A study of the mechanical behaviour of adobe masonry

R. Illampas, I. Ioannou & D. C. Charmpis
Department of Civil and Environmental Engineering,
University of Cyprus, Nicosia, Cyprus

Abstract

Adobe buildings are encountered in almost every region of the world and constitute a significant feature of the international cultural heritage. However, the behaviour of adobe materials and earth masonry has not yet been adequately investigated. This study aims to examine the mechanical properties of mud bricks from Cyprus and the structural response of adobe masonry. Experimental results obtained from the compressive and flexural strength testing of local adobes are presented and analyzed. In addition, the outcomes derived from the implementation of compression tests on adobe assemblages are discussed. Furthermore, the response of earth masonry to cycles of compressive loading-unloading is examined through numerical simulation. Finally, critical issues to be addressed by future research are identified.
Keywords: adobe bricks, earth masonry, compressive strength, structural response, numerical simulation.

1 Introduction

Earthen architecture has been traditionally used for thousands of years. Adobe structures, in particular, are encountered in almost every region of the world and are considered to possess significant historic and cultural value. Unfortunately, information regarding the mechanical behaviour of such structures and the properties of their building materials is, still, rather limited (i.e. [1–3]). As a result, internationally accepted building codes and regulations, such as Eurocode 6, either include definitions of scope which specifically exclude unfired clay or, more often, simply assume masonry to be constructed of stone, fired clay bricks or concrete blocks. Furthermore, the application of formal engineering

WIT Transactions on The Built Environment, Vol 118, © 2011 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR110401

procedures in the design and appraisal of earthen structures is currently precluded due to the lack of adequate experimental data on the properties of adobes and the absence of computational tools to account for their specific characteristics.

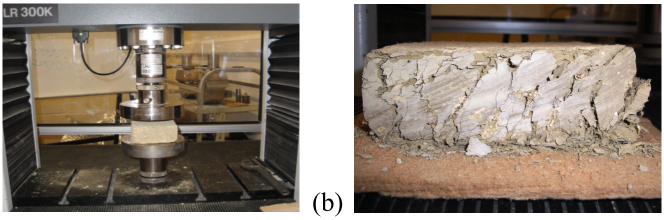
In an effort to assist towards the effective preservation of traditional earthen construction and to promote the use of sustainable earth-based construction materials in contemporary architecture, the University of Cyprus has established a research program that aims to assess the properties of local adobes and to study the structural behaviour of adobe buildings. Research activities include the characterization of adobe materials, the investigation of the mechanical properties of earth masonry and the development of numerical models for the analysis of adobe structures. In this study, compressive and flexural strength values obtained from tests on mud bricks from Cyprus are reported and discussed. Furthermore, the response of adobe masonry assemblages to compressive loading is examined both experimentally and numerically. Last but not least, areas where future research should focus are identified.

2 Assessment of mechanical properties of adobe bricks

For investigating the mechanical behaviour of adobes from Cyprus, several brick samples originating from different local manufacturers (denoted as *Ath*, *Ly* and *Ge*) were tested. The samples had dimensions (height x width x length) 5 x 30 x 45 cm^3 and belonged to various production batches. Their manufacture was based on empirical practice rather than industrialized methods and it involved mixing soil with water and a natural binder (i.e. straw fibres) to plastic consistency and casting the mixture into moulds. The bricks formed were then allowed to dry under the sun. It should be noted that different manufacturers in Cyprus apply different production techniques and use various curing surfaces. In addition, they do not take into account any particular criteria for the selection of raw materials and do not follow a standard mix design. As a result, the end-product is strongly non-homogeneous and has a random grain size distribution.

2.1 Assessment of compressive strength

For assessing the mechanical characteristics of local adobes, a series of uniaxial compression tests was initially performed. In the absence of local and international testing standards referring specifically to adobe, the experimental procedure and form/size of test specimens were decided after thorough literature review. Particular attention was given to EN 772-1:2000 [4]. The test specimens were prisms with dimensions (height x width x length) 5 x 10 x 10 cm^3; these were obtained from full-size mud bricks following dry cutting using a masonry saw. Prior to testing they were oven-dried to constant mass at 70^oC. Their upper and lower surfaces were smoothened by abrasion in order to allow a uniform distribution of the load during the tests. The tests were undertaken using a 300 kN compression testing machine (Lloyd LR300K) with two parallel steel loading plates (Fig. 1). All specimens were tested in the direction in which the brick they were cut from would have been laid for construction purposes. Loading was applied by imposing vertical displacement at a constant rate of 4.5 mm/min until the deformation of the specimen exceeded 33% of its original height. All tests were conducted at ambient conditions (22°C and 55% RH). A total of 187 specimens cut from 47 brick samples were tested.



(a) (b)

Figure 1: Experimental set-up used for the compressive strength testing of adobe specimens (a) and mode of failure under compression (b).

The mode of failure under compression was characterized by the gradual formation of several diagonal cracks on the lateral sides of the specimens (Fig. 1). Immediate failure after a critical load was not recorded. All specimens undertook considerable inelastic deformations, but sustained their ability to withstand compressive loading. This particular behaviour of adobes to compression has been reported by other researchers as well [5–7]. Certain scientists have related this response to a redistribution of the internal forces within the soil matrix through the straw fibres [5, 7]. This can be justified, to some extent, by the observation that following the completion of the compression tests, the material had not fully disintegrated. Instead, the natural fibres held together significant parts of the soil matrix, thus delaying failure. In addition, no rupture of the straw fibres occurred, although a loss of bond between the fibres and the soil matrix was recorded at the vicinity of the cracks. The behaviour of adobes under compression can be further explained by considering the principles of soil mechanics. When pressure is exerted, soil grains slide and shift, thus occupying the voids which exist within the material's matrix. As loading increases progressively, the soil grains are compacted and the material's density increases. Consequently, it gradually becomes stiffer and retains its ability to resist loading.

The lack of valid failure criteria for defining the load-bearing capacity of earth-based construction materials, leads to uncertainties regarding the true value of adobe's compressive strength. Therefore, various failure criteria were used in this study to analyze the experimental data. The compressive strength of each tested specimen was evaluated using the corresponding stress-displacement diagram (Fig. 2). In each case, the initial part of the curve that occurred prior to the initiation of the linearly ascending loading segment was excluded from the analysis as it was considered to be related to the action of the testing machine's platens (pre-loading).

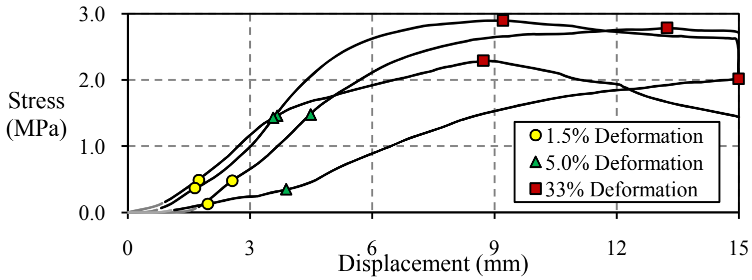


Figure 2: Stress-displacement curves obtained from testing specimens originating from the same adobe brick. The symbols indicate representative values of compressive strength using various failure criteria.

Testing standards referring to masonry materials indicate that the compressive strength of a specimen is equal to the maximum pressure exerted at failure. The compressive strength of adobes tested in the framework of this study, however, was initially assumed to be equal to the highest stress recorded at 33% deformation. This yielded values in the range 1.6 to 12.3 MPa. Nevertheless, it was noted that maximum compressive stresses were generated after a specimen had sustained at least 10% reduction in its height. Such deformation is excessive for common structural applications and will probably result in the failure of an adobe load-bearing member and the detachment of adjacent elements (e.g. roof beams). Consequently, failure criteria accounting for 1.5% and 5% permissible deformation were also examined. When the maximum allowable deformation was set at 1.5%, the compressive strength of adobe specimens was found to be in the range 0.2 to 1.6 MPa, whereas when failure was assumed at 5% deformation, values between 0.5 and 3.2 MPa were obtained. Despite the fact that the values corresponding to 5% deformation are closer to results reported in literature [8–10], further research is required before valid conclusions regarding the reliability of this criterion can be deduced. It should be noted that the values derived when adopting any of the aforementioned two criteria are very sensitive with respect to the data selected for the analysis since the levels of deformation examined are low in comparison to the material's compressibility. A summary of the results is shown in Figure 3. Regardless of the failure criterion selected, the mean compressive strength of different adobe specimens displays considerable deviations. Variations occur in the properties of: (a) adobes produced by different manufactures; (b) adobes made by the same manufacturer but originating from different production batches and (c) specimens originating from the same adobe brick. These can be attributed to the inherent inhomogeneity and randomness of adobes arising from the adoption of non-industrialized production methods, the frequent modification of the mix design and the lack of standard criteria for the selection of raw materials.

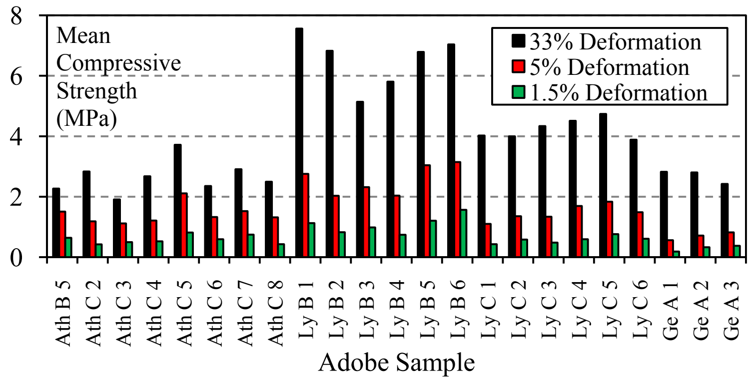


Figure 3: Mean values of compressive strength at 33%, 5% and 1.5% deformation. Samples are referenced as "Xa.b", where "X" refers to the manufacturer (*Ath*, *Ly* or *Ge*), "a" denotes the batch number and "b" indicates the sample (brick) number. At least four specimens from each brick were tested.

2.2 Assessment of flexural strength

Several researchers and national directive documents (e.g. [11, 12]) attempting to correlate flexural with compressive strength suggest that the former can act as an indicator of the material's quality. Bending tests are also used in practice for the in situ quality control of adobe bricks. In the framework of the current study, the flexural strength of adobe bricks was assessed using the three-point bending test. The experimental methodology adopted was mainly based on the New Mexico Building Code [13]. The specimens tested were half bricks cut from full-size adobes in dry conditions using a masonry saw. The test units were placed on two parallel tube supports (30 cm apart) and a concentrated force was applied at a constant rate of 0.9 mm/min to a horizontal tube placed in the middle of the specimen until failure occurred. Tests were performed on a total of 36 specimens cut from 19 adobe bricks. Following flexure testing, the specimens were cut into four 5 x 10 x 10 cm^3 samples which were subjected to further compressive strength tests.

During the tests it was observed that the mode of failure under flexure is greatly influenced by the presence of discontinuities within the mass of the material. The brick homogeneity was often disrupted by shrinkage cracks and/or the presence of gravel. When loading was applied, these discontinuities acted as planes of weakness, decreasing the bearing capacity of the specimens and forcing failure to develop at their vicinity. Failure at the central axis, where loading was exerted, occurred only in homogenous specimens. The effect that pre-existing discontinuities have on the flexural strength of materials composed of unfired clay has been verified by Clementi et al. [14].

The bending strength of the adobe specimens examined and the corresponding values of mean compressive strength derived from testing 5 x 10 x 10 cm^3 specimens cut out of the original flexural test units are shown in Figure 4. The experimental results indicate that the flexural strength of adobe bricks varies significantly. Regarding the correlation between the material's mechanical properties, this is also very much variable and not necessarily within the range quoted in the international literature. It is worth noting that a number of scientists [12, 15] confirm that the flexural strength of adobe, as measured by the three-point bending test, is quite variable; however, they also suggest that the flexural strength test results usually lie between 10% and 20% of the material's compressive strength.

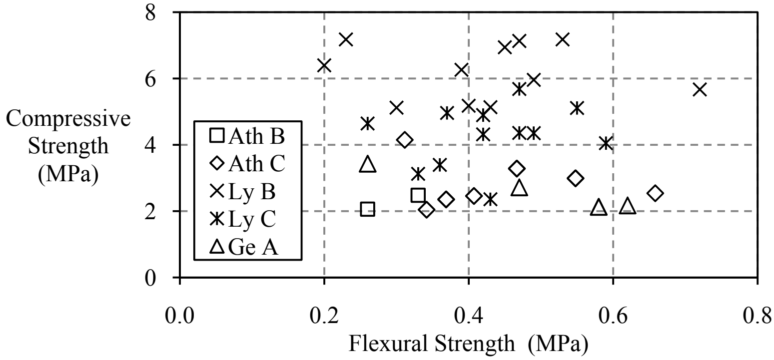


Figure 4: Flexural strength of half-brick specimens and corresponding values of mean compressive strength (at 33% deformation) obtained from testing prisms originating from the initial test units.

3 Investigation of the structural response of adobe masonry to compressive loading

3.1 Experimental tests on adobe masonry assemblages

Following the investigation of the mechanical properties of individual adobe bricks, the response of adobe masonry to compressive loading was examined. For this purpose, a number of uniaxial compression tests were performed on specimens composed of five full-size adobe bricks and corresponding earth mortar joints. All the bricks used for the preparation of the specimens were supplied by manufacturer *Ly* and belonged to the same production batch. The earth mortar had the same composition as the adobe bricks. It was prepared by mixing soil and straw fibres originating from crushed adobes with water (1155 g per 1850 g of solid constituents) to plastic consistency using a mechanical mixer. Stones and gravel with diameter exceeding 4 mm were excluded from the mix. The mortar was applied at relatively thin layers (≤ 10 mm) between the adobes. The average dimensions of the resulting masonry assemblages were (height x width x length) 28 x 30 x 45 cm^3. The wallets were allowed to cure in the laboratory (22±2°C and 42±5% R.H.) in order to ensure sufficient bonding between the adobe bricks and the mortar. Tests were conducted after 3 and 43 weeks of curing.

A CONTROLS Advantest 9 servohydraulic compression testing frame with 5000 kN loading capacity was employed along with the Lloyd LR300K testing machine for the implementation of the tests. The platens mounted on both testing frames incorporated swivel heads to accommodate non-parallel bearing surfaces. During testing, longitudinal displacements were recorded using vertical transducers attached on the corners of the upper loading plate (Fig. 5). Transversal deformations were also monitored by two horizontal transducers placed on each side of the specimen. Compressive loading was applied on the specimens either by exerting a constant force at a rate of 10 kN/min, or by imposing a constant displacement at a rate of 6 mm/min.

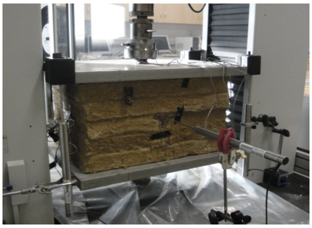
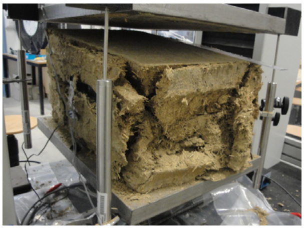
(a)  (b) 

Figure 5: Experimental set-up used for the compressive strength testing of adobe masonry assemblages (a) and mode of failure experienced under compression (b).

A total of thirteen adobe masonry specimens were tested. The value of compressive strength for each specimen was deduced from the resulting stress-displacement diagram. Failure was assumed at 5% vertical deformation. The results obtained are reported in Figure 6. The compressive strength of the assemblages tested lies between 0.45 and 1 MPa. In all specimens examined, failure was characterized by considerable reduction of height and “exfoliation” of the lateral sides (Fig. 5). The gradual application of the compressive load induced inelastic longitudinal and transversal deformations to the assemblages and caused the lateral sides of the adobes to crack and fall off. Furthermore, it was noted that the specimens responded monolithically to vertical loading. Despite the fact that the lateral sides of the bricks sustained significant damage, their central core remained sufficiently integer and did not lose coherence. Compression resulted in the compaction of adobe and mortar in the central axis of the masonry specimens. This led to the formation of a central zone within the body of the masonry where the visual distinction between the individual adobe bricks and the mortar joints was no longer fissile. Moreover, no significant cracks or slips occurred at the joints during the loading procedure. A similar mode of failure has been noted by Quagliarini et al. [16] when testing specimens of the same form.

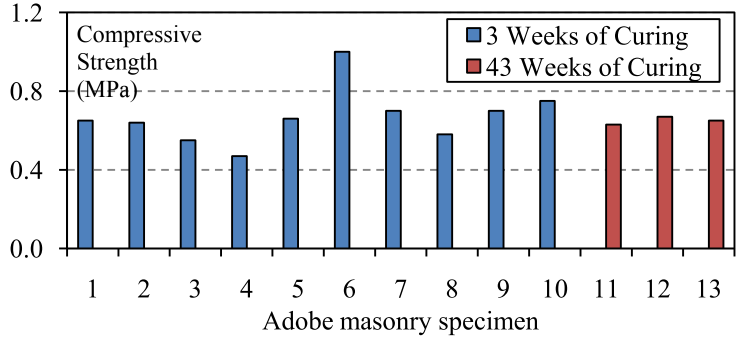


Figure 6: Values of compressive strength (MPa) obtained by testing assemblages composed of five adobe bricks and earth mortar joints.

In addition to monotonic tests, a loading-unloading test was performed in order to investigate the elastic and post-yield structural response of adobe masonry. This was also undertaken using an assemblage composed of five adobe bricks and earth mortar joints. Loading was imposed through the application of displacement at a constant rate of 0.1 mm/sec. Unloading cycles were programmed to take place successively when the applied load reached a value of 10, 30, 50, 100, 150 and 200 kN. The results of the loading-unloading test (Fig. 7) indicate that the behaviour of adobe masonry under compression is non-linear and is characterized by intense plasticity and deformability. The parts of the stress-strain diagram that correspond to the application of loading show that the material exhibits progressive hardening. The form of the unloading branches reveals that when the exerted load is released, induced deformation is only partially removed, while considerable inelastic deformations remain present. Plastic deformations start to develop even when the specimen is subjected to low compressive stresses at the region of 0.08 MPa. This behaviour can be attributed to the fact that the sliding and displacement mechanisms, which take place between the soil grains due to the application of pressure, are non-reversible.

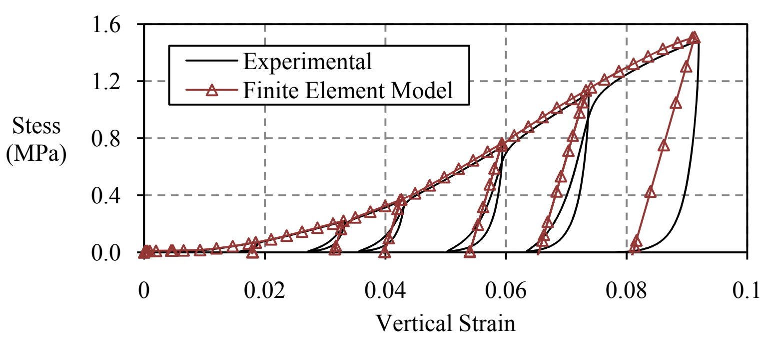


Figure 7: Experimental and numerical stress-strain curves referring to adobe masonry subjected to compressive loading-unloading.

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3.2 Numerical simulation of adobe masonry

A numerical simulation of the loading-unloading experimental test was conducted using the ABAQUS CAE commercial code. Earth masonry was numerically handled in the context of a macro-modelling strategy. It was thus treated as a fictitious homogeneous continuum and no distinction was made between masonry units and mortar joints. This approach was considered to be appropriate for the purpose of the current study, since it constitutes a practice-orientated prediction of the macroscopic structural response (estimation of forces/stresses and elastic/plastic deformations) rather that a detailed microscopic investigation (e.g. detection of crack initiation and propagation). Treating adobe masonry as a homogeneous medium is further justified by the monolithic behaviour exhibited by the specimens in the tests mentioned above.

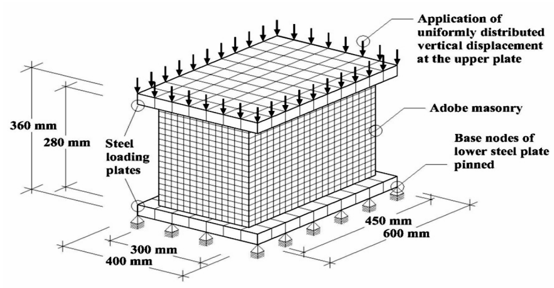

Figure 8: Finite element model used for the analysis of adobe masonry assemblage subjected to compressive loading and unloading.

Both the adobe masonry specimen and the steel loading plates were modelled (Fig. 8). All components of the Finite Element (FE) model were discretized using 8-node 3D linear brick elements (C3D8). Each steel plate was discretized into 70 elements. A FE mesh consisting of 7935 elements was used in the case of the masonry assemblage. Adobe masonry was modelled using a simple isotropic Elastic-Plastic constitutive material model. This is based on classical metal plasticity theory and uses standard Mises yield surface with assorted plastic flow [17]. By default, when cyclic loading scenarios are examined, the aforementioned model assumes that the loading-unloading curves are parallel to the elastic loading curve (with its slope determined through the Young's modulus) [17]. The parameters defined in the FE model for simulating adobe masonry were in line with the results of laboratory tests. The density of adobe (ρ_a= 1300 kg/m^3) was measured gravimetrically, while the Poisson ratio (v_a= 0.35) was deduced from the recorded values of axial and transversal strains. The Young's modulus was derived from the stress-strain curve of the compressive loading-unloading experimental test. Its value (E_a= 135 MPa) was set to be approximately equal to the slope of the three unloading branches that were recorded following a 5% strain. In order to accommodate for the lack of elasticity that characterizes the behaviour of adobe masonry, a very low value of

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yield stress (0.01 MPa) was assigned. Post-yield behaviour was defined by providing a relation between compressive stresses and plastic strains based on the outcomes of the laboratory tests. Failure stress (1.8 MPa) was also assigned according to the results of the monotonic uniaxial compression tests.

The steel plates are extremely stiff when compared to adobe masonry and were thus modelled as a Linear Elastic material model with the following parameters: ρ_s= 7750 kg/m^3, v_a= 0.30, E_s= 220 GPa. The boundary conditions provided were chosen so as to adequately simulate the test setup. The base nodes of the lower steel plate were considered to be pinned. A uniformly distributed vertical displacement was assigned to the upper steel plate. The amplitude of the displacement over time was formulated according to the mean displacement values that were computed from the data recorded by the vertically placed transducers during the experimental procedure. The contact between adobe masonry and the steel plates was assumed to be frictionless.

The numerical results (Fig. 7) show that the FE model, although quite simplistic, reproduces very well the shape of the envelope of the experimental diagram. The difference between the ultimate stress and strain recorded during the experiment and those obtained from the numerical simulation is less than 2%. Taking into consideration the natural randomness and inhomogeneity of adobe, this difference may be considered as negligible. Regarding the loading-unloading branches, these cannot be reproduced in detail by the constitutive model that has been chosen. However, despite the fact that in the FE model the loading-unloading branches coincide, they occur at approximately the same value of strain as the experimental ones. Furthermore, the stress computed by the numerical model after the end of each unloading cycle is equal to zero, as in the case of the actual masonry specimen. Therefore, the simulated response can be deemed adequate for macroscopic investigation of structural behaviour.

4 Conclusion

Laboratory tests on adobe bricks from Cyprus have revealed that the mechanical properties of these materials display significant variations. The results have failed to deduce a definite correlation between adobe's flexural and compressive strengths, despite the fact that such a relationship has been reported in the literature. This is possibly attributed to the inherent inhomogeneity and natural randomness of local adobes. The irregular mechanical behaviour of these adobes is further affected by the application of empirical non-industrialized production methods and the lack of standardized testing methods and formal failure criteria. Future research should therefore focus on the development of testing methodologies that would account for the specific characteristics of adobe. For this purpose, the effect that different forms of specimens (e.g. prisms, cubes, cylinders) have on the results of laboratory tests should be investigated. Furthermore, various failure criteria for the evaluation of adobe's compressive strength should be examined and their applicability should be studied in the context of practical structural analysis.

Experimental results derived from testing assemblages composed of full-sized mud bricks and earth mortar joints have shown that the response of adobe masonry to compressive loading is not as random as that of individual adobe bricks. According to the data obtained, the compressive strength of adobe masonry is approximately 0.6 MPa. In addition, it has been noted that the response of earth masonry to compressive loading is characterized by monolithic behaviour, distinct lack of elasticity and intense deformability. However, in order to fully investigate the response of adobe masonry to compression further research is required. This should include an extended experimental and theoretical study of all the parameters affecting the behaviour and performance of adobe masonry.

The outputs of the numerical analysis indicate that the constitutive hypotheses and input parameters hereby suggested may correctly simulate the general behaviour of earthen construction under compressive loading. A comparison among the numerical and experimental data shows that the FE model can provide sufficiently accurate estimates for stress and deformation, especially when applied to monotonic vertical axial loading scenarios. The good agreement with experimental results and the low computational cost that results from the use of simple constitutive laws appear to be very encouraging for future applications. However, concerns derive from the inability of the model to predict cyclic behaviour involving both compression and tension loading. This limitation is a product of the constraints imposed by the selected constitutive model. Therefore, future work should focus on the modification of existing models and/or the development of a fully adobe masonry-oriented model that will be appropriate for the numerical analysis of adobe structural elements and buildings.

Acknowledgements

The authors would like to acknowledge financial support from the University of Cyprus, the Cyprus Research Promotion Foundation, the Republic of Cyprus and the European Regional Development Fund.

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