SEISMIC RESISTANT RETROFITTING FOR BUILDINGS

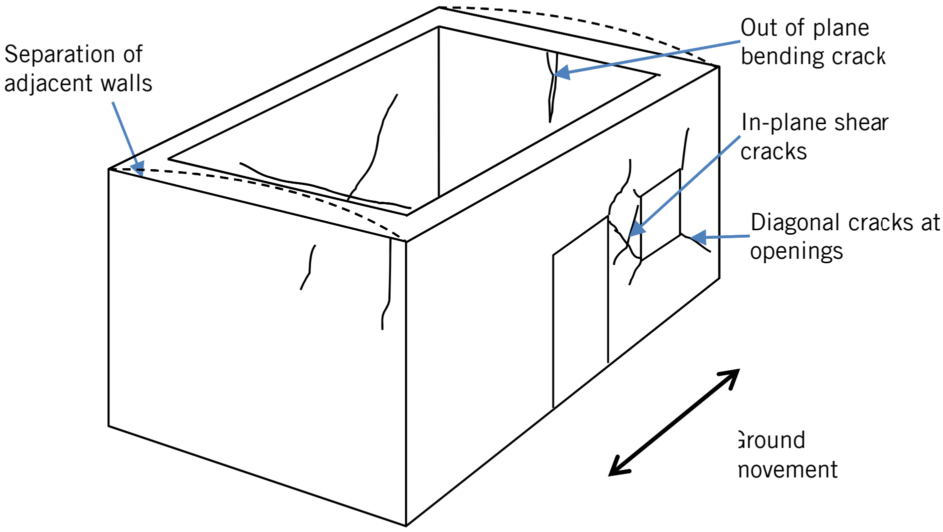
Figure 1: Girl in a place of risk from the damaged building, Peru. Photo: Soluciones Prácticas.

Earthquakes can be the single most devastating natural event, with many lives claimed due to the failure of residential buildings. Whilst there are many building codes and guidelines for building back better to create new, seismic resistant buildings, this option may not be affordable to all whose houses remain standing, but are still at risk of experiencing an earthquake. Seismic retrofitting is defined by Arya (2005) as:

> *"...actions for upgrading the seismic resistance of an existing building so that it becomes safer under the occurrence of probable future earthquakes".*

This brief will look at some methods of retrofitting traditional and 'non-engineered' housing, with suggestions of how to decide which method is appropriate.

Damage types in unreinforced masonry



Unreinforced masonry, whether it is made of stone, adobe bricks, or fired bricks, is a widely used method of building in many developing countries. The methods of retrofitting will focus on these types of buildings as they are most commonly the homes of people who would require affordable retrofit solutions. However, slightly more intrusive, and therefore potentially expensive methods will also be included to give an idea of the possibilities available.

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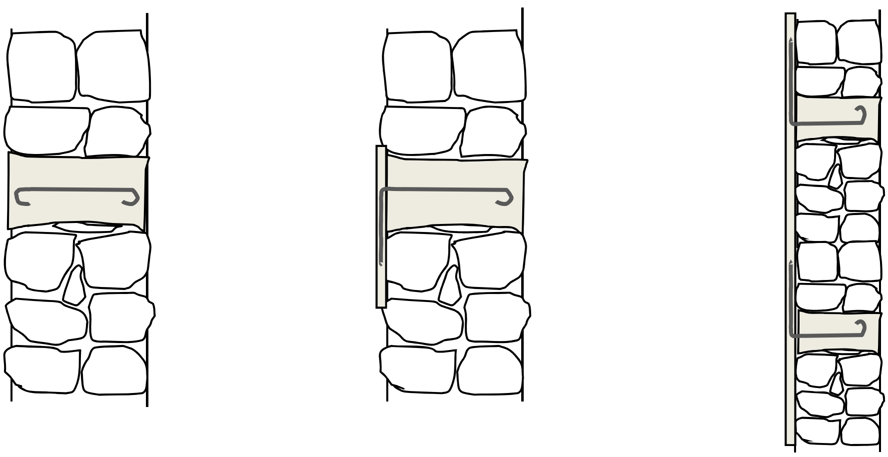
The diagram above describes where cracks may first appear. Walls will experience different modes of failure depending on their orientation to the earthquake movement. Parallel to the ground movement, walls will experience shear and cracks will form in a diagonal fashion. The cracks form an X-shape because shear will be experienced in both directions to follow the ground movement. Diagonal cracks also form from the corners of openings since there stresses are highly concentrated here. Vertical cracks are formed at the middle of walls perpendicular to the ground movement, as this is the location of high bending stresses, as are ends where adjacent walls are attached. Cracking here can lead to separation of the walls at corners. Cracks can propagate and result in sections of the wall falling away and partially collapsing. In some instances, corners, sections of wall or entire walls can fall out of plumb. Prolonged shaking can also lead to delamination, in which a layer of masonry may fall away from the wall, or bulging, where the wall face separates and creates an area of thick wall. Depending on the earthquake intensity and duration, extensive damage can lead to total collapse. It is imperative that inhabitants are able to escape before collapse happens.

Random Rubble Masonry

The predominant type of building in Bhuj, India is random rubble stone masonry. During the 2001 earthquake many walls made of random rubble failed, mostly due to separation of withes and lack of interlock (Madabushi, 2005). The stones used are usually undressed (or uncut) granite and units can vary in the amount of weathering they have been subjected to. This means a variation in surface characteristics and hence a variation in the bonding with mortar. The mortar itself could also be weak in some cases.

The use of 'through stones' ensure withes are interlocked with each other, preventing them from falling away (delamination) or separating in sections (bulging). The placement of 'through stones' can be achieved on an existing wall by using reinforced concrete elements. This involves gently removing stones to create a 75mm (3 inch) hole and inserting concrete reinforced with a hooked bar the length of the wall thickness. The concrete is then cured for a minimum of 10 days. The type of element can be varied depending on the type of bar used, depicted in the figures below.



(a) Stitching element: stitches withes together. Length is 50mm shorter than wall width.

(b) Seismic belt shear connector: anchors seismic belt to wall. Anchor is 150mm in length.

(c) Vertical reinforcement shear connector: anchors vertical reinforcement. Anchor is 400mm in length.

Figure 3: Variety of bond elements based on UNDP India (2007).

Note that the length of the bar should be 50mm shorter than the width of the wall, giving at least 25mm of concrete cover either side. The reinforcement must be completely covered to protect it from rust. The concrete should also be mixed with a polymer additive to prevent shrinkage.

A step-by-step manual of how to install these elements can be found in Chapter 6 of *Manual for Restoration and Retrofitting of Rural Structures in Kashmir,* pages 59-61.

Rubble masonry can also be strengthened with seismic belts, which be discussed in the following section. Seismic belts refer to a retrofit that involves attaching a continuous reinforced cement strip around the perimeter of the building and similarly this method can be used to create vertical reinforcement.

Stone or brick unreinforced masonry

Seismic belts

Masonry walls tend to fail due to in-plane tensile forces and particularly where adjacent walls meet. When masonry fails in shear it manifests in diagonal cracking, often propagating from corners of openings where stresses are concentrated. Horizontal belts can provide continuity between adjacent walls by placing them around the perimeter on both sides of the wall at plinth level, while vertical belts can be applied to corners, wall junctions and to strengthen damaged piers of openings. This provides a restraint for walls that experience bending as they are perpendicular to seismic movement and provide tensile strength for walls parallel to seismic movement. The belts are made of welded wire mesh and covered with a cement plaster. Mild steel bars are used to anchor the belt into the wall. A similar method has also been used on adobe masonry in Peru using small diameter mesh which has been shown to survive earthquakes. See later case study for more information.

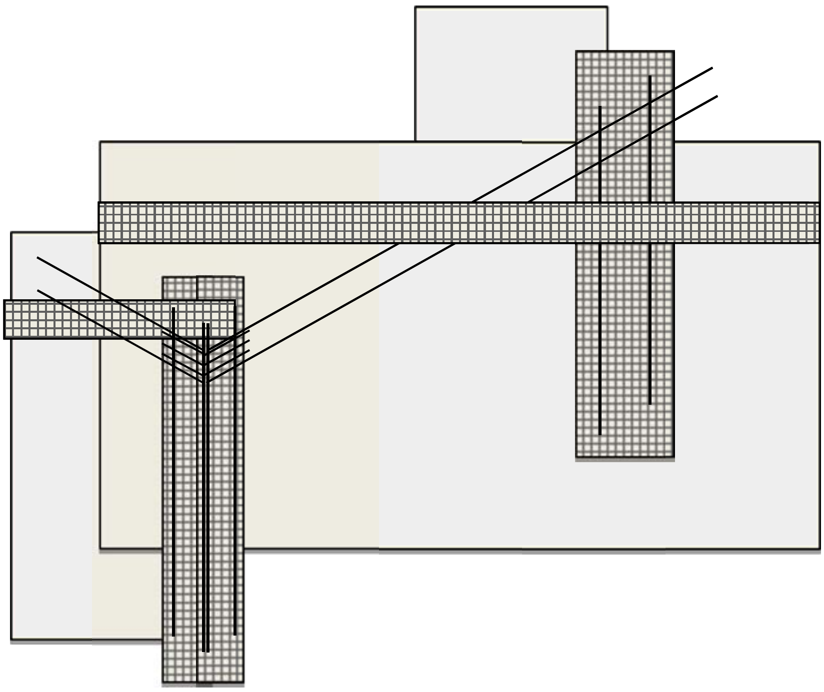


Figure 4: Illustration sketch of welded mesh configuration based on Arya (2005).

A continuous seismic belt should be placed:

- Below eave level
- Just above lintels of doors and windows if there is a significant gap between lintel and eaves (>900mm)
- Below floor level
- Below top edge of gable walls

If reinforced concrete has been used in the floor or roof, or are constructed such that they can act as a diaphragm, then a seismic band will not be needed at these levels. Instead, look if connections between walls and the floor or roof should be improved. (See page 82 of *Manual for Restoration and Retrofitting of Rural Structures in Kashmir.)*

The surface should be prepared so that the mesh has good connection with the wall; this involves removing any plaster layers and cleaning to expose the masonry underneath. The mesh should be continuous and any splices should have at least a 300mm overlap.

The welded mesh should be attached to the longitudinal bars with binding wire. The strip should then be attached with 100-150mm (4-6”) nails with the nails driven into the mortar joints. Spacers should be provided to allow at least 15mm (1/2”) thickness between the wall and the mesh, to ensure the mesh is completely covered by the cement plaster. The ratio of cement: sand should be 1:3.

For a random rubble wall, L-shaped shear connectors should be cast as depicted in Figure 3(b) made of reinforced concrete. These should be installed every 1.25-1.5m (4-5ft) and once the concrete has set, the protruding dowel bar can be attached to the welded mesh strip with binding wire. 100mm (4”) square headed nails should be used to attach the welded mesh to the wall in the fashion described previously.

Step-by-step instructions including illustrations can be found on pages 64-67 of *Manual for Restoration and Retrofitting of Rural Structures in Kashmir.* Recommendations for vertical mesh reinforcement are covered in pages 68-72.

Table 1 - Reinforcement recommendations for horizontal seismic belts (National Disaster Management Division, Govt. of India, 2006)

Length of Wall (m)	Cat. D			Cat. E		
	Gauge	N	H	Gauge	N	H
< 5	g10	8	230	g10	10	280
6	g10	10	280	g10	10	280
				With 2 bars of 6 mm Ø		
7	g10	10	280	g10	10	280
	With 2 bars of 6 mm Ø			With 2 bars of 8 mm Ø		
8	g10	10	280	g10	10	280
	With 2 bars of 8mm Ø			With 3 bars of 8 mm Ø		

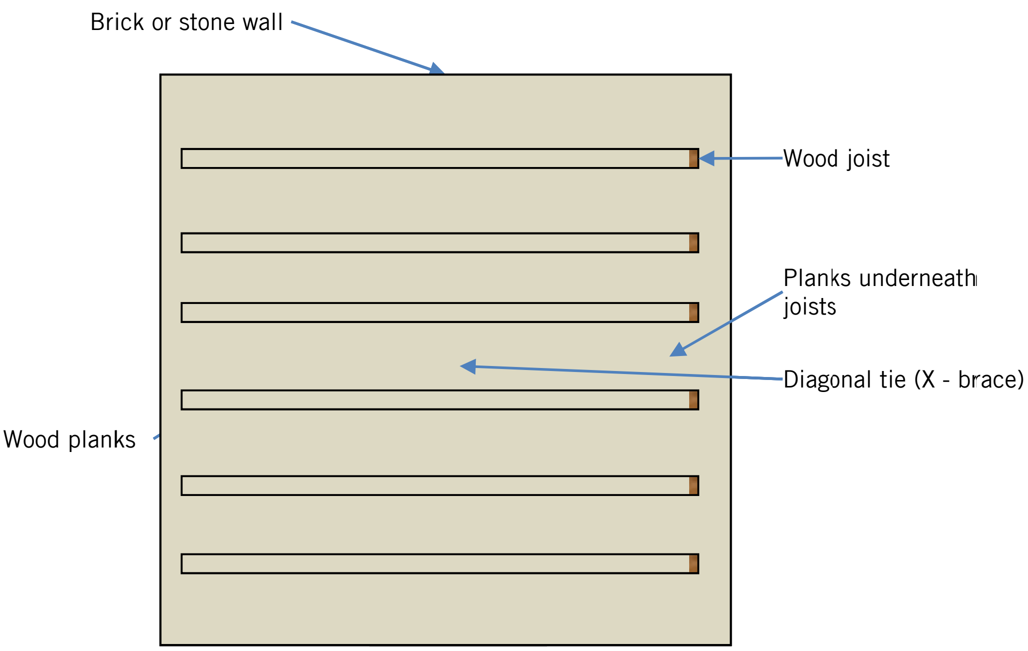
Table 2 - Reinforcement recommendations for vertical reinforcement (National Disaster Management Division, Govt. of India, 2006)

No. of storeys		Cat. D			Cat. E		
		Single Bar, mm	Mesh (g10)		Single Bar, mm	Mesh (g10)	
			N	B		N	B
One	One	10	10	300	12	14	400
Two	Top	10	10	300	12	14	400
	Bottom	12	14	400	16	14	400
						With 1 bars of 12mm Ø	
Three	Top	10	10	300	12	14	400
	Middle	12	14	400	16	14	400
						With 1 bars of 12mm Ø	
	Bottom	12	14	400	16	14	400
						With 1 bars of 12mm Ø	

Notes	Gauge	Diameter	Categorisation of Buildings		
1. N = Number of made longitudinal wires in the belt at spacing of 25 mm. 2. H = Height of belt on wall in micro-concrete, mm. 3. The transverse wires in the mesh could be spaced up to 150 mm. 4. The mesh should be galvanized to save from corrosion.	g10	3.25 mm	Seismic Zone*	Ordinary Buildings	Important Buildings
	g11	2.95 mm	V	E	E
	g12	2.64 mm	IV	D	E
	g13	2.34 mm	III	C	D
	g14	2.03 mm	*Where seismic zone is refers to the Modified Mercalli Intensity scale.		

Roof stiffening

Having a stiff roof that is capable of diaphragm action is important, as this allows loads to be distributed more evenly to the walls to which they are connected. A roof that acts as a diaphragm is able to transfer lateral loads to walls that are able to take in-plane shear. Many flat roofs that are made with parallel timber joists and covered by either earth or planks cannot act as a rigid diaphragm. The roof (or floor) needs to be diagonally braced. Arya (2003) suggests that planks similar to that already used, or galvanised metal strips (1.5mm x 50mm) should be used to create an X-brace. The timber joists should also be nailed at both ends to joists below.



In the case of sloping roofs that are carrying clay tiles or galvanised iron, the roof tends to push out during an earthquake (Arya, 2003). Rafters should be tied to the seismic belt and rafters opposite each other should be tied with cross ties at half the height of the roof, or with collar beam ties at 2/3 of the roof height (UNDP India, 2007).

See page 81-85 of *Manual for Restoration and Retrofitting of Rural Structures in Kashmir.*

Timber construction

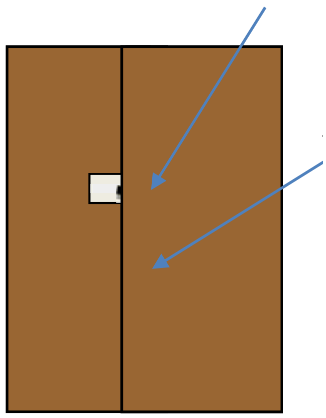
Provided good connections are made and good materials are used, timber buildings usually perform well during earthquakes. Members are lighter, attracting fewer seismic forces, and nailed connections provide ductility. The damage of non-structural elements like masonry infill provides a source of damping, dissipating seismic energy received by the structure (WHE). Timber framed housing may also be safer, since there are fewer sources of crushing weight, compared to masonry buildings with heavy roofs or the use of large concrete blocks. Larger voids are created if there is collapse, so occupants are more likely to survive (Dongagun et al., 2006).

Dhajji-dewari

Dhajji-dewari is a traditional method of construction in India and Pakistan. This consists of a braced timber frame structure with masonry infill, where the masonry is one-withe thick. A report by Rai & Murty (2005) noted that this type of building performed well in the 2005 Kashmir earthquake. Features such as timber studs subdivided the infill and prevented progressive cracking and failure of the masonry. Diagonal bracing, good connections and confinement of the infill are some suggestions made by the UNDP India (2007) guide and by Arya (2005) to improve seismic performance.

Connections

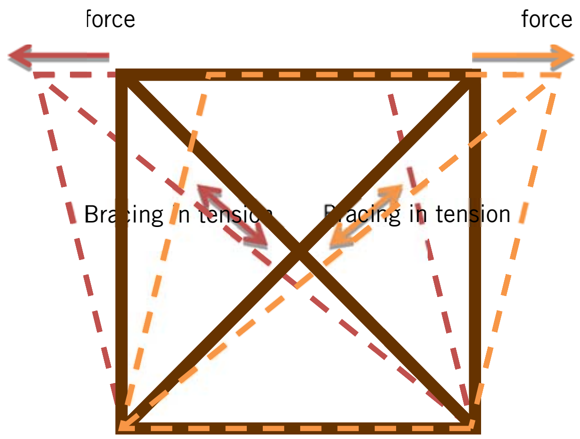
A report by the World Housing Encyclopedia (WHE) notes that insufficient connections are a common seismic deficiency for timber buildings that do not perform well in earthquakes. Inadequate connection of the building to the foundation can cause severe structural damage and cut services off from the building. The guide by UNDP India (2007) suggests that the walls and floors could be provided with better connections by using L-shaped brackets made of 30mm x 3mm mild steel plate, fixed to the floor joists with 10 gauge nails 75-90mm long.



Connections between adjacent masonry walls can be improved by steel reinforced connection, similar to the shear connections mentioned previously. This could consist of L shaped rods anchored and cemented into holes in the walls, to hold the timber post (see sketch).

Diagonal bracing

Placing diagonal members helps the wall to withstand seismic forces in plane, reducing the amount of lateral sway. Diagonal bracing ensures the load is transferred correctly to the timber members. X-bracing is generally better than diagonal bracing since it can take lateral load in both directions. Also,the wider the base of the triangle relative to the height, the stronger the configuration (Tobriner, 1999).



Instructions for how to install timber bracing members can be found on page 78-79 of *Manual for Restoration and Retrofitting of Rural Structures in Kashmir*.

Masonry confinement

The use of chicken wire mesh to confine the masonry was also suggested in the UNDP India guideline. This would prevent large pieces of debris from falling from the wall, but would not necessarily improve structural integrity of the building. This safety measure would simply prevent material from falling on inhabitants.

Adobe masonry

Adobe masonry will have the same failure modes as stone or brick masonry, as mortar joints will be fail in tension. The nature of adobe, however, means that the material will be highly variable. Depending on the quality of the existing bricks, some of the methods outlined above may not be fit for purpose, such as those that require an extensive number of holes to be made. Some less intrusive methods of reinforcing adobe have been researched, as well as methods of reinforcing historical adobe buildings.

Steel mesh reinforcement

A pilot project in Peru was implemented in 2004, retrofitting 20 houses in 6 towns based on the research carried out by the Pontifical Catholic University of Peru (PUCP). The retrofit involved attaching vertical strips welded steel mesh to the corners, intersections and intermediate of long walls, with horizontal strips of mesh at the tops of walls. The mesh had typically 1mm diameter wires with 19mm spacing. It was then covered with a cement mortar. This aimed to delay collapse of an adobe masonry building by providing additional ductility.

An earthquake shook Peru of 7.9 Mw magnitude on 15th August 2007 just offshore near the town of Pisco. While 80% of adobe buildings collapsed in the most affected areas, in Guadalupe, the adobe house that had been retrofitted with steel mesh by the PUCP performed well under this earthquake, failing only where the upgrade was not completed on part of a wall (San Bartolome et. al., 2008). In contrast, the neighbouring buildings were seen to collapse. This retrofit was also particularly effective because it made locals aware of the measures that could be taken to prevent collapse in the future.

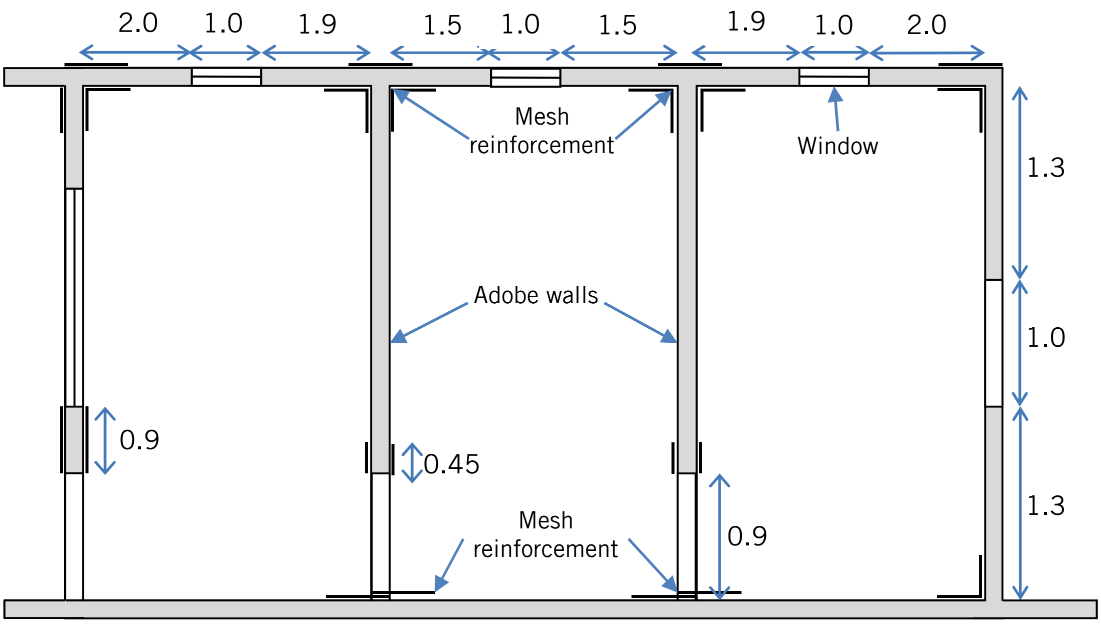


Figure 7: Illustration of wire mesh retrofit locations for a house in Guadalupe, Peru based on San Bartolome et al. (2004).

Polypropylene mesh reinforcement

This method involves encasing unreinforced masonry in polypropylene straps (or PP-bands), which are easy to obtain. It has had practical application in Nepal, Pakistan and Peru with positive reception from the communities involved in the dissemination programme. A demonstration house was constructed for locals to witness its effectiveness at withstanding earthquakes. Static and dynamic testing by Macabuag (2009), shows that this method extended the collapse time of unreinforced masonry buildings and also provided confinement. The PP-bands are able to prevent brittle collapse, since loads can be maintained even after initial failure of walls.

The report for the experimental study can be viewed at:
http://opus.bath.ac.uk/16170/1/papers/Paper%2072.pdf and
http://www.ewb-uk.org/system/files/Macabuag+Bhattacharya+report.pdf

Bamboo reinforcement

An experimental study by Dowling (2006) looked at reinforcing U-shaped adobe walls with vertical bamboo poles and horizontal wire reinforcement. This method was shown to significantly improve seismic resistance of the structures, even more so when including a timber ring beam to provide continuity and confinement to the walls. Since this retrofit is fairly simple and less invasive in design, as well as adaptable to use local available materials, it is an affordable option for buildings in developing countries.

The study was part of the Getty Seismic Adobe project and can be downloaded at:
http://www.getty.edu/conservation/publications/pdf_publications/gsap_part1c.pdf

Retrofitting historical adobe

The Getty Seismic Adobe Project brought together several research studies and projects that looked at making adobe buildings earthquake resistant. Whilst the methods above are relatively low tech and would be affordable to residents of such buildings, there have been several retrofitting projects to improve the resistance of historic adobe buildings. Some of these methods are more intrusive, but tackles the weaknesses commonly found in adobe structures.

Based on the methods developed from previous studies (Tolles 1989, Tolles et al 2002) several retrofitting projects were carried out on historical buildings. Tolles (2006) looks at 5 project cases for which these measures were implemented and can be found here.

Overturning of walls is a common mode of failure in adobe walls. Methods included creating good connections between the walls and floor levels, as these would need to transfer seismic forces. Walls were typically anchored along the tops of walls to the roof. The possibility of progressive failure is addressed by adding vertical nylon straps or centre cores to the walls. This measure prevents out-of-plane failure, while the centre cores improve ductility and strength in both directions (Tolles, 2006). These cores would be threaded through the walls and then anchored into holes with an epoxy grout. In some cases a plywood diaphragm was introduced in the roof to provide the walls restraint in the out-of-plane direction.

The sketches below depict some of these installations, as carried out in the experimental study by Tolles et al (2000). The next figure depicts the retrofit on Castro-been Adobe, a two-storey adobe building part of the San Juan State Historic Monument.

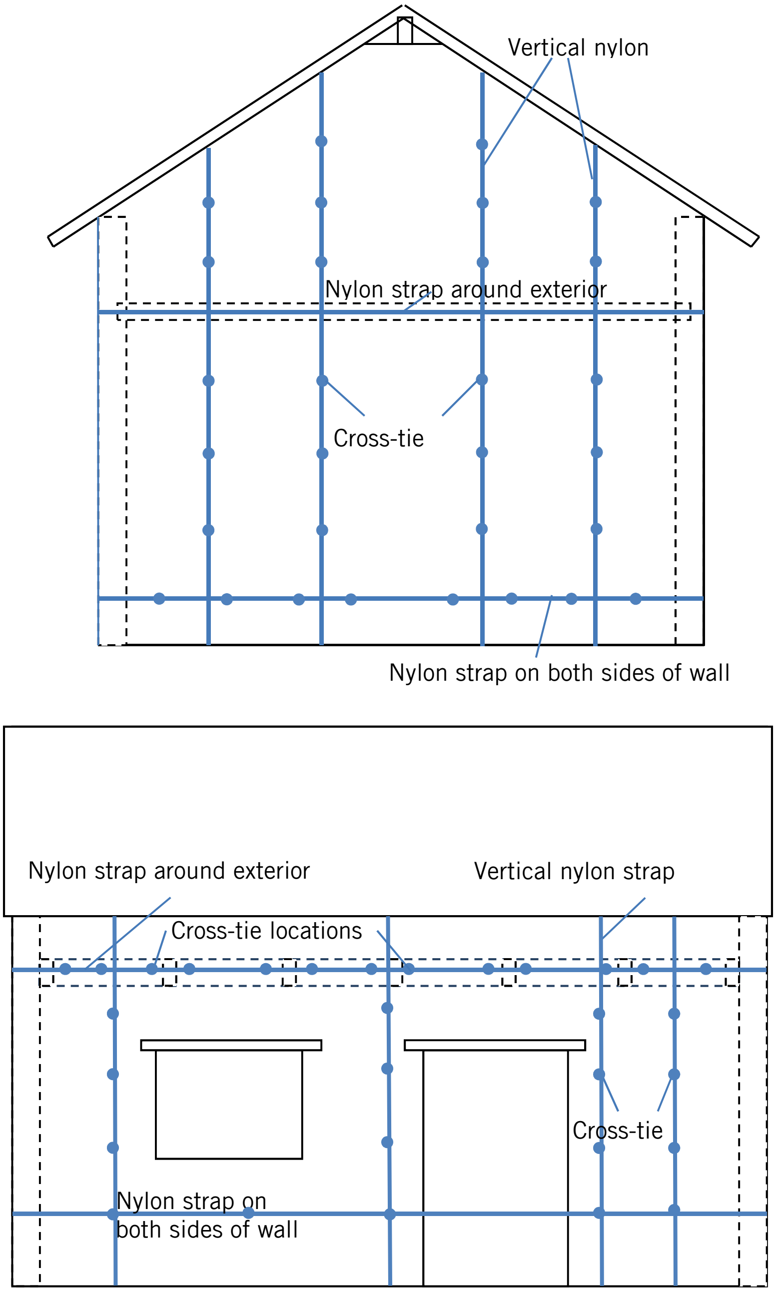


Figure 8: Sketch of nylon strap locations in Tolles et al. (2000).

The nylon straps used in the experiments on 1:5 model buildings were 0.3cm in diameter, flexible and woven. These looped vertically or horizontally around an entire wall or the whole building. The nylon cross-ties were 0.16cm in diameter and reduced crack displacement as well as providing through-wall connection.

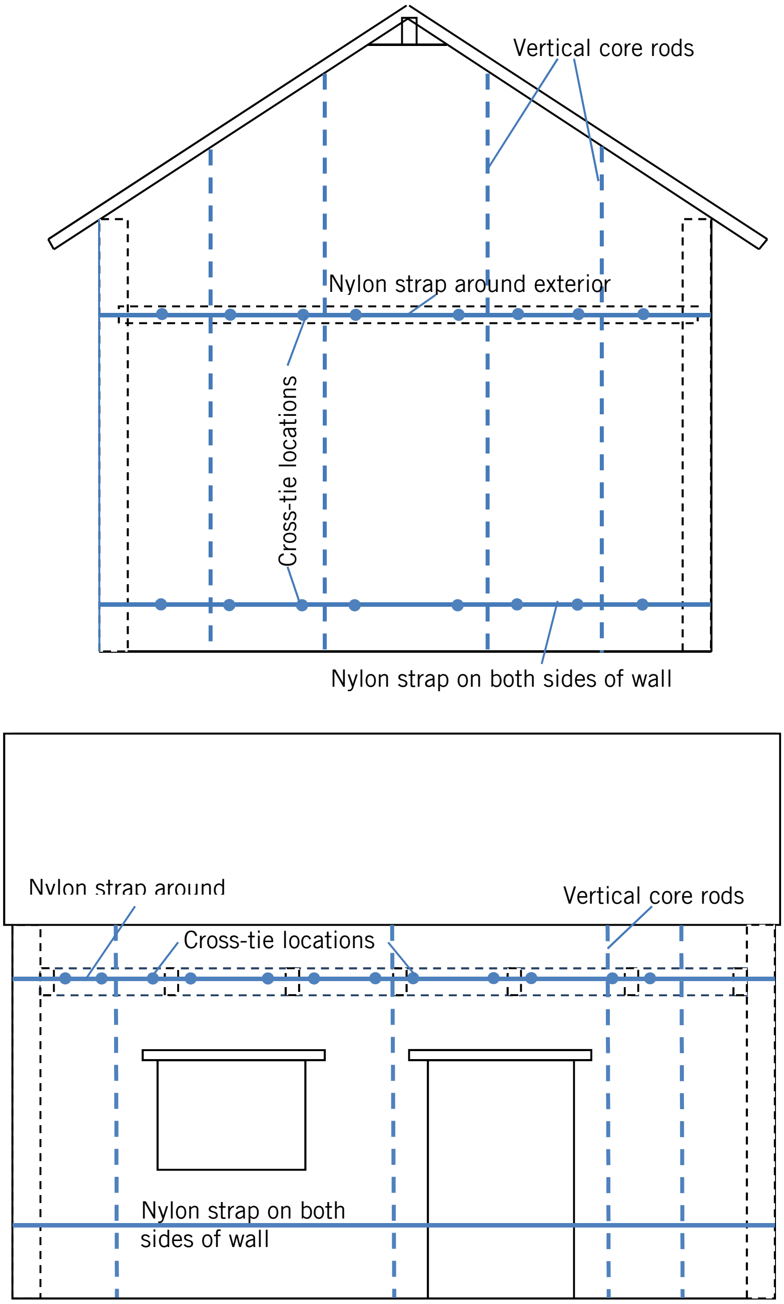


Figure 9: Sketch of vertical bar locations in experimental study by Tolles et al. (2000).

The vertical centre core elements in the model buildings were made of 0.3cm diameter steel drill rod, drilled into the adobe. During the real-life retrofitting of the historical buildings, 2cm diameter rods were used installed in 5cm diameter holes and filled with a non-shrink cementious grout.

In one case a lightweight steel frame was designed with the addition of viscous dampers to improve out of plane stability and reduce displacements during large seismic events. A viscous damper is a device that absorbs energy in the system, reducing the velocity of the building movement and reducing the seismic force on the building. This type of retrofit would be expensive to install and may not be appropriate for developing countries.

Guidelines for designing and implementing the methods described can be found at:
http://www.getty.edu/conservation/publications/pdf_publications/seismic_retrofitting.pdf

Damage assessment and retrofit choice

Although this brief has highlighting various methods for retrofitting buildings, it is essential for an assessment of the building to be made prior to carrying out work. The method chosen should be affordable and feasible depending on several factors like the seismicity of the area, existing damage to the building and costs of materials and labour.

A sample methodology for carrying out a vulnerability assessment can be found in Chapter 4 of (pages 40-44) *Manual for Restoration and Retrofitting of Rural Structures in Kashmir*, whilst a step-by-step procedure for making decisions can be found in Chapter 7 (pages 88-92).

Whilst many different methods have been looked at here, the principles for a structurally safe building under earthquake loads should be a recurring theme throughout this brief. Good connections between walls and floors or foundations, between adjacent walls and between walls and roof are essential. Using lightweight materials can reduce the amount of seismic forces attracted to the building. Having a stiff roof which can transfer loads to walls efficiently can increase the resilience of the structure. Confinement of masonry can prevent large pieces of debris to fall out and injure inhabitants. These concepts should be kept in mind when implementing any retrofit and care must be taken to not introduce additional risks. Following these principles should help delay or prevent the collapse of buildings and reduce the number of lives lost during devastating earthquake events.

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