Analysis of the mechanical behavior of adobe walls without reinforcement through computational modelling

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Abstract. The construction of civil structures on land has played an important role for centuries, however, due to the seismic requirements and the minimum safety standards that are currently required for any structure, this type of construction has been lagged, it is denoted that the related regulations they are widely dispersed and in most cases. In developed countries, numerous technical and legal problems arise to carry out construction with these materials. In relation to this work, a set of models of raw earth type walls are presented, through the SAP 2000 software, having as a supply of the mechanical properties of this material the Peruvian regulation E.080. For the analysis of these models, a static linear analysis for finite elements and a stress analysis of the service limit state concept were studied. Finally, the models with their respective stress studies, management and design recommendations are presented under the criteria of the analyses carried out, leaving open the possibility of both carrying out an experimental phase to develop the analogy with the postulates and proposed results, as well as such as the option to perform a static pressure analysis by finite elements in order to achieve greater precision and calibration of the model with respect to what can be evidenced in laboratory tests.

1. Introduction

Raw earth as a building material is an alternative that dates back from the beginnings of humanity to the present day, currently it has been gaining strength as more and more sustainable and ecological constructions are required. In countries with scarce resources and with great housing needs, it is still the best option due to the facilities offered by this material to get rid of it and its low cost, which is why it is listed as the most important construction material in many regions of the world [1]. However, the disadvantages and shortcomings that appear in this material continue to be an impediment to a greater implementation of this type of construction, since it is a fragile material, with little resistance to traction, and its heterogeneity gives rise to great uncertainty regarding the guarantee of seismic resistance that they can offer [2].

This fact is aggravated by the lack of standards that specify the techniques of obtaining, preparation and construction with raw earth, the knowledge that is currently being implemented is in some cases purely empirical. In relation to the above, the following work is presented that allows to deepen and determine the behavior before seismic requests of civil constructions on land under this type of materials. For this purpose, a static analysis is presented by means of the finite element technique for the stresses of the wall in the face of the established gravitational load stresses. Also, a verification of the conditions with which the admissible capacity is met.

Finally, the results obtained are presented through synthesized tables and images of the trend of failure of the behavior of adobe-type walls in the face of design efforts, highlighting the maximum stress...
values of the wall; An estimate of the percentage of failure that adobe walls can present is also presented, serving as a reference for the validation of the functionality of this type of elements.

2. Method

After drawing the walls in the SAP 2000 structural modelling software [3], the study of these was carried out using the finite element technique. For this purpose, the description of the boundary conditions, application of loads, definition of geometric elements for meshing and mesh size was carried out. The use of finite elements is based on the discretization of walls, however, from the mathematical point of view this method can have a high degree of complexity, which is why certain requirements for proper functioning were considered, such as continuous functions under a global domain that can approximate a series of functions that operate under a finite number of smaller subdomains called elements [4].

The principle of virtual jobs is the equivalent of posing the equilibrium equations of the system, where we consider that each part of the wall is a solid body that occupies a volume V in an instant of time t and is subjected to forces \( b(x,t) \), which act on the contour \( \Gamma_\sigma \) and on the displacements on the contour \( \Gamma_u \). The action of these forces produces in the pieces a field of displacements \( u(x,t) \), of deformations \( \epsilon(x,t) \) and of stresses \( \sigma(x,t) \), the above is expressed by Equation (1).

\[
\int_V \delta \epsilon^T \sigma dV = \int_V \delta u^T b dV + \int_{\Gamma} \delta u^T t d\Gamma,
\]

where, \( \delta \epsilon \) is the virtual field of deformations (Equation (2)), which in tensor notation is defined in Equation (3).

\[
\delta \epsilon = [\delta \epsilon_x \ \delta \epsilon_y \ \delta \epsilon_z \ \delta \epsilon_{xy} \ \delta \epsilon_{xz} \ \delta \epsilon_{yz}]^T,
\]

\[
\epsilon_{ij} = \begin{bmatrix}
\frac{1}{2} \gamma_{xy} & \frac{1}{2} \gamma_{xz} & \frac{1}{2} \gamma_{yz} \\
\frac{1}{2} \gamma_{zy} & \frac{1}{2} \gamma_{zx} & \frac{1}{2} \gamma_{yz} \\
\frac{1}{2} \gamma_{zx} & \frac{1}{2} \gamma_{zy} & \frac{1}{2} \gamma_{xz}
\end{bmatrix}.
\]

In the Equation (3), \( \epsilon_x, \epsilon_y, \epsilon_z \) are part of the main diagonal of the strain tensor and are called longitudinal deformations, as well as \( \gamma_{xy}, \gamma_{xz}, \gamma_{yz} \), which lie outside the main diagonal and are called tangential deformations or shear. Also, \( b = [b_x, b_y, b_z] \), these are the mass and surface forces which exert forces at a distance on the particles inside the continuous medium, such as gravity, inertia, etc.

In addition, the surface forces act on the contour of the volume of each element considered in the analysis, produced by the contact of the particles of the elements with the outer environment where they are located, and \( t = [t_x, t_y, t_z] \), is the former is the traction vector. In the Equation (1), the term of the stresses is considered, and the elements are considered to act on the forces and surface. Taking a differential in each of them in the form of a cube one can have the Cauchy stress tensor, which is defined by Equation (4).

\[
\sigma = \begin{bmatrix}
\sigma_x & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_y & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_z
\end{bmatrix}.
\]

Finally, \( \sigma_x, \sigma_y, \sigma_z \) are the elements of the main diagonal of the stress tensor and are called normal stresses, \( \tau_{xy}, \tau_{xz}, \tau_{yz} \), as well as the previous ones that are outside the main diagonal and are called tangential stresses or shear [2].

3. Simulation of the model

For static analysis by means of the finite element method it is necessary to define a meshing from the geometric information by means of the discretization of finite elements with tetrahedral solid
elements [4]; to achieve a correct modelling, it was necessary to obtain the material data that are evidenced in Table 1, such as the ranges for the mechanical properties of adobe masonry, and the resistance of adobe walls without reinforcement; for this we resorted to the standardized values of the Peruvian standard E.080 [5]. For the Poisson value it was considered that for concrete it is 2.0, therefore, it was concluded that an adequate value would be lower than this, since adobe is less resistant [6,7].

To carry out the modelling, the following considerations were considered, one of them is that, for the analysis and implementation of the finite element technique, it must consider the earth as an isotropic and homogeneous material, however, it is clarified that the earth is an anisotropic and heterogeneous material [2,4]. The results of the analysis are presented in Table 2, Table 3, Table 4 and Table 5; for this purpose, a specific nomenclature will be used; F1 corresponds to the upper left corner; F2 corresponds to the top right corner; F3 corresponds to the lower left corner; F4 corresponds to the lower right corner; and FC corresponds to the center.

Table 1. Features and mechanical properties of adobe.

| Properties               | MPa | KN/m³ |
|--------------------------|-----|-------|
| Modulus of elasticity    | 200 |       |
| Specific weight          |     | 17    |
| Compressive strength     | 0.4 |       |
| Tensile strength         | 0.03|       |
| Poisson                  |     | 0.15  |

3.1. Model type 1: axial X-Y directions stresses
The model 1 wall with dimensions of 2.8 m × 2.8 m × 0.4 m, has a discretization area equal to the number of finite elements for a square mesh equal to 1600 units, with a load of 1 ton equally divided between the nodes of the upper part of the model of the wall without reinforcement, as shown in Figure 1 for the X direction and in Figure 2 for the Y direction. In the study, it was performed with a rigid floor with the same upper horizontal displacement [6,7].

Table 2. Results analysis of axial forces in the X direction for the type 1 wall.

|           | Minimum (T/m²) | Maximum (T/m²) |
|-----------|----------------|----------------|
| F1        | 0.19           | 1.33           |
| F2        | 0.13           | 1.14           |
| F3        | 0.13           | 0.5            |
| F4        | 0.19           | 0.9            |
| FC        | = 0            | ≈ 0            |

Table 3. Results analysis of axial forces in the Y direction for the type 1 wall.

|           | Minimum (T/m²) | Maximum (T/m²) |
|-----------|----------------|----------------|
| F1        | 0              | 2              |
| F2        | 0.9            | 2.2            |
| F3        | 4.2            | 7.2            |
| F4        | 4.0            | 8              |
| FC        | = 0            | ≈ 0            |
3.2. Model type 2: axial X-Y directions stresses

The model 2 wall with dimensions of 2 m \times 2 m \times 0.4 m, has a discretization area equal to the number of finite elements for a square mesh equal to 1600 units, with a load of 1 ton divided equally between the nodes of the upper part of the wall model, no reinforcement, as shown in Figure 3 for the X direction and in Figure 4 for the Y direction, respectively. In the study, it was performed with a rigid floor with the same upper horizontal displacement [6,7].

![Figure 3. Axial stresses direction X (T/m²).](image)

![Figure 4. Axial stresses direction Y (T/m²).](image)

| F1 | 0.4 | 2.4 |
|----|-----|-----|
| F2 | 0.35 | 2.4 |
| F3 | 0.35 | 0.9 |
| F4 | 0.4 | 1.8 |
| FC | ≈ 0 | ≈ 0 |

| F1 | 0.0 | 4.6 |
|----|-----|-----|
| F2 | 2.5 | 4.8 |
| F3 | 7.8 | 13.3 |
| F4 | 7.9 | 16.0 |
| FC | ≈ 0 | ≈ 0 |

3.3. Service limit state review

The service limit state according to the NSR-10 title, is a condition which allows to determine if one or more elements of a structure can fulfill its function [8,9], for this the value of the admissible effort must be obtained, calculating the ultimate effort according to the characterizations regarding the mechanical properties of adobe established in the Peruvian standard E.080 [5] and taking into account a safety factor of 2.5, which considers a threshold in terms of quality of the material, execution and other parameters. The stress values produced by the model throughout its area are compared with the allowable stress value, to determine the percentage of the structural element that is going to lose functionality or deteriorate [10-12].

| Parameter          | Allowable stresses (T/m²) |
|--------------------|---------------------------|
| Compressive strength | 2.71                      |
| Tensile strength   | 0.38                      |

4. Conclusions

Considering the characterizations regarding the mechanical properties of adobe established in the Peruvian standard E.080, the efforts of the type walls could be obtained through modeling in SAP 2000, reviewing the recommended limits so that a structure can maintain its functionality. It was established that the percentage of failure presented to the applied loads is 60% with respect to the failure threshold.
without presenting collapse that is given by a value of 40%, which allows to show that when exceeding this range this element will fail. On the other hand, it was observed that the type 1 wall presents a better behavior and functionality before the compression, traction, and shear efforts. Therefore, it is concluded that the larger the dimensions, the better the mechanical behavior of the wall; thanks to this, it is possible to better understand the reason for the considerable dimensions of this type of structures.

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