Tyre Strap Seismic Reinforcement for Adobe Houses

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SUMMARY:
This paper begins by summarising the research behind seismic reinforcement for adobe houses provided from used car tyre straps before outlining the process of applying this technology to a new or existing house. In this reinforcement system, used car tyre treads are cut into long straps with sufficient tension strength to tie the walls of adobe houses together during an earthquake. The paper then reviews the recommended construction details that have been developed so that the reinforcing system can be applied in the field.
A description of the equipment necessary to install the tyre straps is followed by the reasons behind the preparations required prior to strap installation. Various issues are raised regarding the correct installation of the straps, and then after that process has been discussed, questions related to maintenance, longevity and costs are addressed. Finally, the paper discusses the labour required to incorporate tyre straps into a typical house and notes that most of the work can be undertaken by the house owners themselves under the supervision of a more experienced person, like a skilled mason.

Keywords: tyre tire reinforcement adobe earthquake

1. INTRODUCTION

Of all housing construction types worldwide, earthen construction is among the most fragile with respect to 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 all 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. Tyre strap reinforcement is one response to this unfortunate situation. The basic steps of the application of tyre strap technology is summarized visually in Fig. 1.

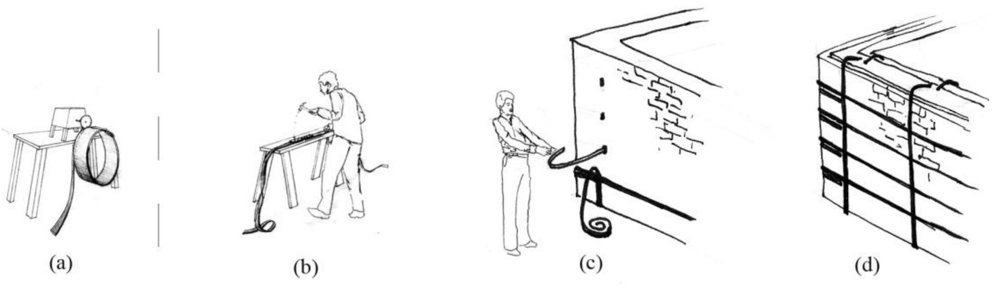

Figure 1. Steps in the process of reinforcing an adobe house with tyre straps. Step (a) is performed in a workshop or factory and (b) to (d) on site. (Courtesy Matthew French)

The concept at the heart of this reinforcement system is for tyre straps to be cut from discarded used tyres in developed countries (where used tyres 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: both existing and new adobe buildings are strengthened at minimal cost with a material that is simple to install and plentiful in supply, and a significant portion of used car tyres are recycled in an environmentally acceptable manner.

In this system, the circumferentially cut straps from the treads of used car tyres that function as tension reinforcement must be cut from steel-belted radial car tyres. Although the steel wires in the two belts are not continuous they give the straps sufficient strength and stiffness to be used as reinforcement.

After approximately six metre-long and 40 mm wide continuous straps have been cut from tyre 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 centres maximum vertically. Vertical straps spaced horizontally at approximately 1.2 m centres 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. The reinforcement provides structural strength and tying-action after the earthen wall material has failed. Figure 2 illustrates the main features of the system.

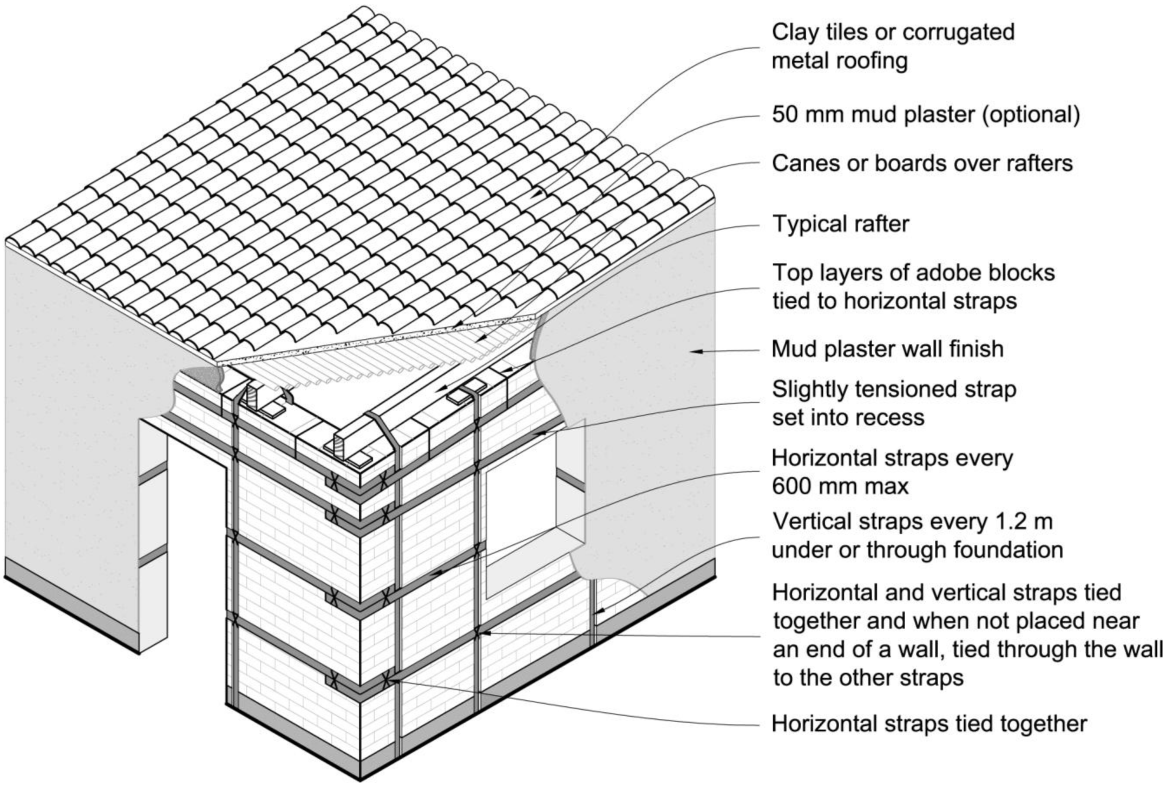

Figure 2. The main features of a strap-reinforced house

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. Until further research is undertaken it is proposed that strap reinforcement be applied 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.

2. SUMMARY OF THE TECHNICAL DEVELOPMENT OF TYRE STRAP REINFORCEMENT

The background research and development is outlined very briefly to give an appreciation of key aspects of the reinforcement system. More detailed information has been reported in previous articles (Charleson 2006, 2010 and 2011, and Charleson and Blondet 2012).

Tensile tests have been conducted on tyre straps cut from the treads of radial steel-belted car tyres. Test results 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. Straps are butted together and connected via two short lengths of overlapping straps to form a butt joint (Fig. 3). The nails are bent carefully to prevent a premature nail pull-though failure mechanism of the joints.

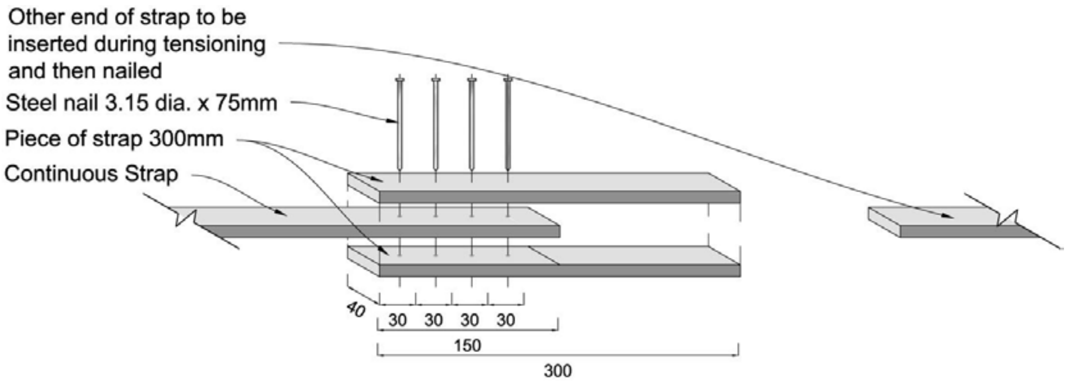

Figure 3. A nailed strap joint

Initial load tests using the tyre straps for in-plane and out-of-plane test specimens on dry-stacked brick walls were successful. They indicated the potential of the system to provide large amounts of ductility and so the system was further developed for use in adobe construction. A small single room full-scale adobe house was built and reinforced and subjected to four phases of earthquake shaking on a uni-directional shaking table (Fig. 4).

Figure 4. The adobe test module on the shaking table.

During the first phase shaking, all the elements of the module remained in the elastic range due to the high quality of adobe materials and workmanship. The straps made no contribution to the module performance. However 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 and many other narrow cracks appeared. Damage intensified during Phase 3. The top of the rear wall was flung vigorously to-and-fro. It fractured into large individual blocks which were restrained by the straps alone. 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. A video clip of the test can be viewed (World Housing Encyclopedia, 2011).

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.

Compared to almost identical non-reinforced adobe test houses which have completely collapsed at the same intensity, the performance of the reinforced module can be considered a success. 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. However the tests highlighted several areas requiring improved detailing that have been incorporated into the Construction Guide (Charleson, 2011).

As well as the dynamic tests, two static cyclic tests were conducted on adobe walls by applying in-plane lateral loads. The first test on a 1.2 m long and 2.4 m high wall was not that useful as the wall rocked on its base, experiencing very little damage. However, when the same loading configuration and cyclic sequencing was applied to a 2.4 m long wall, severe damage was observed. Although severely damaged, the wall strength peaked 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 was well-distributed up the height of the wall and concentrated on the left-hand side (Fig. 5).

Figure 5. Even though subject to a large lateral displacement the wall was still able to resist load

Compared to conventional unreinforced adobe construction these walls displayed excellent structural performance. The performance of the 2.4 m long wall was especially noteworthy. Since straps crossed each of the major cracks, the wall did not fail suddenly as is the case with unreinforced adobe.

3. APPLICATION OF STRAPS TO ADOBE HOUSES

3.1 Equipment

The construction equipment needed to install tyre straps is quite basic and includes most equipment found on a construction site. Specific items of equipment include: claw hammer; hacksaw with fine tooth blades for cutting the steel wires and rubber of tyre 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; 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; and a screw driver for inserting temporary screws for tensioning straps. The only specialist piece of equipment required is a ratchet device with four short lengths of chain (Fig. 6). Ratchets with their nylon straps are widely available and cost only a few dollars each.

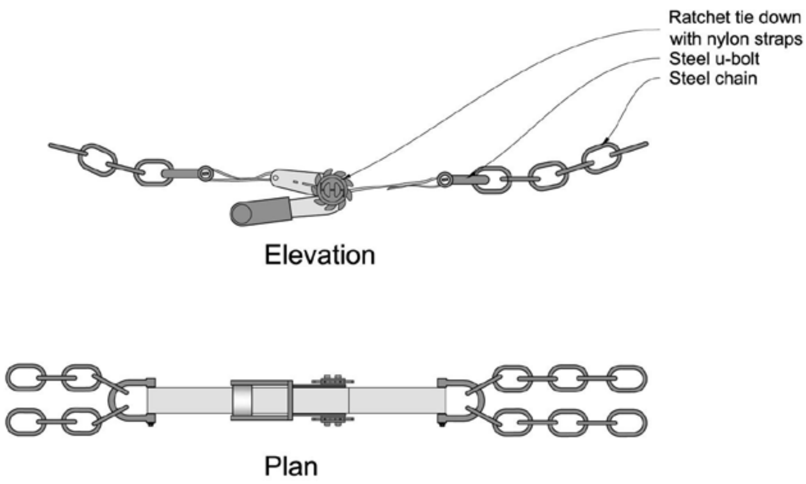

Figure 6. Ratchet, straps and chains for tensioning the tyre straps around adobe walls.

3.2 Materials

The following materials are required for strap installation: tyre 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) and plastic tape for creating waterproof PVC strap sleeves; water resistant paint (in moist and wet climates) and paint to make good the re-plastered 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; and chalks for marking the positions of rebates for straps and holes.

3.3 Preparation prior to strap installation

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 and then locally widen the foundation excavation at those points and place in empty plastic bottles or cans so straps can be threaded under the wall after the wall has been laid (Fig. 7). For an existing house, holes need to be dug under walls where straps are to be positioned.

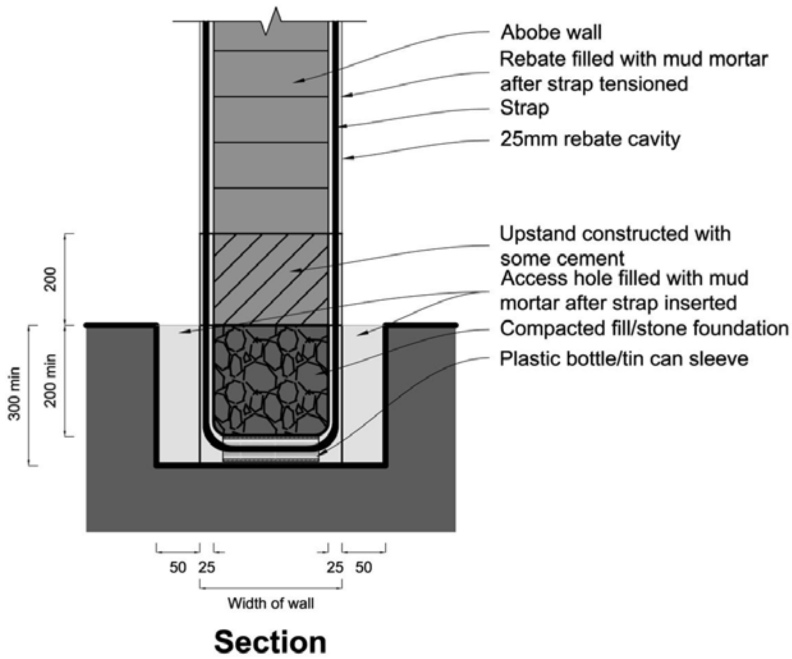

Figure 7. A section through the base of a wall showing a strap threaded through an empty tube. For existing walls a hole is formed by digging from both sides of the wall to pass the strap under.

The preparation of walls prior to strap installation involves forming vertical and horizontal rebates in which the straps are to be positioned and embedded (Fig. 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. 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. 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 tyre belt wires.

In Figure 8 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.

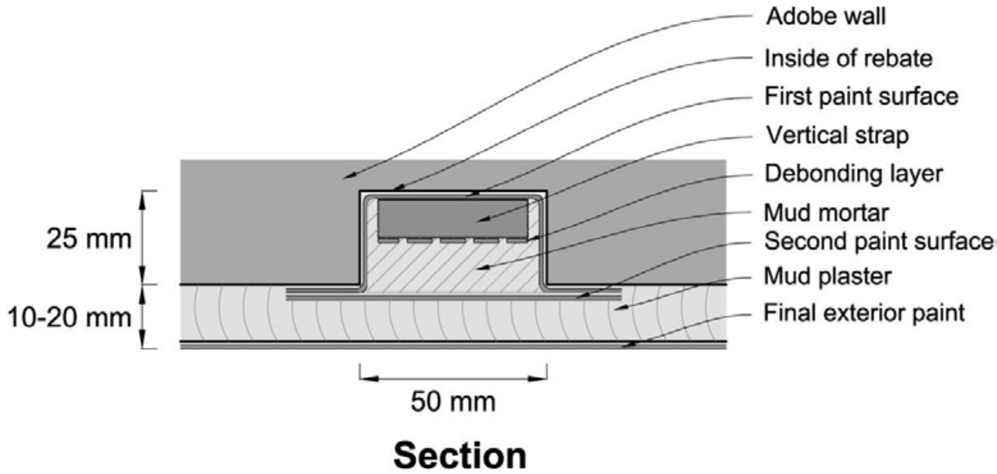

Figure 8. A section through a wall rebate and strap to prevent strap corrosion in wet climates.

3.4 Installation of straps

At this stage of construction, rebates have been completed and painted (if necessary). After choosing a strap of suitable length to minimize wastage, the first half of the nailed joint should be completed (Fig. 3). For moist or wet climates a PVC sheath is placed around the strap where it passes through and up each side of the foundation. The strap is then passed under or through the foundation, passed over the top of the wall, including the rafter if applicable, and then positioned ready to tension (Fig. 9). 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. Tension is applied by firm hand pressure on the ratchet. If too much pressure is applied to the ratchet it can break.

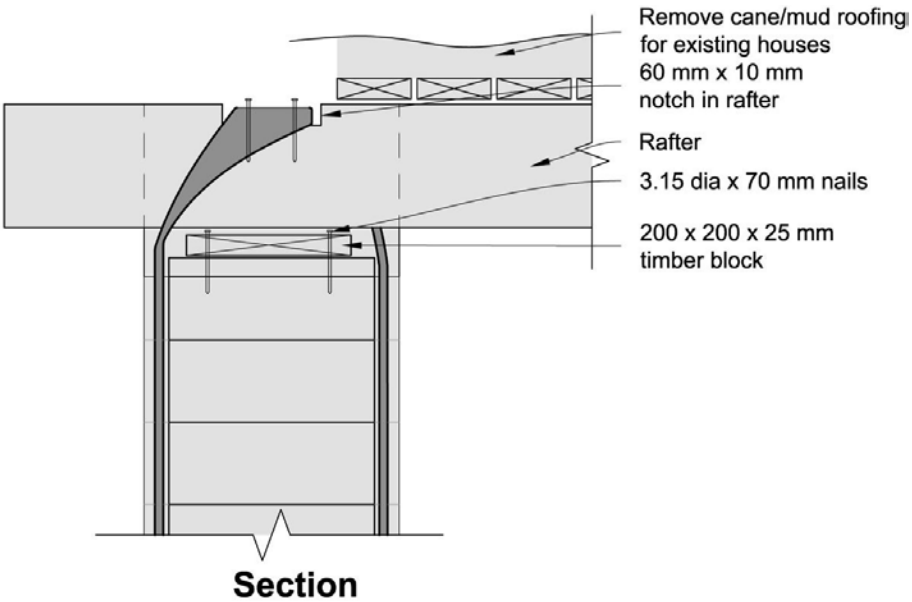

Figure 9. A vertical strap is tensioned over a rafter to prevent it sliding off during earthquake shaking.

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 (Fig. 10). 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.

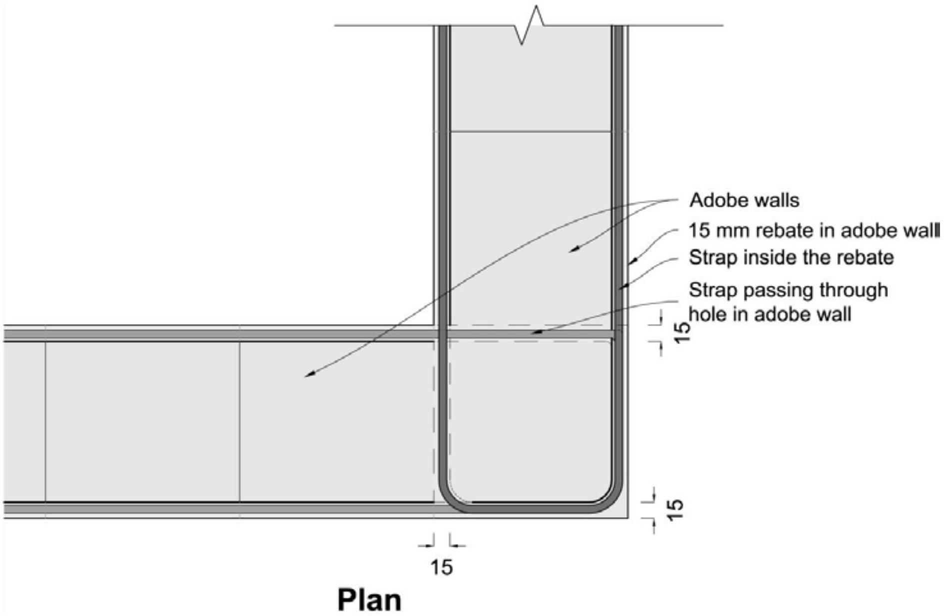

Figure 10. Plan view showing how interior lengths of strap pass through a wall and then wrap around and pass back along the wall, tying the two walls together.

3.5 Tying straps to each other through walls and side-by-side

Full-scale shaking table tests of the 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 with 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. 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. After tying every junction, the wire knot should be hammered into the strap to increase the thickness of mortar and plaster cover and reduce the likelihood of corrosion.

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

3.6 Maintenance and longevity of straps

Houses reinforced with tyre 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. Tyre 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.

Tyre 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. 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 tyre tread, all ends of steel belt wires are exposed. 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 (Fig. 7). Where a vertical strap passes through or under a moist or wet foundation, it should be wrapped in plastic sheeting to keep it dry.

4. COSTS OF MATERIALS AND LABOUR REQUIREMENTS

Assuming there is no cost for the tyre straps, the cost of materials to provide straps to a small 52 m^2 four roomed house has been estimated as US$378 (Charleson 2012). Almost 65% of this cost is for the wall finishing paint.

An estimate of time to complete each construction activity was based on the times taken to reinforce the one room module that was dynamically tested. 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 total time required to install the straps and complete the work will vary due to many factors, including the quality of the equipment and the speed and efficiency of the workers. For the single-roomed test module with a gross area of $10m^2$ and average wall height of 2 m the estimated times are shown in Table 1.

Table 1. 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
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
6	Place, cut, tighten, connect vertical and horizontal straps (requires two workers). Apply corrosion protection to vertical straps where they pass under the foundations.	9.0
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

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 painting or repainting all the interior and exterior surfaces.

5. SUMMARY

This paper describes the reinforcing system comprising straps cut from used car tyres to seismically reinforced adobe houses. The background research and development is summarized and then the construction sequence outlined. Finally, the paper includes information about construction costs and labour requirements.

ACKNOWLEDGEMENTS
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