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Experimental testing and finite element modelling of earth block masonry

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ABSTRACT

The current paper focuses on the determination of reliable numerical models of earth block masonry wallettes under different loading conditions. Uniaxial compression and diagonal compression tests were performed. Experimental behaviour was modelled with a non-linear model able to describe the cracking behaviour. The simplified approach based on macro-modelling shows a satisfactory accuracy and low computational costs. The results reproducing the uniaxial compression are in good correspondence with the post-elastic behaviour observed in the experimental campaign. The micro-modelling approach adopted to reproduce the shear behaviour, even with high computational cost, represents a suitable tool to predict the masonry collapse mechanism.

1. Introduction

The knowledge on the material properties and failure mechanisms of earth block masonry is limited and scattered when compared to the advances in research on stone and brick masonry. Only few systematic investigations into the behaviour of earth block masonry under different load conditions are available [1–6]. Prediction models for the behaviour of historic earth-built examples, e.g. in cases of earthquakes, are therefore only rarely possible; the effect of interventions to improve structural integrity are only beginning to be appreciable.

The scatter of mechanical property values in the literature as shown in Table 1 can be large. This clearly is not only due to factors such as workmanship and weathering, but also to different testing procedures, for instance in the derivation of Young's modulus.

Earth block masonry consists of earth blocks and mortar, usually an earth mortar. Sometimes stabilising additives, such as lime, cement or gypsum have been/are being used for mortars and blocks. Nowadays earth blocks can have various forms and sizes with or without perforations. The manufacture of earth block masonry usually follows the same principles as those used for fired clay brick masonry. In the past, blocks without perforation were usually used in various sizes. These blocks were produced by throwing a handful of a malleable mass of earth into a mould. Due to the higher water content, the plastic earth cannot be compacted.

Although earth block is a widely utilised building material since prehistoric times, it also represents a type of masonry block that yields the lowest strength values. Typical values for compressive strength of historical unstabilised earth blocks are in a range of 0.6–6.6 N/mm^2 [11,14–19]. The modulus of elasticity measured on modern earth blocks with similar compressive strength and particle size distribution as historical earth blocks is in the range of 400–2000 N/mm^2. Compared to some building stones or fired bricks, earth blocks show a rather moderate to low anisotropic effect towards their mechanical and physical properties.

The experimental results evidenced how the global performance of earth block masonry elements is mainly governed by the non-linear behaviour of constituent materials (earthen blocks and mortar) and by the properties at the unit-mortar joint interface. In the past, few attempts in numerical modelling of earth block masonry were undertaken considering the possibility to simulate its real inelastic behaviour and global deformability. The limited and scattered information about the material's properties from experimental tests are usually reflected in modelling strategies based on simple assumptions on the material behaviour. Therefore, the analysis is limited to the linear elastic field or rather simple non-linear constitutive laws are used, thus evidencing the

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Notation

c	cohesion coefficient (N/mm^2)
C_{ss}	coefficient for contribution of shear stresses to failure (–)
E	Young's modulus (N/mm^2)
$E_{1/3}$	Young's modulus (measured at 1/3 maximum load) (N/mm^2)
E_{block}	block Young's modulus (N/mm^2)
E_m	mean Young's modulus (N/mm^2)
E_{wall}	masonry Young's modulus (N/mm^2)
f_c	compressive strength (N/mm^2)
f_{cm}	mean compressive strength (N/mm^2)
$f_{c,joint}$	interface compressive strength (N/mm^2)
f_{ck}	characteristic compressive strength (N/mm^2)
f_f	flexural strength (N/mm^2)
f_{fm}	mean flexural strength (N/mm^2)
f_{fk}	characteristic flexural strength (N/mm^2)
f_t	tensile strength (N/mm^2)
$f_{t,crack}$	unit crack interface tensile strength (N/mm^2)
$f_{t,joint}$	interface tensile strength (N/mm^2)
f_{tm}	mean tensile strength (N/mm^2)
f_{tk}	characteristic tensile strength (N/mm^2)
f_{vk0}	initial characteristic shear strength (with earth blocks) (N/mm^2)
$f_{vk0,avg}$	initial shear strength (with earth blocks) (N/mm^2)
G	shear modulus (N/mm^2)
$G_{1/3}$	secant shear modulus (measured at 1/3 maximum load) (N/mm^2)
G_f^c	compressive fracture energy (N/mm)
G_f^I	first mode (tensile) fracture energy (N/mm)
$G_{f,crack}^I$	unit crack interface first mode (tensile) fracture energy (N/mm)
G_f^{II}	second mode (shear) fracture energy (N/mm)
h	height of the earthen block (mm)
k_n	unit crack interface normal stiffness (N/mm^3)
$K_{n,joint}$	joint interface normal stiffness (N/mm^3)
k_s	unit crack interface tangential stiffness (N/mm^3)
$K_{s,joint}$	joint interface tangential stiffness (N/mm^3)
RH	relative humidity (%)
β	coefficient of shear retention (–)
γ	generic shear strain (%)
$\gamma_{1/3}$	shear strain (measured at 1/3 maximum load) (%)
ε	generic strain (%)
ε_c	compressive strain (%)
φ	internal friction angle (°)
ψ	dilatancy angle (°)
ν	Poisson's ratio (–)
ν_m	mean Poisson's ratio (–)
ρ	bulk density (kg/m^3)
σ	generic stress (N/mm^2)
σ_c	compressive stress (N/mm^2)
σ_{max}	maximum compressive stress (N/mm^2)
σ_u	compressive strength (N/mm^2)
τ	generic shear stress (N/mm^2)
τ_{max}	maximum shear stress (N/mm^2)
τ_u	shear strength (N/mm^2)

difficulties in the prediction of the post-peak behaviour [20,21] through reliable finite element models. Attempts in the numerical modelling of earth block masonry elements, accounting for the non-linear behaviour of the material, can be found in [20], regarding earth block masonry with earth mortar tested in compression and diagonal shear, and [22], regarding reinforced earth block masonry tested under horizontal cyclic loads. The definition of accurate and reliable models for the description of the complete non-linear behaviour requires additional mechanical properties, which are sometimes difficult to evaluate by means of experimental tests. This lack of mechanical properties limits the use of complex continuum or discontinuous approaches.

The current paper focuses on the determination of reliable numerical models of earth block masonry wallettes under different loading conditions. In the first part the results from laboratory tests are shown. The entire experimental programme was performed in the laboratories of BAM, Berlin. The wallettes considered in the experiments consisted of one leaf earth block masonry with earth mortar tested under compression and diagonal compression loads. The experimental campaign described in the presented study, based on displacement-controlled tests, represents an important contribution for the acquisition of detailed information regarding the mechanical behaviour of earth block masonry. Such information is necessary for a comprehensive characterisation and advanced modelling of earthen structures. In addition to wider experimental characterisation of materials, the employment of non-linear techniques, essential for this type of studies, implicitly requires a higher computational effort compared to simple linear analysis.

The second part of the paper deals with the numerical modelling of the earth block masonry wallettes tested under axial compression and diagonal compression. The non-linear constitutive laws adopted are based on the multi-directional fixed crack model and combined interface model implemented in DIANA software [23]. The aim of the numerical analysis is to simulate the non-linear shear behaviour of earth block masonry. Both macro- and micro-modelling approaches were considered for the simulation of the experimental tests, and the respective FEM models were

Table 1
Summary of material properties for earth block masonry in the literature.

ρ (kg/m^3)	σ_u (N/mm^2)	E (N/mm^2)	τ_u (N/mm^2)	G (N/mm^2)	Reference
1800	1.35	250	0.12	180	[1]
1800	0.79–1.60	250	0.11	75	[2]
1800	2.14	150–200	0.12	105	[3]
nd	0.33	664	0.026	40	[6]
nd	nd	nd	0.026	40	[7]
nd	1.60	180	0.07	nd	[8]
nd	1.03	160	0.06	nd	[9]
nd	0.8–1.7	nd	0.05–0.18	nd	[10]
1870	2.15	315	nd	nd	[11]
nd	0.8–1.2	nd	0.14–0.25	nd	[12]
nd	0.9–1.0	nd	nd	nd	[13]

nd = not determined.