FEASIBILITY OF CONFINED MASONRY DESIGN IN AZORES

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SUMMARY

In the recent years, small size buildings built with resistant confined masonry demonstrated an acceptable behaviour due to earthquakes actions. On the other hand, many experimental studies have been corroborating these findings. As proved in recent work, and according to the Eurocodes, the security can not be accomplished when using confined masonry made with Portuguese traditional clay units. In this context, the aim of the present work was to determine the feasibility of construction using confined masonry, in small buildings, made with hollow aggregate concrete units and designed according to Eurocodes 6 and 8. These results can be relevant for the Azores because this type of construction is still being used in the region. The structural evaluation of the dwellings is supported on tests made at the laboratories of Civil Engineering Department of University of Algarve, mainly to characterize the shear strength of masonry. The contribution of cement render to the shear resistance of confined masonry was also verified.

1. INTRODUCTION

The conservation of Azores traditional architecture is a challenge for every one that has public responsibilities at the islands. The socio-economic development of the region, and the impact of natural disasters, such as earthquakes, contributes to the disappearance of this kind of architecture, mainly of rural type.

In the beginning of Azores colonisation, land was not a problem so rural dwellings were constructed without any space restrictions. In spite of the influence of Portuguese mainland regions (such as Algarve or Alentejo, for example), traditional Azores architecture have their own cultural identity, and dwellings can be divided in three main groups according to the relative position of the kitchen (Tostões *et al.*, 2007):

- dwellings with separated kitchen;
- linear dwellings, with one facade. Rooms are disposed in a straight line or in a L shaped line with the kichen occupying the extremity;
- one volume dwellings, usually symmetric, including the kitchen in itself.

All the Azores traditional dwellings have a wood-fired oven in the kitchen but their configurations and dimensions are very variable (Tostões *et al.*, 2007).

The seismic behaviour of Azores traditional dwellings was not satisfactory, namely during the 1980's earthquake (January 1, 1980) that destroyed 5000 buildings and damage more 10000 of a total of 30000 (Guedes and Oliveira, 1992). The unsatisfactory seismic response of Azores traditional masonry is related to the wall typology and its mechanical proprieties (Guedes and Oliveira, 1992; Costa, 2002).

The first masonry constructions in Azores that include concrete structural elements are from the late fifties of the 20th century. They were made with solid concrete masonry units, and the lack of quality control was evident. Later in the seventies, constructors started to use hollow concrete units instead. The seismic response of this kind of buildings proved to be very satisfactory during the Azores 1980's earthquake (Oliveira, 1992).

In contrast with Portuguese mainland traditional infill masonry, confined masonry is design to resist to seismic actions.

To increase the global ductility of the masonry, confined masonry includes vertical and horizontal reinforced concrete elements. To assure the strength and the ductility of the structural system, concrete is poured directly to the masonry walls (Tomaževič, 1999).

The use of confined masonry is common in Latin America. Earthquakes that affected those regions have shown that confined masonry preformed better then unconfined masonry. In most cases confined masonry buildings remained undamaged (Klingner, 2006). Based on the observation of the seismic performance of confined masonry, in South America, due to several earthquakes, the following deficiencies have been identified (Moroni *et al.*, 2004):

• limited shear strength;

• limited ductility;

• lack of confining vertical elements at all openings that diminishes the shear strength and displacement capacity post-shear cracking;

• excessive separation between vertical elements or lack of horizontal confining elements that may cause out-of-plane damage;

• shear cracks that propagate through the vertical concrete confining elements and reduce the stiffness and resistance capacity.

These problems are considered in the provisions given in Eurocodes 6 and 8 (CEN, 2004a; b).

The resisting mechanism of this structural system on the lateral load is a combination of tension force in the tension side tie column and inclined compressive force in a concrete block masonry wall that is the resulting force of normal and shear stress on mortar joints (Hori *et al.*, 2006).

Mortar tests are very important because experimental investigations have shown that mortars governs the non-linear behaviour and failure mode of hollow concrete masonry (Mohamad *et al.*, 2007).

One problem related to confined masonry is that the prevailing failure mechanism, when shear behaviour controls the response, corresponds to a first soft story. One way to prevent this problem is to provide horizontal reinforcement in the masonry walls (Casabonne, 2000).

Recently it was shown that the use of Portuguese traditional clay units in confined masonry, do not satisfies the Eurocodes safety demands (Braga and Estêvão, 2007). In this work it is presented an experimental investigation, supported by numerical analysis, on the use of hollow aggregate concrete units in confined masonry design.

2. STATIC LOAD TESTS

Confined masonry seismic analysis and design demands the knowledge of the mechanical properties of the masonry. For that purpose, several hollow block concrete masonry triplets were tested at the laboratories of Civil Engineering Department of University of Algarve, to characterize the elastic modulus and the shear strength of hollow concrete block masonry structures. Triplets were made by a professional worker, with and without cement render (±1 cm in each side of the block triplet).

2.1. Mortar prisms

Mortar (type 1:4 for the bed joints and type 1:5 for the cement render) used in masonry triplets was tested as described in EN 1015-11 (CEN, 1999).

Sixteen small mortar prisms (with 160×40×40 mm) were prepared (eight for mortar used in bed joint and eight for mortar used in cement render), and tested 28 days after. Flexural mortar test was carried out first, followed by the compression test, as presented in Figure 1. For mortar used in bed joint, the flexural strength obtained was 1.840 N/mm^2 (with a standard deviation of 0.095), and the compressive strength (f_m) obtained was 5.110 N/mm^2 (with a standard deviation of 0.395). The results for mortar used in cement render was 1.266 N/mm^2 (with a standard deviation of 0.081), and the compressive strength obtained was 3.573 N/mm^2 (with a standard deviation of 0.189).

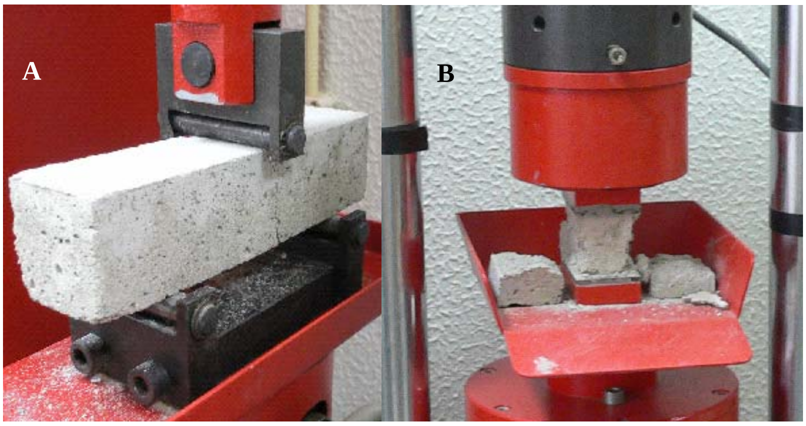

Figure 1: A) Mortar flexural strength test. B) Mortar compression test.

2.2. Shear strength of hollow block masonry triplets

Hollow concrete masonry units (Figure 2) SECIL prebetão B20 (Olhão, Portugal), classified as Category II and Group 3 (CEN, 2004a), were used to prepare sixteen block masonry triplets (half with cement render and half without cement render).

Twelve units were tested for the determination of compressive strength (f_b) to compare it with the product technical information. A value of 9.846 N/mm^2 (with a standard deviation of 0.546) was obtained. The product technical information refers 9.1 N/mm^2, for this parameter.

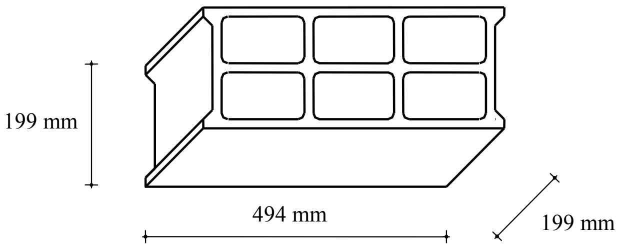

Figure 2: Hollow concrete masonry unit.

The shear strength of masonry triplets was obtained as described in EN 1052-3 (CEN, 2002). Two load cells were used to carry out the shear tests (Figure 3). One load cell was used for monitoring the shear force and the other for monitoring compressive force acting perpendicular to the shear force. First, the desired compressive force was applied to the prism and remained constant during the test, while shear force was increased until the masonry triplet rupture occurred.

Three pre-compressive stresses were adopted, as proposed in EN 1052-3, namely 0.1 N/mm^2, 0.3 N/mm^2 and 0.5 N/mm^2. The shear stresses obtained with the eighteen conducted tests (with and without cement render) are presented in Figure 4. It is also presented the linear regression as proposed in EN 1052-3.

Triplets shear failure occurred mainly at mortar bed joints, but sometimes the crack also propagate to the hollow concrete unit. The predominant failure shape is presented in Figure 5.

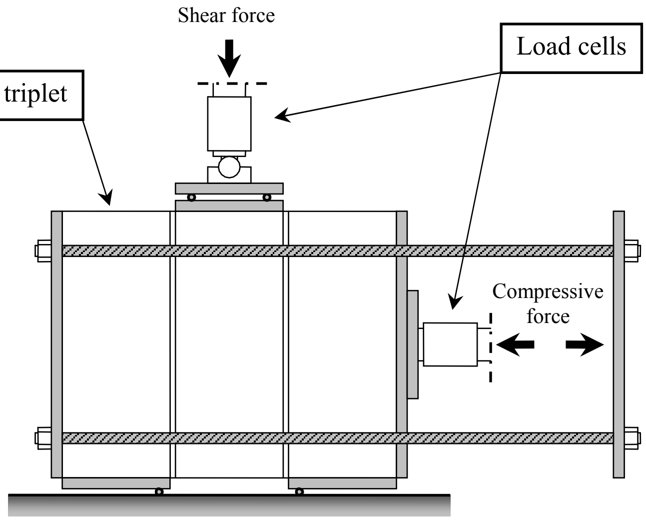

Figure 3: Shear masonry triplet test.

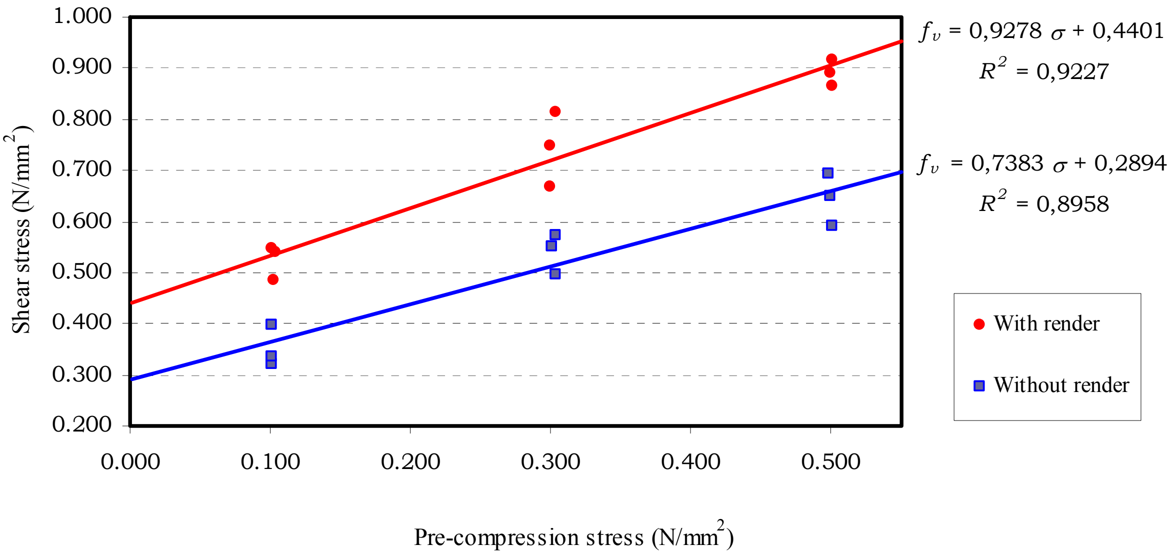

Figure 4: Shear resistance graphic test results.

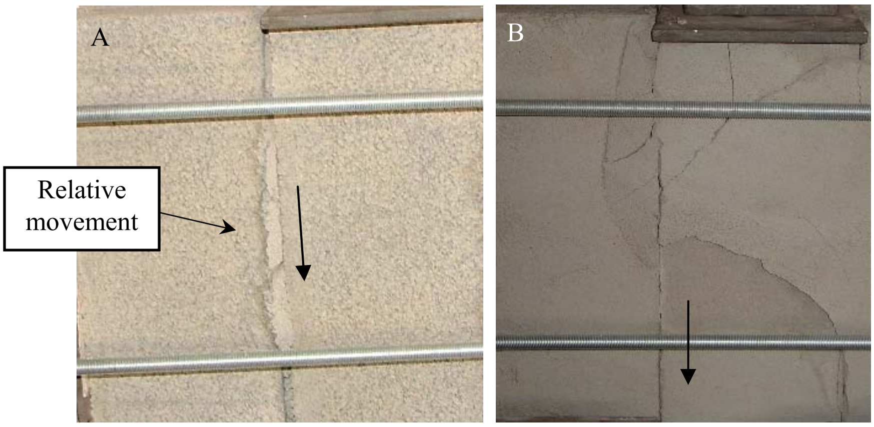

Figure 5: Hollow concrete masonry triplet predominant failure: A) without render; B) with render.

As described in EN 1052-3, the characteristic shear strength (f_{vk}) of masonry result from the multiplication of test results (Figure 4) by a 0.8 factor. So, the following expressions correspond to the characteristic shear strength obtained for masonry made without render (1) and made with cement render (2):

$$f_{vk} = 0.23 + 0.59 \cdot \sigma_d \tag{1}$$

$$f_{vk} = 0.35 + 0.74 \cdot \sigma_d \tag{2}$$

The characteristic initial shear strength (f_{vko}), under zero compressive stress, obtained in result of the tests were 0.23 N/mm^2 without render, and 0.35 N/mm^2 with cement render, which correspond linear shear resistances of 45.77 kN/m and 69.65 kN/m, respectively.

2.3. Compressive strength and elasticity modulus

According to Eurocode 6, the compressive strength of masonry (f_k) can be obtained from a relationship between the compressive strength of the hollow concrete masonry units (f_b) and mortar strength (f_m):

$$f_k = 0.40 \cdot f_b^{0.7} \cdot f_m^{0.3} \tag{3}$$

For the experimental values obtained (f_b = 9.846 N/mm^2 and f_m= 5.110 N/mm^2), f_k is 3.23 N/mm^2. The elastic modulus was obtained for a tension value which is one third of f_k, as defined in Eurocode 6. Tests indicated a mean value of 5.472 GPa. The tests carried out for the determination of elastic modulus (Figure 6) were preformed as defined in EN 1052-1:1998 (CEN, 1998).

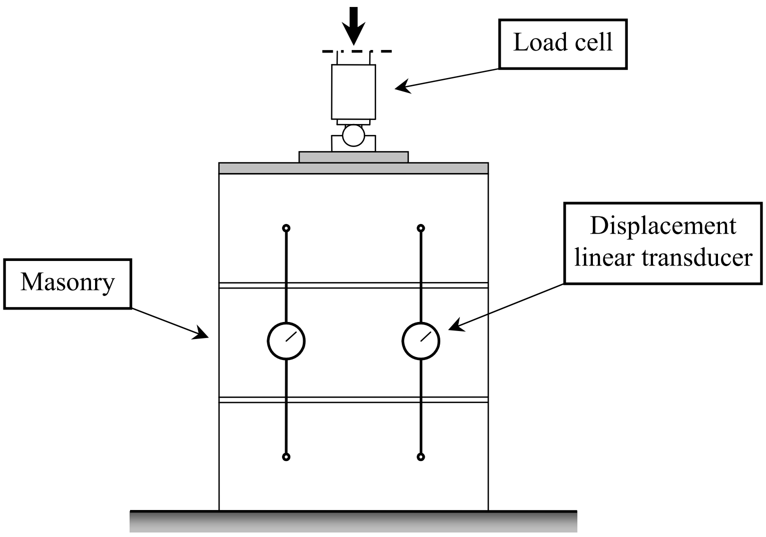

Figure 6: Elastic modulus prism test.

3. STRUCTURAL ANALYSIS

To verify if it is feasible to build Azores traditional dwellings with confined masonry, according to Eurocodes 6 and 8, an adaptation of a two storey Graciosa old rural house plan (Tostões *et al.*, 2007) was used, as presented in Figure 7.

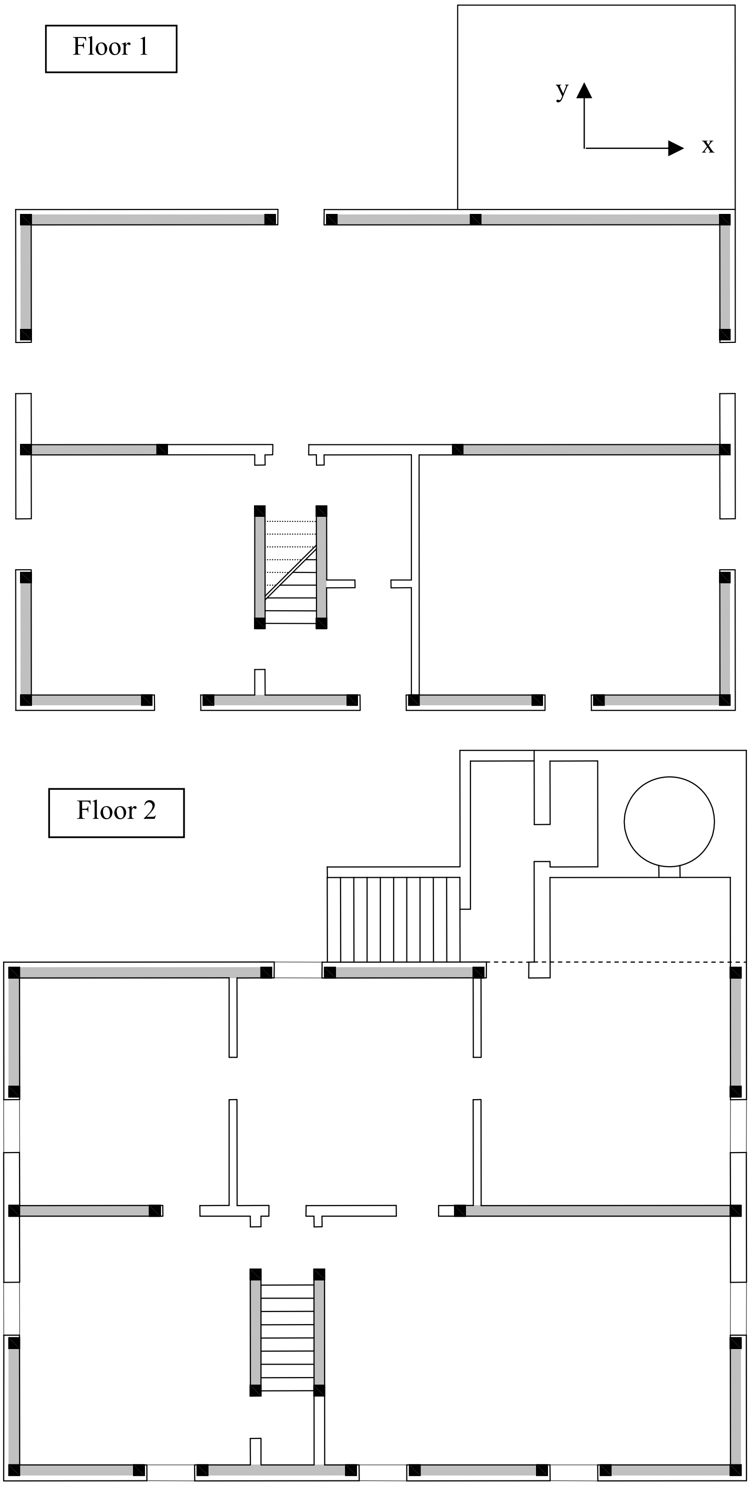

Figure 7: Architectural plan with the definition of primary structural walls (shaded areas) and confining vertical elements (■).

The detached wood-fired oven was considered structurally independent from the main building by a seismic joint to reduce the torsion effects.

Vertical concrete confining elements localizations follow Eurocodes 6 and 8, and the masonry walls located between them (shaded area of Figure 7) were considered as primary seismic elements. The remaining walls were considered as secondary seismic elements, and their end moments were released in the model.

Masonry structural analysis was carried out with a three-dimensional equivalent frame model (Figure 8) because of the simplicity of the analysis in terms of structural design, and because it is a method that gives good results in comparison with more sophisticated methods (Kappos *et al.*, 2002).

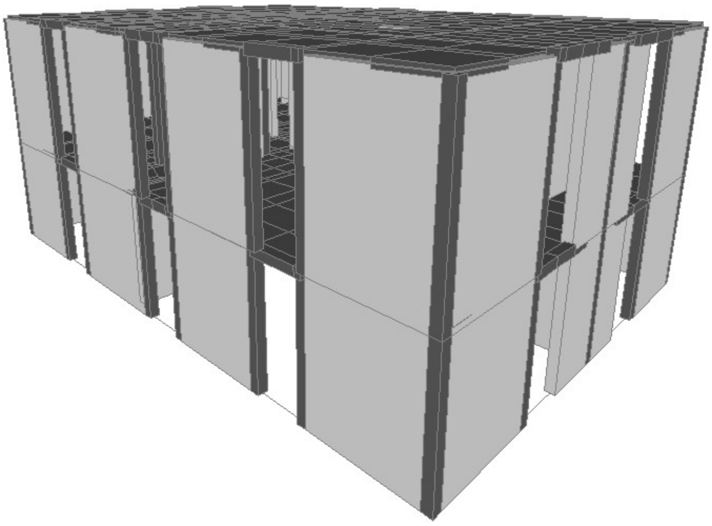

Figure 8: Three-dimensional equivalent frame structural model.

Reinforced concrete floors (0.15 m) were considered and modelled by finite elements. Staircases were also modelled by finite elements.

Concrete C20/25 was adopted for all elements.

The masonry stiffness and vertical confining concrete elements stiffness were taken as one-half of the corresponding stiffness of the uncracked elements.

Seismic analysis was carry out with the Portuguese EC8 National Annex proposal for the near field earthquake response spectrum (Carvalho, 2007), for zone 1 and ground type A (a_g= 170 cm/s^2, S= 1 , T_B= 0.1 s, T_C= 0.25 s and T_D= 2 s). A modal response spectrum analysis was performed with two orthogonal components of horizontal seismic action. The structure response maxima values were estimated by the Complete Quadratic Combination of individual vibration modes contribution, and by the square root of the sum of the squared values of the action effect due to each horizontal component.

The results were obtained with a behaviour factor of two, the lower value that is presented in Eurocode 8 for confined masonry design.

The computer program SAP200 (Computers & Structures, 2005) was used for the structural seismic analysis.

Seventeen vibration modes were needed to mobilize 99% of the total mass, because many floor local vertical vibration modes present a lower frequency value than the horizontal ones, due to masonry walls high stiffness, and because of the existence of lower frequency value torsion modes. The modal mass contribution of the most important vibration modes that involves the horizontal floor displacements are presented in Table 1.

The design base shear forces that result from the contribution of the seventeen modes that were considered in the seismic analysis were $F_{b,x}$= 493.54 kN and $F_{b,y}$= 560.45 kN.

Table 1 – Modal mass contribution of most important vibration modes

Mode number	Period (s)	X modal mass (%)	Y modal mass (%)	X modal mass sum (%)	X modal mass sum (%)
1	0.180416	0	81.074	0	81.074
2	0.117657	48.874	0.118	48.874	81.191
3	0.108323	35.070	0.218	83.944	81.409
9	0.063281	0	17.180	84.045	98.781
17	0.045151	9.443	0.155	99.122	99.623

4. STRUCTURAL SAFETY

To verify the safety of the structure a comparison between the resisting masonry wall values and the acting design values was carried out.

For each design axial force acting on a wall, the resisting moment was obtained throught the equilibrium of sectional forces at flexural failure, assuming a rectangular stress distribution (Tomaževič, 1999).

The shear resistance of each wall was obtained as proposed by Eurocode 6, being equal to the sum of the shear resistance of the masonry and of the concrete of the confining vertical elements. The resistance of the vertical confining elements resulted from the application of the Eurocode 2 rules (CEN, 2004c), without considering the shear reinforcement. The calculation of the shear resistance of the masonry walls was carried out following the Eurocode 6 rules for unreinforced masonry walls, considering for *Lc* the length of the masonry element:

$$V_{Rd} = \underbrace{f_{vd} \cdot t \cdot L_c}_{\textbf{EC6}} + \underbrace{V_{Rd,c}}_{\textbf{EC2}} \tag{4}$$

in which t is the masonry wall thickness, and f_{vd} is the design value of the shear strength of masonry, considered equal to the characteristic value obtained from the laboratorial tests divided by a partial factor of three.

For the contribution of shear base resistance there are 28.45 m of seismic primary resistance confined masonry walls in X direction, and 12.50 m in Y direction. Eight vertical reinforcing bars (10 mm diameter) were considered in each of the twenty five vertical confining concrete elements (0.20×0.20 m).

All the confined walls satisfy the Eurocodes safety requirements. The total base shear resisting forces obtained, without considering wall cement render and neglecting the compression effect, were $F_{b,Rd\ x}$ = 1020.37 kN and $F_{b,Rd\ y}$ = 777.02 kN. These values are much higher then the acting design forces ($F_{b,x}$=493.54 kN and $F_{b,y}$=560.45 kN), suggesting that the structure probably could resist to a higher seismic action.

5. CONCLUSIONS

Based on the conducted experimental tests and the numerical seismic analysis, it seems that it is feasible to design traditional Azores dwellings with confined masonry structures made with hollow concrete units. If the architectural plan adopted has regular geometry, and if a seismic joint to make the wood-fired oven structurally independent is considered, stresses will probably be uniformly distributed through the walls, and safety demands will be verified.

The results obtained in the present work seem to indicate that the cement render has an important contribution to the initial masonry shear strength. The tests revealed an increase of more than fifty percent in the characteristic initial shear strength when considering triplets with cement render (±1 cm thickness). Because

global seismic resistance of confined masonry is dependent on masonry shear resistance, the contribution of masonry cement render can reduce the seismic risk of new and old masonry constructions.
Further investigations should be carried out to evaluate the mechanical characteristics of Azores hollow concrete masonry considering local materials.

6. ACKNOWLEDGMENTS

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