Rammed earth for modelling and standardization in seismically active areas: the RE-forMS project

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Abstract: Earth houses provide housing solution for around 30 % of the world's population. Building with soil is cheap and supports sustainable building. Albeit present, rammed earth (RE) houses in Croatia are mostly abandoned and heavily damaged due to an insufficiently raised level of awareness of their significance. In addition, current Croatian design standards do not recognize RE as a load-bearing element, and thus do not support the construction of new or reconstruction of existing earth houses. Project RE-forMS embodies the synergy of modern design of structural walls and traditional building with RE. Data and samples from existing earth houses will be collected through field surveys. The controlled cultivation and testing of agricultural crops will define the natural fibres for strategic reinforcement of RE walls. Properties of both RE samples from the field as well as improved RE mixtures reinforced with natural fibres will be determined in laboratories. Via experimental testing the thermal and seismic performance of RE walls and mock-up houses will be tested. Measured data will be used for studies through nonlinear numerical simulations. This project is transformational with expected impact on the preservation of cultural heritage, encouraging sustainable building and developing Croatian norms for design of RE houses.

Keywords: sustainable building, rammed earth walls, design standards, agricultural crops

1. Introduction

Earth houses provide housing solution for around 30 % of the world's population (Perić, Kraus, Kaluđer and Kraus, 2021). Building with soil is inexpensive and supports sustainable building because soil contains low embodied energy (Bui et al., 2011; Tripura and Singh, 2015). Albeit present, rammed earth (RE) houses in Croatia are abandoned, in

deteriorated and heavily damaged state mostly due to an insufficiently raised level of awareness of their importance and significance. Moreover, earth houses in Croatia are often bypassed for modern housing because of their association with poverty. However, available evidences assert Eastern Croatia earth houses as masterpieces of Croatian rustic building and place vernacular Croatian earth houses as the national wealth as they embody authenticity (Lončar-Vicković and Stober, 2011; Španiček, 1992). On the other end, researchers from all around the world confirm the increased number of houses built from rammed earth because people have become aware of sustainable building (Baiche et al. 2016, Cheah et al., 2012).

a) b)

Fig. 1 - Traditional Croatian RE house: a) view from the backyard, b) side view

Although superior in terms of ecological and sustainable building, RE's Kryptonite is its low stiffness and strength. Namely, RE has almost 20 times lower strength than concrete or clay brick (Bui et al., 2011; Perić, Kraus, Kaluđer and Kraus, 2021).

Earth houses were usually built ad hoc and by applying material which was a part of the immediate surroundings of the house or was a result of digging a basement (Lončar-Vicković and Stober, 2011; Vinceslas et al., 2018). Empirically acquired knowledge was passed on the generations by word of mouth, with no scientific grant for load-bearing capacity and resistance of the structural elements. Given the fact that 30 % of the world population lives in earth houses mostly built without employing design standards, it is disturbing that most of such houses often appear in places with high seismic activity (Silva et al., 2014; Perić, Kraus, Kaluđer and Kraus, 2021). Due to very low compressive strength, and even lower tensile strength, it is clear that earth houses are positioned very low on a scale of houses safe to live in high seismically active areas, especially if the rules of seismic design are neglected. With the goal to improve the durability and bearing properties, the earth is stabilized by adding cement or lime (Ciancio and Boulter, 2012; Gupta, 2014; Narloch et al., 2015). By adding cement, one is detached from traditional and sustainable building, as the possibility to recycle building materials is lowered and embodied energy is increased.

Croatia is located in a seismic-prone area where it is binding to design earthquake resistant houses. Yet, current Croatian design standards do not recognize RE as a load-bearing element, and thus do not support the construction of new or reconstruction of existing RE houses.

Most of the previous research conducted at the Faculty of Civil Engineering and Architecture Osijek, in the context of large-scale projects financed by competent domestic

and international sources, was primarily focused on reinforced concrete structures with masonry infill, numerical analysis of the behaviour of reinforced concrete structures and concrete with addition of waste and recycled materials as a replacement for the natural aggregate.

The installation research project RE-forMS (31 December 2020 – 30 December 2025) will assess the thermal performance of RE elements and also the resistance of RE walls to both gravity and lateral loads used to simulate earthquake action. The implementation of extensive numerical and experimental research in the field of rammed earth in Croatia began last year (Kraus, Perić, Kaluđer and Kraus, 2021; Perić, Kraus and Krstić, 2021; Perić, Kraus and Krolo, 2021).

World examples show the possibility of reinforcing earth walls with hemp and straw (Cheah et al., 2012; Calatan et al., 2016). In this context, the main hypothesis of the project is formed by embodying the synergy of modern design of reinforced concrete walls and traditional building with RE, aiming to assess the possibility of reinforcing earth walls with the stems of different agricultural crops.

Within the RE-forMS project, data, and samples from existing traditional RE houses from Eastern Croatia will be collected through field surveys. The physical, mechanical, and thermal properties of traditional materials collected in the field will be determined in laboratories. The tensile strength of the stems of different agricultural crops for micro-reinforcement will be experimentally tested, and the strategy of reinforcing concrete walls will be applied to RE. Properties of both traditional RE samples from the field as well as improved soil mixtures reinforced with natural fibres will be determined in laboratories. Via experimental testing of RE walls and mock-up houses thermal performance and behaviour to simulated seismic action will be tested. All measured data will be used for studies employing nonlinear numerical simulations.

2. Project objectives

Traditional earth houses in Croatia are buildings with natural, locally available material as well as durability and integrity which were maintained during several decades in seismically active areas. It is a known that such houses can last more than 60 years (Bui et al. 2009).

The main goal of the RE-forMS project is to make RE walls full-fledged structural elements for building in seismically active areas. This five-year project is directed towards perseverance of the traditional and cultural heritage, encouraging sustainable building in Croatia, and making of recommendations and guidelines for design of RE houses.

The first and primary focus of the research within the project is the seismically resistant rammed earth wall strengthened with natural fibres. Fibre strengthening will be assessed by means of zone reinforcing of concrete wall, where the web is differently reinforced with respect to the flanges. The second focus is put on testing the effect of fertilization on the mechanical properties of crop fibres as a natural micro-reinforcement for rammed earth walls. Within the project, the mechanical properties of five crops will be examined, as well as the chemical structure and fibre structure. Also, model rammed earth walls will be tested subjected to in- and out-of plane loads while model rammed earth houses will be subjected to simulated earthquake using a shaking table. Prior to demolition by applying lateral out-of plane load, the walls will be assessed during several months in the context of energy efficiency and thermal conductivity what is the third focus of the project.

Specific goals of the project include, inter alia:

1) Establishing an interdisciplinary research group for the development of independent research in the field of RE.
2) Analysis of physical, mechanical, and thermal properties of traditional and improved soil mixtures for choosing optimal mixtures for design of houses in seismically active areas.
3) Assessment of the behaviour of RE walls and houses subjected to artificial ground motions, and development of strategic distribution of optimal soil mixtures for design of new and retrofit of existing RE walls in seismically active areas.
4) At the level of load-bearing elements and houses, experimentally investigate the thermal properties of soil mixtures to encourage building of new houses.
5) To prepare recommendations and guidelines for design of new and retrofit of existing RE structures in Croatia, but also to upgrade and improve Croatian design standards.
6) Investigate the influence of plant species and mineral fertilization on stem parameters and the concentration of chemical elements to select the optimal agricultural crop for strengthening RE walls.
7) Promote project results, and disseminate new knowledge and experience through workshops and mini-symposia organized by the RE-forMS group.

3. Methodology

The RE-forMS project will be conducted through three successive phases (Figure 2). In the first phase of the project material properties will be examined. The second phase will examine air permeability, thermal conductivity, and load-bearing capacity of walls on horizontal forces until the collapse. In the third phase, however, the resistance of mock-up RE houses to simulated earthquakes will be examined by employing a shaking table, also until the collapse. The very beginning of the project will include: i) a detailed review of the literature and ii) a field research with the goal to measure and photodocument the existing traditional earth houses, as well as to collect samples of traditional mixtures.

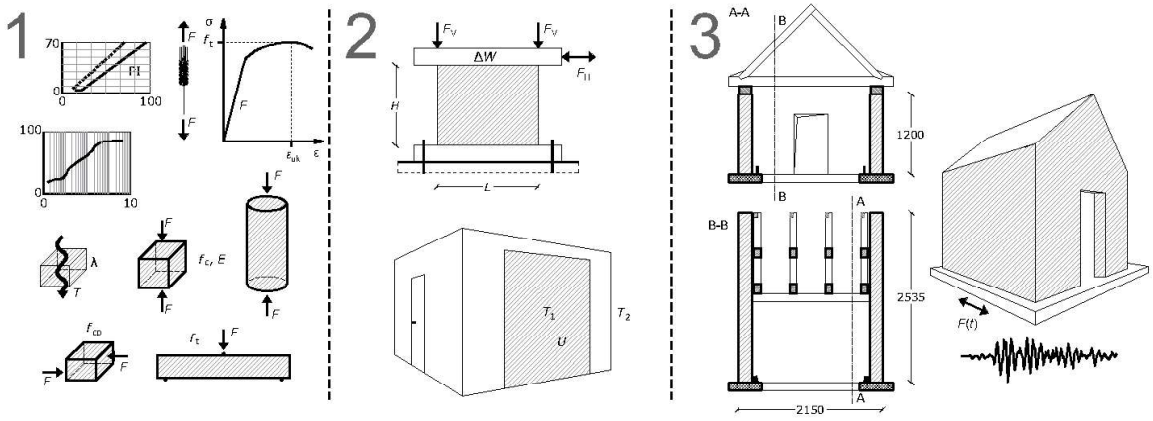

Fig. 2 – Three phases of experimental testing within the RE-forMS project

Most of the experiments will be conducted in testing facilities of the Faculty of Civil Engineering and Architecture Osijek, and the Faculty of Civil Engineering in Rijeka (Figure 3). The activities of the last year of the project will be carried out mostly in the

Laboratory for seismic testing in Žrnovnica, near Split. Laboratory for seismic testing in Žrnovnica is the only such institution in Croatia with a shaking table, which can truly reproduce arbitrary ground motions.

Physical and mechanical properties will be determined on collected samples. These project activities will be mostly conducted in the laboratories of the Faculty of Civil Engineering and Architecture Osijek, Croatia. After testing of the traditional mixtures, optimisation will be conducted on 15 different soil mixtures with the goal to enhance strength, ductility, and resistance of RE houses to external actions. Local soil from around Osijek will be tested, as well as mixtures of local soil with the supplements (sand, lime, and plants/fibres of five different agricultural crops). Properties such as Atterberg's limits, specific density, calcium carbonate and organic matter content, optimum compaction and thermal conductivity coefficient will be carefully determined for soil mixtures.

a) b) c)

Fig. 3 – Testing facilities: a) the Laboratory for Experimental Mechanics "Vladimir Sigmund" at the Faculty of Civil Engineering and Architecture Osijek, b) universal testing machine with temperature chamber at the Faculty of Civil Engineering in Rijeka, c) airtightness testing chamber at the Faculty of Civil Engineering and Architecture Osijek

In total 945 samples of RE will be tested using universal testing machines and direct-shear devices to determine the mechanical properties of materials (compressive, tensile and shear strength, and elastic modulus). Assessment of mechanical properties of RE will be conducted on cubes, prisms, and cylinders. Measuring mechanical properties on the samples of different shapes (cube and cylinder) will provide correlation of the measured quantities, ease the use of data, and will provide comparison of the measured quantities in available literature. Every year during the project, shear strength of the earth material will be determined in a direct shear-testing machine. Shear strength will be determined for three different vertical stresses which are compatible with the state of the material in different places in real construction, and in different situations. The walls will be tested until the collapse in the second, third and fourth year of the RE-forMS project.

In overall 12 walls subjected to cyclic in-plane loading will be tested using reactive steel frame and hydraulic presses while six walls subjected to a monotonically increasing out-of-plane loading will be tested using a lever chain hoist. Tests conducted on RE walls will give insight into collapse mechanism which will contribute to a strategy of strengthening using natural fibres as micro reinforcement for such walls. A part of samples, taken from soil mixtures prepared for building walls, will be tested immediately prior to wall tests, while the rest of the samples will be tested during the following years of the project with the goal to investigate effects of aging and late strengths growth because of the pozzolanic reactions in soil mixtures with lime.

Shaking tables enable assessment of building structures until collapse by applying simulated ground motions, and in such a way they provide a complete insight into a real

dynamic behaviour of buildings. There is a very limited number of institutions that have such sophisticated equipment for structural dynamic assessment. Two models of RE houses with the roof will be examined on the shaking table in Žrnovnica, Croatia. One model will represent a typical Croatian traditional RE house, while the other model of the house will be made by employing the improved soil mixture and strategically distributed natural fibres.

Each large-scale experiment will be preceded by a blind prediction of the behaviour of the observed RE model using numerical simulations. After every experiment, numerical models will be calibrated and improved for implementation of the parametric studies. Studies on numerical models will be conducted using computer programs (e.g. ANSYS, OpenSees). Nonlinear static and dynamic numerical analyses will be conducted to carry out parametric studies and also to validate and verify constitutive models and analytical expressions for assessment of seismic performance of RE structures.

The controlled cultivation of five agricultural crops (wheat, barley, rye, oat and industrial hemp) will provide fibres and stems for strengthening assessment of RE with natural micro reinforcement. The Faculty of Agrobiotechnical Sciences Osijek, Croatia will use the available mechanization for the needs of setting and implementing field tests on an experimental site. The tests will be set in three recurrences in which case the basic surface of each recurrence with agricultural crops will be 1000 m^2, and with hemp 500 m^2, which makes a total of 40.500 m^2 of the sowed surface every year. Five agricultural crops and three levels of mineral fertilization of biological crop and other parameters of the plant (height, weight, N, P, K and Ca concentration, strengths, elasticity) will be examined. Electron microscope Olympus SZX9 with digital camera and belonging software will be used with the aim to determine stem diameter.

The thermal conductivity coefficient λ for RE samples will be determined on 153 samples using FOX 200. Airtightness (Minneapolis BlowerDoor) will be assessed in a testing chamber with RE walls installed (Figure 3). The assessment of the thermal conductivity coefficient (U value) will be conducted on six RE walls in overall. These walls will be removed from the chamber by a lever chain hoist, which will give an insight into the wall behaviour under the action of a monotonically increasing lateral load that will simulate the earthquake action normal to the wall plane.

The U value assessment will be conducted using two non-destructive in-situ methods: a Heat Flow Meter method by measuring the flow of heat through a building element and a Temperature Based Method, based on three temperature measures. During assessment of the U value of the walls in the model house, the temperature sensors will be additionally used with NI cRIO-9114, and the moisture and air flow from the internal and moisture from the external side of the wall will be measured. That part of the assessment will be conducted during winter months when it is possible to provide lower temperatures and necessary minimum temperature difference of the external side of the chamber.

The walls will be examined continuously during three winter months. Such assessment will be conducted during three years, and at the end of each year walls will be replaced by new walls with different physical and mechanical properties.

During the RE-forMS project, tensile strength of field crops will be examined in the laboratory of the Faculty of Civil Engineering in Rijeka, Croatia. With the aim to check the guidelines for making mixtures and implementation into the sample moulds and for the purpose of the cross examination of the measured quantities, the materials for making earth mixtures together with the recipes for making mixtures will be sent to Rijeka.

4. Expected impact and results

Although present in Croatia, earth houses are abandoned and very often in an adverse state. The results which are realized by means of experimental and numerical assessment will raise the value of soil as a building material which is sustainable and safe for the environment and healthy living, as well as for perseverance of the existing traditional old earth houses.

The results of the RE-forMS project will create a potential for building new RE houses and retrofitting the existing ones. New RE houses can easily serve as a temporary home for, for example people from war-affected areas or areas affected by natural disasters (e.g. flood, earthquake, wildfire). RE houses are possible to build from locally available material using simple technologies. When leaving those houses permanently, there is a possibility for load-bearing walls to be recycled or returned to nature. Hard mechanization or use of explosives for example, is necessary for demolition of concrete structures in which case the constituent parts can no longer be returned to nature in their original state. So, it can be said that earth houses are almost perfectly compliant with ecological and sustainable building.

Soil is easily available, cheap, easily recycled and leaves a very small ecological footprint. Scientific community will be provided with implementation of parameter studies by means of expanding the database of measured data which are a result of rare and expensive experimental research. Expanded database of experimental data will enable analysis by applying statistical methods, numerical programs for simulating behaviour of buildings and neural networks which will increase the level of knowledge regarding application of RE. Tests conducted on full-scale models and shaking tables are rare and expensive because structures of large mass and strength are examined until they collapse by means of strong devices for simulating destructive natural phenomena. However, such tests are extremely important as they give an insight into real phenomena and mechanisms. On the other hand, numerical assessment of structural behaviour is significantly faster, non-risky regarding people's safety and relatively cheap if considered that in a very short time behaviour of a larger number of structures can be examined, and it can be done by way of making a model copy and by changing an input parameter.

The analysis of mechanical properties of different agricultural crops for the purpose of defining natural fibres for micro reinforcement of RE wall will provide the results which will potentially give additional value to agricultural crops.

Experimental tests of traditional RE walls and mock-up houses will give insight into the collapse mechanisms, which will enable the development of design and strengthening of RE walls using natural fibres.

Acquired knowledge and measurement results of thermal properties of RE have the potential to complement technical regulation regarding rational use of energy and thermal protection in buildings which currently do not recognize soil as a building material. Acquired knowledge, skills, experience, and analysed measuring data will be dispersed among academic community and the profession as well as among students and interested public, and it will be carried out by:

1) publishing scientific papers in international conferences and peer-reviewed journals
2) organizing workshops and mini-symposia on the applicant's Organization during the project
3) webpage of home Organization and partner Organizations

4) participating on Science Festivals or other festivals whose goal is to encourage younger generations and the interested population to be engaged in science and innovations.

Successful project realization opens a possibility of creating new course in civil engineering and architecture studies. All the steps within the project are directed towards persevering cultural heritage, encouraging ecological building, and making of recommendations and guidelines for design of houses made of RE in seismically active areas and all with the purpose to provide safe and healthy place to live. The project will produce the following key results:

1) a booklet with a detailed description of traditional RE houses from Eastern Croatia, and an accompanying publicly available online database with measured physical, mechanical, and thermal properties of traditional soil mixtures
2) a publicly available database of experimental test results conducted on 18 RE walls tested under monotonically increasing and pseudo-dynamic loading and two RE mock-up houses tested on a shaking table.
3) a publicly available database of mechanical properties and results of chemical and fibre analysis for five different crops covered by the project.
4) a publicly available database of thermal properties (U value and heat transfer coefficient) for the traditional and improved soil mixtures.
5) publicly available online report describing hysteresis loops, capacity curves, equivalent viscous damping, limit states, failure mechanisms, and critical zones of RE walls
6) publicly available report on the technologies and procedure of making RE walls and recipes for making earth mixtures
7) guidelines and recommendations for the design and modelling of RE walls, complying with actual Eurocode standards.

5. Conclusions and discussion

Available evidences assert Eastern Croatia rammed earth (RE) houses as masterpieces of Croatian rustic building and place vernacular Croatian earth houses as the national wealth as they embody authenticity. Yet, the preservation of existing traditional earth houses is difficult and/or limited because actual Croatian design standards and technical regulations do not recognize soil as structural material for building in earthquake-prone areas. Studies on seismic performance of RE structures have been conducted worldwide, but not in Croatia. All the world studies were conducted on RE made using local materials peculiar to the observed area, so the obtained results cannot be fully used to understand the seismic resistance of Croatian traditional RE houses. Also, the potential of reinforcing earth walls using agricultural crops is not clear.

The RE-forMS project implies the following: i) analysis of soil and plant material as architectural solution for green and sustainable living, ii) analysis of RE walls micro reinforced with natural fibres and by following the strategy of reinforcing concrete walls for seismically active areas, iii) analysis of dynamic properties of RE mock-up houses for behaviour assessment of new and existing traditional houses, and iv) analysis of thermal properties of RE walls to support energy efficiency. The project RE-forMS embodies the synergy of contemporary design of reinforced concrete and traditional building with soil, and thus closely intertwines the required knowledge in the fields of civil engineering, architecture, geotechnics, agriculture, and energy efficiency.

The main goal of the RE-forMS project is to make RE walls full-fledged structural elements for building in seismically active areas. This five-year project is directed towards perseverance of the traditional and cultural heritage, encouraging sustainable building in Croatia and making of recommendations and guidelines for design of RE houses. Furthermore, the results obtained from conducted experimental tests on both the airtightness of a house with RE walls and the thermal properties of the RE will sensitise the new use of traditional RE houses in earthquake-prone areas and create the potential to supplement Croatia's technical regulations regarding thermal properties of materials. The project is transformational with expected impact on the preservation of cultural heritage, encouraging sustainable building and developing standards for design of RE houses in seismic-prone areas.

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