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Seismic behaviour of traditional Croatian earth architecture

Ivan Kraus[1], Ana Perić[2], Jelena Kaluđer[3], Lucija Kraus[4]

[1] *Assistant Professor,* University of Josip Juraj Strossmayer in Osijek, Faculty of Civil Engineering and Architecture, *ikraus@gfos.hr*

[2] *Graduate student*, University of Josip Juraj Strossmayer in Osijek, Faculty of Civil Engineering and Architecture, *a.peric.296@gmail.com*

[3] *Teaching and research assistant*, University of Josip Juraj Strossmayer in Osijek, Faculty of Civil Engineering and Architecture, *jkaluder@gfos.hr*

[4] *Teaching and research assistant*, University of Josip Juraj Strossmayer in Osijek, Faculty of Civil Engineering and Architecture, *lucija@gfos.hr*

Abstract

Available evidence classifies traditional earth architecture as Croatia's treasure as they embody authenticity and uniqueness. Thereunto, Baranja's earth houses are presented as the best realizations of traditional Croatian rural architecture. Although present in Croatia, earth houses are often relinquished, damaged, or in an adverse state. The Act on Protection and Preservation of Cultural Goods defines the traditional earth house as an immovable cultural good which, as such, needs to be protected from disappearing. Nevertheless, until today there has been no conducted research on traditional Croatian earth architecture to assess their behaviour and performance. Croatia is situated in an earthquake-prone area, thus the design of all load-bearing structures has to be done in accordance with standards from the HRN EN 1998 series. In this paper, the seismic behaviour and dynamic properties of a typical Croatian earth house were investigated. The paper consists of three main parts. The first part is dedicated to the description of the geometry and materials of a typical traditional Croatian house. The second part presents numerical model developed using the ANSYS software package, which allowed assessment of the dynamic properties and seismic capacity of the house. The third and last part of the paper provides a discussion on results considering the nonlinear behaviour of the traditional earth house.

Key words: traditional architecture, Croatian house, rammed earth, seismic behaviour, 3D numerical model, ANSYS, force-displacement response, scaling rules

1 Introduction

Earth houses provide a housing solution for 30 % of the world's population [1]. It is possible to find them in least developed countries, but also in most technologically advanced countries. The authors located earthen houses in the villages of Slavonia and Baranja (e.g. in Erdut, Lug, Dopsin, and Karanac), in the urban fabric of the city of Osijek (e.g. Ivana Gundulića Street and Ružina Street), but also in Bjelovar-Bilogora County (e.g. in Velika Barna). Available evidence (e.g., [2, 3]) asserts Baranja earth houses as masterpieces of Croatian rural building and places vernacular Croatian earth houses as the national wealth as they embody authenticity. According to those evidences, Baranja rammed earth houses are amongst the best realizations of traditional rural building in Croatia. Although present, earthen houses in Croatia have been abandoned (Fig.1 and Fig.2), and as potential homes for modern housing, they are being bypassed because of their connection to poverty. This negative trend is supported by the fact that there are no Croatian norms that would allow building of new or rehabilitation of existing traditional earth houses. Moreover, during the post-war reconstruction, at the end of the 20th century, many earthen houses in Slavonia and Baranja were demolished due to dilapidation and damage. They have been replaced by new houses made of brick and concrete. However, according to the Act on Protection and Preservation of Cultural Goods (Official Gazette 69/99) the traditional earth house is considered as an immovable cultural good, and as such, it is necessary to protect it from disappearing.

Earth-based building is inexpensive and supports sustainability because it contains low embodied energy. Although superior in terms of ecological and sustainable building, earth's Kryptonite are its low stiffness and strength. Croatia is located in a seismic-prone area where it is binding to design earthquake resistant houses. However, current Croatian design standards do not recognize rammed earth as a load-bearing element in earthquake-prone areas, and thus do not support the construction of new or reconstruction of existing earth houses. To support the development of such standards, it is necessary to conduct meticulous numerical and experimental research.

Figure 1. Ground floor of an earth house in Dopsin, shortly before the demolition (taken: July 2020)

Figure 2. Floor structure of an earth house in Dopsin, shortly before the demolition (taken: July 2020)

To the best of our knowledge this is the first attempt to investigate nonlinear seismic behaviour of traditional Croatian earth architecture. To date, however, much research on earth architecture has been conducted in other European countries, e.g. France [4], Germany [5], and Portugal [6].

Structural systems of earthen architecture [3] included rammed earth walls, walls made of adobe brick (hr. ćerpič), and walls with wooden skeleton (hr. *kanat, bondruk*) and earthen infill. Here, the research is focused on houses with rammed earth walls.

2 Computational model

Nonlinear spatial model was made using the ANSYS software package [7]. The model represents a three-part earth house, resembling a typical traditional Croatian earth house (Fig. 1), as described in [2] and [3]. A house with a three-part ground plan was also found by the authors in the village of Dopsin, near Osijek. However, this house was demolished by the owner (Fig. 1 and Fig. 2) and was not observed in this study. Instead, an earthen house for which a detailed technical drawing was found in [3] was used in this study. The dimensions of the floor plan of the house are 16,5 x 5,6 m. A typical traditional Croatian earth house comprises three rooms, with the main entrance located in the central room. The house observed is regular both in elevation and in plane.

2.1 Geometry and material

The computational model was developed as a part of graduation thesis using the student version of ANSYS software package [7]. Due to limitations of the student license, the house was modelled in small scale 1:2 (Fig. 3 and Fig. 4) following the principles of scaling physical models [8].

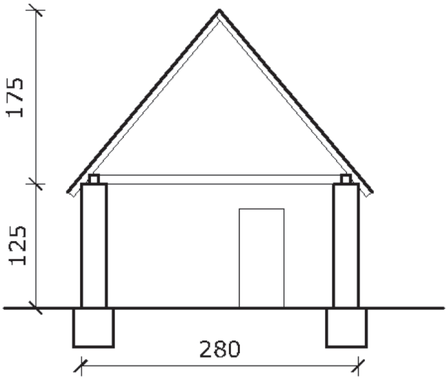

Figure 3. Vertical cross section of the rammed earth house model (scale 1:2), in cm

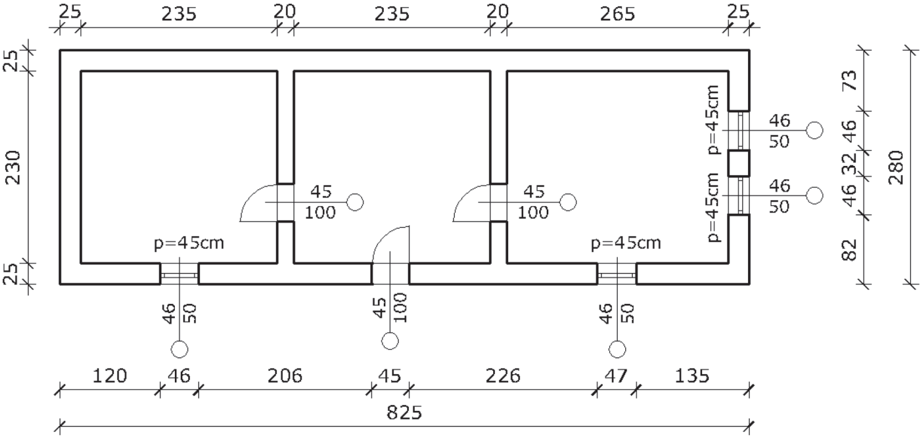

Figure 4. Ground plan of the rammed earth house model (scale 1:2), in cm

The material collected by the authors in the field in Dopsin could not be thoroughly analysed, so its properties were not used here. According to [2] and [3], traditional rammed earth house in Croatia were usually built using loam, combined with clay if needed. Due to the lack of specific information about material used traditionally in Croatia, the earth material with known mechanical properties and grain distribution described in [4] was used in this study. Mechanical properties that were not available in [4] where taken from [9]. Namely, both studies considered soil from the Rhone-Alpine region, France. The soil used consists of around 20 % clay, around 70 % silt and around 10 % sand (Fig. 5). Average material properties of the material used here are listed in Table 1.

The literature review showed that the moisture content and particle size distribution can affect earth compaction during the manufacturing process ([5, 10]). Moreover, high percentages of fine grains can cause better compaction and thus higher cohesion of earth material. In addition, it is known that the modulus of elasticity and compressive strength change with the aging of the material ([10]). These findings will be additionally researched within the research project RE-forMS, funded by the Croatian Science Foundation. The project started at the end of 2020 and is led by Dr. sc. Kraus, Faculty of Civil Engineering and Architecture Osijek. The project deals with traditional soil mixtures from the area of Slavonia and Baranja.

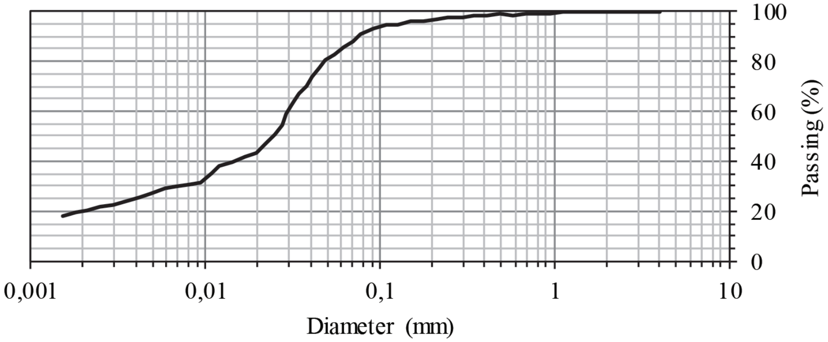

Figure 5. Grain size distribution adopted from [4]

Table 1. Average material properties used

Quantity		Units	Value	Reference
ρ	Density	kg/m^3	2300	[9]
E	Modulus of elasticity	N/mm^2	400	[4, 9]
ν	Poisson's ratio	-	0,22	[9]
f_c	Compressive strength (cylinder)	N/mm^2	2,0	[4, 9]
f_t	Tensile strength	N/mm^2	0,13	[9]
ϕ	Friction angle	°	45	[9]
ψ	Dilatancy angle	°	12	[9]

2.2 Loading

The gable walls, double-pitched tiled roof, and the floor diaphragm were not modelled directly using finite elements. However, they were considered as loads. The self-weight of the structural walls was automatically considered by the computer program.

The weight of the roof, gable walls, and snow was applied to the model as a stress along the upper edge of the wall. All loads applied to the model were selected and defined in accordance with HRN EN 1991 [11]. The load combinations were defined in accordance with HRN EN 1990 [12] for seismic design situations. Only the load combination resulting in the maximum vertical stress on the walls was observed in this paper. The scaled vertical stress of 57 kPa was applied to the exterior walls along the longer side of the house, while the scaled vertical stress of 16 kPa was applied to the exterior walls along the shorter side of the house. In this way, the longer walls take the load from the roof and snow, while the shorter walls take over the load from the gable walls.

The seismic load was modelled using the pushover method [13]. The horizontal force was applied at the top of a shorter exterior wall perpendicular to its plane. The horizontal load monotonically increased until reaching the predetermined target displacement of 10 mm at the top of the wall. Pushover analysis was used to evaluate the seismic capacity of the structure. The target displacement was selected following the recommendations and observations provided in [4, 9].

2.3 Finite elements and assumptions

Computational model (Fig.6) consists of rammed earth walls, rigidly connected to the ground. The deformability of the foundation was not considered in the model. The walls incorporate openings for doors and windows.

Finite element model shown in Fig. 6, was built using SOLID186 elements from homogeneous material. Each finite element has the shape of a cube with side length of approximately 180 mm. Finite element size was selected according to the limitations of the student license of ANSYS software package. Thus, the height of one finite element corresponds approximately to the height of three layers of rammed earth in an actual house. Namely, in Slavonia and Baranja rammed earth layers are usually performed in layers of 100 to 150 mm.

A Mohr-Coulomb model was employed to model the behaviour of the rammed earth. In [14], the cohesion of rammed earth is defined as a function of compression strength.

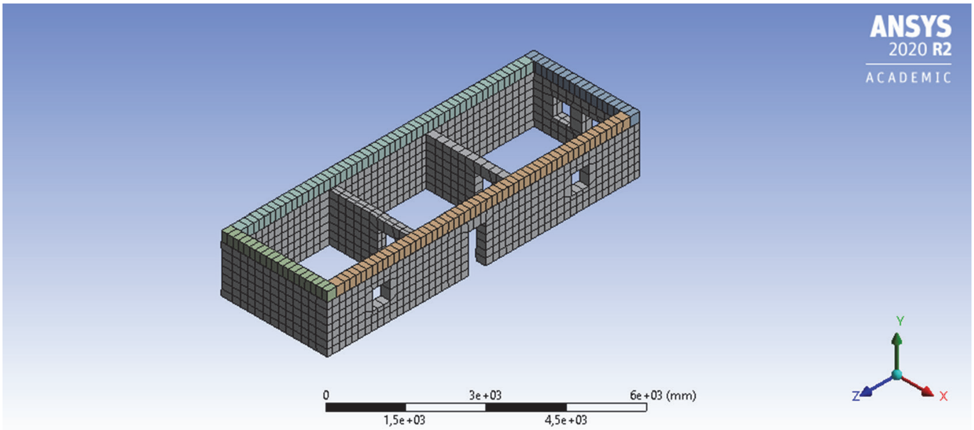

Figure 6. Finite element model of the rammed earth house observed

3 Results and discussion

The capacity curve, or pushover curve, represents the non-linear behaviour of the structure under the horizontal load but also the deformation capacity of the structure. Fig. 7 depicts the capacity curve (average top displacement against base shear) for loading applied parallel to the longer side of the house. The capacity curve is plotted up to the attainment of the target displacement.

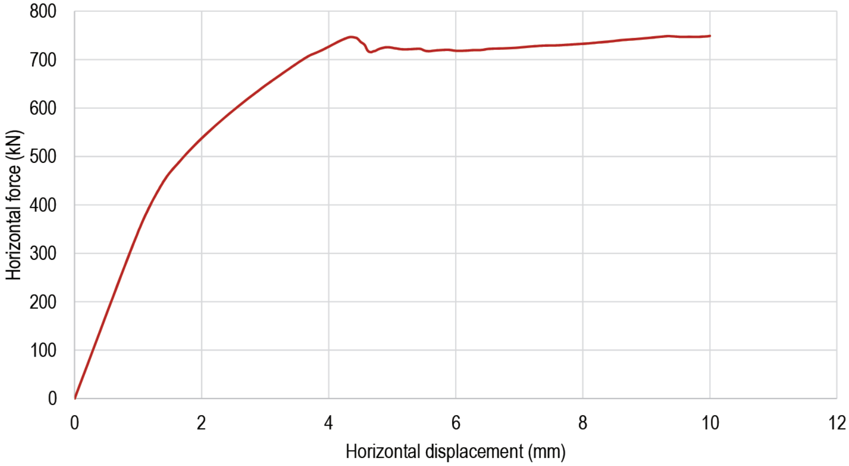

Figure 7. Capacity curve (in scale 1:2)

The model exhibits elastic behaviour until the base shear corresponding to approximately double the total gravitational load is reached. Fig.7 indicates the onset of yielding starts at the top displacement of approximately 1 mm, that is at the interstory drift of approximately 0,08 %. A sharp drop in stiffness occurs at a peak displacement of about 4,5 mm, viz. at the interstory drift of approximately 0,36 %. The onset of the sharp drop in the stiffness of the structure is observed at a moment when the base shear force is approximately equal to three times the value of the total gravity load for seismic design situation.

Limit values of interstory drifts are defined in [4] according to which it is possible to assess structural damage. Interstory drifts up to a value of 0,1 % suggest minor structural damage and/or moderate damage to nonstructural elements. If interstory drifts of up to 0,1 % have been achieved, the building can be used after an earthquake without the need for significant remediation or repairs to the structural elements. Interstory drifts with values between 0,1 % and 0,3 % suggest significant structural damage and extensive damage to nonstructural elements. In such a case, the structure needs to be significantly repaired after an earthquake. Exceeding the value of the interstory drift of 0,3 % suggests that the structure has suffered very severe damage so that the repair is uneconomical or not feasible. In such a case, it is proposed to demolish the building in order to prevent endangering people's lives.

In Fig. 7, it is interesting to note that after reaching a displacement of 6 mm, which corresponds to the interstory drift of 0,5 %, the increase in stiffness occurs again. However, this observation needs to be checked against experimental results.

Higher values of total deformation were observed at the corners of the house, above the openings and at wall junctions (Fig. 8). The total deformations decrease gradually by approaching the base of walls.

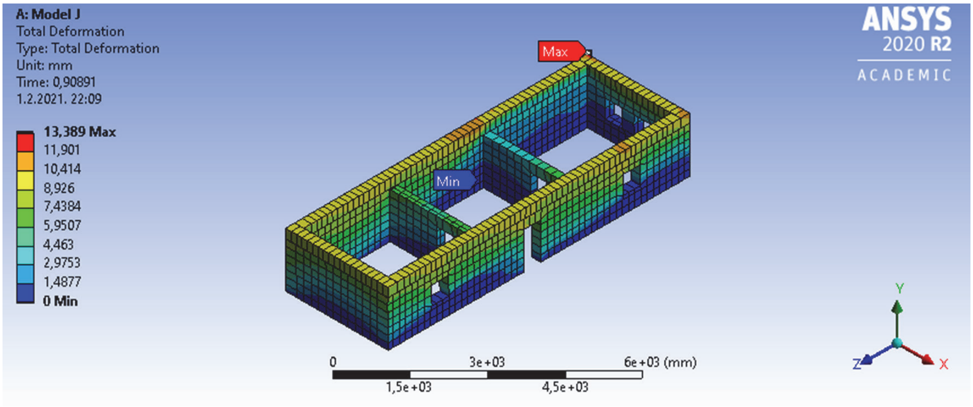

Figure 8. Total deformation

Furthermore, modal analysis was conducted to better understand seismic behaviour of the rammed earth house observed. The fundamental period of vibration T_1 of the house in small scale was calculated equal to 0,20 s. Thus, for the real house, following the scaling rules, the fundamental period of vibration is 0,10 s. To verify the calculated fundamental period of vibration two different coded expressions were employed.

According to HRN EN 1998-1 [13] the fundamental period of vibration for general type of structures can be estimated for the real house using the following expression:

$$T_1 = 0{,}050 \cdot H^{0{,}75} \tag{1}$$

where H is the height of the building, in m, from the foundation. Using expression (1), the fundamental period of vibration calculated is equal to 0,099 s, providing that the height of the real structure is equal to 2,50 m. Moreover, according to HRN EN 1998-1 [13] the fundamental period of vibration for general type of structures can be estimated using the following expression:

$$T_1 = 2 \cdot d^{0{,}5} \tag{2}$$

where d is the lateral elastic displacement of the top of the building, in m, due to the gravity load applied in the horizontal direction. Using expression (2), the fundamental period of vibration calculated for the real house is equal to 0,08 s, providing that the lateral elastic displacement of the top of the real structure is 1,6 mm due to the gravity load applied in the horizontal direction. Finally, it was found that the fundamental periods of vibration estimated using expressions (1) and (2) match well with the value determined using the computational model.

4 Conclusion

In the Republic of Croatia, it is still possible to find rammed earth houses and other earth architecture made using traditional technologies. However, such houses are often abandoned, unmaintained and prone to decay. Moreover, during the post-war reconstruction, at the end of the 20th century, many earth houses in Slavonia and Baranja were demolished due to dilapidation and damage. Only meticulous numerical and experimental research followed by the development of Croatian norms for rammed earth would allow building of new and/or rehabilitation of existing traditional earth houses. This could prevent the complete disappearance of earth architecture in the Republic of Croatia.
To the best of the authors' knowledge, this is the first attempt to investigate nonlinear seismic behaviour of traditional Croatian earth architecture. To date, however, much research on earth architecture has been conducted in other European countries, e.g. France, Germany, and Portugal. For the needs of this research, a spatial model of a single-story traditional rammed earth house of Slavonia and Baranja was made. The numerical model was created as a part of graduation thesis using the student version of the ANSYS computer package. Due to the restrictions of the computer package used, the model was made in a scale of 1:2 using the rules for scaling physical models. All the gravity and seismic loads on the model were defined according to the actual Croatian norms. A modal and pushover analysis was carried out to determine the behaviour of the structure observed. The results of this study underline that:

- the traditional Croatian earth house may exhibit elastic behaviour until the base shear reaches approximately double the gravitational load;
- the onset of yielding of the rammed earth house observed starts at the interstory drift of approximately 0,08 %;
- a sharp drop in stiffness of the rammed earth house observed occurs at the interstory drift of approximately 0,36 %;
- the onset of the sharp drop in stiffness of the rammed earth house observed starts when the base shear force is approximately equal to three times the value of the total gravity load;
- expressions from HRN EN 1998-1 defined for concrete structures can estimate the fundamental period of vibration of a single-story rammed earth structure.

These results provide a significant first step towards the understanding of seismic behaviour of traditional Croatian earth architecture. Further researched will be conducted by the authors within the ongoing research project RE-forMS, funded by the Croatian Science Foundation.

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