APPENDIX IV: CASE STUDIES: NEPAL AND PERU

In order to demonstrate some of the principles and strategies outlined in this Primer, two papers are included below which describe case study programs for the seismic strengthening of housing in Nepal and Peru. Both case studies focus on rural adobe housing but the lessons are prevalent across locations and construction types.

The first paper describes the development (testing and analysis) of a particular seismic retrofit technique followed by a pilot project for implementing that retrofit technique in rural communities. The implementation phase involved a training program for rural masons in Nepal, a public shake-table demonstration, and the retrofit of a house. This implementation model proved effective at reaching rural communities but highlighted that subsidies are required to incentivize the safeguarding of homes among low-income communities, and that the long-term utilization of taught retrofitting and construction techniques is not guaranteed.

The second case study examines this conclusion further by exploring some of the technical, financial, and social challenges faced in the dissemination of seismic retrofit techniques to remote rural communities. A field investigation was carried out in Peru whereby sites of previous dissemination programs were visited and interviews were conducted with members of the affected communities and representatives of the organizations originally involved. This investigation highlighted that although programs must target communities directly, lessons taught to those communities are often lost over time.

Both case studies are useful in demonstrating the principles and strategies outlined in the Overview section of this Primer. They each present programs in which retrofit training has been used to also train in simple anti-seismic construction techniques to both build local capacity and change local construction practice. Technical excellence from around the world has been used to develop retrofit techniques which are simple enough to be applied by local masons or homeowners themselves. The retrofit techniques used are location specific, where the required materials and expertise are widely available in the local communities, and those communities are directly engaged through public demonstrations, training, and assisted self-build. Directly engaging masons is shown to be an effective way of transferring knowledge of earthquake-safe construction directly to those responsible for the construction, and the "cascade" model (training technicians to teach a larger number who then supervise construction) is an effective way of reaching the community while minimizing cost.

The two main conclusions that may be drawn from the following two case studies are:

- The buildings most at risk are built without engineering input, so retrofitting and construction techniques must be simple to apply and programs must target communities directly
- Lessons taught to communities are lost over time and so long-term intervention is essential

SEISMIC RETROFITTING OF NON-ENGINEERED MASONRY IN RURAL NEPAL

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ABSTRACT

One of the greatest causes of casualties in major earthquakes around the world is the collapse of non-engineered masonry buildings (those built without engineering input). Yet by definition non-engineered structures remain largely outside of the scope of modern engineering research, meaning that the majority of those at risk often remain so. A further barrier to realising research in this field is the significant social and economic challenge of implementation in low-income communities, where non-engineered housing is prevalent. This paper introduces a retrofitting technique aimed at preventing or prolonging the collapse of adobe (mud brick) houses under strong earthquakes. This technique uses common polypropylene packaging straps to form a mesh, which is then used to encase structural walls. The aim of this paper is to give an overview of the retrofitting technique's development and implementation. The key development stages of static, dynamic and numerical testing are presented, showing that the proposed technique effectively prevents brittle masonry collapse and the loss of debris. An implementation project is then discussed, involving a training programme for rural masons in Nepal, a public shake-table demonstration and the retrofit of a real house. The implementation project proved effective at reaching rural communities but highlighted that government subsidies are required to incentivise the safeguarding of homes among low-income communities.

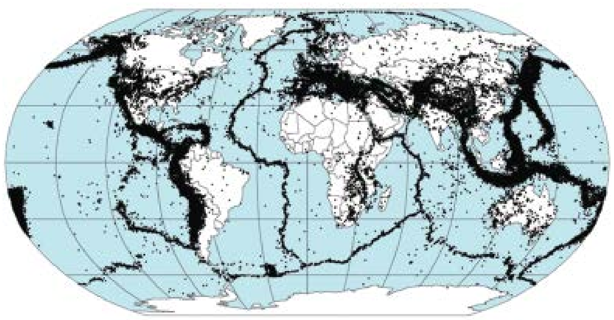
1. INTRODUCTION

1.1. MOTIVATION FOR THIS STUDY

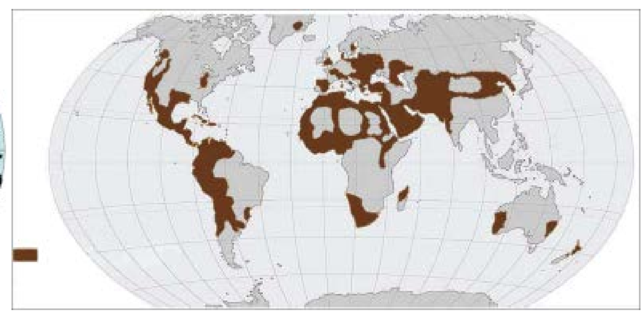
> "The replacement of existing dwellings with 'earthquake-resistant houses' is neither feasible nor, perhaps, desirable. It has been found more realistic to think, rather, in terms of low-cost upgrading of traditional structures, with the aim of limiting damage caused by normal earthquakes and giving their occupants a good chance of escape in the once-in-a-lifetime event of a large earthquake." (Coburn and Spence, 2002).

Nearly 75% of all earthquake fatalities in the last century have resulted from building failures with a growing disparity between vulnerability of those in developing and developed countries (GeoHazards International, 2001). The greatest risk is by far presented to inhabitants of non-engineered masonry structures (Figure 1) 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 2) 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.

Figure 1. Non-engineered adobe house in Peru showing vertical crack and separation of orthogonal walls owing to out-of plane forces



(a)



(b)

Figure 2. Geographical distribution of all recorded earthquake epicentres (left (Lowman and Montgomery, 1998)) and global distribution of adobe construction (right (De Sensi, 2003))

> "It remains something of a paradox that the failures of non-engineered buildings that kill most people in earthquakes attract the least attention from the engineering profession."
> (UN/ISDR, 2004).

Non-engineered adobe structures are classified by the European Macroseismic scale as being the most vulnerable category of housing (Grunthal, 1998). This is attributed to the nature of the material (high mass, low strength, brittle) and, in the case of low-cost housing, also the lack of proper design and maintenance. Almost 50% of the population in the developing world live in earthen dwellings (Houben and Guillaud, 1994) (Figure 2) yet technical research into this housing type is limited. Consider, for example, the limited volume of design guidance and supporting research in the adobe building codes of, say, Peru and New Zealand, compared with established masonry design codes such as Eurocode 6 (BSI, 2005). Research is often not realised because of the difficulty of communicating developments to communities that conduct selfbuild without professional input. This paper, therefore, highlights some of the key stages of developing a seismic retrofit for non-engineered dwellings, from early development to community implementation.

1.2. CURRENTLY AVAILABLE RETROFITTING TECHNIQUES FOR NON-ENGINEERED MASONRY

Structural collapse under seismic loading displays many possible failure mechanisms often related to the interaction between structural components (e.g. separation of walls or floor–wall connections). When considering individual walls, earthquake loading can have components both within the plane of the wall (in-plane, Figure 5) and orthogonal to the plane of the wall (out-of-plane, Figure 1).

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. Some examples of low-cost retrofitting techniques suitable for nonengineered, non-reinforced masonry dwellings are given in Table 1. There are several other examples in literature (Redman and Smith, 2009).

Table 1. Existing Retrofitting Techniques for Non-Reinforced Masonry in the Developing World

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 and Meguro, 2001).
Wire meshing	Pontificia Universidad Católica del Peru, Peru.	Similar to pp-meshing, but using a steel wire (Macabuag, 2010).
External vertical bamboo reinforcement	Sydney University, Australia.	External vertical bamboo reinforcement.

This paper focuses on the technique of polypropylene (PP) meshing and presents example numerical and physical tests that isolate the in-plane behaviour of masonry walls (sections 2.2 and 2.3).

1.3. THE APPLIED ELEMENT METHOD FOR NUMERICAL MODELING OF BLOCK MASONRY

Masonry is discontinuous, brittle and individual units (e.g. bricks) are free to separate, especially during dynamic loading. General finite element method (FEM) can simulate pre-failure behaviour in the linear-elastic range. Several FEM techniques and discrete element methods have been developed for non-linear modelling of effects such as crack propagation and structural collapse. However, these techniques are computationally intensive, limiting the size of models and duration of simulation. In the applied element method (AEM), the structure is discretised into elements, as in the FEM. However, the AEM elements are rigid, carry only the system's mass and damping and are connected at coincident faces with normal and shear springs representing the material properties (Figure 3). AEM can easily follow crack formation and propagation by allowing the separation of adjacent elements and is less computationally expensive than FEM for modelling similar effects (Meguro and Tagel-Din, 1997). AEM was originally developed by Meguro Lab, Tokyo University and is briefly introduced in this paper as a possible method for efficiently modelling masonry retrofitting techniques.

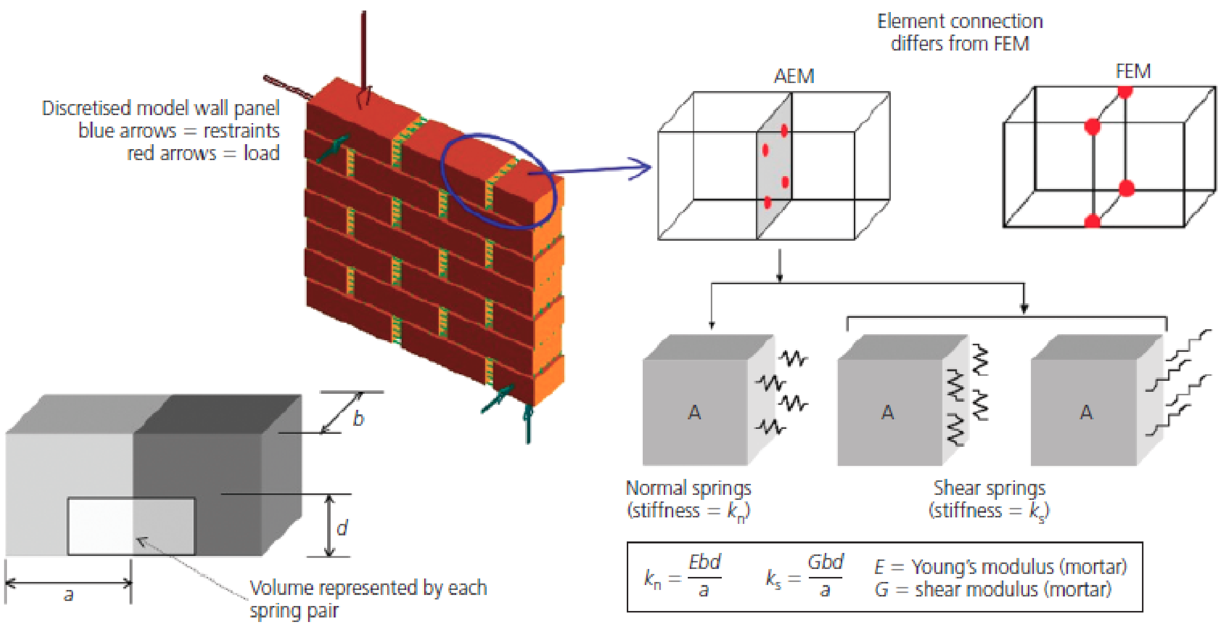


Figure 3. Applied element method (AEM) – element connectivity

1.4. OBJECTIVES

This paper aims to give an overview of the development and implementation of a retrofitting technique for non-engineered adobe:

PP meshing. The intended value of this overview is to highlight a major area of seismic risk and demonstrate the wider technical and socio-economical considerations of developing and delivering appropriate retrofitting techniques. The work presented is a mixture of literature review (where references are given) and work conducted by the authors.

Therefore, this paper will:

(a) present key stages in the development of PP meshing, giving examples of static, dynamic and numerical experimentation (section 2); detailed analysis will be omitted for brevity (the reader is directed to the references given), the objective being instead to provide an overview of the development process

(b) present a pilot project for the implementation of PP retrofitting in a seismically active region of Nepal (section 3); this is to highlight social and financial barriers to the dissemination of retrofitting techniques to low-income communities in developing countries.

2. A PROPOSED RETROFITTING TECHNIQUE: POLYPROPYLENE MESHING

2.1. PROCEDURE AND PREVIOUS USES

PP meshing uses common PP packaging straps (PP bands) to form a mesh, which is then used to encase masonry walls (i.e. fixing to both faces of each wall). The mesh prevents the separation of structural elements and the escape of debris, maintaining sufficient structural integrity to prevent collapse.

The mesh is formed by arranging the individual bands into a grid and electrically ‘welding’ at intersecting points (using a plastic welder such as that shown later in Figure 15(c)). Each wall to be retrofitted is stripped of existing render or covering, holes are drilled through the wall at regular spacing, anchor beams are installed at ground level (Figure 15(a), see later) and a ring beam at top of wall level if lacking. The mesh is connected to both faces of the wall, fixing to the anchor beams and ring beam and passing through openings and around corners with sufficient overlap. Meshes are connected together through the wall by wires passing through the previously drilled holes. Finally the mesh is rendered over protecting the mesh from sunlight, improving fixity to the wall and making the retrofit invisible (Figure 4).

(a) (b)

Figure 4. Retrofitted house in Pakistan before and after application of covering mortar layer. Note that the mesh is also applied to the inner face of the walls, with inner and outer meshes connected with through-wall ties. Photograph: Meguro Lab, Tokyo University

PP bands are used as packaging the world over (e.g. tying furniture flat-packs in the UK) and are, therefore, cheap and readily available, while the retrofitting technique is simple and suitable for local builders. PP meshing has had application in Nepal, Pakistan and Kathmandu. Figure 4 shows a retrofitted house in Pakistan following the 2005 earthquake.

PP meshing was first formally proposed in 2000, and published in 2001 (Mayorca and Meguro, 2001). This section gives brief examples of some of the static, dynamic and numerical experimentation that has been carried out as well as a financial study into the impact of potential programmes for subsidising the retrofit to low-income communities. Practical details of the retrofitting method are discussed in Section 3.3.

2.2. STATIC LOADING TESTS

Correctly modelling individual failure mechanisms both demonstrates the action of the PP mesh and provides behavioural parameters for the development of an accurate earthquake model. This section presents tests isolating in-plane behaviour. Other isolated failure mechanisms can be found in literature (Meguro et al., 2005).

Determination of masonry shear resistance to in-plane lateral load was achieved by testing both retrofitted and non-retrofitted square prisms in compression along one diagonal (ASTM, 2002) (Figure 5). Full-size and small-scale modelling, at a linear scale of 1:4 was conducted. In addition to fully retrofitted masonry panels, meshes incorporating only vertical or horizontal bands were also tested to further isolate and understand the action of the mesh (Macabuag et al., 2008) (Figures 5(e) and 5(f)). PP bands were 12 mm wide and approximately 0.4 mm thick (exact measurement was not possible owing to a patterned surface). Rupture strength and failure strain of the bands used were measured in tension tests as 1.5 kN and 14% respectively. Note that the normal procedure for forming the mesh is to electrically 'weld' bands at intersecting nodes (Figure 15(c), see later) but in this case each band was individually applied to the wall to differentiate from previous tests (Meguro et al., 2005) and investigate the effect of reduced mesh action by not fixing orthogonal bands to each other.

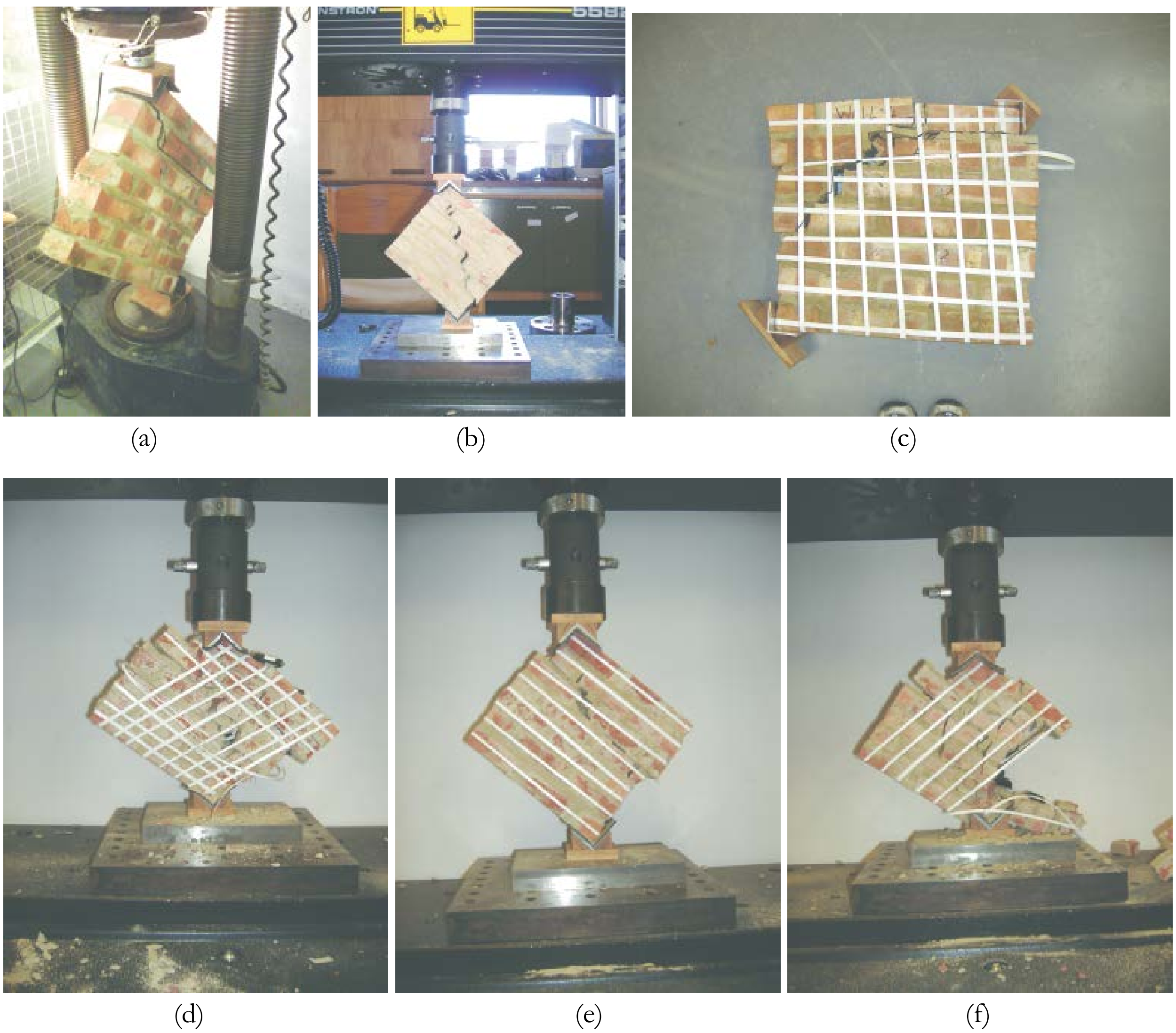


Figure 5. Full and small-scale model failures. (a) Full-scale specimen at brittle failure. (b) Small-scale specimen at brittle failure. (c) Full-scale specimen after testing. Note displacement and rotation of the corner section but maintained wall integrity. (d) Specimen continued to maintain load after 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

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).

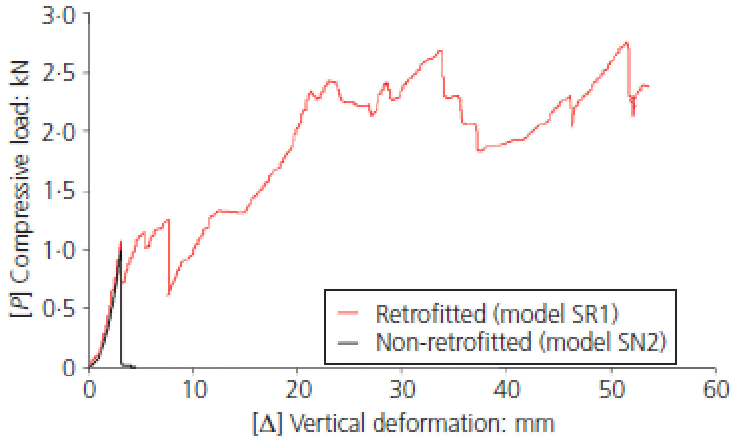


Figure 6. Load plotted against displacement for retrofitted and non-retrofitted small-scale models

2.2.1. CONCLUSIONS FROM STATIC LOADING TESTS

(a) Initial failure stress is unaffected by the presence of the mesh (Figure 6), as the stiffness of the masonry is far greater than that of the mesh and so the mesh is not engaged until the masonry deforms.

(b) Retrofitted specimens continued to maintain load after initial failure of the masonry.

(i) Retrofitting parallel to masonry rows directly resists the separation of bricks within the same row (Figure 5(e)).

(ii) Retrofitting perpendicular to masonry rows applies a force normal to the sliding brick courses, increasing their frictional resistance to further displacement (Figure 5(f)).

(c) The complete mesh effectively prevents loss of material and maintains wall integrity for large deformations, allowing redistribution of the load throughout the mesh and masonry. Note that the effectiveness of the mesh is less than that used in practice as this mesh was formed of individual bands not connected to one another, rather than the single coherent mesh recommended, yet a similar effect was achieved.

2.3. NUMERICAL MODELLING USING THE APPLIED ELEMENT METHOD

This section shows some simple in-plane shear models aimed at showing that the AEM can produce realistic behaviour for minimal computational requirements.

Figure 7 shows simulated diagonal compression tests giving realistic failure mechanisms using simple single-element bricks with connection springs containing the mortar properties, although this particular model required further refinement as failure loads were lower than those observed in physical tests. Figure 8 shows a more detailed study conducted by Meguro Lab, Tokyo University. The simulated test involved 9 kN vertical pre-loading of a masonry wall followed by displacement-controlled shearing (horizontal force applied to the top of the wall, within the plane of the wall). Behavioural patterns of flexural cracking and shear cracking were recreated, an accurate peak strength (just before shear cracking) was achieved and comparable post-peak behaviour was shown.

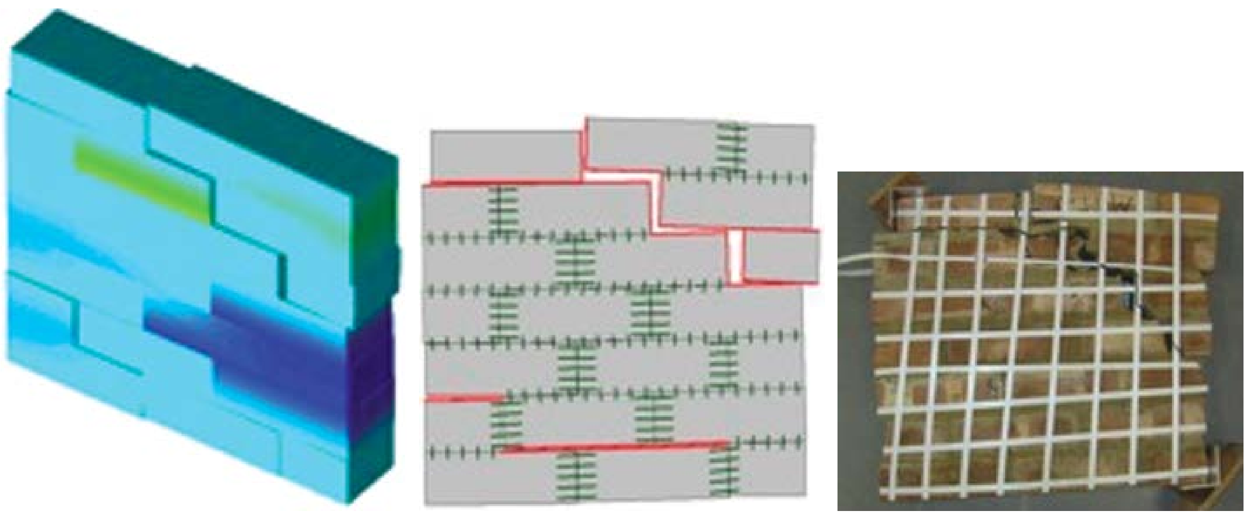


Figure 7. Simulated diagonal compression tests using the applied element method (AEM)

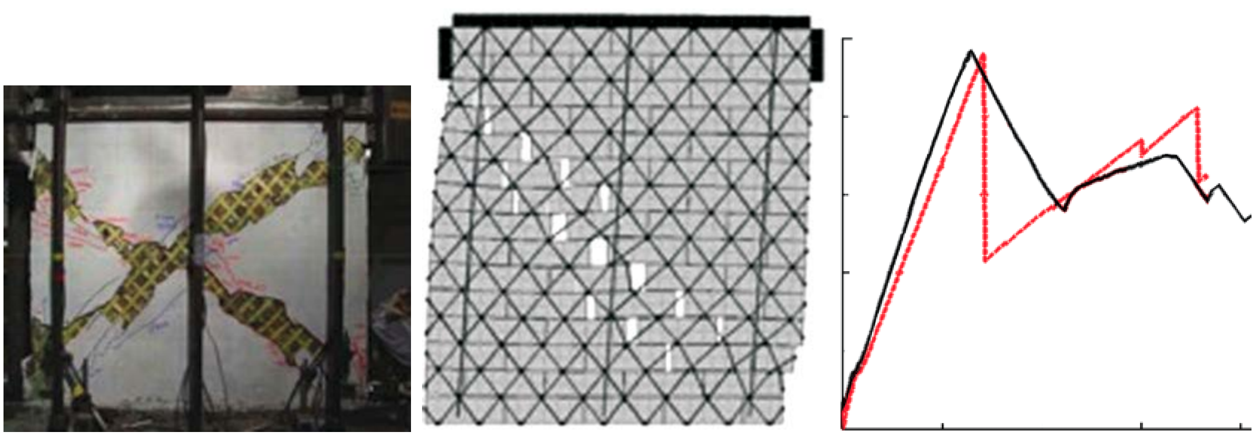


Figure 8. Comparison of real (black line) and simulated (grey line) shear test of a retrofitted wall using AEM (Mayorca and Meguro, 2001)

More complex models can be found in literature where AEM has been used for dynamic full-structure simulation through large deformation to progressive and ultimate collapse.

2.3.1. CONCLUSIONS OF NUMERICAL TESTS

(a) AEM models of PP retrofitting produced realistic behaviour for minimal computational requirements.

(b) In comparison to many other numerical methods, AEM's ability to easily model element separation and interaction makes it suitable for the modelling of blocky masonry behaviour under static and dynamic loading, through cracking and large deformation to ultimate collapse.

2.4. DYNAMIC TESTING, TOKYO UNIVERSITY

After developing a retrofit through static and numerical tests, it is necessary to consider the fully dynamic behaviour. The example below discusses full-scale shake-table testing conducted on retrofitted and non-retrofitted models by Meguro Lab, Tokyo University (Nesheli et al., 2006). Retrofitted models used fully coherent meshes, applied as described in section 2.1. Sinusoidal input motions, ranging from 2 Hz to 35 Hz with amplitudes from 0.05g to 1.4g, were applied to obtain the dynamic response of the structures (Figure 9). Figure 10 shows their responses.

(a) (b) (c)

Figure 9. Full-scale shake table testing of non-retrofitted (a) and retrofitted (b, c) models (Nesheli et al., 2006): (a) Collapse of nonretrofitted model after 47th run (intensity gradually increasing per run) at an earthquake intensity of JMA 5+. (b) Retrofitted model at JMA 5+ (the intensity at which the non-retrofitted model collapsed). Cracking has occurred but integrity is maintained. (c) Retrofitted model after 53rd run reaching JMA 6+

Index	JMA –4	JMA 5–	JMA 5+	JMA 6–	JMA 6+	JMA 7

D0: No damage	D3: Heavy structural damage - Large and deep cracks in masonry walls. Some bricks are fall down. Failure in connection between two walls.
D1: Light structural damage - Hair line cracks in very few walls. The structure resistance capacity has not been reduce noticeably.	D4: Partially collapse - Serious failure of walls. Partial structural failure of roofs. The building is in dangerous condition.
D2: Small cracks in masonry walls, falling of plaster block. The structure resistance capacity is partially reduced.	D5: Total or near collapse

Table 2a: Performance of Non-Retrofitted Model								
Acceleration (g)	Frequency (Hz)							
	2	5	10	15	20	25	30	35
1·4								
1·2								
1·0								
0·8		D5	D3	D3	D2	D2	D1	D1
0·6		D5	D3	D2	D2	D2	D1	D1
0·4		D4	D3	D2	D2	D1	D1	D1
0·2	D5	D0	D0	D0	D0	D0	D0	D0
0·1	D0	D0	D0	D0	D0	D0	D0	D0
0·05	D0	D0	D0	D0	D0	D0	D0	D0

Table 2b: Performance of Retrofitted Model								
Acceleration (g)	Frequency (Hz)							
	2	5	10	15	20	25	30	35
1·4		D3						
1·2	D4	D3						
1·0		D2						
0·8	D4	D2	D2	D2	D1	D1	D0	D0
0·6	D3	D2	D2	D1	D1	D0	D0	D0
0·4	D3	D2	D2	D1	D1	D0	D0	D0
0·2	D2	D0	D0	D0	D0	D0	D0	D0
0·1	D0	D0	D0	D0	D0	D0	D0	D0
0·05	D0	D0	D0	D0	D0	D0	D0	D0

Figure 10. Performance and damage levels of full-scale models under dynamic loading: (a) performance on non-retrofitted model; (b) performance of retrofitted model (Meguro, 2008)

Shake table motion is given in terms of the Japan Meteorological Agency (JMA) seismic intensity scale, calculated from the shaketable peak acceleration for any given run. The JMA scale runs from 0 to 7, with 7 being the strongest: for example, JMA 5+ corresponds to a peak ground acceleration of around 2.5 m/s2, leading to the toppling of heavy furniture and severe difficulty for people to move.

2.4.1. CONCLUSIONS FROM DYNAMIC TESTING

(a) The result showed that the pp-band retrofit enhanced the seismic resistance of the masonry model significantly. Heavy structural damage capacity (D3) was enhanced from JMA,4 (for the non-retrofitted model) to JMA 6+ intensity (noting that this was also after several runs at lower intensities), and total collapse was prevented until JMA 7.

(b) By allowing cracking without the loss of wall integrity, the PP mesh enhances structural ductility and energy dissipation capacity whilst holding disintegrated structural elements together, thus preventing collapse.

(c) PP retrofitting was shown to enhance the safety of existing single-storey masonry buildings even in worst-case earthquake scenarios such as intensity JMA 7.

2.5. RETROFIT SUBSIDISATION PROGRAMMES FOR LOW-INCOME COMMUNITIES

PP band retrofitting is specifically aimed at the lowest-income communities, costing about $30–$70/house for materials (Meguro, 2008). However, such lowest-income communities may struggle to meet basic needs and so retrofitting for earthquake safety still cannot be afforded without additional subsidy. Considering this economical issue is, therefore, crucial to be able to disseminate the technology to the low-income communities that most need it.

Meguro Lab, Tokyo University has proposed several systems for subsidising seismic retrofits including the 'two-step incentive system' (Meguro, 2008) and 'new earthquake micro-insurance system'. In the proposed two-step incentive system, house owners are encouraged to retrofit their homes by receiving the necessary materials and a subsidy upon satisfactorily carrying out the work. If the retrofitted houses are damaged in an earthquake, the owners then receive twice the compensation than the house owners who did not retrofit (Figure 11). Table 2 shows predictions for the number of lives saved for several earthquakes, using data from dynamic experiments (such as that presented in section 2.4) to calculate the percentage of building collapses that could have been prevented.

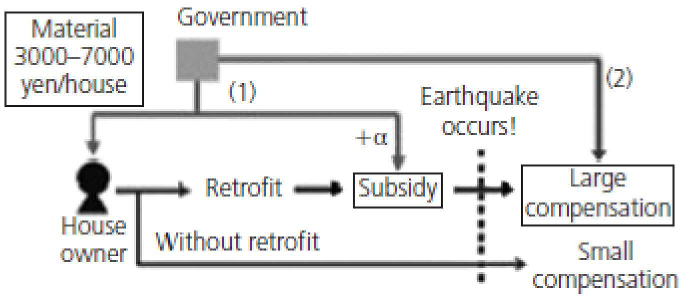


Figure 11. Subsidisation programme – 'two-step incentive system' (Meguro, 2008). Note 1 GBP = 200 yen (approximately)

Table 2. Reduction in Casualties Had the 'Two-Step Incentive System' Been Adopted (Meguro, 2008)

	Bam earthquake (2003)		Kashmir earthquake (2005)		Java earthquake (2006)	
	Without retrofitting	**Estimated with retrofitting**	**Without retrofitting**	**Estimated with retrofitting**	**Without retrofitting**	**Estimated with retrofitting**
Totally collapsed houses	49,000	8200 (83% reduction)	203,579	5847 (97% reduction)	154,098	13,080 (92% reduction)
Partially collapsed houses			196,573	67,561 (66% reduction)	199,160	78,550 (61% reduction)
Fatalities due to total collapses	43,200	7275 (83% reduction)	58,668	1685 (97% reduction)	4559	387 (92% reduction)
Fatalities owing to partial collapses			16,367	5625 (66% reduction)	1140	450 (61% reduction)

Considering the percentage of buildings potentially saved (Table 2) the reduction in expenditure of both the government and homeowners if this two-step incentive system had been in place was also estimated (Figure 12).

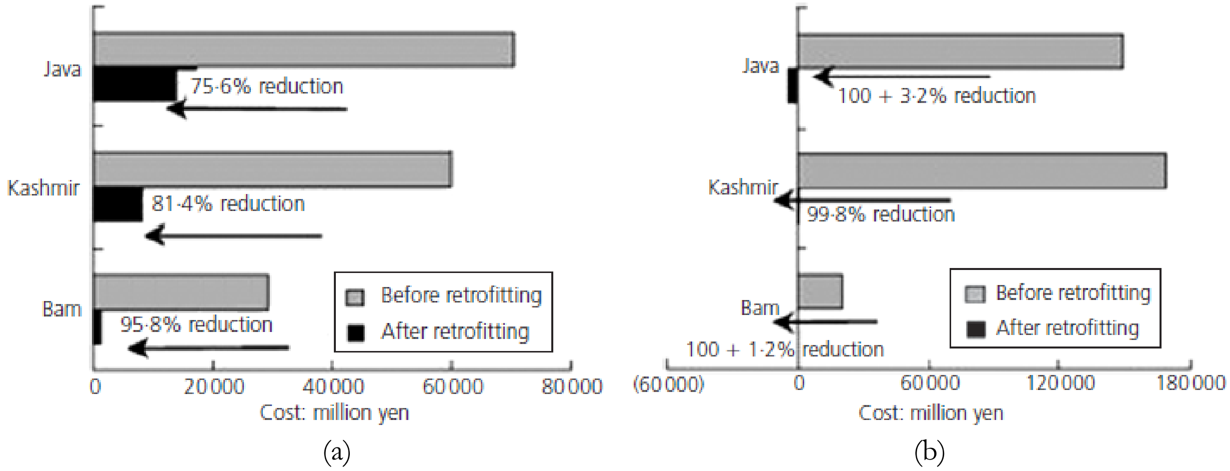


Figure 12. Reduction in expenditure had the 'two-step incentive system' been adopted (Meguro, 2008). Note 1 pound ¼ 200 yen (approximately)

3. IMPLEMENTATION OF THE PROPOSED RETROFITTING TECHNIQUE

To investigate the practical issues of implementation a pilot scheme was conducted in a seismically active region of the Kathmandu Valley, Nepal.

The Himalayan region is an example of one area of constant seismic activity, high population density, and wide-spread use of non-reinforced masonry built outside of current building standards. Given the high potential for future loss of life several PP band implementation programmes have been run in this region.

Given that the dwellings most at risk are built outside of building regulations it is clear that a sustainable solution can only be achieved by raising local awareness of available methods and allowing the building owners and tradesman to themselves become the disseminators of the proposed solution.

In 2006 a public, low-tech shake-table demonstration was held in Kashmir (following the 2005 earthquake) followed by the retrofit of a full-scale building by local masons under supervision (Figure 4). Material costs for the retrofit were around US$30 and the total installation cost was less than 5% of the total construction cost.

This section describes an implementation programme conducted in November 2008, funded by the Mondialogo Engineering Award. The programme was conducted as a partnership between Oxford University; the Institute of Industrial Science, Tokyo University; the Indian Institute of Technology, Bombay; Nepal Engineering College; Khwopa Engineering College, Nepal and the National Society of Earthquake

Technology (NSET). The implementation project involved a six-day training course for local, rural masons, focusing on both earthquake construction and the pp-retrofitting technique. At the end of the course was a public low-tech shake-table demonstration of the PP band technology, inviting the community, press and key individuals and institutions.

3.1. TRAINING PROGRAMMES FOR RURAL MASONS

The training course was coordinated by Khwopa Engineering College and engaged rural masons in several aspects of earthquake construction: appropriate site selection, building layout and construction techniques (in masonry, timber and reinforced concrete (RC)), strengthening and repairing of existing structures and retrofitting using the PP mesh.

Many of the masons were very experienced in their trades but had never received training, or a formal education (a high level of illiteracy is another reason why a training course is required over simply producing training manuals). The aim was, therefore, to introduce small changes to current practice that can be implemented through simple rules of thumb but which significantly improve building earthquake safety. Some example features are shown in Figure 13.

Figure 13(a) shows a load bearing masonry wall with buttressing and vertical reinforcement and with the masons preparing to add horizontal reinforcement at corners and orthogonal walls. Figure 13(b) shows often-omitted details for local RC frames such as a double-cage for the column with a link within the beam/column joint and the beam rebar being completely contained within the column rebar and continuous through the joint.

Figure 13(c) shows a simplified introduction to applying the PP mesh to a masonry wall. Note that the PP mesh would not usually be applied in conjunction with internal reinforcement but was applied to the reinforced masonry model (Figure 13(a)) purely as a simple tool for demonstrating the basics of applying the mesh. During the course it was stressed that PP retrofitting is intended for use with adobe where holes can be drilled through bricks as well as mortar, allowing more accurate spacing of through-wall connectors, giving a tighter mesh. The real retrofit is also continued and overlapped around corners and through openings and connected to the foundations and ring-beam (Figure 15, see below).

(b)

(a) (c)

Figure 13. Six-day training programme for rural masons, Bhaktapur, Nepal 2008

3.2. PUBLIC LOW-TECH SHAKE TABLE DEMONSTRATION

The public demonstration was coordinated by NSET, involved two 1:6 scale masonry models (one with the PP mesh and one without) and utilised a simple spring-loaded shake-table (Figure 14). The demonstration was designed to allow the masons to apply what they had learnt, for the public to graphically witness the necessity to safeguard their homes and to encourage municipalities and other potential funders to adopt a retrofitting programme. The event received radio and television coverage in Nepal. Note that the simple table used is not intended to simulate accurate earthquake motion, but simply to demonstrate the effect that general ground motion can have on structures.

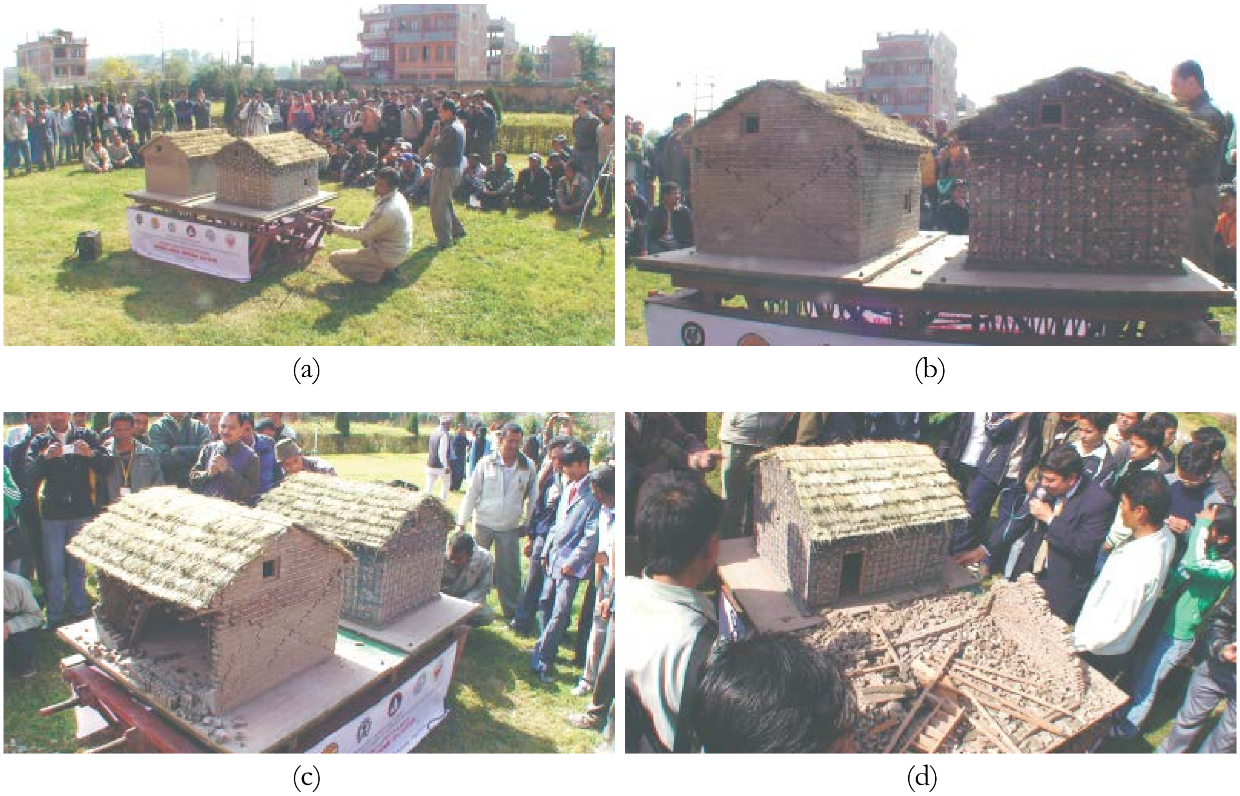


Figure 14. Public demonstration, Bhaktapur, Nepal 2008

3.2.1. OUTCOMES OF TRAINING COURSE AND DEMONSTRATION

Following the training course, feedback from the masons was that they were motivated on the need for earthquake safety, very positive to be armed with simple rules-of-thumb that can be implemented easily but have an impact and keen to learn more about the PP retrofit.

The main feedback from the community after the demonstration was that community members were also motivated on the need for earthquake safety, keen to retrofit their homes but concerned over the cost of retrofitting. Municipalities and officials were keen to retrofit homes but concerned over costs.

This shows that once awareness has been raised, people are keen to safeguard their homes but subsidisation will be necessary if retrofitting is to be an option for low-income communities. It can also be seen that studies, such as that given in section 2.5, are necessary to quantitatively show municipalities and other funders the benefits of pre-emptively retrofitting rather than rebuilding post-disaster.

3.3. REAL RETROFIT OF ADOBE HOME IN NEPAL

The final stage of the pilot implementation programme involved retrofitting an adobe residential building in Nangkhel Village of Bhaktapur District, Nepal. The masons involved had taken part in the training course from section 3.1. The objectives of the real scale implementation work were:

(a) to retrofit a pilot building using the PP band retrofitting technique

(b) to observe practically the technical, economical and cultural appropriateness of the retrofitting technique under the local site conditions

(c) to give hands-on training to the local masons on the retrofitting technique and receive feedback and practical suggestions to improve the retrofitting process.

The retrofitting procedure differed from that used previously (section 2.1) in that rather than preparing the mesh off-site and fixing to the wall, the mesh was formed directly onto the wall (Figures 15(b) and (c)). This change was proposed by the masons themselves to improve buildability and it was suggested that in this way, it might no longer be necessary to connect the bands using the plastic welder for future projects (previously the most expensive part of the retrofit technique). This suggestion requires further investigation (e.g. following on from work in section 2.2).

The general process of the retrofit can be seen in Figure 15. An anchor beam was first fixed to the base of the wall inside and out; vertical PP bands were fixed between the internal and external base anchor beams; horizontal bands were then woven between and welded to the vertical bands; meshes on opposite faces of each wall were connected to each other through the wall by steel wires passing through drilled holes; finally a render was applied to cover the mesh. Note that this house also required additional refurbishment work in replacing rotten floor and roof beams and infilling unnecessary openings.

(a) (b)

(c) (d)

Figure 15. Retrofit of a real adobe dwelling, Nangkhel, Nepal 2009. Photographs: NSET

The work was carried out by one NSET technician, two masons and two unskilled labourers over 4 weeks. The material costs associated with the PP retrofit came to $250. Details on full-scale retrofitting and the process described here are given in the final report of the implementation work (NSET, 2009).

The outcomes of the live retrofit were as follows:

(a) the retrofit was successfully implemented and showed that it is technically feasible to retrofit residential adobe houses using the PP band retrofitting technique

(b) by training through hands-on implementation the masons are now able to do this type of retrofitting independently

(c) the modification to the retrofitting process proposed by the masons of forming the mesh directly onto the wall proved an effective time saver; this highlights the potential benefits of developing the technique alongside those who will implement it.

4. SUMMARY AND RECOMMENDATIONS

This paper has introduced the technique of polypropylene meshing for preventing or prolonging the collapse of adobe buildings under strong earthquakes. Both development and implementation of this technique was considered. The main findings during the development of PP meshing are as follows:

(a) the complete PP mesh prevents loss of material and maintains wall integrity for large deformations, allowing redistribution of the load throughout the mesh and masonry

(b) PP retrofitting was shown to enhance the safety of existing single-storey masonry buildings even in worst-case earthquake scenarios such as intensity JMA 7

(c) PP band technology is cheap, readily available and easy to install, so is suitable as a retrofit for low-income communities

(d) In comparison to many other numerical methods, the ability of the AEM to easily model element separation and interaction makes it suitable for modelling the behaviour of blocky masonry plus retrofit through cracking and large deformation to ultimate collapse. AEM is, therefore, a suitable tool when developing retrofitting methods for the large number of masonry types available.

The main objective of the implementation work was to help disseminate safer seismic construction and retrofitting techniques to rural communities with a high proportion of non-engineered dwellings.

(a) The pilot implementation programme in Kathmandu, Nepal (training course for rural masons and public shake-table demonstration) showed that

> (i) directly engaging masons is an effective way of transferring knowledge of earthquake-safe construction directly to those responsible for the construction
>
> (ii) communities and officials are keen to retrofit homes but despite the low-cost, were still concerned over expense for low-income communities where supply of basic needs was more urgent.

(b) Subsidisation schemes are required to make retrofitting an attractive option for low-income households. The increased number of retrofits would in-turn lead to a substantial reduction in loss of life and cost following the next strong earthquake, for both governments and homeowners.

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SEISMIC REINFORCEMENT OF ADOBE IN RURAL PERU

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SYNOPSIS

Several seismic regions throughout the world demonstrate a high proportion of earthquake-vulnerable adobe (mud-brick) construction amongst poorer communities. Several adobe earthquake-retrofitting techniques have been developed, but dissemination of these techniques to the many communities at risk is a very significant challenge. This study looked at some of the technical, financial and social aspects of development and implementation of retrofitting techniques in Peru.

INTRODUCTION

The vast majority of earthquake fatalities in the last century have resulted from building failures with a growing disparity between vulnerability of those in developing and developed countries. The greatest risk is by far presented to inhabitants of non-engineered adobe (Fig 1) as demonstrated in the 2003 Bam (Iran) earthquake, where many of the thousands of deaths were attributable to vulnerable adobe (sun-dried mud brick) structures.

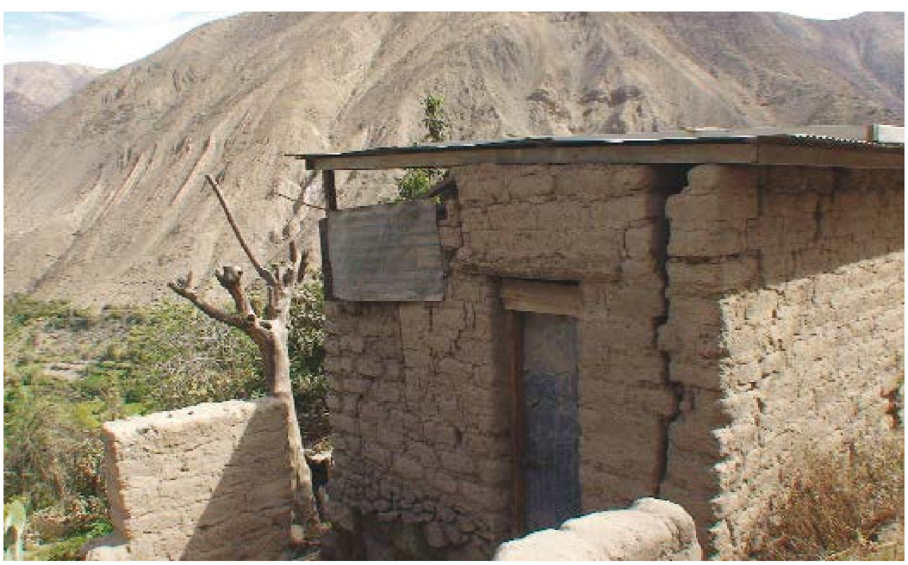

Fig 1. Non-engineered adobe in Condesuyos, Peru. Vertical crack typical of poorly bonded orthogonal walls. Walls are adobe blocks laid in mud mortar. Roof consists of timber planks covered with corrugated sheeting

Non-engineered adobe structures are classified by the European Macroseismic scale as being the most vulnerable category of housing. This is due, in part to adobe's high mass, brittleness and low strength (wall compressive strengths can be in the region of 0.8-1.2N/mm2 and shear strength 0.03-0.05N/mm2 as compared with 5-15N/mm2 and 0.5-0.7N/mm2 respectively for burnt clay bricks in cement mortar in the UK). In the case of non-engineered housing, vulnerability is also due to lack of proper design and maintenance. Fig 2 shows common failure modes for non-engineered masonry houses.

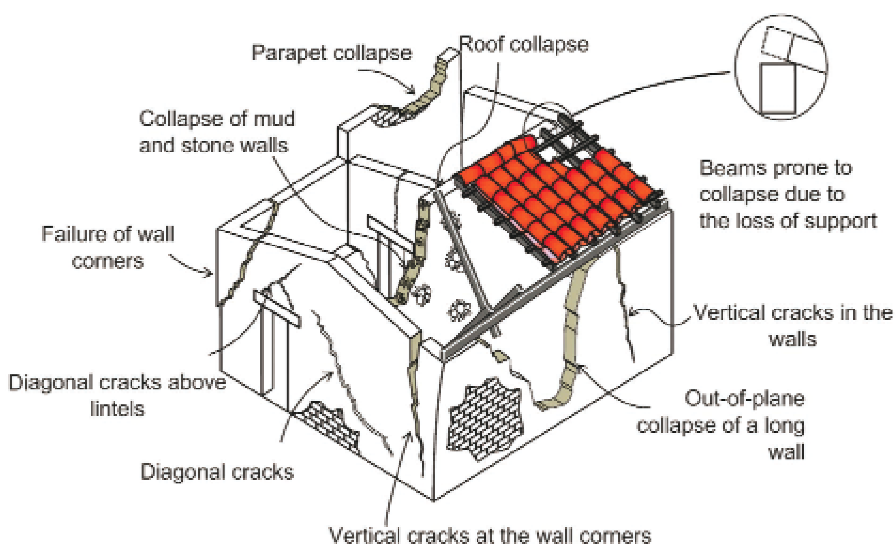

Fig 2. Examples of typical failure modes for nonengineered masonry dwellings (Blondet)

OBJECTIVES

Research question: What are the key technical, social and economical considerations for the development of adobe seismic reinforcing techniques and their dissemination to remote rural communities?

A field investigation, funded by the Pai Lin Li Travel Award, was carried out in Peru during late 2009. A particular retrofitting technique was investigated, sites of previous dissemination programmes were visited and interviews were conducted with members of the affected communities and representatives of the organisations originally involved. This was carried out with the following objectives:

– Identify key features of an example adobe reinforcing technique and important stages of its development.

– Highlight the main successes and failures of previous programs for the dissemination of this and other adobe strengthening techniques in rural Peru.

– Outline key considerations for projects to disseminate seismic adobe construction and retrofitting techniques to rural communities.

HOUSING IN PERU

In Peru, 35% of the population still resides in earthen dwellings despite poor performances of these structures in major earthquakes in 2001 (south Peru, Mw = 8.4) and 2007 (central Peru, Mw = 8).

As a rural example, consider the Provinces of Castilla and Condesuyos, areas of the Peruvian High Andes that were heavily affected by the 2001 Peru earthquake. 72% of homes are adobe with 40% being less than 40m2 on plan and of only 1 or 2 rooms. Walls are 300-800mm thick, supporting a light-weight, flexible timber roof. Strip footings of stone rubble in cement or mud-mortar are generally used. Half of the houses are constructed solely by members of the family, with structural defects and poor site selection common [Perez-Palma]. Most families survive on agriculture with 50% of households earning less than $115 per month (pm) including 20% on less than $60pm per household. Adobe is the favoured technique as it is cheap and doesn't require additional energy resources, often using soil from the home owner's yard.

More modern construction methods are beyond the means of a large proportion of the population in remote rural areas. However, adobe is often associated with poverty meaning that those with limited means are opting for non-engineered masonry or confined masonry leading to poor quality construction (Fig 3a) or vulnerable hybrid structures, combining materials inappropriately (Fig 3b).

(a) (b)

Fig 3. Non-engineered structures using modern construction methods resulting from the negative perception of adobe but limited means of the homeowner: a) Non-engineered confined masonry dwellings in Chincha that performed badly in the 2007 Peru earthquake b) Non-engineered hybrid structure in Lunahuaná displaying slender adobe walls with long clear spans supporting a heavy concrete ring beam with no vertical tie members

ADOBE RETROFIT – STEEL WIRE MESH REINFORCEMENT

Steel wire mesh reinforcement utilises a mesh often used for fencing in parts of South America, which comprises 1mm diameter wire at 19mm (3/4in.) spacing. The system was designed as a retrofit for existing adobe homes (Fig 4) as the mesh is readily available in even remote parts of Peru. The technique was developed by the Structures Laboratory of the Pontifical Catholic University of Peru (PUCP) [Quiun] and utilises a number of strips of wire mesh (approximately 500mm wide), nailed to both sides of the internal and external adobe walls. Vertical strips are nailed to the wall at the intersection of orthogonal walls, at the centre of long walls and at free ends. A horizontal strip runs across the top of the walls, connecting all of the vertical strips. The mesh is then rendered over to fully connect the mesh to the wall and to protect the mesh from corrosion.

(a) (b) (c)

Fig 4. Existing adobe houses retrofitted with steel mesh reinforcement: a) Partially reinforced wall in La Tinguiña. Performed well in the 2001 earthquake b) Two-storey reinforced house in Andahuaylillas, Cuzco c) Reinforced house in Moquegua without damage after 2001 earthquake and neighbouring unreinforced house with severe damage (Quiun)

SHAKE TABLE TESTING

Fig 5 shows shake-table tests conducted in the structural lab of PUCP. Three 10m2 adobe modules were tested: one without reinforcement, one with mesh reinforcement, and another reinforced with the mesh and a concrete ring beam. The models were subjected to unidirectional earthquake motion based on the L-Wave (surface 'side-to-side' wave) component of the 1970 Peru earthquake as recorded in Lima, with a 30s duration. Given that multi-directional movement could not be simulated on the available table and all frequencies of the L-Wave could not be reproduced, the results are to be considered qualitative rather than quantitative. Each model was tested in six phases increasing the motion amplitude to correspond with earthquakes of increasing intensity (Table 1).

(a) (b) (c)

Fig 5. Shake-table test: Modules at failure (Zegarra): a) Unreinforced module at phase 5 (MMI IX) b) Mesh-reinforced module at phase 6 (MMI X) c) Mesh & collar beam-reinforced module at phase 6 (MMI X)

Table 1. Shake-Table Test: Definition of Test Phases (Zegarra)

Test phase	Max table acceleration	Max table displacement	Approximate corresponding earthquake intensity (Modified Mercalli Intensity scale (MMI)).
1	0.15g	15mm	MMI III: Felt by people indoors. Vibration similar to passing truck.
2	0.35g	30mm	MMI VI: Felt by all. Books fall off shelves. Furniture may move or overturn.
3	0.65g	60mm	MMI VII. Difficult to stand. Noticed by people driving motorcars. Some chimneys broken.
4	0.80g	80mm	MMI VIII: Fall of factory stacks, columns, monuments, walls. Heavy furniture moved.
5	1.00g	100mm	MMI IX: General panic. Damage considerable in specially designed structures. Buildings shifted off foundations.
6	1.20g	120mm	MMI X: Disastrous. Most masonry and frame structures destroyed with foundations. Rails bent.

The non-reinforced modules showed sudden and brittle failure from MM VII (0.65g) to complete collapse at MM IX (1.0g) whereas the reinforced modules showed progressive damage from an earthquake intensity of MM VIII (0.8g) to near collapse at MM X (1.2g) (Table 2).

Table 2. Shake-Table Test: Level of Damage at Each Test Phase (Zegarra)

Test phase	Unreinforced Module	Mesh-reinforced Module	Mesh & collar beam-reinforced module
1	D0	D0	D0
2	D0	D0	D0
3	D3	D0	D1
4	D4	D1	D1
5	D5	D3	D2
6		D4	D4
D0: No structural damage		D1: Light structural damage – Hairline cracks in very few walls	
D2: Moderate structural damage – Small cracks in masonry walls, falling of plaster. Structural capacity is partially reduced		D3: Heavy structural damage – Large cracks in masonry walls. Failure in connection between two walls	
D4: Partial collapse – Serious failure of walls. Partial failure of roof		D5: Collapse	

The tests show qualitatively that as well as adding strength, the mesh also adds ductility to an otherwise stiff and brittle structure. By allowing cracking whilst maintaining structural integrity energy dissipation systems are introduced allowing the structure to resist strong, high frequency excitations. e.g. for the mesh reinforced structure, the peak stresses experienced at the junction of the horizontal and vertical mesh strips resisting in-plane forces caused the mesh to yield (see the vertical crack in Fig 5b) without breaking allowing energy absorption through successive cycles, while maintaining structural integrity.

While the tests suggest some improvements that could be made (e.g. connection to the foundations to prevent rocking and sliding failures at the base), they show qualitatively that the simple retrofit system proposed fulfils the basic goal of preventing brittle collapse, reducing the loss of debris and, in large earthquakes, delaying collapse to allow occupants the opportunity to escape.

PILOT IMPLEMENTATION PROJECTS (1990S)

20 existing houses in six towns across Peru were retrofitted with the steel mesh as pilot projects, with five of these being two-storey accommodations. Six retrofitted houses were affected by a major earthquake in 2001 (South Peru, Mw = 8.4) and five retrofitted houses by an earthquake in 2007 (central Peru, Mw = 8). These houses demonstrated no visible damage, while neighbouring houses of traditional adobe without reinforcement showed heavy damage or complete collapse (Fig 4c).

COMMUNITY DISSEMINATION PROGRAMMES IN PERU

POST-EARTHQUAKE RECONSTRUCTION PROGRAMME, AREQUIPA (2001-2002)

The success of wire mesh reinforced houses during the 2001 Peru earthquake motivated several reconstruction programs for new adobe houses in remote Andean towns within the Region of Arequipa incorporating this wire mesh system.

PHASE 1 POST-EARTHQUAKE RECONSTRUCTION

360 reinforced adobe houses (Fig 6) were built in the Arequipa region as a collaboration between several organisations. The project was funded by the German Technical Cooperation Agency (GTZ), the design of the adobe houses was carried out by the Pontifical Catholic University of Peru (PUCP) and the Peruvian National Service for Capacity Building and Research in Construction (SENCICO), and implementation was carried out in collaboration with the Special Project of the Regional Government of Arequipa (COPASA). The project aimed to reduce the future vulnerability of the participating communities by engaging them in the construction process, so increasing their capacity to build and

reinforce earthquake-resistant houses in adobe, the primary construction material in the region.

Fig 6. House design for reconstruction programme. Incorporates steel wire mesh at intersection of orthogonal walls, RC ring-beam and raft foundation (San Bartolome)

Members of PUCP conducted a 5-day training course in construction of the reinforced adobe houses for 20 SENCICO technicians plus 42 selected rural persons (maestros) from highrisk communities. The members of the community then built their own houses under the supervision of the trained maestros. Each maestro was assigned two assistants and supervised the construction of up to three houses at any one time. COPASA-GTZ technicians supervised the rural construction 3 days per week and each zone had one permanent SENCICO technical supervisor. The programme was in collaboration with the local government.

360 houses of 36m 2 plan area were constructed within 17 months with construction costs of approximately $1700 per house (approximately $50/m2) (Table 3). GTZ-COPASA provided 67% of the cost of the house with the beneficiaries providing 33% mainly through the supply of local unskilled labour and local materials.

Table 3. Comparing Construction Costs for Different Building Methods (Haider)

	Total cost	Cost/m^2	Relative cost
Traditional adobe	$850	$24	100%
Steel mesh reinforced adobe	$1774	$50	217%
Confined masonry	$3400	$95	408%

PHASE 2 PROTECTION FROM NATURAL DISASTERS WITH A FOCUS ON FOOD SECURITY

Phase 2 sought sustainability of the intervention by motivating the communities to strengthen their homes. Several public workshops showed videos of phase 1 and instructional material was distributed on anti-seismic adobe construction and the manufacture of adobe blocks. The public was then engaged in the construction of public buildings such as school classrooms and small health centres. 30 trained masons from phase 1 were employed to facilitate.

RECONSTRUCTION PROGRAMME FOLLOWING THE 2007 PISCO EARTHQUAKE (2008)

Other adobe reinforcing techniques have been used in Peru such as a program for reconstruction and mass dissemination of seismic construction techniques in adobe utilising a reinforcing technique that uses a polypropylene mesh (commonly used for fencing) to provide confinement of walls [Rubiños].

Key stages of the project are shown in Fig 7. The community capacitation programme incorporated literature and videos and taught 883 in theoretical workshops and 276 in practical exercises and live construction. The construction of each four-roomed, 50m2 house cost $3155 ($65/m2).

(a) (b) (c)

Fig 7. Various stages of the post-2007 reconstruction and capacitation programme: a) Example house reinforced with the plastic mesh, used during the initial training of masons, engineers and NGO personnel (Rubiños) b) Fabrication of adobe blocks in Cañete, carried out by hired masons (Rubiños) c) Completed house in Chincha Baja, constructed by the public under supervision (after theoretical workshops and practical exercises). Nine houses were completed throughout Cañete, Chincha and Pisco

DISCUSSION ON DISSEMINATION

IS ADOBE AN APPROPRIATE MATERIAL?

Given the dangers of non-engineered adobe, in areas with ready access to materials techniques such as confined masonry are more appropriate than adobe. This is illustrated by the Pisco reconstruction programme where many of the wealthier families were reconstructing their homes of masonry or confined masonry, as materials are readily available in nearby urban centres. However, many of these confined masonry houses showed dangerous defects (Fig 3) showing that training in confined masonry would have been more appropriate in this case.

However, newer construction techniques are inappropriate for remote impoverished communities, due to material transportation costs and lack of the necessary construction skills. These communities are currently dwelling in and building with vulnerable, non-engineered adobe and so adobe strengthening techniques must be disseminated in these locations.

THE COST OF RETROFITTING

Outside of NGO-led reconstruction programmes, communities have not used the adobe reinforcing techniques for subsequent adobe constructions or retrofits for reasons of cost and low importance attached to home security compared to other basic needs. However, consider the case of the Arequipa programme where the difference in price between reinforced and traditional adobe houses was nearly $1000 but the cost of the reinforcement was only $112 (Fig 8). The difference comes in additional features such as a ground slab, concrete ring beam and more expensive roof construction.

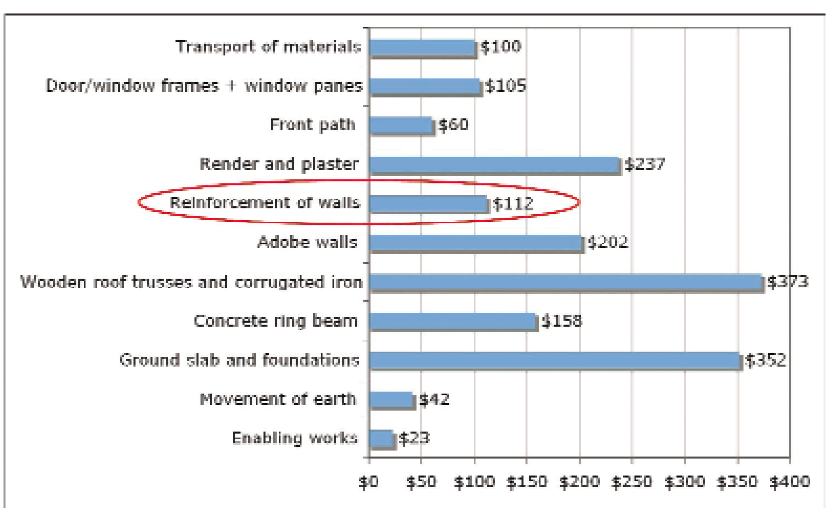

Fig 8. Breakdown of construction costs for 36m2 reinforced adobe house in the Arequipa Reconstruction Programme ($1774/house) (Haider)

Therefore, the basic mesh retrofit to an existing house could cost less than Table 3 would suggest, and fulfil the basic goal of preventing or prolonging collapse provided other structural repairs are not needed. However, this basic cost may still be beyond the means of many families. This suggests that government incentive programmes need to be established to financially assist and encourage communities to reinforce existing adobe structures, reducing future vulnerability.

THE NEED FOR LONG-TERM INTERVENTIONS

All of the houses built during the programmes described were performing well but several non-reinforced adobe structures built by communities after the programmes showed errors (Fig 9), showing that many lessons had been lost because of no further training input after the initial programmes.

(a)

(b)

Fig 9. 2001 reconstruction project in Arequipa: Errors in construction or subsequent modifications: a) Rear wall being used as retaining wall to a public road b) Holes cut into wall for electrical and mechanical services, undermining the wall connection and forming a hole in the reinforcing mesh [photo: Chuquimia]

NGOs and cooperation agencies led and bore the brunt of the costs in the programmes presented but operational costs are a significant proportion of overall expenditure for technical agencies, inhibiting long-term interventions. Local municipalities do have long-term presence in even remote communities but lack the funding and capacity to provide long-term assistance and although local authorities were involved in the projects of this report, local government expenditure was generally limited (e.g. 3% of the project costs in a similar project in Ruruca, Arequipa [COSUDE]).

THE ROLE OF THE ENGINEER

As well as developing and providing training in the techniques to be used, engineering input is also needed to assess buildings for retrofitting (e.g. assessing the condition of roof timbers and connections and the size/locations of wall openings etc) and advising where additional structural repairs are required.

A stepping stone to increased engineering input in adobe design is the development of adobe standards and design codes in seismic regions. Some countries, including Peru, do have empirical guidance on adobe construction and detailing but not on detailed analysis of adobe structures that would allow accurate, engineered designs.

KEY CONSIDERATIONS FOR COMMUNITY DISSEMINATION PROGRAMMES

The respective roles for community dissemination programmes are summarised in Fig 10 and the necessary features of the programmes are given below:

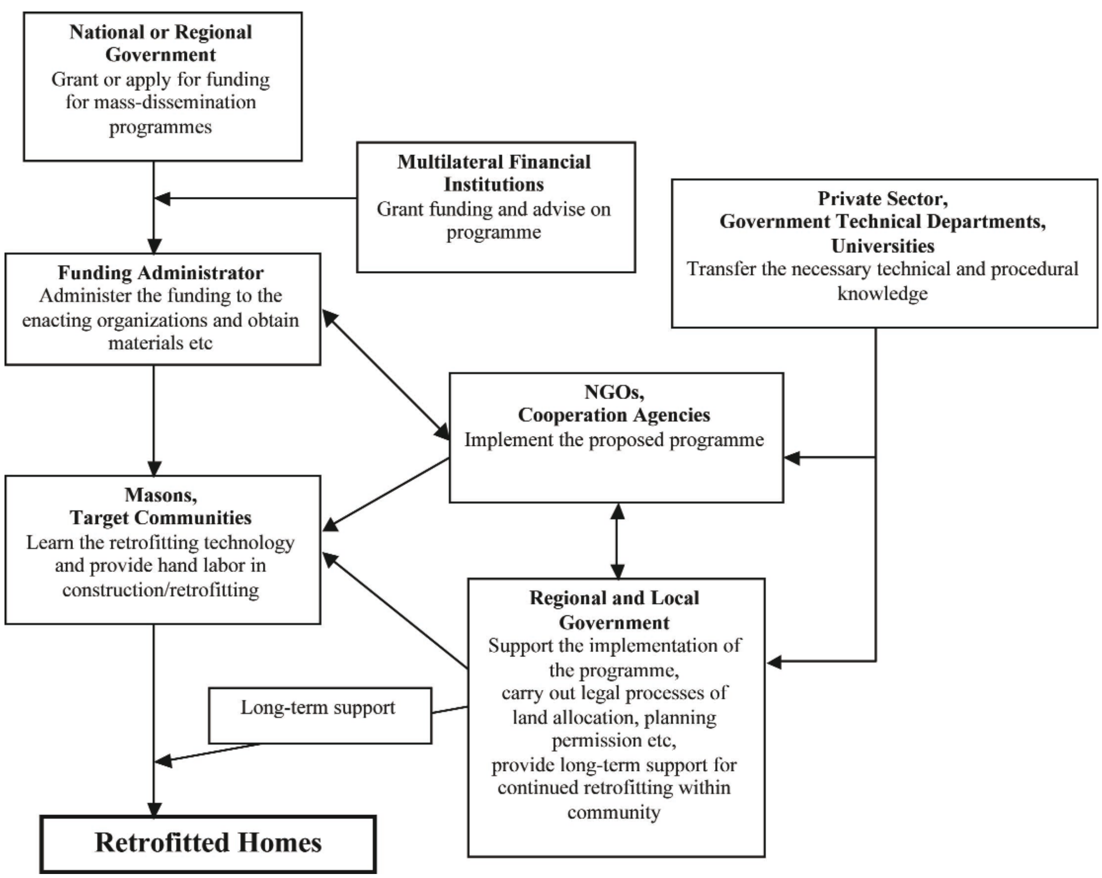

Fig 10. Interrelation of organisations for programmes of mass-dissemination of seismic retrofitting techniques (adapted from Rubiños)

PREPARATION PHASE

– Regions must be identified whereby adobe is the predominant material and it is inappropriate to promote other materials (due to local poverty and inaccessibility of the region).

– National or regional government by-in is required to feasibly conduct a sustainable, larger-scale dissemination programme. Local municipalities must be empowered and engaged to support the programme.

– Widespread awareness and training programmes must be conducted to promote the lesson that adobe houses must be reinforced.

CAPACITATION PHASE

– Training for the NGOs and technical agencies, masons and general population must consider the level of experience and education of the persons being trained (e.g. consider potential illiteracy within the community).

IMPLEMENTATION PHASE

– Create a realistic programme of activity, considering potential delays and source materials early (e.g. a constant supply of water is required for adobe block fabrication).

– Participation of the beneficiaries is key. Careful selection of beneficiaries and monitoring of progress is required to prevent mistakes being made and repeated.

– Technical assistance is required in site selection, selection of soil for adobe and pouring of ring beams if required.

POST-COMPLETION PHASE

– Given the high operational costs of NGOs and cooperation agencies acting in remote locations and the dangers of unsupervised self-construction in adobe, long-term intervention by local municipalities is required to promote and support safe adobe construction/reinforcement and reduce unsafe practices.

CONCLUSIONS

The buildings most at-risk are built without engineering input, so techniques must be simple to apply and programmes must target communities directly. The ‘cascade’ model (training technicians to teach a larger number who then supervise self-construction) is an effective way of reaching large numbers of the community whilst minimising cost.

Remote communities cannot afford well-constructed houses using modern methods of construction. However, these communities are not using reinforced adobe at their own cost due to other basic needs and the poor perception of adobe. This shows that financial incentives are required and that public adobe buildings are needed to raise confidence in adobe as a construction material.

Lessons taught to communities are lost over time. Therefore, long-term interventions are essential.

Operational costs are a significant proportion of the total project costs for NGOs and technical agencies making long-term interventions difficult. Local municipalities have long-term presence but lack capacity and funding. Therefore, capacitation of local municipalities is a necessary feature for the sustainability of any community project.

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