The Effect of Slenderness Ratio on Seismic Performance of Unreinforced Masonry Walls

Pritha Chudal
Graduate Studemt
Institute of Engineering,
Thapathali Campus
Kathmandu, Nepal
prithachudal@gmail.com

Prem Nath Maskey
Professor of Civil Engineering
Institute of Engineering,
Pulchowk Campus
Kathmandu, Nepal
pnmaskey@live.com

***Abstract*—During Gorkha Earthquake 2015, most of unreinforced masonry buildings were partially or fully collapsed. Unreinforced brick masonry buildings (URBM), have relatively high compressive strength but low tensile strength. Its lateral load carrying capacity is relatively low by which it is highly vulnerable to earthquake. In this paper a brief study of the capacity of URM walls on the basis of slenderness ratio is carried out and a limiting slenderness value is suggested in reference with literature reviews. It is observed that slenderness ratio affects stability of URM walls during an earthquake and hence is an appropriate parameter to address out-of–plane stability. Increment of slenderness ratio showed the decrement of the load carrying capacity of URM walls. The paper also suggests the value of slenderness ratio of URM wall shall be within 9 to 20.**

Keywords—unreinforced masonry, loading eccentricity, slenderness ratio, out-of-plane

I. INTRODUCTION

Unreinforced brick masonry (URBM) has been the principal construction material for buildings in Nepal for a long time. Bricks most commonly used in Nepal are of size 230mm × 110mm × 55mm. Unreinforced brick masonry has high compressive strength but is much lower in tensile or shearing strength. Hence, the lateral load resisting capacity of masonry construction is low.

In an earthquake, the heavy mass of masonry walls contributes to high earthquake forces. Inertial forces are the product of the mass of an object and the acceleration of its motions; thus, heavier the buildings, higher the forces they are shaken with.

Unreinforced masonry buildings perform poorly in earthquake. The walls aligned along the direction of seismic load are subjected to in-plane forces and the walls perpendicular to the loads to out-of-plane forces. The walls perpendicular to the lateral loads have much lesser resistance compared to the walls along the direction. The concrete if present, floor acts as a rigid floor diaphragm in its own plane. Hence the lateral forces acting are distributed to walls in accordance to their stiffness. The loads distributed are transmitted through shearing action to the foundation. Due to heavy mass of masonry wall leading to high inertial forces, poor connection between the walls and diaphragms be separated from roof leading to the collapse of the building. Unreinforced masonry is weak in resisting such lateral forces. (FEMA, 774)

The study highlights the need for enhancement of the research on the URM buildings behavior under earthquake loading. The extensive studies with the action of the tests and researches of URM have focused on in-plane walls. Although walls perpendicular to the direction of earthquake are not the direct path to the loads, they need to be able to resist the force exerted. Since URM walls have low tensile strength, slender masonry walls are vulnerable to out-of-plane failure and belongs to one of the most controlling modes of failure Out of plane failures are most vulnerable in case of masonry during earthquake. It causes greatest risk to the safety of people inside and outside of the building as it causes collapse of the walls leading to partial or complete collapse of the building. Here this study focuses on the effect of slenderness ratio, eccentricity of load on the stability of URM wall.

II. NEED TO STUDY

Seismic activities in Nepal are very frequent, which are caused by the continental collision of Indian plates and Eurasian plates. On 25th April 2015, an earthquake of moment magnitude Mw 7.8 with a focal depth of <15km struck about 80km northwest of the capital, Kathmandu (USGS 2015). The earthquake caused thousands of deaths as well as damaged a huge number of buildings. The large scale of damage has indicated that the study and research of the general practice of building construction in Nepal and the assessment of their capacity of such buildings are necessary to understand.

Brick masonry is one of the most popular construction materials in developing countries like Nepal. Unreinforced masonry structures normally have high compressive strength by which there are strong in gravity loads but are very weak in tensile strength i.e. lateral forces causing are high vulnerable in earthquakes. During earthquakes, in plane forces cause sliding or shearing whereas out-of-plane causes bending leading to flexural strain.

The need to investigate the URM buildings is substantiated from the following reasons:

- A substantial number of URM buildings are still being built in the areas which are considered seismically active areas causing a potential threat to life safety of people residing in such places during a relatively high intensity earthquake. Despite the huge practice of RCC buildings in urban areas, URM buildings are unavoidable. There is necessity to understand the seismic performance of unreinforced brick masonry buildings.
- According to the review of the available existing research work in URM in Nepal, it is found that most of the research work are directed towards RCC frame structures of reinforced masonry structure and a little or no effort has been drawn towards a typical URM buildings despite the fact such buildings fill many parts of the country and still such buildings are in practice.
- In Nepal, there has not been much study in unreinforced masonry structure and also lacks appropriate codal provisions for URM buildings.
- Most of the existing buildings in Nepal are URM buildings. It is imperative that a research on seismic vulnerability of the existing masonry buildings is necessary to mitigate the risk.

Hereby, it has become imperative that a thorough research work in URM be undertaken and a system of procedures be defined to provide a guideline for the new construction of URM buildings in seismically active region.

III. LITERATURE REVIEW

According to (Ferreira, Costa 2014), the seismic behavior of an unreinforced masonry structure can be vewied by the simple, but critical, features one of which is the restricted slenderness of the walls which is responsible for out of plane stability of the wall [1].

(Derakhshan, Ingham, & Griffith, 2010) performed a set of time-history analyses on several unreinforced masonry (URM) walls with various slenderness ratios to study the out-of-plane behavior of unreinforced walls on the basis of slenderness ratio. Thirteen wall models were considered of height 3000 mm to 7000 mm and three storey such that most of the houses in News land were covered. Three wall properties height, thickness, and overburden for thirteen models were considered. An overburden ratio was also considered for ground floors. Thirty ground motion records were considered. Maximum displacements of the walls were observed in each of nearly 18,000 incremental time history analyses. The analysis showed that the wall slenderness ratio influenced out-of-plane stability of wall. Higher the slenderness ratio, higher was the vulnerability. Hence it was confirmed that slenderness ratio is an appropriate parameter for the prediction of out-of-plane stability. The effect of slenderness ratio is shown in Fig. 1 [2].

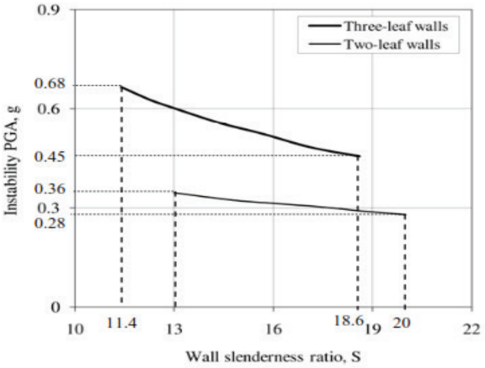


Fig. 1. Effects of wall slenderness ratio, average from all records [2]

An extensive research was undertaken in USA and a report, ABK Topical Report 04 was published by (ABK Joint Venture 1981). According to the report an experimental program conducted on unreinforced masonry (URM) walls subjected to dynamic out-of-plane motions to check on the capacity of URM walls to resist the collapse due to dynamic out of plane motions and thereby to provide data to build out the guidelines and criteria. The Full-scale component tests on URM walls subjected to dynamic, out-of-plane motions were conducted on 20 wall specimens subjected to 194 dynamic test sequences. The wall prototypes experimented included 3 Wythe common brick, clay block, and concrete block. A constant axial load was applied along with the dynamic controlled lateral displacement histories. The failure occurred at the mid-height leading to collapse of the wall after the cracks at the mid-height and near base. The URM wall prototypes were 6 ft wide and 10 to 16 ft (3.0 to 4.9 m) high with height-to-thickness ratios (H/T) of the walls from 14 to 25. The parameters altered in the wall specimens were thickness, height, unit weight, overburden weight and input motions such that it covered various exterior walls and bearing wall. The tests produced valuable data for establishing bounds on the resistance of URM walls to collapse when subjected to dynamic out of-plane motions. The research report also states that the information obtained in these dynamic tests is believed to be applicable in all seismic zones within the United States and since the geographic United States spans the total range of seismic intensity the information gained can be utilized outside its boundary [3].

The guidelines were provided by (Kariotis et. al, 1981) based on the results obtained from the extensive research by ABK, in accordance with the three seismic hazard levels of the 1978 ATC provisions based on effective peak accelerations of 0.1, 0.2, and 0.4 g.The full-scale testing experimental data along with analytical model was considered to determine the dynamic stability of fully anchored unreinforced walls subjected to out-of- plane motions. One of the parameters that affected stability among others was height/thickness (H/T) ratio of the wall in the storey under consideration as shown in Fig. 2. Based on the results allowable H/T ratios of walls with minimum quality mortar for several types of buildings were

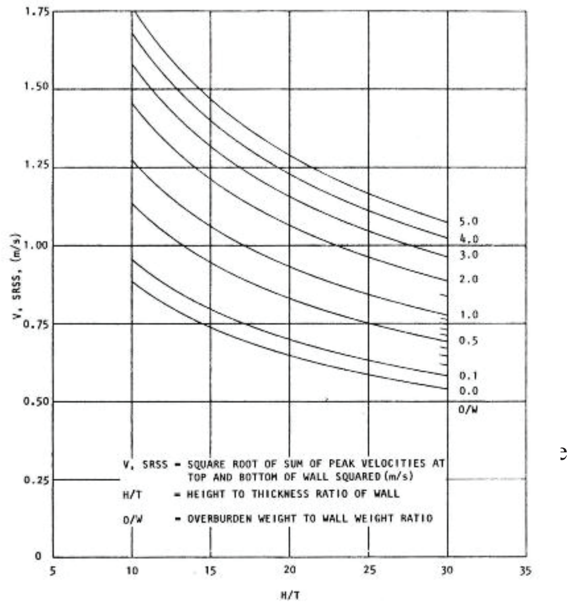


Fig. 2. Unreinforced masonry wall stability criteria [4]

ascertained which is provided in Table I [4].

(ASCE 41, 2007) Seismic Rehabilitation Standard also provides guidelines for permissible H/T ratios. A rigid body numerical model, regulated to full-scale shake table tests, was used to determine the H/T limits. The guidelines states that for life safety and collapse prevention, stability need not be checked for walls spanning vertically with a height-to thickness (H/T) ratio less than that given in Table II. It also further specifies to refer ABK 1984 for further information on evaluation of stability of unreinforced masonry wall out-of-plane [5].

(Sharif et al, 2007) performed rigid body rocking analysis using commercially available software Working Model (Knowledge and Revolution) along with the shake table tests of the walls and compared the relative displacements at crack from WM analysis to the results obtained from full-scale shake table tests as shown in Fig 3. The results indicated that WM adequately represent the out-of-plane rocking response of URM wall. For further evaluation of ASCE 41 height-to-thickness (H/T) ratio limits for out-of-plane URM walls, the model was extended for further Working Model analysis of URM walls with varying H/T ratios. To change H/T ratio of wall in the model, h was kept constant at 4.25 meters and thickness was changed. Eighty different ground motion inputs were used from different types of sites (varying from soft to hard and stiff). For those input motions where collapse was observed, the smallest H/T ratio producing collapse of the wall was recorded. The average of the H/T ratios producing collapse for different considered crack heights was taken as the collapse limit, H/Tcol. The probability of collapse of the wall for each H/T limit set by ASCE 41, was obtained [6].

TABLE I. ALLOWABLE H/T RATIO OF URM WALLS WITH MINIMUM QUALITY MORTAR [4]

Wall Types	Crosswalls	All Other Buildings
Walls of one storey buildings	20	14
First-storey walls of multistorey buildings	20	20
Walls in top storey of multistorey buildings	14	9
All other walls	20	15

TABLE II. PERMISSIBLE H/T RATIOS FOR URM OUT-OF-PLANE WALLS [5]

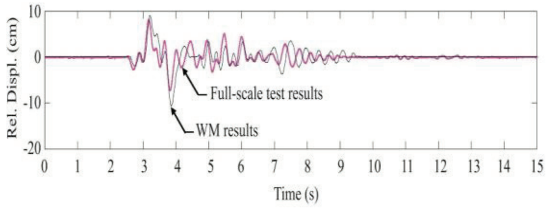
Wall Types	Sx1 ≤ 0.24 g	0.24 g < Sx1 ≤ 0.37 g	Sx1 > 0.37 g
Walls of one storey buildings	20	16	13
First-storey walls of multistorey buildings	20	18	15
Walls in top storey of multistorey buildings	14	14	9
All other walls	20	16	13

This paper has concluded that :

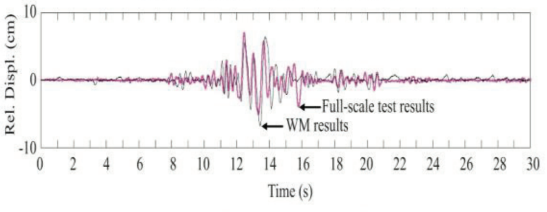
- The H/T limits specified in ASCE 41 for walls with limited overburden are less than the mean minus one standard deviation results for H/Tcol. Unreinforced masonry wall stability criteria [6].

- Walls satisfying the H/T limits in ASCE 41 will have a probability of collapse less than 8%, regardless of site class or ground motion intensity. [6].

The research carried out by (Sandoval.et al , 2011) on a ¼ scale experiment in laboratory of a total of 36 brick masonry walls with uniformly distributed vertical loads to study the load carrying capacity and the response of masonry walls from the point of view of varying slenderness ratio and load eccentricities. Both the upper and the lower hinges were located to cause the same eccentricity at both ends. The eccentricities provided were of e =0, e = t/6 and e = t/3, where t is the wall thickness. Walls with slenderness of 6.8, 12.6, 18.7 and 25.6 were tested. All the specimens were tested with a 200 kN capacity testing machine under displacement control until the collapse. It was observed that along with the increase



(a) Relative Displacement at Crack, Wall PC



(b) Relative Displacement at Crack, Wall PD

Fig. 3. Working model and full scale test comparison [6]

in slenderness ratio, the capacity of the wall decreased as shown in Fig 4. The decrease in strength increased with the increment of loading eccentricities. The loss of observed load capacity is observed upto 40% for slenderness 6.8 and upto 70% for slenderness 25.6, for the eccentricity t/6 compared with null eccentricity. On the basis of these results it can be stated that increment in slenderness ratio and loading eccentricities adversely affect the capacity of masonry walls [12].

Along with the experimental tests, numerical analyses were performed with the micro-model proposed by Lourenço and Rots performed employing DIANA software. The model assigns elastic behavior to the units whereas masonry inelastic behavior is transferred to the joints. A 2D plane stress condition was assumed, using interface elements to simulate the behavior of joints under tension. The analyses were carried out by means of a direct displacement control and considering the geometric non-linearity. Similar results were obtained beside some unavoidable differences which is shown in Fig 5 [12].

(Bernet, Gill and Roca, 2014) attempted to formulate a practical approach to calculate the load bearing capacity of an unreinforced brick masonry under eccentric axial load. After the formulation of an analytical method of calculation considering second order bending effects, the results were compared with the experimental data for the authentication of the analytical approach which is presented Fig 6. The experiment involved 18 unreinforced eccentrically loaded walls under large eccentricities and 16 walls with small eccentricities of the load .Among the other three calculation procedures (Eurocode-6 (EC-6), Southwell Plot method, ACI-530), the herein proposed method is more accurate than ACI-530 or the FEM for the most slender walls, whereas the numerical model is better than the other two for the moderate slender wall and the standard ACI-530 provides the better accuracy for the less slender walls. On the basis of the analysis of the outcomes of the study in the paper it can be concluded that there lacks a simple, practical and accurate analytical method to calculate the load-bearing capacity of unreinforced brick masonry walls subjected to eccentric axial loads and slenderness of the walls [13].

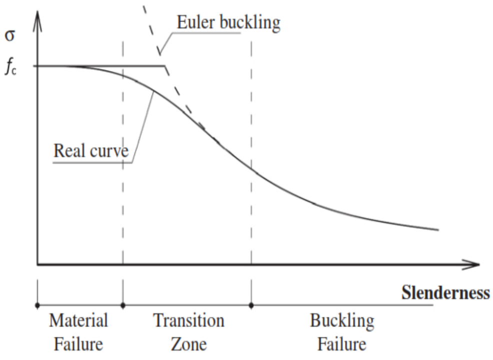


Fig. 4. Wall compressive stress against slenderness ratio [12]

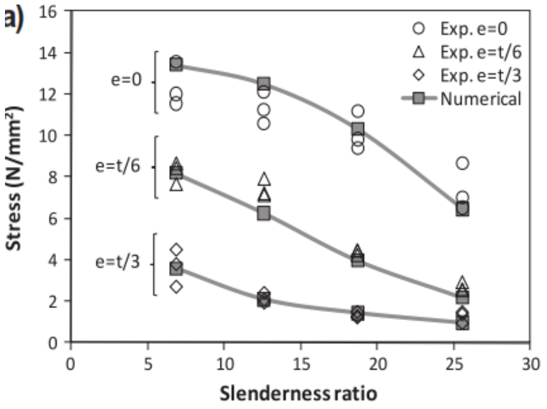
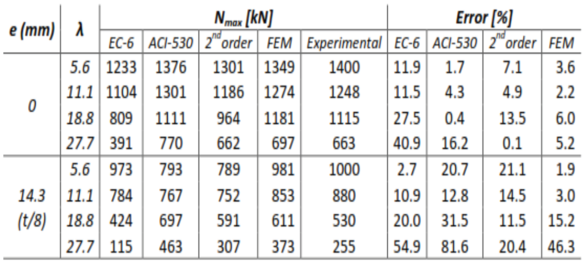


Fig. 5. Comparison between numerical and experimental ultimate capacities [12]



e (mm)	λ	N_{max} [kN]					Error [%]			
		EC-6	ACI-530	2^{nd} order	FEM	Experimental	EC-6	ACI-530	2^{nd} order	FEM
0	5.6	1233	1376	1301	1349	1400	11.9	1.7	7.1	3.6
	11.1	1104	1301	1186	1274	1248	11.5	4.3	4.9	2.2
	18.8	809	1111	964	1181	1115	27.5	0.4	13.5	6.0
	27.7	391	770	662	697	663	40.9	16.2	0.1	5.2
14.3 (t/8)	5.6	973	793	789	981	1000	2.7	20.7	21.1	1.9
	11.1	784	767	752	853	880	10.9	12.8	14.5	3.0
	18.8	424	697	591	611	530	20.0	31.5	11.5	15.2
	27.7	115	463	307	373	255	54.9	81.6	20.4	46.3

Fig. 6. Results of the different calculation methods considered in the research (except Southwell Plot) compared with the experimental results (average values from two walls for each case) and absolute value of the relative error for each case [13]

IV. CODAL PROVISIONS

According to (Bangladesh National Building Code, 2015) for a wall, slenderness ratio shall be the ratio of effective height to effective thickness or effective length to effective thickness whichever less is. In case of a load bearing wall, slenderness ratio shall not exceed 20 [7].

According to (Pakistan code, 2007) for a wall, slenderness ratio shall be effective height divided by effective thickness or effective length divided by the effective thickness, whichever is less. In case of a load bearing wall, slenderness ratio shall not exceed 27 in cement mortar and 20, 13 in lime mortar for upto 2 and exceeding 2 stories respectively [8].

According to (Indian Code, 1995) for a wall, slenderness ratio shall be effective height divided by effective thickness or effective length divided by the effective thickness, whichever is less. In case of load bearing wall, slenderness ratio shall not exceed 27 in cement mortar and 20, 13 in lime mortar for upto 2 and exceeding 2 stories respectively [9].

According to (Euro code, 2005) the slenderness ratio of a masonry wall shall be obtained by dividing the value of the effective height h_{ct} by the value of the effective thickness, t_{cf} and the slenderness ratio of the masonry wall should not be greater 27 than when subjected to mainly vertical loading [10].

According to (British code, 2003) the slenderness ratio should not exceed 27, except in the case of walls less than 90 mm thick, in buildings of more than two storey, where it should not exceed 20. A lateral support may be provided along either a horizontal or a vertical line, depending on whether the slenderness ratio is based on a vertical or horizontal dimension [11].

V. CONCLUSION

On the basis of the study it is observed that slenderness ratio affects stability of URM walls during an earthquake and hence is an appropriate parameter to address out-of –plane stability. Based on literature reviews, slenderness ratio of wall is determined to be 13 to 20 for ground floor and first storey and 9 to 14 for top storey.

It is also concluded that increase in slenderness ratio and loading eccentricity decreases the load carrying capacity of masonry wall and that there lacks a simple, practical and accurate analytical method to calculate the load-bearing capacity of unreinforced brick masonry walls subjected to eccentric axial loads and slenderness of the walls. The complexity of this problem indicates the necessity of further study.

REFERENCES

[1] T. M. Ferreira, A. A. Costa and A. Costa, "Analysis of the Out-of-Plane Seismic Behaviour of Unreinforced Masonry: A Literature Review," International Journal of Architectural Heritage, vol. 9, no. 8, pp. 949-972, Nov. 2014

[2] H. Derakhshan, J.M. Ingham and M.C. Griffith, "Effects of unreinforced masonry wall slenderness ratio on out-of-plane post-cracking dynamic stability", Proceedings of the 2010 NZSEE Annual Conference, 2010

[3] ABK Joint Venture, ABK Topical Report 04, "Methodology for Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings: Wall Testing, Out-Of-Plane", 1981

[4] J.C. Kariotis, R.D. Ewing, A.W. Johnson, (Co-Principal Investigators), and S.A. Adham. ABK, A Joint Venture, El Segundo, California, USA, "Methodology for Mitigation Of Earthquake Hazards In Unreinforced Brick Masonry Buildings", 1981

[5] ASCE/SEI 41-06. Reston, VA: American Society of Civil Engineers. ASCE, "Seismic Rehabilitation of Existing Buildings", 2007

[6] I. Sharif, M. Eeri, S. M. Christopher and K. J. Elwood, "Assessment of ASCE 41 Height-to Thickness Ratio Limits for URM Walls ', Earthquake Spectra, Earthquake Engineering Research Institute, 2007, Vol. 23, No. 4

[7] Housing and Building Research Institute, "Bangladesh National Building Code Part 6 (Structural Design)", 2015

[8] Government of Islamic Republic of Pakistan Ministry of Housing and Works, Islamabad, "Building Code of Pakistan (Seismic Provisions)", 2007

[9] Bureau of Indian Standards, New Delhi, "Indian Standard Code of Practice for Structural Use of Unreinforced Masonry (Third Revision), 1995

[10] European Committee for Standardization, "Eurocode 6 - Design of Masonry Structures - Part 1-1: General," Nov. 2005

[11] Sheffield University, "British Standard Code of Practice for Use of Masonry - Part 1: Structural Use of Unreinforced Masonry," 2003

[12] C. Sandoval, P. Roca, E. Bernat, L. Gil, "Testing and numerical modelling of buckling failure of masonry walls" Construction and Building Materials , 2011, 25, Elsevier.

[13] E. Bernat, L. L. Gil and P. Roca, "Analytical Method for the Assessment Of Unreinforced Brick Masonry Walls Subjected To Eccentric Compressive Loads" Construction and Building Materials, 2014, 73