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RESEARCH ARTICLE

Performance Analysis of Wooden Reinforcement in Rammed Earth Walls

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Abstract
In diverse parts of the world there exist some building systems that are generated for structural and constructive response to the earth constructions. In particular, this article discusses about the perpendicular unions of the walls of rammed earth. This is why, after a brief description of the reinforcement system, its advantages and consequences are developed, compared to other reinforcement systems. In this way, quantitative conclusions are obtained, demonstrating the increasing global resistance of the wall corners compared to horizontal efforts (wind and earthquake) according to the constructive reinforcement system which does not have it. It has also been analysed the collapse of these walls facing gravitational and horizontal loads. The ultimate goal of this work is to preserve the cultural heritage, traditional construction systems and to apply them, by implementing actual improvements, to their recovery.

Keywords
rammed earth, traditional construction, perpendicular wall encounters

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1 Introduction

Land constructions have been used since antiquity in Spain with the arrival of the Romans [1]. It appears more often in the central and southern areas of the peninsula where the natural composition of the earth provides a strong base for its use in construction. The earth wall structures were present in all types of constructions, from defensive strongholds and public buildings to family homes and partition walls.

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 necessary thickness and the poor joining of rammed earth wall sections. This means that any horizontal action (wind and seismic activity) could prove extremely dangerous for users if appropriate security measures are not taken.

Another structural aspect of the construction design 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 also 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 [2]:

- 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.
- 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 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.

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 [3–4], other techniques and modern elements 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; the integral masonry system [5]; plastering the walls with reinforced mortar or geogrid or wire mesh and cement mortar [6].

Improving soil, will improve its characteristics and structural strength. Traditionally in Spain great improvements have been made to the behaviour of adobe walls by modifying its composition (adding lime) or by bettering the constructive method (steel wall, cemented wall, etc.) [7–8]. Although these improvements increase resistance in constructions, they do not provide the solution to the weakness caused by the lack of tensile resistance in the uppermost corners and the joints between walls. The solutions to this problem are three types of corner bracings: placing ashlars or rough stone into the corners in place of earth; using ring beams; embedding wooden struts into the walls.

Throughout the region of Albacete, Spain, they developed their own techniques for bracings which are traditionally used in family homes, the wooden reinforcement. In this article, we will analyse in detail this system and we will compare its resistance, structural behaviour, bracing systems, composition, materials, constructive solution and aesthetics against models where no bracing is used.

2 Wooden reinforcement

2.1 Description of the system

The performance analysis of the wooden reinforcement is being developed and expanded to bring an architectural, constructive and structural vision which allows us to make comparisons between different traditional systems of bracings for earth constructions. The wooden reinforcement is one bracing option for rammed earth structures common to the Albacete. It is usually used in corner buildings or blocks and on sloped ground in order to absorb the tensile pressure and the consequent movements between the corner walls. While the wooden reinforcement was only really seen in the Albacete region, the use of ashlars or rough stone into the corners, embedding wooden struts into the uppermost section of the corners and ring beams were the most common types of bracing systems used throughout the rest of Spain and Portugal where earth was used in construction. The system is made up of three elements: the reinforcement, the pins or arms which cross on the exterior and the wedge which hold them in place. It consists of reeling the walls together using wooden struts and pins on the exterior of the wall limiting their movement. This was thought up as a way of absorbing tensile pressure localised to the uppermost corners of the wall joints where no beams are found, taking advantage of the compression pressure exerted by the reinforcement and the pins (Fig.1).

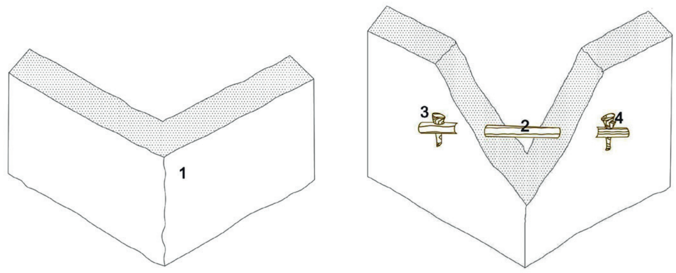

Fig. 1 Components of the wooden reinforcement system: 1.Earth wall – 2. Reinforcement – 3.Pin – 4.Wedge

The reinforcement is normally a straight tree trunk, in the same way that the trunks form beams, tie-beams, lintels etc. of the building. With the bark removed and with a radius of around 10 and 25cm (depending on the house). At both ends a cut out is made to fit the pins, this is around 30–40 cm from the end so as not to tear the post. The pins are straight or curved, made of wood (squared-off trunks or sawn-off planks) or metallic (ploughtails). They are placed in the cut-outs on the side, parallel or perpendicular to the floor for an easier placement and hammered into position. The wedges are used during construction to fasten the pins into place in the cut-outs, either with one wedge, or with two (one on top of the other crossing over at the points). Throughout the life-span of the construction, either due to weather conditions or just old age, the wood warps and any problems can be avoided by simply adjusting the pins against the walls and adding new wedges. Load bearing wedges are usually used to fix the pins to the half lap joint hooks. The wood used in Albacete area is the Aleppo Pine and the Common Pine tree. It is also possible that stronger woods are used in the pins and wedges such as Holm Oak and Common Oak.

The dimensions of the different elements vary greatly. A greater distance, a greater length and a greater diameter. Looking at the history, builders who used rammed earth were used to the mechanics of compression bracing and its different elements. The pressure put on the earth during the implementation of rammed earth walls over timbers was counteracted by the wooden crossbeams, iron struts or esparto fixings in order to create spaces to be filled with earth. Therefore, it is possible to borrow and transfer these stability elements and the framework of the timbers and use it in rammed earth wall constructions to counteract the tensile pressure in the corners. The oldest and most important earth constructions in the area had wooden struts embedded in the corners or the ring beams as their bracing system. In some cases, a reinforcement was placed diagonally and this joined the elements in the corners as a supplement. On the other hand, the wooden reinforcement was limited to the Albaceteña region and to humble living quarters. It was a much simpler interpretation of the embedded struts or the ring beams. In the houses built for farmers or humble families, economic possibilities were fewer. The wooden reinforcement full fills all necessities and is an ingenious and simple wall reinforcement using few materials and labour is also reduced. Another advantage worth pointing out is that as they remain in sight, they can be easily checked and their performance maintained.

2.2 Positive aspects and problems

From a constructive and structural point of view, the wooden reinforcement is a simple connection for walls (both parallel and perpendicular), which absorbs tensile pressure produced in the uppermost part of the joints. Being in sight, this system allows an easy maintenance of the wood and, if necessary, the pins can be easily readjusted or replaced when subjected to wear and tear. Disadvantages would be that firstly, without adequate protection of the reinforcement heads where the pins are inserted, the wood can rot and call for adjustment or even replacement later on in the life of the structure. Secondly, an aesthetic point of view, having the ends of the reinforcements with their pins and wedges in sight in the uppermost corners of the facades, as with the reinforcement in sight in the interior too hindering the use of that space on the top floor.

3 Method of structural calculations

The calculation uses a scalar damage model for frictional plastic materials, with a program developed by the Polytechnic University of Valencia. 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 performance of the earth using the damage theory. The appearance of cracks and their evolution overtime 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 [9–16].

The typological model is a traditional house with two floors above ground of 7.20 × 9.20 m (facade x dividing wall) and load-bearing wall parallel to facade for supporting floor slab and ridge beam. Load-bearing walls are rammed earth wall 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 reinforcements 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.

In attempts to analyse the influence of the wooden reinforcement in earth constructions, the variants of the walls in terms of their composition (single, hooped, linked, reinforced with lime…) or the composition of materials used (earth, improved, gravel, ceramic pieces…) haven't been taken into account [7–8]. Basic physic-mechanic and general characteristics of the earth have been adopted, without improving the composition of the construction, materials or treatments, applying them to models of wooden reinforcements and non-reinforcements structures so that they are comparable and therefore achieving a generic solution, without depending on the common traditions of each site or of each skill of the workmen involved.

Table 1 Physic-mechanic characteristics of materials used

	Modulus of Elasticity E (N/mm^2)	Load G (N/mm^2)	Density (Kg/m^3)	Compressive Resistance Fc (N/mm^2)	Shear Resistance Ft (N/mm^2)	Fracture energy Gf (Nmm/mm^2)
Wood	11200	4480	450	1,5	1	0,06
Earth	500	208,3	2000	1	0,025	0,06

Evidently, an improvement in the material or the composition of the walls generally implies an improvement in the structural behaviour of this combination. 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 physic-mechanical properties has been adopted for materials from the results of tests (from Albacete area) and literature [3, 7, 17,18] (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 [18].
- Earthquakes: according to the Spanish law [19]. 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 calculation process 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 steps, 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.

3.1 Analysis of traditional methods

The current study has concentrated on the comparison between un-reinforcement mud walls and those with wooden reinforcement:

Case of the earth walls without reinforcements.

Rammed earth walls with corner framework or making a vertical recess in the finished wall so when the two walls are put together they join perfectly. Case of the earth walls 40 cm thick without reinforcements. This is the base model for implementing the analysed reinforcement and comparing performances and results. It is used as the reference. Case of the earth walls 60 cm thick without reinforcements. This case tests the influence of the thickness on the structure performance against the loads.

Case of the rammed earth walls 40 cm thick with wooden reinforcements in the corners with struts of 15 cm in diameter 1 m from the interior corner. Cases where the wooden reinforcement has been applied to the four superior corners of the first floor with rammed earth walls 40 cm thick.

4 Experimental

4.1 Efforts

Analyzing the efforts obtained either from a load combination or the whole load combination, we are able to measure the performance of the structure and see the areas where the force exceeds the material's point of resistance.

- Linear static method under gravity loads and wind.

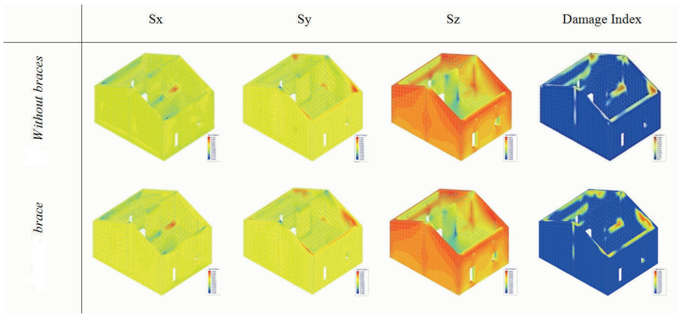

Fig. 2 Static lineal method using gravitational and wind pressure

In the model without bracing we can see that the major pressures are felt in the upper joints between the walls. However, the wooden reinforcement model shows less pressure on the joints between walls, it is better distributed towards the reinforcement joint (Fig. 2). In Figure 3 we can see in detail the superior wall joints. The pressure produced on the corners is greater on the non- reinforcement model and in the wooden reinforcement model we can see that this pressure is produced where the reinforcement lies. The wooden reinforcement allows a redistribution of pressure and tension thereby avoiding cracks in the superior wall joints.

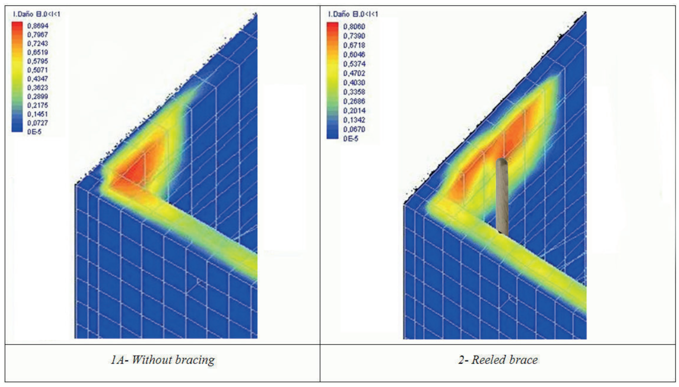

Fig. 3 Static lineal method using gravitational and wind pressure. Enlarged view of wall joints

- Nonlinear static method, under the combination of gravity and horizontal loads until collapse.

In the graphs, with the consecutive increases of load (collapse load at 25%, 50%, 75% and 95%), there are consecutive increases of the pressure in the construction. (Fig. 4) (Fig. 5) (Fig. 6)

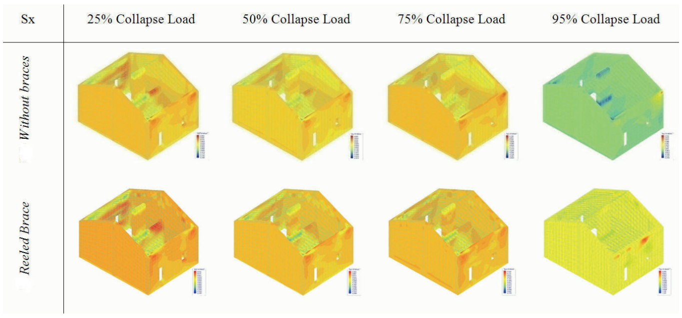

Fig. 4 Nonlinear static method, bearing gravitational and horizontal loads until collapse. Axis Sx

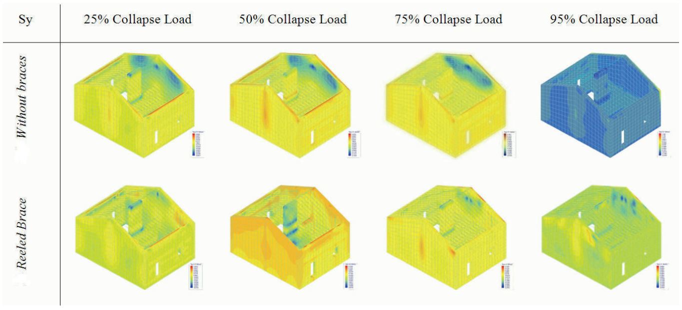

Fig. 5 Nonlinear static method, bearing gravitational and horizontal loads until collapse. Axis Sy

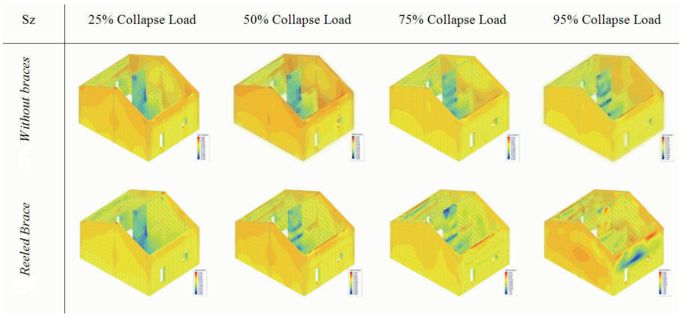

Fig. 6 Nonlinear static method, bearing gravitational and horizontal loads until collapse. Axis Sz

- Dynamic-seismic method.

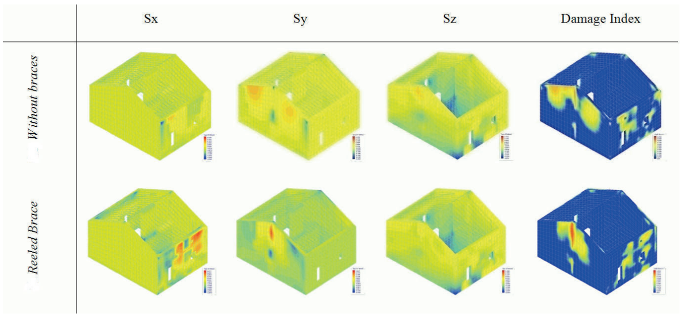

Fig. 7 Dynamic-seismic method

Under earthquake conditions, there are clearly two types of common failure in the soil based construction and that would lead to the collapse of the building either by wall overturning

failure or other unstable elements: failure by bending and shear failure (see failures at section 1 Introduction). (Fig. 7)

4.2 Damage rate

From calculating the pressures, we can obtain a damage index which allows us to check the areas where the material no longer collaborates because it has been exposed to loads above its resistance capacity. This is especially interesting in the non-linear static calculation because of a combination of loads all gradually increasing we can analyse all damage suffered as the load gets heavier. This way with the evolution of damage according to the increase in loads, we can study the response of the cases dels as the loads increase according to the damage rate and see at what point the building will collapse.

Worn out material usually comes from the top of the joints between the walls, and progressively worsen as load increases, thereby collapsing the wall in two directions, thickness and height. The collapse of the wall occurs when the cracks penetrate the wall completely and the walls become independent without lateral stability, so continuing to support loads will lead to collapse due to overturning failure.

From the wooden reinforcement case we can see that the process is similar except that the reinforcements provide support between the walls increasing the collapse load capacity (Fig. 8).

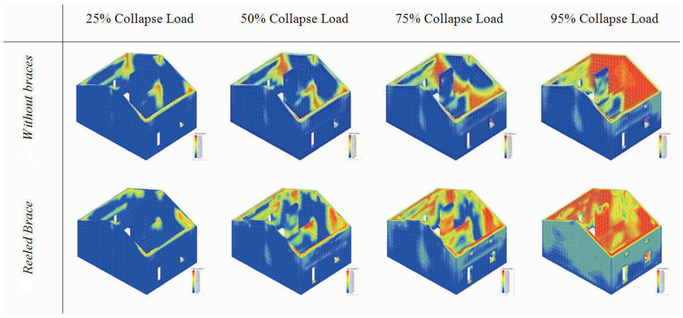

Fig. 8 Evolution of damages according to increasing loads

With same combination and increases, the exact load that collapses each case can be compared. 100% is the usual maximum load in the life of the building, increasing loads until they collapse, thereby obtaining the collapse load for each case referenced in Figure 9 and Figure 10. With all the results and using case of the earth walls 40 cm thick without reinforcements as a reference, we can compare the overall response of each of the cases. This table gives a simple and direct comparison between the cases analysed.

They show the different performances, assessing and quantifying their effectiveness and also graphics for a better understanding. (Fig. 9) (Fig. 10)

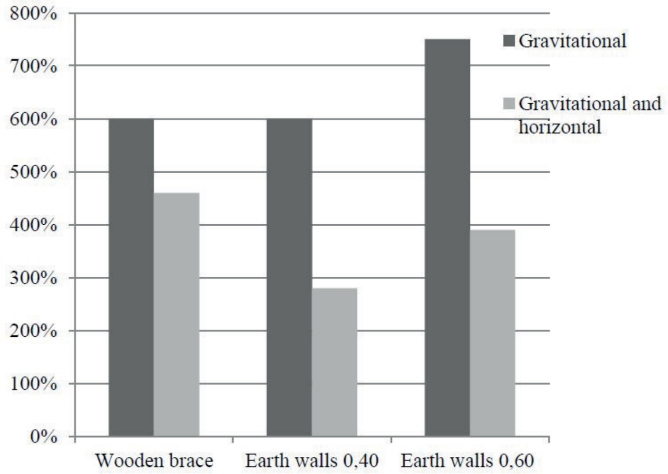

Fig. 9 Collapse load

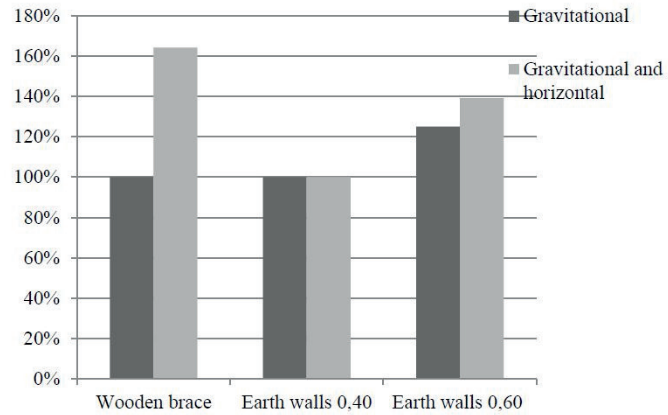

Fig. 10 Coefficient breaking reference

5 Results and discussion

In the cases without reinforcements, the greatest tension is found in the upper corners of the walls. If these tensions are greater than the resistance of the material, cracks will appear making walls independent and therefore starting the process of a building collapse due to lack of lateral stability in the walls. In the case of the earth walls 60 cm thick without reinforcements, we see a significant increase in global resistance of the structure. As expected, increasing the section of the material increases its resistance in these areas and therefore the overall resistance of the structure. With regard to gravity loads this is the case del with the highest resistance due to being the case with more area in its resistant section. It also increases resistance to horizontal forces and has a greater inertia against lateral overturning. Analyzing the damage rate in the consecutive increases of loads, we observe in the figure 8 that the crack starts at the top of the walls in the corners. From one side of the wall, the crack advances as specific sections of the wall buckle under the pressure, both transversely (wall width) and vertically (wall height). Finally, if the load that made both walls separate from each other continues, it causes the collapse of the structure. This process corresponds to the usual failure of the soil based construction mentioned in the section 1 Introduction due to low tensile strength of earth. In the case of 2.- Wooden reinforcement although the joints between the walls crack, separating the walls from one another, the reinforcements supply some reinforcement allowing the walls to continue to work together, limiting the collapse due to failure in the joints. This solution produces a significant increase in resistance against cracking at the top of the corners due to the effect of being bound, reinforcement and attached to each other. As result, there is a redistribution of tension along the wooden strut, acting only at the joint between the walls. From (Fig. 9) (Fig. 10) collapse load and coefficient breaking reference, under gravity loads, the table shows that cases of the earth walls 40 cm thick without reinforcements and wooden reinforcements have the same value, due to their walls being 40 cm thick. Here we highlight case of the earth walls 60 cm thick without reinforcements, with an increase of 20 cm thickness (50% thickness) increased by 25% the overall resistance of the structure against gravitational loads; the logical consequence of this being that earth walls are the elements that transmit vertical loads. Therefore, increasing their thickness will increase the resistant area and hence its resistance to these loads. In the same way, under gravitational and horizontal pressure (wind) we can see that case of the wooden reinforcement the global resistance of the structure increases substantially. This implies that using the same material with which the slabs are done (thick pieces of wood), sewing to them the upper corners we can increase the global resistance of the structure considerably compared with the same building without reinforcements, on the upper areas where the walls join, areas in which the weakness is usually caused in earth structures. Developed cases are studied and compared with existing structures. A complete series of traditional houses still standing in Albacete have been studied, but only a small number of them had walls with wooden reinforcements. Lastly, it is important to add that the in existing un-refurbished houses studied cracks could be seen in the upper joints between the walls. This issue, in addition to the fact that these inhabited places have not been maintained has caused a discoloration of the material surrounding the crack and therefore instability in not only the walls but also the roof, causing major problems and ultimately the house becomes ruins. The earth constructions with roofs and facades which have not been adequately looked after begin to gradually break down and decay. In the case of structures with wooden reinforcements, and adequate maintenance of the reinforcements, the roofs and the linings of the walls are free from cracks in the joints of the walls.

6 Conclusions

The soil based constructions, and in particular rammed earth walls and adobe, are vulnerable to tensile forces which are derived mainly from important horizontal external loads. This is accentuated in the case of earthquakes: earthquakes with 0,20g acceleration can bring soil based constructions without reinforcements to the brink of a collapse; and these kinds of earthquakes are frequent in area of high seismic activity where people continue to live and build earth constructions. The common failure of these buildings comes from the top of the joint between walls, becoming independent, losing lateral stability and giving way to collapse. Traditionally, bracing systems have been used with the aim of reducing this problem, which becomes more or less important depending on the characteristics of the building and weight to be borne. The solution of bracings, wooden reinforcement in particular, increases the global resistance of the building considerably and also the collapse loads capacity against extreme horizontal pressures. In terms of vertical pressures, increasing the width of the walls (50%) is the most adequate solution to increase the global pressure by 25%. In the case of horizontal pressures, increasing the width increases the global resistance by 39% and with the use of wooden reinforcements, this increase goes up to 64% giving us the optimum solution not only structurally but also economically requiring less materials and labour. The elements which make up the wooden reinforcement are left in sight (the dowel, pins and wedges) allowing for a better control and maintenance throughout the life of the building. Therefore, it is recommended that the wooden reinforcement of Albacete or a different bracing solution be used in all adobe constructions in order to guarantee the effectiveness of the walls. As shown, the bracing of the walls significantly increases their ability to withstand horizontal loads by creating an adequate joint between two walls. Reinforcements are a necessity for global stability and monolithic nature of the earth buildings, and is an essential security element in seismic areas.

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. This is why the understanding of how earth 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 countries under criteria of sustainability, and developing countries because of the lack of housing and of construction materials.

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