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INFLUENCE OF DISTINCT REINFORCING SCHEMES ON THE SHEAR RESSISTANCE OF MASONRY

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One of the major concerns about the use of unreinforced masonry in seismic prone regions is its inadequate behavior under seismic loads, which has been shown from recent earthquakes. If fact, it has been seen that unreinforced masonry buildings present commonly considerable in-plane damage, which is associated to the low shear resistance of unreinforced masonry and to low capacity to dissipate energy. The improvement of the overall behavior of structural masonry under shear can be achieved by the addition of horizontal and vertical reinforcement. Tgis paper presents the results of a series of diagonal compression tests carried out on concrete block masonry with distinct types of reinforcement's arrangements. It was seen that the better configuration for the reinforcement arrangement is the combination of vertical and horizontal reinforcements leading simultaneously to the improvement of shear strength and ductility.

Keywords: *concrete block masonry, diagonal compression tests, truss type reinforcements, shear strength*

INTRODUCTION

Over the last decades considerable research has been conducted on masonry structures. Masonry walls were mainly designed to bear gravity loads in spite of they have also an important role in improving seismic resistance and in global stability of masonry buildings since they can afford significant horizontal loads induced by earthquakes, which led to the idea that unreinforced masonry walls behave inadequately under seismic loading, being not allowed in zones with moderate to high seismic hazard. The brittleness of the failure of unreinforced masonry shear walls, which is more remarkable with high axial loads, may be reduced by the use of steel reinforcement. The role of the horizontal reinforcement on the shear resistance of masonry walls has been investigated in recent past in the perspective of the development of novel solution for reinforced masonry walls (Haach, 2009, Haach et al., 2010, Haach et al., 2011; da Porto et al., 2011). According to the findings of Haach et al. (2011), it was seen that the influence of the horizontal reinforcement can be moderate if flexural mechanisms predominates over shear resisting mechanisms.

Thus, the main goal of the present paper is to evaluate the influence of distinct arrangements of horizontal and vertical reinforcement, namely truss type reinforcements, on the shear strength of concrete block masonry. This is made based on diagonal compression tests, when shear stresses predominate. Diagonal compression tests have been used by several authors to evaluate the shear behavior of masonry (Corradi et al., 2008, Gabor et al., 2006, Valuzzi,

2001; Kubica and Kaluza, 20.11). Recently Calderini et al. (2010) have proposed the use of diagonal compression tests to derive the shear resisting properties in case of masonry in which crack patterns develop along the unit-mortar interfaces.
Besides, unreinforced concrete block masonry has been tested as a reference, masonry specimens with horizontal truss type reinforcement, specimens with vertical reinforcement placed in a vertical continuous joint a distinct combinations of vertical and horizontal reinforcement have been considered.

EXPERIMENTAL CAMPAIGN

In order to assess the influence of the bed joint and vertical truss type reinforcements in the shear strength of concrete block masonry, it was decided to carry out diagonal compression tests, in which it is supposed to develop pure shear considering distinct reinforcement arrangements, see Figure 1.

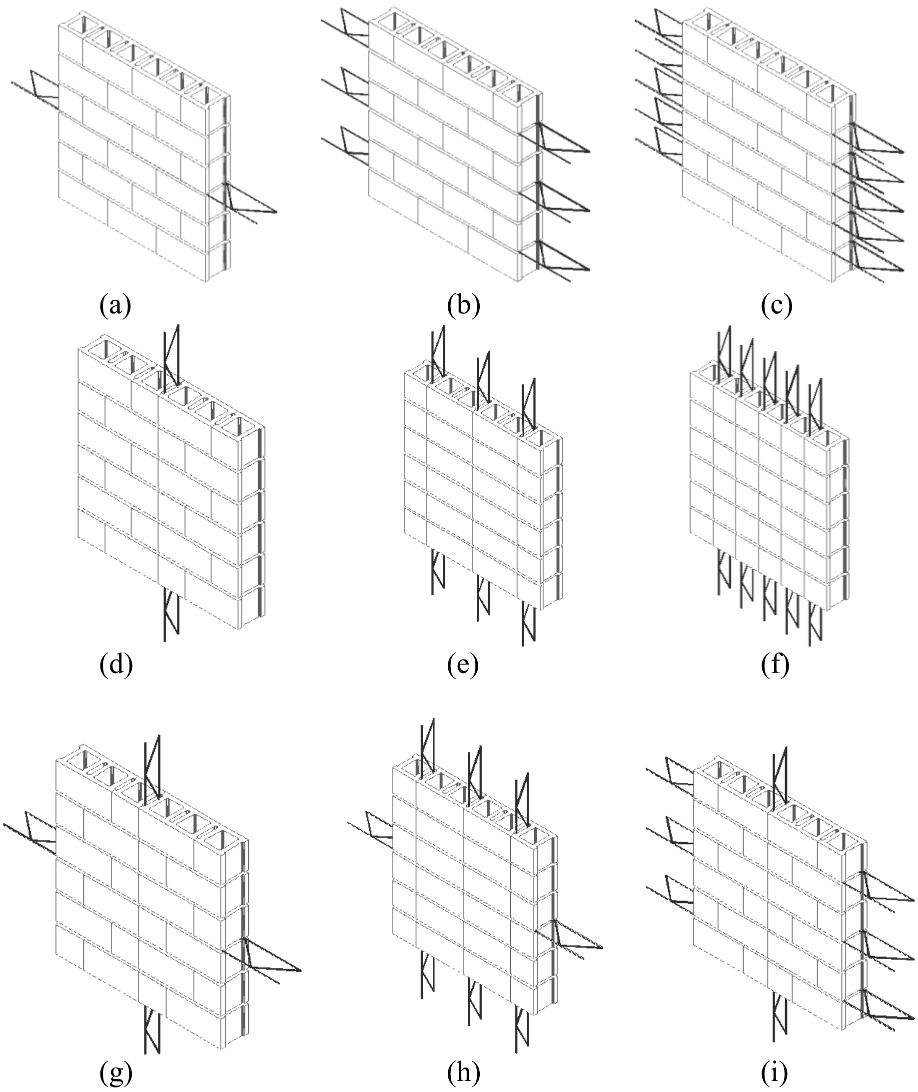


Figure 1: Reinforcement arrangements for the vertical and horizontal reinforcements; (a) specimen HRM1; (b) specimen HRM2; (c) specimen HRM3; (d) specimen VRM1; (e) specimen VRM2; (f) specimen VRM3; (g) specimen VHRM2 (h) specimen; VHRM2; (i) specimen VHRM3

This hypothesis is considered in international normalization (ASTM E519-02, 2002; Rilem, 1994) and was considered by Brignola et al. (2009) as acceptable since the non-linear range the stress redistribution occurring in the panel does not significantly affect the value of maximum principal stress.
The influence of the vertical and horizontal reinforcement on the lateral strength of masonry walls was studied in a recent past based on shear wall tests (Haach et al., 2010).
However, it should be said that the boundary conditions found for this type of tests (cantilever walls) can induce flexural behavior leading to the difficulty of evaluating the influence of the reinforcement arrangements on the shear lateral strength. In fact, according to the parametric study pointed out by Haach et al. (2011), the influence of vertical and horizontal reinforcement is dependent on the stress field developed in the masonry, which is also related to the boundary conditions. In cantilever walls, flexural mechanisms can be predominant, leading to ambiguous conclusions about the role of the horizontal and vertical reinforcement on the shear resistance of concrete block masonry walls. From the numerical parametric study, it was evident that the contribution of the horizontal reinforcements to the shear resistance, when fixed ended boundary conditions were considered, meaning that the horizontal reinforcement works when shear mode prevails.
Therefore, aiming at having more clear ideas about the effect of the horizontal, vertical and the combination of vertical and horizontal truss type reinforcements on the shear resistance of concrete block masonry, nine reinforcement arrangements, corresponding mainly to distinct spacing for the vertical and horizontal reinforcements were adopted, see Table 1. The specimens have 600mm length, 605mm height, corresponding to six rows and 5 bed joints of about 8mm. The adopted dimensions for the specimens are related to the concrete blocks produced at half scale so that representative specimens could be found and with the recommended dimensions given by ASTM E519-02 (2002). The half blocks were also used in reduced scale masonry buildings tested at the shaking table of the National Laboratory of Civil Engineering (LNEC) (Avila et al., 2012). The truss type reinforcements have 60cm length and the spacing of the diagonal is 20cm. The latter dimension is approximately half of the commercial one so that the half scale of the blocks is considered.

Table 1. Reinforcement percentage for each configuration

Specimen tipology	**Number of speciemens**	**ρ_h(%)**	**ρ_v(%)**
HRM1	3	0.024	-
HRM2	3	0.071	-
HRM3	3	0.118	-
VRM1	3	-	0.042
VRM2	3	-	0.126
VRM3	3	-	0.209
VHRM1	3	0.024	0.042
VHRM2	3	0.071	0.042
VHRM3	3	0.024	0.126

The diameter of the longitudinal bars used for the horizontal direction was 3mm and for vertical direction was 4mm, according to the configuration adopted in the construction of the half scale masonry buildings (Avila et al., 2012). The percentage of reinforcement corresponding to the adopted configurations is presented in Table 1. It should be noticed that some reinforcing configurations lead to considerable high reinforcement ratios.

As can be seen from Figure 1, the unreinforced masonry wallets were tested with traditional masonry bond with unfilled vertical joints to work as a reference. The specimens where only horizontal reinforcements were placed had also running masonry bond. The European code, EC8 (2004) requires the filling of the vertical joints with masonry mortar in case of masonry is used in seismic regions. However, as previously mentioned, in the scope of previous research, studies were carried out to validate the seismic performance of concrete block masonry with unfilled vertical joints. Note that the construction technology can be considerable made easier and some increase on the productivity can be obtained. On the other hand, the specimens with vertical reinforcements have vertical continuous joints so that the construction technology in real buildings can be simplified. In fact the blocks used are two cell blocks with end frogs, where vertical truss type reinforcements can be placed (Haach, 2009). The vertical continuous joints, formed by the frogged ends of the concrete block units, have about 10mm and were filled with the general purpose mortar used for the laying of the units.

The specimens were built with general purpose cement mortar in a proportion in volume of cement and sand of 1:3. The control of the construction quality was made by gathering mortar used in the construction of the specimens and further tested under uniaxial compression and flexure. The specimens were cured at laboratory environmental conditions in a place where the air relative humidity is almost constant and approximately equal to 65%.

The concrete blocks were also tested under uniaxial compression. The mean compressive strength obtained for mortar, taken as the average of 12 specimens, was of 18.77MPa, with a coefficient of variation of 12.4%. The mean compressive strength obtained for the concrete blocks, taken from the average of 12 specimens, was 11.41MPa with a coefficient of variation of 15.5%.

The diagonal compression tests were carried out according to the recommendation of ASTM E519-02 (2002). The vertical load was applied by mean of servo-controlled actuator, connected to a steel frame, with a load cell of 200kN, see Figure 2. The diagonal compression tests were carried out under displacement control, by means of a LVDT placed in the vertical actuator, at a rate of 2µm/s.

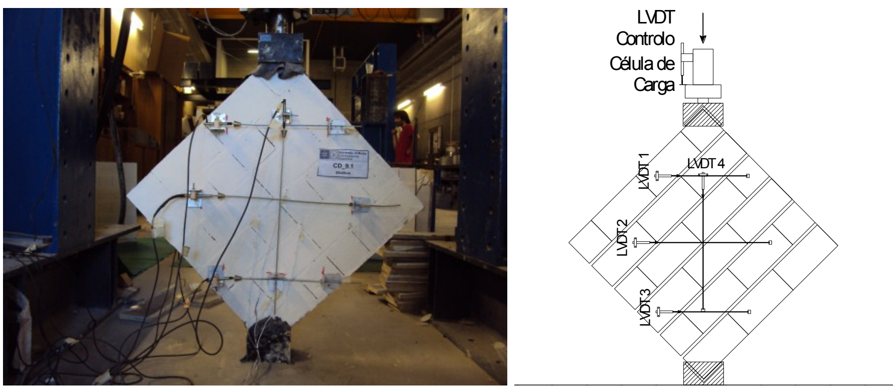


Figure 2: Instrumentation of the specimens

To measure the vertical and horizontal deformations, linear voltage displacement transducers (LVDT) were used, according to the arrangement shown in Figure 2. One LVDT was positioned at each surface of the specimens and three LVDTs were placed in both surfaces of the specimen.

Due to irregularities of the surfaces, it was decided to apply a high strength mortar reinforced with glass fibers to level the surface where the steel angles are to be placed. In this way, it was possible that the vertical load was applied uniformly.

ANALYSIS OF RESULTS

The analysis of results is made based on the resistance parameters, force-displacement diagrams and failure modes.

The shear strength of the specimens was calculated according to ASTM E519-02 (2002), being given by eq. 1, where P is the vertical load applied and A_n is the horizontal gross section of the specimens. The shear deformation is calculated based on eq.2, where ΔH and ΔV are the deformation measured along the compressed and tensioned diagonals and g is the width of the diagonal of the panel. The shear modulus is calculated by the ratio between the shear stress and the shear deformation, see eq. 3.

$$\tau = 0.707 \cdot \frac{P}{A} \quad (1)$$

$$\gamma = \frac{\Delta V + \Delta H}{g} \quad (2)$$

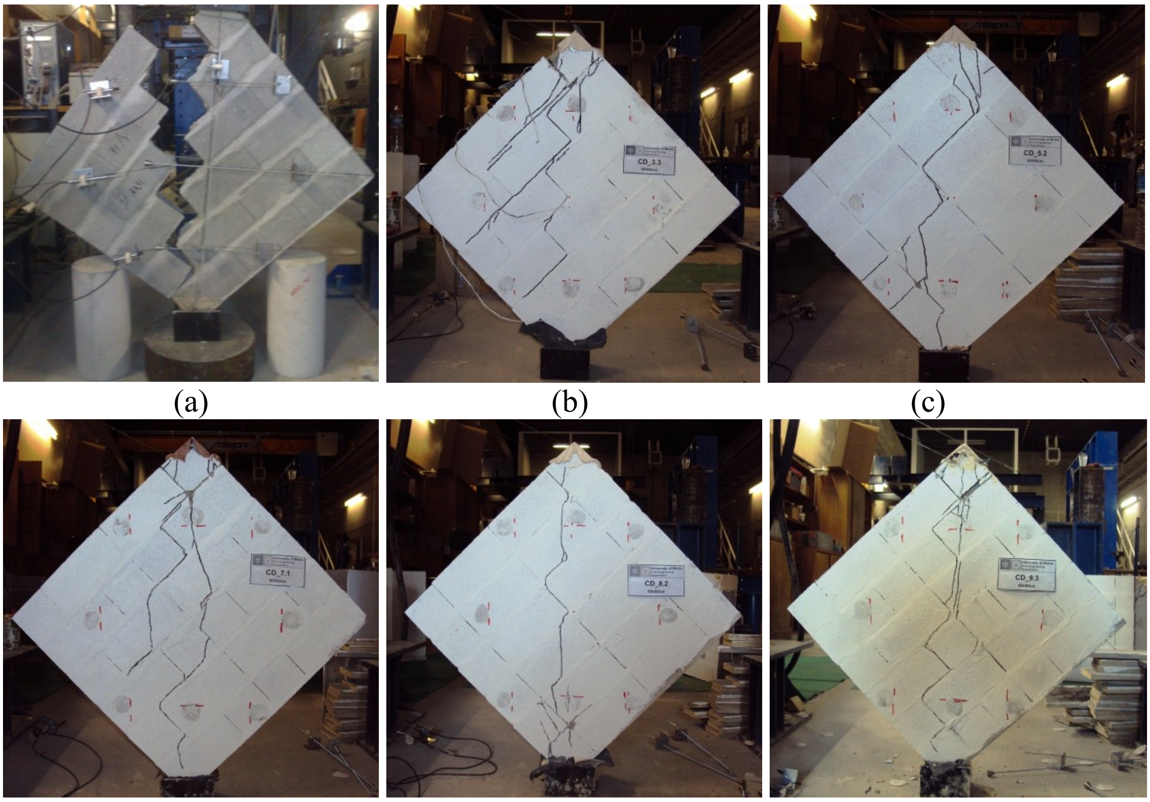
$$G = \frac{\tau}{\gamma} \quad (3)$$

Failure modes and force-displacement diagrams

Similarly to what happened in previous researches (Calderini et al., 2010, Kubica and Kaluza, 2011), the typical failure mode found in current modern unreinforced masonry composed of regular units and submitted to diagonal compression load results from the opening of a stair stepped crack along the unit-mortar interface developing in the direction of load. The crack developed in the perpendicular direction to the tensile stresses, meaning that it appears when the tensile stress in masonry is reached. The failure of unreinforced masonry occurs suddenly being considered very brittle, see Figure 3a. According to Haach (2009) and Kubica and Kaluza (2011), the unfilling of vertical joints appears not to significantly influence the crack patterns and failure modes of unreinforced masonry, even if it can clearly influence the shear strength of masonry.

In the presence of horizontal reinforcement, the crack pattern is composed also of a stair stepped crack but with horizontal branches developed along the horizontal joints, where horizontal reinforcement is placed, see Figure 3b. These secondary horizontal branches can be related to the stress redistribution between masonry and reinforcement. After opening the first diagonal crack, stress redistribution occurs between masonry and steel, leading to the increasing of the tensile deformation of the reinforcement, which results in the breaking of the unit-mortar shear bond. This effect is particularly evident when only one horizontal reinforcement in placed in the central bed joint. The influence of the horizontal reinforcement in the shear behavior of masonry can be also seen from Figure 4a and Figure 4b, where the stress-strain diagrams are displayed for unreinforced and horizontally reinforced masonry

respectively. It can be seen that a first peak of load is reached, corresponding to the opening of the diagonal crack, after which the tensile strength of the masonry is increasing for increasing displacements. It is seen that the addition of horizontal reinforcement contributes definitely for the improvement on the shear resistance for ductility of masonry. Notice that both ultimate horizontal and vertical deformations clearly increase when horizontal reinforcement is added. This is also true for the vertical strain corresponding to the peak shear stress. In general, the stress-strain diagrams present an initial high stiffness and a great linear extent and only in the neighborhood of the peak stress, the non-linear behavior develops.
The increase on the horizontal reinforcement ratio contributes also for the increase on the shear strength of masonry. The increase on the shear strength is of 21% for the addition of one steel truss type reinforcement, and of 76% and 109% in case of addition of two and three truss type reinforcements at bed joints, see Table 2. The shear strength of unreinforced masonry obtained in this work is practically the double in relation to the value pointed out in Haach et al. (2010) for the same type of masonry (0.19MPa). This can be associated to the much better resistance of mortar obtained in this work resulting also is a better shear bond of the concrete block-mortar interface. Notice that given the cracking pattern developed along the unit-mortar interfaces, the shear bond strength plays an important role on the shear strength of masonry.
The addition of vertical reinforcement contributes also for the improvement on the shear strength of masonry. The shear strength of masonry, where one central vertical truss type reinforcement was added, is about 2.2 times the shear strength obtained in unreinforced masonry.



(a) (b) (c)

(d) (e) (f)

Figure 3: Crack patterns for distinct reinforcement configurations; (a) unreinforced masonry; (b) specimen HRM3; (c) specimen VRM2; (d) specimen HVRM1 (e) specimen HVRM2; (f) specimen HVRM2

It should be mentioned that the considerable improvement on the shear strength is attributed to the presence of vertical reinforcement combined with the filling of vertical continuous joint, where the vertical reinforcement is placed.

Notice that, according to what was mentioned above, the vertical continuous joints have about 10mm. With this respect, it should be mentioned that Haach et al. (2010) pointed out an increase of about 25% on the shear strength in case of filling the vertical joints. This means that, in any case, the contribution to the resistance of vertical reinforcements is considered. The shear strength increases to 2.8 and to 2.7 times the shear strength obtained in unreinforced masonry when three and five truss type reinforcement bars were added. The slight decrease obtained for the latter reinforcement arrangement is related to the limitation of the shear stress by the cracking of the concrete blocks.

In fact, for the highest vertical reinforcement ratio, it is seen that there is a trend for the compressive crushing of the concrete blocks, see Figure 3c. The cracking patterns defined in the specimens with vertical reinforcement involves cracking at the unit-mortar interfaces but also cracking of the concrete blocks, see Figure 3c.The same behavior follows when a combination of vertical and horizontal reinforcement is present, see Figure 3d-f.

The introduction of vertical reinforcement and particularly the increase on the vertical reinforcement ratio result in the increase on the brittleness of the concrete block masonry.

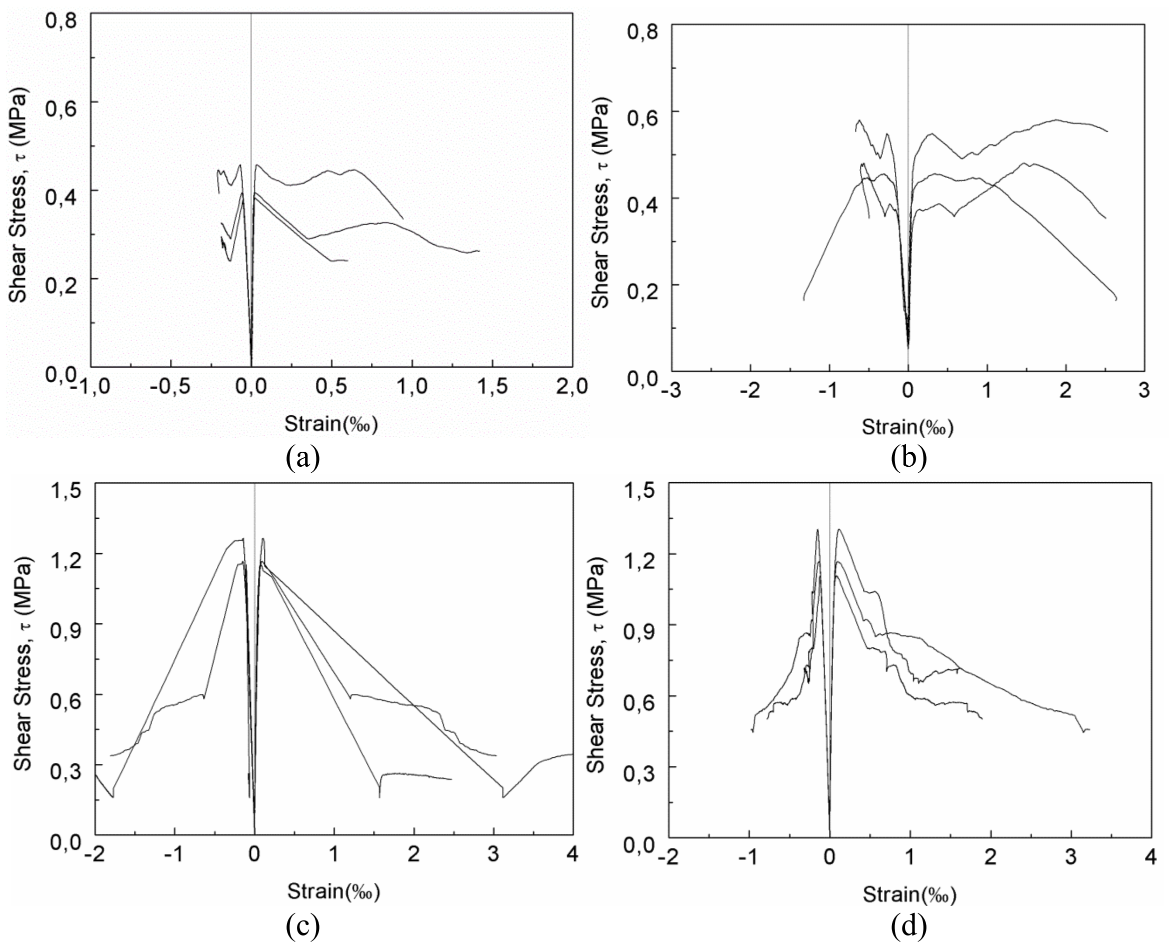


Figure 4: Shear stress-strain diagrams; (a) unreinforced masonry; (b) specimen HRM1; (c) specimen VRM2; (d) specimen VHRM2

From Figure 4c, where the stress-strain diagram for the specimen VRM2, corresponding to the existence of three vertical reinforced continuous vertical joints, is presented, it can be seen that there an abrupt decrease on the shear strength, even if some recover of the strength for increasing displacements occurred.
In case of the highest vertical reinforcement, there was no record of the post peak behavior. The brittleness of the vertical reinforced masonry is clearly enhanced when horizontal reinforcement is added.
In Figure 4d, where the stress-strain diagram obtained for the specimen VHRM2 (specimen with three vertical reinforcements confined with the presence of one horizontal reinforcement at bed joints), is shown, it can be observed that the post-peak is characterized by a much more smooth diagram corresponding to a progressive decrease of the shear strength with increasing deformations. This behavior is the difference of having or not the central bed joint reinforcement, see Figure 4c and Figure 4d. This means that behavior of concrete block masonry can be improved by the addition of a combination of vertical and horizontal reinforcement. Besides the increase on the shear strength in relation to the unreinforced solution, there is an improvement of the deformability of masonry by applying horizontal reinforcements, leading to considerable ductile behavior.
It should be mentioned that the masonry bond did not influence the crack patterns, which can be observed through the crack patterns found in case of specimens with reinforced continuous vertical joints. The crack patterns could follow simultaneously the interfaces as both bed and head joints.
From the value of shear modulus pointed out in Table 2, it is observed that mean value obtained for the unreinforced masonry is considerable high in comparison to the value obtained by Haach et al. (2010) for the same type of masonry. This can be attributed to the better quality of mortar used in the construction of the specimen tested in this work. The horizontal reinforcements contribute to the increase on the shear stiffness (maximum increase of 14%). The increase on the shear modulus associated to the addition of vertical reinforcements can be attributed both to vertical reinforcements and to the filling of vertical joints with mortar. The individualization of each effect should be further studied by testing masonry with unreinforced continuous vertical joints filled with mortar.

Table 2. Shear strength and shear modulus

Specimen tipology	τ (MPa)	G (GPa)
UM	0.42	4.05
HRM1	0.51	3.82
HRM2	0.74	4.48
HRM3	0.88	4.63
VRM1	0.92	4.74
VRM2	1.20	7.50
VRM3	1.15	7.37
VHRM1	0.91	4.83
VHRM2	1.20	7.24
VHRM3	0.87	4.64

CONCLUSIONS

This paper presents the results of diagonal compression tests of concrete block masonry reinforced with distinct reinforcing arrangements, namely bed joint and vertical truss type reinforcements. The idea was to evaluate the influence of reinforcement in the mechanical behaviour of masonry under diagonal compression, where shear stress field predominate and isolate the flexural effects which occur in shear walls tests, particularly in case of cantilever walls are tested. From the experimental results some conclusion can be pointed out:

- The behaviour of unreinforced concrete block masonry present is characterized by the opening of stair stepped diagonal cracks following the unit-mortar interfaces. In spite of sliding mechanism along the unit mortar interfaces for ultimate stages, it is seen that unreinforced masonry present a fragile behaviour. The shear cracking occurs suddenly.
- The truss type reinforcement contributes for the increase on the shear strength of masonry, leading to the more ductile response.
- The vertical reinforcement, placed in vertical continuous joints composed by the frogged ends of the concrete blocks lead to the considerable increase on the shear strength but results simultaneously for the more fragility of the reinforced masonry. In this case, the crack patterns I composed by mixed cracking following the unit-mortar interfaces and the concrete blocks.
- The combination of vertical and horizontal reinforcements consist of the better reinforcement arrangement as combine the increase on the shear strength with the improvement on ductility.

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