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Rammed earth walls strengthened with polyester fabric strips: Experimental analysis under in-plane cyclic loading

Lorenzo Miccoli [a,*], Urs Müller [b], Stanislav Pospíšil [c]

[a] Bundesanstalt für Materialforschung und –prüfung (BAM), Division Building Materials, Unter den Eichen 87, 12205 Berlin, Germany
[b] CBI Swedish Cement and Concrete Research Institute, c/o SP, Box 857, Brinellgatan 4, 50462 Borås, Sweden
[c] Institute of Theoretical and Applied Mechanics, v.v.i., Prosecká 76, 190 00 Prague, Czech Republic

HIGHLIGHTS

- The performance of unstrengthened and strengthened rammed earth walls was analysed.
- The strengthening technique is based on the use of vertical polyester fabric strips.
- The use of the strengthening technique requires low-tech equipment and workmanship.
- The strengthening provides an increase of horizontal load and displacement capacity.

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ABSTRACT

This study analyses the mechanical behaviour under pseudo-dynamic loading of structural elements built in rammed earth and strengthened with polyester fabric strips. This strengthening technique was developed to exploit the strength potential of rammed earth and to solve its lack of tensile strength. For this reason, in-plane cyclic tests were carried out to investigate the shear behaviour of unstrengthened and strengthened walls. The strengthening technique requires low-tech equipment and workmanship, uses readily available, not expensive and industrially standardised materials. The experimental results were analysed in terms of stiffness degradation, energy dissipation capacity and equivalent viscous damping. Although the unstrengthened and strengthened walls confirmed a limited ductile behaviour, the findings confirm that the strengthening contributes to limit the spread of the diagonal cracks and provide an increase of strength in terms of horizontal load and displacement capacity.

1. Introduction

Rammed earth is among the oldest building materials and one of the least understood in terms of structural behaviour under dynamic actions. The layered structure due to the compaction process of moistened earth in a wooden formwork has influence on the crack mechanism, even if its behaviour cannot be considered distinctively anisotropic. A considerable number of rammed constructions are present in regions suffering severe seismic events as China, New Zealand, South America and the Mediterranean area. This aspect has highlighted the importance to investigate its mechanical behaviour under dynamic actions and to develop effective strengthening techniques. In spite of this, systematic data on the dynamic performances of rammed earth are still rare and the knowledge about its energy dissipation capability needs to be improved. In the last years, Bui et al. [1] measured the natural frequencies, modal shapes and damping ratios of a rammed earth structure, Wang et al. [2] performed shaking table tests to validate a strengthening system based on externally bonded fibres. A few more studies are available on unstrengthened [3] and strengthened walls [4–6] made of stabilised rammed earth tested under in-plane cyclic loading. Arslan et al. [7] compared the cyclic behaviour of the rammed earth walls non-stabilised and cement stabilised with masonry brick and aerated concrete walls.

In comparison with studies carried on the earth block masonry [8,9], the experimental campaigns on strengthening systems for rammed earth are limited to few studies only. Experimental campaigns were carried out on rammed earth samples to assess to effectiveness of strengthening system using externally bonded fibres [10] or using reinforcement systems form textile grids [11] to increase the energy dissipation. Shaking table tests on lab scale models strengthened with boundary wooden elements were performed by Ruiz et al. [12].

* Corresponding author.
E-mail address: lorenzo.miccoli@bam.de (L. Miccoli).

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Nomenclature

$d_{H,max}$	displacement corresponding to peak horizontal load of the *i* cycle (mm)
E	Young's modulus (N/mm^2)
E_{diss}	dissipated hysteretic energy (kN·m)
E_{inp}	input energy (kN·m)
f_c	uniaxial compressive strength (N/mm^2)
f_s	shear strength (N/mm^2)
f_t	tensile strength (N/mm^2)
H	horizontal load (kN)
H_{cr}	horizontal load at crack limit (kN)
H_f	horizontal load at flexural cracking limit (kN)
H_{max}	maximum horizontal load (kN)
$H_{max,i}$	peak horizontal load of the *i* cycle (kN)
H_u	horizontal load at ultimate displacement (kN)
$I_{E,diss}$	indicator of the energy dissipation (-)
$K_{s,i}$	secant stiffness (kN/mm)
t	time (sec)
α	adhesion strength (N/mm^2)
δ	displacement (mm)
μ	vapour diffusion (–)
ρ_v	vertical reinforcement (%)
ξ_{eq}	equivalent viscous damping coefficient (–)
ρ	bulk density (kg/m^3)
σ	vertical compressive stress (N/mm^2)
ψ_{cr}	lateral drift at crack limit (%)
ψ_f	lateral drift at flexural cracking limit (%)
ψ_{max}	lateral drift at maximum horizontal load (%)
ψ_u	lateral drift at ultimate displacement (%)

As extension of the previous findings, this study assesses the mechanical behaviour of rammed earth walls unstrengthened (REW) and strengthened with polyester fabric strips (REWS) under in-plane cyclic shear-compression tests. The improvement introduced by the strengthening techniques was evaluated analysing the response of the walls in terms of horizontal load, displacement capacity, stiffness degradation and energy dissipation. The strengthening technique adopted was developed to enhance the in-plane response of the rammed earth walls according to the definition of robustness reported in Eurocode 8 [13] and Tomaževič [14].

The performance-based engineering criteria for unreinforced masonry elements were used to associate a particular damage level of the wall to a certain displacement. These criteria let us to idealise the walls behaviour under the progressive increment of the applied lateral displacement through four limit states.

The results of the presented study represent an important development of the data partially reported in [15], i.e., assessment of energy dissipation capacity, equivalent viscous damping and stiffness degradation, together with the investigation of the influence of polyester fabric strips creating the strengthening system.

2. Experimental programme

2.1. Materials and samples preparation

Five rammed earth walls of size 1300 mm × 1050 mm × 250 mm were built at Bundesanstalt für Materialforschung und –prüfung (BAM) in Berlin and tested under cyclic shear-compression load. In the manufacturing process, earth with a moisture content in the range of 9–10 mass-% (Fig. 1a) was placed in a plywood formwork (Fig. 1b). The original layer thickness of approximately 150 mm was mechanically compacted with a rammer to a thickness of approximately 100 mm (Fig. 1c). The samples, showing thirteen layers (Fig. 1d), were leave to dry for two months in the laboratory. Before testing the moisture content was in the range of 2–3 mass-% corresponding to an average value of bulk density (ρ) equal to 2190 kg/m^3. No measurement of bulk density was carried out at the time of wall manufacturing. For this reason, it was not possible to assess the variation of bulk density related to the variation of moisture content and compressive strength. Static tests on rammed earth samples (500 mm × 500 mm × 100 mm) exhibited a compressive strength (f_c) of 3.73 N/mm^2 and a shear strength (f_s) of 0.70 N/mm^2. The detailed description of the mechanical characterisation is reported in a previous study [16], as well as the mineralogical and granulometric properties of the rammed earth used [17].

In this work, a strengthening system is proposed to exploit the strength potential of rammed earth and to solve its lack of tensile strength, significantly increasing strength and displacement capacity. The principle of this technique is to embed the low cost and high tensile strength materials into the rammed earth wall. Vertical strips made of polyester fabric inserted in wall slits to take up horizontal loads over the height of a wall were employed. Polyester fabric strips are textile strips used as heavy duty belts for fixing goods and are available essentially everywhere (Fig. 2a). They have a tensile strength (f_t) of 40 N/mm^2, a Young's modulus (E) of 140 N/mm^2 and can be loaded only in the tensile direction.

A base coat mortar with an adhesion strength (α) > 0.08 N/mm^2 and a water vapour diffusion (μ) ≤ 20 was chosen [18] as an adhesive for fixing the vertical polyester fabric strips. This adhesive is a premixed polymer-modified cement based mortar with the addition of polymer fibres and water-repellent agents. The main binder components are cement and pozzolan. Base coat mortar was adopted considering its good mechanical performance, workability, fast hardening and its low invasiveness in comparison with other adhesive as epoxy resin or polyurethane foam [20]. The adhesive has a small particles size suitable to fill the thin slits and a compressive strength in the range of 10–20 MPa, about three time higher than the compressive strength shown by rammed earth. Although the strength of the base coat mortar is not mechanically compatible with rammed earth, it must be stressed out that its application is limited to a small portion of the wall (about 0.8–0.9% of the volume).

The cement based mortar was chosen in alternative to a high hydraulic mortar thanks to their quick preparation and facility of application in thin layer. Considering the application in very thin layers only the bond with earthen substrate was measured. The adhesion strength was tested with pull-off tests on earth blocks according to EN 1015-12 [19].

The principle of the strip strengthening procedure is shown in Fig. 2b. Slits 56 mm deep and 9 mm wide were cut every 250 mm using a disc grinder. The slits in the walls create a point of weakness that had to be compensated by the combination of the appropriate adhesive and strips. To avoid the creation of too many points of weakness along the wall section the distance between slits was not less than five times the width of the strips. For the same reason the width of the strips was not more than one third of the wall thickness.

The slits were cleaned from dust with compressed air and wetted with sprayed water. A water-based polymethylmethacrylate (PMMA) emulsion was sprayed in the slits to develop the bond among the porous substrate and the base coat mortar. Based on the results of a previous study [20] where different adhesives were