EXTENDING THE COLLAPSE TIME OF NON-ENGINEERED MASONRY BUILDINGS UNDER SEISMIC LOADING

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ABSTRACT :

THE COLLAPSE OF NON-ENGINEERED MASONRY IS ONE OF THE GREATEST CAUSES OF DEATH IN MAJOR EARTHQUAKE EVENTS AROUND THE WORLD. THIS PAPER INVESTIGATES A RECENTLY DEVELOPED RETROFITTING TECHNOLOGY SPECIFICALLY AIMED AT PREVENTING OR PROLONGING THE COLLAPSE OF ADOBE (MUD BRICK) BUILDINGS UNDER STRONG EARTHQUAKES. THIS TECHNOLOGY USES COMMON POLYPROPYLENE PACKAGING STRAPS TO FORM A MESH, WHICH IS THEN USED TO PREVENT BRITTLE MASONRY COLLAPSE. THE RETROFITTING TECHNIQUE IS TESTED USING STATIC, DIAGONAL LOADING OF MODEL WALL PANELS. IT IS SHOWN THAT THE PROPOSED TECHNIQUE EFFECTIVELY PREVENTS BRITTLE COLLAPSE OF THE PANEL AND THE LOSS OF DEBRIS. PARTIAL MESHES OF VARIOUS ORIENTATIONS ARE ALSO INVESTIGATED IN ORDER TO BETTER IDENTIFY THE ACTION OF THE MESH. FINALLY, A CASE STUDY IS PRESENTED FOR THE IMPLEMENTATION OF THIS TECHNOLOGY IN RURAL COMMUNITIES THROUGHOUT NEPAL.

KEYWORDS: **ADOBE, SEISMIC LOADING, SMALL-SCALE TESTING, PHYSICAL MODELLING, SIMILITUDE, MASONRY SHEAR STRENGTH**

1. INTRODUCTION

1.1. Motivation For This Study

"The replacement of existing dwellings with 'earthquake-resistant houses' is neither feasible nor, perhaps, desirable. It has been found more realistic to think, rather, in terms of low-cost upgrading of traditional structures, with the aim of limiting damage caused by normal earthquakes and giving their occupants a good chance of escape in the once-in-a-lifetime event of a large earthquake." [*Coburn and Spence*]

The great majority of all earthquake fatalities result from building failures with a growing disparity between vulnerability of those in developing and developed countries [*GHI*]. The greatest risk is by far presented to inhabitants of non-engineered masonry structures as demonstrated in the 2003 Bam (Iran) earthquake, where many of the thousands of deaths were attributable to vulnerable adobe (mud brick) structures. Similarly vulnerable, non-engineered masonry is widespread throughout the developing world (figure 1) and replacement of all such dwellings is both infeasible and undesirable, given that they are often the embodiment of local culture and tradition. Therefore, it is often more feasible to consider low-cost retrofitting of such buildings.

1.2. Masonry Collapse

Structural collapse under seismic loading displays many possible failure mechanisms often related to interaction between structural components (e.g. separation of walls or floor-wall connections). When considering the failure of individual walls, the inertia forces induced by seismic action can act out-of-plane (e.g. so as to cause toppling) or in-plane (figure 2).

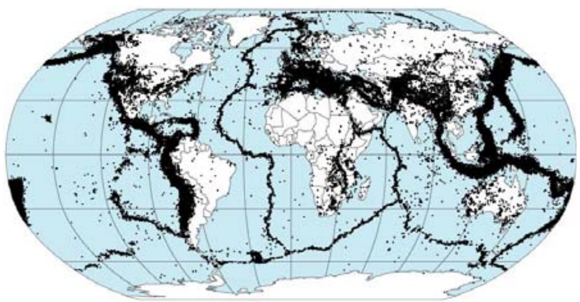


Figure 1a: Geographical distribution of all recorded earthquake epicentres from 1960 [*Lowman*]

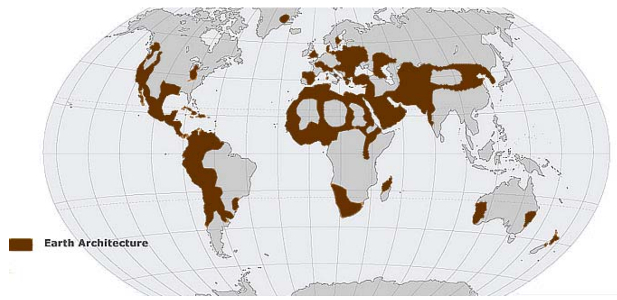


Figure 1b: Global distribution of adobe construction [De *Sensi*]

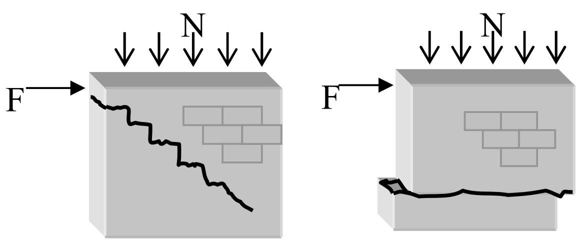


Figure 2: Shear failure modes

$$\boxed{\tau_f = \tau_o + \mu N} \qquad (1.1)$$

where:

F = laterally applied, in-plane load
N = normal compressive stress

τ_f = failure shear strength,
τ_o = shear strength under zero compressive stress,
μ = coefficient of friction.

In-plane failure is a fundamental failure mode for unreinforced masonry and determination of wall shear strength is necessary for defining its resistance to this mode of failure. For shear failures (figure 2), the shear strength [τ_f] of plain masonry walls is given by the frictional relationship presented in equation 1.1 [*EC6, BS1052-3*].

1.3. Currently Available Retrofitting Techniques for Non-Engineered Masonry

Methods required to meet the needs of the large populations in danger of non-engineered masonry collapse must be simple and inexpensive to match the available resources and skills [*Mayorca*]. Notable low-cost retrofitting techniques suitable for non-engineered, unreinforced masonry dwellings are given in Table 1.

Method	Developing Institute	Description
Polypropylene (PP) Meshing	Institute of Industrial Science (IIS), Tokyo University, Japan	Encasing masonry walls with a mesh constructed of polypropylene strapping used for packaging worldwide [*Mayorca*]
Wire Meshing	Pontificia Universidad Católica del Peru, Peru	Similar to pp-meshing, but using a steel wire mesh [*Blondet*]
External Vertical Bamboo Reinforcement	Sydney University, Australia	External vertical bamboo reinforcement [*Dowling*]

Table 1: Existing retrofitting techniques for unreinforced masonry in the developing world

This paper focuses on the technique of polypropylene (pp) meshing. PP-meshing was first formally proposed in 2003 [*Mayorca*], is still under active research and currently has application in Nepal, Pakistan and Kathmandu. Figure 3 shows a retrofitted house in Pakistan.

Figure 3: Retrofitted house in Pakistan before and after application of covering mortar layer[1]

1.4. Objectives

This paper is concerned with investigating a method for prolonging the collapse life of non-engineered masonry under seismic loading, using polypropylene meshing. Validation of a proposed method requires extensive testing under various conditions. As masonry is one of the world's oldest building materials, a vast number of masonry types have evolved. Therefore, full-scale testing of all available masonry types is infeasible and so efficient modelling techniques are required.

Therefore, this paper aims to:

- investigate the effectiveness of pp-meshing in preventing brittle failure of unreinforced masonry specimens, under in-plane loading,
- investigate the scaling issues associated with small-scale modelling of the pp-mesh,
- identify the precise action of the mesh in more detail,
- discuss the implementation of pp-meshing in a seismically active region of Nepal.

2. DIAGONAL COMPRESSION OF FULL AND SMALL-SCALE MASONRY

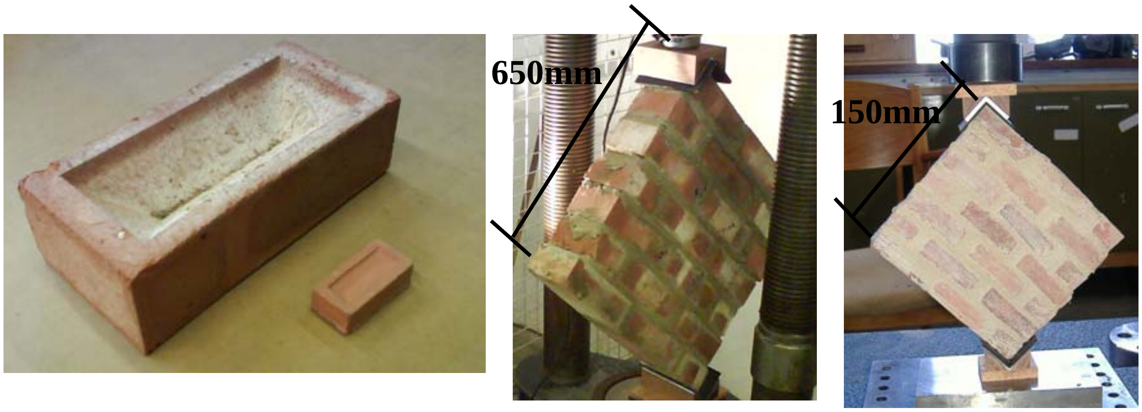
Small-scale modelling was conducted at a linear scale of 1:4 as shown in figure 4. Determination of masonry shear resistance [τ_f] to in-plane lateral load was achieved by testing both retrofitted and non-retrofitted square prisms in compression along one diagonal (figure 4). There is as yet no British or European standard for determining panel shear-resistance, and so the American Standard has been followed [*ASTM E 519-02*].

Two full-scale walls and three small-scale models were constructed for non-retrofitted testing under diagonal compression. For retrofitted testing two full-scale walls were constructed (parallel band spacing: 60mm) and nine small-scale models (band spacing: 15mm). Three of the small-scale retrofitted models shared the same mortar with the non-retrofitted specimens.

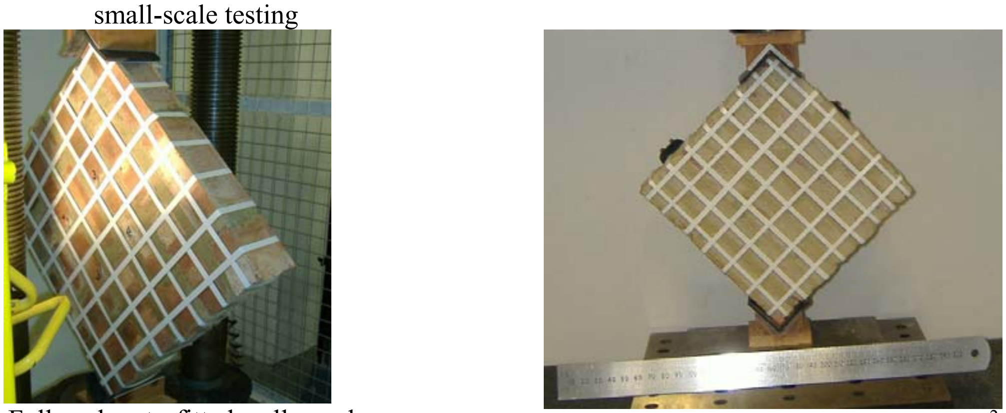
In addition to fully retrofitted masonry panels, meshes of various types were also tested to further isolate and understand the action of the mesh (figures 6e & f). To achieve this, the remaining small-scale specimens were tested in two batches of three with both batches using a different mortar and consisting of one fully retrofitted specimen, one with only horizontal reinforcement (parallel to the mortar bed joint) and one with only vertical (perpendicular).

Standard packaging strapping was used, and fastened with clips provided by the band manufacturers. Note that the clips used do not represent the method used in practice for applying the mesh. The aim of this test was to examine the effect of the pp-mesh on masonry failure and so recreating the installation method was not a requirement.

[1] Photos have been provided by Meguro Lab, Institute of Industrial Science, Tokyo University, Japan



a: Full size brick with ¼ size brick used for small-scale testing
b: Full-scale wall panel
c: Small-scale wall panel



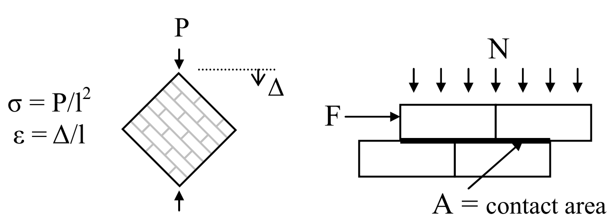
d: Full-scale retrofitted wall panel
e: Small-scale fully retrofitted specimen[2]

Figure 4: Full and small-scale models ready for testing

2.1. Similitude of Model Mortar & Mesh

In order for a small-scale model to accurately represent full-scale behaviour, the model and prototype should present the same stress-strain profiles when subjected to equivalent loading types [*Harris and Sabnis*]. Thus for the full and small-scale models to be similar the failure stresses [σ_f] and failure strains [ε_f] must be equal.

In the diagonal compression test the mortar bed is to be orientated at 45˚ to the horizontal, and so the stresses in the mortar may be approximated (in the proximity of the applied force [P]) as in figure 5:



$$\therefore \tau = N = \frac{P}{A\sqrt{2}} \qquad \textbf{(2.1)}$$

Figure 5: Diagonal compression test variables

where,

P is the diagonally applied load as shown in figure 5
l is a representative length,

[2] The ruler shown in figure 4e is a 30cm metal rule.

Therefore, substituting these stresses (equation 2.1) into the definition of shear failure (equation 1.1) and making the initial assumption that brick surface friction and mortar aggregate size will be controlled such that the coefficient of friction will be comparable for large and small-scale models (μ = const), gives the condition:

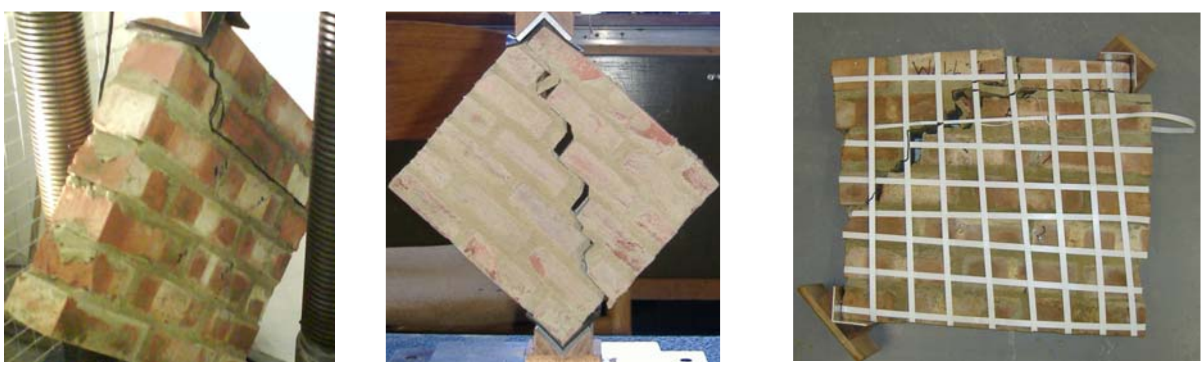
$$\boxed{\tau_{mo} = \tau_{po}} \qquad (2.2)$$

Equation 2.2 shows that in order to obtain identical stress-strain curves for diagonal shear test specimens of different scales, identical mortar strength must be ensured. Note that for dynamic testing this analysis no longer applies.

It must be noted that both mesh and masonry must be scaled equally to satisfy similitude. As the small-scale models used in these tests are at a linear scale of ¼, then the cross-sectional area of the pp-bands must be reduced by a factor of 16. Much of the previous small-scale testing of pp-meshing has used meshes of different scales to the masonry due to difficulties in producing bands of the required cross-section. To recreate this discrepancy ¼-width bands were used for the small-scale testing discussed in this paper to investigate how well meshes of this scale describe full-size behaviour.

3. RESULTS AND DISCUSSION

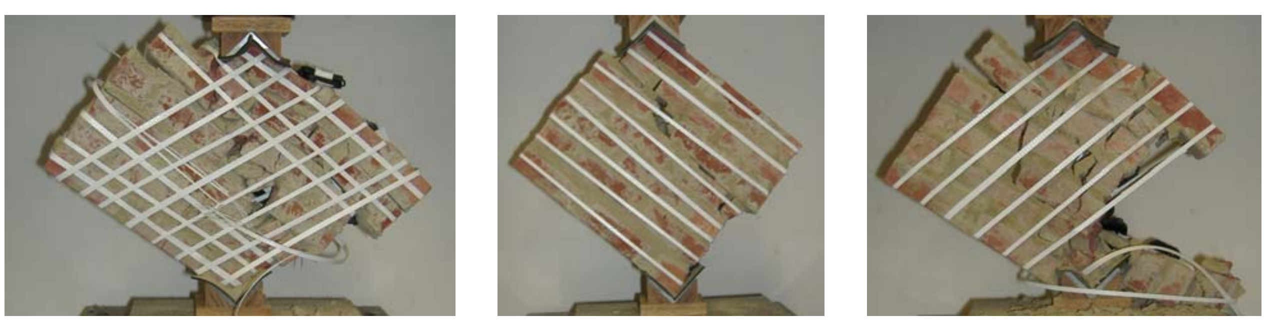
All failures of full and small-scale non-retrofitted walls were brittle with no further load being maintained whereas retrofitted models continued to carry load after initial failure (figure 6). Example specimen failure loads are given in figure 7.



a: Full-scale specimen at brittle failure

b: Small-scale specimen at brittle failure

c: Full-scale specimen after testing. Note displacement and rotation of corner section



d: Continuing to maintain load after second band failure. Further cracking suggests redistribution of load

e: Intact sections suggest little redistribution of load. Total collapse observed after failure of the supporting band.

f: Load redistributing through specimen (shown by continued cracking) but little support offered by vertical bands. Note loss of debris.

Figure 6: Full and small-scale model failures

3.1. *Comparing Retrofitted and Non-Retrofitted Failure*

Non-retrofitted specimens displayed brittle failure and collapse whereas retrofitted specimens continued to maintain load after initial failure of the masonry (figure 7). There was also no significant loss of debris until several bands were broken. During loading, the mesh acted to maintain panel integrity allowing the load to be redistributed throughout the mesh and masonry (shown by the formation of further cracks upon continued loading). Individual band failures showed that significant load was also carried by the mesh and it should be noted that all band failures occurred in horizontal bands at brick vertices. Figure 7 plots the comparative performances.

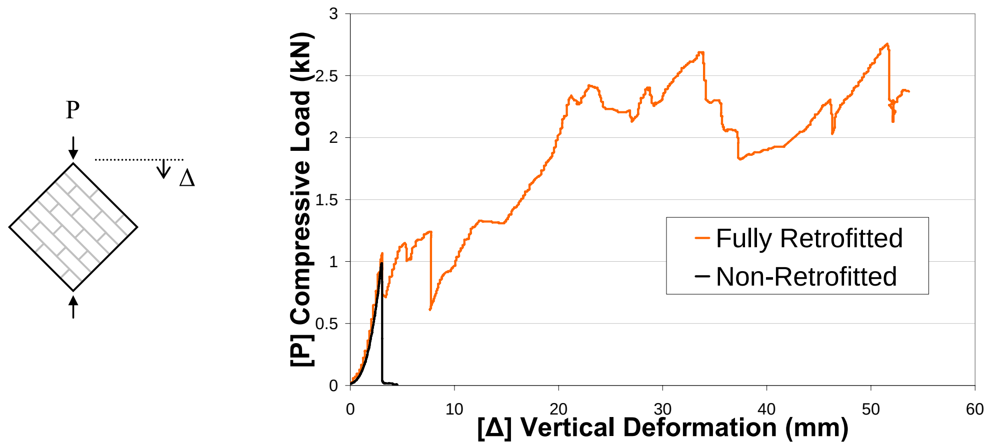


Figure 7: Load vs Displacement for retrofitted and non-retrofitted small-scale models

3.2. *Comparing Mesh Orientation*

Horizontal and vertical retrofitting was investigated individually in order to isolate the effects of the mesh parallel and perpendicular to the mortar bed joint, respectively. These tests showed that the main effect of the mesh is to restrain separated sections of masonry allowing for redistribution of the load within the masonry itself. Vertical bands provide little direct resistance to lateral sliding but upon panel deformation, band tension acts perpendicular to the horizontal mortar joints allowing frictional effects between sliding rows to resist further collapse. However, the specimen shown in figure 6f highlights that the incomplete, vertical mesh was unable to prevent loss of material, so limiting the redistribution of load. Horizontal retrofitting is shown to resist the separation of bricks within the same row and so is effective when diagonal or vertical cracking has taken place (figure 6e). That horizontal bands directly resist the load can also be seen in the fact that all band failures occurred in horizontal bands.

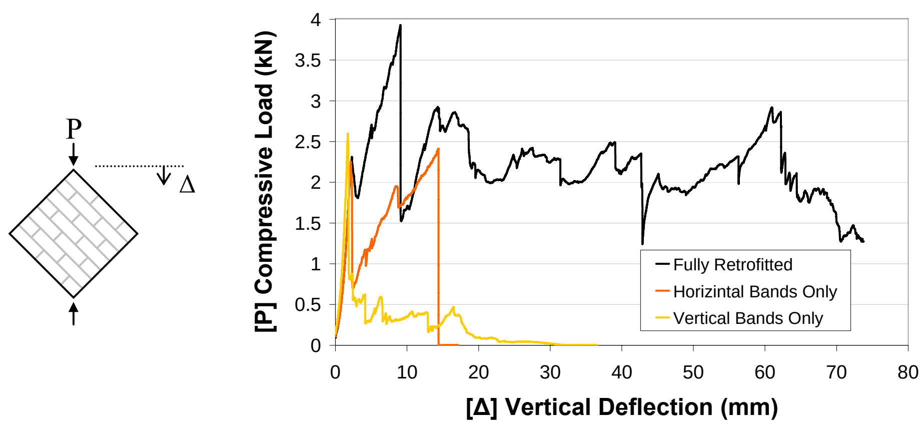


Figure 8: Comparing horizontally, vertically and fully retrofitted models

3.3. Comparing Full and Small-Scale Failure

Initial failure stress and pre-failure behaviour was unaffected by the presence of the pp-mesh due to the masonry's relative rigidity (figure 7). Therefore, pre-failure data of retrofitted and non-retrofitted specimens may be compared. However, a comparison of full and small-scale retrofitted post-failure profiles reveals that the small-scale specimen is able to maintain a far greater ultimate load relative to its initial failure loads (figure 9). This is to be expected given that the small-scale mesh used was not of the same linear scale.

If post-failure behaviour were purely defined by the action of the mesh, then reducing (by a factor of four. i.e. to the scale of the mesh) the load-displacement curve for the small-scale specimen should lead to correlation with the full-scale curve. However, performing this adjustment gives non-dimensional loads below that of the full-scale specimen (figure 9). This trend was shown by all tested specimens. This therefore highlights the fact that post-failure behaviour is a complex interaction of masonry and mesh and not solely due to mesh properties.

Therefore, to simulate accurate quantitative post-failure behaviour, mesh and wall must be of the same linear scale. However, the observed retrofitted failure patterns are common to both full and small-scale specimens despite the lack of similitude. Therefore for the purposes of investigating qualitative mesh/masonry behaviour and interactions (e.g. for testing of different mesh types/orientations, pitches etc) it is not necessary that similitude of both the masonry and mesh be satisfied.

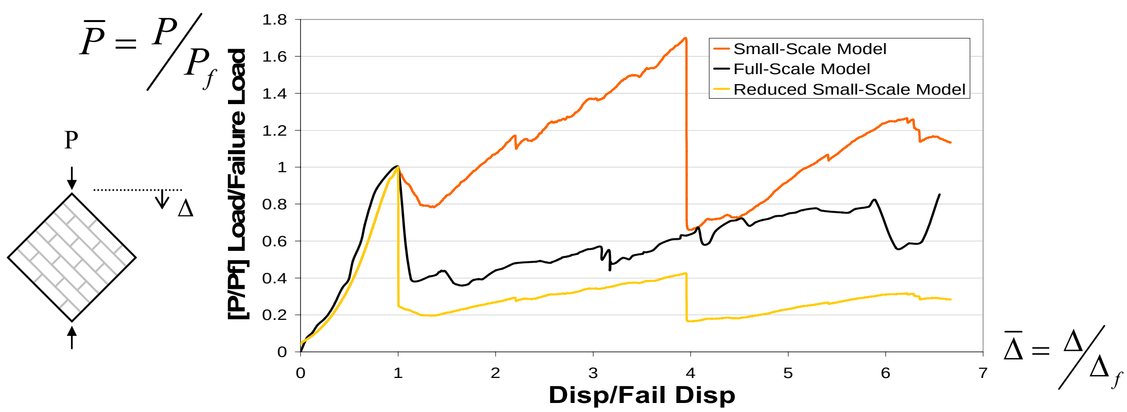


Figure 9: Non-dimensionalised load vs displacement for full and small-scale specimens. Small-scale model load adjusted to account for similitude violation between mesh and masonry

4. IMPLEMENTATION OF THE PROPOSED RETROFITTING TECHNIQUE

To investigate the practical issues of implementation a pilot scheme is to be conducted in a seismically active region of the Kathmandu Valley, Nepal. The scheme will incorporate a training course for local, rural masons, focusing on both earthquake construction and the pp-retrofitting technique, during which the students will prepare for a public low-tech shake-table demonstration of the pp-band technology. The masons will be engaged in all aspects of earthquake construction: appropriate site selection, planning and construction techniques, strengthening and repairing of existing structures and retrofitting using the pp-mesh. The demonstration is designed to allow the masons to apply what they have learnt and allow the public to graphically witness the necessity to improve upon traditional building techniques and to safeguard existing buildings against collapse. In addition to furthering the understanding issues of implementation, the long-term aim is to extend this original training program and demonstration to other areas of high-risk throughout the Himalayan region.

The scheme will take place in November 2008 as a partnership between Oxford University; the Institute of Industrial Science, Tokyo University; the Indian Institute of Technology, Bombay; the National Society of Earthquake Technology – Nepal; Nepal Engineering College and Khwopa Engineering College, Nepal.

a: trainee masons building model b: public shake-table test

Figure 10: PP-Band demonstration, Muzaffarabad 2006.

5. SUMMARY

This paper has investigated the technique of polypropylene meshing for preventing or prolonging the collapse of adobe buildings under strong earthquakes. The behaviours of full-scale and small-scale models have been compared to identify scaling issues of modelling retrofitted specimens. Various mesh types have also been tested to investigate the action of the mesh. Finally, a pilot scheme for pp-mesh implementation in rural Nepal has been introduced.

The main findings of this paper are summarised as follows:

- Non-retrofitted walls showed sudden brittle failure and were unable to maintain further load. It is this brittle failure that poses significant danger to building occupants during earthquakes.
- Retrofitting masonry walls with polypropylene meshing allowed specimens to maintain load after initial failure of the masonry and prevented the loss of debris, even after the failure of several straps. Given the low cost, high availability and relative simplicity of the pp-meshing technique, this technology may potentially be used to prevent/delay brittle collapse of non-engineered structures under seismic loading.
- Separating the effect of horizontal and vertical reinforcement showed that:
  - Vertical bands apply normal compression once sliding of rows occurs, increasing the masonry's frictional resistance to shear sliding.
  - Horizontal bands directly bear load by resisting the separation of bricks within the same row.
- Band failure occurred in horizontal bands at brick vertices. This suggests that further investigation should be focused on reducing stress the concentrations experienced at masonry corners.
- Small-scale retrofitted models gave good qualitative indication of full-scale behaviour even where similitude between the mesh and wall was not maintained. However, quantitative assumptions of full-scale behaviour cannot be obtained from small-scale testing if mesh and wall are not of the same scale.

REFERENCES

Blondet, M., G. Villa Garcia, and S. Brzev (2003), Earthquake-resistant construction of adobe buildings: A tutorial. EERI/IAEE World Housing Encyclopedia.

Coburn A., Spence R. (2002), Earthquake Protection (2nd edition), John Wiley & Sons Inc.

Dowling, D.M., and Samali, B. (2006), Low-cost, low-tech means of improving the earthquake resistance of adobe-mudbrick houses, *Proceedings of the International Conference on Earthquake Engineering (ICEE 2006)*, Lahore, Pakistan.

GeoHazards International, Global Earthquake Safety Initiative – Pilot Project, United Nations Centre for Regional Development (2001).

Harris, H.G. and G.M. Sabnis (1999), Structural modeling and experimental techniques. CRC Press.

Mayorca, P. (2003), Strengthening of Unreinforced Masonry Structures in Earthquake Prone Regions, Ph.D. Dissertation, The University of Tokyo, Japan.