SEISMIC STRENGTHENING OF EARTHEN HOUSES USING STRAPS CUT FROM USED CAR TIRES: A CONSTRUCTION GUIDE

Andrew Charleson

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Cover Photo: The cover image shows an adobe test module being lowered onto a shaking table prior to dynamic testing.

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Preface

The origins of this document are found in a concern for the poor in developing countries who often build and inhabit unsafe houses. Earthen houses are notable for their lack of tensile resistance. There is nothing strong enough to hold wall and roof elements together during a damaging earthquake. They break apart and fall, causing loss of life and injury.

A search then began for waste material that could be transformed into ropes or straps with reasonable tension strength. Any material other than waste would most likely be unaffordable. The break-through occurred when following-up the conviction that useful strength might be obtained from used car tires. How to avoid burying them in landfills but to recycling them to improve seismic safety? It was then discovered that if tire treads are spirally cut, like the way orange skins can be peeled into continuous lengths, usefully long and strong straps are obtained.

The implementation of this technology will require collaboration between the tire industry and NGOs or government agencies who are concerned about the seismic vulnerability of earthen houses. The vision is for the tire industry to produce straps from used tires rather than paying for them to be disposed of, and donating and transporting them free of charge to organizations improving housing safety in developing countries.

Andrew Charleson

Acknowledgements

Many people have contributed to this project. Matthew French's research for his M. Arch degree involved developing, testing and refining the technology, while for her Masters degree in Developmental studies, Marcela Markland explored socio-economic and cultural challenges in the context of Peru. The project was also a vehicle for two undergraduate studies by Matthew French and Samuel Gwynn, who also completed the bulk of the diagrams. Nabil Allaf finished off the diagrams and formatted the manual.

The technical assistance in the workshops at the School of Architecture, Victoria University of Wellington and the Catholic University of Peru, Lima has been essential in developing the tire strap reinforcement. Thanks to Marcial Blondet and his academic colleagues for their support in Lima, and also Johanna Aranda for her dual role as a research assistant and Spanish translator for the adobe tests.

The project could not have been completed without a research grant from Victoria University of Wellington. The grant covered all the costs associated with the testing program in Lima.

Finally, thanks to reviewers Dominik Lang and Marcial Blondet, and to Marjorie Greene and her assistants working at EERI for the World Housing Encyclopedia who have applied all the necessary finishing touches.

1. INTRODUCTION

1.1 Background

Before embarking upon the aims of this construction guide, its content is summarized visually in Figure 1. This diagram attempts to convey how the various materials, especially straps cut from the treads of used car tires, are used to reinforce an earthen (adobe) house to prevent it collapsing during high intensity earthquake shaking.

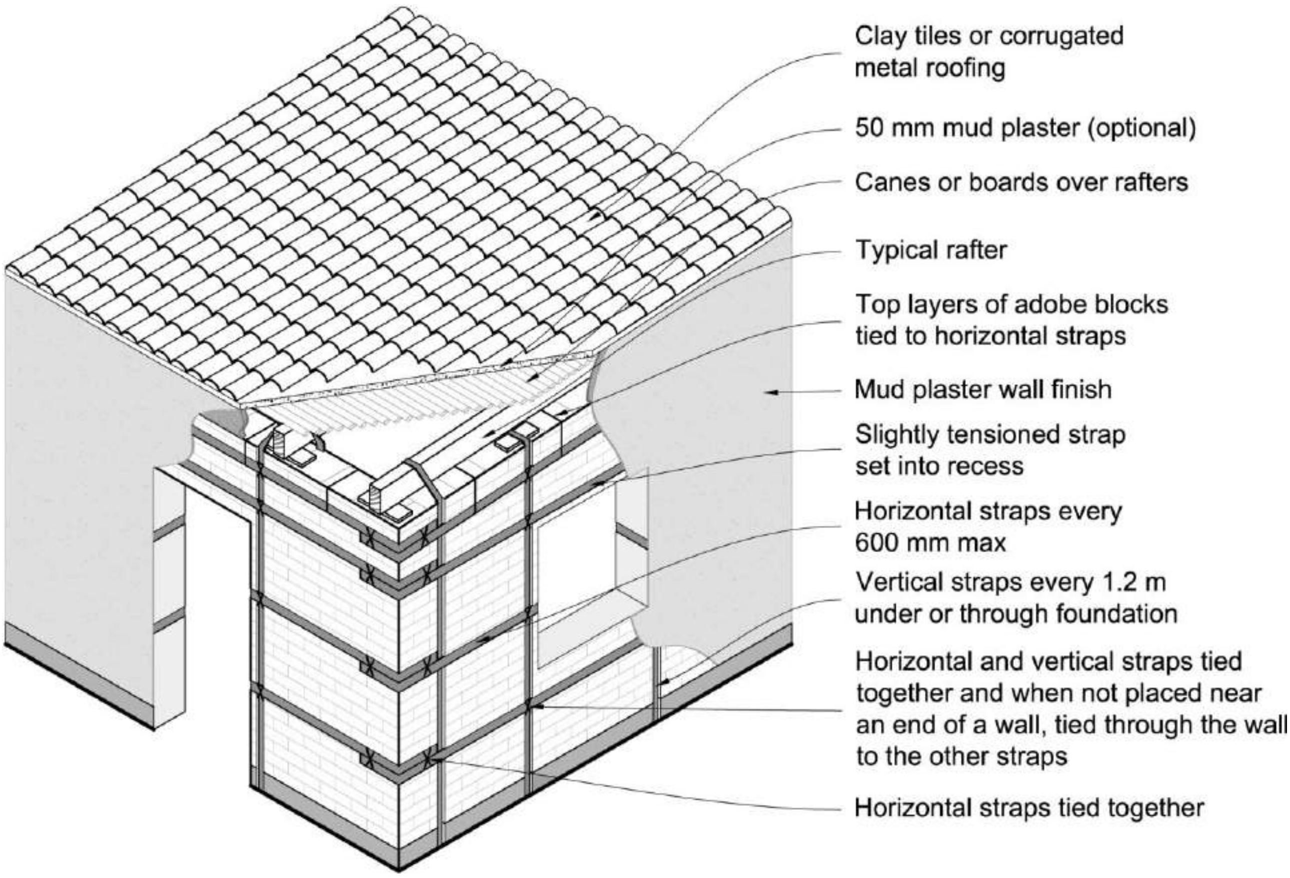


Figure 1.1 Sketch illustrates the main features of a strap-reinforced house

This guide explains the reasons to reinforce earthen, and in particular adobe houses in seismic areas. It outlines the background to the strap reinforcement system and then shows, by illustrations and photographs, how to apply this technology in the field. It is hoped that, after removing some of the technical content and translation into the local languages of at-risk communities, the manual will enable strap reinforcement to be correctly applied so as to prevent earthen houses collapsing during medium to severe earthquake shaking. The main purpose of this strengthening method is to improve life safety rather than preventing economic loss of property during an earthquake.

This guide is applicable to both new and existing construction. Tire strap reinforcement can be applied in both situations.

The concept at the heart of this reinforcement system is for tire straps to be cut from discarded used tires in developed countries (where used tires are generally not too badly damaged and worn and may be costly to dispose of) and then donated and transported to developing countries, where at minimal cost homeowners incorporate them in new or existing houses. Two very desirable outcomes eventuate:

1. Both existing and new adobe buildings are strengthened at minimal cost with a material that is simple to install and plentiful in supply, and
2. a significant portion of used car tires are recycled in an environmentally acceptable manner.

Figure 1.2 A tire strap approximately 6 m long ready to be applied to a house.

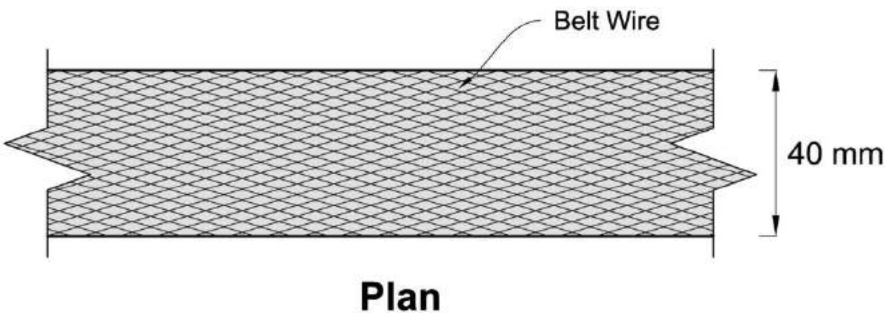


Figure 1.3 A length of strap cut from the tread of a steel belted radial tire showing the orientation of the belt wires.

In this system, circumferentially cut straps from the treads of used car tires function as tension reinforcement to improve the seismic safety of earthen wall construction. Straps must be cut from steel-belted radial car tires. Although the steel wires in the two belts are not continuous they give the straps sufficient strength and stiffness to be used as reinforcement (Figures 1.2 and 1.3).

The focus of this manual is upon single-storey residential buildings with light to medium-weight roofs. Figure 1.4 provides a pictorial summary of the system. After approximately six meter-long continuous straps have been cut from tire treads, they are connected on site using a special yet simple nailed joint. Once the walls of a house are constructed and holes drilled or formed during construction to allow straps to pass through, straps are then wrapped horizontally around walls at 600 mm centers maximum vertically. Vertical straps spaced horizontally at approximately 1.2 m centers pass underneath or through the foundations, then rise up both sides of the walls, wrap over them and are connected and finally nailed to roof timbers. This type of reinforcing pattern is designed so as at least one pair of straps, either vertical or horizontal, cross every large potential crack that will open during an earthquake (Figure 1.5). The reinforcement provides structural strength and tying-action after the earthen wall material has failed.

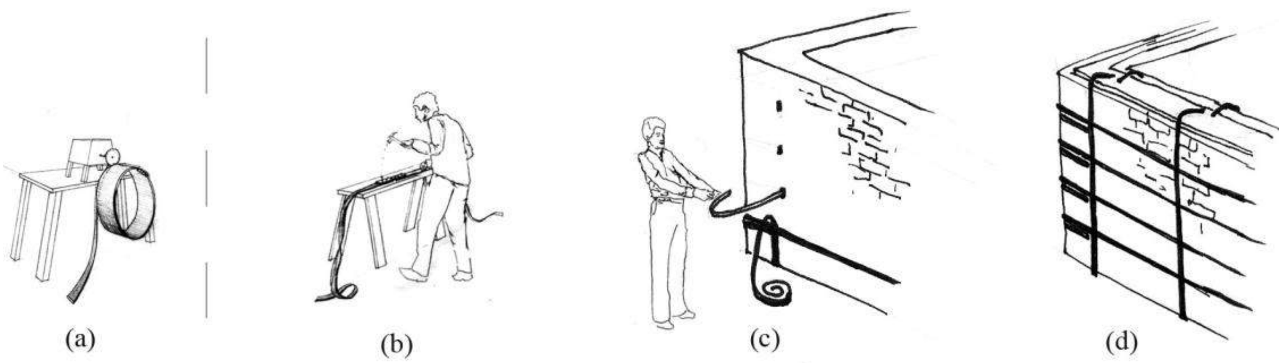


Figure 1.4 Steps in the process of reinforcing an earthen (adobe) house with tire straps. Step (a) is performed in a workshop or factory and (b) to (d) on site. (Courtesy Matthew French)

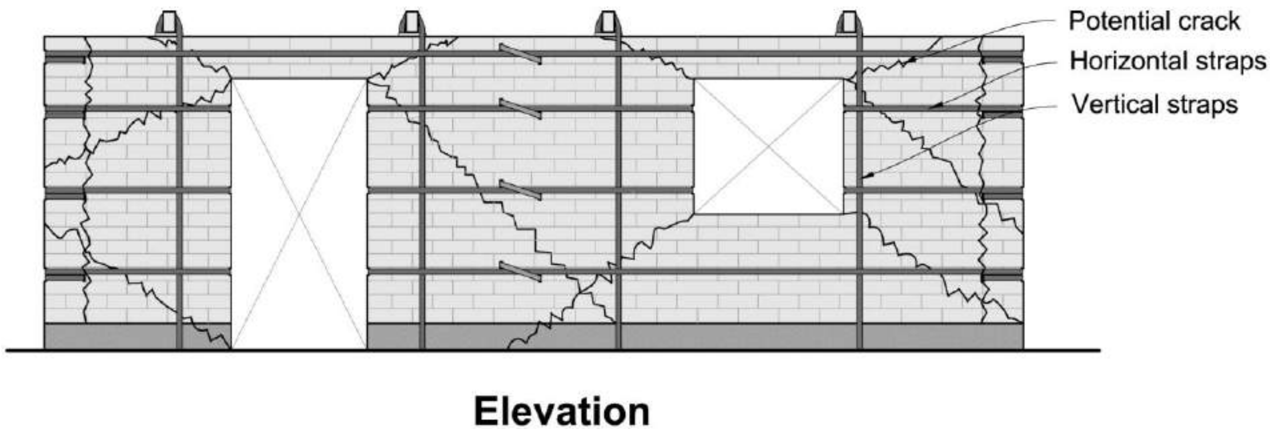


Figure 1.5 An elevation of a typical wall showing positions of expected cracks and strap placement that ensures at least one strap crosses every potential crack.

1.2 Vulnerability of Earthen Houses

The likelihood of any type of construction suffering earthquake damage depends on two factors; the hazard(s) likely to affect the region or site, and the fragility of construction. The hazard that this manual addresses arises primarily from the geological site conditions in the form of earthquake action, and to a lesser degree, climatic actions like storms. Although the techniques described herein are designed to improve the earthquake resilience of houses by preventing collapse, they will also reduce damage during wind storms. For example, the detail of wrapping vertical straps over roofing timbers ties roofs to walls and prevents roofs lifting off in high winds.

The earthquake hazard, if any, can be assessed in most countries by referring to earthquake hazard maps of one sort or another. Usually this information can be found in building codes or standards that professionals use when they design buildings. If unavailable, information on historic earthquake activity in the region can be helpful. If earthquakes have occurred in the past then it is almost certain that earthquakes of comparable magnitude will continue to occur in the future. Unfortunately, a lack of evidence of past earthquake activity affecting a certain geographical area is no guarantee of future seismic inactivity. Although an appreciation of a region's seismic hazard may be obtained, local soil and topographic conditions can increase that hazard locally. Deep layers of soft soils in alluvial valleys or near coastlines may amplify ground shaking or be prone to liquefaction, both of which increase damage to buildings considerably. Steep terrain is subject to earthquake-induced landslides against which individual house reinforcing is likely to be ineffective.

Of all housing construction types worldwide, earthen construction is among the most fragile with respect to the horizontal loads experienced during earthquakes. Although there are many different types of earthen and related construction, including random rubble and dressed stone construction either laid dry or in mud mortar, they share two serious structural deficiencies: (1) of having little if any tension strength, and (2) brittleness. As tragically witnessed after every damaging earthquake in developing countries, due to their high mass and lack of tensile resistance that has the potential to tie the elements of buildings, like walls together, the seismic performance of these forms of construction is very poor (IAEE 2004, Kuroiwa 2004).

Typical earthquake damage patterns of earthen housing shown in Figure 1.6 include:

- Poor connections between the different elements of the building that lead to walls separating at corners and falling outwards
- Falling of both gable and ordinary walls that often leads to collapse of the roof
- Delamination and bulging of walls built from essentially two vertical layers of stones
- Diagonal cracking in walls. This weakens them and leaves them very vulnerable to total collapse.

These types of damage are serious. They lead to severe injuries and loss of life. Furthermore, they can occur at low intensities of earthquake shaking depending on the quality of construction materials and their maintenance. Many earthen houses have cracks in and between walls, and roofs not tied to walls before an earthquake strikes. In this situation it takes little more than a tremor to start the walls rocking. If the shaking intensity increases, wall collapse is almost inevitable.

These failure modes were observed as recently as August 2007 after the Pisco, Peru earthquake. In Pisco, the city closest to the epicenter, more than 80% of the adobe houses either collapsed or sustained heavy damage (EERI 2007).

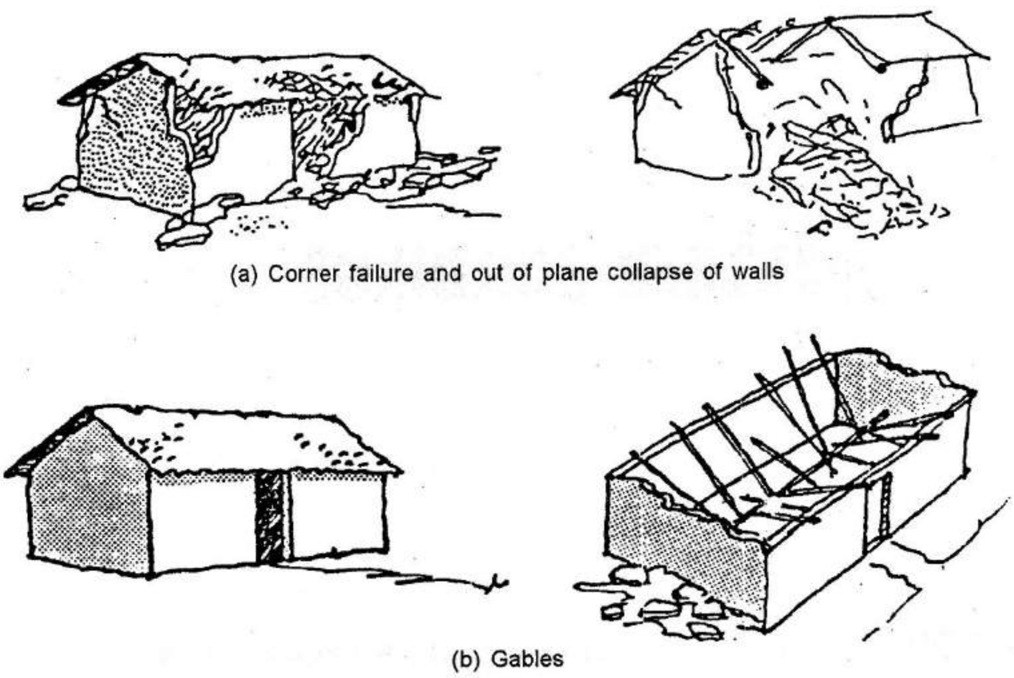


Figure 1.6 Typical damage and collapse of earthen buildings (from IAEE 2004).

1.3 Methods of Reinforcing Earthen Houses

The particular reinforcing method explained in this guide is new and additional to several methods that are occasionally used in practice. The most widely disseminated method of reinforcing adobe houses, now over 30 years old, consists of using cane-type materials (IAEE 1980). Vertical canes or small bamboo rods at about 450 mm centers together with lengths of crushed cane every few horizontal block courses are embedded in the mud mortar of adobe houses. This reinforcement which is placed within adobe walls during construction is supplemented by substantial timber or reinforced concrete ring or collar beams at the tops of walls. Where the distance between return or bracing walls is excessive, buttresses or pilasters reduce wall out-of-plane vulnerability. Although full-scale shaking table tests have shown the effectiveness of these measures in preventing collapse, they have not been widely adopted. Canes and bamboos are often not easily or cheaply available, and there is reluctance or lack of awareness regarding embedding reinforcing material into adobe walls.

This method has been recommended again more recently (Blondet et al 2003), but also supplemented by other techniques including using horizontal wires in conjunction with the vertical reinforcing, and the use of plastered welded steel mesh. Several mesh-reinforced houses performed exceptionally well during the 2001 Arequipa earthquake, Peru, where neighboring non-reinforced adobe construction was badly damaged. In an attempt to make such reinforcement more affordable, research attention has focused upon synthetic materials. Plastic mesh systems have demonstrated their effectiveness in laboratory tests. At least one simple construction manual based upon the use of geomesh but also relying upon a strong eaves-level timber ring beam communicates this technology (Vargas-Neumann et al 2007). Mayorca and Meguro (2008) report on a similar approach where a closely-spaced mesh of polypropylene straps, an inexpensive material commonly used for packing, wraps around walls to increase their seismic performance.

Plastic reinforcement in the form of polypropylene straps placed on the outside of walls is also a reinforcement option, having been shown to be effective in a major U.S. research project (Tolles et al 2002). This approach requires designers to predict the locations and patterns of cracks, which are mainly diagonally orientated and emanate from the corners of openings. The placement of horizontal and vertical straps responds to probable failure modes. Although it has already been applied to retrofitted historic buildings in the U.S. (Crocker 2005), its cost prevents widespread uptake in developing countries.

Two low-cost strap solutions applying used car tires have been proposed, one by another researcher. Both methods are appropriate for new construction and retrofitting. In one system, developed for unreinforced masonry, inter-connected car tire treads form a tensioned eaves-level band to tie perimeter walls together. Identical post-tensioned vertical straps improve in-plane pier lateral load resistance (Turer et al 2007). While from a structural engineering perspective this method may have limited applicability to earthen construction, the bulky nature of the numerous steel connection devices and their expense will limit its up-take. The second solution, also using car tire straps but based upon thinner and longer straps, is the subject of this manual. Table 1.1 summarizes the three most suitable earthen reinforcement systems.

Table 1.1 Advantages and disadvantages of three earthen housing reinforcement systems.

	Reinforcement System		
	Vertical canes and crushed horizontal canes	**Geomesh wrapped around and tied through walls and plastered**	**Tire strap reinforcement as per this manual**
Advantages	Low-cost, low-tech reinforcement. Prevents collapse. Walls don't require plastering.	Provides a high level of structural resilience. Collapse is prevented and construction suffers less damage than the other two methods.	Uses recycled materials. Additional timber structure such as a ring beam may not be required. Is applicable for both new and existing construction. Most of the work can be done by the house owner. Only areas near the shallow recessed straps require re-plastering where an existing house is strengthened.
Disadvantages	In many regions canes are not readily available. The need to place vertical canes within adobe walls makes construction more difficult and is not popular with masons. Requires a substantial timber or RC eaves beam. Can't be used to retrofit existing construction.	Geomesh is relatively expensive so material costs are high unless subsidized. A substantial timber or RC eaves beam is recommended. Difficult to apply to existing construction. Every wall surface would require re-plastering and the connection between foundation and geomesh has yet to be developed.	Tire straps have to be donated. While collapse is prevented, damage will occur. In damp or wet conditions, special measures are required to protect the straps from corrosion.
Summary	Low-tech and proven to prevent collapse.	Structurally, the most resilient solution but is relatively expensive. Requires additional timber and is applicable at this stage to new construction only.	Prevents collapse by tying walls and roofs together. Minimal intervention and suitable for self-build. Suited to retrofitting existing houses.

1.4 Applicability of Tire Strap Reinforcement

This system is suitable for new and existing earthen houses in areas of moderate to high seismicity. It could also be employed shortly after a damaging earthquake to enable seismically resilient reconstruction to proceed using materials salvaged from badly damaged and collapsed houses. Taucer et al. (2008) note:

> *'Self reconstruction of non-engineered houses may be seen as a way for the local population to cover immediate shelter needs and the deficit resulting from insufficient resources (both in budget and timing) of the Government to finance the reconstruction of engineered houses. Therefore, some kind of assistance and control aimed at increasing the quality and earthquake resistance of the rebuilding of houses not assisted directly by the Government would be desirable to diminish the risk from future similar earthquake events. This type of objective can only be achieved by implementing a comprehensive program that involves the participation of institutional organizations, NGO's, Universities, and most important, the active participation of the local population.*

The background research and development of the tire strap reinforcement is outlined in Appendix A. The full-scale module tested on a shaking table, described in Appendix A, showed how significantly the roof structure and wall lintels affected the dynamic performance of the module. Therefore, at this stage in the use and continuing development of the reinforcement system a refined mathematical model is unwarranted. The suggested approach is therefore to apply strap reinforcement to earthen houses whose designs broadly comply with the most recent unreinforced adobe construction guidelines (Blondet et al 2003), namely:

- Single storey construction,
- Wall openings not to exceed one-third of wall lengths,
- No openings wider than 1.2 m,
- Maximum wall thickness 400 mm
- Piers at least 1.2 m wide,
- Horizontal clear distance between return, cross-walls or buttresses to be no greater than 10 times the wall thickness nor 4 m, and
- Wall height is to be no greater than 8 times the wall thickness nor 3.2 m.

Further, it is recommended that:

- Roof construction should not be heavier than timber framing supporting 100 mm of compacted earth beneath clay tiles. Roof weight varies from approximately 1.5% of the weight of house earthen walls in the case of corrugated steel roofing over timber framing to 20% where roofing is 100 mm thick earth covered by clay tiles. Any heavier roof construction may exceed the seismic capacity of the proposed reinforcement system unless proven otherwise by full-scale testing.
- A ring beam (usually considered a necessity in earthquake resistant adobe houses) may not be required given the presence of horizontal and vertical straps. In the full-scale dynamic test vertical and horizontal straps tied walls together, crossed all expected cracks and provided reliable seismic force paths without a ring beam.

As well as satisfying the criteria above, the following points should be noted:

Corrosion of straps: Since the cut ends of steel fibers are exposed along the sides of straps, corrosion protection is required where walls are moistened by rain or foundations are damp. Unless precautions as detailed in this manual are taken, this system is to be restricted to very dry geographic areas.

House dimensions: The technique is applicable to any plan dimensions provided cross-walls are placed frequently as noted above.

Wall thickness: The system is beneficial for walls up to 400 mm thick. Thicker walls may exceed the seismic capacity of the proposed reinforcement system unless proven otherwise by testing.

Wall materials: The system can be used for a range of earthen materials. Although research has focused upon dry laid bricks and adobe blocks laid in mud mortar, the system is expected to be effective for dressed stone walls, dry laid or laid in mud mortar. Further research will establish how effective it is for random rubble in mud mortar, but due to the way straps confine both a house as a whole and individual elements like walls, straps can be expected to improve seismic performance.

The system is most effective when earthen blocks and mortar are of good quality and strength, and vertical joints are completely filled with mortar.

Building condition: When considering retrofitting existing houses the following criteria should be met –

- Walls not to be severely out-of-plumb
- No significant foundation settlement
- Eroded areas of walls made good
- Missing blocks inserted to achieve a solid wall
- Rotting or insect infested roofing timbers replaced
- Timber props provided to the ends of lintel beams if they are insufficiently deeply embedded in walls

Construction details of the reinforcing system are designed for maximum longevity of the straps and for ease of construction. Both to prevent UV embrittlement of the straps and for aesthetic reasons, straps should be covered by mud plaster. In most cases straps will be recessed in either 15 mm or 25 mm deep chases cut into the faces of adobe walls. It is proposed to remove any excess rubber tread depth from the straps during the cutting process to achieve straps less than or equal to 8 mm thick. As well as reducing the necessary depth of the chases cut into the adobe, thin straps are easier to handle, cheaper to transport, and commercially valuable recyclable fiber-free rubber is obtained when excess tread rubber is removed.

By strapping walls after their completion the effects of wall vertical shortening due to self-weight are reduced. Since vertical straps need to be wrapped under, or at least through the foundations, they can be placed during foundation construction, or alternatively, some cheap flexible piping provided to enable easy installation of the straps later in the construction process.

Provided these criteria are satisfied, strap reinforced adobe houses are expected to undergo large lateral earthquake displacements without collapse.

Development of this system to date has concentrated on 'stand alone' houses. In reality, many houses share party-walls with others or have their walls built directly against those of other houses (Figure 1.7).

Figure 1.7 Adobe houses built up against each other

Further research is required to determine the best strategy for protecting houses in these situations. In the interim, horizontal straps should wrap around party-walls or two walls built against each other. In this case where two walls are being confined, both horizontal and vertical straps should be doubled up. Such a strategy that involves tying several houses together requires considerable cooperation between adjacent house owners and must respect relevant legal requirements.

1.5 Longevity of Straps

Tire straps are subject to a number of threats to their longevity. Ozone, moisture, ultraviolet light, temperature and oxidation are agents with the potential to reduce tensile strength. These threats are overcome by suitable construction detailing. For example, straps are placed in rebates which are then filled and covered by mud mortar before the entire wall is plastered, and then finally painted. Ultraviolet light is therefore removed as a possible source of deterioration, and given that the straps are shielded from the sun's heating rays by at least 20 mm of mud mortar, damage from high temperatures is unlikely.

Encasement by mud mortar also reduces ozone attack, although this is not expected to be a problem due to the fact that the straps are very lightly tensioned. The highest tensions occur where straps wrap around the corners of walls. But provided sharp edges are rounded, the combination of direct tensile and bending strains in the straps remains low.

The effect of moisture upon straps needs to be taken seriously. Due to the way a strap is cut circumferentially around a tire tread, all ends of steel belt wires are exposed (Figure 1.3). In dry desert-like environments, where many adobe houses are found, corrosion is not a problem, however in wetter areas straps must be protected from moisture. In these cases the straps are protected by a coat of paint enclosing the strap in its mud plastered rebate (Figure 3.12). Where a vertical strap passes through or under a moist or wet foundation, it should be wrapped in plastic sheeting to keep it dry.

The remaining threat to strap longevity is oxidation – specifically the oxidation of the skim rubber into which belt wires are vulcanized and which adheres the two belts of a tire tread together. The main source of oxidation is the internally pressurized air of an inflated tire, so once treads are cut into straps the main driver of oxidation disappears. Limited testing of forty-three tires of up to 25 years of age by the author suggests that straps will have sufficient strength to resist earthquake forces after a period of at least fifty years.

2. EQUIPMENT AND MATERIALS

2.1 Equipment

The construction equipment needed to install tire straps is quite basic and includes most equipment found on a simple construction site. Specific items of equipment include:

- Claw hammer
- Hacksaw with fine tooth blades for cutting the steel wires and rubber of tire straps
- Leather gloves for handling rough edged straps caused by protruding belt wires
- Chisel with cutting edge 20-50 mm wide
- Steel bar approximately 1.0 m long and 20 mm diameter with chisel end
- Electric drill with a 400 mm long masonry drill bit 10-20 mm diameter
- Ratchet device with four short lengths of chain (Figure 2.1)
- Small steel plate, approximately 200 x 100 x 6 mm thick
- Pliers to cut and work tie wire when tying straps together on the faces of walls and through walls.
- Screw driver for inserting temporary screws for tensioning straps.

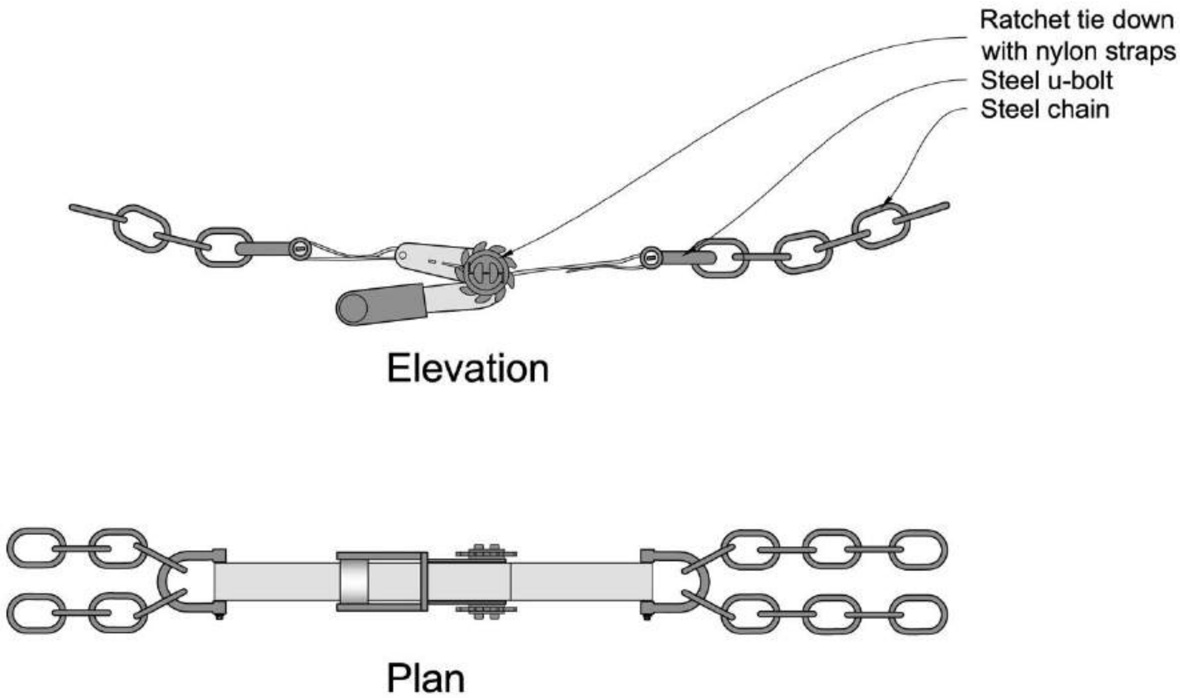


Figure 2.1 Elevation and plan of a simple ratchet device and attachments used to lightly tension straps during installation.

2.2 Materials

The following materials are required for strap installation:

- Tire straps, approximately 6.0 m long by 40 mm wide
- Nails 3.15 mm dia 70 mm long
- PVC sheeting 250 microns thick (where foundations are moist or wet)
- Plastic tape for creating waterproof PVC strap sleeves
- Water resistant paint (in moist and wet climates) and paint to make good the replastered areas over newly installed straps
- Mud mortar
- Plastic bottles or cans to create sleeves through which to pass straps in or under the foundations of new houses
- Screws for the strap tensioning process
- Tie wire for tying straps together
- Chalks for marking the positions of rebates for straps and holes

Information regarding the quantities of each of these materials is provided in Appendix C.

3. PREPARATION PRIOR TO STRAP INSTALLATION

3.1 Foundations

For a new house, the foundation is constructed using normal practice and materials. After setting out the foundation, excavations are completed and then once all door and window openings are planned it is necessary to mark out where the vertical straps will pass through the foundation (Figure 3.1).

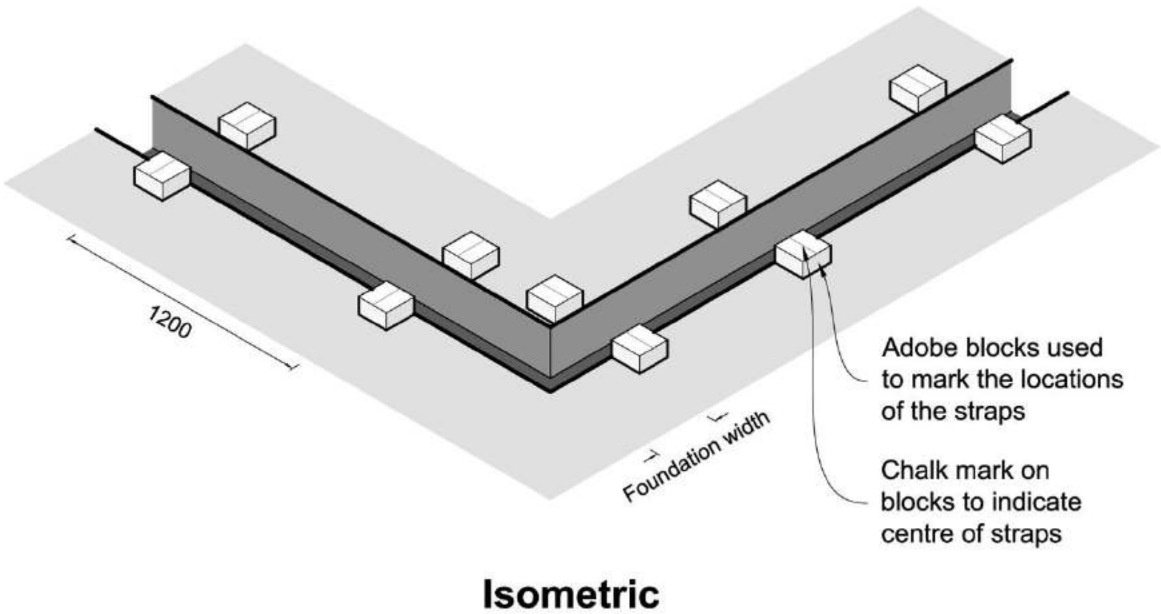


Figure 3.3.1 Adobe blocks are placed to mark the locations of the straps.

At this early stage of construction consideration must be given to the layout of the roof structure. This is because vertical straps must wrap over the rafters, tying them to the walls and preventing them from dislodging and falling during earthquake shaking. For this reason vertical straps must initially be positioned on the centerlines of as many rafters as possible, and then one strap of each pair of straps be off-set by 100 mm in plan. The off-set enables each strap to pass vertically up the wall and to pass over the rafter (Figures 3.2 and 3.3).

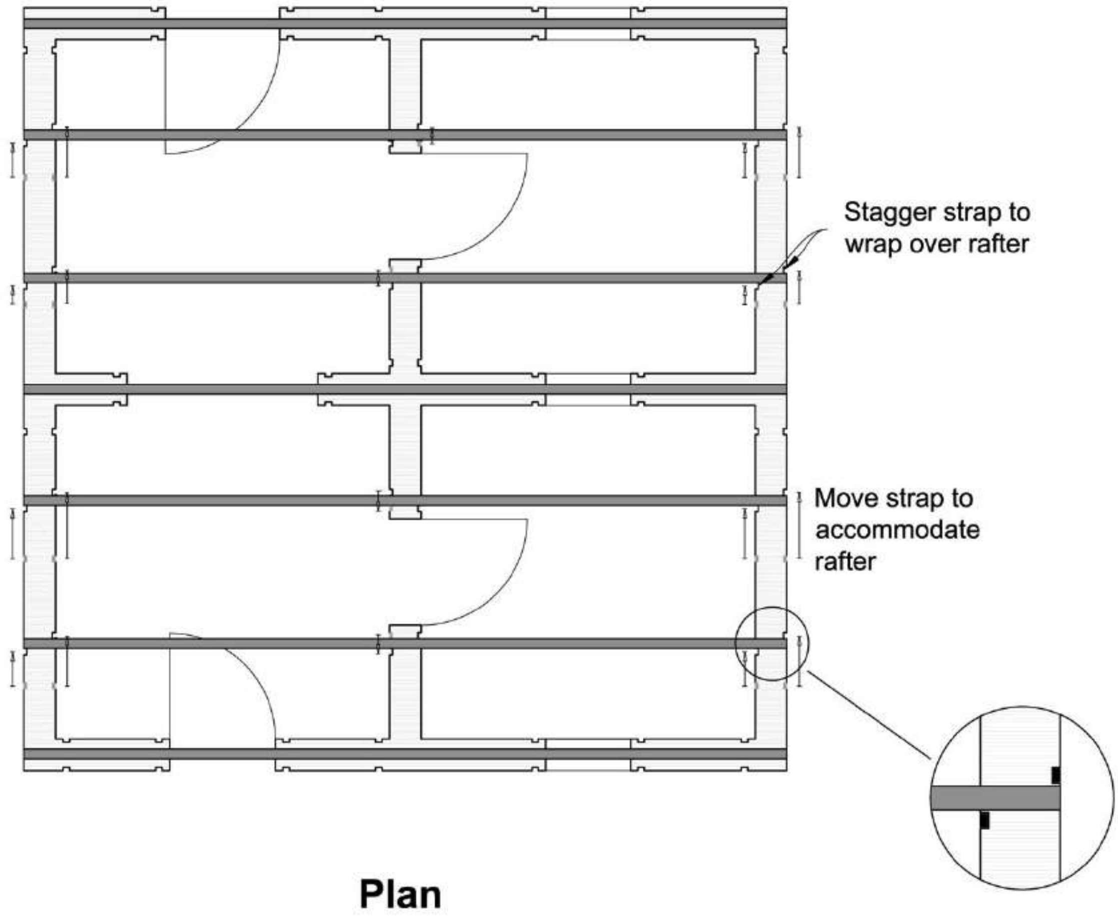


Figure 3.3.2 Plan of a house with walls and rafters shown. Straps need to be positioned under rafters where ever possible, and then off-set or staggered so they rise vertically up the wall and wrap over the rafters.

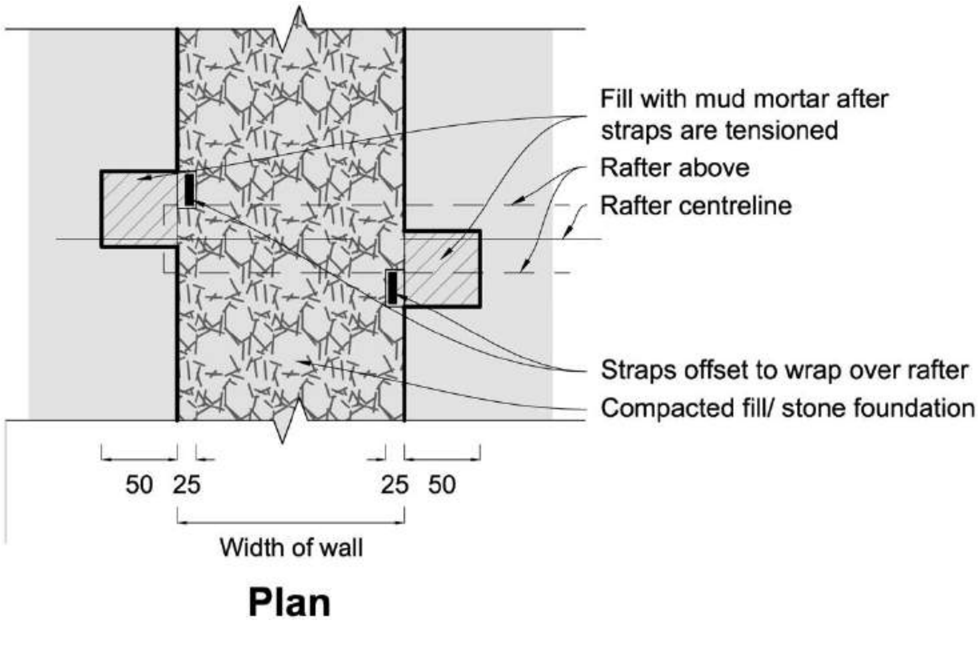


Figure 3.3 A plan view of a length of the foundation showing the position of off-set straps under a rafter and how they are set into the width of the wall.

The next step for new construction is to make a sleeve that is embedded within the foundation (Figure 3.4). A strap will pass through it after the wall is complete and rafters are placed. As a sleeve is placed it is also necessary to make a small excavation beyond the sleeve at each end so the strap can be inserted once the wall is constructed. Adobe blocks temporarily cover these voids to keep them free of construction debris, and are slid back when required to place the strap (Figures 3.5 and 3.6).

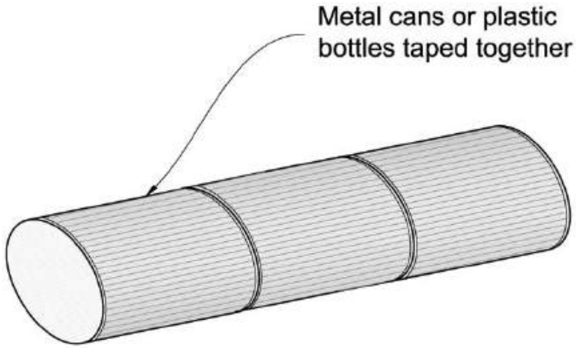


Figure 3.4 A sleeve is constructed from any (recycled) material provided the internal diameter is over 50 mm.

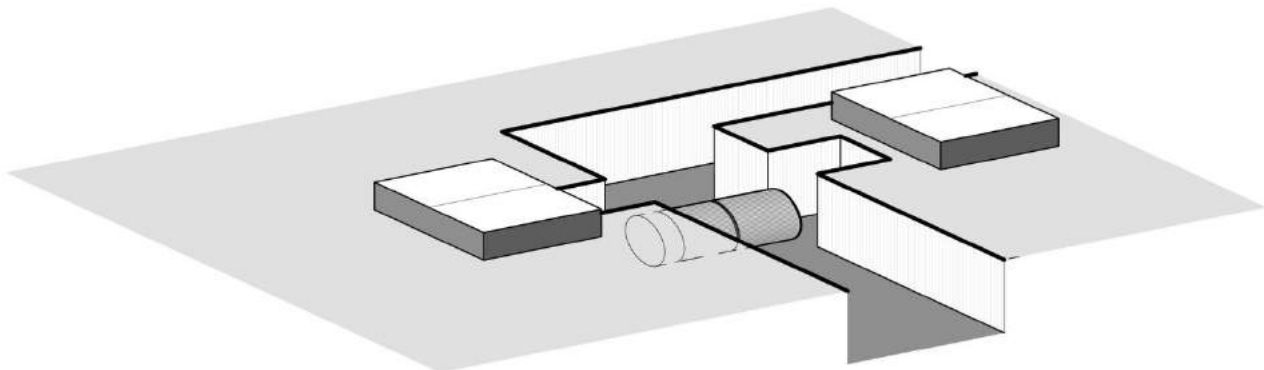


Figure 3.5 A sleeve is placed and small side-excavations made.

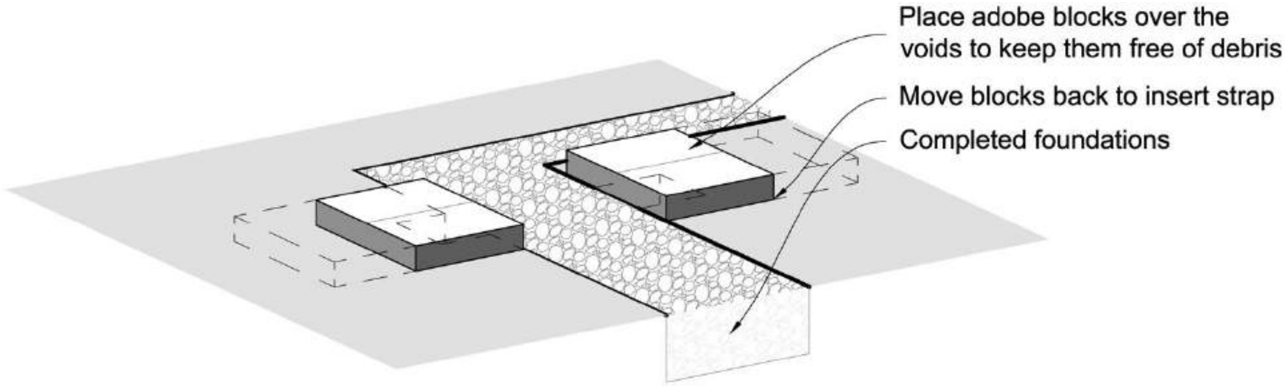


Figure 3.6 Adobe blocks protect the small excavations from filling up with debris and are slid back immediately prior to installing the strap under the wall.

Where straps are applied to the walls of an existing house it is not necessary to use sleeves. Holes must be dug on each side of the wall and then a hole made under or through the existing foundation no closer than 200 mm to ground level. The minimum hole diameter should be 50 mm and any rough edges smoothed so the waterproofing pvc sheet sleeve (if required) as well as the strap itself is not damaged on sharp edges during tensioning or during an earthquake (Figure 3.8(b).

3.2 Walls

The preparation of walls prior to strap installation involves forming vertical and horizontal rebates in which the straps are to be positioned and embedded (Figures 3.7 and 3.8). Vertical rebates are 25 mm deep, while horizontal rebates need be only 15 mm deep since they accommodate horizontal straps that are placed after the vertical straps and are therefore located closer to the exterior surfaces of the walls.

Horizontal holes at wall corners are also to be formed. In new construction, temporary slot formers can be placed and then removed (Figure 3.9). This avoids the task of drilling through corners that is inevitable for existing houses. These holes are best formed by a combination of drilling and then enlarged by hand using a sharpened steel rod.

In order to accommodate the relatively thick nailed joint where the two ends of a strap are joined, each strap requires a short length of rebate that is 10 mm deeper (Figures 3.10 and 3.11).

In moist and wet climates, at least rebates on exterior wall surfaces should be painted with a water-resistant paint such as a bituminous paint prior to strap installation. The intention is to ensure that the strap is enclosed by a continuous painted surface to prevent the ingress of moisture that corrodes tire belt wires (Figure 3.12).

In Figure 3.12 a debonding layer is shown between the outside surface of the strap and the mud plaster that fills the remainder of the recess in the adobe. The purpose of this layer, which could be of moistened newspaper or thin plastic is to prevent the plaster bonding to the rubber. This detail is to accommodate differential temperature movement between the straps and the adobe. Measurements of the coefficient of linear expansion of straps show that for a temperature variation of 40 degrees Celsius a three meter length of strap will expand or contract 4 mm more than the same length of adobe. By introducing a de-bonding layer between rubber and plaster, strains introduced into the straps will be more uniform along their lengths and therefore less likely to cause cracking of the mud plaster on the outside of the straps.

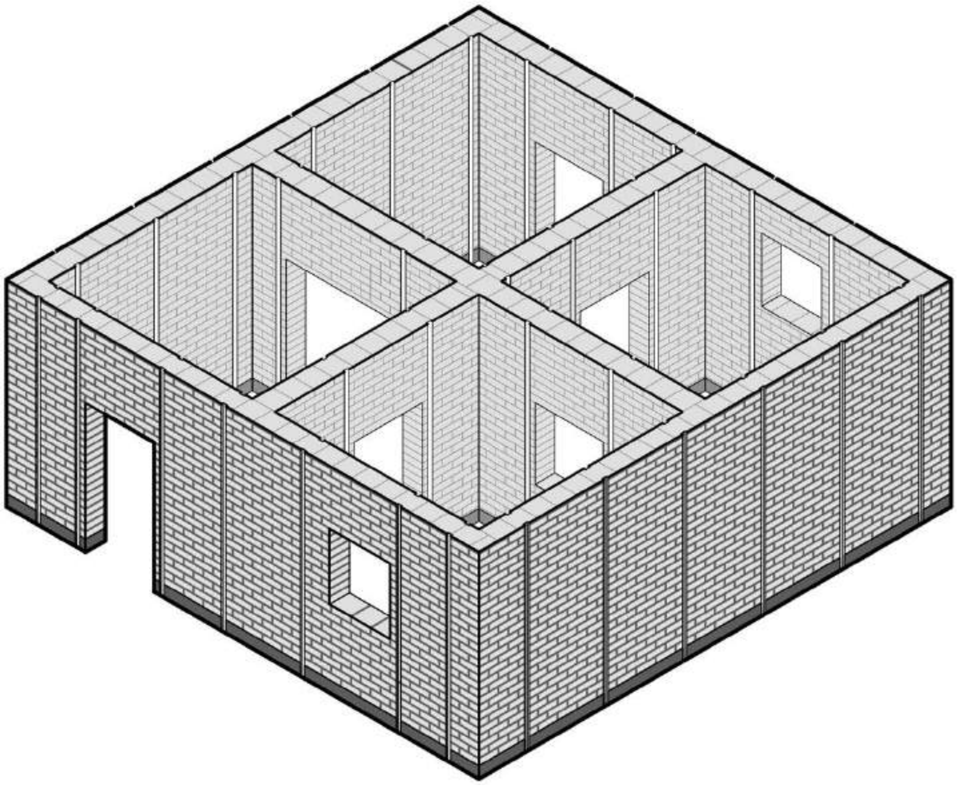


Figure 3.7 House with rebates completed for vertical straps.

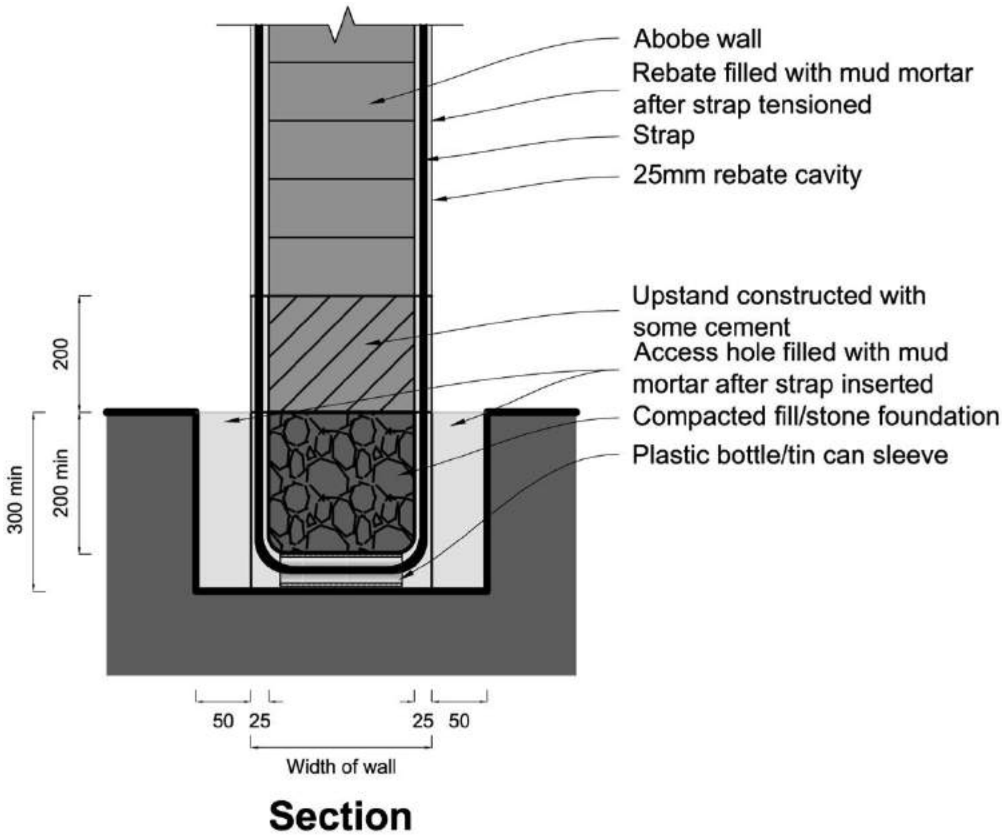


Figure 3.8 (a) Section through new wall construction showing a strap passing under the foundation and the position of the vertical strap in its rebate.

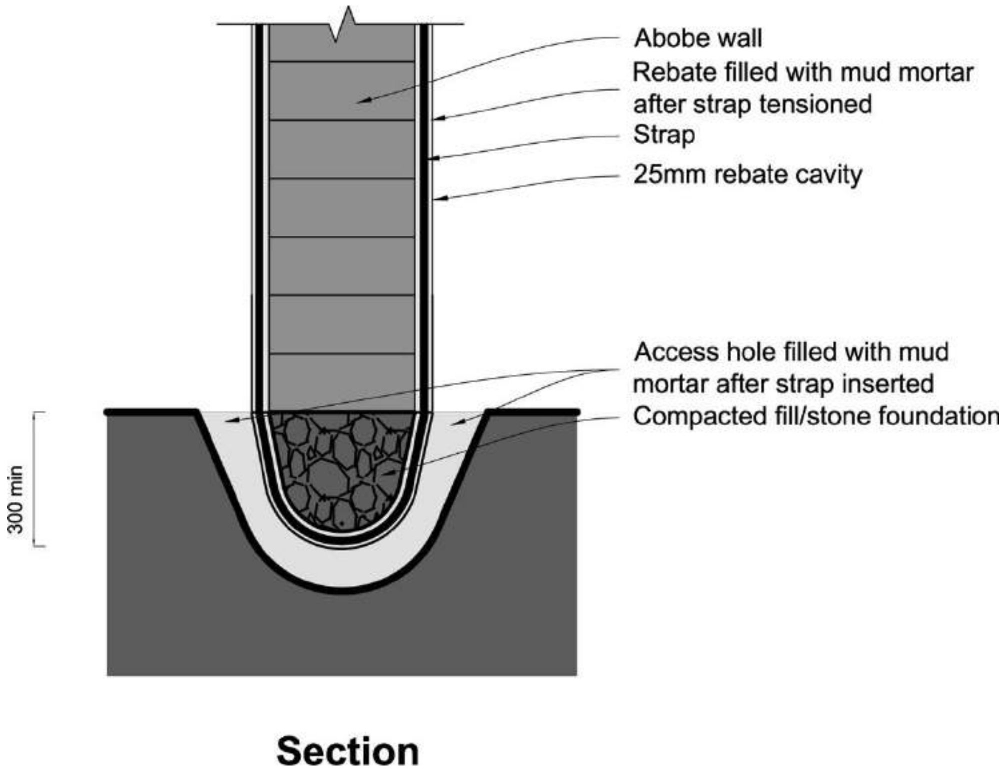


Figure 3.8 (b) Section through a wall showing a strap passing under the foundation of an existing wall.

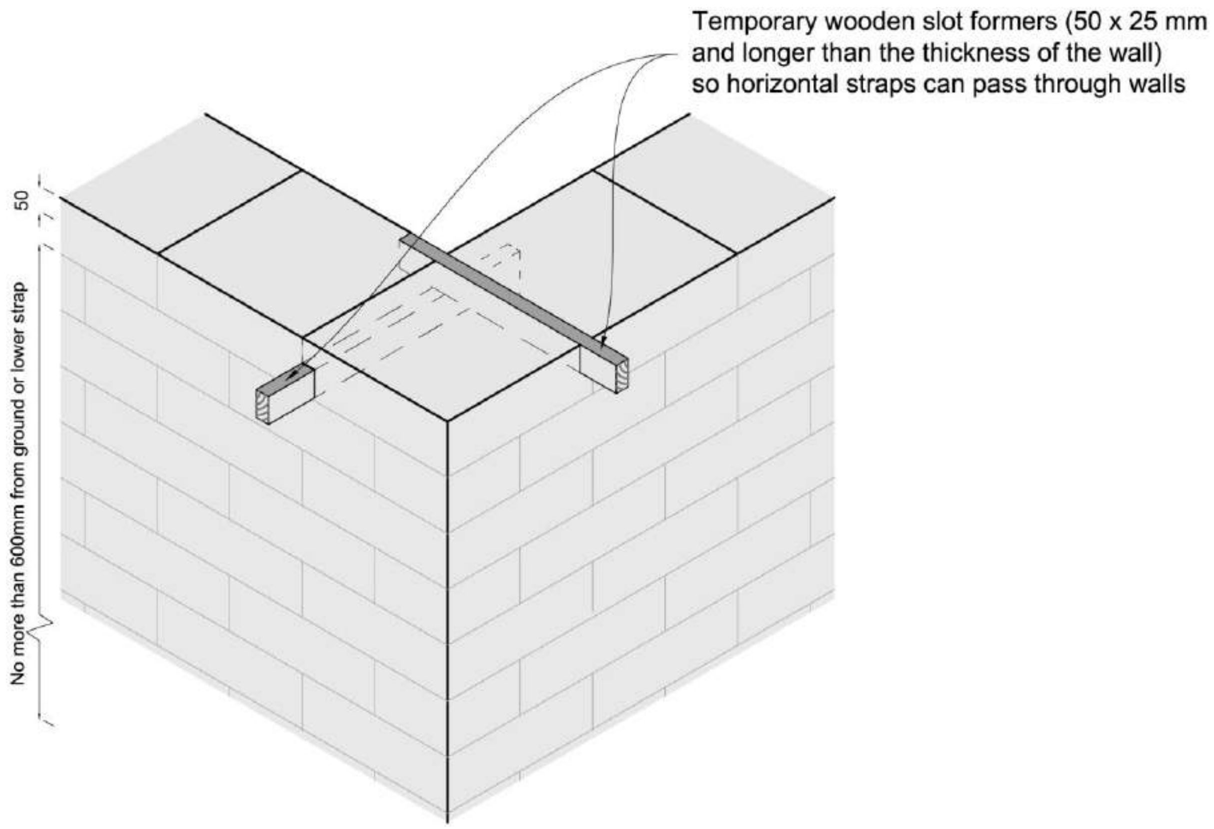


Figure 3.9 Slot formers reduce the need to drill through walls at the corners of new construction.

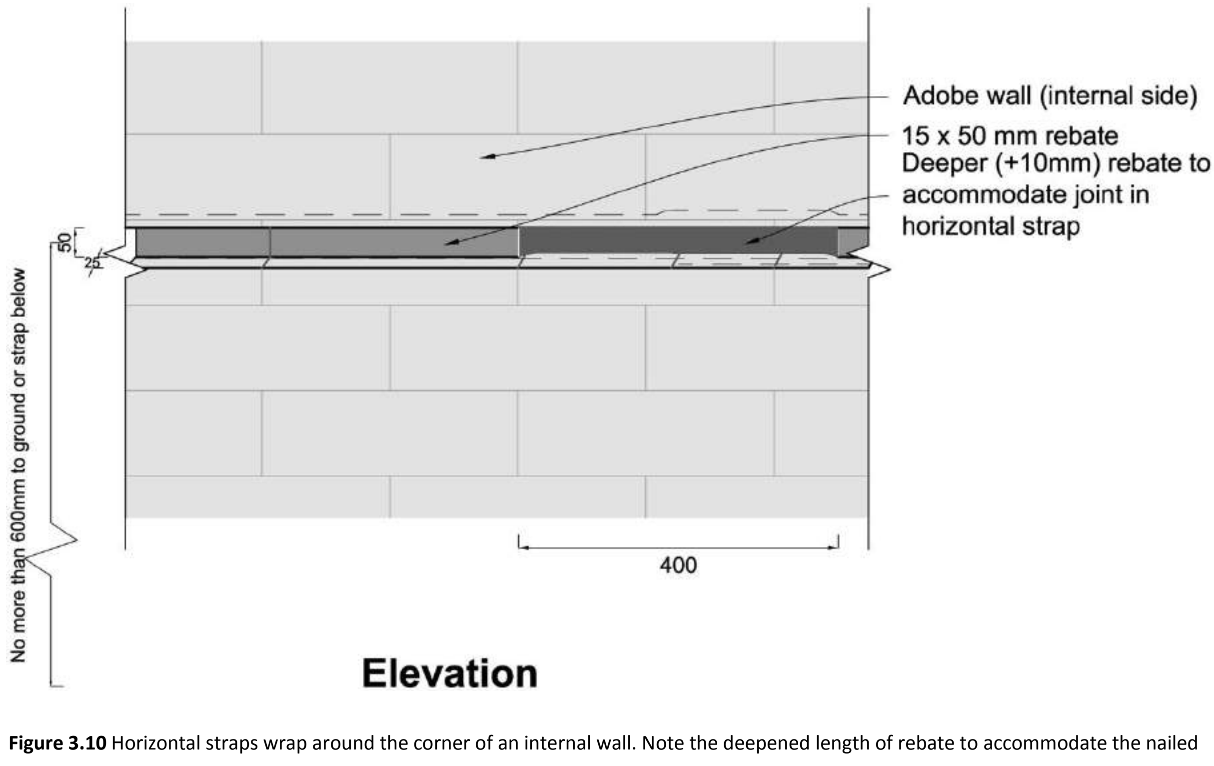


Figure 3.10 Horizontal straps wrap around the corner of an internal wall. Note the deepened length of rebate to accommodate the nailed joint of the strap. The position of the deepening should allow for easy strap tensioning of the joint, avoid clashing with a vertical strap running at right angles and be on the inside face of a wall to reduce the risk of corrosion.

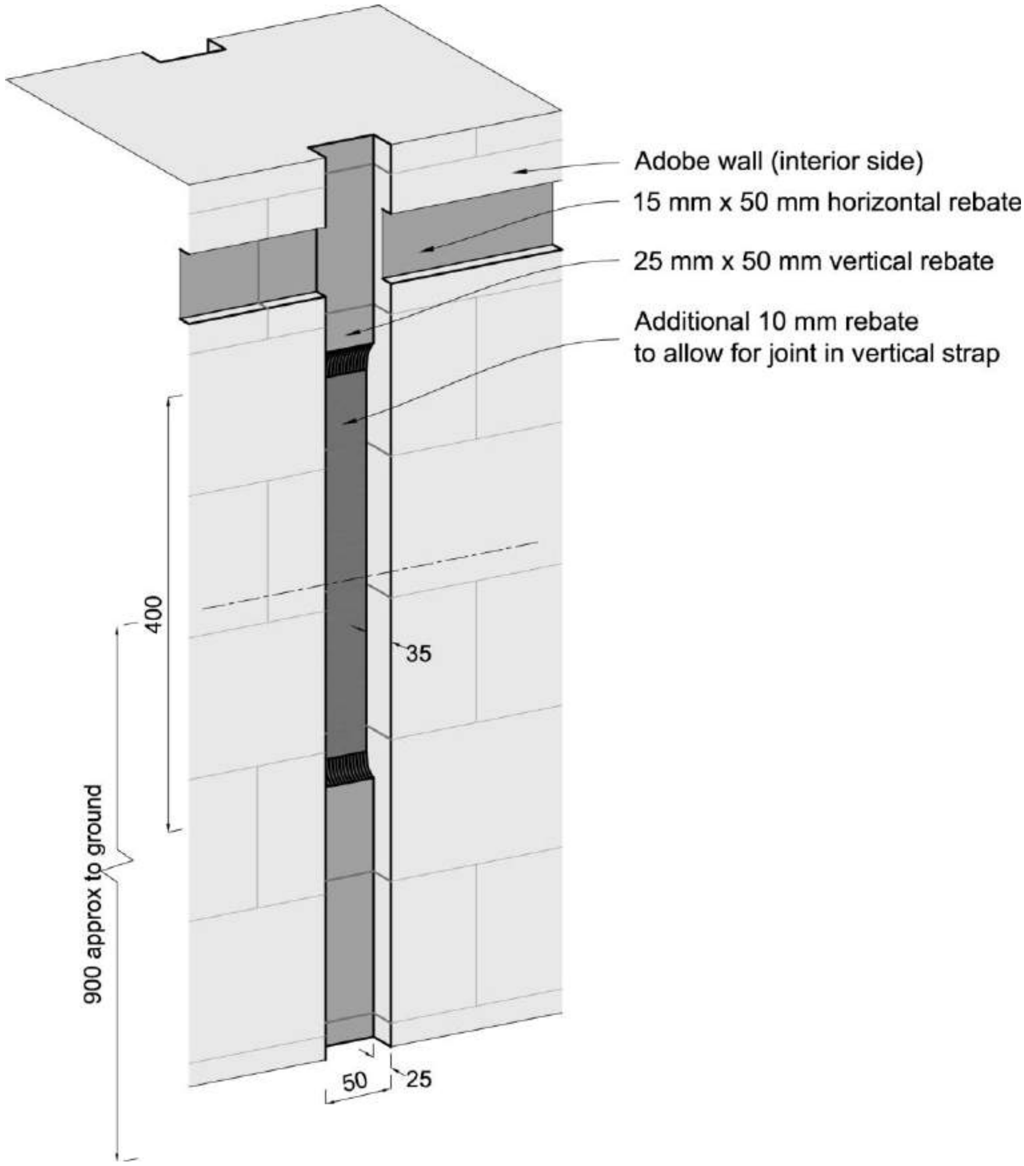


Figure 3.11 A typical vertical rebate on an inside wall surface with a deepened length for the strap joint.

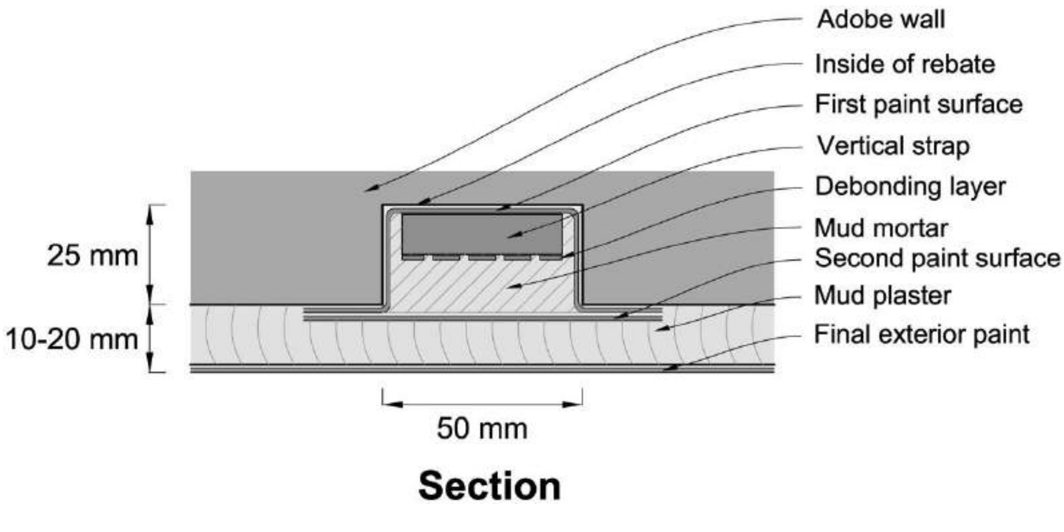
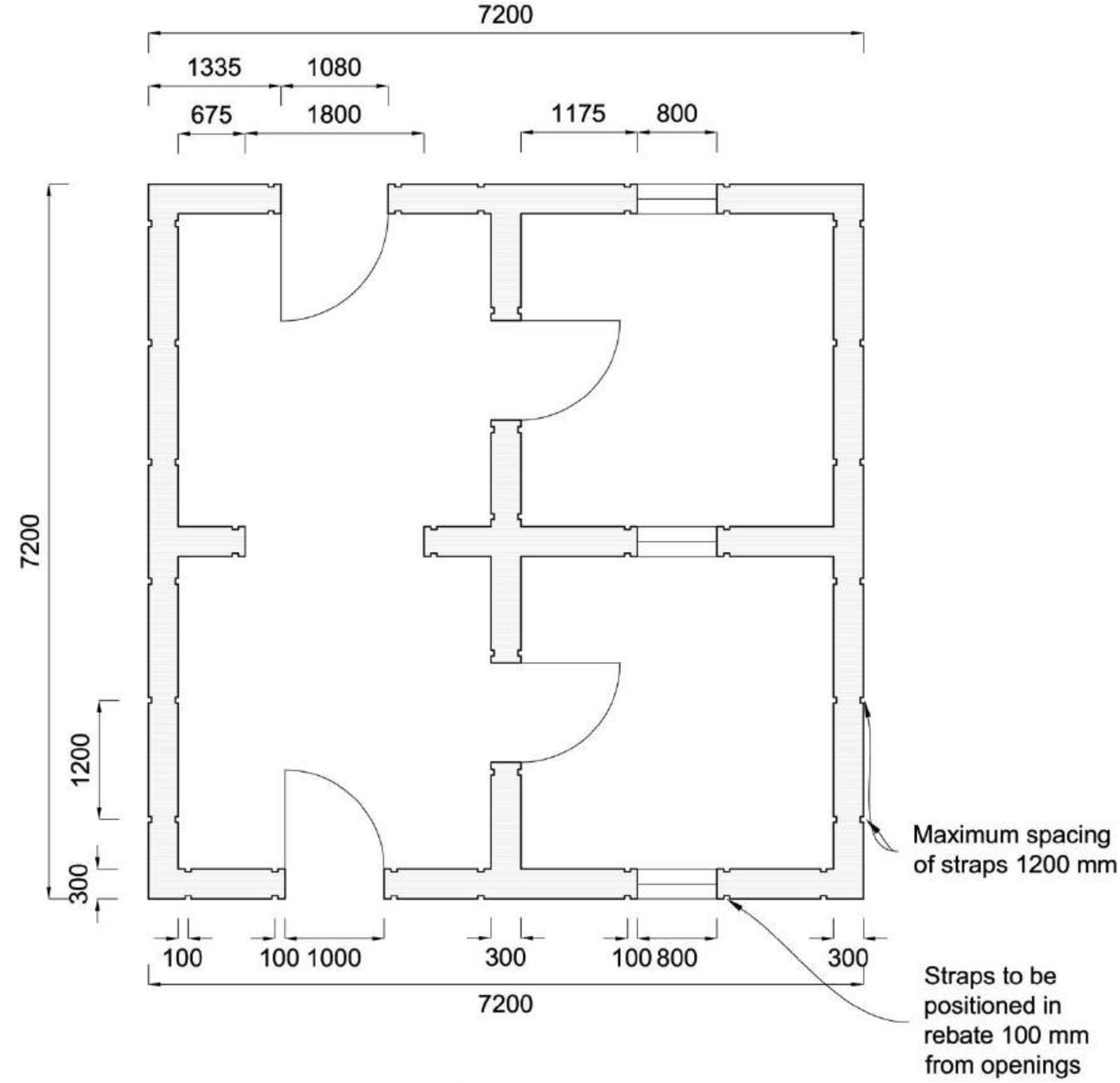


Figure 3.12 Section through a vertical strap showing the two internal painted surfaces to protect the strap from moisture.

4. INSTALLATION OF STRAPS

4.1 Vertical Straps

At this stage of construction, rebates have been completed and painted (if necessary) (Figure 4.1). After choosing a strap of suitable length to minimize wastage, the first half of the nailed joint should be completed (Figures 4.2 to 4.5). For moist or wet climates a pvc sheath is placed around the strap where it passes through and up each side of the foundation (Figures 4.6 to 4.7).



Plan

Figure 4.1 Plan sketch showing idealized locations of vertical rebates and straps. Off-sets (see Figure 3.3) allow for wrapping the straps over the rafters.

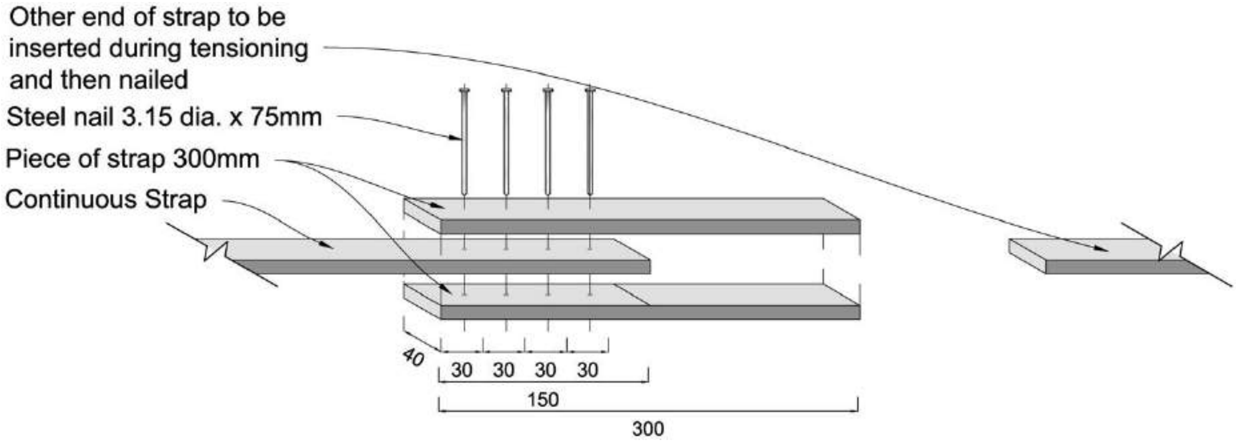


Figure 4.2 Joint nailing at one end of a strap to be completed before tensioning the strap. For a high or long wall it may be necessary to join two straps using this detail before tensioning.

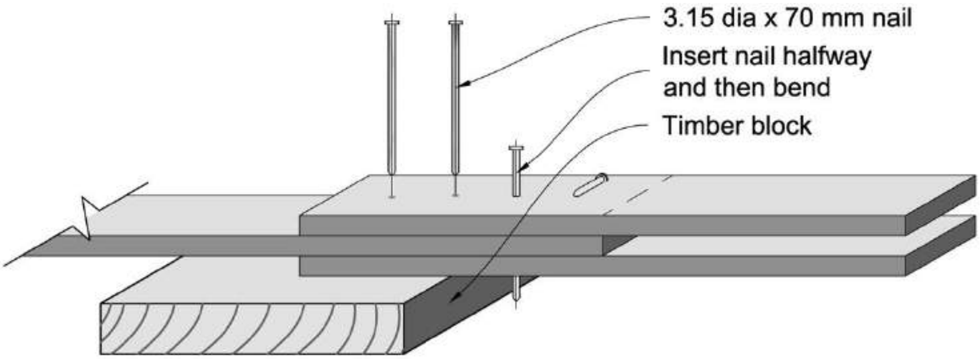


Figure 4.3 A partially nailed joint.

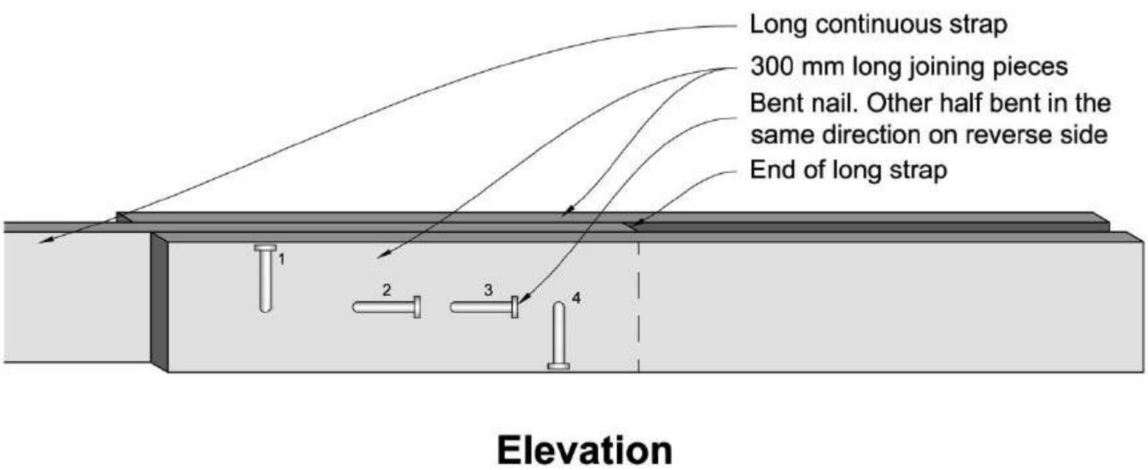


Figure 4.4 A half completed joint showing the all-important bending of nails to prevent them pulling through under high tension forces. This nail layout and bending pattern must always be implemented as shown.

Figure 4.5 A firm support and a steel plate assist the nailing and nail bending process.

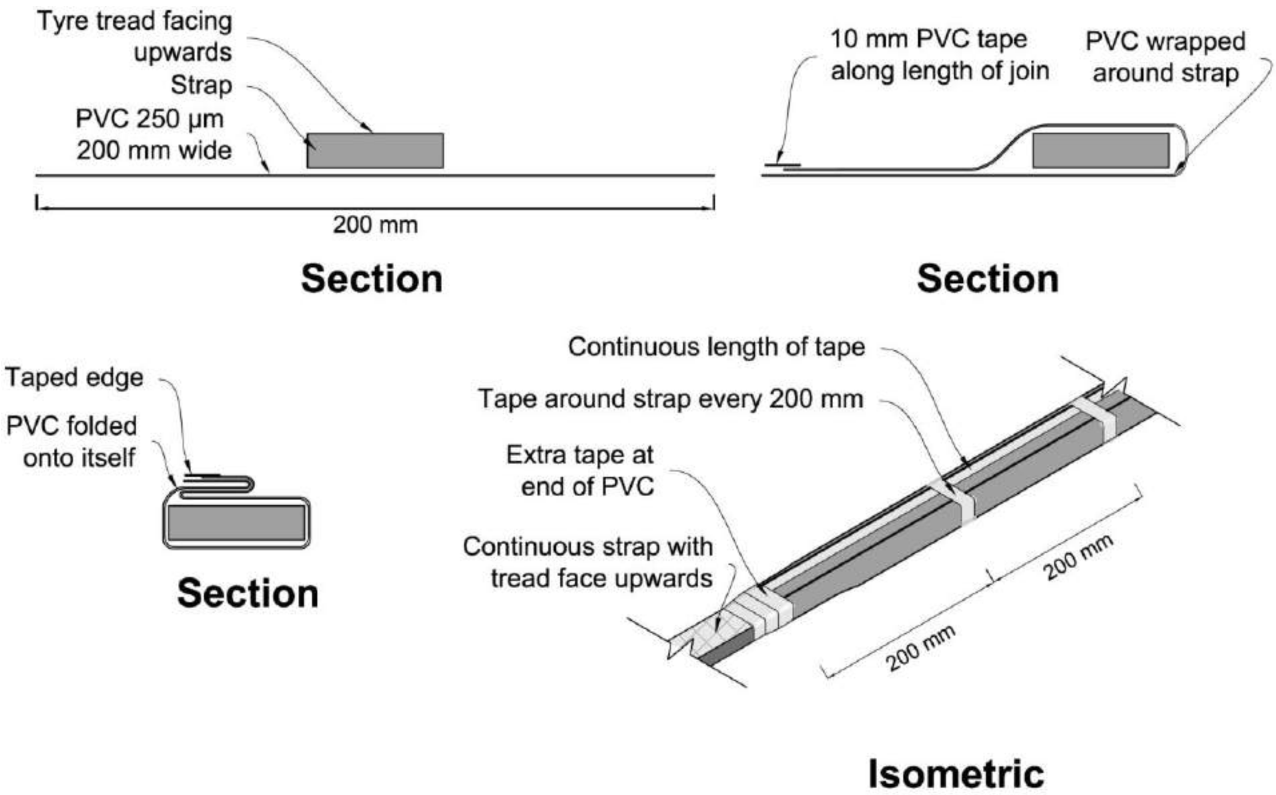


Figure 4.6 A detail of how the PVC sheet is made watertight.

Figure 4.7 A strap with a length of PVC sheet to provide water protection to the strap below ground level and up to the height where the strap is protected by mud mortar and painted surfaces.

The strap is then passed under or through the foundation, passed over the top of the wall, including the rafter if applicable (Figures 4.8 to 4.11), and then positioned ready to tension (Figure 4.12). Two chains engage each screw near the ends of the strap and tensioning begins. It is important to ensure that the lengths of strap on *both sides* of the wall are tensioned equally. A steel bar providing additional tension from the top of the wall can help to achieve this (Figure 4.13). Tension is applied by firm hand pressure on the ratchet. If too much pressure is applied to the ratchet it might break.

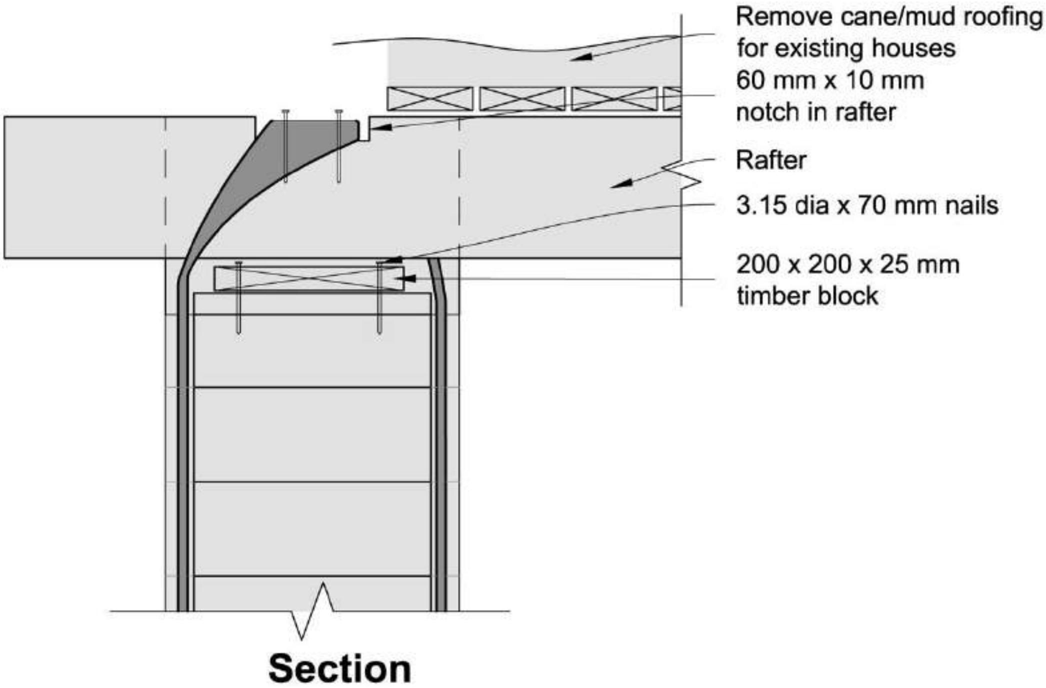


Figure 4.8 A vertical strap wraps over a rafter. Its location in a shallow notch prevents the rafter falling from the wall. In an existing house an area of roofing needs to be removed to achieve this detail.

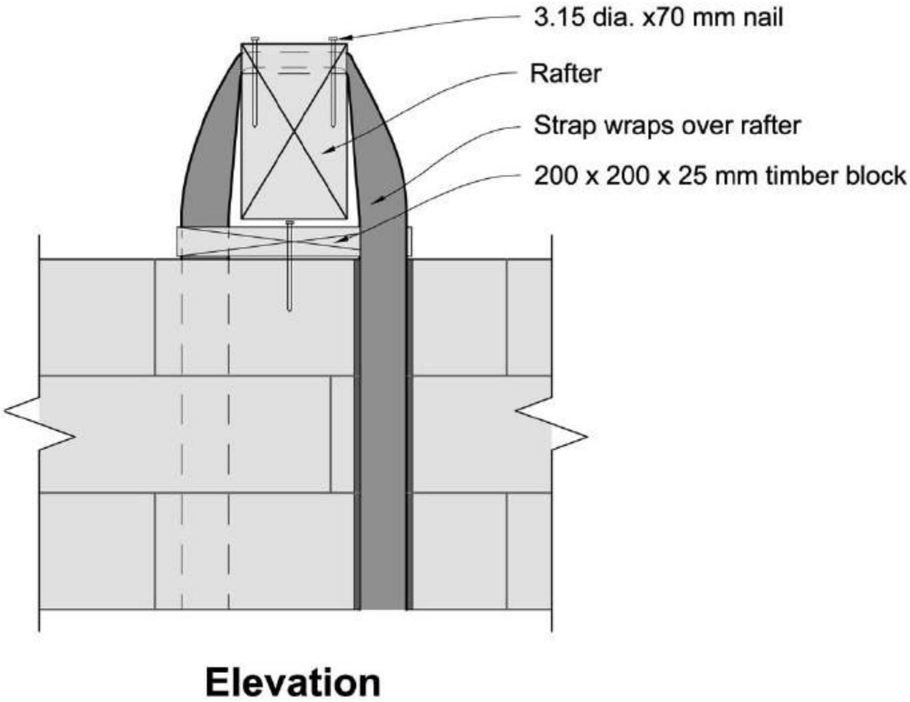


Figure 4.9 A strap wraps of the rafter and after tensioning is complete, is nailed to it.

Figure 4.10 A strap wrapping over a rafter. In this trial house the straps were not placed in wall rebates and the rafters were not notched.

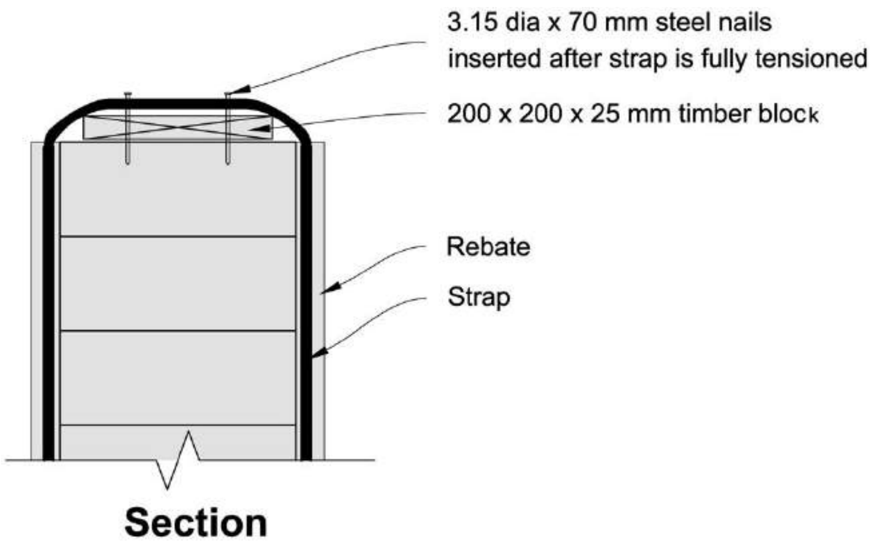


Figure 4.11 Where straps do not meet rafters they should pass over a short wooden block and be nailed to it after tensioning.

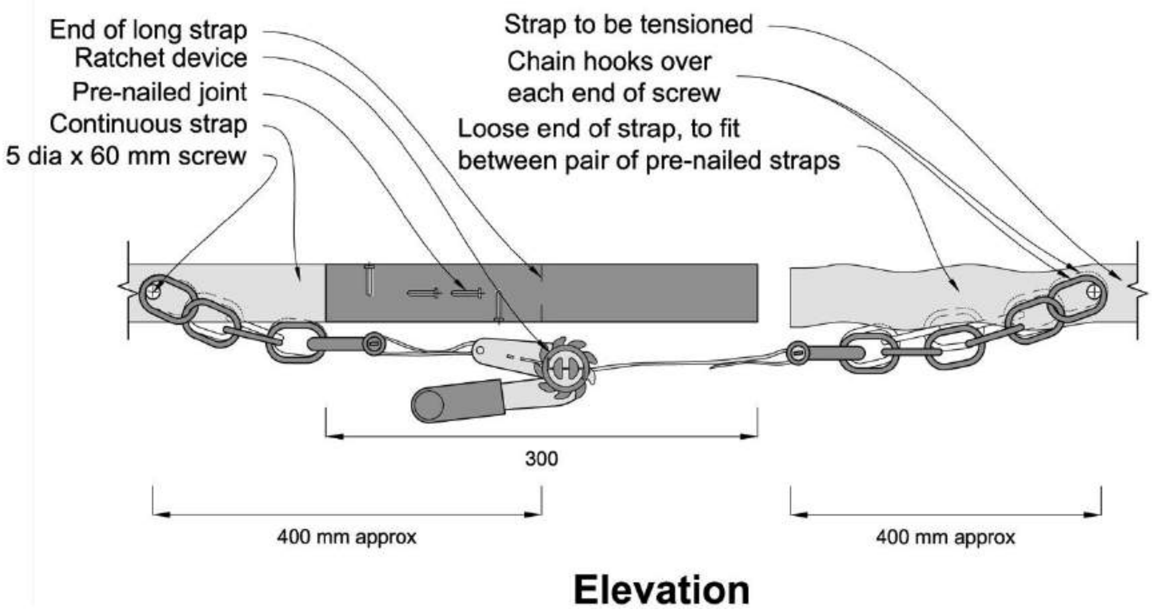


Figure 4.12 After a screw is positioned near each end of the tire strap, the ratchet and chains are attached and tensioning begins. (Strap and ratchet drawn in horizontal position).

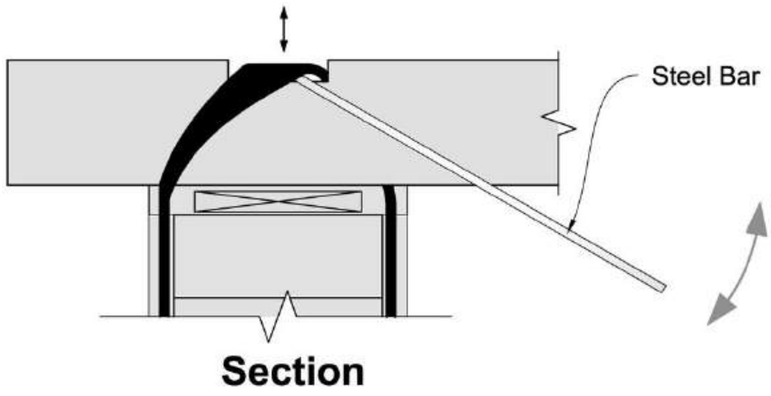


Figure 4.13 Strap tension on both sides of the wall is equalized using a steel bar during the tensioning process.

During tensioning an adequate gap must be provided between both ends of the strap to allow for the strap stretching. It may be necessary to reduce the length of the strap during tensioning by releasing the tension and trimming the non-nailed end of the strap. After final tensioning the gap between the two ends should be less than 20 mm (Figures 4.14 and 4.15). The procedure is completed when the other end of the joint is then nailed, and the ratchet and chains released and removed. Check to see if the straps are taut after driving the first nail. If not, remove the nail, shorten the strap and re-tension.

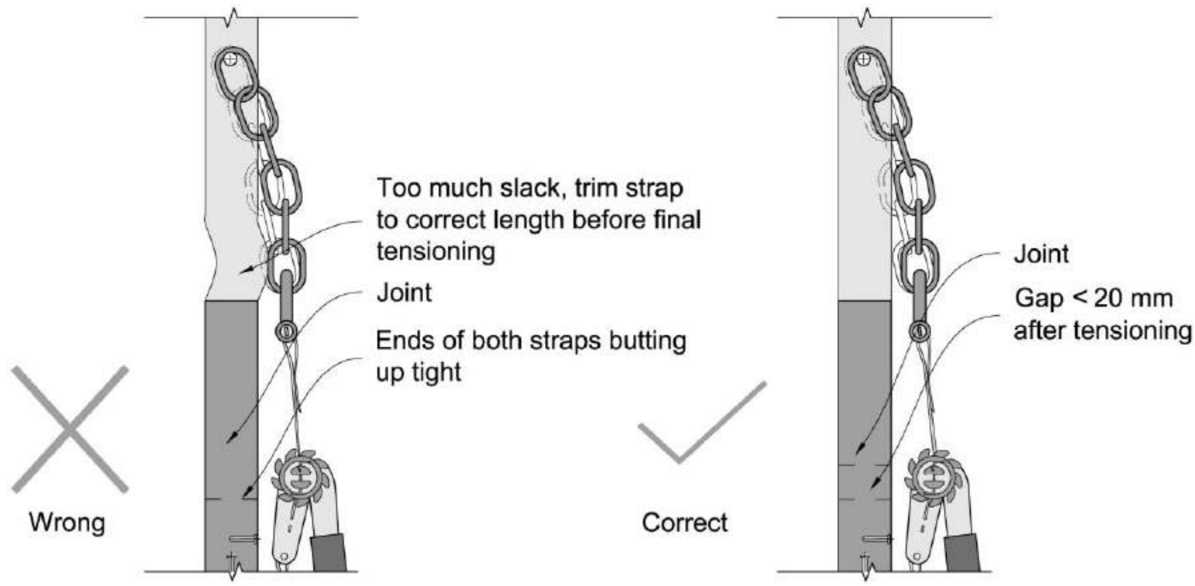


Figure 4.14 The strap length might need reducing during tensioning to allow full tension to be achieved before the ends of the strap meet.

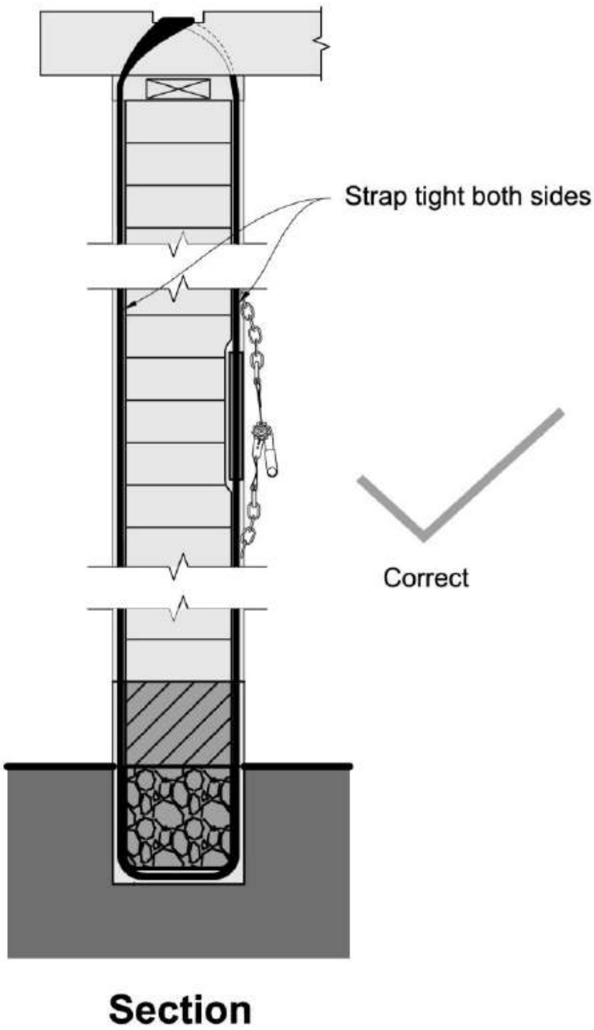


Figure 4.15 Successfully stressed strap awaiting final nailing and removal of tensioning equipment.

4.2 Horizontal Straps

After the installation of vertical straps is completed, horizontal straps are prepared and installed. In principle, the steps outlined previously apply to the installation of horizontal straps as well. The objective is to achieve slightly tensioned or taut straps at a maximum of 600 mm vertical spacing up the wall. The uppermost strap should be less than 300 mm from the top of the wall. This might mean reducing the vertical spacing between the top two horizontal straps.

If straps wrap around a wall or pier less than 900 mm long the vertical spacing between straps should be reduced to 300 mm. The extra straps will ensure any diagonal cracks are crossed by straps, and provide better confinement of the wall to improve its seismic performance.

Each strap is to wrap around a wall. It often needs to pass through another wall at right angles in the process (Figures 4.16 and 4.17). The tensioning process is the same as for vertical straps and working the strap at one end of a wall with a bar to equalize tensions on both sides of the wall is necessary (Figures 4.18 to 4.20).

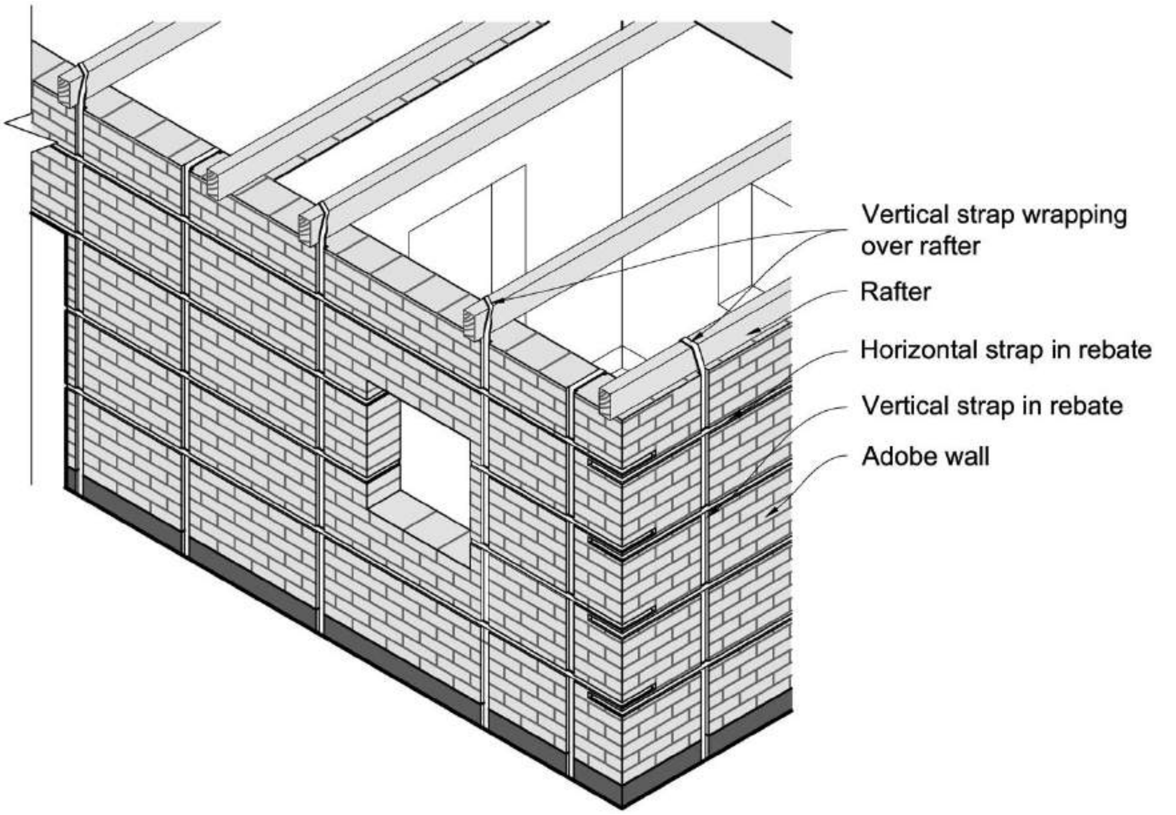


Figure 4.16 Vertical and horizontal straps have been installed. Note how horizontal straps wrap around walls and pass through walls at right angles in order to form a continuous band.

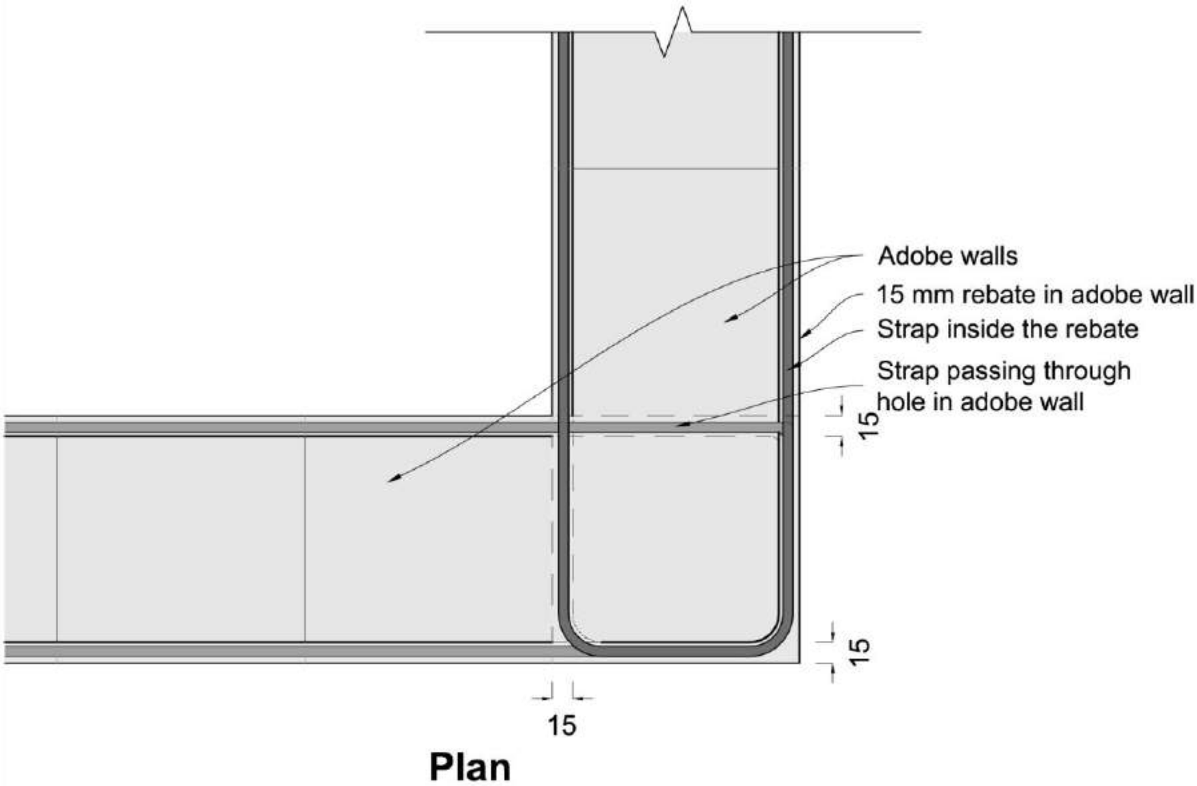


Figure 4.17 Plan view of a layer of two horizontal straps at an exterior corner. Note that because horizontal straps are applied after the vertical straps, their rebate is shallower (15 mm).

Figure 4.18 The upper strap is taut but requires shortening using a hacksaw before nailing the joint.

Figure 4.19 Strap is tensioned with the half pre-nailed joint hanging down. The right-hand end of the strap requires shortening.

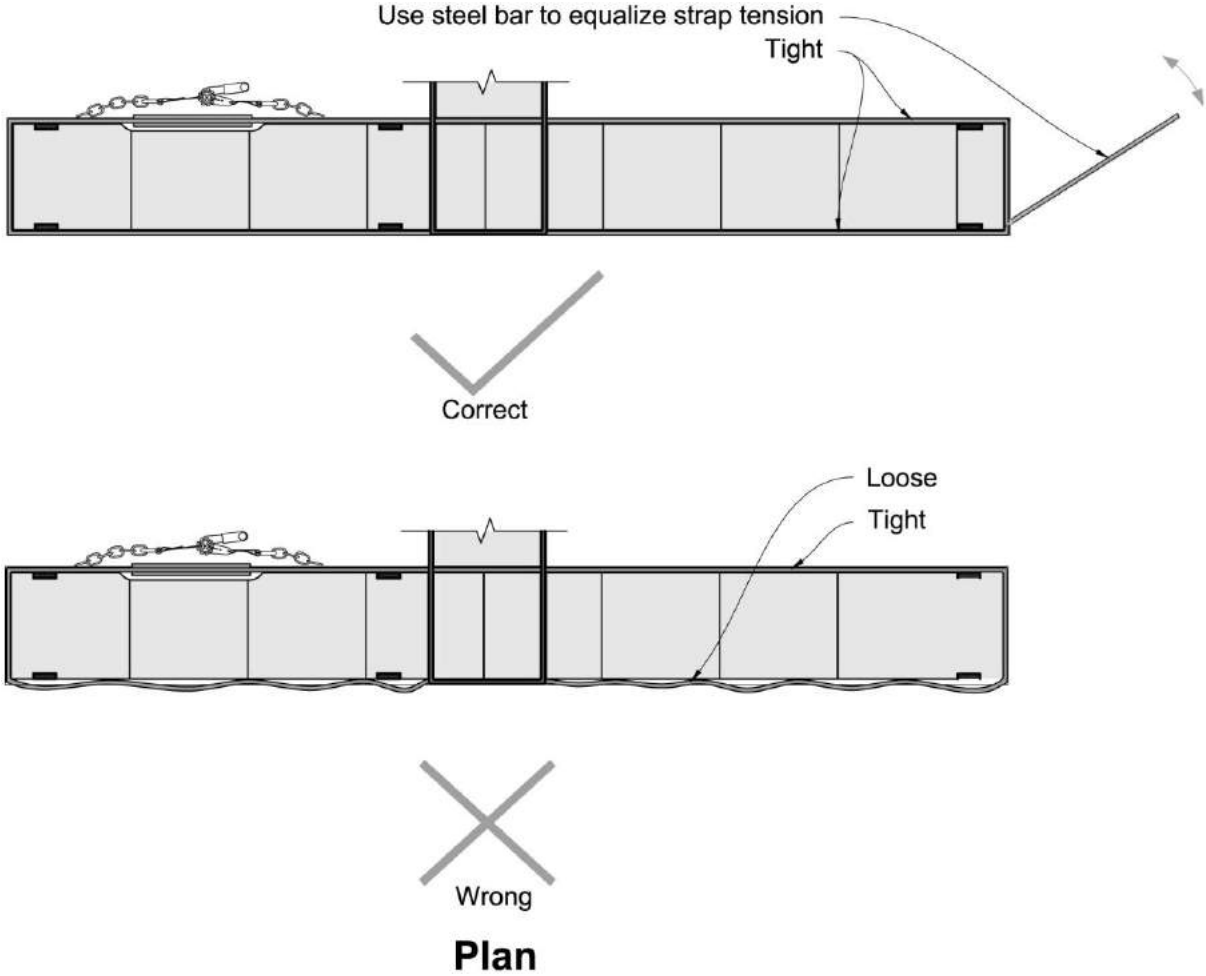


Figure 4.20 Levering the strap at the end of a wall is necessary to achieve equal tension on each side of the wall.

Before nailing a joint (Figure 4.21), check that the level of the horizontal joint between two straps at a corner is positioned along the centre of an adobe block, or a stone in the case of a stone masonry building (Figure 4.22), and not a horizontal (mortar) joint. The reinforcement system is weakened if the joint between straps aligns with a horizontal joint between adobe blocks.

Where horizontal straps pass across and through a return wall, such as shown in Figure 4.20), the horizontal strap should pass through a u-strap from the return wall. This means the U-strap needs to be slightly tilted to allow the horizontal strap to pass through (Figure 4.23)

Figure 4.21 After using a wooden backing block to drive a nail half-way through, a steel plate helps bend the nail down on the back of a strap.

Figure 4.22 Two straps around an exterior corner. The upper edge of the top strap is aligned with the horizontal mortar joint. The horizontal joint between the two straps is therefore approximately mid-height of an adobe block. Note that the hole for the lower strap is deeper vertically than necessary.

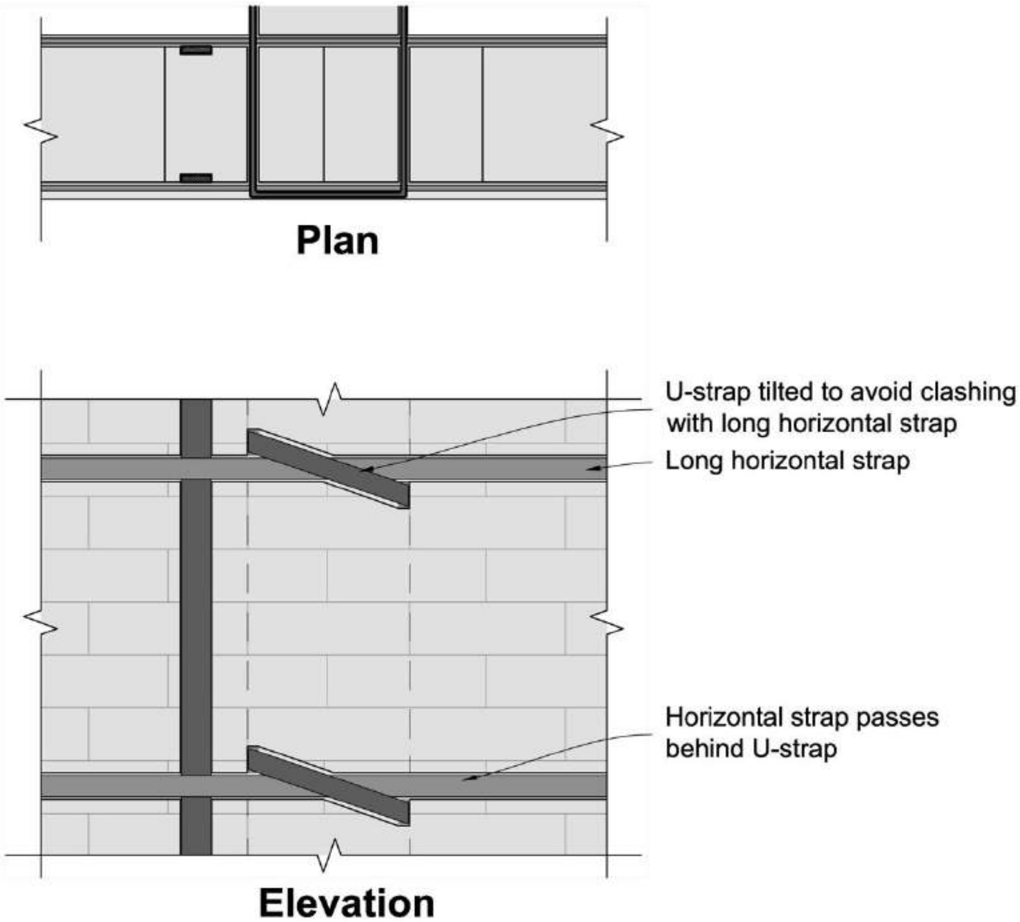


Figure 4.23 At a T-junction outer straps pass through the U-straps from the return wall.

4.3 Parapets and Gable Walls

Where parapets occur, vertical straps should wrap over the top of the parapet, passing down both sides of the wall. A detail like a U-strap, using a length of normal tire reinforcing strap, ties the outer vertical strap, and the wall, back to a rafter (Figures 4.24 and 4.25). In the situation with gable walls, straps should be taken up and over the wall. If rafters meet the wall the straps should wrap over them and sit in shallow notches cut into the top edge of the rafters (Figure 4.8). Otherwise tie any roof timbers to the gable wall with U-straps (Figure 4.26).

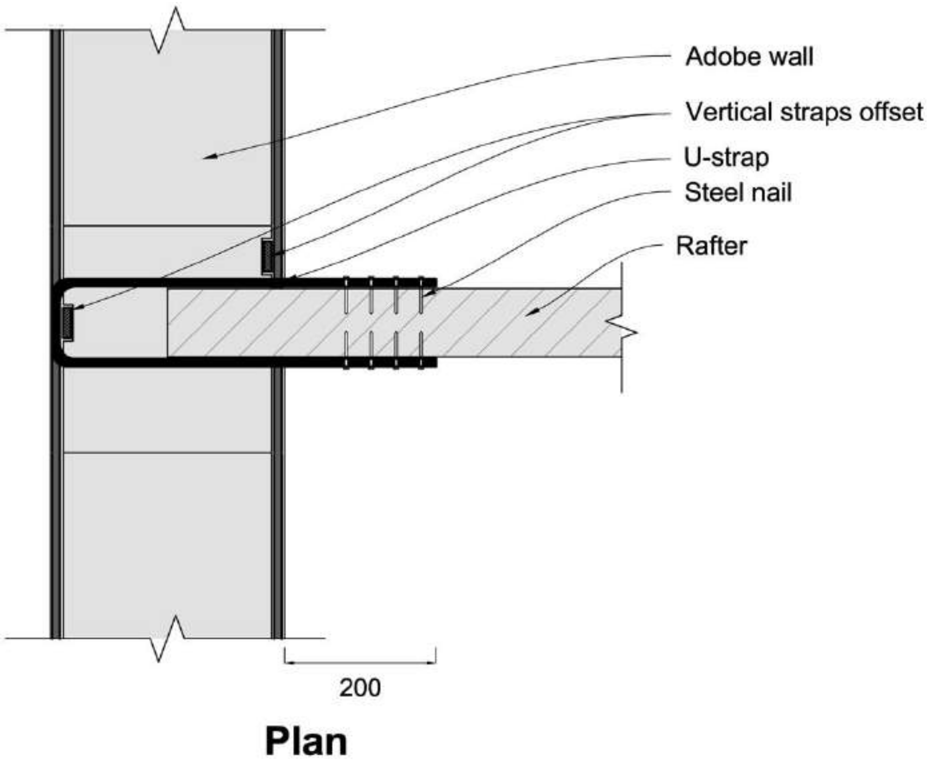


Figure 4.24 A length of a parapet wall at rafter height.

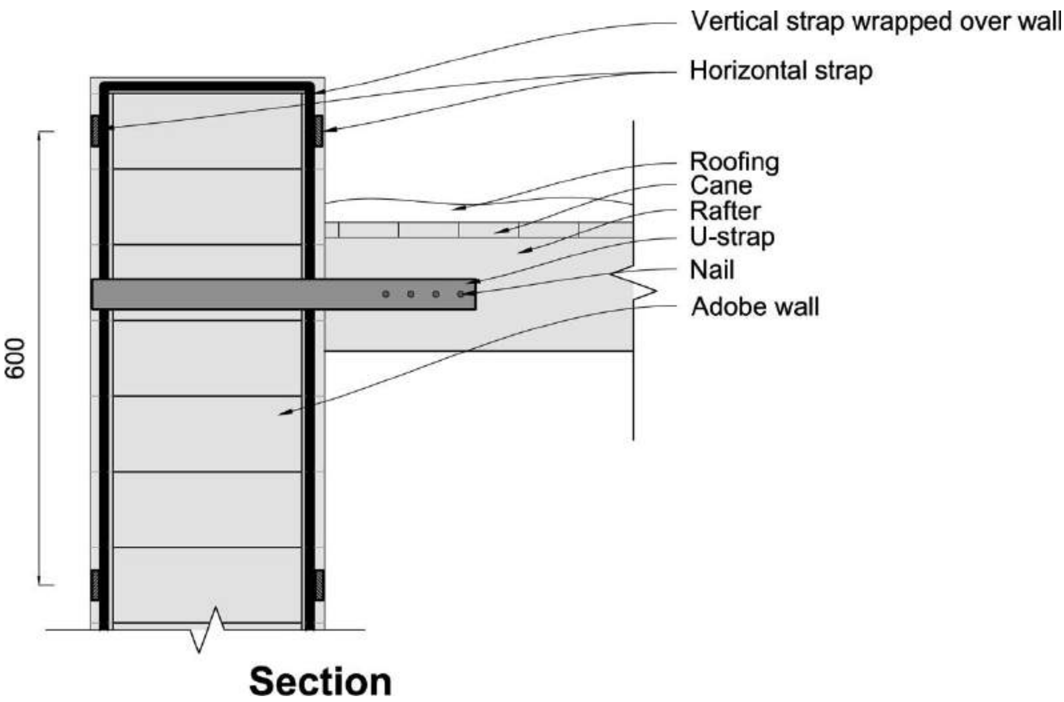


Figure 4.25 Section through the top of a parapet wall showing a U-strap wrapping around a vertical strap and nailed to a rafter. This detail prevents the wall moving away from the rafter, causing it to fall.

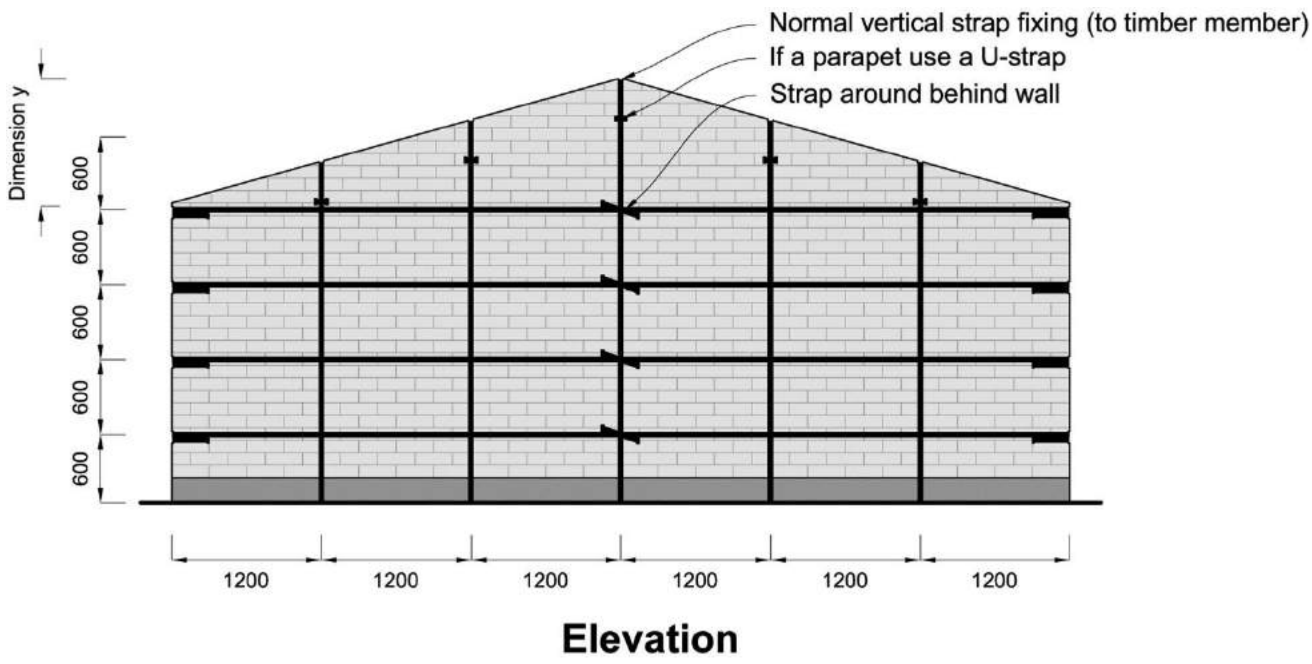


Figure 4.26 A gable and a parapet wall. There is a wall behind the middle of the gable wall. If 'y" is greater than 1000 mm, use two top horizontal straps side by side along the return wall to tie it to the gable wall.

4.4 Tying Straps to Each Other through Walls and Side-by-Side

Full-scale shaking table tests of an adobe house have shown how important it is to tie *all* vertical and horizontal straps together and that most of these junctions be tied *through* the walls. Only where junctions are less than 300 mm from a return wall or where a horizontal strap wraps around a wall is it unnecessary to tie through a wall. Figures 4.27 and 4.28 illustrate how corner straps are tied. Use approximately 1 mm diameter mild steel reinforcing tie wire.

At all horizontal and vertical strap junctions away from corners and wall ends, holes are drilled through the walls and the straps tied together (Figures 4.29 and 4.30). This applies even to the top horizontal strap of a wall which is always close to the top of the wall. This area of the wall, particularly in the mid-span region, experiences the most severe shaking.

If the top horizontal strap is not giving horizontal support to the top layer of adobe blocks every second top adobe block should be tied to the strap to prevent the uppermost blocks dislodging and falling from the top of the wall causing injury (Figure 4.31).

After tying every junction, hammer the wire knot into the strap to increase the amount of mortar and plaster cover and reduce the likelihood of corrosion.

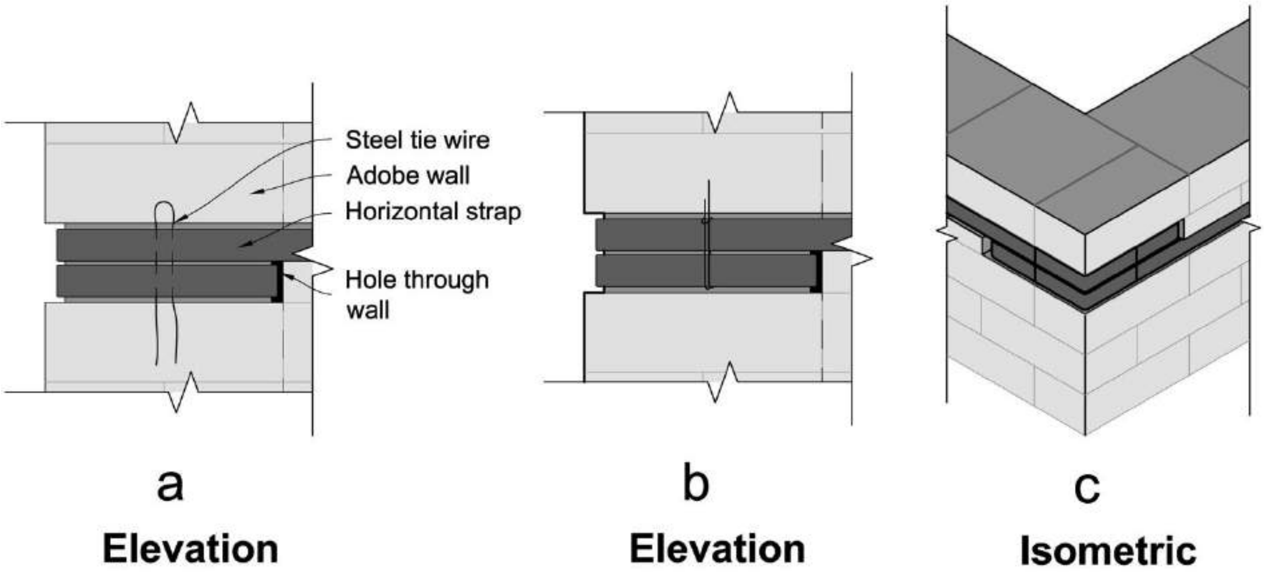


Figure 4.27 Corner horizontal straps are tied together with surface ties.

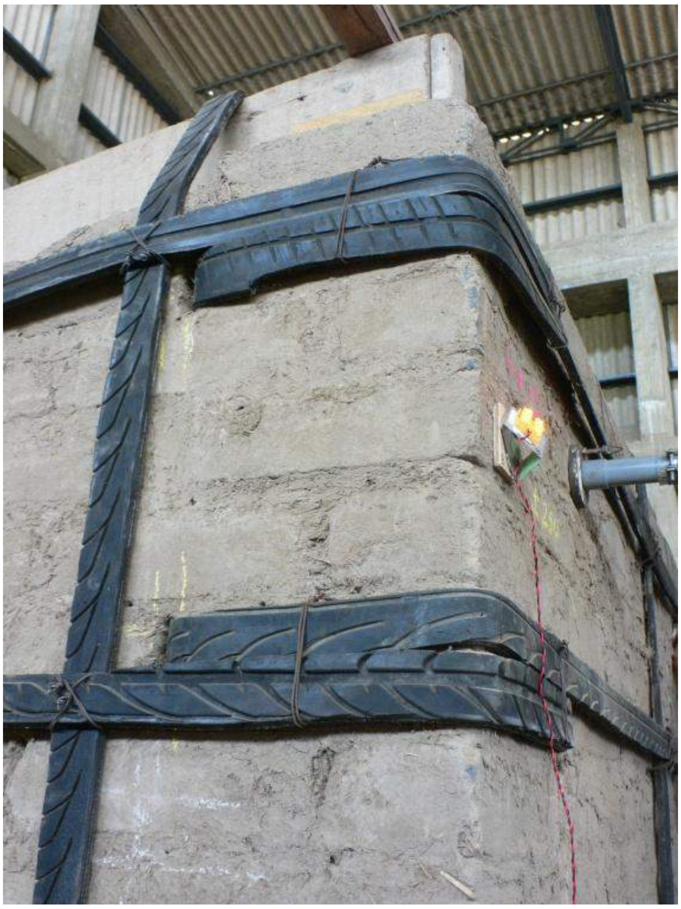


Figure 4.28 Corner horizontal straps are tied together on each side of the corner. Because the junction of the horizontal and vertical straps is close to a return wall they are tied together, but not through the walls.

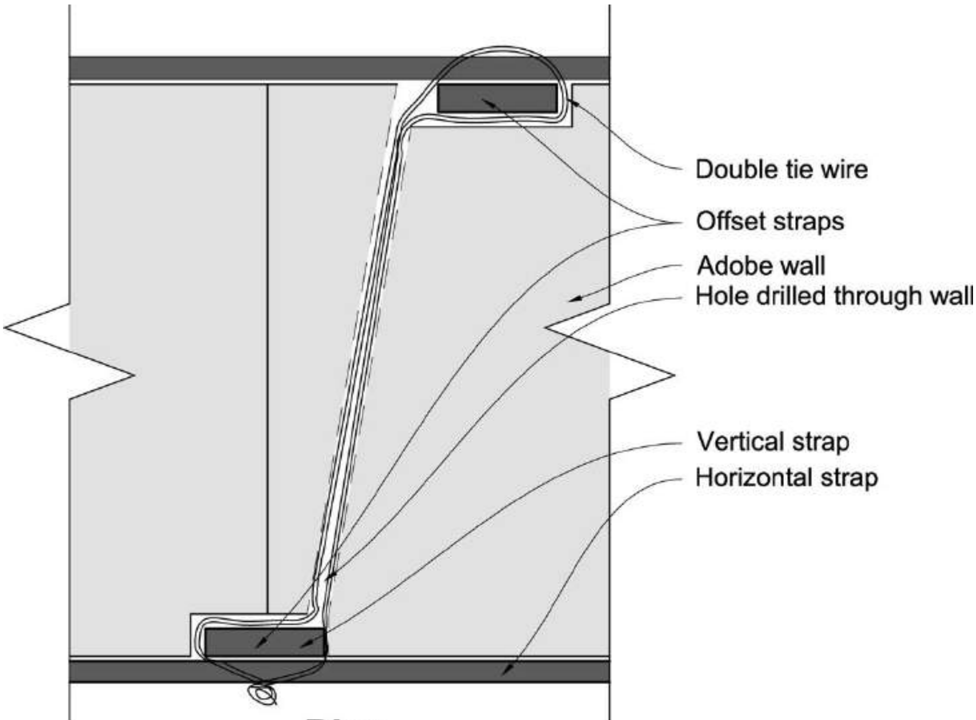


Figure 4.29 Horizontal hole and tie wire connecting two junctions of horizontal and vertical straps.

Figure 4.30 A strap junction tied together and through the wall tightly by a pair of tie wires.

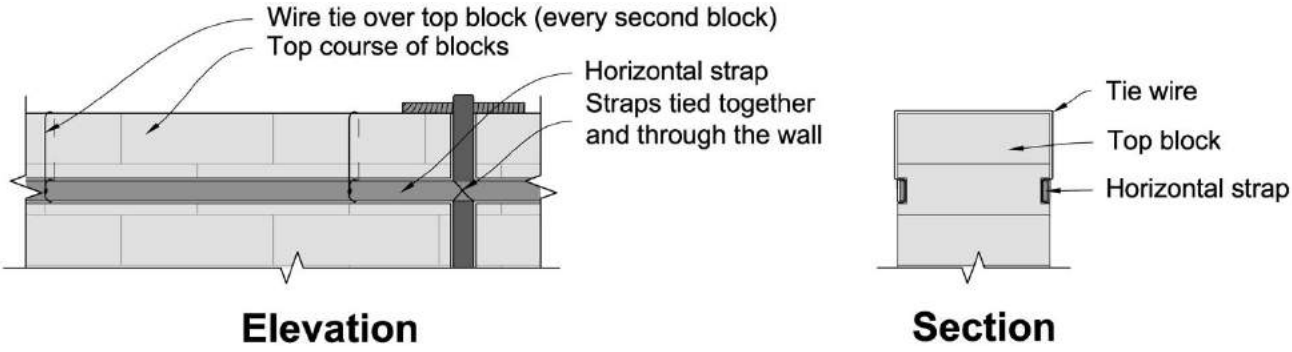


Figure 4.31 Tying the top course(s) of adobe blocks to the top horizontal strap to prevent blocks being dislodged and falling during an earthquake.

4.5 Finishing Off

Once all the junctions between horizontal and vertical straps and the top course of adobe blocks are tied, straps can be mortared into their rebates. Once the mortar is thoroughly dry, a second layer of water-resistant paint is applied (in moist and wet climates only) to the exterior rebates. The wall can now be plastered to a smooth finish and be given its final coats of paint.

5. MAINTENANCE

Houses reinforced with tire straps are not expected to require any additional maintenance due to the presence of the straps. However, maintenance is required wherever damage to exterior plaster leads to strap reinforcement being exposed to the elements. As explained earlier, tire straps deteriorate if exposed to sunlight or moisture. In a situation where straps are exposed, repair should be undertaken within a month or so. Areas of missing mortar should be replastered. If required, any inner protective paint layer should be repainted before replastering the damaged area and repainting the exterior surface.

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APPENDIX A. SUMMARY OF THE TECHNICAL DEVELOPMENT OF TIRE STRAP REINFORCEMENT

In this appendix the background research and development is outlined to give an appreciation of aspects of the reinforcement system. For more detailed information readers should refer to the cited references. Structural and other concepts at the basis of this research have been reported on in previous articles (Charleson and French 2005 and 2008, Charleson 2006 and 2010, Charleson and Blondet 2012), but because of the innovative use of materials they are also briefly outlined here.

A.1. Tire Straps and Connections

Tensile tests have been conducted on tire straps cut from the treads of radial steel-belted car tires. These straps have their strength and stiffness enhanced greatly by the presence of two layers of very fine steel wires or belts that are angled at approximately twenty-three degrees to the length of a spirally cut strap. Tests on various widths of strap confirm that given the necessity for desirable strength and stiffness, and the need to avoid short strap lengths with large numbers of connections, 40 mm wide straps are the most suitable. They possess tensile strengths between 10 - 15 kN. Since most designs are expected to be deformation-critical, strap tensions will generally be well below their ultimate tensile values. The average length of a 40 mm wide strap that can be cut from a radial car tire is 6.3 m.

Straps are butted together and connected via two short lengths of overlapping straps to form a butt joint. Four 3.15 mm diameter by 70 mm long nails on each side of the joint are bent carefully to prevent a premature nail pull-though failure mechanism (Figure A.1).

Figure A.1 A completed nailed joint showing the bent nails.

A.2. Out-of-Plane Forces or Forces Acting Perpendicular to the Lengths of Walls

Another stage in the investigation was to construct brick walls and apply out-of-plane forces. To eliminate the possibility of mortar tension strength contributing to wall shear and bending strength, all bricks were laid dry-stacked. This weak method of construction replicates that of many buildings in developing countries and provided the best opportunity for the proposed reinforcing system to prove itself.

Nominally 200 mm thick test walls 3.4 m long, with a 200 mm thick return at each end, were tied to timber reaction frames (Figure A.2). Recycled bricks formed 600 mm high walls that were constructed on five equally-spaced and well-lubricated load-skates placed on steel plates. This method of support allowed almost unrestrained movement normal to the wall. The walls were then loaded horizontally. Walls reinforced with a horizontal tire strap wrapped around and tied through the walls withstood far much more load than those without reinforcement. As expected, unreinforced walls failed at extremely low load levels. These tests showed that if straps are wrapped horizontally around walls at regular, say, 600 mm centers up the height of a wall they resist face-loads and transfer them to cross-walls. In buildings with roofs lacking effective diaphragm action, most face-loads will be transferred horizontally in bending and shear to cross- or return-walls.

Beneficial dynamic behavior of a reinforced face-loaded wall was observed during testing. When loads were suddenly released, walls slowly sprung back to their original positions. Calculations indicate an out-of-plane natural period of vibration of approximately 1.5 seconds which means a relatively low seismic acceleration response. The disadvantage of such a flexible system, however, is large lateral displacements and subsequent damage to the building fabric.

Tests also confirmed that proposed vertical straps running up both sides of walls and located at approximately 1200 mm centers along the walls could also provide out-of-plane resistance (Figure A.3). In the vicinity of wall openings they function as vertical trimmer-beams, but they also perform other roles, such as tying walls to the roof structure. This prevents the roof becoming separated from the wall and collapsing. In addition, they improve the sliding-shear capacity of walls due to their initial nominal clamping force and increased tensile force at large wall horizontal deflections. Finally, they enable in-plane wall diagonal compression struts to develop.

Figure A.2 An out-of-plane test with the wall pushed towards the supports

Figure A.3 Out-of-plane load transferred vertically

A.3. In-Plane Forces

Diagonal-tension shear failure is observed in earthquake damaged adobe construction. However, it is not as common as might be expected due to the lack of any tension resistance between out-of-plane laden walls and the cross-walls that would ideally provide restraint. Regularly-spaced horizontal tension reinforcement has the potential to create a rational strut-and-tie shear force resisting mechanism, Horizontal and vertical straps thus work together to improve in-plane shear strength.

Free-standing 1800 mm high, 1300 mm long and 240 mm thick dry-stacked walls with a wooden top plate were loaded in-plane (Figure A.4). The tests showed that horizontal straps are partially effective in resisting shear forces. Measured lateral wall strengths were many times larger than those expected of non-reinforced walls. The influence of reducing the vertical spacing between horizontal straps from 600 (Wall 1) to 300 mm (Wall 2) was investigated. Both walls were loaded near their top course and subjected to a similar cyclic loading regime.

Both walls achieved peak loads of 3.5 kN in both directions, but Wall 2 with its superior confinement withstood the relatively large horizontal deflections with considerably less damage. More closely-spaced straps have the effect of reducing the widths of diagonal cracks. The failure mechanism is expected be a gradual softening and slumping of the wall due to loss of bricks and spalling at the toes of the walls at deformations exceeding 10% of the wall height. This ability to withstand large displacements is far preferable to a brittle and sudden collapse.

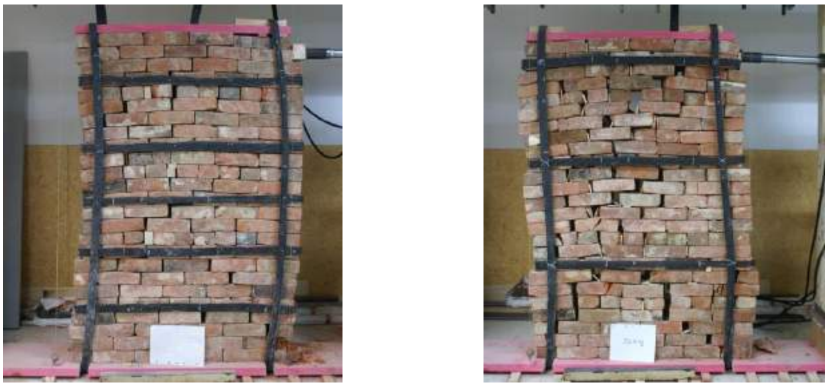

Figure A.4 Walls 1 (left) and 2 at a similar stage of their cyclic loading sequence.

A.4. Dynamic Tests of Adobe Construction

Given encouraging results from the New Zealand experimental tests, the next stage was to apply the strap reinforcement to a full-scale adobe house. The purpose of the tests was to verify that the reinforcement system could meet the performance objective of preventing building collapse in moderate to severe earthquakes, and to obtain data to pre-engineer these strap-reinforced structures.

The Catholic University of Perú, Lima, was chosen as the venue because of its extensive experience in adobe research and its suitable laboratory facilities. Numerous university staff have conducted many static and dynamic tests on adobe structures, some of which can be used to benchmark the performance of the proposed tire strap reinforcement system (Ottazzi et al 1989).

A.4.1. Shaking Table Set-Up

The test module consisted of a single room, 3.25 m square in plan with the front wall 2.0 m high incorporating a central door opening, and a rear wall 2.25 m high (Figure A.5). This wall had no openings. Each side wall contained a centrally-placed window 1 m square. The walls were built upon a reinforced concrete foundation beam, square in plan, to facilitate craning of the specimen onto the shaking table, to which it was bolted down rigidly.

Figure A.5 The module being lowered onto the shaking table.

The walls were constructed from 250 x 250 x 70 mm thick sun-dried adobe blocks fabricated from a mixture of sifted soil, course sand and straw in the volumetric ratio of 5:1:1. Sufficient water was added to ensure thorough mixing and ease of workability. The hardened blocks were laid in mud mortar from the same constituents in the ratio of 3:1:1. The adobe materials were of a high quality and the blocks were laid in accordance with current best practice by an experienced and skilled mason.

Timber rafters and purlins were supported by the walls. No ring beam was provided. The rafters were skew nailed to 200 x 100 x 25 mm wooden blocks directly bearing onto and fixed to adobe blocks by four nails. Roof cladding was omitted to prevent it improving the performance of the module by providing diaphragm action. All walls were reinforced with tire straps. Four levels of horizontal straps were placed approximately 600 mm apart, and the spacing between vertical straps was nominally 1.2 m, but they were more widely spaced in the centre of the front and rear walls to match the two central rafters placed on either side of the front door opening. It is important to fix the vertical straps to rafters so they can tie the two walls together. Relative movement of the tops of the walls and the potential to have rafters lose support is thereby prevented. End walls (parallel to the rafters) are not tied together so there is a risk of some purlins in the middle areas of these walls losing support resulting in local damage.

The straps were hand-cut from approximately 40 steel-belted used car tires. While each tire contained two layers of steel fibers, the numbers of nylon and polyester layers varied. The extreme lengths of straps were 8.5 m and 4.8 m with an average length of 6.3 m. After placed in position on the test module, straps were lightly tensioned using a domestic-scale ratchet tensioning device. Tensioning was aimed to achieve tautness rather than pre-tensioning action. Straps were anchored to the side of foundation beam, rather than passing under as is intended in the field, and taken over the top of rafter ends and nailed to them after they had been tensioned and connected. Straps were tightly tied to each other where they crossed with reinforcing steel tie-wire and were also tied through the wall on the rear wall at the uppermost six crossing points. Three strap specimens were tested in tension. Their average strength was 11.5 kN, and an average strain of 0.10 at 10 kN tension was measured. These mechanical properties are similar to those of straps tested previously both in New Zealand and India.

A.4.2. Test procedures

The module was subject to uni-directional shaking from a record of the Lima, May 1970 earthquake. The peak shaking table amplitudes for different test phases were set at three values; 50 mm, 90 mm and 130 mm. These phases produced peak shaking table accelerations of 0.4, 0.7, and 1.2 g respectively. Three earthquakes, a small, moderate and severe earthquake, were simulated. The damage potential of the largest amplitude shaking, as determined by its Arias Intensity, exceeds that of the renowned 1940 El Centro record (Ottazzi et al1989). Instrumentation consisted of linear variable displacement transducers and accelerometers, as well as optical markers whose three-dimensional displacements were recorded by high speed cameras. Three video cameras located at diverse vantage points also captured the tests.

A.4.3. Module performance

During Phase 1 shaking all the elements of the module remained in the elastic range. This behavior was due to the high quality of adobe materials and workmanship. The straps made no contribution to the module performance.

During the second half of Phase 2 shaking, a vertical crack formed in the middle of the rear wall due to out-of-plane response. Small areas of spalling and loss of adobe material occurred in the vicinity of the crack. Small movement compatibility diagonal cracks migrated from the base of this vertical crack to the bottom corners of the wall. A vertical crack formed between the rear wall and a return wall. Narrow cracks appeared in both side walls, and on the front wall the lintel beam was displaced horizontally relative to its supporting wall causing cracking and internal spalling. The horizontal straps prevented the rear wall from collapsing in its top and middle area and from detaching from the two rear piers (side walls).

Damage intensified during Phase 3. The top of the rear wall was flung vigorously to-and-fro. It fractured into relatively large individual blocks which were restrained by the straps alone (Figure A.6). The horizontal straps wrapping around the side walls crossed wide vertical cracks that had opened up between the side walls and the rear wall, certainly preventing it from falling outwards. Diagonal tension shear cracks formed in the vicinity of the bases of the piers but straps crossing them kept closing them up. Initially the rafters followed the rear wall movements, but then slid on their wood seating blocks after the skew nails failed. One uppermost adobe block fell outwards from the rear wall.

Figure A.6 Damage to the rear wall after the Phase 3 (maximum shaking) (left) and the most heavily damaged pier.

Compared to almost identical non-reinforced adobe test houses which have completely collapsed at this intensity, the performance of the reinforced module can be considered a success. More detailed information will be available in the most recent article on the system (Charleson and Blondet 2012).

Even though by this time the module was quite badly damaged it was subject to a repeat of Phase 3 shaking for a fourth Phase. The upper-most large blocks of adobe continued to be flung about and two areas of masonry in the lower half of the wall fell out from between the horizontal straps onto the module floor. Damage increased everywhere although side wall damage remained modest. By this time the module had been subject to the unrealistic scenario of two large earthquakes. At no time did it look likely to suffer partial or full collapse.

The tests highlighted several areas requiring further attention:

- Improve the wire tying of the top course of adobe blocks to the top horizontal straps to prevent blocks dislodging and falling,
- Tie horizontal straps together through the wall in selected areas where there may not be any vertical straps crossing to improve the confinement of areas of cracked adobe, and
- Wall lintel beams and roof structure have a large influence upon the dynamic performance of a house.

Given that the design philosophy is collapse prevention, the seismic performance of the reinforced house exceeded expectations. No damage was observed to any strap, strap connection or interface between strap and adobe.

A.5. Static Cyclic Load Tests on Adobe Walls

Although several in-plane tests had been conducted on dry-stacked brick walls as noted previously, similar testing was under taken on two adobe walls. The post-elastic performance of dry-stacked walls was dominated by both sliding shear and diagonal tension displacements. The main unknowns for adobe construction were whether sliding shear would be as prominent, and what were the maximum shear strength values.

A.5.1. A 1.2 M Long Tire-Strap Reinforced Wall

The wall, shown in Figure A.7, is 1.2 m long and 2.4 m high. Its construction was identical to that of the dynamically tested module; namely adobe blocks laid in mud mortar. An unusual aspect of this test was the loading method. Since adobe houses rarely possess structurally adequate roof diaphragms, the cyclic horizontal load was applied to the top of a steel post, pin-jointed at its base. The post then transferred loads acting to the right to the wall via a wood compression block located at each horizontal strap. Loads acting to the left were transferred to the wall by tire straps that wrapped around the vertical post as it pulled away. This method of load application partially simulates the loading of an in-plane wall where one return wall presses against one vertical end and a second return wall, when falling away from the other end, has its inertia forces transferred back through straps acting in tension. In conventional unreinforced adobe construction these tension forces rarely occur as return walls fall away from bracing walls due to the weak or non-existent tension strength between them. A more realistic representation of in-plane loading could have been achieved by simultaneously pushing the wall on one edge while pulling it on the other, but this was not possible given the limited resources available. Effectively, the wall is subject to inverted triangular loading.

Under cyclic loading of steadily increasing displacement amplitudes, the wall rocked on its base. Unlike the dry-stacked brick specimens, no horizontal sliding or diagonal tension deformations occurred. A series of stable hysteric loops were formed. Since this behavior was not providing any information about the ability of the adobe wall to resist internal forces, the wooden compression blocks and horizontal straps were progressively removed from top down. This had the effect of reducing the height of the point of application of horizontal load. Eventually, when the entire load was transferred through the lowest block attached to the lowest strap, 600 mm above the foundation, diagonal tension shear failure was induced.

It is interesting to compare the performance of this wall to those dry-stacked masonry walls tested earlier. Whereas the adobe wall rocked as a rigid body for most of the test, the dry-stacked walls behaved very differently. As vertical gaps opened up between adjacent bricks due to diagonal cracking the wall length elongated and the vulnerability of the wall increased. The maximum shear strength of adobe was more than three times that of the dry-stacked walls.

A.5.2. A 2.4 m Long Tire-Strap Reinforced Wall

The same loading configuration and cyclic sequencing was applied to a 2.4 m long wall. The strap configuration was as for the shorter wall but a central vertical strap was provided to maintain the horizontal spacing between vertical straps to 1.2 m. Where horizontal straps crossed the middle strap they were tied through the wall with steel tie wire.

Although severely damaged, the wall strength peaked at 33 kN when the top of the wall had undergone 160 mm displacement. Most of the deterioration was due to diagonal tension cracking, but some sliding was also evident. Unlike an unreinforced adobe wall loaded at its top, the cracking is well distributed up the height of the wall and concentrated on the left-hand side. Had the lateral forces in each direction been of the same magnitude, a more even spread of cracks over the face of the wall might have been expected.

Near the end of the test the bottom horizontal strap failed in tension. Its 35 mm width was on the limit of acceptability (40 ± 5 mm), but the width of its internal steel fibers was only 30 mm. This failure was a reminder of the importance of all straps satisfying minimum dimensional requirements.

Figure A.7 Horizontal load is applied to the top of a vertical steel post pin-jointed at its base which then transfers loads to the wall in compression, via wooden blocks, and tension, via horizontal straps. The 1.2 m long wall (left) is being pulled to the left and is rocking at its base while the 2.4 m long wall (right) has undergone five cycles of loading.

A.5.3. Summary of In-Plane Tests

Compared to conventional unreinforced adobe construction these walls displayed excellent structural performance. Due to combination of the special loading condition which is valid only for the proposed structural system, the horizontal and vertical tire straps of both walls prevented catastrophic collapse. The performance of the 2.4 m long wall was especially noteworthy. Since straps crossed each of the major cracks the wall was unlikely to fail suddenly. During long-duration strong shaking one can imagine the wall slowly disintegrating. The fact that it was able to reach its maximum strength at a large displacement and with heavy damage gives rise to optimism that the dynamic test module’s rear wall, so badly damaged from face-loads, would be able to resist satisfactory levels of in-plane shear force and displacement during two dimensional horizontal shaking.

APPENDIX B. SPECIFICATION OF TIRE STRAPS

B.1. Tires

- Use car tires only. (Truck tires are too difficult to cut and work with.)
- Tires to be two-ply steel belted radials.
- Each tire tread to be fully covered by rubber (no polyester or nylon fibers visible) and free of any hole, split or crack > 5 mm.
- No sign of rubber embrittlement or of delamination between steel belts.
- Each tire requires a visual check before cutting.

B.2. Straps

- 40 mm width ± 3 mm.
- Ends of cut steel fibers to be visible along each strap face. This means the outer edge of the initial length of a usable strap is approximately 20 mm from the edge of the tire tread, where belt wires commence.
- Tensile strength of strap to be greater or equal to 10 kN (1 Tonne).
- Quality control test one specimen from each of three tires before starting mass production of the straps and thereafter one specimen per 100 tires. If any specimen does not achieve the required strength discard similar tires of that brand or source unless further testing shows they meet the required standard.

B.3. Cutting straps

- Any cutting method can be used, but preferably one using a purpose designed cutting machine that reduces the jagged edge that the cut ends of steel fibers can create. A smooth edge will reduce injuries during handling of straps. Minimize environmental pollution during the cutting process.
- After removing tire walls commence the continuous spiral cut of the treads gradually. Smoothly increase the strap width so that the 40 mm width is achieved after cutting approximately half way around the tread circumference.
- Avoid any abrupt change in strap geometry.
- If necessary remove excess tread (for recycling). The strap thickness is to be no greater than 8 mm. This is to reduce transportation costs, allow for easier installation and shallower rebates.
- Cut off lengths of strap at each end that are under the specified width.

B.4. Finishing and storing straps

- Tightly coil each strap and tie it with a length of reinforcing steel tie wire (which could be reused) to prevent it unraveling.
- Store away from direct sunlight in a dry area for loading into a shipping container.

APPENDIX C. QUANTITIES OF MATERIALS AND RESOURCES REQUIRED

C.1. Quantities and Costs of Materials

Table C.1 All the materials required for the four-roomed house in Figure C.1

Material	Quantity	Cost NZ$[1]	Cost US$	Comments
Tire straps	90	-	-	560 m of strap is required. Assume no cost to house owner.
Nails	1000	20	14	10% wastage assumed.
Screws	10	2	1	Screws are required for the strap-tensioning process and are reused.
Used bottles or cans	60-90	-	-	Plastic bottles or cans are used in new construction for passing straps through or under the foundations. The numbers required depend on the widths of walls and the lengths of cans or bottles. Assume recycled materials used.
Plastic adhesive tape	50 m	5	3	One or two rolls of tape are required to seal the PVC sheets that provide waterproof protection to tire straps under moist ground.
PVC sheet	7m^2	14	10	Sheet 250 microns thick.
Tie wire	100 m	4	3	Approx. 1 mm dia and purchased in a coil. This wire is normally used to tie reinforcing bars together prior to pouring concrete.
Paint	5 liters	87	61	Bituminous or an equivalent type of paint is to provide corrosion protection to straps on the exterior surfaces of houses. About 5 liters is needed.
Finishing paint	20 liters	350	245	Two coats over all exterior and interior surfaces. Paint may be considerably cheaper in developing countries.
Mud mortar/		-	-	Required to fill the rebates and make good any areas of damage needing reinstatement after a strengthening project.
Miscellaneous: Ratchets, gloves, chains, costs of making good		60	40	To the sums above must be added the cost of one or two ratchets ($US 10), several pairs of leather gloves ($US10), the reusable chains for the strap tensioning process (say $ US10) and the costs of making good damage to exterior and interior walking and flooring surfaces caused by excavations for vertical straps ($US 10).
Total		542	378	

[1] Based upon 2009 prices

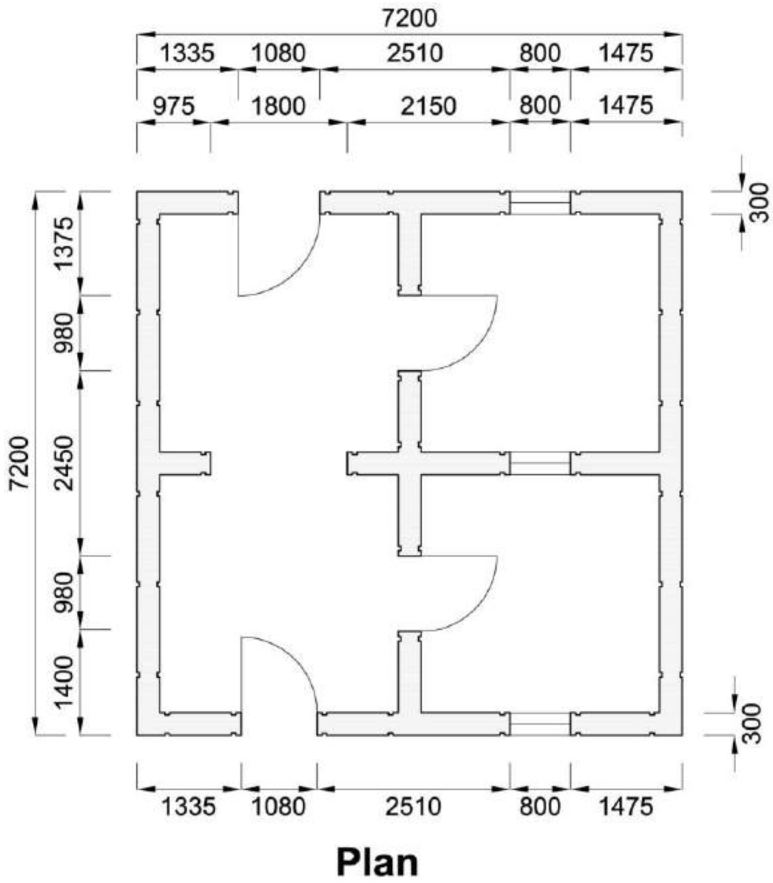

Figure C.1 Plan of house at level of windows used to calculate quantities of materials.

C.2. Labor Requirements

Table C.2 provides an estimate of time to complete each construction activity. These estimates are based on the times taken to reinforce the one room module that was dynamically tested (Appendix A). In that case one experienced mason worked with a person with little building experience. It is feasible for most of the work to be undertaken by an unskilled worker or the house owner with occasional supervision by a mason. The times given in the table are approximate and will vary due to many factors including the quality of the equipment and the speed and efficiency of the workers.

The module that was reinforced and tested had 250 mm thick walls with an average height of 2 m and a gross area of approximately 10 m^2. The time taken to reinforce a larger house can be approximately determined on a pro rata basis. Extra time needs to be allowed for if walls are thicker and higher, and if there are gable ends and/or parapets. No allowance is made for repainting all the interior and exterior surfaces.

Table C.2. List of construction activities and worker days.

Steps	Construction activities	Worker days
1	Mark the position of horizontal straps and vertical straps using chalk.	0.5
2	Cut rebates into adobe walls to accommodate straps.	2.0
3	Form holes under/through foundations for vertical straps.	1.5[2]
4	Drill 50 mm by 10 mm holes at wall corners for horizontal straps to pass through, and paint exterior rebates for straps.	2.0
5	Remove areas of roof and ceiling to pass vertical straps over rafters.	1.5[1]
6	Place, cut, tighten, connect vertical and horizontal straps (requires two workers). Apply corrosion protection to vertical straps where they pass under the foundations.	9
7	Drill 5 – 10 mm dia holes through walls, tie straps together and provide ties to top course of adobe blocks.	1.5
8	Plaster over straps with mud mortar. After mortar is dry, paint over the straps with water-resistant paint.	1.5
9	Miscellaneous	1.0
	Total	20.5

[1] Applies where houses are retrofitted