Out-of-plane strengthening of adobe masonry using hemp fibre ropes: An experimental investigation

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Abstract

Adobe masonry structures are common in many parts of the world, particularly in developing countries. Whilst the ease of construction, low cost and familiarity of the material make it a popular building method, adobe is vulnerable to out-of-plane forces. Many countries where adobe structures are abundant are often subject to extreme natural events such as cyclones, seismic actions etc., these can result in significant horizontal forces leading to serious damage or collapse. This paper presents an experimental study of a novel strengthening method involving the application of hemp fibre rope nets to the surface of adobe walls. The method can be applied during construction and also as a retro-fit for existing structures. Hemp fibre ropes were chosen as the strengthening system in order to match the low cost, sustainability and buildability credentials of adobe itself. A series of plain and strengthened adobe panels were subject to bending, both parallel and perpendicular to the bed joints. The rope reinforced panels exhibited significant enhancements in strength and deformation capacity, with the latter achieving up to 10 times that of the un-strengthened case.
Keywords: Strengthening adobe walls, out-of-plane behaviour, hemp fibre rope reinforcement, experimental investigation

1. Introduction

Earthen masonry is one of the oldest natural building materials and has been widely used for building houses and low rise structures for thousands of years. Multi-storey earthen structures were constructed by the ancient Egyptians and other cultures in the Near East. Modern examples can be found today in places such as Shibam city in Yemen [1] and Djenne mosque in Mali [2]. Earthen masonry structures are still widely prevalent in many regions around the world, it is estimated that around 30% of world’s population use earthen construction for living and/or working space [3]. The majority of the rural population and at least 20% of the urban population in developing countries live in earthen houses. In some developed countries, earthen construction was fairly common up until the 18th century industrial revolution and is still used in some areas, for instance in France, 15% of the rural population lives in homes made with earth such as adobe or rammed earth [4]. Today, earthen construction can still be found in some parts of the UK such as Devon and Cumbria [5].

Varied construction techniques have been adopted for earthen buildings around the world, the most common techniques are known as homogenous monolithic constructions such as rammed earth and unit constructions such as adobe [6]. The latter is the most common and the basis of many forms of earthen construction [5]. Adobe as a potential building material has been considered to be a sustainable solution for construction and as such has been the subject of increased research interest in recent years (the term adobe is referred to both masonry units made from a soil mixture, formed into a mould and air dried, and to structures made from adobe units forming an adobe masonry assembly). In addition to its inherent sustainability, adobe has other attractive properties such as its low cost, the ease of access and
availability of the material, excellent thermal and acoustic insulation characteristics and ease of construction by unskilled labour [7].

Despite the aforementioned advantages, the weakest point of this form of structure is the susceptibility to significant horizontal loads which may result from extreme natural events e.g. seismic activity, flooding, cyclones etc. This susceptibility is mainly due to the nature of adobe itself, i.e. its relatively high mass, the brittleness of the material, the typical absence of reinforcement and lack of maintenance [8]. In addition, there are a lack of technical guidelines and often no access to professional engineering advice in the areas of developing countries where the adobe structures are most common. Adobe structures usually possess poor quality of construction with thin walls, large openings and irregularities in configuration [9]. Hence, the terms ‘non-engineered construction’ or ‘informal construction’ are often applied to adobe structures [3]. In view of this, the European macro-seismic scale classifies typical adobe structures as the most susceptible class for housing [10].

The sudden collapse of adobe structures is a major contributor to fatalities, serious injuries and economical losses resulting from natural disasters around the world in general and in developing countries in particular. For instance, the 2003 earthquake in Bam, Iran, caused thousands of causalities due to collapse of adobe structures [11] and 519 deaths and collapse of more than 70,000 mainly adobe houses were recorded in the 2007 earthquake along the Central Coast of Peru [8].

Strengthening of existing adobe structures to withstand extreme horizontal forces, both in plane and out-of-plane is vital to limit damage and minimise loss of life. Such strengthening is intended to enhance the structural performance, provide deformation capacity and prolong the collapse time. Several strengthening methods have been implemented in the last few decades to retrofit and enhance the structural performance of adobe masonry structures in
particular. An effective strengthening solution should not only provide the structural enhancement but should be compatible with the adobe structures in other important aspects such as cost, sustainability, accessibility, ease of application in addition to minimising both spatial impact and additional mass to the structure.

The most common strengthening techniques for adobe structures are externally applied to the surface of adobe walls. One of the most widely adopted strengthening techniques for adobe is steel wire mesh reinforcement. In this technique, strips of welded steel wire mesh are applied to the relatively weak regions of the walls i.e. the corners at the intersection of perpendicular return walls, the centre of the long span walls and the top free ends. Holes are drilled at about every 500 mm in those regions; connecting bars are then embedded inside the holes and fixed through a cement mortar. Steel wire mesh strips are then horizontally and vertically fixed to both sides of the walls via previously installed connecting bars and nails. The wire mesh reinforcement is usually covered using a cement mortar [8]. Another common strengthening technique is polymer mesh reinforcement. The polymer mesh is fixed to both sides of the adobe walls by making use of plastic strings which are previously threaded through the wall thickness. The polymer mesh is usually coated with a mud plaster that is usually made of a mixture of clay, sand and binders such as straw fibres [9]. Various materials have been used to form the polymer reinforcement such as polypropylene bands [12] and recycled plastic carrier bags [13].

Charleson and French (2008) [14] implemented the use of post-tensioned elastic strip reinforcement formed by rubber tyres to reinforce adobe. The strips are cut from the tyre’s thread with a typical width of 40mm and attached together to produce continuous lengths via nailing. These are then horizontally and vertically placed to wrap the walls at approximately 600 mm and 1200mm intervals, respectively. After positioning, the strips are lightly tensioned by an ordinary ratchet tensioning tool. [14, 15]. Bamboo has also been employed to
reinforce adobe walls as a natural substitute for other strengthening materials such as steel wire mesh and polymer mesh. Bamboo is applied to the external face of the existing adobe walls or placed internally inside the walls during construction [16]. However, depending on the species, the size of bamboo sections (known as culms) required to achieve an effect commensurate with other available strengthening techniques can make internal application impractical in many cases. Table 1 provides a brief summary of the performance of the aforementioned strengthening systems in terms of the capacity enhancement compared to the corresponding un-strengthened adobe wall and associated failure modes.

<table>
<thead>
<tr>
<th>Strengthening System</th>
<th>Reference</th>
<th>Loading Regime</th>
<th>% Load Capacity increase</th>
<th>Reported Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel wire mesh reinforcement</td>
<td>[17]</td>
<td>LR1</td>
<td>≥20%</td>
<td>Plain: sudden brittle collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: more distributed cracks, total collapse prevented</td>
</tr>
<tr>
<td>*Steel wire mesh reinforcement</td>
<td>[18]</td>
<td>LR2</td>
<td>120%</td>
<td>Plain: brittle collapse, severe cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: less severe and better distributed cracks, yielding of steel mesh, total collapse prevented</td>
</tr>
<tr>
<td>Polymer mesh reinforcement</td>
<td>[19, 20]</td>
<td>LR1</td>
<td>50%</td>
<td>Plain: severe cracking, brittle collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: less severe cracks, total collapse prevented</td>
</tr>
<tr>
<td>*Polymer mesh reinforcement</td>
<td>[18]</td>
<td>LR2</td>
<td>100%</td>
<td>Plain: brittle collapse, severe cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: less severe cracks, compressive failure of adobe at corners, total collapse prevented.</td>
</tr>
<tr>
<td>Rubber tyre straps</td>
<td>[15]</td>
<td>LR1</td>
<td>20%</td>
<td>Plain: severe cracking, brittle collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: severe cracking, total collapse prevented</td>
</tr>
<tr>
<td>Bamboo mesh</td>
<td>[16]</td>
<td>LR3</td>
<td>50 to 100%</td>
<td>Plain: severe cracking, brittle collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: better crack distribution, total collapse prevented</td>
</tr>
<tr>
<td>*Bamboo mesh</td>
<td>[18]</td>
<td>LR2</td>
<td>90%</td>
<td>Plain: brittle collapse, severe cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strengthened: cracks with smaller openings, Local compressive failure of bamboo reinforcement and adobe at wall corners.</td>
</tr>
</tbody>
</table>

*denotes numerical study, all others are experimental studies.

LR1: Cyclic loading via shaking table tests, both in-plane and out-of-plane
LR2: Static loading, out-of-plane
LR3: Cyclic loading, out-of-plane

Table 1: Summary of the effectiveness of various strengthening methods on the behaviour of adobe
Other strengthening techniques have been employed to reinforce standard masonry walls, for example fibre reinforced polymer (FRP) reinforcement [21], engineered cementitious composite reinforcement (ECC) [22], shotcrete [23], basalt fibre rope reinforcement [24], hemp fibre composite grid reinforcement [25]. More recently, Meybodan et al. (2020) [26] have used palm fibres to reinforce adobe walls subject to cyclic in-plane loading and reported peak load enhancements of up to 50%.

As previously mentioned, the challenge for developing a strengthening technique for adobe masonry is not simply the enhancement of structural performance, but also the compatibility of the technique with adobe based on factors such as cost, sustainability, accessibility, ease of application, etc. By taking these factors into consideration, this paper proposes a strengthening technique using externally bonded natural hemp fibre ropes as a suitable and compatible material for adobe masonry. This is the first study of its kind to use hemp rope in this application. The ability of the proposed technique to enhance the structural performance of adobe masonry specimens under out-of-plane loads is examined through experimental studies. The experimental investigations are carried out by comparing the structural performance and failure modes of hemp fibre rope reinforced adobe masonry panels with unreinforced adobe panels. Furthermore, the compatibility of the proposed strengthening method for adobe structures is also evaluated, in terms of the aforementioned additional aspects.

The remainder of this paper is structured as follows. Firstly the properties of the hemp fibre rope itself, including mechanical properties are detailed. The experimental programme, details on preparation of adobe masonry specimens, application of rope reinforcement and test methodology are then introduced. Both unreinforced and rope reinforced adobe wall panel specimens are tested under static four point bending considering both loading directions i.e. parallel and perpendicular the bed joints. The results are then presented and the influence
of rope reinforcement on the capacity and failure mechanism of the specimens are discussed. Lastly, the conclusions are drawn.

2. **Use of hemp fibre rope as a strengthening material**

Ropes have been used for millennia for various purposes such as shipping, fishing, bridge construction, etc. Ropes are made of various constituents such as natural materials e.g. plant fibres, animal fibres and skins, or man-made materials e.g. synthetic polymers, or metallic materials such as steel [27]. The use of natural fibre ropes is the focus for this study and in particular the use of hemp fibre ropes due to the various advantages over other fibre types. In general, the tensile strength and stiffness of plant fibres are higher than the strength of animal fibres [28]. Relatively high tensile strength and moduli of elasticity can be obtained from natural fibres like hemp, ramie and flax, Table 2. Among natural fibres, hemp fibre is the most popular type as the hemp plant is widely spread in many regions around the world [29].

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Density (gm/cm³)</th>
<th>Typical length (mm)</th>
<th>Failure strain (%)</th>
<th>Tensile Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemp</td>
<td>1.5</td>
<td>5–55</td>
<td>1.6</td>
<td>550–1110</td>
<td>58–70</td>
</tr>
<tr>
<td>Ramie</td>
<td>1.5</td>
<td>900–1200</td>
<td>2.0–3.8</td>
<td>400–938</td>
<td>44–128</td>
</tr>
<tr>
<td>Flax</td>
<td>1.5</td>
<td>5–900</td>
<td>1.2–3.2</td>
<td>345–1830</td>
<td>27–80</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of commonly used natural fibres [28]

Other advantages of hemp are that the hemp plant does not need pesticides, it is drought resistant, frost resistant, grows faster than many other commonly used natural fibres and has greater fibre yields, for example, 10% more than flax fibre [30]. The use of hemp fibre ropes as a potential material for strengthening adobe structures has wider advantages such as sustainability, cost effectiveness and availability of the raw materials. In terms of sustainability, hemp fibres are natural and a renewable resource; they absorb carbon dioxide and return oxygen to the environment. During processing, hemp fibres consume relatively low energy and are non-abrasive to processing machines. Furthermore, natural fibres are
highly recyclable, they have less emission of toxic fumes than other types of fibres when heated [28, 31]. The cost of hemp fibre ropes is relatively low compared to the other common strengthening materials. Hemp fibres are widely available in many countries around the world i.e. from China spread across Asia to Europe and America [32], so it is easily accessible to local people with no excessive need for additional transportation costs. Moreover, hemp fibre ropes are relatively light in weight and can therefore be easily handled, used and stored. In terms of safety, the hazards of the manufacturing process for hemp fibres are relatively low i.e. there is no health risk in inhaling fibres and they are safe to handle [28, 31].

An experimental investigation of the mechanical properties of the particular hemp fibre ropes employed in this study was conducted to obtain the ultimate tensile strength and elongation capacity. Six hemp fibre rope samples were prepared for pull-out tests i.e. direct tensile tests. The rope samples were taken from the hemp rope used to reinforce adobe masonry panels in this research. The rope consisted of three strands plaited together. The hemp rope was supplied by the company Cheap Rope based in Kent, UK. The effective length of each sample was 300 mm, the diameter was 6 mm. Both ends of the samples were fixed to hollow steel cylinders, so that the samples could be gripped by the testing machine. The use of steel cylinders aimed to prevent both ends of the rope samples from slipping during the tests, Figure 1.
The rope samples were tested using an Instron 4507 universal testing machine with a 10kN load cell capacity. The load was applied at a rate of 5 mm/min under displacement control up to rupture of samples. The strains in the rope samples were obtained by means of a clip-on Instron 2630 extensometer with a gauge length of 50mm attached to the middle of the samples to measure the axial strain. During the tests, the average recorded temperature and relative humidity in the laboratory were 22°C and 31%, respectively. The tensile stresses were calculated by dividing the loads by the initial cross-sectional area of the rope samples. The mean maximum tensile strength of the six rope samples was 90.23 MPa, the corresponding mean strain at ultimate tensile stress was 0.067. The modulus of elasticity of the samples were also calculated by dividing the ultimate tensile stress by the corresponding strain, the mean elastic modulus of the hemp rope samples was 1356 MPa. All rope samples exhibited a linear relationship between tensile stresses and strains up to reaching the ultimate
tensile strength. Following this, a sudden drop to about 80% of the maximum tensile strength was observed due to the rupture of one of the strands, Figure 2. The subsequent stress peaks observed in Figure 2 were due to the progressive rupture of the remaining strands. The summary of the test results for all the rope samples are illustrated in Table 3.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Corresponding strain at maximum tensile strength (mm/mm)</th>
<th>Elastic modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rope-S1</td>
<td>90.87</td>
<td>0.063</td>
<td>1430</td>
</tr>
<tr>
<td>Rope-S2</td>
<td>99.67</td>
<td>0.068</td>
<td>1470</td>
</tr>
<tr>
<td>Rope-S3</td>
<td>90.55</td>
<td>0.069</td>
<td>1306</td>
</tr>
<tr>
<td>Rope-S4</td>
<td>86.05</td>
<td>0.065</td>
<td>1318</td>
</tr>
<tr>
<td>Rope-S5</td>
<td>82.00</td>
<td>0.068</td>
<td>1199</td>
</tr>
<tr>
<td>Rope-S6</td>
<td>92.24</td>
<td>0.065</td>
<td>1411</td>
</tr>
<tr>
<td>Mean (μ)</td>
<td>90.23</td>
<td>0.067</td>
<td>1356</td>
</tr>
<tr>
<td>Standard deviation (σ)</td>
<td>5.98</td>
<td>0.002</td>
<td>100</td>
</tr>
<tr>
<td>Coefficient of variation, %</td>
<td>6.63</td>
<td>3.53</td>
<td>7.39</td>
</tr>
</tbody>
</table>

Table 3: Summary of results obtained from testing hemp fibre rope samples

Figure 2: Tensile stress-strain plots of hemp fibre rope samples
3. Experimental programme

3.1. Preparation of adobe masonry specimens

The adobe masonry units were made of a mixture of sandy clay soil (77.5%), straw fibres (0.5%) and water (22%) by weight. The soil contained clay (16.3%), silt (33.7%), sand (32.4%) and gravel (17.6%) by weight. These fractions were selected in order to represent a traditional adobe mixture seen in the field as recommended by Jaquin and Augarde [5]. The mortar was also made of the same mixture as the units. A comprehensive mechanical characterisation for the adobe material itself including compressive, tensile and shear properties was previously conducted by the authors and has been reported in [33]. Table 4 summarises the mean mechanical properties of the adobe materials used in the present study.

<table>
<thead>
<tr>
<th>Elastic modulus of adobe masonry (MPa)</th>
<th>Compressive strength of adobe masonry (MPa)</th>
<th>Compressive strength of adobe units (MPa)</th>
<th>Tensile strength of adobe units (MPa)</th>
<th>Tensile bond strength between adobe units (MPa)</th>
<th>Initial shear bond strength between adobe units (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>127</td>
<td>1.24</td>
<td>1.45</td>
<td>0.212</td>
<td>0.041</td>
<td>0.091</td>
</tr>
</tbody>
</table>

Table 4: Mean values of the mechanical properties of the adobe materials

The adobe masonry panels were constructed to compare the behaviour of plain and hemp rope reinforced specimens under out-of-plane loading via four point-bending tests. The construction of the adobe masonry panels and the application of the hemp ropes are detailed below. In total, 10 adobe masonry panels were prepared: 6 plain panels and 4 reinforced panels, see Table 5. All the adobe panels were kept at room temperature, around 20°C, and tested at the 28th day from the built date.

3.1.1. Plain Adobe Masonry Panels

Six plain adobe masonry panels were built using a mud mortar made of the same soil mixture as the adobe units with a bed thickness ranging from 10 to 15 mm. The surfaces of the adobe
units were moistened via a sponge prior to laying them. The geometry of the panels was adopted to satisfy the recommendations provided in BS EN 1052-2 [34] for determination of flexural strength of standard masonry panels. Three panels were prepared for the four point-bending tests in which the direction of the loading bars was parallel to their bed joints. The final average dimensions of the three panels were 428 mm x 140 mm x 550 mm. Each panel consisted of 10 courses with 2 adobe units laid in each course following a typical stretcher bond pattern, Figure 3 (a).

The other three plain specimens were prepared for tests in which the loading direction was perpendicular to the bed joints. The final average dimensions of the panels were 852 mm x 140 mm x 440 mm. Each panel consisted of 8 courses with 4 adobe units laid in each course following a typical stretcher bond pattern, Figure 3 (b). The specimens were left to air-dry for 28 days at room temperature (average of 20°C) prior to being tested.
Figure 3: Geometry and configuration of adobe masonry panels, (a) loading direction perpendicular to the bed joints; (b) loading direction parallel to the bed joints

3.1.2. Rope Reinforced Adobe Masonry Panels

Four reinforced adobe masonry panels were prepared for the experiments i.e. four point-bending tests. The geometry of the plain and reinforced adobe panels was kept the same, this aimed to exclusively investigate the effects of hemp fibre ropes on the behaviour of
reinforced panels and allow direct comparison to the plain unreinforced panels. The specimens were denoted as shown in Table 5.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Para-P-S1</td>
<td>Plain (unreinforced) adobe masonry specimens loaded in a direction parallel to their bed joints</td>
</tr>
<tr>
<td>Para-P-S2</td>
<td></td>
</tr>
<tr>
<td>Para-P-S3</td>
<td></td>
</tr>
<tr>
<td>Perp-P-S1</td>
<td>Plain (unreinforced) adobe masonry specimens loaded in a direction perpendicular to their bed joints</td>
</tr>
<tr>
<td>Perp-P-S2</td>
<td></td>
</tr>
<tr>
<td>Perp-P-S3</td>
<td></td>
</tr>
<tr>
<td>Para-R-S1</td>
<td>Hemp fibre rope reinforced adobe masonry specimens loaded in a direction parallel to their bed joints</td>
</tr>
<tr>
<td>Para-R-S2</td>
<td></td>
</tr>
<tr>
<td>Perp-R-S1</td>
<td>Hemp fibre rope reinforced adobe masonry specimens loaded in a direction perpendicular to their bed joints</td>
</tr>
<tr>
<td>Perp-R-S2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Description of adobe masonry specimens

3.2. Application of rope reinforcement

The hemp fibre ropes were used to horizontally and vertically wrap the masonry panels forming a mesh with regular spacing, ranging from 100 mm to 110 mm, Figure 4 (a). The process of the application of the ropes is described as follows:

- Ropes were cut into pieces of around 350 mm using normal scissors. This length was determined as the original thickness (140 mm) of the adobe wall plus 200 mm extra length.

- During the construction of the adobe panels, the rope pieces were placed in the mud mortar in the first bed joint at around 100-110 mm spacing in a direction perpendicular to the thickness of the walls, Figure 4 (b). The rope pieces were placed in such a way that around 100 mm long rope was left on each side of the adobe wall. In the same way, the rope pieces were placed in the mortar at every other bed joint up to completion of the
adobe wall. It was also ensured that the rope pieces were positioned in every other bed joint and were vertically aligned within the wall as much as possible, Figure 4 (c).

Note that in practice, the rope pieces may be placed in existing adobe walls by firstly drilling the walls to form 8-10 mm diameter holes perpendicular to the thickness of the walls at spacing equal to the spacing of the desired rope mesh size.

- The adobe masonry walls were then left for around 24 hours to air dry i.e. to allow initial setting to take place in the mortar.

- Following this, the process of forming the rope reinforcement mesh commenced. Firstly, the 100 mm long rope pieces protruding from each side of the adobe walls were un-woven into three strands. This process can easily be undertaken safely by hand, Figure 4 (d).

Figure 4: (a) an adobe masonry panel reinforced with hemp fibre ropes; (b) placing rope pieces in bed joints; (c) typical alignment of rope pieces; (d) un-weaving the rope pieces to three strands.
• Next, the ropes were horizontally positioned at around 100-110 mm spacing intersecting with the previously installed rope pieces in the walls. Ropes were arranged to wrap the adobe panels, starting from one side of the walls, horizontally passing through the other faces of the walls and returning to the starting face. Both ends of the horizontal ropes were then firmly knotted at the side face by hand.

• Following this, the ropes were vertically positioned forming a square mesh with around 100-110 mm spacing, intersecting with previously placed horizontal ropes at the locations of rope pieces installed inside the walls. The ropes started from the top face, going down from one face underneath the horizontal ropes, passing through the bottom of the wall and going up from the other face to the top. Both ends of the vertical ropes were then firmly knotted at the top of the walls.

• Finally, the vertical and horizontal ropes were connected at their intersection points through the previously installed rope pieces inside the walls. The strands of those rope pieces (rope pieces previously un-woven), were used to tightly fasten the vertical and horizontal ropes through making three consecutive knots by hand, as illustrated in Figure 5. It is recommended to use gloves when knots were tied due to the risk of skin abrasion, because of the rough nature of hemp fibre ropes.
3.3. Test Set-up and Procedures

A testing frame was manufactured to create the required boundary conditions i.e. loading directions either parallel or perpendicular to the bed joints of the adobe masonry panels. Figure 6 illustrates the layout of the testing frame. The position of the steel supports and geometry of the support and loading bearings were arranged in such a way that allowed adaptation of the frame for testing the specimens in each loading scenario. The tests were carried out following the guidelines specified in BS EN 1052-2 [34] for determination of flexural strength of standard masonry panels. The span of the bearings and the position of the adobe specimens within the testing frame are shown in Figure 3.

A polytetrafluoroethylene (PTFE) sheet (1200 mm x 300 mm x 1mm) was attached to the base of the rig to minimise the effects of friction between the base of the adobe specimens and the rig. A hydraulic jack was placed between the reaction steel frame and the loading
bearings to generate the horizontal forces. A 15kN capacity load cell was also placed between the base of the loading bearings and the hydraulic jack to measure the applied horizontal forces. Three LVDTs with 100 mm travel allowance were employed to monitor the relative displacements. One LVDT was attached to the hydraulic jack to measure the displacement applied by the jack. The other two LVDTs were employed to measure the horizontal displacements at the back of adobe specimens at the points shown in Figure 7 for both loading bearings parallel and perpendicular to the bed joints cases.

Figure 6: Assemblage and scheme of the test set-up

The horizontal force was incrementally applied under displacement control up to the complete failure of the plain specimens or the late non-linear stage of the reinforced specimens. The average temperature and relative humidity in the laboratory during both the curing and testing period was 20°C and 39.5%, respectively. The load was applied at a constant rate of 0.5 mm/min. The outputs from the load cell and LVDTs were collected via a computer controlled data logger. The horizontal force was directly obtained from the readings
of the load cell; the displacement at the centre line in the bending direction at the back of the specimens was taken as the average of readings of two LVDTs i.e. LVDT 2 and LVDT 3 in Figure 7.

![Positions of the LVDTs at the back of adobe masonry panels](image)

Figure 7: Positions of the LVDTs at the back of adobe masonry panels; (a) loading parallel to the bed joints; (b) loading perpendicular to the bed joints

### 4. Test Results and Discussion

The responses of the plain specimens in terms of horizontal force versus horizontal displacement at the centre of the rear face of the walls are shown in Figure 8 and Figure 10. In general, the response of the plain specimens for both loading cases was linear up to reaching the ultimate horizontal load carrying capacity; this linear behaviour was followed by a sudden reduction in their capacity due to formation of brittle cracks.

In specimens with loading direction parallel to their bed joints, the average maximum horizontal load sustained was 2.29 kN, when the average horizontal displacement at the centre of the rear face was 0.77 mm, Table 6. After reaching its maximum value, the horizontal load carrying capacity dropped due to propagation of brittle cracks along the bed and head joints. As expected, the cracks propagated in the joints in the central region on the
rear face of specimens i.e. region of maximum bending moment. The formation of cracks was mainly due to de-bonding at the interfaces between adobe units and mud mortar. The crack patterns in the three tested specimens were slightly different, Figure 9, this phenomenon may be the result of un-even distribution of the strength of the joints within the specimens due to the nature of the mud materials used as in the mortar i.e. un-even distribution of its particle sizes, differences in the surface quality of adobe units and workmanship. Another factor was the imperfect geometry of the specimens due to the achievable tolerances when working with adobe i.e. final dimensions of the specimens varied by around ±1.5%. However, the cracks in all specimens were within the joints located in the central region of the specimens. The cracks first suddenly occurred just after reaching the ultimate load carrying capacity with widths around 1 mm. Due to the sudden loss in horizontal load carrying capacity, the specimens further deformed and the crack openings widened. The crack widths were around 2 mm at the end of the tests. At this point, the test data records were stopped due to removal of the LVDTs to avoid them being damaged. After the removal of LVDTs, the load was continuously applied to better visualise the deformed shape and crack path of the specimens, as shown in Figure 9.
In specimens with loading direction perpendicular to their bed joints, the average maximum horizontal load sustained was 4.65 kN, when the average horizontal displacement at the centre of the rear face was 3.2 mm, Table 5. The horizontal force versus horizontal displacement plots for all specimens were linear up to reaching ultimate horizontal load.
carrying capacity, Figure 10. Beyond this point, a sudden noise due to fracture of the specimens and propagation of brittle cracks was heard; this resulted in a drop in horizontal load carrying capacity. The cracks were mainly vertical passing through the adobe units and head joints located on the rear surface of the specimens within the span of the load bearings. However, the crack path in each specimen was slightly different for the same reasons mentioned above as in the previous specimens, Figure 11. At the beginning, the crack width was estimated at around 3 mm. Under continuing horizontal force, the load carrying capacity reduced and the cracks further widened. The post-peak behaviour and loss of load carrying capacity of specimens was relatively gradual compared to the previous specimens loaded in a direction parallel to bed joints, as the cracks propagated in the adobe units along with the head joints i.e. not only in the joint interfaces as before. Propagation of cracks in the adobe units resulted in the mobilisation of the straw fibres in taking stresses as the fibres bridged the cracked surfaces and then the bond between the straw fibres and soil matrix gradually failed, Figure 12. The tests were continued until the horizontal load carrying capacity of the specimens dropped to around 20% of the ultimate value. At this point, the cracks were severe with openings around 25 to 30 mm, almost cutting the specimens into two main pieces.
From testing the hemp fibre rope reinforced specimens, the response of all reinforced specimens in terms of horizontal load carrying capacity versus horizontal displacements in the beginning of the tests was generally similar to the plain specimens, Table 7. The response was linear up to the ultimate horizontal load carrying capacity i.e. the rope reinforcement did not take significant stresses in the early stage of the tests. Due to practical constraints and the flexible nature of ropes, the ropes were not in perfect contact with the surface of adobe panels, the deformation in the adobe specimens from the beginning of the tests was not enough to strain the ropes and consequently they did not take stresses initially. This phenomenon continued up to propagation of cracks and a drop in the horizontal load carrying capacity to around 70% of its original ultimate capacity. After that point, the deformation in the adobe specimens mobilised the rope reinforcement. Consequently, the rope reinforcement enhanced the horizontal load carrying capacity of the specimens and provided a degree of ductility; see Figure 13 and Figure 15.
Figure 11: Conditions of plain adobe specimens loaded in a direction perpendicular to bed joints at the end of tests
In the reinforced specimens with loading direction parallel to their bed joints, the average maximum horizontal load sustained at first crack prior to the contribution of the rope reinforcement was 2.61 kN, Table 7. The cracks propagated horizontally at the unit-mortar interfaces in the bed joints located in the central region of the adobe panels. In the first specimen, Para-R-S1, the crack propagated along the 5th bed joint i.e. mid-height of the specimen. In the second specimen, Para-R-S2, the crack propagated along the 4th bed joint from bottom, Figure 14. The differences in the crack locations between the two specimens may be due to the same practical factors mentioned above, i.e. the rope reinforcement has no major influence on the propagation of the first cracks.
<table>
<thead>
<tr>
<th>Sample name</th>
<th>Maximum load sustained at first crack (kN)</th>
<th>Horizontal displacement in the specimens at first crack (mm)</th>
<th>Load carrying capacity of the specimen at the end of the tests (kN)</th>
<th>Horizontal displacement in the specimens at the end of the tests (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Para-R-S1</td>
<td>2.43</td>
<td>0.90</td>
<td>6.47</td>
<td>21.64</td>
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<tr>
<td>Para-R-S2</td>
<td>2.79</td>
<td>0.95</td>
<td>7.61</td>
<td>22.45</td>
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<tr>
<td>Mean (μ)</td>
<td><strong>2.61</strong></td>
<td><strong>0.93</strong></td>
<td><strong>7.04</strong></td>
<td><strong>22.05</strong></td>
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<tr>
<td>Standard deviation (σ)</td>
<td>0.25</td>
<td>0.03</td>
<td>0.81</td>
<td>0.57</td>
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<td>Coefficient of variation, %</td>
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<td>3.45</td>
<td>11.46</td>
<td>2.60</td>
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<tr>
<td>Perp-R-S1</td>
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<td>39.75</td>
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<tr>
<td>Perp-R-S2</td>
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<td>4.20</td>
<td>9.32</td>
<td>40.17</td>
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<td>Mean (μ)</td>
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<td><strong>4.13</strong></td>
<td><strong>9.98</strong></td>
<td><strong>39.96</strong></td>
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<td>Standard deviation (σ)</td>
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<td>0.11</td>
<td>0.92</td>
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<td>Coefficient of variation, %</td>
<td>9.59</td>
<td>2.57</td>
<td>9.25</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 7: Summary of results obtained from testing hemp fibre reinforced adobe specimens

After the drop in horizontal load carrying capacity due to formation of cracks, the vertical ropes started to mobilise and gradually regained the capacity of the specimens; this was when the crack opening width was estimated between 2 and 3 mm. Due to further deformation of the specimens and cracks’ opening, the vertical ropes perpendicular to the crack path
continued to strain, eventually the original load carrying capacity of the specimens was restored when the horizontal displacement at the centre was around 5 mm, while the plain specimens totally lost their capacity before reaching 2 mm in horizontal displacement in the same location. Further horizontal loading was sustained beyond this point, the average capacity of the reinforced specimens was 7.04 kN, around 3 times more than the capacity of the plain specimens, Figure 13. The average horizontal displacement was around 22 mm, the opening of the cracks estimated at 30 mm i.e. no further cracks apart from the initial ones propagated. The value of horizontal displacement was around 27 times more than the value at which the ultimate load of the plain specimens was achieved.

In reinforced specimens with loading direction perpendicular to their bed joints, the average maximum horizontal load at first cracking was 4.38 kN, Table 7. Following this brittle cracks with around 3 mm width occurred either vertically along the adobe units and head joints or passing through a bed joint, Figure 16. The occurrence of these cracks caused a drop in the initial capacity of the specimens. When the opening of the cracks reached around 8 mm, the rope reinforcement i.e. horizontal ropes perpendicular to the crack started to redistribute stresses and gradually regain the load carrying capacity. The first peak (pre-crack) capacity of the specimens was restored when the horizontal displacement at the centre of specimens was below 20 mm. At the same displacement in the unreinforced specimens, the capacity dropped to around 30% of the first peak capacity. Following this, the capacity continuously increased due to further deformation of the specimens and straining in the rope reinforcement. At the end of the tests, the average horizontal load carrying capacity of the reinforced specimens was around 10 kN, this value was around 2.2 times higher than the ultimate capacity of the plain specimens, Figure 15. The deformation capacity of the reinforcement specimens was around 10 times higher than the deformation of plain specimens at their ultimate capacity.
It should be noted that the reinforced specimens via the effect of the rope reinforcement would continue to sustain more deformation; the tests were stopped to avoid damaging the instrumentation. However, the relatively high level of deformation provided by the rope reinforcement is likely to already introduce instability into the full scale adobe walls in practice. At the end of the tests, no rupture in any of the ropes occurred, due to the high tensile capacity of the rope material. However, it was noticed the ropes were significantly tight during and at the end of the tests, the evidence of that was the obvious stretching of the ropes at the crack locations when the specimens were de-loaded after the tests, Figure 17 (a). As a result of high stresses, the ropes caused localised crushing and penetrated into the mortar joints at the corners of the specimens, Figure 17 (b). This issue may be remedied by introducing small pieces of timber or plastic to reduce the stresses in these locations. Furthermore, the ropes on the compressive side of the specimens were loose and did not have any noticeable effects on their performance. No crushing was in evidence on the compressive side of the reinforced specimens. In summary, the rope reinforcement significantly enhanced the capacity and deformation capacity of the adobe specimens, but no significant effect on the crack pattern and failure modes was observed.
Cracks propagated in the bed and head joints in the central region of specimen, 1 mm wide. Ropes started to regain the capacity when the crack width was between 2 and 3 mm. Initial cracks severely opened i.e. 30 mm wide. Rope held specimen pieces together.

Figure 13: Horizontal load-displacement responses of rope reinforced adobe specimens loaded in a direction parallel to bed joints.
Severe cracks with widths of 25 to 30 mm, almost cutting the specimens into two main pieces.

Fracture of specimens and propagation cracks with estimated width of 3 mm.

Width of the cracks reached around 8 mm, the rope reinforcement then started to redistribute stresses.

Severe cracks with widths of 25 to 30 mm, almost cutting the specimens into two main pieces.

Wide cracks cut the specimens in two pieces, the rope reinforcement still held the pieces together.

Figure 14: Failure modes of rope reinforced adobe panels loaded in a direction parallel to bed joints at the end of the tests.

Figure 15: Horizontal load-displacement responses of rope reinforced adobe specimens loaded in a direction perpendicular to bed joints.
Figure 16: Failure modes of rope reinforced adobe panels loaded in a direction perpendicular to bed joints at the end of the tests
Figure 17: (a) residual stretching in the ropes after de-loading of the specimens; (b) crushing the corners of adobe specimens and penetration of the ropes

5. Conclusions

Two sets of plain adobe masonry panels were experimentally tested under four point bending. In the first set, the specimens were loaded parallel to their bed joints, the failure mode of this set was due to propagation of brittle cracks along the joint interfaces. In the second set, the specimens were loaded perpendicular to their bed joints, failure was due to propagation of cracks along both joint interfaces and adobe units. The post-peak behaviour for both sets was a sudden drop in their load carrying capacity as the result of the propagation of the brittle cracks. The flexural strength of the second set was double that of the first set. The following conclusions can be drawn:

- The failure mode and crack pattern of adobe specimens from the same set experienced slight differences due to the natural variation in the material and achievable tolerances in construction of the panels.
- Two sets of hemp rope reinforced masonry adobe panels were tested under the same boundary conditions as the plain panels. The rope reinforcement had no influence on either initial stiffness up to first cracking or failure mode of the reinforced panels
since the deformation of the adobe panels up to this stage was not large enough to mobilise the rope reinforcement.

- Following occurrence of the first cracks, the rope reinforcement mobilised and significantly enhanced the horizontal load carrying capacity of the reinforced panels. For the 100mm x 100mm rope mesh size adopted in the experiments, the enhancement factor ranged from 2 to 3 times more than the ultimate horizontal load carrying capacity of plain panels for both load cases i.e. parallel and perpendicular to the bed joints.

- Due to the relative high strain capacity of the hemp fibre ropes, the reinforcement provided significant enhanced deformation capacity to the panels, while the stresses in the rope were still below the ultimate strength i.e. no rupture in any strands of the ropes was observed in the experiments. In addition, no crushing of adobe on the compression side occurred.

- The proposed strengthening technique, in addition to the sustainability and availability of the rope raw material, is also cost effective, easy to apply, results in no great additional mass to the adobe structure and no significant increase in wall thickness. The system can be used as a practical retrofit for existing structures and can also be easily applied in new construction.

The results obtained in these experiments show the proposed method has significant potential in achieving a low cost, practical and sustainable means of strengthening adobe walls subject to out-of-plane loading. The test results should be viewed within the context of the limited number of specimens examined, the specimen scale and the specific material properties of the adobe mix adopted. The significant enhancement in deformation capacity of the strengthened walls has clear implications for robustness and underlines the potential of the method to prevent collapse and save lives. Further investigation is required to understand the application of the method to structures in the field and the associated practical implications. Similarly, optimisation of the reinforcement system requires more investigation e.g. enhancement of the reinforcement effectiveness may be gained by pre-stressing.
Furthermore, the experimental results from this study can be used to derive practical design formulae to predict flexural strength of unreinforced and rope reinforced adobe masonry panels. These future investigations can be pursued by considering the principles of limit analysis and accounting for the orthotropy of adobe masonry by following the homogenisation techniques as proposed, for example, in [35, 36].

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References


