Construction and Building Materials 30 (2012) 389–399

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Traditional braces of earth constructions

Quiteria Angulo-Ibáñez *, Ángeles Mas-Tomás, Vicente Galvañ-LLopis, José Luis Sántolaria-Montesinos

Department of Architectural Constructions, Polytechnic University of Valencia, Camino de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Received 2 September 2011
Received in revised form 5 October 2011
Accepted 24 November 2011
Available online 30 December 2011

Keywords:
Earth
Adobe
Rammed earth
Wall
Traditional
Structure
Braces
Reinforcement
Stiffen

ABSTRACT

This paper studies the structural performance of various traditional brace solutions for walls in soil based construction comparing systems used in Spain with the most representative from Peru, Chile, Brazil, Morocco, Mexico, Cuba and others. A unique model for similar loads, seeing the differences to be analyzed, compared and later used in new construction (sustainable and low cost architecture) and rehabilitation. It covers both the ineffectiveness of certain braces (*Buttresses and increased inside corners*); increments with *wooden beams embedded* and *Tiranta aspada*, and the significant improvements of others, such as ring beams, ashlars or reeds lattice to prevent the collapse of the soil based constructions against the horizontal forces of wind and earthquakes.

1. Introduction

The natural soil, earth, etc. is a building material which has been used for over 11,000 years. The city of Jericho, the Mesopotamian Ziggurats, Athens, the Great Wall of China and the Andean cities are historic examples of the use of earth as a construction material throughout the world. At present, it is estimated that over 30% of the world's population still live in houses built using soil systems, 50% of which represent third world countries [1–9].

In many developing countries there is a lack of housing and of construction material, resulting in the self-construction of a living space using surrounding materials such as earth and wood. Developed countries, under criteria of sustainability, are recovering ancient construction systems which, thanks to being cost effective, efficiently achieve the desired objectives.

This is why the understanding of how soil-based constructions work and behave is so important. Above all for the conservation and rehabilitation of the many existing World Heritage Sites, but also because of the necessity to construct new buildings in both developed and developing countries.

We must study the past; learn from the mistakes and implement the positives so that new technologies and materials will allow for a better existence in accordance with people's needs and the overall geo-environmental and development requirements such as safety and sustainability.

Structurally soil as a building material performs well against compression forces but has a low tensile strength. Therefore it is important to mold and condition the material towards compression and avoiding tensile forces. Another problem is the poor joining of rammed earth wall sections, and adobes and mortar. This means that any seismic activity could prove extremely dangerous for users if appropriate security measures are not taken. Improving soil for either adobe or rammed earth walls, will improve its characteristics and structural strength [10–17].

Another structural aspect of the construction design which is concerning is that usually in earth construction, floor slabs and roofs are not connected to walls with horizontal and vertical reinforcements. Due to this, the floor slabs or roofs do not connect directly to the framework and thus do not distribute pressure nor reinforce the building. Walls become independent structures positioned under external loads. This worrying issue of horizontal pressure is increased in areas of regular seismic activity.

Failures that lead to the collapse of soil based constructions due to external loads, in particular those made of adobe or rammed earth, usually occur as follows:

- The first failure is usually due to bending. The low tensile resistance of the soil causes the walls to detach from one another in the corners. Starting from the top, the walls become independent of each other; they become separate elements with no lateral stability.

* Corresponding author. Address: Departamento de Construcciones Arquitectónicas, Universidad Politécnica de Valencia, Camino Vera s/n, 46022 Valencia, Spain. Tel.: +34 650 31 23 13; fax: +34 963 87 74 59.

E-mail addresses: quianib@csa.upv.es (Q. Angulo), amas@csa.upv.es (Á. Mas), vgalvan@csa.upv.es (V. Galvañ), josanmo2@arqt.upv.es (J.L. Santolaria).

0950-0618/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.11.024

– The following failure is usually due to shear. If you control the joint between the walls and the possible failure of the corners, they better withstand horizontal pressures on the surface that could lead to failure by shear and in turn the appearance of diagonal cracks. In adobe walls, following the horizontal and vertical joints in a diagonal direction. In rammed earth walls, following the horizontal joints along the wall.
– Finally, failure due to overturning. Once the walls become independent (bending failure) or once they begin to crack and break (shear failure), they behave as independent rigid structures which solely rely on their own weight and strength against external pressures. If the acting momentum exceeds the resistant momentum, the wall or structure would collapse by falling off balance, and the roof on top of them could also fall down.

Depending on available materials and various weights to be borne during construction, different techniques and bracings systems have been developed all over the planet in an effort to solve these problems. These construction systems have adapted to a greater or lesser extent to the characteristics and the requirements of both the terrain and the users. Depending on success, power and communication they may have been globalized and exported to other locations or they may have remained local.

Currently, soil based constructions are being updated in areas of high seismicity to improve resistance against earthquakes. In addition to the improvement of earth characteristic and the traditional guidelines and bracing systems [6,18–29], other techniques and modern elements (not being studied in this paper) are being incorporated, even if this means extra cost and the acquisition of materials that are not always available:

– Columns and concrete beams as stiffeners reinforcements attached both horizontally and vertically with earthwork infill. A main structure of reinforced concrete with walls of rammed earth or adobe with a sealing function. The connection between the main structure and the earth walls to prevent walls collapsing, but not implicating the global collapse of the building, is very important [30].
– The integral masonry system, galvanized wire braided in the form of truss in walls and slabs [31–36].
– Plastering the walls with reinforced mortar or geogrid or wire mesh and cement mortar [37–54].

The objectives of this study is to analyze various traditional systems of bracing earth constructions and their influence in the response to the stresses that occur throughout the life of a building.

There is no point in making an exhaustive calculation of different braces under specific loads, but an analysis of their performance in terms of the traditional design of a single model and with the same loads is the appropriate option. This method allows qualitative and quantitative comparison, therefore it is necessary to perform some structural calculations.

In conclusion, it aims to assess the braces tested in accordance with the structural benefits they provide and make some constructive recommendations arising from its application.

2. Calculation methods: description of the model, materials and loads

The calculation uses a scalar damage model for frictional plastic materials, with a program developed by the Polytechnic University of Valencia (see Acknowledgements). In the CID, structural analysis program for CAD environments building structures, an application has been implemented of the isotropic damage model developed in the last two decades. This application is based on damage mechanic, which is part of internal variables that introduce microstructural changes in the behavior of materials, modeling the influence of history of material behavior in the evolution of stresses. With the proper definition of the damage function representing the material response in compression and tension, you can model the nonlinear behavior of the earth using the damage theory. The appearance of cracks and their evolution over time describe trajectories of several damaged spots, represented as an effect of local damage in terms of material parameters and functions that control the progression of damage to the successive state of tension at each point. This application has been calibrated with several works and studies as well as existing physical elements [55–61].

The typological model is a traditional house with two floors above ground of 7.20 × 9.20 m (facade × dividing wall) and load-bearing wall parallel to facade for supporting floor slab and ridge beam. Load-bearing walls are rammed earth wall and/or adobe 40–60 cm thick depending on their slenderness and loads. Floor slab with wooden struts 15 cm diameter every 50 cm with infill support of vault loam (adobe bricks and loam) or wattle and mortar on top of the beams. Pitched roof made with logs, wattle and clay tiles supported on the load-bearing walls (facade and intermediate wall). Ground height of 3.90 m and 6.00 m ridge. The height of ground floor is 2.5 m.

The structural model is discretized with finite hexahedral solid elements (volumetric) for earth walls and finite bar elements (linear) in order to replace beams and braces supported at the solid nodes and substituting floor infill for the appropriate loads. Model has 1.972 hexahedron of 0.20 × 0.40 × 0.40 m per side with 8 nodes each, 61 bars for roof and slab beams and 9 bars for lintels.

The soil based constructions to be analyzed are adobe and rammed earth walls. Both types of construction have the same building solutions and same struts are applied, as they have the same physical–mechanical characteristics and suffer the same type of pathology and collapse. Although they have perform slightly differently because of their different systems (the rammed earth walls are constructions made with "homogeneous" material whereas adobe is composed of smaller pieces joined together; they have been modeled as a single homogeneous material since their overall performance is similar. Therefore, although models have been discretized as mud walls without joints, they can be compared to adobe walls.

This paper does not take into account different variants of rammed earth walls depending on their material and composition as it seeks to analyze the influence of different bracing solutions in soil based construction. For the same reasons, this paper does not study other traditional systems such as wattle and daub, textile wall elements filled with earth, and direct forming with wet loam. Wattle and daub, thanks to their lightness and flexibility of materials (rods and branches) prove to be a good solution in areas of high seismicity risk.

The analysis adopts media and general physical–mechanical characteristics for earth material, without material implements neither composition. A unique model with same characteristics and loads for all braces for having an appropriate comparison.

Earth characteristics of the corners elements were defined with less mechanical resistance because of the difficulty of creating the corners inside the frameworks and/or poor joints with vertical recess solution. Middle and conservative physico-mechanical properties has been adopted for materials from the results of tests (from La Manchuela, Albacete, Spain) and literature [6,18,62–71] (Table 1).

For the hypothesis of loads and load combinations we have adopted the values of official documents and regulations:

– Selfweights loads: values from the tests results.
– Live loads: based on current Spanish law [72].
– Earthquakes: according to the Spanish law [73]. Values have been taken to analyze worst possible result, although this legislation would prevent the construction of soil based buildings under such conditions.

In the process of calculation three methods were employed:

– Linear static calculation: based on the assumption of linear elastic performance of materials and taking into account the balance of the structure without becoming deformed. Loads and load combinations are considered for the two main directions.
– Nonlinear static calculation: this takes into account the stress–strain performance of nonlinear material and geometric nonlinearity, i.e. achieving balance of the structure in its deformed state. We analyzed four independent load combinations for the two main directions, introducing proportional increases in 20 loads, taking into account geometric variations and materials:
– Gravitational loads (selfweights and live loads) without majority.
– Gravitational loads (selfweights and live loads) and horizontal (wind) without majority.
– Gravitational loads (selfweights and live loads) to collapse.
– Gravitational loads (selfweights and live loads) and horizontal (wind) to collapse.
– Dynamic–seismic calculation, we have analyzed two equivalent static load combinations for earthquakes for the two main directions of the model.

3. Traditional analyzed braces

Before description of analyzed braces for earth construction, we should highlight some basics concepts about the design, construction and maintenance of earth buildings. Although not the objec-