USED CAR TYRE STRAPS AS SEISMIC REINFORCEMENT FOR ADOBE HOUSES

A.W. Charleson[1] **and M. A. French**[2]

[1] *Associate Professor, School of Architecture, Victoria University of Wellington*
[2] *PhD student, The Martin Centre for Architectural and Urban Studies, Cambridge University, UK*
Email: andrew.charleson@vuw.ac.nz, maf50@cam.ac.uk

ABSTRACT :

This on-going research project responds to both the extreme seismic vulnerability of adobe houses and the abundant supply of environmentally-harmful used car tyres. An introductory section briefly describes the seismic problems this low-cost and technologically appropriate approach attempts to resolve. After describing how used car tyre straps are intended to improve seismic safety, the paper summarizes laboratory test results on components such as the straps and their connections. It then discusses the behaviour of the system as a whole. It shows how the proposed horizontal and vertical strap reinforcement greatly enhances the in-plane and out-of-plane seismic load capacity of vertical dry-stacked brick wall panels, intended to approximate adobe walls. The relatively long natural periods of walls utilizing this flexible type of reinforcement provide beneficial dynamic characteristics. Finally, the economic viability of the proposed system and cultural factors affecting its possible implementation in developing countries are discussed.

KEYWORDS: Adobe, housing, developing countries, damage mitigation, seismic design, tyres

1. INTRODUCTION

Typical earthquake damage patterns of adobe housing have been widely documented and include:

- Poor connections between different building elements that lead to walls separating at corners and falling outwards,
- Falling of gable and ordinary walls due to out-of-plane loads, leading to collapse of roofs, and
- Diagonal tension shear cracking due to in-plane forces. This weakens walls and leaves them very vulnerable to out-of-plane forces.

These failure modes were again observed as recently as August 2007 after the Pisco, Peru earthquake. In Pisco, the city closest to the epicentre, more than 80% of the adobe houses collapsed or sustained heavy damage (EERI, 2007) (Figs 1 and 2).

The challenge is to find or develop low- or even no-cost tension-resistant materials to reinforce such vulnerable construction. It is assumed that due to economic realities, adobe buildings utilizing readily obtained and naturally occurring materials will continue to be built. However, in urban areas with limited land availability and greater aspirations for modern materials the need is to retrofit the substantial adobe building stock. One possible solution to this challenge as outlined above, is to use material from used car tyres. At least in the so-called developed countries, used car tyres create a huge environmental problem. They require disposal at a rate of approximately one used tyre per head of population per year.

Figure 1 Partially collapsed adobe house. (D. C. Hopkins)

Figure 2 Adobe walls along the street frontage have collapsed. (D. C. Hopkins)

2. THE CONCEPT

Structural and other concepts at the basis of this research have been reported on previously (Charleson and French, 2004 and Charleson, 2006) but because of the innovative use of materials they are outlined briefly so readers can appreciate the general approach being taken.

The concept is to circumferentially cut straps from the treads of used car tyres to provide tension resistance and therefore improved seismic safety for adobe construction. The initial focus is upon single-storey residential buildings with light to medium-weight roofs. Figure 3 provides a pictorial summary of the concept. After approximately five metre-long continuous straps have been cut from tyre treads, they are joined on site by a specially developed yet simple nailed joint. Once the walls of an adobe house have been constructed and holes formed to allow straps to pass through, the straps are then wrapped horizontally around walls at approximately 600 mm centres vertically to provide in-plane and out-of-plane resistance. Pairs of vertical straps anchored into the foundations rise up the walls to be nailed to roof timbers.

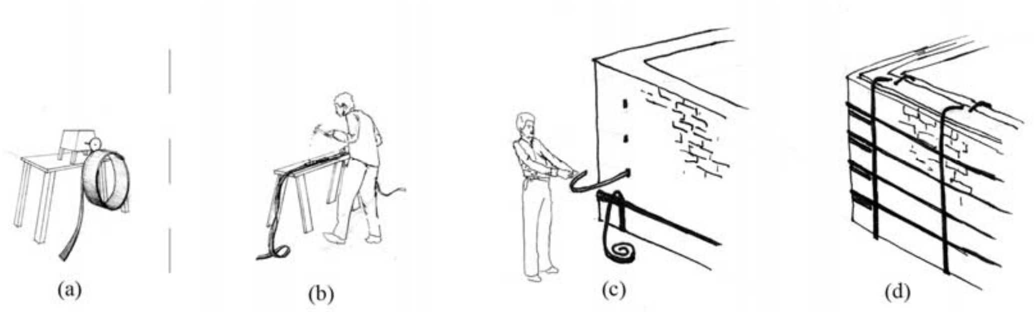

Figure 3 Pictorial summary of strap formation and application. The initial cutting of tyre treads into straps (a) is likely to occur in a factory while all the other stages of construction will occur on-site.

Once the technical adequacy of the concept has been fully developed and rigorously tested both theoretically and experimentally, the vision is for tyre straps to be mass-produced in developed countries and then transported to developing countries, where, at no or minimal cost homeowners will incorporate them into their new or existing houses. A very desirable outcome eventuates. Both existing and new adobe buildings can be strengthened at minimal cost with a material that is simple to install and plentiful in supply. In addition, the proposed system goes some way in dealing with the issue of used car tyre disposal.

3. STRUCTURAL DESCRIPTION

Vertical and horizontal tyre straps are intended to provide the tension strength necessary to resist all earthquake-induced forces acting on a building, as discussed below.

3.1. Out-of-plane forces

At regular, say 600 mm intervals up the height of a wall, straps are wrapped horizontally around walls to resist wall face-loads and transfer them to cross-walls. The composite system, which can be described as a strutted-catenary, can be thought of as the opposite of a tied-arch. The tension force in a tyre strap that is developed as a wall bends out-of-plane is equilibrated by a horizontal compression strut within the outer thickness of the wall (Fig. 4). In buildings with light-weight roofs lacking effective diaphragm action, most face-loads will be transferred horizontally in bending and shear to cross- or return-walls.

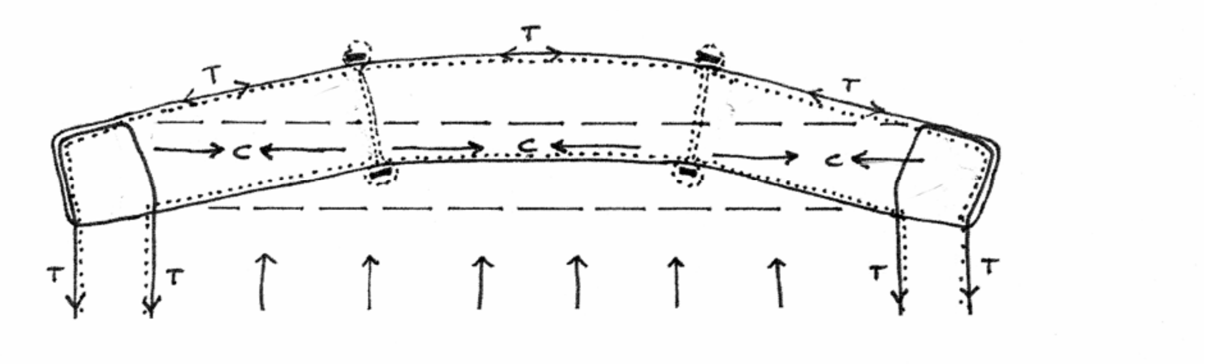

Figure 4 Plan of an adobe wall reinforced with car tyre straps subject to out-of-plane loading away from internal return walls. Tension forces in the straps (solid lines) and compression forces within the adobe are illustrated. The small dotted lines outline the adobe walls and the horizontal tie wires.

Pairs of vertical straps running up both sides of walls are located at approximately 1200 mm centres along wall lengths. As well as providing some out-of-plane resistance, particularly in the vicinity of door and other wall openings where they function as vertical trimmer-beams, they also perform other roles. They enable the roof structure to be reliably tied to the wall, preventing the roof being separated from the wall and its ensuing collapse. Also they improve the sliding-shear capacity of walls due to their nominal clamping force, and finally they help in-plane wall diagonal compression struts develop. Free-standing elements like short walls and piers surrounded by openings might require vertical straps to facilitate vertical transfer of face-loads to horizontal tyre strap reinforced bands at eaves and lintel levels. In the unusual situation of achieving reliable roof diaphragm action, vertical face-load transfer will become a more significant component of the seismic force load path.

3.2. In-plane forces

Diagonal-tension shear failure is commonly observed in earthquake damaged adobe construction. Regularly-spaced horizontal tension reinforcement has the potential to create a rational strut-and-tie shear force resisting mechanism. Horizontal and vertical straps work together to improve in–plane shear strength. Horizontal tyre straps act in the same way as horizontal reinforcement resists shear forces in reinforced concrete walls but due to their considerable axial flexibility they are only partially effective.

4. COMPONENT TESTING

4.1. Straps

Tensile tests have been conducted on tyre straps cut from steel-belted radial car tyres. These straps have their strength and stiffness enhanced greatly by the presence of two layers of very fine steel wires that are orientated at approximately twenty-three degrees to the length of a spirally cut strap. The wires reinforce the rubber and inhibit conventional tensile elongation and failure, increasing axial stiffness by a factor of between five and ten. Tensile failure occurs when the slither of rubber several millimetres thick between the two layers of wires fails by in-plane shearing action and de-bonding from the steel wires.

After testing straps varying in width from 10 mm to 50 mm, envisaging how straps might be placed around walls and considering the length of strap that can be cut from a single tyre, a decision was made to use 40 mm wide straps. Straps of this width possess strengths of approximately 15 kN.

During tensile tests conducted at a relatively slow strain-rate, the specimens exhibited significant creep. Dynamic test results indicate a factor of 1.20 allows for the dynamic enhancement of tension strength during an earthquake. While the strength of the straps is of vital importance, their stiffness is likely to be the critical structural property. Since most designs are expected to be deformation-limited, strap stresses will generally be kept well below their ultimate tensile values.

4.2. Strap Connections

The length of 40 mm wide strap that can be cut from car tyre treads depends on the tyre diameter and tread width. Typically it varies from between 4 m to 6 m, so there is a need for a reliable and straightforward on-site connection. Two connection options were investigated – bolts and nailing, but nailing proved to be the most effective. Two straps are butted together and connected via two short lengths of strap overlapping each side of the butt joint. A joint where nails on each side of the joint were bent carefully in certain directions provided the highest tension load, even though a nail pull-though failure mechanism still occurred (Figs 5 and 6). Nails had to be bent both parallel to and normal to the strip length for optimum performance. This connection, almost as strong as the strap itself, failed at 11.8 kN with four 3.15 mm diameter by 70 mm long nails through each strap on each side of the butt joint.

Figure 5 A completed nailed joint showing the bent nails that prevent premature nail pull-through.

Figure 6 A failed connection where the originally bent nails have pulled-through.

The nailed, butted and lapped joints were also subject to dynamic tests which again showed strength enhancement at higher strain rates likely during seismic shaking.

5. SYSTEM TESTING

5.1. In-plane Loads

A free-standing 1800 mm high, 1300 mm long and 240 mm thick dry-stacked wall with a wooden top plate was loaded in-plane. The top pair of tyre straps were pulled and a brick at the same height pushed when loading reversed. During the 'pull cycle' the wall sustained a peak load of 6 kN (0.02 MPa average shear stress) at a 250 mm displacement. When the load was reversed the same peak load was resisted at a negative displacement of 20 mm. At the end of this first and final cycle the wall was badly damaged (Fig. 7).

In this test the tyre straps did not simply wrap around the wall as is now proposed, but rather crossed over each other at two points to approximate two catenaries in-plan. This more complex strap geometry increased the wall damage. It is expected that further tests utilizing simple wrapped straps will demonstrate improved performance. However it *is* clear that the horizontal straps are partially effective in resisting shear forces. Diagonal compression struts as well as diagonal tension cracks form between the straps, rather than from the top to bottom of an unreinforced wall.

The two pairs of external vertical straps also contributed to the in-plane performance of the wall. During construction the straps were manually pretensioned using a simple lever technique. This additional compression force within the wall increased the lateral load at which sliding of blocks of bricks between the horizontal straps occurred. At the maximum lateral load of 6 kN, the calculated tension in the straps countering overturning was approximately only 10% of their tensile capacity and about 50% of their pretension.

Analysis of the hysteretic loop (Fig. 8) indicates the damping of the wall to be approximately 15% of critical damping. The natural period of vibration of a typical wall supported by return walls in an adobe house is calculated to be in the range of 1.3 to 2.6 secs. Both the relatively high damping and long period of vibration reduce the seismic demand upon such in-plane laden walls.

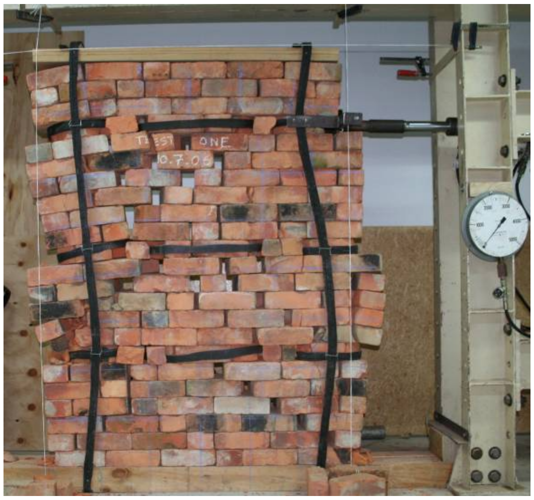

Figure 7 Wall after one reversed cycle.

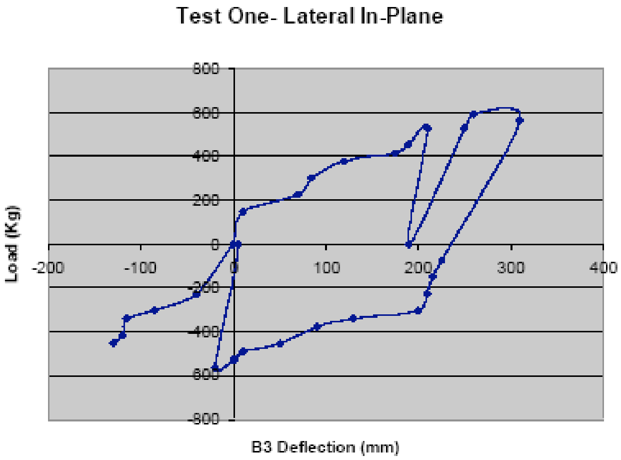

Figure 8 Load-deflection graph of the in-plane laden wall.

5.2. Out-of-plane Loads

Five different tyre strap configurations to achieve horizontal transfer of out-of-plane forces to return walls have been tested. The tests, beginning with an unreinforced wall are shown in their order of testing in Fig. 9.

The nominally 240 mm thick test walls were 3.4 m long. They were formed from dry-stacked recycled red bricks 600 mm high and constructed on well-lubricated load-skates to allow virtually unrestrained movement normal to the wall length. The walls were then loaded horizontally at either two or three points along their lengths. When the unreinforced wall was loaded towards the return walls (the stronger direction) it failed at 0.13 g. The strap reinforced wall of Figure 9 (e) sustained an out-of-plane force equivalent to 0.5 g at a horizontal deflection of 400 mm.

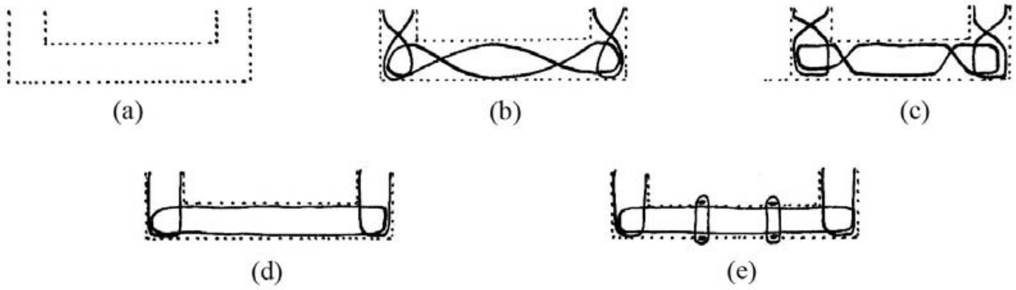

Figure 9 Different tyre strap plan configurations that have been tested for reversed out-of-plane loads: (a) an unreinforced wall, (b) catenaries, (c) modified catenaries to aid construction and (d) simple wrapping around wall elements. In (e), the recommended option, horizontal straps wrap the walls and are tied through and to vertical straps with 2 mm dia. wire or equivalent.

Unanticipated dynamic behaviour of a reinforced face-loaded wall was observed during testing. When loads were suddenly released the wall slowly sprung back towards its original position. Calculations indicate an out-of-plane natural period of vibration of approximately 1.5 seconds. As for an in-plane laden wall, this flexibility will result in a relatively low seismic acceleration response. A disadvantage of such a flexible system is the magnitude of lateral displacements and subsequent damage to the building fabric. P-Δ effects need to be accounted for in subsequent design development.

In order to resist out-of-plane forces acting on walls in the vicinity of window and door openings a vertical load-path is required. For this reason a dry-stacked wall reinforced with two pairs of vertical wrapped straps was tested (Fig. 11). When the hydraulic jack reached its maximum extension, the point load equivalent to 0.4 g, had caused a mid-height deflection of 120 mm. In a typical adobe house lacking a roof or ceiling diaphragm the vertical straps will span from the foundations to horizontal straps spanning between return walls.

Figure 10 The out-of-plane test set-up with the wall pushed towards its supports.

Figure 11 Out-of-plane load transferred vertically.

6. ECOMOMIC MODEL

The application of tyre straps to reinforce adobe construction will eventuate in developing countries only if the cost of the material is absolutely minimal, if not free. A detailed economic model encompassing all financial aspects of producing and delivering tyre straps has enabled an assessment of the scheme's financial viability (Markland, 2006). The assumption at this stage is that tyres from more developed countries, like New Zealand in this instance, are collected, transformed into reinforcing straps and shipped to a developing country to be incorporated into adobe houses. Car safety regulations in developed countries result in tyres of reasonable quality for turning into structural straps whereas in developing countries tyres are used for far longer periods of time. When they have reached the end of their lives, those car tyres are often badly damaged and unsuitable for transforming into straps.

The economic model is based upon the premise that a NGO manages the four primary activities of site establishment, used tyre collection, tyre processing, and packing and shipping. Processing facilities are assumed to be located on a Wellington landfill site (free of charge) and the NGO processes 45% (121,000) of the city's annual volume of used car tyres. Two trucks and drivers are necessary to collect the used tyres and four other staff manually operate de-beading and tyre tread cutting machines, roll the straps and pack them, and possibly the tyre beads as well, in containers for shipping. After separating the beads from the tyre walls (assumed to be recycled by others at no cost), and the walls from the treads and the transformation of the treads into straps, the straps are rolled and fitted into the tyre beads, placed on pallets and packed into shipping containers. A standard 20 ft shipping container can hold 5000 straps, enough for up to 50 three-roomed adobe houses (60 m^2) or 70 two-roomed dwellings.

Figure 12 summarizes the main areas of expense and their relative costs. These figures are based on shipping the straps to India. No allowance is made for the costs of transporting the materials within India. The relativity between expenses can be expected to vary considerably for different cities in developed countries.

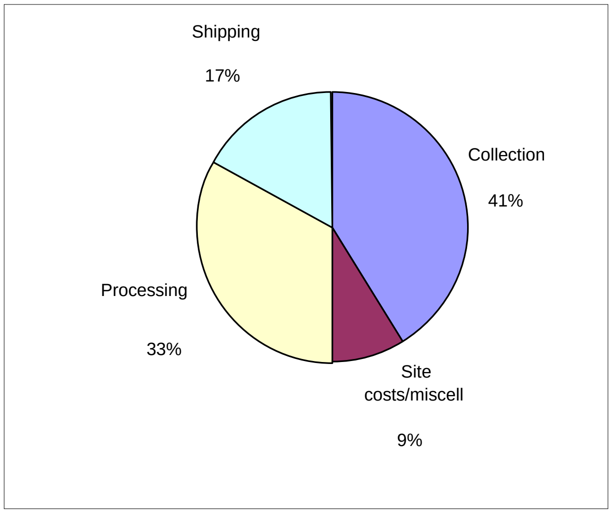

Figure 12 The four main expenses and their relative significance (Markland, 2006).

The model assumes the worst case scenario that the sole source of income for the collection, tyre processing and shipping is from vehicle workshops and garages paying to have their used car tyres disposed of. No financial incentives from government, or other organizations are assumed. Currently it costs up to $US2.00 to dispose a tyre in a New Zealand landfill. However specialist businesses with truck-mounted tyre shredders charge about half of that fee for disposal. They collect and shred the tyres at source before dumping them in a landfill at a relatively low cost per tonne. To be competitive, the NGO income from garages is assumed to be $US1.00 per tyre. This is insufficient to meet all costs, which taken over a five year period, amount to $US3.00 per tyre.

Although the model shows that the idea is not financially viable in Wellington in 2006, this may not be the case in other cities and countries. For example, in a larger and more compact city the cost of tyre collection could be reduced considerably and shipping costs to developing countries could benefit from a more competitive market and closer access. Another processing location where the idea could be viable is alongside existing mountains of used tyres. Increasing landfill charges and environmental awareness by governments and tyre manufactures could also make the economics more viable.

7. CULTURAL CONSIDERATIONS

As part of an investigation into cultural issues that might affect the implementation of the proposed reinforcing scheme, twenty-three interviews were held for interested parties in Lima, Peru (Markland, 2006). These groups of potential stake-holders comprised a community housing group, two aid-focus NGOs, local and central government agencies and a university research organization. Discussions focused upon perceived socio-economic advantages and disadvantages, cultural and aesthetic considerations, other challenges and finally, support from and constraints of regulating authorities.

It is clear there are many significant challenges to be overcome before achieving a reasonable and sustainable uptake of the proposed reinforcing system. However, none appear to be insurmountable.

8. CONCLUSIONS

The tests reported in this paper give grounds for optimism that the proposed system of reinforcing adobe walls with straps cut from used car tyre treads can prevent building collapse during code-level design earthquakes. Further research is required before the system can be designed and implemented in full-scale construction. Not only do some technical aspects require resolution but cultural considerations need further attention prior to application to local contexts. While an economic study shows that the vision of collecting used car tyres, converting them into straps and shipping them to a developing country for free is not financially viable for Wellington-based conditions in 2006, it may be possible in other locations.

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