Static behaviour of cob: experimental testing and finite element modelling

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Abstract

The aim of this paper is to implement a numerical model to reproduce the non-linear behaviour of cob walls under shear loading. Axial compression, pull-off and diagonal compression tests, were carried out to derive the mechanical parameters. In addition, the stress-strain relationships, the non-linear behaviour and the failure modes were defined. The experimental results were then used to calibrate a finite element model. The material behaviour was simulated through a macro-modelling approach adopting the total strain rotating crack model. A sensitivity analysis was conducted to assess the effects of varying the parameters with higher uncertainty on the structural behaviour. The numerical model achieved good correspondence with the experimental results, namely in terms of simulation of the shear stress-shear strain relationship and of damage pattern.

Keywords: cob; compression behaviour; shear behaviour; digital image correlation; finite element method

INTRODUCTION

Earthen materials show interesting environmental advantages when used as building materials (Pacheco-Torgal et al. 2012, Fabbri et al. 2016). Nowadays, there are several available techniques where these materials can be used with structural purposes, namely as earth blocks (adobe), compressed earth blocks (CEB), rammed earth and cob (Niroumand et al. 2013). Constructions based on vernacular or traditional building materials and techniques are currently being used in Europe (McCann 2004, Forster et al. 2008, Harrison 1999), North America (Swan et al. 2011) and New Zealand, but the lack of scientific data and lack of experience by the mainstream construction industry in using these materials are still obstacles to be worked around (Niroumand et al. 2013, MacDougall 2008, Hamard et al. 2016). These materials are gaining growing interest also for their thermal performances (Allinson and Hall 2010, Collet et al. 2006). In the case of modern cob walls, their high thermal mass induces a thermal insulation that is two times the minimum thermal requirements in United Kingdom (Goodhew and Griffiths 2005). In some cases earthen materials are reinforced with fibres, which were shown to improve their mechanical performances (Quagliarini and Lenci 2010, Ghavami et al. 1999, Bouhicha et al. 2005, Parisi et al. 2015, Yetgin et al. 2008).

Within the last decade, research on earth construction is mainly focused on the mechanical characterisation of earth block masonry, CEBs and rammed earth, while little has been done with respect to cob (Quagliarini et al. 2010, Rafi and Lodi 2017). Cob is a mixture of earth and plant fibres, thus walls made of cob can be regarded as fibre-reinforced structural elements with a monolithic appearance. According to Keefe (2005), a good grain size distribution for cob is made by 30–40% gravel, 25–30% sand and 10–20% silt. The use of large graded materials contributes to contain the shrinkage cracks. If so, the content of fibres can be reduced (Hamard et al. 2016).

Building with cob refers to a great variety of forms related to the slight differences developed within the several local techniques. To provide a more accurate description of this construction process, some authors (Houben and Guillaud 1994) proposed to name this technique “piled earth”. In this study the cob specimens were manufactured following the cob technique traditional of Germany named *lehmweller* (Hamard et al. 2016, Ziegert 2003). For this technique, the largest particle size of the soil usually does not exceed the sand fraction.

The earth is mixed with water to a plastic consistency and then the straw fibres are added. The mix of soil is kneaded under pressure (traditionally by the hooves of livestock) and then shaped into large clods. The clods of earth snatched from the cob mixture pile are either piled or forcefully thrown onto the wall with a fork or with hands. The clods are often arranged diagonally layer by layer onto the cob heap (Quagliarini et al. 2010, Miccoli et al. 2014). The cob material is then stacked to usually about 0.6 m high lifts (Hamard et al. 2016) and left to dry.

When the masses show adequate moisture content, the wall sides are cut vertically by a spade. Due to the high fibre content the material usually has a bulk density (ρ) in the range of 1400–1700 kg/m^3 (Schroeder 2016). The Young's modulus (E_0) is in the range of 200–500 MPa; where the corresponding compressive strength ranges between 0.5–1.5 MPa (Ziegert 2003, Miccoli et al. 2014). The original structural behaviour of cob buildings can be impacted by many environmental influences. Increased water content (due to uprising damp or faulty roof) not only lowers material strength but can also initiate decomposition of the fibres. The high fibre content enables insects or rodents to dig deep in cob walls. All these factors impair the overall structural behaviour of cob walls.

Although in last decade several studies were carried out to numerically model the behaviour of earthen materials under both static (Piattoni et al. 2011, Miccoli et al. 2015a, 2015b, Giamundo et al. 2014, Ortega et al. 2015, Caporale et al. 2015, Jaquin 2008, Nowamooz and Chazallon 2011, Bui et al. 2016) and pseudo-dynamic loading (Gomes et al. 2012, Garofano et al. 2016, Miccoli et al. 2016), references on the numerical modelling of cob constructions are not present in literature. The prediction of the non-linear behaviour has great importance to assess the seismic performances of a cob construction, where severe deformation is expected. Therefore, an accurate simulation of the structural behaviour of cob constructions requires complex constitutive laws. To define these laws, a detailed experimental characterisation of the cob properties is required. In addition, the material characterization and its modelling are hardly predictable due to the variability shown by the raw earthen materials. In light of the aforementioned aspects, the constitutive model, selected referring to the material behaviour and the analysis computational demand, needs to provide a good match between representativeness, complexity, accuracy and reliability.

The material and mechanical characterisation of cob is presented in the first part of the paper. Firstly, granulometric and mineralogical analyses were carried out on the soil used to prepare the cob specimens (small walls). Then, the small walls manufactured in the BAM laboratories were tested under axial and diagonal compression. In addition, pull-off tests on small specimens were performed to derive the tensile strength values. The goal of the experimental programme was to derive the basic mechanical properties in a controlled environment to employ in the numerical simulation. There was no intent to investigate the main variables that control the strength and the behaviour of the composite material studied. For this reason, fundamental issues usually encountered during the usage of natural fibres as reinforcement were not investigated. Among them, there are the optimum water/soil ratios necessary to produce a high-strength soil matrix, fibres orientation, bond between soil matrix and fibres, fibres optimum length and reinforcement/soil ratios.

Several studies already explain how and why the behaviour of soil changes with the addition of vegetable fibres. Bouhicha et al. (2005) analysed the performances of composite soil taking into account the optimal reinforcement ratio in relation to decreasing shrinkage, reducing the curing time and enhancing the compressive strength. Ghavami et al. (1999) investigated the usage of natural fibres as reinforcement of soil, like fibre/matrix ratios and water soil ratios. The literature review carried out by Hejazi et al. (2012) showed that the strength of fibre reinforced soil depends mainly on the fibre characteristics, sand characteristics and test conditions. Aymerich et al. (2012) demonstrated that a wool fibre reinforcement for earthen materials is beneficial in terms of strength and post-fracture performance.

In the second part of the paper, the numerical modelling of the small walls tested under diagonal compression is presented. The non-linear constitutive law used refers to the total strain rotating crack model (TSRCM) implemented in TNO DIANA software (TNO 2015). The TSRCM is common in the non-linear FEM analysis of brittle materials, such as concrete (Qapo et al. 2015, Martinola et al. 2010, Bao et al. 2008) or masonry (Ghiassi et al. 2013, da Porto et al. 2010). The goal of the numerical analysis is to reproduce the non-linear shear behaviour of cob. A macro-modelling approach was taken over to simulate the experimental tests, where the model was tuned to match the experimental results. Following the tuning procedure, a sensitivity analysis was also conducted to determine the dominant parameters with higher uncertainty on the structural behaviour.

This work is expected to contribute to the prediction of the monotonic shear behaviour of cob walls based on the use of advanced FEM modelling tools. This knowledge is particularly valuable for the accurate evaluation of the performance of cob structures under horizontal loads, namely wind and earthquakes. Furthermore, advanced FEM modelling tools are indicated for safety assessment of new or existing cob buildings in regions with important seismic hazard, as cob is recognised as a material with low mechanical properties and important nonlinear behaviour.

EXPERIMENTAL PROGRAMME

Materials and preparation of the specimens

The soil used to prepare cob specimens was provided by a local manufacturer (Claytec GmbH, Germany) as well as the wheat straw fibres. It was assumed that the type of straw has no relevant influence on the cob behaviour. The straw fibres were processed according to the traditional processing line. Firstly, the decorticated fibres were separated from the freshly harvested material. Then, the fibres were conditioned and cleaned. After the drying process, straw bales were produced.

To identify the earth composition and the clay minerals content of the soil, granulometric and mineralogical analyses were carried out. The specimens were characterised for phase composition by X-ray powder diffraction (XRD). The particle size distribution (PSD) was determined according to DIN 18123 (DIN 2011) using sieve and sedimentation analysis. The results of granulometric and mineralogical analysis are reported in Table 1. The grain size distribution showed that the clay size fraction is 21% while the silt, sand/gravel size fractions are 61% and 18% respectively. Grain constituents include quartz and feldspar, although in lower proportions. The clay fraction is dominated by kaolin and lesser amounts of smectite-illite and illite.

Cob was manufactured at BAM laboratories using a concrete mixer, the soil was mixed with 24 mass-% of water to a mass of plastic consistency. The flow table test, performed according to EN 196-3 (CEN 2005), showed a spread flow of 170 mm. Afterwards, 1.7 mass-% straw fibres (moisture content in the range of 2–3% by mass) with a length in the range of 20–30 cm was added (Fig. 1a). An uniform dispersion of the fibres prevents the ‘balling effect’ (Wafa 1990). For this reason, the fibres were sprinkled into the mix by hand to avoid that they clamp together.

After the mixing process no balling effect was noticed and the cob clods (Fig. 1b) were thrown onto the heap (Fig. 1c,d) according to the traditional cob technique *lehmweller*. By throwing the plastic cob mass void space and air inclusions are minimized. After a drying period of four weeks in a climate room at 23 °C and 50% relative humidity (RH), test specimens (small walls) with dimensions of about 420 × 420 × 115 mm^3 (width × height × thickness) were cut out from the cob heap (Fig. 1e) with a saw (Fig. 1f), thus preserving the original texture of the cob.

The small walls were stored for at about 28 days in a climate room at 23 ºC and 50% RH for drying. The drying process was ended when the difference of the specimens' weight was less than 0.2% by weight within 24 h. After drying, a final bulk density of 1475 kg/m^3 was determined according to DIN 18945 (DIN 2013a). The small walls were removed from the climate room shortly before mechanical tests. To determine the dry weight, a small wall was dried in the oven at a constant temperature of 40 ºC as suggested by DIN 18945 (DIN 2013a). The results showed that the equilibrium moisture content of the small walls before testing was about 2.0 mass-%.

In the experimental programme eleven small walls were tested, four under axial compression and seven under diagonal compression. Pull-off tests on ten small specimens were performed to derive the tensile strength values.

Axial compression tests

A layer of low strength cement mortar was used between the top and bottom surfaces of specimens and the supports to regularise the mutual contact. The distribution of the load applied to the specimens was given by means of two I steel profiles fixed at the top and bottom surfaces. The four compression tests were performed with displacement control according EN 1052-1 (CEN 1998). The test speed was set to 0.25 mm/min to reach the failure after 15 to 30 min. For the suggested loading rate, no creep effects can occur. The deformations of the specimens were measured through linear variable differential transformers (LVDTs) bonded on both sides of the small walls through a layer of two-component epoxy adhesive (Fig. 2a). Fig. 2b reports the compression tests results in terms of axial stress-strain curves and the respective envelope. The compression stresses were derived dividing the vertical load applied (V) by the cross sectional area perpendicular to the loading direction. The stress-strain curves draw attention to the non-linear behaviour of cob under compression. The mechanical properties obtained from compression tests are summarised in Table 2.

The Young's modulus (E_0) was calculated between 5% and 30% of compressive strength (f_c) by linear fitting. There is still a lack of references regarding the definition of methodologies for the estimation of the elastic parameters of earthen materials, which are known for presenting high non-linear behaviour. For this reason, the range of 5–30% was adopted, as within this range the stress-strain curves seem to have a linear-elastic development. Furthermore, the first 5% of the curves is not considered in order to remove the initial noise of the LVDTs due to small displacement measurements and the ineffective reaction provided by the test setup. Furthermore, it should be noted that the maximum compression stress level of a 1-2 storey cob building is expected to vary between 0.08 MPa and 0.30 MPa, meaning that the range selected to compute the Young's modulus comprises the expected service stress levels of typical cob buildings.

The values of f_c showed relatively low scattering and varied in the range of 1.55–1.63 MPa. Also E_0 presented relatively low scattering and varied in the range of 977–1084 MPa.

The deformations of the specimens were relatively high, where the maximum values measured for axial strain (ε) were higher than 0.30%. Due to the presence of straw, the cob specimens showed a ductile behaviour under compressive load, without distinctive maximum in a long post-peak phase. Although the crack pattern shown in Fig. 3 seems to be influenced by the LVDTs fixations, the crack patterns of the other small walls were almost random and only in one specimen a cone shaped failure was observed.

The values of f_c obtained exceed the range of values provided by Keefe (2005) and Saxton (1995) in about 10–15%. In the first case, the cob walls strength ranges between 0.6 and 1.1 MPa, and up to 1.4 MPa when clay-rich soils are employed. In the second case, the results of cylindrical specimens (150 mm diameter, 300 mm height) with a straw content of 1.5 mass-% and moisture content of about 2.0 mass-% provide values of f_c in the range of 0.8–1.3 MPa. On the other hand, the experimental results on prismatic specimens (300 × 100 × 150 mm^3) with a moisture content of 2.0 mass-% reported by Greer (1996) reveal low values of f_c, in the range of 0.3–0.6 MPa. The cylindric specimens (150 mm diameter, 300 mm height) tested by Pullen (2009) exhibit values of f_c ranging between 0.5 and 0.9 MPa.

Pull-off tests

Due to the lack of standard methods to estimate the tensile strength (f_t) of cob, pull-off tests were performed. Considering the mechanical strength of cob material comparable with the strength of mortar for masonry, the pull-off tests were carried out according to EN 1015-12 (CEN 2015). This standard is also suggested to derive the adhesion strength of earthen plasters as reported in DIN 18947 (DIN 2013b).

The tensile strength is derived from the axial load required to pull-off a metallic disc (50 mm diameter) bonded to the cob substrate through a layer of two-component epoxy adhesive (Fig. 4). Before the application of the adhesive the cob substrate was cleaned from dust with compressed air. The tests were performed after an adequate period to cure the resin (adhesive) and the axial load was applied at a rate of 10

N/s to the disc, using a portable pull-off tester (maximum load capacity of 5 kN with an accuracy in the range of 0.2–0.3%). Six specimens were tested, which resulted on an average tensile strength of about 0.32 MPa with a coefficient of variation (CoV) of 22%. For all the specimens, the failure was concentrated within the cob substrate and not at the adhesive-cob interface. The value obtained from these tests is expected to be higher than the real tensile strength of cob due to some limitations of the test, such as resin impregnation and lack of control regarding the failure mechanism. The average value obtained corresponds to about 20% of f_c, which is a relatively high relation when compared with the 10% relation generally assumed in the modelling of masonry materials.

Diagonal compression tests

Diagonal compression tests were performed according to the standard ASTM E 519 (ASTM 2010). Although the standard suggests a specimen size of 120 × 120 cm^2, the size of the cob specimens tested was 42 × 42 cm^2. The size of the small walls was limited by the blade length of the saw (42 cm), with which they were cut out from a larger block. The LVDTs were fixed at both sides of the specimens, as shown in the test setup (Fig. 5a). The corners are supported from the steel loading shoes, so cob corners are not visible. A layer of low strength cement mortar was used between the bases of specimens and the supports to regularise the mutual contact. In two of the small walls (DWUC_6 and DWUC_7) the LVDTs were fixed only at one of the sides, while the other was used for digital image correlation (DIC) using a photogrammetric camera system (ARAMIS). This system was measuring the in-plane displacements on the cob surface during the test with a subpixel accuracy of displacement measurement of 0.01%. The basic idea of this method is that an optical pattern (spray pattern reference) is applied to the surface of the specimen and geometrical changes of this pattern are recognised by means of digital image analysis. The optical pattern is made by a graphite spray for optical decoration on white gypsum plaster threaded additionally with white acrylic spray.

Measurements were carried out through two digital cameras (maximal resolution 2048 × 2048 pixels) placed behind the testing device and able to monitor deformations of a specimen surface of approximately 250 × 350 mm^2. Prior to test, the specimens were plastered with a thin white gypsum render and sprayed with a marker. The deformation of the specimens was measured by stereographic recording of the movement of the singular marker points and additionally by one set of LVDTs fixed on the back side of the specimen.

The tests were performed with force control at a rate of about 130 N/s. Fig. 5b presents the shear stress-shear strain curves of the specimens, along with the respective envelope. Although the tests were undertaken with force control, the stress-strain curves plot the hardening phase after yield and a part of the post-peak strain. In opposition to the compressive behaviour, the shear behaviour presents very high scattering.

The small walls exhibited almost a noticeable non-linear behaviour in shear, with a very large hardening phase. This phase is probably depending from the contribution of the fibres to the shear behaviour. The fibres can control the crack opening while maintaining the shear stress levels, thus allowing the small walls to achieve large shear strains (higher than 0.8%) before failure.

The mechanical properties obtained from the diagonal compression tests are listed in Table 3, where the shear modulus (G_0) was calculated between 5% and 30% of shear strength (f_s) by linear fitting.

As for the compression tests, the range of 5–30% was adopted due to the linear-elastic behaviour exhibited by the stress-strain curves in this range. The shear stress (S_s) at applied load (V) was determined by using the following equation:

$$S_s = \frac{0.707V}{A_n} \tag{1}$$

in which A_n is the cross-horizontal section of the panel, determined as the average of the width and height of the specimen multiplied by its thickness.

All parameters showed relatively high scattering, where f_s varied in the range of 0.37–0.64 MPa, shear strain at the maximum shear stress (γ_s) in the range of 0.56–1.07 % and G_0 in the range 311–634 MPa. With respect to γ_s, an outlier value was identified according to the one-sided T-statistic test considering an upper significance level of 5%, as preconized in ASTM E 178 (ASTM 2002).

The specimens' failure occurred with the initiation of a main crack in the middle of the specimens, which progressed towards the supports in diagonal direction. Crack initiation was observed to occur near the maximum load. The typical failure mode of the small walls is illustrated in Fig. 6 showing the cracking pattern evolution at failure.

NUMERICAL MODELLING

Initial considerations

The finite element method (FEM) was used to numerically simulate the diagonal compression tests of the small walls. The model was prepared and calculated by means of the FEM software TNO DIANA 9.6 (TNO 2015). The dimensions of the numerical model, namely 401 × 407 × 123 mm^3 (width × height × thickness), were defined taking into account the average dimension of the tested small walls after cutting, which are slightly smaller than those initially defined. It is important to realise that the model presents a deviation from a square geometry. Plane stress state was assumed in the modelling, since a 2D analysis is expected to represent a valid option in relation to the geometry of the small walls and the in-plane loading applied. The mesh of the model was highly discretised, namely by means of 400 eight-nodded quadrilateral elements (CQ16M) with regular shape, to minimise discretisation errors. Furthermore, the discretisation also took into account the length covered by the supports in each edge (125 mm), where the corresponding nodes were restrained in the horizontal and vertical directions. A uniform distribution of vertical displacements on the constrained nodes at the top of the model reproduces the application of the load. Although force and displacement based numerical loadings produce equivalent numerical responses, displacement-based loading was preferred, since it allows for a better numerical convergence of the model. As the self-weight was expected to be marginal for its contribution to the stress state, it was not considered in the modelling.

Constitutive laws

The material behaviour of cob was simulated by using the TSRCM implemented in TNO DIANA 9.6 (TNO 2015). The TSRCM coincides to a model of distributed and rotating cracks based on total strains. In this model the crack direction rotates with the principal strain axes (Figueiras 1983, Damjamic 1984, Póvoas 1991), it embodies several possible non-linear stress-strain relationships for the compressive and tensile behaviours. TSRCM is often used in the numerical modelling of historical constructions, where the compressive behaviour of masonry is in general represented with a parabolic relationship (Mendes et al. 2014, Carpinteri et al. 2005). However, this relationship was shown to be excessively stiff and incapable to capture the large non-linear behaviour of earthen materials (Miccoli et al. 2015a, Silva et al. 2014). A multi-linear approach for the compressive behaviour, proposed by Miccoli et al. (2015a), is adopted here for the modelling of cob, which is presented in Fig. 7a. This relationship includes a linear branch up to $0.3f_c$, proportional to the average E_0. The compression tests did not allow defining the post-peak behaviour in its full extension, since the damage of the specimens occurring in this phase affected the readings of the LVDTs. Nevertheless, the stress reduction was observed to be very resilient. Thus, a negative stiffness equal to 2.0% of the average E_0 was considered, assuming the apparent linear trend of the envelope of the axial stress-strain curves. As shown in Fig 7b, the relationship in tension was presumed to be exponential, where the total reduction of tensile stress upon cracking may be described by the following equation:

$$\frac{\sigma^{cr}(\varepsilon^{cr})}{f_t} = e^{\left(-\frac{\varepsilon^{cr}}{\varepsilon_{ult}}\right)} \tag{2}$$

Where σ^{cr} is crack stress, ε^{cr} the crack strain, f_t the tensile strength and ε_{ult} the ultimate crack strain, given by:

$$\varepsilon_{ult} = \frac{G_f^I}{h\,f_t} \tag{3}$$

Where G_f^I is the mode-I tensile fracture energy and h is the crack band width, assumed to depend on the element area (A) and computed according to Eq. (4). This assumption assures objectivity of the results with respect to the size of the mesh (Bažant and Oh 1983, Dahlblom and Ottosen 1990). The unloading and reloading of the TSRCM is simulated by a secant approach (TNO 2015, Mendes 2012).

$$h = \sqrt{A} \tag{4}$$

The initial values assumed for the parameters required by the TSRCM were based on average values obtained from the compression tests, namely the compressive strength (f_c), Young's modulus (E_0) and Poisson's ratio (ν). Since the estimation of tensile strength provided by the pull-off tests is expected to be leading to an overestimation of this parameter, it was decided to estimate the parameters required by the exponential relationship with basis on suggested values for historical masonry. The initial value of f_t was estimated as $0.1f_c$, while that of G_f^I [N/mm] as $0.029f_t$ [MPa] (Lourenço 2002, Mendes and Lourenço 2009). It should be noted that the last relationship is empirical, meaning that the dimensions prescribed must be respected. Table 4 summarises the initial values of the parameters adopted in the model.

Calibration of the model and results

The calibration of the model was carried out through an iterative process of comparison between the numerical response and the experimental envelope. This process was carried out by fixing the initial values of the parameters obtained directly from tests, namely f_c, E_0 and ν, while f_t and G_f^I were adjusted based on reasonable range intervals. It should be noted that the behaviour of a small wall tested under diagonal compression is expected to be mainly controlled by the tensile properties of the material. Fig. 8 presents the shear stress-shear strain curve of the model considering the initial values of the input parameters and those after calibration.

The initial values adopted do not seem to promote a good match with the experimental results. In this case, the maximum shear strength of the model achieves a value of about 0.35 MPa, which corresponds to 70% of the average value obtained from the experimental tests. The respective shear strain achieved a value of 1.27%, which corresponds to a deviation of 51% in relation to the experimental average. Furthermore, the numerical response seems to be leading to a rather brittle failure when compared with the experimental behaviour, where the shear strain boosts after achieving a peak shear stress. This means that the relationships typically used for historical masonry for estimating f_t and G_f^I do not seem to be adequate in the case of cob.

The calibration of the model was achieved after increasing the initial values of f_t and G_f^I in about 1.3 and 25 times, respectively (see Table 4). The fact that cob presents straw (fibres) in its constitution, justifies an increase in tensile strength with respect to the initial value, as well as a much larger increase of the fracture energy value. For instance, Aymerich et al. (2012) reports bending tests on beams made of earth reinforced with wool fibres, where the calculated G_f^I achieves to values of about 2 N/mm, which is still higher than the value used in the calibrated model.

On average terms, the calibrated model shows good match with the experimental response. The model achieved a maximum shear stress of about 0.45 MPa, which corresponds to 90% of the average value obtained from the experimental tests, while the respective shear strain was of about 0.76%, corresponding to a deviation of about 10%. The shear modulus found in the calibrated model was about 363 MPa, corresponding to a deviation of about 18% in relation to the average of the experimental values. The shear modulus of the calibrated model is controlled by the elastic parameters (E_0 and ν), which were defined with basis on the compression tests. Despite of the deviation found, these parameters still result within the range of variation of the experimental tests of shear modulus of the model. The calibrated properties are part of TSRCM and they control the (smeared) cracking initiation and propagation.

The judgement on the agreement between numerical and experimental responses is largely affected by the high scattering observed in the diagonal compression tests, which can be associated to several factors, such as variability in the raw materials, in the production process and in moisture content upon testing. Therefore, it was decided to assess the agreement in terms of normalised shear stress-shear strain curves, see Fig. 9.

Each of the normalised curves was obtained by dividing shear stresses and shear strains by the corresponding f_s and γ_s, respectively. As expected, the normalised experimental curves show lower scattering than the non-normalised ones. Furthermore, normalisation shows that the experimental curves present a quite similar development, meaning that the shear behaviour of cob is proportional to f_s and γ_s. With respect to the normalised numerical response, a good agreement is found with the experimental results. This means that the numerical model is also capable of capturing well the development of the shear stress-shear strain curves of the experimental tests.

The simulation of the damage occurring in the experimental tests was also possible, as shown by the comparison between the numerical maximum principal strains with those calculated from DIC for DWUC_6 and DWUC_7, in four critical load levels. Fig. 10 presents these load levels normalised as function of f_s, namely $0.83f_s$, $0.92f_s$, $0.97f_s$ and $1.0f_s$, whose definition corresponds to damage stages visually observed during the tests, respectively: (i) uncracked; (ii) cracking onset; (iii) cracking development; (iv) maximum strength capacity. The maximum principal strains obtained in these critical load levels are compared in Figs. 11-14.

The maximum principal strains fields of small walls DWUC_6 and DWUC_7 were obtained for a central window with dimensions of about 250 mm × 350 mm, with centre coincident with that of the specimens. In general, the numerical model replicates well the damage observed in the small walls during their test. In stress level $0.83f_s$ (Fig. 11) no relevant cracking was detected in the specimens, where the numerical model demonstrates lack of this type of damage. The initiation of cracking damage was observed in the specimens to occur just before $0.92f_s$ (Fig. 12), where the numerical model seems to show the initiation of a middle crack. The numerical model in stress level $0.97f_s$ (Fig. 13) evidences the development of the middle crack towards the supports and the development of damage in terms of crack widening. This observation is also depicted in the DIC images of both small walls. Finally, stress level 1.0f_s (Fig. 14) shows the full development of the crack in both the specimens and the model. However, after the peak load, DIC results lose coherence and the comparison is not relevant. The numerical model is incapable of capturing the diagonal orientation of the crack observed in the experimental tests, which is most probably a consequence of lack of symmetry in the specimens (e.g. imperfections) and testing setup.

The calibrated parameters were also used for the simulation of the compression tests, but this verification was found irrelevant for the present discussion, as the compressive behaviour depends basically on the defined TSRCM model in compression. Thus, the simulation of the compression tests is practically coincident with the development of the multilinear relationship. This result was previously evidenced in a previous study on rammed earth material (Miccoli et al. 2015a). Regarding the simulation of the cracking pattern, the numerical model showed that cracking initiates at the corners next to the top and bottom supports, which agrees with most of the experimental observations.

Sensitivity analysis

The influence of the variability of the mechanical properties on the response of the model was assessed through a sensitivity analysis. The parameters addressed are those with a higher level of uncertainty, namely the tensile strength (f_t) and tensile fracture energy (G_f^I). In addition, the post-peak stiffness under compression (α) was also addressed, since its definition was based on a simplified approach based on considerable uncertainty, associated to the measurement of post-peak deformations. The variation of the aforementioned parameters was achieved by considering factors of 0.5, 0.75, 1.5 and 2.0 times. The influence of the variation of the parameters on the shear strength and corresponding shear strain is presented in Fig. 15, where the three independent parameters considered are termed as X and the different results are plotted with respect to the calibrated model results ($f_s/f_{s,cal}$ and $\gamma_s/\gamma_{s,cal}$). The parameters varied have a small influence on the shear strength of the model. However, the shear strain at peak stress is shown to be much more sensitive to the variation of the parameters, namely with respect to tensile strength. In fact, the three parameters considered have great influence on the nonlinear deformability of the model, meaning that their characterisation should be carefully addressed in the mechanical testing of cob materials.

CONCLUSIONS

In this study, the shear behaviour of cob, both in terms of experimental characterisation and numerical modelling, was analysed. It is important to underline that the representativeness of the results is limited to the cob technique employed in this study (*lehmweller*), where a key role is played by the soil used, the fibre content and the moisture content of the specimens at the time of the tests.

The experimental programme included axial compression tests, diagonal compression tests and pull-off tests on representative cob small walls in a controlled environment. This programme allowed the characterisation of important mechanical properties, such as compressive strength, Young's modulus, Poisson's ratio, tensile strength (pull-off tests), shear strength and shear modulus. In addition, it allowed to evidence the pronounced non-linear behaviour of this material. However, the strength properties of the small walls are influenced by the size of the specimens. For this reason, an aspect ratio correction factor must be applied when the application of strength parameters to a complete structures is necessary. At the current status, the New Zealand code (NZS 1998) provides correction factors only for unfired earth in the form of adobe, pressed earth brick, rammed earth or poured earth. A future research should include an extensive experimental campaign on cob specimens to define the correction factors suitable for this material.

The experimental parameters were then used to calibrate a FEM model for simulating the monotonic behaviour of cob under diagonal compression tests, where the TSRCM was adopted. The calibration of the model allowed the authors to verify that relationships typically used for estimating tensile parameters in historical masonry (namely f_t and G_f^I) are not adequate for cob. With this respect, the calibration of the model resulted in new relationships, where f_t was estimated as $0.13f_c$ and G_f^I [N/mm] as $0.558f_t$ [MPa]. These relationships are of great numerical interest as testing of the behaviour in tension is often a difficult task.

The response of the small walls tested under diagonal compression was found to present great variability. However, the numerical model was found to present good match with the experimental data, on average terms. Furthermore, the numerical model was found to capture well the development of the shear stress-shear strain curves and the development of the damage generated during the tests. Therefore, the modelling approach used seems adequate to provide a reliable simulation of the local and global shear behaviour of cob.

The calibrated parameters simulating the diagonal compression behaviour provide a first insight for future works on the numerical simulation of cob walls and should be valued as one of the first works done on the topic, and thus considered as a real contribution to the state of the art. The calibrated material can be used in most of the advanced FEM software packages available in the market, as they usually include nonlinear material analysis based on smeared cracking damage models, often used for modelling concrete and masonry structures.

A further development of this study would include cyclic behaviour testing, in order to validate the numerical approach presented in the paper, namely with respect to the simulation of the hysteretic behaviour.

With respect to the sensitivity analysis, it was found that the shear deformability of the model is highly affected by the variation of tensile strength, tensile fracture energy and post-peak stiffness under compression. Thus, in a problem where the deformation capacity is important (such as in the modelling of the seismic behaviour), these parameters should be carefully estimated from mechanical tests. Further studies will include a thorough experimental programme novel in terms of mix proportioning with the analysis of the fundamental issues to consider during the usage of natural fibres as reinforcement. In addition, the effects on the mechanical behaviour induced by different storing conditions as well as by freeze and thaw cycles will be investigated.

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COMPLIANCE WITH ETHICAL STANDARDS

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LIST OF FIGURE CAPTIONS

Fig. 9. Comparison of the responses of the numerical model and experimental tests: normalised shear stress-shear strain curves

Fig. 10. Critical points used to compare the damage in the model and that occurred in small walls DWUC_6 and DWUC_7

Fig. 11. Comparison between the maximum principal strains for stress level $0.83f_s$ obtained by means of DIC (a,b) and those obtained in the numerical model (c) for the critical points

Fig. 12. Comparison between the maximum principal strains for stress level $0.92f_s$ obtained by means of DIC (a,b) and those obtained in the numerical model (c) for the critical points

Fig. 13. Comparison between the maximum principal strains for stress level $0.97f_s$ obtained by means of DIC (a,b) and those obtained in the numerical model (c) for the critical points

Fig. 14. Comparison between the maximum principal strains for stress level $1.00f_s$ obtained by means of DIC (a,b) and those obtained in the numerical model (c) for the critical points

Fig. 15. Influence of the varied parameters on the: (a) shear strength; (b) shear strain at peak shear stress

LIST OF TABLES

Table 1. Grain size distribution and mineralogical properties of cob

Size fraction range			Mineralogical composition				
% of clay	% of silt	% of sand/gravel	Grain constituents		Clay fraction		
< 0.002 mm	=0.002-0.063 mm	> 0.063 mm	Quartz	Feldspar	Smectite-illite	Kaolin	Illite
21	61	18	+++	+	++	+++	++

Quantities: +++ = high, ++ = medium, + = low

Table 2. Results of the axial compression tests

Small wall	f_c (MPa)	E_0 (MPa)	v (-)
CWUC_1	1.60	988	0.13
CWUC_2	1.63	1084	0.11
CWUC_3	1.58	1036	0.23
CWUC_4	1.55	977	0.09
Average	1.59	1021	0.14
CoV (%)	2	5	46

Table 3. Results of the diagonal compression tests

Small wall	f_s (MPa)	γ_s (%)	G_0 (MPa)
DWUC_1	0.37	2.04*	311
DWUC_2	0.46	1.07	434
DWUC_3	0.47	0.80	375
DWUC_4	0.56	0.87	462
DWUC_5	0.63	0.74	634
DWUC_6	0.37	0.56	455
DWUC_7	0.64	0.98	421
Average	0.50	0.84	442
CoV (%)	23	22	23

* Outlier according to ASTM E 178 (ASTM 2002). Not used to compute the average value.

Table 4. Initial and calibrated values of the parameters in the model

	f_c (MPa)	E_0 (MPa)	ν (-)	f_t (MPa)	G_f^I (N/mm)
Initial values	1.59	1,021	0.14	0.159	0.0046
Calibrated values	1.59	1,021	0.14	0.207	0.1155