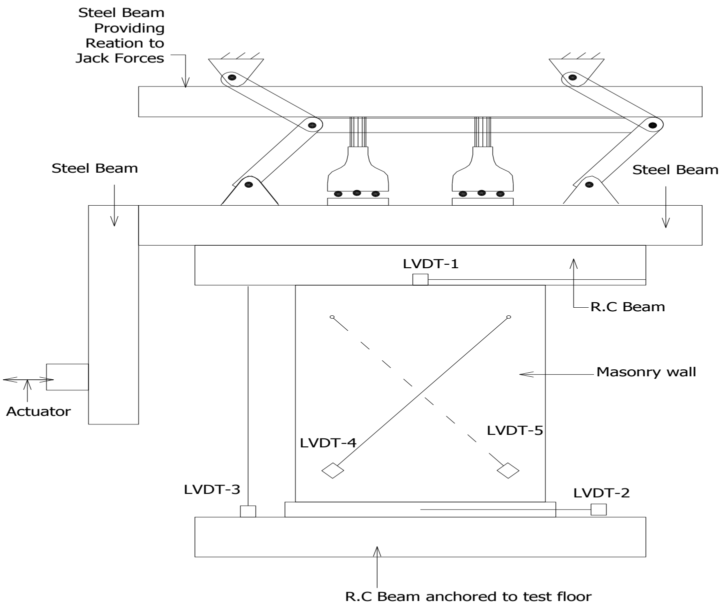

Fig. 2: Testing Setup used for Conducting in-plane Quasi-Static Cyclic Tests on URBM Walls.

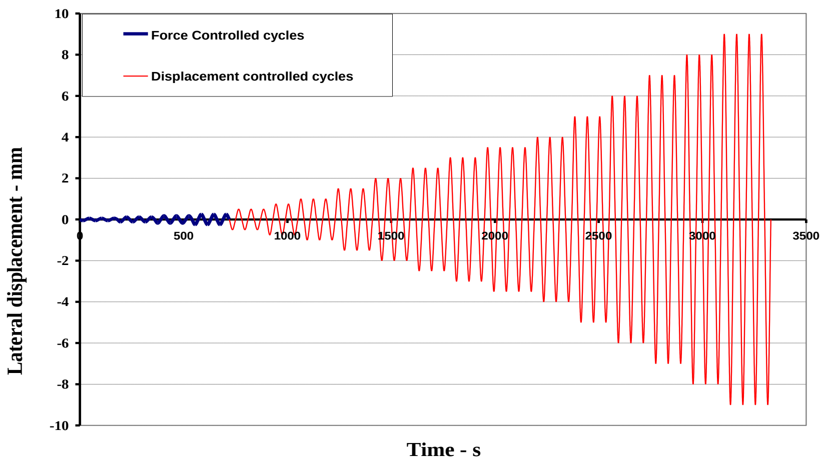

Fig. 3: Displacement History Imposed on the Walls Top during Quasi-static Cyclic Tests.

Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23

Data of the four wall specimens could not be recorded due to technical problems with the data acquisition system during their testing. Hence, the results of eight out of twelve tested walls are discussed in detail in the paper.

2.3. Cracking Pattern and Failure Modes

As a consequence of the chosen geometry of walls and pre-compression levels, two failure modes, namely diagonal tensile shear cracking and bed joint sliding accompanied by diagonal tensile shear cracking, were observed in the tested walls. Walls with high to medium aspect ratios (WI through WIII), failed in diagonal tension shear without any rocking effect. In the case of squat walls (WIV series) bed joint sliding was observed after the formation of diagonal tension cracks. No rocking was observed in the wall series WIV as well.

The cracking pattern of wall WII series indicated that cracks produced were wider but less in number as compared to cracks in wall WIII series. The damages in wall WII series were relatively extensive as portion of the walls were on the verge of complete collapse because of the produced wider cracks. However, the damages in wall WIII series were not extensive as the relatively wider cracks were distributed throughout each wall of the series. This suggests that increase in pre-compression although increases the number of cracks but reduces crack width thus resulting in mitigating the seismic disaster by keeping the walls intact.

The hysteresis loop of a representative wall from each series with envelopes and bi-linear idealized curves, developed by using the method proposed by Magenes and Calvi [11], discussed in sub-section 3.1 are shown in Figures 4 through 7. The point on envelope shown by a larger solid circle corresponds to the formation of first significant crack, defined as the crack which produced significant reduction in the lateral stiffness of the wall. A larger solid rectangular point on the envelope curve corresponded to the first diagonal tension shear crack. Envelopes with no solid circular point indicate that the first diagonal tension shear crack was also the first significant crack.

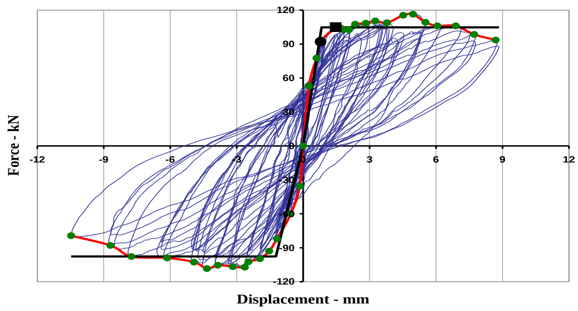

Fig. 4: *Hysteresis Loop, Envelope and bi-linear Idealized Curve of the Wall WIc.*

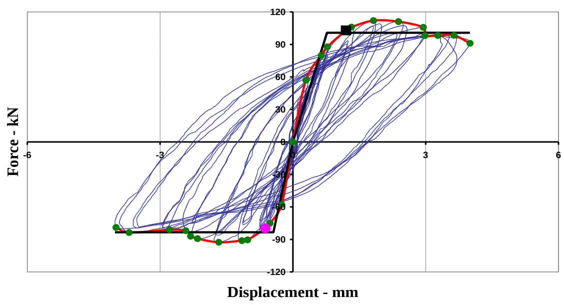

Fig. 5: *Hysteresis Loop, Envelope and Bi-linear Idealized Curve of the Wall WIIb.*

ISSN: 2249 –8753

Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23

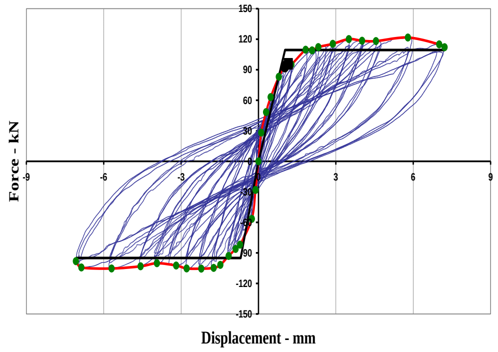

Fig. 6: Hysteresis Loop, Envelope and Bi-linear Idealized Curve of the Wall WIIIb.

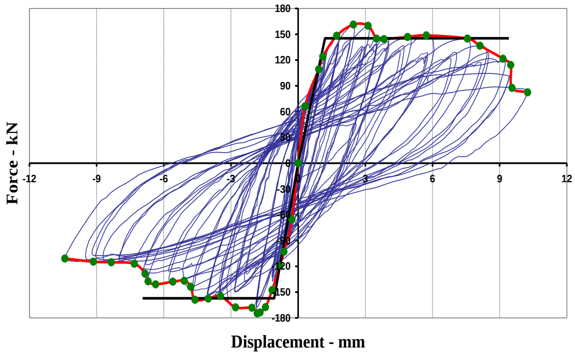

Fig. 7: Hysteresis Loop, Envelope and Bi-linear Idealized Curve of the Wall WIVa

3. ANALYSIS OF TESTS RESULTS

Results obtained from experimental work on the tested walls regarding displacement ductility factors and drift capacity, modulus of elasticity and energy dissipation characteristics are analyzed, discussed and presented in a quantifiable way in the following subsections.

3. 1 Displacement Ductility Factor

Displacement ductility factor, μ_w, of a structural element/system indicates its ability to deform in the inelastic range after yielding. In simple words, greater the μ_w of a structural member/system, better will be its seismic performance and vice versa. Displacement to $0.75V_u$); and d_u = Lateral displacement at the top of the wall when the experimental lateral force V drops by 20% of V_u along the degrading curve, as shown in Figure 8. The lateral force-displacement data used for determining μ_w and other relevant properties corresponded to the first cycle of loading.

ductility factors of walls were determined by using bi-linear idealization approach of the lateral force-displacement curve proposed by Magenes and Calvi [11], as shown in the Figure 8. The displacement ductility factor for an URM wall, μ_w, using the recommended criteria, was calculated by using the relation:

$$\mu_w = \frac{d_u}{d_y} \quad \text{..................................} \quad (1)$$

where d_y = Lateral displacement at the top of a wall at the end of elastic limit = V_u / K_e in which V_u = 0.9 V_{max} (V_{max} = the maximum resistance of the wall in the lateral direction); K_e = elastic stiffness of the wall = $0.75V_u$/ $d_{0.75Vu}$ ($d_{0.75Vu}$ = the displacement corresponding Displacement ductility factors of the tested walls are given in Table 3. The average value of μ_w for tested walls was found to be 6.31 with a C.O.V. of 26.3%. The higher ductility of walls as compared to the ones reported in literature [12] suggest that URBM construction carried out using stone dust is capable of absorbing more energy and thus can mitigate the seismic disaster.

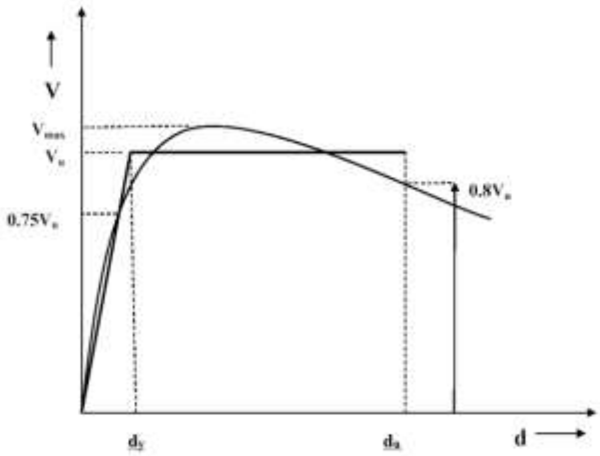

Fig. 8: *Bi-linear Idealization of URM Walls.*

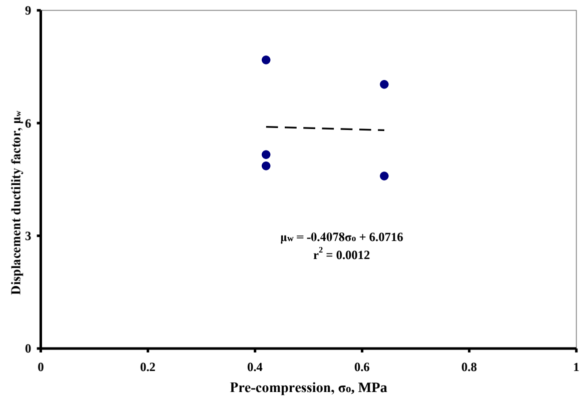

Fig. 9: *Effect of Pre-compression on Displacement Ductility Factors.*

Vasconcelos [13] investigated the influence of pre-compression level on μ_w in unreinforced stone masonry (URSM) walls and reported that the increase in pre-compression level decreases the μ_w. To validate this for URBM s pecimens under this study, regression analysis was carried out between σ_o and μ_w for WII and WIII series walls having σ_o=0.42 and 0.64 Mpa, respectively. These walls series were specifically selected due to the reason that walls in this series were having same aspect ratio but different pre-compression levels. However, no correlation was found between μ_w and pre-compression level as indicated by the coefficient of correlation, r, which was as low, as 0.035 as shown in Figure 9. The difference in behavior may be attributed to the different constituent materials of the masonry walls used in both investigations.

Table III. *Displacement Ductility Factors for Tested Wall Specimens.*

Wall designation	Loading direction	V_u (kN)	V_{min}/V_u	K_e (kN/mm)	d_y (mm)	d_u (mm)	δ_u (%)	μ_w
WIc	+	104.8	0.89*	125	0.83	8.84	0.53	10.69
	-	97.7	0.81*	80	1.23	10.47	0.63	8.54
WIIa	+	121.6	1.05*	165	0.73	3.59	0.28	4.86
	-	71.3	0.93*	128	0.57	6.36	0.49	11.03
WIIb	+	100.8	0.90*	132	0.77	4.00	0.31	5.16
	-	83.4	0.95*	193	0.44	4.02	0.31	9.09
WIIc	+	87.8	0.99*	115	0.77	5.94	0.46	7.68
	-	76.2	1.00*	158	0.47	5.89	0.46	12.62
WIIIa	+	114.8	0.89*	129	0.88	4.04	0.32	4.59
	-	111.4	0.83*	169	0.67	7.44	0.58	11.16
WIIIb	+	109.4	1.02*	105	1.03	7.22	0.56	7.03
	-	95.0	1.03*	139	0.69	7.08	0.55	10.21
WIVa	+	145.3	0.60	122	1.20	9.41	1.05	8.71
	-	157.2	0.71	147	1.07	6.95	0.77	7.24
WIVb	+	150.8	0.88*	424	0.35	6.47	0.72	18.66
	-	136.4	0.82*	767	0.19	6.11	0.68	32.46

* *Test was stopped before lateral force reduced to 0.8 V_u*

Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23
STM JOURNALS

3.2 Ultimate Drift Ratio, δ_u

Ultimate drift ratio, $\delta_{u,}$ of a structural element/ structural system indicates the extent of damages it can experience before collapse. Higher ultimate drift ratio, δ_u, of a structural element/ structural system indicates its ability to undergo substantial damage before collapse before and vice versa. In order to investigate the influence of pre-compression on the ultimate drift ratio of URBM, regression analysis was carried out using the data of walls belonging to WII and WIII series. A direct relationship between δ_u and pre-compression level was found with a coefficient correlation of 0.7 as shown in Figure 10.

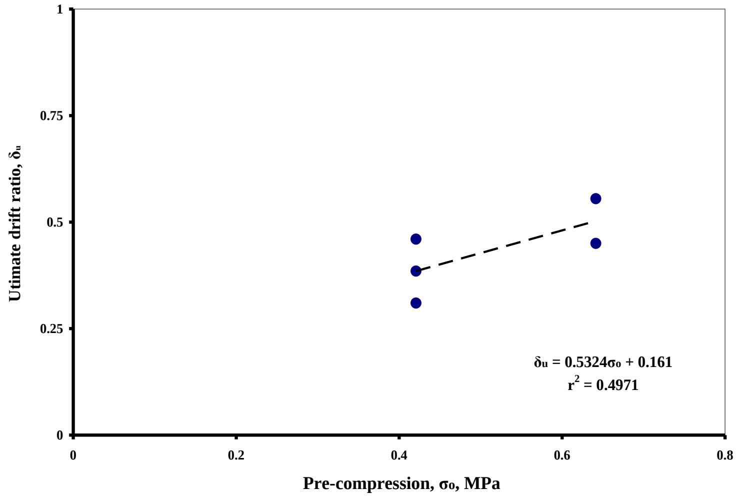

Fig. 10: *Effect of Pre-compression on Ultimate Drift Ratio.*

3.3. Energy Dissipation

Unreinforced masonry when loaded in inelastic range undergoes macro cracking. The energy is dissipated due to the release of fracture energy. The subsequent friction of cracked surfaces over each other further increases energy dissipation. The dissipation of energy in a normalized quantified way is determined by calculating the "coefficient of equivalent viscous damping" (ξ_{eq}) using the following equation:

$$\xi_{eq} = \frac{E_d}{2\pi\, E_i} \quad \text{.................................} \quad (2)$$

where E_i = energy required in one cycle to impose a target lateral force/displacement in the wall. Normally, for the purpose of simplicity, it is calculated as the sum of triangular area of force-displacement diagram on positive and negative loading sides of the curves [14].

However, the correct approach, based on the above mentioned definition of E_i, is to determine it by computing the area of force-displacement diagram, both in positive and negative loading directions, as shown in Figure 11a [13]; and E_d = Energy dissipated in one cycle of imposed lateral

Recent Trends in Civil Engineering & Technology
Volume 2, Issue 3, December2012, Pages 11-23

force/displacement and is determined by computing the areas under the positive and negative branches of force displacement hysteresis loops, as shown in Figure 11b [13].

In general, higher the value of ξ_{eq}, greater will be the damages experienced by the corresponding structural element/structural system and vice versa. In the other words, for the mitigation of seismic disaster, ξ_{eq} shall be as small as possible.

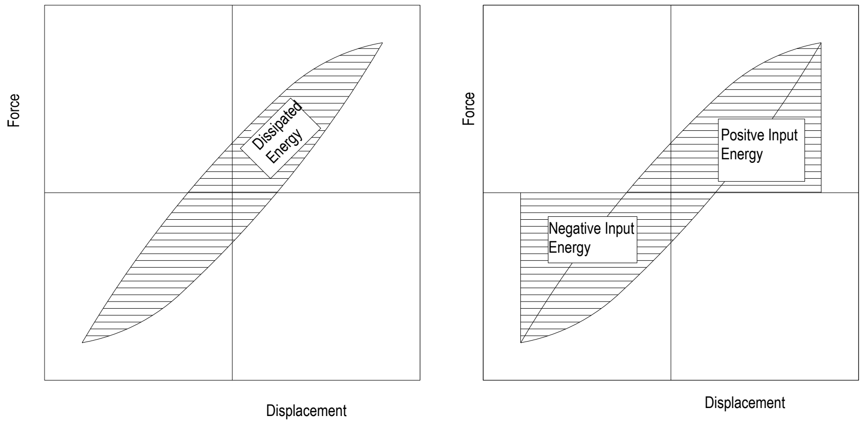

Fig. 11: *Energy Determination in One Cycle of Loading [12] a). Dissipated Energy b). Input Energy.*

Variation in the coefficient of equivalent viscous damping with the increase in the drift ratios for the tested walls is shown in Figure 12**.** It was found that coefficient of equivalent viscous damping, ξ_{eq}, of slender walls (WIc) before diagonal tensile shear cracking was found to be relatively lower as compared to other walls. One of the possible reasons for this behaviour may be higher flexural deformation in slender walls which tends to give a less dissipative behaviour. Thus walls failing in flexure mode mitigate the seismic disaster relatively more as compared to the walls failing in diagonal tension. Flexure failure in the walls can be achieved by increasing its aspect ratio (i.e., height to length ratio).

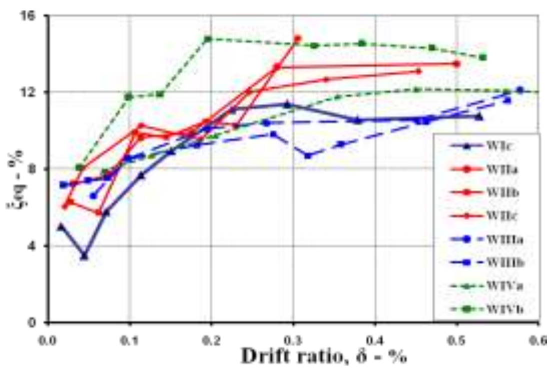

Fig. 12: *Variation in Coefficient of Equivalent Viscous Damping with the Increase in Drift Ratio.*

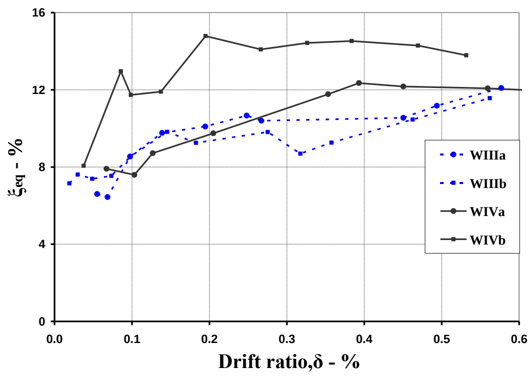

Fig. 13: *Influence of Aspect Ratio on Coefficient of Equivalent Viscous Damping.*

Similarly, by comparing the results of WIII (aspect ratio = 0.93) and WIV series of walls (aspect ratio =0.66) in Figure 13, it can be observed that ξ_{eq} increases by the decreasing the aspect ratio to an extent so that walls fail in bed-joint sliding. This may be attributed to high dissipation of energy due to friction caused by bed joint sliding. Squat walls failing in bed-joint sliding although have greater value of ξ_{eq}.

It can be concluded walls with high and low aspect ratio mitigate the seismic disaster more effectively as compared to walls with intermediate aspect ratio, specially supporting higher vertical loads.

4. CONCLUSIONS

Based on the experimental seismic performance investigation carried out on URBM walls built with stone dust (*Khaka)* mortar, the following conclusions are made:

1. Higher the pre-compression level, greater were the number of cracks with narrow width and vice versa. Thus it is concluded that increase in pre-compression level on walls mitigate the seismic disaster of URBM construction.
2. No correlation was found between displacement ductility factors and pre-compression levels from statistical regression analysis. However, this correlation may need to be substantiated with more test data.
3. Linear regression analysis between σ_o and δ_u for the walls, having same aspect ratio but different values of σ_o, indicated a direct relation between them
4. URBM walls having high aspect ratio mitigate the seismic disaster, relatively more as compared to the walls having moderate aspect ratio
5. Squat URBM walls with low to moderate pre-compression also mitigate the seismic disaster.
6. The average value of displacement ductility factor found in this study is 6.31 which indicate that URBM construction using stone dust mortar is capable of absorbing more energy and thus help in seismic disaster mitigation.

ACKNOWLEDGMENTS

The first author is grateful to the University of Engineering and Technology, for granting him study leave during his PhD studies to carry out the experimental work and the Higher Education Commission (HEC) for providing funds for his research project.

REFERENCES

1. Javed M., Khan A. N., Magenes G. *Performance of Masonry Structures during Earthquake -2005 in Kashmir*. Mehran University Research Journal of Engineering & Technology. 2008. Vol. 27. 271–282p.

2. Javed M. *Seismic Risk Assessment of Unreinforced Brick Masonry Building Systems of Northern Pakistan*, Ph.D. Thesis. 2009. Civil Engineering Dept. NWFP University of Engineering and Technology, Peshawar, Pakistan.
3. FEMA 356. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. 2000. ASCE-FEMA. Washington.
4. ASCE-SEI 41-06. *Seismic Rehabilitation of Existing Buildings*. 2007. ASCE–SEI. Reston Virginia.
5. CEN. *Eurocode 8: Design of Structures for Earthquake Resistance - Part 3: Assessment and Retrofitting of Buildings*. 2005. EN 1998-3. Brussels. Belgium.
6. Bosiljkov V., Page A., Bokan-Bosiljkove V., et al. *Masonry International*. 2003. 16. 39–50p.
7. ASTM C1314-11. *Standard Test Method for Compressive Strength of Masonry Prisms, American Society for Testing and Materials*. 2002. Philadelphia, USA.
8. ASTM, E 519-02. *Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*. 2002. American Society for Testing and Materials, Philadelphia, USA.
9. RILEM. LUM B6. Diagonal Tensile Strength Tests of Small Wall Specimens. *Tech. Rep*. 1994. RILEM.
10. EN-1052-3. *Methods of Test for Masonry – Part 3: Determination of Initial Shear Strength*, Brussels. Belgium.
11. Magenes G. and Calvi G.M. In-plane Seismic Response of Brick Masonry Walls. *Earthquake Engineering and Structural Dynamics*. 1997. 26. 1091–112p.
12. Tomaževic M. *Earthquake-resistant Design of Masonry Buildings*. 1999. Imperial College Press, London.
13. Vasconcelos G. *Experimental Investigations on the Mechanics of Stone Masonry: Characterization of Granites and Behaviour of Ancient Masonry Shear Walls*. PhD. Thesis. 2004. University of Minho. Portugal.
14. Chopra A.K. *Dynamics of Structures-Theory and Application to Earthquake Engineering*. Second Edn. 2001. *Prentice Hall Publishers*. New Jersey.