Numerical assessment of out-of-plane behaviour of rammed earth walls

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Abstract: Earthen architecture, even though still very present today, lacks meticulous research, especially in Croatia. Therefore, the aim of this research is to gain new insight on seismic behaviour of rammed earth walls. To accomplish that, two rammed earth walls were built using traditional techniques. In addition to that, preliminary numerical models were made using ANSYS (v. 2020 R2) software to predict load required for demolition of walls by pull down method. It was observed that out of two walls, built with 10 cm difference in thickness, the thicker wall achieves higher out-of-plane bearing capacity, of around 16 kN, while the thinner wall achieves out-of-plane bearing capacity of around 10.5 kN. Moreover, contrary to the initial opinion, thicker wall exhibited plastic behaviour at lower horizontal displacement. Therefore, it was observed that the thinner wall endured 20 % higher inter-storey drift (IDR) before experiencing plastic behaviour. However, further numerical modelling and experimental testing of rammed earth walls are necessary.

Keywords: traditional rammed earth building technique, seismic behaviour, numerical modelling, ANSYS, load bearing capacity

1. Introduction

According to Gomes et al. (2014), more than half of the world's population today lives in earthen houses. Moreover, earthen architecture is located in both more or less seismically prone areas (Arrigoni et al. (2018); Arslan et al. (2017); Bui et al. (2011); Jaquin et al. (2009); Kraus et al. (2020); Lončar-Vicković & Stober (2011); Momin et al. (2021); Perić (2021); Perić et al. (2021a); Shrestha et al. (2020); Zhou & Liu (2019)).

Earth-building techniques include adobe (Aguilar et al (2019); Momin et al (2021); Niroumand et al (2013)), cob (Hamard et al (2016); Vinceslas et al. (2016)), compressed earth block (Hema et al. (2020); Mostafa & Uddin (2015); Sassu et al. (2018)) and rammed earth (Gomes et al. (2014); Jaquin et al. (2009); Lončar-Vicković & Stober (2011)). However, this paper focuses only on walls built using unstabilized rammed earth technique.

Out-of-plane behaviour of rammed earth walls has not been widely examined yet. To the authors' best knowledge, merely five papers have been written on this topic to date. Hamilton et al. (2006) presented results from experimental testing of walls, with cyclic lateral force concentrated on top of the wall. Ciancio and Augarde (2013) tested out-of plane stability of walls subjected to wind load uniformly applied on the wall's surface. Wangmo et al. (2018) described experimental testing and numerical modelling of two rammed earth walls, one as part of an old rammed earth building and one newly made for purpose of experiment. Allahvirdizadeh et al. (2019) and Bui et al. (2020) conducted extensive numerical modelling of U-shaped rammed earth walls subjected to lateral load.

Rammed earth walls are usually constructed inside wooden or metal formwork, where earthen material is poured in layers and compacted using manual or pneumatic rammers (Bui et al. (2014); Narloch & Woyciechowski (2020); Silva et al. (2018)). Process continues until desired wall height is reached. Later, the formwork can be removed and used at another construction site. The soil composition varies based on building location. However, suitable soil always comprises clay, silt, and sand (Arslan et al. (2017); Bui et al. (2011); Gomes et al. (2014)). Clay is the most important part since it acts as natural binder holding particles once the formwork is removed.

Through the field research, the authors have observed a large number of earthen houses in Eastern Croatia. Despite being built in seismically prone area, over 100 years ago, a lot of those houses resisted the ravages of time and are still being used for housing or as outbuildings. However, no previous research on mechanical properties or seismic capacity have been conducted. Thus, this is the first research in Croatia dealing with assessment of seismic performance of earthen architecture. The aim of this research is to provide better understanding on the behaviour of rammed earth constructions through the combination of numerical and experimental techniques.

This paper presents building process of two rammed earth walls for assessment of out-of-plane behaviour. In this phase, preliminary numerical models were made using ANSYS (v.2020 R2) software to predict wall's out-of-plane behaviour. The two walls were built with different thicknesses. Thus, the core assumption is that thicker walls can achieve higher load bearing capacity and endure greater horizontal displacements before beginning of plasticisation.

2. Building process

Two rammed earth walls were built by local experienced masons using traditional techniques. Walls were built inside of an industrial hall primarily for testing the air permeability and thermal conductivity of rammed earth. Thus, the walls were protected from natural weathering. After five months stored in the hall and in laboratory conditions and after conducting all the necessary experiments regarding energy efficiency, walls will be tested by pull-down method to gain additional data. Walls were built using local soil from Osijek. The soil used consists mostly of clay and silt (Figure 1).

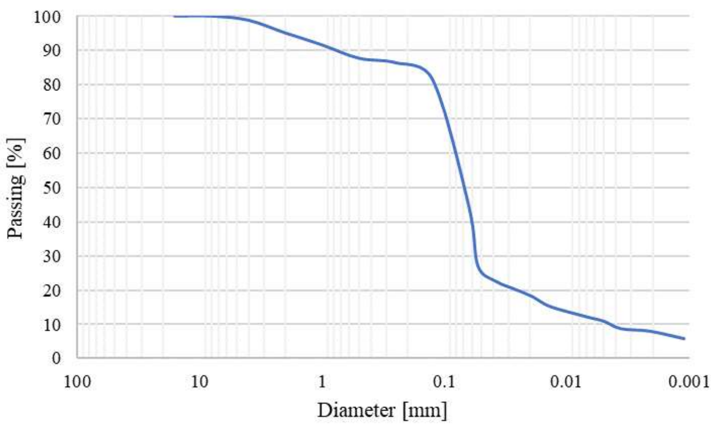
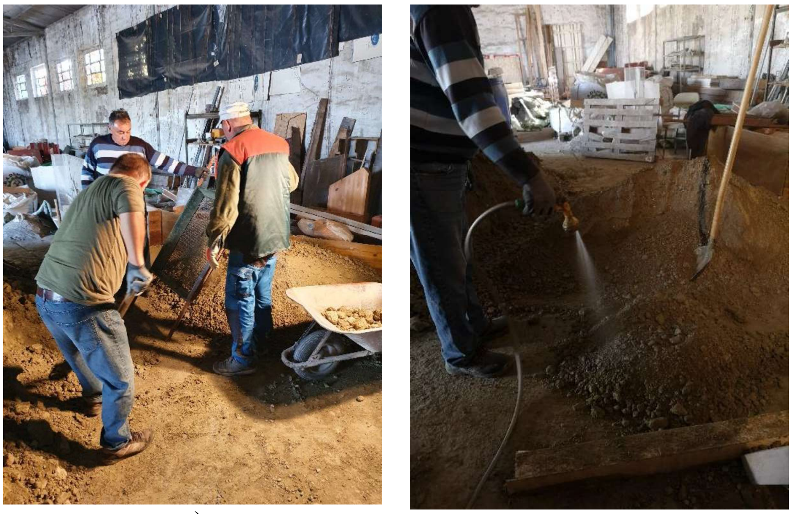


Fig. 1. Grain distribution of soil

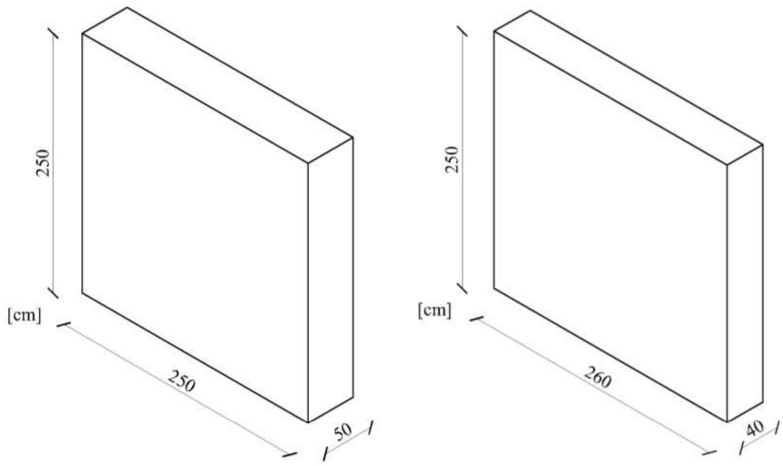
Masons used 16 mm sieve (Figure 2a.) to prepare the material. Water was added by spraying the surface of the material (Figure 2b.) and mixing it on the ground using shovel. Wet material was stored for 24 h in the hall before the building began.



a) b)

Fig. 2. Preparing material: a) sieving, b) adding water

Dimensions of the walls are demonstrated in Figure 3. The two walls were built in different thicknesses, in order to examine the influence of the thickness on their out-of-plane behaviour. At the beginning of the construction the formwork was risen to approximately half of the height of the wall (Figure 4.). Later more parts were added as the wall grew taller.



a) b)

Fig. 3. Dimensions of the walls: a) wall W-50, b) wall W-40

Fig. 4. Formwork assembled before building the wall

For every layer, approximately 0.15 m^3 of prepared material was added. Before ramming, the material was first evenly distributed within the formwork. Then masons walked over the distributed material before ramming it by using manual rammer. The ramming was performed using wooden rammer (Figure 5.) until the layer was firmly compacted, not showing eye-noticeable large deformations after further blows. Water was then sprayed over the surface, before adding material for the new layer. The thickness of finished layer varied from approximately 9 to 12 cm.

Fig. 5. Rammer used for building walls

One week after completion of the walls, formwork was disassembled. The curing period of one week was necessary to minimize the creep caused by great self-weight of the wall. Moreover, lateral supporting wooden elements were left after the formwork was disassembled, only to secure the stability of the wall.

3. Numerical models

Numerical models of the walls were made to predict their out-of-plane seismic behaviour before conducting the experimental testing in the next phase. Preliminary numerical models were made using academic version of ANSYS (v. 2020 R2) software. The models were defined having the same boundary conditions. Since the material properties are unknown in this phase, the properties shown in Table 1 were used.

Table 1. Material properties Perić et al. (2021b)

Material property	Symbol	Value
Density	d [kg/m^3]	1969
Poisson's ratio	v [-]	0,22
Modulus of elasticity	E [MPa]	900
Compressive strength	f_c [MPa]	1.72
Tensile strength	f_t [MPa]	0.22
Cohesion	c [kPa]	112.8
Friction angle	φ [°]	45.5

The loading is planned at the upper third of the wall (Figure 6.). According to previous research (Hamilton et al. (2006); Wangmo et al. (2018)) the fracture is expected at the lower third of the wall, closer to the base.

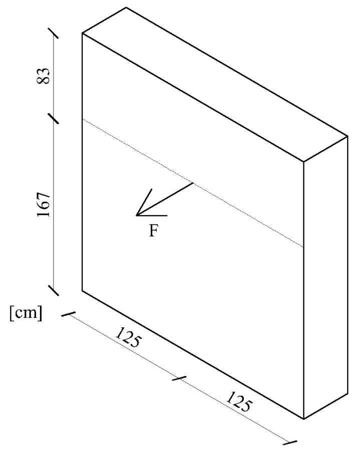


Fig. 6. Planned load placement at 2/3 hight of the wall

Numerical models were divided into the finite elements of 100 mm. Namely, the number of finite elements is limited when using academic licence of ANSYS software. To simulate the influence of out-of-plane loading, wall models were rigidly constrained at their base. Out-of-plane loading was defined using the displacement control of 1 mm/s. Figure 7 demonstrates the results of the conducted analysis for both walls. The behaviour of both walls subjected to out-of-plane loading is essentially the same, with difference in the bearing capacity.

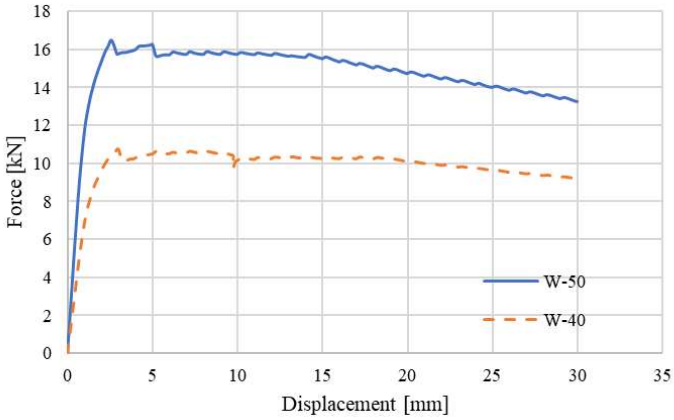


Fig. 7. Capacity curves of rammed earth walls

After meeting the peak force, slight drop in bearing capacity is exhibited. Model W-50 achieved peak force of around 16 kN, while model W-40 achieved peak force of around 10.5 kN. Moreover, for model W-50, plastic behaviour begins at 2.5 mm of horizontal displacement, while for model W-40 plastic behaviour begins at 3 mm of horizontal displacement. Thus, the inter-story drift (IDR) at the beginning of plasticisation is 1.76 % and 1.47 %, for W-40 and W-50 respectively.

As it was expected, W-40 has lower load bearing capacity in comparison to W-50. It was noted that 10 cm reduction in thickness results in 50 % lower load bearing capacity. In addition, even though it was expected that the thicker wall will endure higher level of horizontal displacement before the onset of plasticisation, W-50 in fact exhibited plastic behaviour at lower level of horizontal displacement and IDR when compared to W-40.

4. Conclusions

Earthen architecture makes up a large share of world building fund. In addition, during field research, authors have discovered a large number of earthen houses in Eastern Croatia. However, their deteriorated state is accounted for lack of research and building standards in Croatia. The aim of this research is, therefore, to gain new insight on seismic behaviour of rammed earth structures, especially on rammed earth walls built using traditional building techniques characteristic for Eastern Croatia. To comprehend that, two rammed earth walls, with different thicknesses, were built using the traditional building technique. Experienced masons used manual rammer to build the walls using local soil. To predict the load bearing capacity employing the out-of-plane testing method, two preliminary numerical models of the rammed earth walls were made using the ANSYS software. As expected, thinner wall had lower load bearing capacity than the thicker wall. Namely, when reducing the thickness of the wall for 10 cm, the load bearing capacity reduces for about 50 %. However, even though it was expected for thinner wall to achieve plastic behaviour before the thicker wall (i.e. at lower level of horizontal displacement), that was not the case. Namely, it was observed that a 40 cm thick wall can endure almost 20 % higher level of IDR before experiencing plastic behaviour, when compared to 50 cm thick wall. Further investigation on the out-of-plane behaviour of rammed earth walls is still necessary to grasp better understanding on the behaviour of existing rammed earth structures as well as to create the possibility on designing new rammed earth structures following specific guidelines and standards.

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References

Aguilar, R., Noel, M.F., Ramos, L.F. (2019) Integration of reverse engineering and non-linear numerical analysis for the seismic assessment of historical adobe buildings. Autom. Constr., 98, 1–15. https://doi.org/10.1016/j.autcon.2018.11.010

R. Allahvirdizadeh, R., Oliveira, D.V., Silva, R.A., (2019) Numerical modeling of the seismic out-of-plane response of a plain and TRM-strengthened rammed earth subassembly, Eng. Struct. 193 43–56. https://doi.org/10.1016/j.engstruct.2019.05.022

Arrigoni, A., Beckett, C.T.S., Ciancio, D., Pelosato, R., Dotelli, G., Grillet, A.C. (2018) Rammed Earth incorporating Recycled Concrete Aggregate: A sustainable, resistant and breathable construction solution. Resour. Conserv. Recycl., 137, 11–20. https://doi.org/10.1016/j.resconrec.2018.05.025

Arslan, M.E., Emiroğlu, M., Yalama, A. (2017) Structural behavior of rammed earth walls under lateral cyclic loading: A comparative experimental study. Constr. Build. Mater., 133, 433–442. https://doi.org/10.1016/j.conbuildmat.2016.12.093

Bui, Q.-B., Hans, S., Morel, J.-C., Do, A.-P. (2011) First exploratory study on dynamic characteristics of rammed earth buildings. Eng. Struct., 33, 3690–3695. https://doi.org/10.1016/j.engstruct.2011.08.004

Bui, T.-T., Bui, Q.-B., Limam, A., Maximilien, S. (2014) Failure of rammed earth walls: From observations to quantifications. Constr. Build. Mater., 51, 295–302. https://doi.org/10.1016/j.conbuildmat.2013.10.053

Bui, T.-L., Bui, T.-T., Bui, Q.-B., Nguyen, X.-H., Limam, A., (2020) Out-of-plane behavior of rammed earth walls under seismic loading: Finite element simulation, Structures 24 191–208. https://doi.org/10.1016/j.istruc.2020.01.009

Ciancio, D., Augarde, C. (2013) Capacity of unreinforced rammed earth walls subject to lateral wind force: elastic analysis versus ultimate strength analysis. Mater Struct 46, 1569–1585. https://doi.org/10.1617/s11527-012-9998-8

Gomes, M.I., Gonçalves, T.D., Faria, P. (2014) Unstabilized rammed earth: Characterization of material collected from old constructions in south Portugal and comparison to normative requirements. Int. J. Archit. Herit., 8, 185–212. https://doi.org/10.1080/15583058.2012.683133

Hamard, E., Cazacliu, B., Razakamanantsoa, A., Morel, J.-C. (2016) Cob, a vernacular earth construction process in the context of modern sustainable building. Build. Environ., 106, 103–119. https://doi.org/10.1016/j.buildenv.2016.06.009

Hamilton HR, McBride J, Grill J. (2006) Cyclic Testing of Rammed-Earth Walls Containing Post-tensioned Reinforcement. Earthquake Spectra, 22:937–59. http://dx.doi.org/10.1193/1.2358382

Hema, C., Messan, A., Lawane, A., Van Moeseke, G. (2020) Impact of the Design of Walls Made of Compressed Earth Blocks on the Thermal Comfort of Housing in Hot Climate. Buildings, 10, 157. https://doi.org/10.3390/buildings10090157

Jaquin, P.A., Augarde, C., Gallipoli, D., Toll, D.G. (2009) The strength of unstabilised rammed earth materials. Geotechnique, 59, 487–490. https://doi.org/10.1680/geot.2007.00129

Kraus, I., Perić, A., Kaluđer, J., Kraus, L. Seismic behaviour of traditional Croatian earth architecture. Proceedings of 1st Croatian Conference on Earthquake Engineering 1CroCEE, Zagreb, Croatia. https://doi.org/10.5592/CO/1CroCEE.2021.115

Lončar-Vicković, S., Stober, D. (2011) Tradicijska Kuća Slavonije i Baranje, Ministarstvo turzima Republike Hrvatske, Sveučilište Josipa Jurja Strossmayera u Osijeku, Građevinski fakultet Osijek: Osijek, Croatia, Available online: https://mint.gov.hr/UserDocsImages//arhiva//150514_Slavonija_Baranja.pdf (accessed on 13 August 2021).

Momin, S., Lovon, H., Silva, V., Ferreira, T.M., Vicente, R. (2021) Seismic Vulnerability Assessment of Portugese Adobe Buildings. Buildings, 11, 200. https://doi.org/10.3390/buildings11050200

Mostafa, M., Uddin, N. (2015) Effect of banana fibers on the compressive and flexural strength of compressed earth blocks. Buildings, 5, 282–296. https://doi.org/10.3390/buildings5010282

Narloch, P., Woyciechowski, P. (2020) Assessing cement stabilized rammed earth durability in a humid continental climate. Buildings, 10, 26. https://doi.org/10.3390/buildings10020026

Niroumand, H., Zain, M.F.M., Jamil, M. (2013) Various Types of Earth Buildings. Procedia Soc. Behav. Sci., 89, 226–230. https://doi.org/10.1016/j.sbspro.2013.08.839

Perić, A. (2021) Characterization of materials used for earth architecture in Eastern Croatia. IOP Conference Series: Materials Science and Engineering, Volume 1209, Young Scientist 2021 (YS21) 13th-15th October 2021, High Tatras, Slovakia, 012044. doi:10.1088/1757-899X/1209/1/012044

Perić, A., Kraus, I., Krstić, H. (2021a) Thermal conductivity coefficient of a traditional earth house from Eastern Croatia: a case study. COMMON FOUNDATIONS 2021: 8th Congress of Young Researchers in the Field of Construction and Related Technical Sciences. https://doi.org/10.5592/CO/ZT.2021

Perić, A., Kraus, I., Kaluđer, J., Kraus, L. (2021b) Experimental Campaigns on Mechanical Properties and Seismic Performance of Unstabilized Rammed Earth—A Literature Review. Buildings, 11, 367. https://doi.org/10.3390/buildings11080367

Sassu, M., Romanazzi, A., Giresini, L., Franco, W., Ferraresi, C., Quaglia, G., Orefice, E. (2018) Production procedures and mechanical behaviour of interlocking stabilized compressed earth blocks (ISCEBs) manufactured using float ram 1.0 press. Eng. Solid Mech., 6, 89–104.

Shrestha, K.C., Aoki, T., Miyamoto, M., Wangmo, P. (2020) In-plane shear resistance between the rammed earth blocks with simple interventions: Experimentation and finite element study. Buildings, 10, 57. https://doi.org/10.3390/buildings10030057

Silva, R.A., Mendes, N., Oliveira, D.V., Romanazzi, A., Domínguez-Martínez, O., Miranda, T. (2018) Evaluating the seismic behaviour of rammed earth buildings from Portugal: From simple tools to advanced approaches. Eng. Struct., 157, 144–156. https://doi.org/10.1016/j.engstruct.2017.12.021

Vinceslas, T., Hamard, E., Razakamanantsoa, A., Bendahmane, F. (2016) Further development of a laboratory procedure to assess the mechanical performance of cob. Environ. Geotech., 7, 200–207.

Wangmo, P., Shrestha, K., Miyamoto, M., Aoki T., (2019) Assessment of out-of-plane behavior of rammed earth walls by pull-down tests, International Journal of Architectural Heritage, 13:2, 273-287, https://doi.org/10.1080/15583058.2018.1433903

Zhou, T., Liu, B. (2019) Experimental study on the shaking table tests of a modern inner-reinforced rammed earth structure. Constr. Build. Mater., 203, 567–578. https://doi.org/10.1016/j.conbuildmat.2019.01.070