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In-plane behaviour of rammed earth under cyclic loading: Experimental testing and finite element modelling

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ABSTRACT

The purpose of this paper is to numerically simulate the in-plane behaviour of rammed earth walls under cyclic shear-compression tests. The experimental testing allowed obtaining the maximum horizontal loads, the displacement capacity and the level of non-linear behaviour of the respective load-displacement relationships as well as the failure modes. The calibration of the numerical model (finite element method) was carried out based on the experimental results. Within this framework, a micro-modelling approach was considered. The behaviour of the rammed earth material was simulated using a total strain rotating crack model. A Mohr-Coulomb failure criterion was used to reproduce the behaviour of the interfaces between the layers.

Although the numerical results achieved a satisfactory agreement with the experimental results a sensitivity analysis of the parameters involved was performed. The sensitivity analysis aimed at determining which parameters of the model have a significant impact in the model's results.

As expected the sensitivity analysis pointed out that the sliding failure occurrence is mainly influenced by two parameters of the interface elements: the interface tensile strength f_t^i and the friction angle φ. Moreover the cohesion c and the layers thickness showed a limited effect on the shear behaviour. It should be noted that the results mentioned above are related to the cases where a significant level of vertical compressive stress σ is employed.

1. Introduction

Earthen buildings constitute an important part of our cultural heritage. Earthen materials are among the oldest materials used in construction, and perhaps the least understood in terms of strength and deformation capacity. This statement is indeed true since the role of earth as a structural or non-structural material is often obscured.

The intent of this paper is to investigate the mechanical behaviour of rammed earth walls under in-plane cyclic shear-compression tests. The goal of the experiments was to test the general response of monolithic rammed earth walls under pseudo-dynamic horizontal loading in terms of lateral load increase and displacement capacity.

Rammed earth is an earthen construction technique in which 'soil-moist' earth is compacted in consecutive layers in the range of 10–15 cm within a wooden formwork. Due to the compaction process rammed earth has a distinctive layered appearance. Often the single formwork lifts can be recognized. In cases where the clay content of the earth was too low or the grain size distribution was not optimal, lime was often added to the rammed earth mix or filled into the formwork in layers to increase its strength and cohesiveness [1].

The layered structure influences the crack mechanics but the mechanical behaviour of rammed earth seems not to be distinctively anisotropic [2]. Although some numerical models for earthen structures can be developed, their correlation to real-life situations or experiments as a means of verification and validation has yet to be thoroughly analysed. However, only few testing campaigns on pseudo-dynamic horizontal loading, aiming at defining quantitative properties, were carried out to better understand the behaviour of rammed earth under in-plane cyclic loading.

Walker and Morris [3] tested rammed earth walls stabilised with 10% cement and reinforced with steel rods under in-plane cyclic loading. Hamilton [4] performed tests on 3% cement stabilised rammed earth walls with and without post tensioned

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Nomenclature

Symbol	Description
c	cohesion coefficient (N/mm^2)
E	Young's modulus (N/mm^2)
f_c	uniaxial compressive strength (N/mm^2)
f_t	tensile strength (N/mm^2)
f_t^i	interface tensile strength (N/mm)
G	shear modulus (N/mm^2)
G_c	compressive fracture energy (N/mm)
G_f^I	tensile fracture energy (N/mm)
H	horizontal load (kN)
H_{cr}	horizontal load at crack limit (kN)
H_f	horizontal load at flexural cracking limit (kN)
H_{low}	horizontal load at the lower value of the parameter considered (kN)
$H_{\max}$	maximum horizontal load (kN)
H_u	horizontal load at ultimate displacement (kN)
H_{upp}	horizontal load at the upper value of the parameter considered (kN)
k_n	interface normal stiffness (N/mm^3)
k_s	interface tangential stiffness (N/mm^3)
δ	displacement (mm)
δ_{cr}	displacement at crack limit (mm)
δ_f	displacement at flexural cracking limit (mm)
$\delta_{\max}$	displacement at maximum horizontal load (mm)
δ_u	ultimate displacement (mm)
σ	vertical compressive stress (N/mm^2)
$\tau_{\max}$	nominal shear strength (N/mm^2)
θ_{cr}	rotation angle at crack limit (%)
θ_f	rotation angle at flexural cracking limit (%)
$\theta_{\max}$	rotation angle at maximum horizontal load (%)
θ_u	rotation angle at ultimate displacement (%)
ν	Poisson's ratio (–)
φ	internal friction angle (°)
ψ	dilatancy angle (°)

strengthening both in-plane and out-of-plane. These walls were built with base and capping beams made of concrete.

Experimental results offer limited data to develop reliable non-linear models. Moreover most of the few studies on modelling rammed earth with finite element modelling (FEM) were used to simulate stress distributions and collapse mechanisms under static loading [2,5,6]. So far only few studies on the numerical modelling of rammed earth walls subjected to dynamic loading [7,8] and to pseudo-dynamic loading [9] are available.

In the first part of this study the mechanical characterisation of rammed earth walls tested under in-plane cyclic shear-compression loading is presented. The results were used to implement the finite element simulations.

The numerical modelling of the rammed earth walls tested is then discussed in the second part. A non-linear constitutive law based on the total strain rotating crack model (TSRCM) was employed as implemented in the DIANA® software [10]. This model was used successfully in a previous study to simulate the behaviour of rammed earth under uniaxial and diagonal compression [11]. The TSRCM is common in the non-linear FEM analysis of several brittle materials, such as concrete [12–14] or masonry [15,16]. Since from the earliest studies on masonry materials, the micro-modelling strategy aimed at a development of a reliable interface model [17]. This model was then implemented through a refined description of the dilatancy phenomena [18]. The use of smeared crack models was then refined in several studies [19–21].

The aim of the numerical analysis presented here is to simulate the behaviour of rammed earth under in-plane cyclic loading. The micro-modelling approach was applied for the simulation of the experimental tests, and the respective FEM model was calibrated with the experimental results. The rammed earth layers were represented by continuum elements, the contact surfaces between layers by interface elements. This approach allowed assessing the influence of the apparent weakness of the interfaces between layers on the shear behaviour of rammed earth.

The goal of the numerical simulation of the cyclic tests was to establish the adequacy of common analytical methods (e.g. used for masonry) applied to the analysis of rammed earth. Rammed earth exhibits the brittle characteristics similar to masonry materials and is used in geometrical typologies, such as walls, common in masonry construction. In addition to the simulation of the experimental tests, a sensitivity analysis was performed. Its purpose was to assess the sensitivity of the response of rammed earth walls under the variation of eight different material parameters.

2. Experimental programme

2.1. Materials and preparation of the samples

Three rammed earth walls were manufactured at BAM and used for cyclic shear-compression tests. A local manufacturer of prefabricated earthen materials (Claytec GmbH, Germany) provided the earth used for the samples. The rammed earth walls of size 1300 mm × 1050 mm × 250 mm had a bulk density of 2190 kg/m^3, a particle size range of 0–16 mm and a drying shrinkage of 0.5%. During the manufacturing process 'soil-moist' earth (moisture content in the range of 9–10% by mass) was mechanically compacted in thirteen layers within a plywood formwork using a mechanical rammer. Here, the original layer thickness of ca. 150 mm was compacted to a thickness of ca. 100 mm.

After production, the walls were stored for two months in the laboratory for drying. Before testing the walls showed an equilibrium moisture content in the range of 2–3% by mass.

Mechanical properties of rammed earth under static loading were determined in the BAM laboratories on wallettes (500 mm × 500 mm × 100 mm). The wallettes' results showed a uniaxial compressive strength f_c of 3.73 N/mm^2 and a shear strength $\tau_{\max}$ of 0.70 N/mm^2. The Young's modulus E and the shear modulus G, determined as a secant-modulus of the stress at 1/3 of the maximum load, were respectively of 4143 N/mm^2 and 1582 N/mm^2. The detailed descriptions of the materials characterisation and static tests are reported elsewhere [22].

2.2. Test setup

Three cyclic in-plane shear-compression tests were carried out at the Institute of Theoretical and Applied Mechanics (ITAM) in Prague. The tests were performed in the framework of the EC project NIKER (New integrated knowledge based approaches to the protection of cultural heritage from earthquake induced risk) in which BAM and ITAM were part of the project consortium [23]. The in-plane cyclic shear-compression tests were carried out following the procedure given in RILEM TC 76-LUMC3 [24].

The samples were placed into a testing rig able to provide simultaneously uniform compression and cyclic horizontal loads at the top of the sample. The walls were tested with a cantilever-type boundary condition, the base of the walls was fixed and the top end was free to rotate. The top of the wall was wrapped by a