TECHNOLOGICAL INNOVATION FOR SEISMIC-RESISTANT HOUSING OF REINFORCED ADOBE WITH TRUSS BEAMS OF GALVANIZED STEEL

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Abstract

This paper describes the advantages of the Integral Masonry System (IMS) for adobe houses, which consists in the use of an earthen filling in a lattice of pre-welded or properly bonded frame, which transmits exertion between each other to sustain the walls. The prefabricated frame consists of bars of galvanized steel, which are organized in the form of trusses of 24-cm to 30-cm wide and 6-m long. These intersect in three spatial directions, thereby achieving a frame that forms the skeleton of walls and ceilings, as the trusses are very light and easy to install by hand. Subsequently, the gaps are filled in with adobe, rammed earth, or other materials, including recycled materials, to build the walls. These can also incorporate planks on the horizontal-lattice trusses to form the floors.

After an earthquake, re-plastering is recommended due to the cracks that occur in the direction of the frame, as was demonstrated in the prototype test of a ½-scale study in 2008, in the seismic-simulation table at the Structural Laboratory of the Pontifical Catholic University of Peru. Four movements were carried out (20 mm, 50 mm, 80 mm and 130 mm), which coincided with ground displacement according to the degree of earthquake of 2, 5, 8, and more than 10, respectively, on the Richter scale. The end result was a stable structure that withstood these movements. As has been demonstrated, the construction process is simple, the building is resistant to earthquakes, and the reconstruction process can reduce time and costs once the disaster has occurred.

1. INTRODUCTION

During the 2005 Sismo Adobe Congress held in Lima, self-construction of adobe housing in seismic prone areas was proposed, with a new type of pre-welded truss-like frame. Also, in 2007 at the International Symposium on Earthen Structures (ISES-2007) held in Bangalore, India, the paper "The Integral Masonry System with earth-based materials: rubble based earthquake resistant construction" was presented. Being an unconventional system, its effectiveness needed to be experimentally proven, and following this, a research project was planned.

The 2007 earthquake in Pisco, Peru highlighted the need to implement an earthquake-resistant alternative building system, allowing for the reconstruction of collapsed or damaged houses in such a manner as to be secure from any other possible occurrence. Following the earthquake, actions were initiated to develop a research project, in a joint effort between the Universidad Politécnica de Madrid (UPM) and the Civil Engineering Section of the Department of Engineering at the Pontifical Catholic University of Peru (PUCP).

2. BACKGROUND

Earthen building has led to construction systems of mixed walls in which the wooden, cane or concrete-reinforcement structure is responsible for the flexible framework, acting thus complementing and strengthening the earthen materials against forces it would not otherwise withstand. Aiming at solving the problem of resistance to seismic activity, reinforcement techniques have been put forward in Peru, which can be divided into two:

- Improving quincha trusses (studies at the National University of Engineering of Lima on the resistance of quincha panels under earthquake action);
- Strengthening of adobe walls by applying a geogrid. Based on the seismic-simulation tests conducted in PUCP, geogrid behavior resembles that of an elastic material, resulting from the influence of the grid on the adobe.

Naturally, the recommendations issued for decades are also reiterated: a suitable foundation, confinement of masonry, and walls in both directions of the plan, with particular attention drawn to the building of closure elements. Coincidentally, the greatest loss of life was caused by the collapse of façades in the earthquake of May 1970.

This research intends to cover the vulnerabilities registered with earthen construction, i.e. reinforced adobe with galvanized steel. The traditional wooden lattices are filled with gypsum rubbles, bricks, or cane mixed with clay. Construction systems based on ceilings, joists and studs are replaced with steel trusses.

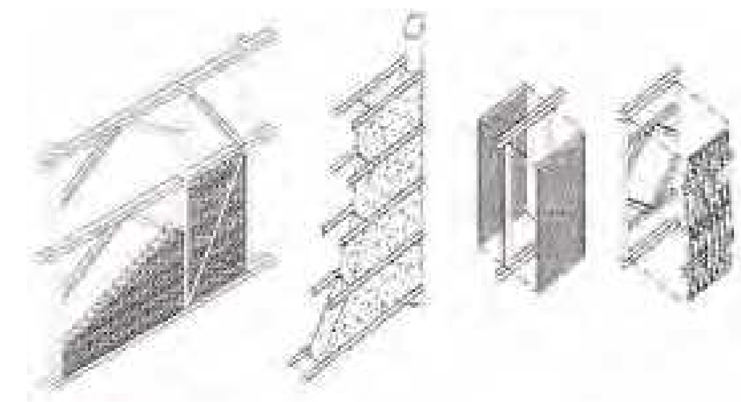

Fig.1 Types of timber and cane frames (credits: Monjo, 1998)

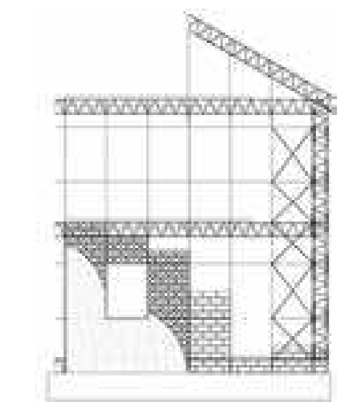

Fig.2 IMS with galvanized-steel trusses (credits: Adell et al., 2007)

3. AIMS

The main and immediate aim of the project was to experimentally verify the seismic behavior of adobe houses as an alternative for individual or massive programs of housing construction. The concept was for adobe houses to be both economically viable and able to ensure structural safety during the occurrence of an earthquake. In addition, if successful, the intention is to apply it to other building types (schools, workshops, etc.).

4. SELECTION OF A PROTOTYPE

From the six housing types reviewed in 2005, Type 5, a two story-high structure with 3 bedrooms and 72 m^2 built area (58 m^2 of usable area) was selected. Its cubic volume of 6 m/side is perfectly conform to the possibilities of the 4.40 m/side square seismic-testing table at the Seismic-Resistant Structures Laboratory of PUCP, which allows testing of the whole house, although built to half scale.

5. THE BUILDING SYSTEM

The reinforcing technology applied consists of a prefabricated truss-shaped braided formwork, with longitudinal and transverse wires welded together and a galvanized coating preventing their corrosion. The connection between these prefabricated 6-m long trusses is accomplished by hand using specifically designed screws, welding or tie wires. Together with the lightness of these wire-frame structures (about 3 kg for a 6-m truss), this allows for easy self-construction of a simple earthquake-resistant structure for walls, ceilings and roofs.

The novelty of this construction system is that the exertion between the frames is not conveyed through a collaboration of with concrete, since none is present. Nor is it due to the adobe, which contributes little. Instead it is the connections that enable cohesion between all of the horizontal and vertical trusses of the building, the latter in-filled with adobe. In terms of seismic action, the calculations performed for, the implementation of this new technology offers a very promising theoretical result, as each of the metal elements were previously tested separately in Europe.

6. REINFORCED ADOBE

The characteristics of the materials used for the reinforced adobe construction system are:

- Adobe compressive strength: 0.3 to 0.5 MPa
- Adobe weight: 18 kN/m^3
- Steel: B-500-S, fs = 500/1.15/1.54=282 N/mm^2
- Steel weight: 78 kN/m ^{3}

The dimensions selected were as follows:

- Frame of the test model (3 m x 3 m x 3 m): Two longitudinal wires of 5 mm to each side of a zigzag wire truss of 5 mm, 150 mm apart. The arrangement of the wall and ceiling frames were configured with a vertical and horizontal module of 45 cm/side. The adobe-wall prototype tested was 15 cm of section
- Frame of a building of 6 m x 6 m x 6 m: Two longitudinal wires 10 mm to each side of a zigzag wire truss with two wires of 5 mm, 300 mm apart. The adobe wall tested was 30 cm of section.

The arrangement of wall and floor frames of a 45-cm prototype corresponds to a module of 90 cm in reality. It is module that allows for openings for doors and windows, as well as stairs in a habitable building.

Fig.3 The unreinforced corner had no major complications. Note that the rack truss, which functions as the ceiling joists, also functions as a perimeter beam (credits: Adell, 2008)

Fig.4 Prototype before Phase 1 testing (credits: Adell, 2008)

7. EXPERIMENT PLAN

The model under experiment consisted of a module at half scale, depicting a two-story adobe house with a square plan of 2.70 m/side and a height of 2.70 m, both nominal dimensions. Steel beams of 8" x 8" formed the base, which acted as the foundation of the module. The beams were welded to create a square frame of 3 m/side (external dimension). Gussets were added, not only to give rigidity to the element, but also to be the accessories required for the transfer and attachment to the earthquake simulator platform.

For practical reasons, erection of a corner (two vertical L racks) was first accomplished, and then the horizontally middle rack was connected to it. Subsequently, the other two vertical racks were placed, ending with the top horizontal rack. During assembly, cuts and folds necessary at the ends of the trusses were performed to generate connection and welding points, responsible for maintaining the stability of the structure.

As a solution, four rows of adobe were erected with a standard horizontal joint of 15 mm, plus a fifth row with lower height adobes, which were cut with manual tools from slightly larger units (leftovers from other projects). The adobe units used presented nominal dimensions of 28 cm x 15 cm x 8 cm ("whole") and 14 cm x 15 cm x 8 cm ("halves"). Both dimensions were needed to enclose the walls. 810 adobes and 690 halves of adobes were manufactured. The mixture used was a combination of soil, sand and straw (grass) in a 5:1:1 proportion by volume. The soil was clay of low plasticity typically known as tierra de chacra.

Furthermore, a 10-mm hollow geogrid attached with raffia ties on two sides of the prototype coincided with the frames. This was done to show whether or not a plaster or earthen finish of 20-mm thick could avoid cracking during the dynamic test of the walls (MD and MA), one longitudinal and another crossing the movement simulator. This masonry prototype was completed one month before the date of the trial to ensure that the earth would be dry before the test on the simulator.

The module was weighed before the walls were plastered, to ensure that the load limit of the simulation table was not exceeded. A value of 86.86 kN was obtained, allowing for sufficient margin to add the finish (after drying, the weight was registered 94.71 kN), as well as the placing of the additional overload. Fig.4 illustrates the characteristics of the finished prototype. The total weight, including overload, was 102.35 kN.

8. SEISMIC EXPERIMENT

8.1 Description of the experiment

The standard command signal (register shift that defines the simulator platform's motion) of the laboratory comes from the longitudinal component (N8°O) of the acceleration measured in Lima during the earthquake of Ancash on May 31, 1970. The original record, obtained from an analog accelerometer, was given by the United States Geological Survey (USGS) to obtain a corrected digital acceleration, which served as the basis for generating the command signal named "mayo70". For this experiment, because it uses a half-scale model, a compressed version of "mayo70" time was used, in order to modify the content of the predominant frequencies of the signal, in accordance with the variation of the structure's fundamental frequencies, as a result of its scale.

Compression was the method used to overcome the original signal at 133.3 points/second by 100 points/second

in the modified signal, according to the physical half-scale factor of the prototype. As a result of this operation, for a given movement, the compressed signal ("mayo70co") produced higher accelerations than the original signal. The movement and acceleration on the uncharged platform of the simulator, when "mayo70co" was activated, was also foreseen.

The dynamic experiment consisted of a sequence of movements (phases) of increasing amplitude, but with the same command signal. Also, the absolute maximum movement reached defined each phase. Initially, the execution of three phases were planned, each one associated with an increase of intensity of what would be a frequent (slight), occasional (moderate), and rare (severe) earthquake. In the case of "mayo70co", these movements corresponded to a maximum displacement of 20 mm, 50 mm and 80 mm, respectively. The expected accelerations on the base of the module from those movements were 0.3 g, 0.7 g and 1.1 g, approximately.

Assuming that the prototype remained in good condition after the execution of the three stages mentioned, a fourth phase was performed repeating the simulation of a severe earthquake (a maximum movement of 80 mm). However, during the test performance for fourth phase, the original command signal of "mayo70" was used with a breath of 130 mm (the maximum capacity of the simulator). The intermediate horizontal rack was not functioning as a mezzanine, by which the structure would behave if it were a full-scale model, hence it was desirable to refer to a signal containing the appropriate frequency for such a model, "mayo70". Table 1 depicts a summary of all movements made to the test module.

8.2 Testing equipment

Eight accelerometers and ten movement transducers (LVDT) were used to measure the movement and the damage to the walls. In addition, movement and acceleration of the simulator platform were recorded, as well as the pressure (Fa) transducer, which allowed calculation of the shear force induced by the equipment onto the steel-module base set.

9. RESULTS

The prototype exhibited a behavior that can be characterized as earthquake-resistant insofar as it bore all the movements without the structure collapsing. There was neither any local collapse (loose adobes in the corners did not fall out), nor was there any major structural damage. The worst effect was on the MP wall trusses delimiting the door and window openings of the first level, which suffered out-of-plane deformations. The cracks on the walls, as indicated below, related mainly to the separation of adobes from the trusses that contained them.

After each stage, the presence of cracks on each of the walls of the prototype and the appearance of any damage in the structure was noted as follows:

MOVEMENT	SIGNAL	BREATH (mm)
Initial free vibration	ondarec	1.5
Phase 1	mayo70co	20
Free vibration post-Phase 1	ondarec	1.5
Phase 2	mayo70co	50
Free vibration post-Phase 2	ondarec	1.5
Phase 3	mayo70co	80
Free vibration post-Phase 3	ondarec	1.5
Phase 4	mayo70	130

Table 1. Movements of the seismic-simulation experiment (credits: PUCP Seismic Resistant Structures Laboratory, 2008)

- Post-Phase 1: Very small damage was observed only on MP and MD walls, which could almost be confused with those produced by the shrinkage of adobe when drying.
- Post-Phase 2: MI and MD walls presented vertical cracks in the corners, and horizontal cracks between adobe fabric and trusses. The same was observed on the MP wall, but only at the first level. The MA wall did not present any cracks.
- Post-Phase 3: On the MI and MD walls, in addition to the cracks between adobes and trusses, which had increased, there was also some damage inside the enclosure throughout the mortar and adobe. In the MP wall, the existing cracks were aggravated and new cracks were visible on the second level. The MA wall showed the first wall cracks, both horizontal and vertical, corresponding to the adobe/truss adhesion surfaces. The vertical truss that delimited the door opening on the MP wall suffered slight out-of-plane deformation.
- Post-Phase 4: This was the last phase. The two trusses delimiting the doorway on the MP wall are deformed, as well as the one at the window opening of the first level. The elevations illustrate the location of cracks following the fourth phase (130mm). Notwithstanding, the prototype remained standing.

10. CONCLUSIONS

In this research, the prototype model proved to have seismic-resistant behavior against the dynamics of the earthquake simulator. Not only was collapse averted in the final state of the model, but also in the case of a real house, only a modest repair would be necessary to re-endow the structure with adequate strength. In addition, the construction system was easy to implement as demonstrated by the erection of the model, in which the workers executed the procedure without major difficulty, thereby also providing the possibility of self-reliant and rapid construction after a disaster occurs.

However, the production of adobe pieces compatible with the structure was required, along with partial reinforcement with geogrid mesh. In any case, the total surface assembly can prevent cracks from occurring, provided that a true bond is created between the dissimilar materials, earth and steel. This constitutes, therefore, a future line of research. Finally, the construction system resembles the building tradition of half-timbering, which also provides a basis of repair for the architectural heritage of adobe.

Fig.5 Detachments and cracks of the geogrid-reinforced plaster coating on the side perpendicular to the direction of the earthquake-movement simulation, after the fourth phase (displacement of 130 mm) (credits: Adell, 2008)

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HYGRO-THERMO-MECHANICAL PROPERTIES OF EARTHEN MATERIALS FOR CONSTRUCTION: A LITERATURE REVIEW

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Abstract

Although earth has been used in construction for millennia and is still one of the most widely used building materials in the world, it is difficult to find reliable values of hygro-thermal and mechanical properties of earthen materials. Little scientific research has been conducted on this material compared to the huge amount of literature available for cementitious materials. Considering the literature on earthen materials, a majority of studies deal with cement stabilized earth for compressed-earth blocks or rammed earth. Less has been done about natural unstabilized earth.

The only existing comprehensive overview on the properties of earthen materials was authored by CRAterre-ENSAG and published 25 years ago. For the second time in its 30 years of existence, CRAterre-ENSAG has undertaken the task of re-actualizing this synthetic knowledge by writing a comprehensive review of the existing literature on the subject.

In the present work, we intend to compile the most reliable experimental data on hygro-thermal and mechanical properties of natural earth. We will inventory the performances determined by several research teams for rammed earth, compressed-earth blocks, adobe, cob and mortar. We will discuss the reliability of the experimental techniques used. We will provide an overview on the state of knowledge concerning the different properties, as well as on the lacking data. Finally, this literature review will also give some orientation for further scientific research.

1. INTRODUCTION

Building with earth requires that artisans have a very good knowledge of the material. Yet, there is limited scientific knowledge of the material. While builders develop their knowledge in the field through direct experience, engineering-consulting firms are hampered by a lack of reliable data regarding the properties of earth. Norms and standards are few, partial and often deal with compressed-earth blocks (CEB) stabilized with cement. However, there are many other reliable construction techniques involving earth that do not require the use of mineral stabilizers, as demonstrated through centuries-old examples such as the buildings, mosques and skyscrapers in the towns of Ghadames (Libya) and Shibam (Yemen), some sections of the Great Wall of China, the tulous – large residential complexes of the Hakka in China, or more locally, the many farms built with earth around the Rhône-Alpes region in France (Fontaine and Anger, 2009). These examples show that earth can be used for the construction of sustainable buildings.

This report is an update on the knowledge available on the hygrometric, mechanical, and thermal properties of earth. It deals mainly with the intrinsic properties of the material. This update is an opportunity make an inventory of knowledge and highlight the technical data gaps that could be usefully filled. Documents and information were gathered through CRAterre's Documentation Centre and scientific journals. Only results for which the materials and experimental protocols are described at least briefly have been included; this significantly reduced the number of documents that were used in this survey. In addition, we were interested in non-stabilized earth exclusively, which disqualified a great portion of the scientific data available.

2. DRY DENSITY

The dry density of soil is the ratio between its mass and its volume measured in the dry state, after oven drying at 105°C. This property depends on several parameters, dealing mainly with grain-size distribution, the volume and nature of the binding phase, the water content involved in the implementation of the earthen materials, and the energy involved in compaction of earthen materials compacted for building purposes.