Seismic Analysis of a Rammed Earth Building

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Abstract

In this paper, a study for the seismic analysis of a rammed earth building will be presented. The Portuguese continental territory is a space that presents a high seismic risk, so the seismic vulnerability of this type of structures is a very relevant problem.

For this study a building was created with the current typology of this construction type, with only a floor and walls of several dimensions, chosen to be used as a prototype for analytical purposes. The main stresses acting in these structures are identified and analysis models are created for the evaluation of each one of these stresses.

Some reinforcement methods are also tested, to solve some of the problems that appeared in the analysis made.

1. Introduction

The construction with raw earth is a very old technique that has been coming gradually to disappear. In Portugal, the earth construction also has a great tradition. In the last decades, these traditional techniques have been coming to be substituted for others that use new constructive materials. However, the rammed earth has been gaining new followers in the last years, especially in the South of the national territory.

It is quite probable that earthquakes of great destructive potential happen in the future in Portugal. The most part of the old rammed earth constructions and the ones built in our days are located precisely in the national territory areas of higher seismic risk.

This study pretends to contribute for the approach development of the structural analysis of rammed earth buildings and, at the same time, for the definition of a building model, whose structural characteristics guarantee his safety in case of seismic occurrence.

The study that is present here just contemplates the rammed earth constructive technique of the new constructions without the use of concrete vertical elements. The reinforcement and rehabilitation of existent buildings are out of scope.

Another concern in this study is the urgent need of creating regulations for the seismic resistant earth construction, just as they already exist at other countries.

2. Rammed Earth Construction in Portugal

In Portugal, among the main traditional techniques of earth construction, the rammed earth is, probably, the more disseminated. The rammed earth term has been traditionally used to denominate indistinctly the material and the construction process, that basically consists in the execution of great blocks of earth moulded and compacted inside the formwork (Figure 1) [Rocha, 2005].

In Alentejo, the traditional rammed earth house generally presents a simple and rectangular plant and has only one floor. The thickness of the walls is usually 50cm, increasing only in the case of higher buildings.

The walls’s footing used to be in stone, normally with 30 to 50cm height and with the same thickness of the walls. Today, these foundations are frequently executed in concrete with approximately the same dimensions. The wall blocks are built over these foundations in successive rows until it reaches the intended wall height.
The roofs have low slope and are supported by a wooden structure. Usually the Portuguese tile (Lusa) is used [Correia e Merten, 2005].

The mechanical performance of the soil is the parameter that has larger influence in the resistance of a construction with raw earth. The most important components of the earth are clay, sand and silt. To improve the mechanical behaviour, the soil can be stabilized with the addition of lime, cement or both.

3. Modelling of the Rammed Earth Building

To test the resistance of a rammed earth construction to seismic action it was opted to model a building in the program SAP2000 to perform a three-dimensional dynamic analysis. A building was conceived with the help of Architect Henrique Schreck, with just a floor and walls of several dimensions, presented in the Figure 3.

The walls were modelled with a thickness of 50cm, because this is the value that is commonly used for buildings with only one floor. The remaining dimensions of the building are presented in the analysis results (Tables 4 and 5).
Seismic Analysis of a Rammed Earth Building

Figure 3 Analysed Building: plan (on the left) and perspective (on the right), Architect Henrique Schreck’s drawings.

Material Properties

The rammed earth is an isotropic material of poor quality because of its reduced mechanical resistance and its fragile behaviour. The ideal form of determining the properties of this material would be through laboratory tests, but that wasn’t possible to accomplish.

Table 1 Material properties values introduced in the program.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass per Unit Volume $\rho$ [ton/m$^3$]</th>
<th>Weight per Unit Volume $\gamma$ [kN/m$^3$]</th>
<th>Modulus of Elasticity $E$ [MPa]</th>
<th>Poisson’s Ratio $\nu$ [-]</th>
<th>Damping $\zeta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rammed Earth</td>
<td>2,04</td>
<td>20,00</td>
<td>300,00</td>
<td>0,20</td>
<td>5,00</td>
</tr>
<tr>
<td>Concrete (C25/30)</td>
<td>2,55</td>
<td>25,00</td>
<td>30500,00</td>
<td>0,20</td>
<td>5,00</td>
</tr>
</tbody>
</table>

Table 1 shows the material properties values used in the analysis. This rammed earth data was based on international standards that supply reference values or define expressions to calculate these parameters [Parreira, 2007]. For the definition of the concrete characteristics common properties were used.

Model Development

The modelling of the several components of the building was carried out using two different finite elements available in the program SAP2000. Each component of the building was modelled with the element that presented the most appropriate behaviour. Three-dimensional elements were used (solid) to model the rammed earth walls with 50cm of thickness and, bar elements (frame) were used to model the concrete bond beams with the same thickness of the walls and with 20cm height (Figure 4).

Figure 4 Mesh of finite elements in the walls (on the right) and the several finite elements used in the building modelling (on the left).

The definition of two different elements for the building modelling was necessary to solve some problems to obtain a compatible mesh of finite elements. The main problem was the connection of the wall and the bond beam that was solved with the use of a frame element, denominated “Rigid Beam”. However, using only the solid elements it is already difficult to make a compatible mesh (Figure 4) [Parreira, 2007].
The footings were not introduced in the model, because this element is located near the floor level, so it would have small influence in the obtained results of the seismic analysis. Therefore, the walls were modelled as fixed in the base and linked to the bond beam in its tops (Figure 5).

The roof and its structure were also not modelled. However, their effect was simulated with the introduction of loads and masses along the bond beams. The roof was assumed to be composed by Portuguese tile (Lusa) on a wooden structure. The value taken for its action was 0.7kN/m². In the model only the roof vertical actions were introduced, assuming that the horizontal actions are supported by the wooden structure of the roof [Parreira, 2007].

The doors were modelled with approximately 2m height and 1m wide. The windows were modelled as square with 1m each side (Figure 5). Any elements were introduced in the model to simulate the lintels effect.

The modelling of the building walls would be much easier and fast with the use of plane elements in alternative to the three-dimensional elements (solid). However, the solid element has the big advantage of allowing the visualization of the tensions distribution along the wall’s thickness that is essential to understand its operation. Thus, the difficulties during the elements modelling process were rewarded.

4. Analysis of the Building Seismic Vulnerability

The seismic vulnerability of the rammed earth buildings can be considered as one of the most important subjects and one that raises a lot of doubts about the structural safety of this construction type.

Seismic Action

The evaluation of the seismic response was based in a modal analysis with response spectrum. It was just considered in the analysis the Seismic Action Type 1, defined in the Portuguese Code (RSA) [RSA, 2005] and it was also considered that the building is located in the Seismic Zone A (RSA). The damping was admitted as 5% and a Soil Type II too (RSA). In the calculation analysis it was not considered the vertical seismic action and the structural ductility factor was taken as 1 (RSA).

Combinations

The other considered actions were the walls weight ($PP_{Walls}$), the bond beams weight ($PP_{Beams}$) and the roof weight ($PP_{Roof}$). It was not considered in the analysis any live load. The used combinations were conducted according to the Ultimate Limits States verification in agreement with RSA. A Combination 1 was created representing the permanent loads action ($CP$) and were also created other two combinations simulating the seismic action in different directions: Combination 2 – X direction and Combination 3 – Y direction (Table 2).

<table>
<thead>
<tr>
<th>Combination</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 1</td>
<td>$CP = 1 \times PP_{Walls} + 1 \times PP_{Beams} + 1 \times PP_{Walls}$</td>
</tr>
<tr>
<td>Combination 2</td>
<td>$Earthquake , X = 1.5 \times Action , X + 0.3 \times (1.5 \times Action , Y)$</td>
</tr>
<tr>
<td>Combination 3</td>
<td>$Earthquake , Y = 0.3 \times (1.5 \times Action , X) + 1.5 \times Action , Y$</td>
</tr>
</tbody>
</table>
Rammed Earth Mechanical Properties

The definition of the mechanical characteristics of the material is also fundamental to assure the quality of the analysis made. The adopted value for the compressive strength was 1MPa [Bastos, 2007]. The remaining mechanical characteristics and also the Modulus of Elasticity were determined through expressions defined in the New Zealand standards [NZ 4297, 1998] and they are presented in the Table 2.

<table>
<thead>
<tr>
<th>Strength Parameter</th>
<th>Value [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{C,Rd}$ - Compressive strength (flexural or direct compression)</td>
<td>1000</td>
</tr>
<tr>
<td>$\sigma_{T,Rd}$ - Flexural tensile strength</td>
<td>$0.10 \times \sigma_{C,Rd} = 100$</td>
</tr>
<tr>
<td>$\sigma_{V,Rd}$ - Shear strength</td>
<td>$0.07 \times \sigma_{C,Rd} = 70$ or $(70 + 5 \times h)$</td>
</tr>
</tbody>
</table>

$h$ – wall height (in meters)

Stresses Identification

The main stresses due to seismic action that affect the rammed earth wall are the stresses due to flexure and shear forces (Figure 6). The flexure can be separated in two different effects: the horizontal bending ($M_{\text{horizontal}}$) and the vertical bending ($M_{\text{vertical}}$). Similarly, the shear forces can also be distinguished in two components: longitudinal shear ($V_{\text{Longitudinal}}$) and the transversal shear ($V_{\text{Transversal}}$).

All the safety verifications in this study were made based upon tension analysis. The stress due to the horizontal bending ($M_{\text{horizontal}}$) can be obtained through the tensions $\sigma_{33}$ (Figure 6). The values of the stresses due to the vertical bending ($M_{\text{vertical}}$), in the case of a wall along the X direction, are obtained through the tensions $\sigma_{11}$ (Figure 6) and if the wall in analysis is along the Y direction, the tensions related with this stress are the tensions $\sigma_{22}$.

In case of shear, the tensions that are related with each of the two components of this stress ($V_{\text{Longitudinal}}$ e $V_{\text{Transversal}}$) also diverge according to the wall orientation (Table 3).

<table>
<thead>
<tr>
<th>Wall Orientation</th>
<th>$V_{\text{Longitudinal}}$</th>
<th>$V_{\text{Transversal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$\sigma_{13}$</td>
<td>$\sigma_{23}$</td>
</tr>
<tr>
<td>Y</td>
<td>$\sigma_{23}$</td>
<td>$\sigma_{13}$</td>
</tr>
</tbody>
</table>
**Stress Analysis Models**

The stress analysis was based in the elastic response of the rammed earth walls. The design tension was obtained through the analysis model of each stress and it was compared with the resistant tension to verify the resistance Ultimate Limits States. The structure absolute value tensions due to seismic action were determined through the program model.

The horizontal bending in the rammed earth walls is composed by the simultaneous action of bending and compressive forces. In the tension analysis due to horizontal bending (σ₃₃) it was opted to separate the tensions originated by the permanent loads (σ₃₃,CP) of the tensions originated for the seismic action (σ₃₃,S) as the outline of the Figure 7 shows.

![Figure 7 First analysis model of the tensions due to horizontal bending.](image)

The compression (σ₃₃,Cd) and tensile (σ₃₃,Sd) design tensions were calculated and two safety checks were done, one due to compression and other due to flexural tensile (Figure 7).

In the case of the horizontal bending, a second analysis model was defined to use if the safety wasn’t verified by the first analysis model previously described. In this new model it is assumed that the wall partially cracks and the action is balanced just with the compressive tensions (Figure 8).

![Figure 8 Second analysis model of the tensions due to horizontal bending.](image)

After the calculation of several parameters it is necessary to verify two different criterions so that the walls safety, in agreement of the Ultimate Limits States, be guaranteed [Parreira, 2007]:

**Criterion 1:** e ≤ t/2  
**Criterion 2:** σ₃₃,Cd ≤ σ₃₃,Rd

If the Criterion 1 fails automatically flaw the Criterion 2. Passing the Criterion 1, it can or not to verify the Criterion 2.

In case of the vertical bending, the existent compression tensions (σ₁₁,CP) due to the permanent loads are almost zero. These tensions were ignored and a simple bending analysis was made, just considering the tensions with origin in the seismic dynamic action (σ₁₁,S). Two verifications were made:

Walls oriented second X direction:  σ₃₃,Sd = σ₁₁,S ≤ σ₃₃,Rd

Walls oriented second Y direction:  σ₃₃,Sd = σ₂₂,S ≤ σ₃₃,Rd

![Figure 9 Analysis model of the tensions due to vertical bending.](image)
The shear analysis was done in a global way in each wall. The values for this analysis were taken in several points along a longitudinal line of the wall plan. With these values an average value for the longitudinal direction was obtained ($\sigma_{V,L}$ - obtained by the seismic action in the walls longitudinal direction) and other for the traversal direction ($\sigma_{V,T}$ – result of the seismic action in the perpendicular direction to the wall plan). The following verifications were made:

- Longitudinal shear: $\sigma_{V,L} \leq \sigma_{V,Rd}$
- Transversal shear: $\sigma_{V,T} \leq \sigma_{V,Rd}$

An analysis was made to the slide between the rammed earth wall and the bond beam, based upon the analysis model of a footing’s slide. This analysis was based on the comparison between the shear forces in this interface ($V_{sd}$) and the resistant attrite force ($F_{Ra}$). The shear tensions ($\sigma_{V,L}$ e $\sigma_{V,T}$) and the local compression tension due to the permanent loads ($\sigma_{33,CP}$) were obtained with the same method used for the shear analysis [Parreira, 2007]. The static friction coefficient ($\mu$) was taken as 0,4. So, the following verification was done:

$$V_{sd} \leq F_{Ra} \leftrightarrow \sigma_{V} \leq \mu \times \sigma_{33,CP}$$

### Analysis Results

![Figure 10 Outline of the walls identification (dimensions in meters).](image)

All the walls were subjected to the tensions analysis in agreement with the analysis models previously explained. It was attributed to the walls oriented according the X direction the designation of "Wall Xi" and the walls oriented according the Y direction the designation of "Wall Yi" (Figure 10).

Every building walls were analyzed in terms of bending, shear and slide in the rammed earth wall-bond beam connection (Tables 4 and 5).

Table 4 Summary results of the verifications done in the walls oriented according to the X direction.

<table>
<thead>
<tr>
<th>Wall</th>
<th>$L$ [m]</th>
<th>$h$ [m]</th>
<th>$M_{Horizontal}$</th>
<th>$M_{Vertical}$</th>
<th>$V_{Longitudinal}$</th>
<th>$V_{Transversal}$</th>
<th>Wall-Bond Beam Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>7,00</td>
<td>3,00</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>X2</td>
<td>7,00</td>
<td>4,50</td>
<td>Don’t Verify</td>
<td>Don’t Verify</td>
<td>Don’t Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>X3</td>
<td>7,00</td>
<td>3,00</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>X4</td>
<td>5,00</td>
<td>3,00</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>X5</td>
<td>5,00</td>
<td>4,50</td>
<td>Verify</td>
<td>Don’t Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>X6</td>
<td>5,00</td>
<td>3,60</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Don’t Verify</td>
</tr>
</tbody>
</table>
Table 5 Summary results of the verifications done in the walls oriented according to the Y direction.

<table>
<thead>
<tr>
<th>Wall</th>
<th>(L) [m]</th>
<th>(h^*) [m]</th>
<th>(M_{Horizontal})</th>
<th>(M_{Vertical})</th>
<th>(V_{Longitudinal})</th>
<th>(V_{Transversal})</th>
<th>Wall-Bond Beam Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>5.00</td>
<td>3.75</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y2</td>
<td>5.00</td>
<td>3.75</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y3</td>
<td>5.00</td>
<td>3.75</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y4</td>
<td>3.00</td>
<td>4.05</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y5</td>
<td>2.00</td>
<td>3.30</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y6</td>
<td>5.00</td>
<td>3.75</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
<tr>
<td>Y7</td>
<td>3.00</td>
<td>4.05</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
<td>Verify</td>
</tr>
</tbody>
</table>

\(h^*\) - walls medium height

The stresses that control the wall’s structural safety of this kind of construction are mainly due to horizontal bending, vertical bending and also the shear forces in the longitudinal direction of the walls. The values of the bending stresses basically vary according to the wall dimensions namely with the wall’s free length and with their height.

The longitudinal shear stresses in a wall depend essentially of the number of walls that it braces that is the number of walls that intersect it. The resistant shear capacity of the walls is larger as minor is the openings area. So the resistance problems of a building to the seismic action are essentially due to the distribution of the elements in plan and to the walls height.

This study also points out that the use of bond beams over all building walls with structural function is essential. These elements besides increasing the wall’s stiffness to the vertical bending are also fundamental to make the displacements between the several walls compatible, guaranteeing that the whole building has a compatible movement.

It is also concluded that the connection between the walls and the bond beam can be a serious problem. The link between bond beams and the link between the walls themselves should be executed with precaution because it is essential for a better global behaviour of the structure to the seismic action.

5. Reinforcement Solutions

After the analysis conclusion, it was verified that this rammed earth building presents some resistance problems when subjected to the seismic action. Some of them can be solved with the implementation of several reinforcement solutions.

Wall-Bond Beam Connection

The main problem detected is the failure to comply with the safety verification of the slide between the rammed earth wall and the bond beam (Tables 4 and 5). The best solution found to solve this problem comes enunciated in international standards that recommend the use of anchor bolts in the connection of these two elements.

![Figure 11 Reinforcement of the rammed earth wall and bond beam connection with anchor bolts (dimensions in meters).](image)
**Lintels**

In the rammed earth construction is usual the use of small lintels on the openings. The objective of this study was the verification of the structural influence of these elements in the building resistance to the seismic horizontal action.

The chosen wall for this analysis was the Wall X5 that verifies the safety verifications in all analyzed stresses in exception of the vertical bending (Table 6). The lintel used was a concrete element with 20cm of height and with the wall’s thickness (50cm).

<table>
<thead>
<tr>
<th>Study Case</th>
<th>$L$ [m]</th>
<th>$h$ [m]</th>
<th>$M_{\text{Vertical}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall X5 - Without lintel on the opening</td>
<td>5.00</td>
<td>4.50</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>Wall X5 - With lintel on the opening</td>
<td>5.00</td>
<td>4.50</td>
<td>Verify</td>
</tr>
</tbody>
</table>

With the lintel on the opening, the Wall X5 already passes the vertical bending verification (Table 6). The concrete lintel is a much more rigid element than the rammed earth wall so it absorbs great part of the bending stresses, that before were supported only by the earth wall.

Just as in the case of the rammed earth wall and bond beam connection it was also detected problems in the lintel and wall connection. Then the solution pointed for the resolution of this problem is the same, which is the use of anchor bolts.

**Bond Beams**

To better understand the structural influence of the bond beams it was created a new model with bond beams of 40cm of height and with a thickness of 50cm. The study done was based on the comparative analysis of the vertical bending in the Wall X5 between the initial model and this second one (Table 7).

<table>
<thead>
<tr>
<th>Study Case</th>
<th>$L$ [m]</th>
<th>$h$ [m]</th>
<th>$M_{\text{Vertical}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall X5 - Initial Model (B. B. 0.2x0.5m$^2$)</td>
<td>5.00</td>
<td>4.50</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>Wall X5 - Second Model (B.B. 0.4x0.5m$^2$)</td>
<td>5.00</td>
<td>4.50</td>
<td>Verify</td>
</tr>
</tbody>
</table>

This wall in the initial model didn’t pass the vertical bending verification but with this second model the Wall X5 already passes (Table 7). It is verified that as a consequence of the placement of a bond beam, with larger stiffness (bigger inertia), the vertical bending stresses globally reduce in this wall.

**Buttresses**

A typical aspect of the rammed earth constructions is the frequent use of buttresses. In this work it was studied the utility of these elements when the structure is subjected to the seismic action. To make this study, a comparative analysis between the Wall Y1+Y2 (10m of free length) with and without buttress was made.

Figure 12 A buttress (on the left), building model with buttress in the Wall Y1+Y2 (on the centre) and outline of the buttress with the used dimensions, in meters (on the right).
Table 8 presents the results from the stress verifications of the horizontal and vertical bending obtained for the Wall Y1+Y2 with and without buttress. This wall without buttress has some problems in terms of flexure that are resolved with the placement of a buttress in the middle of the free length of the wall.

Table 8 Verifications results in the Wall Y1+Y2 with and without buttress.

<table>
<thead>
<tr>
<th>Study Case</th>
<th>$L$ [m]</th>
<th>$h^*$ [m]</th>
<th>$M_{\text{Horizontal}}$</th>
<th>$M_{\text{Vertical}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Y1+Y2 – Without Buttress</td>
<td>10,00</td>
<td>4,5</td>
<td>Don’t Verify</td>
<td>Don’t Verify</td>
</tr>
<tr>
<td>Wall Y1+Y2 – With Buttress</td>
<td>5,00</td>
<td>3,75</td>
<td>Verify</td>
<td>Verify</td>
</tr>
</tbody>
</table>

It was concluded that the use of buttresses in the intermediate area of rammed earth walls with elevated free length is a good solution to assure their stability to seismic action, because the buttresses work as bracing elements. However, it is important to guarantee that the buttress is well linked to the wall and that it presents enough resistance to guarantee its stability.

6. Conclusions

The main conclusion of this study is that it is possible to build rammed earth buildings with only a floor, which verify the resistance Ultimate Limits States defined in RSA. However, the rammed earth is a material with low mechanical resistance, so these buildings have limitations in the wall’s dimension and in its distribution in plan.

The reinforcement solutions studied: the use of lintels on the openings, the increase of the bond beam section and the use of buttresses, revealed to be very positive for the increase of the building structural resistance to the horizontal seismic actions.

The resurgence of the raw earth construction in Portugal, namely in rammed earth, force the urgent adoption of norms that serve as support to designers and builders, compliant with the national reality and its seismic risk.

References


