Chapter 7

Wooden Reinforcement for Earth Constructions in the Castile Area of Spain

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Additional information is available at the end of the chapter

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Abstract

This chapter studies wooden reinforcements for earth constructions. Analysing vernacular houses from Castile, Spain, I discovered this reinforcement and started to compare its performance with other traditional bracings for earth construction. At present, approximately over 30% of the world's population still live in earth houses, 50% of which are in the third world countries. This is why it is so important to understand how earthwork constructions behave. Most importantly, for the rehabilitation and preservation of existing World Heritage Sites, also there is a great need to construct new buildings in developed countries under the criteria of sustainability and developing countries because of housing shortages and lack of materials. The main failure of earth constructions is because of the low tensile resistance of the earth, causing walls to detach in the corners under horizontal loads. This chapter analyses a vernacular wooden reinforcement from Castile, Spain: its history, composition, construction and structural behaviour. It compares it with earth constructions without reinforcements, using a unique model under the same conditions. This makes a qualitative and quantitative comparison possible. The conclusions can be applied to rehabilitation or construction of new-build depending on the loads, distances and height, which can be a security condition or a vital necessity.

Keywords: wooden, round pole timber, wooden bracing, vernacular construction

1. Introduction

In Spain, earth constructions have been in existence since before the arrival of the Romans [1], and the remains of an earth wall from the ninth century B.C. have been found in the substrata which dates it before the Iberians. They are more numerous in the south and central regions of the peninsula where the soil conditions are conducive to their construction. Earth wall structures were prolific across a wide spectrum of building types, from fortifications and public buildings to residential dwellings. In compression, earth as a construction material performs well structurally, but has a low tensile strength. Therefore it is important to mould, shape and condition the material to avoid tension and work in compression. In addition, the need for massively thick earthen wall sections and underperformance in their connections means that any horizontal movement (seismic activity and wind loading) could be exceptionally perilous to occupants if the risk of collapse is not considered.

Another area in the structural design of earth construction, that proves complex, is the lack of horizontal and vertical bracing between walls, floor slabs and roofs. Therefore, as floor slabs and/or roofs are not directly connected to the framework, the loads are neither distributed evenly throughout the building load, nor act to strengthen the building. Therefore, walls become independent structures under external pressures; this inherent weakness along with horizontal loading is amplified in earthquake zones. External loading conditions that cause earthen constructions to collapse, in particular adobe or rammed earth structures, manifest themselves as highlighted below [2]:

- Bending normally causes failure in the first instance. The limited tensile strength within the earth causes the walls to separate at the corners. Beginning at the top, the walls split and become individual vertical cantilevers with stability.

- Secondary failure can be due to shear forces developing in the walls. If one eliminates the above and manages the detailing between the walls, the walls are better able to withstand horizontal pressures; however, diagonal cracking may appear caused by the shear forces in the walls along the jointing.

- Finally, failure due to overturning. Once the walls fail due to bending (become independent) or fail due to shear cracking, breaking appears and they become individual vertical cantilevers. If equilibrium is not maintained, this will result in catastrophic failure and most likely total collapse. At present, earthen structures are being revised in areas prone to earthquakes. Alongside innovations in soil types and vernacular guidelines and bracing reinforcing 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. Vernacularly in Spain great improvements have been made to the behaviour of adobe walls by modifying their composition (adding lime) or by bettering the constructive method (steel wall, cemented wall, etc.) [7–8]. While these innovations help to reinforce structures, they do not solve the inherent problem caused by lack of tensile strength in the connection between walls and the uppermost corners. The answer to this problem is to use one of three types of corner bracings: (i) placing ashlar blocks, quoins or rough stones into the corners of the walls; (ii) using ring beams; or (iii) embedding timber struts into the walls. These are all valid solutions to this problem.

Throughout the region of Castile, Spain, there is a vernacular wooden bracing detail employed for residential dwellings. I will endeavour to explain the method in in-depth detail

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and compare its resistance, structural behaviour, bracing systems, composition, materials, constructive solution and aesthetics against models where bracing is absent.

2. Description of the system

The performance analysis of the wooden reinforcement [9] is being investigated to bring an architectural, structural and construction vision, which allows the comparison between different vernacular systems of bracings for earthen structures. One option for rammed earth structures common to the Castile area is with a wooden reinforcement. It is usually commonly used in gable ends or blocks, and on sloped ground inclines to absorb tensile pressure and the resultant movements between the corner walls. While wooden reinforcements are only really seen in the Castile region, the use of stone quoins, 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. There are three elements [10] that make up the system: the pegs, the wooden wedge, which holds them in position and the round pole reinforcement itself. These hold the walls together using the wedges and pegs on the exterior to limit lateral movement. This was conceived as a way of absorbing tensile forces in the upper corners of the wall's joint where there is an absence of beams, and utilizing the compressive force inherent in the round pole reinforcement and the pegs (**Figure 1**).

The reinforcement is usually a straight de-barked round pole timber, (also used to create beams, tie beams, lintels etc.) with a radius of approximately 10 and 25 cm (depending on the house type). At alternate ends a hole is drilled to house the pegs; the hole is situated in a proximity of 30–40 cm from the extremities to prevent the pole from splitting. The pegs or wooden pegs can be straight or curved (made from squared-off trunks or sawn-off planks or metallic pegs, or plough tails). They are positioned in the holes, parallel or perpendicular to the floor construction for build ability and hammered into position. During construction wedges are used to jam the pegs in place, either with one wedge, or with two (one on top of the other crossing over at the points). Throughout the lifespan of the building, either due to wear and tear or weathering, the wooden pole may warp, and problems may be avoided by

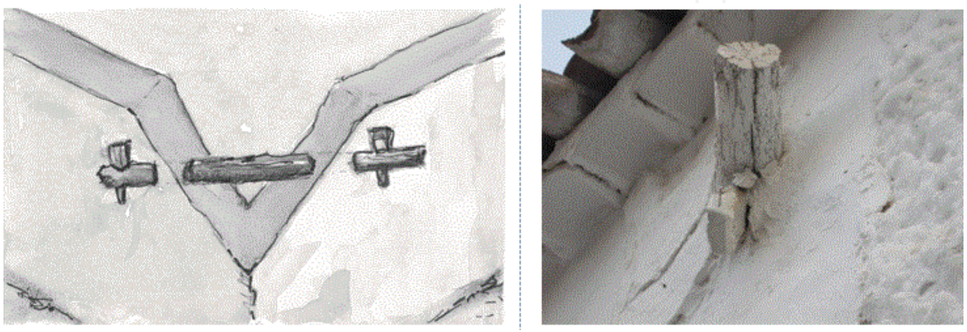

Figure 1. Components of the wooden reinforcement system: Earth wall—reinforcement—peg—wedge.

adjusting the pegs against the walls and by adding new wedges. Larger load-bearing wedges are usually used to fix the pegs to the half lap joint hooks. The wood used in the Castile area is Aleppo pine and the common pine tree. It is also possible that stronger woods are used for the pegs and wedges, such as holm oak and common oak.

The sizes differ vastly. For larger spans, a longer round pole with a greater diameter is employed. Analysing the evolution of this system, builders who built with rammed earth were well aware of the mechanics of compression bracing and its design. The loadings placed on the soil during the construction phase of rammed earth walls over timbers were counteracted by wooden cross members, iron struts or esparto fixings to create the shuttering to hold the soil. Consequently, the transferability of one technology to the other was possible. Wooden struts embedded into the corners and/or ridge beams for bracing systems were found in some of the oldest and most important earth constructions in the area. In some cases, additional, diagonal structural supports were employed working together with the corner bracings described above. From another standpoint, in the Castile region builders were limited to wooden reinforcements for vernacular dwellings. This method shows a more simplistic approach than embedded struts or ridge beams. In poor vernacular farmhouses, wooden reinforcement fulfilled all needs and is an economical, ingenious and simple solution using a minimum amount of materials and labour. Furthermore, as they are visible, they can be easily maintained and inspected.

The wooden bracings are simple wall connectors, looking from a structural and construction viewpoint [9] (both parallel and perpendicular), absorbing tensile loading at the top of the corner joints. Being exposed to the exterior, permitting ease of access for maintenance purposes and, in addition, the pegs can be simply readjusted or replaced when subjected to wear and tear. One disadvantage is that without suitable protection at the ends of the round poles where the pegs are placed, wood rot may take hold and result in modifications needed or even total system replacement. Another issue is aesthetical; with the cantilevering of the extremities, the pegs and wedges are in full sight on the façade and in addition the diagonal member obstructs the full use of the internal corner.

Maintenance and general upkeep in earth soil system construction, good detailing and workmanship are essential to prevent water ingress into the structure. Another extremely necessary element to maintain is the rendering on the façade. This acts as a rain screen for the earthen walls and keeps the walls and timber bracing structure dry to prevent failure.

The lack of a protective coating on the exterior wood may cause a knock-on effect weakening the timber bracing, which in turn could cause failure in the wall itself. The protection of the beams normally consists of three techniques: the initial wall covering (if the cantilever of the bracing structure was minimal, the earth-lime wash would simply be employed over it); with terracotta pan tiles embedded over the timber extremities and also protecting the pegs and wedges; and in recent years zinc panelling nailed directly on top of the wood. It is worth noting again that having the bracings visible makes inspecting their state, and, if necessary, making any adjustments or substitutions much easier in relation to general maintenance. It is not uncommon that as time goes by, the variations in temperature and humidity warp the wood, making it necessary to replace pegs or new wedges.

3. Calculation techniques. Description of the models, materials and loads

The calculation uses a scalar damage model for frictional plastic materials, with an application developed by the Polytechnic University of Valencia. In the CID (Calculation & Structural Design & Foundations), structural analysis program for CAD environments building structures [11, 12], a programme has been initiated referring to the isotropic damage model developed in the last 20 years. This programme is based on damage mechanics, which is part of the internal variables that introduce microstructural changes in the behaviour of materials, modelling the influence of the history of material behaviour in the evolution of stresses. With the correct description of the damage function representing the material response in compression and tension, you can model the non-linear performance of the soil using the damage theory. The appearance of fissures and their progression over time describe trajectories of numerous 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 programme has been calibrated with several examples and studies as well as with existing physical elements [13, 20].

The typological model is a vernacular house with two floors above ground of 7.20 x 9.20 m (façade x dividing wall) and load-bearing wall parallel to façade for supporting floor slab and ridge beam. Load-bearing walls are of rammed earth, 40–60 cm in section depending on their slenderness and loads. The floor construction is made up of timber struts 15 cm in diameter at 50-cm centres, filled with supporting vaults (mud bricks and loam) or wattle and mortar on top of the beams. Pitched roof made with round pole timbers, wattle and clay supports for tiles on the load-bearing walls (façade and intermediate wall). Ground height of 3.90 m and 6.00 m ridge. A ground floor of height 2.5 m. The structural model is discretized with finite hexahedra solid elements (volumetric) for earthen 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. The model has 1.972 hexahedra of 0.20 x 0.40 x 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 included [7–8]. Basic physic-mechanics and the general qualities of the soil have been employed, without improving the composition of the construction, materials or treatments, applying them to models of wooden braced and non-braced construction so that they are equivalent and consequently achieving a common result, without depending on the traditions of each site or of each skill that the tradesmen employed.

Evidently, an improvement in the material or the composition of the walls generally implies an improvement in the structural behaviour of this combination. Soil characteristics of the corner 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 solutions. Middle and conservative physic-mechanical properties have been adopted for materials from the results of tests (from the Castile area) and literature [3, 7, 21, 22] (**Table 1**).

	Deformation E (N/mm^2)	Poisson	Density (Kg/m^3)	Compressive Resistance Fc (N/mm^2)	Shear Resistance Ft (N/mm^2)
Earth	500	0,2	2.000	1	0,025
Earth of the corners	500	0,2	2.000	60	4,5
Wood	11.000	0,25	550	12	10

Table 1. Physic-mechanics characteristics of materials used.

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

- Dead loads: values from the tests results.

- Live loads: based on current Spanish legislation [21].

- Earthquakes: according to the Spanish legislation [22]. Values have been taken to analyse the worst-case scenario, although this regulation would preclude the construction of soil-based buildings under such conditions.

In the analysis three methods were used:

- Linear static calculation: based on the hypothesis of linear elastic performance of materials and noting the balance of the structure without becoming deformed. Loads and load combinations are considered for the two main directions.

- Non-linear static calculation: this highlights the stress-strain performance of non-linear material and geometric non-linearity, i.e. achieving balance of the structure in its deformed state. We analysed four independent load combinations for the two main directions, introducing proportional increases in 20 steps, taking into account geometric variations and materials:

- Gravitational loads (dead and live loads) without majority.

- Gravitational loads (dead and live loads) and horizontal (wind) without majority.

- Gravitational loads (dead and live loads) to collapse.

- Gravitational loads (dead and live loads) and horizontal (wind) to collapse.

- Dynamic-seismic calculation: we have analysed two equivalent static load combinations for earthquakes for the two main directions of the model.

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

Model 1.- 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. 1A. -Earth walls 40-cm thick without bracings. This is the base model for implementing the analysed bracings and comparing

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performances and results. It is employed as the reference. 1B. -Earth walls 60-cm thick without bracings. This model tests the influence of the thickness on the structure performance against the loads.

Model 2.- 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. Models 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

Analysing 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.

In the model without bracing we can see that the major pressures are felt in the upper joints between the walls. However, the model shows less pressure on the joints between walls; it is better distributed towards the reinforcement joint (**Figure 2**). In **Figure 3** we can see in detail the superior wall joints. The pressure produced on the corners is greater on the non-reinforced model and in the wooden reinforcement model we can see that this pressure is

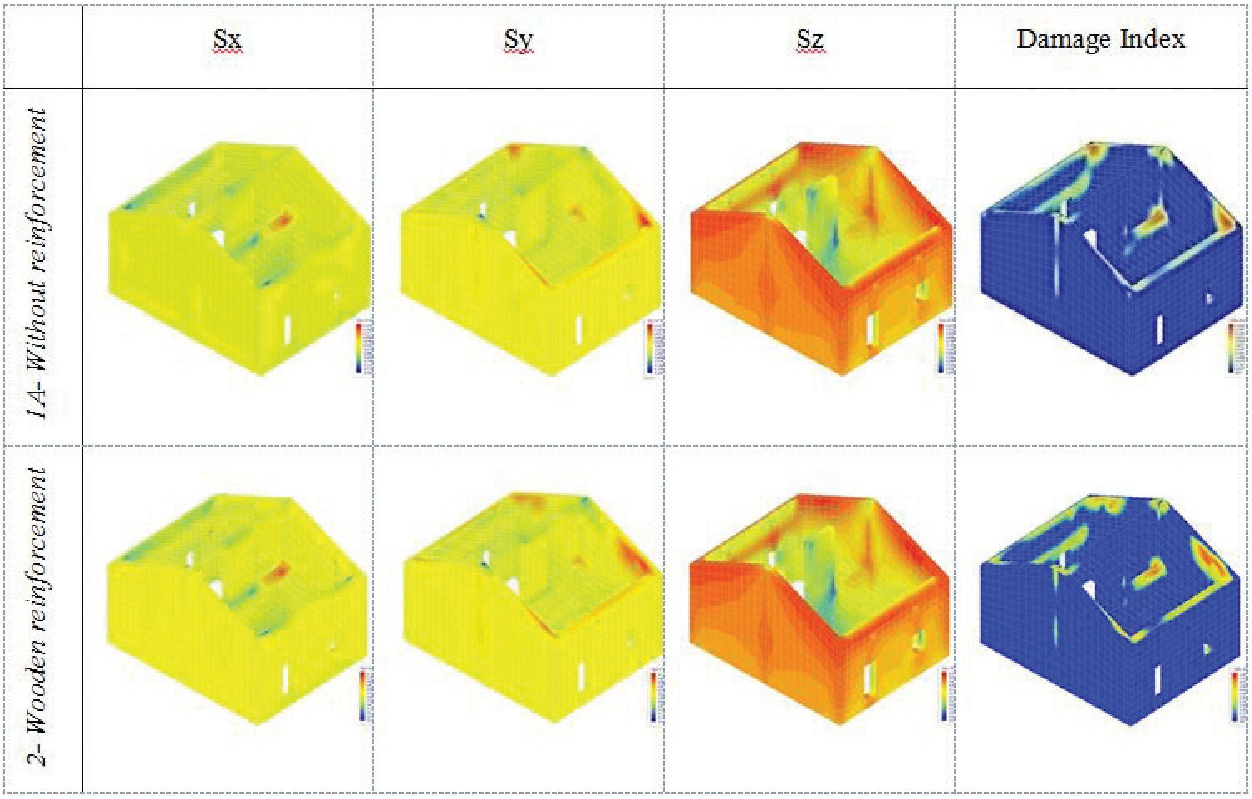

Figure 2. Static lineal method using gravitational and wind pressure.

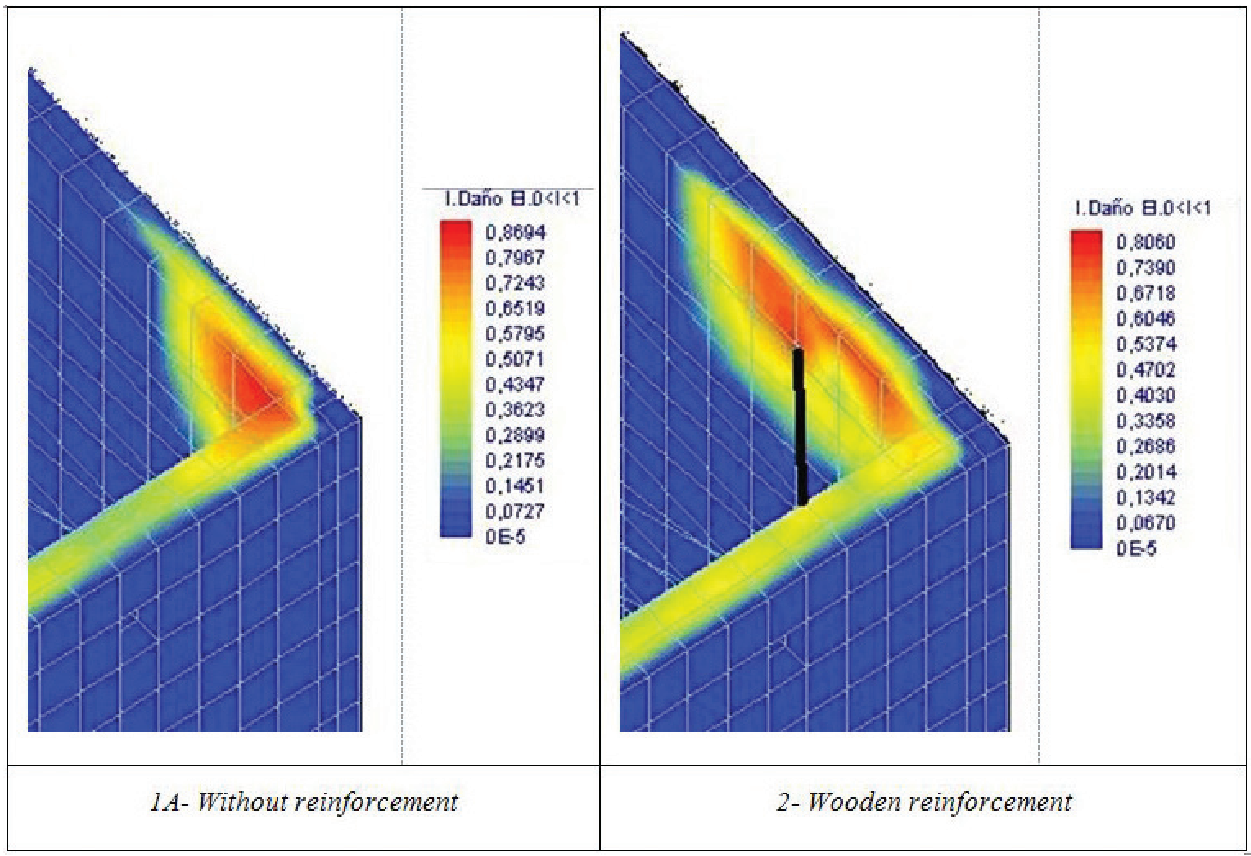

Figure 3. Static lineal method using gravitational and wind pressure. Enlarged view of wall joints.

produced where the reinforcement lies. The wooden reinforcement allows a redistribution of pressure and tension, thereby avoiding cracks in the superior wall joints.

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

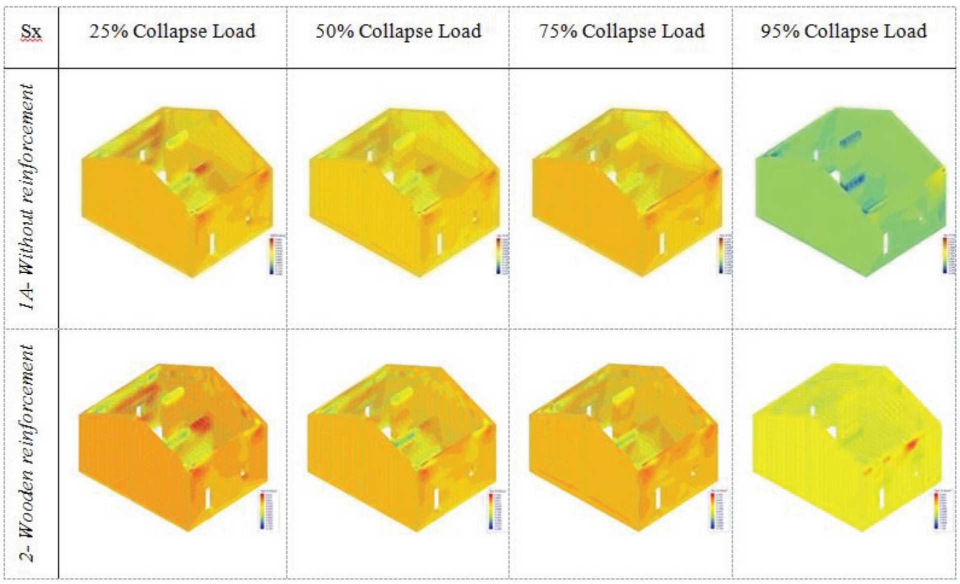

Figure 4. Non-linear static method, bearing gravitational and horizontal loads until collapse. Axis Sx.

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

- Dynamic-seismic method.

Under seismic conditions, evidently there are two types of common failures in earth-based structures and they would develop into the collapse of the building either by wall overturning failure or other unstable elements: failure by bending and shear failure (note failures in the introduction, Section 1) (**Figure 7**).

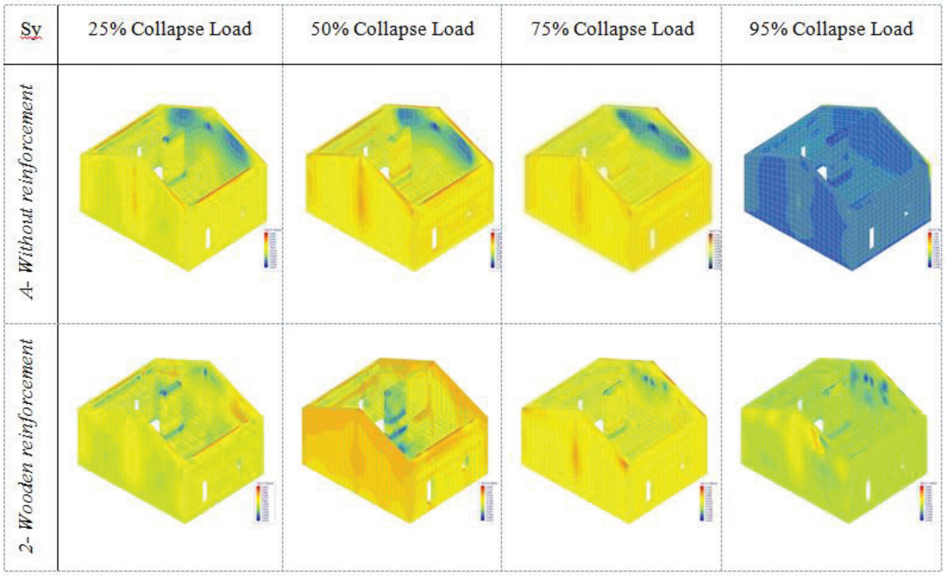

Figure 5. Non-linear static method, bearing gravitational and horizontal loads until collapse. Axis Sy.

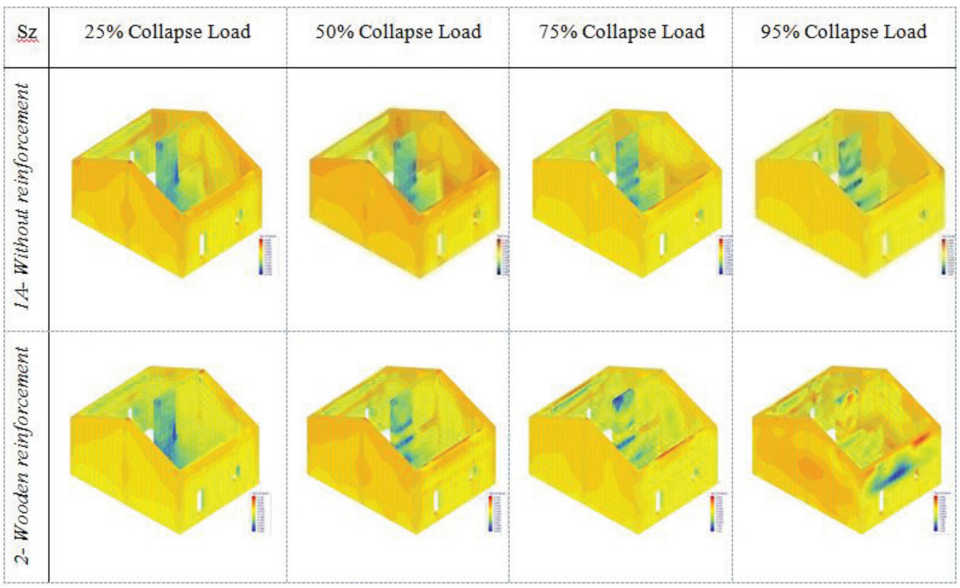

Figure 6. Non-linear static method, bearing gravitational and horizontal loads until collapse. Axis Sz.

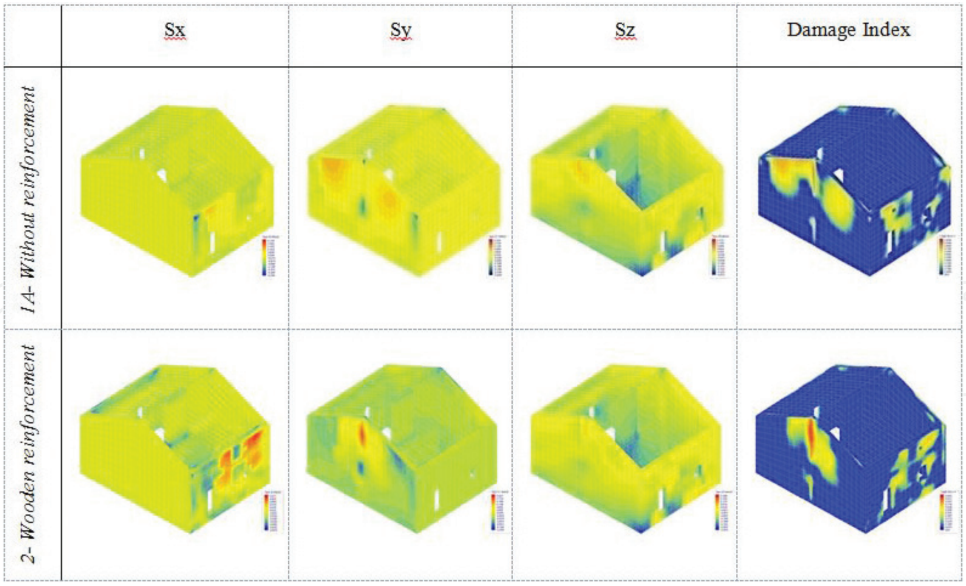

Figure 7. Dynamic-seismic method.

5. Damage rate

By calculating the pressures, we can acquire a damage index, which allows us to test 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 models as the loads increase according to the damage rate and see at what point the building will collapse.

Damaged material [10] normally comes from the top of the joints between the walls and progressively worsens as the load increases, thus causing the wall to collapse in two directions, thickness and height. The failure of the wall occurs when the fissures breach the wall completely and the walls become independent vertical cantilevers without lateral stability, so continuing to support loads will lead to collapse due to overturning failure.

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

With same combination and increases, the exact load that collapses each model can be compared. 100% is the reference, maximum load buildings life, increasing loads until they fail, in so doing obtaining the collapse load for each model referenced in **Table 2**. With all the results and using model 1A as a reference, we can contrast the overall response of each of the models. This table gives a straightforward and direct comparison between the models analysed.

They show the different performances, assessing and quantifying their effectiveness and also graphics for a better understanding (**Table 2**) (**Figures 9** and **10**).

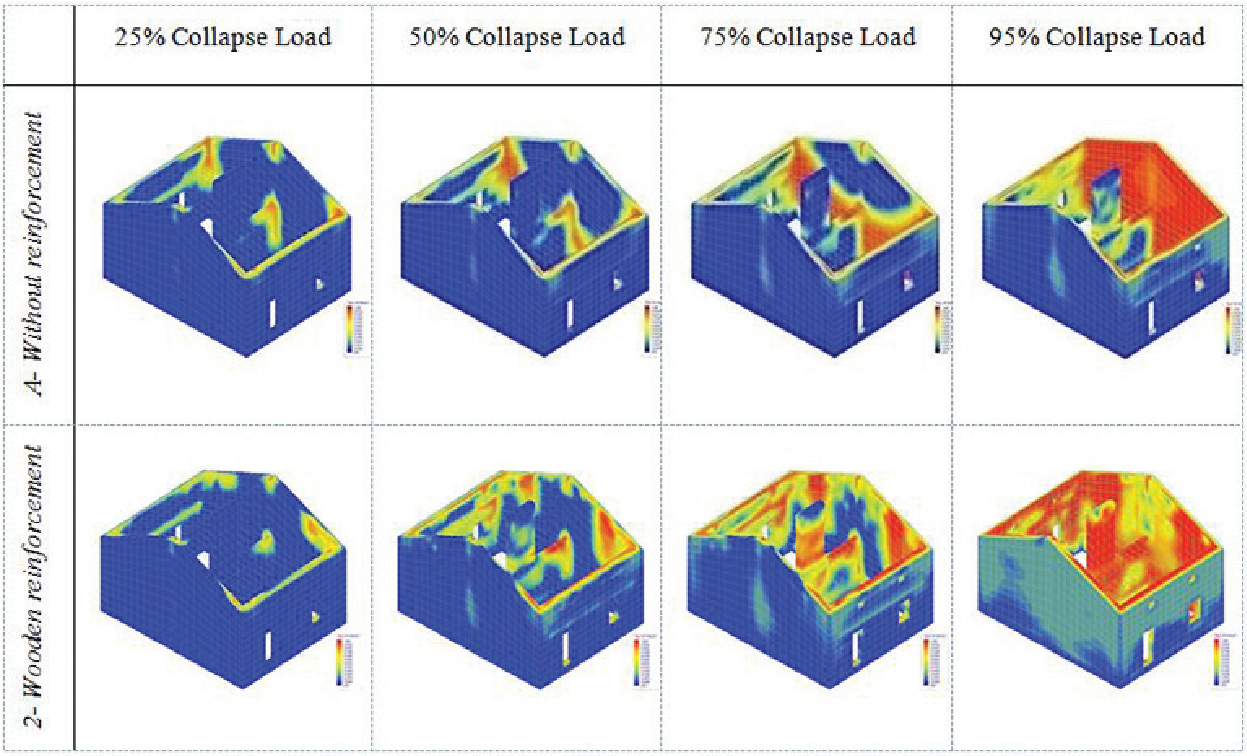

Figure 8. Evolution of damages according to increasing loads.

	Gravitational and horizontal (%)		Gravitational (%)	
	Collapse	Reference	Collapse	Reference
40-cm wall	280	100	600	100
60-cm wall	390	139	750	125
Wooden reinforcement	460	164	600	100

Table 2. Collapse load and coefficient breaking reference.

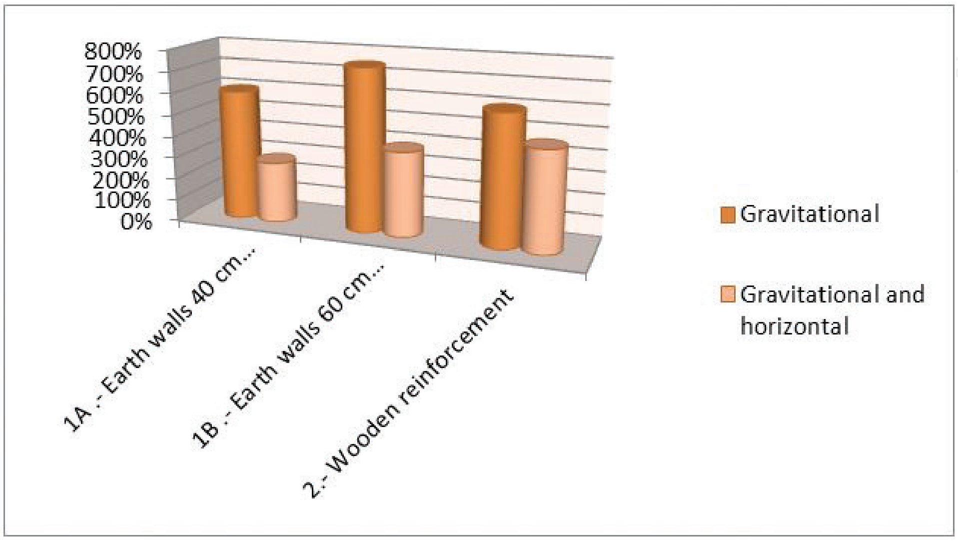

Figure 9. Collapse load.

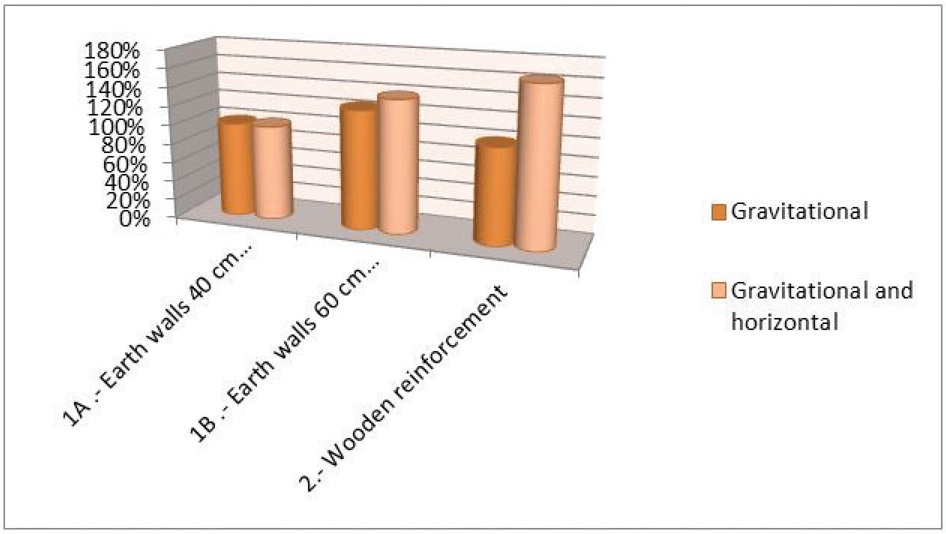

Figure 10. Coefficient breaking reference.

6. Results and discussion

In the models without reinforcements, the maximum tension is found in the uppermost corners of the walls. If these tensile forces are more than the resistance of the material, fissures will appear causing the walls to act as vertical cantilevers, and as a result beginning the process of building collapse due to a deficit in lateral wall stability. In model 1B, with a 50% thickness increase (40 cm to 60 cm), we see a considerable raise in global resistance of the structure. As predicted, an increased wall thickness dramatically increases its resistance in these areas and consequently its global structural strength [9]. Being the model with more area in its resistant section, in relation to gravity loads, this is the model with the highest resistance. This gives greater inertia against lateral overturning and also increases resistance to horizontal forces. Analysing the damage rate in the consecutive increase of loads, we can note that the fissure begins at the uppermost corner of the walls. From one side of the wall, the crack continues as particular wall sections buckle under the load, both transversely (wall width) and vertically (wall height). In the end, if the forces that created the initial split in the wall continue, the structure will fail. This process corresponds to the usual failure of the soil-based construction mentioned in Section 1, due to the low tensile strength of earth. Although with model 2, while wall separation occurs, the bracings give some reinforcement, permitting the walls to continue to work together, limiting the collapse due to failure in the joints. Owing to the effect of being tied, braced and joined to each other, this solution produces a significant increase in resistance against cracking at the uppermost part of the corners, resulting in a redistribution of tensile forces along the round pole timber, focused entirely at its joint. From **Table 2**. Collapse load and coefficient breaking reference, under gravity loads, the table shows that models 1A and model 2 has the same value, due to their walls being 40 cm thick. Model 1B highlight with an increase wall of 20 cm thickness (50% thickness) increases by 25% the total structural resistance against gravitational forces; the rational outcome of this being that vertical loads are transmitted through earthen walls. Thus, increasing their section will increase the resistant

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area and therefore its resistance to these forces. In the same way, under gravitational and horizontal pressure (wind), we can see that model 2—the global resistance of the structure increases substantially. Whereas the global resistance of model 1B increases 39%, placing wooden reinforcements into the walls increases the global resistance against these pressure by 64% more than the same model without reinforcements (1A). In spite of the round pole timber bracing solely interacting with the buildings' corners, it increases the collapse loads capacity significantly. This suggests that using the same material with which the slabs are built (thick round pole timber), contacting the upper corners to them, we can augment the global resistance of the structure significantly in comparison with the identical building without bracings, on the uppermost section where the walls join, areas in which earth structures are normally weakest. Developed models are studied and compared with existing structures. A complete series of vernacular houses still standing in the Castile area have been studied, but only a small number of them had walls with wooden reinforcements. Lastly, it is important to add that the cracks studied in the existing un-refurbished houses 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.

7. Conclusions

Soil-based structures, focusing on rammed earth walls and adobe, are susceptible to tensile loads, which are derived mainly from important horizontal external forces. This is amplified in the case of earthquakes: earthquakes with 0.20 g acceleration can bring earth-based structures without bracings to the verge of collapse; these kinds of earthquakes are common in regions where people continue to live and build earth constructions and where high seismic activity exists.

Common building failure occurs at the uppermost part of the joint between walls, causing them to become independent, losing lateral stability and giving way to collapse. Traditionally, reinforcing systems have been used with the aim of reducing this problem, which becomes more or less important depending on the building type and loading capacity. The solution of struts, round pole timbers in particular, increases the global resistance of the building significantly and also the collapse loads capacity against extreme horizontal forces. In terms of vertical pressures, increasing the wall section (50%) is the most adequate solution to increase the global pressure by 25%.

To increase the global resistance by 39% regarding horizontal pressures, one needs to increase wall thickness and employing round pole timber bracing, this benefit increases to 64% giving us the optimum solution not only structurally but also economically, requiring minimal materials and man-hours.

The detailing of the round pole timber bracings is left exposed (the pegs and wedges), allowing for a better control and maintenance during the building's lifecycle. Thus, it is recommended that the round pole timber bracing of the Castile region or a different reinforcement system be employed in all adobe structures to assure the stability of the walls. As indicated, the wall struts considerably increase their ability to withstand horizontal forces by creating an acceptable fixing between two walls. Bracing is a must for global stability and the monolithic nature of soil systems, and in seismic areas is a fundamental stabilising element.

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