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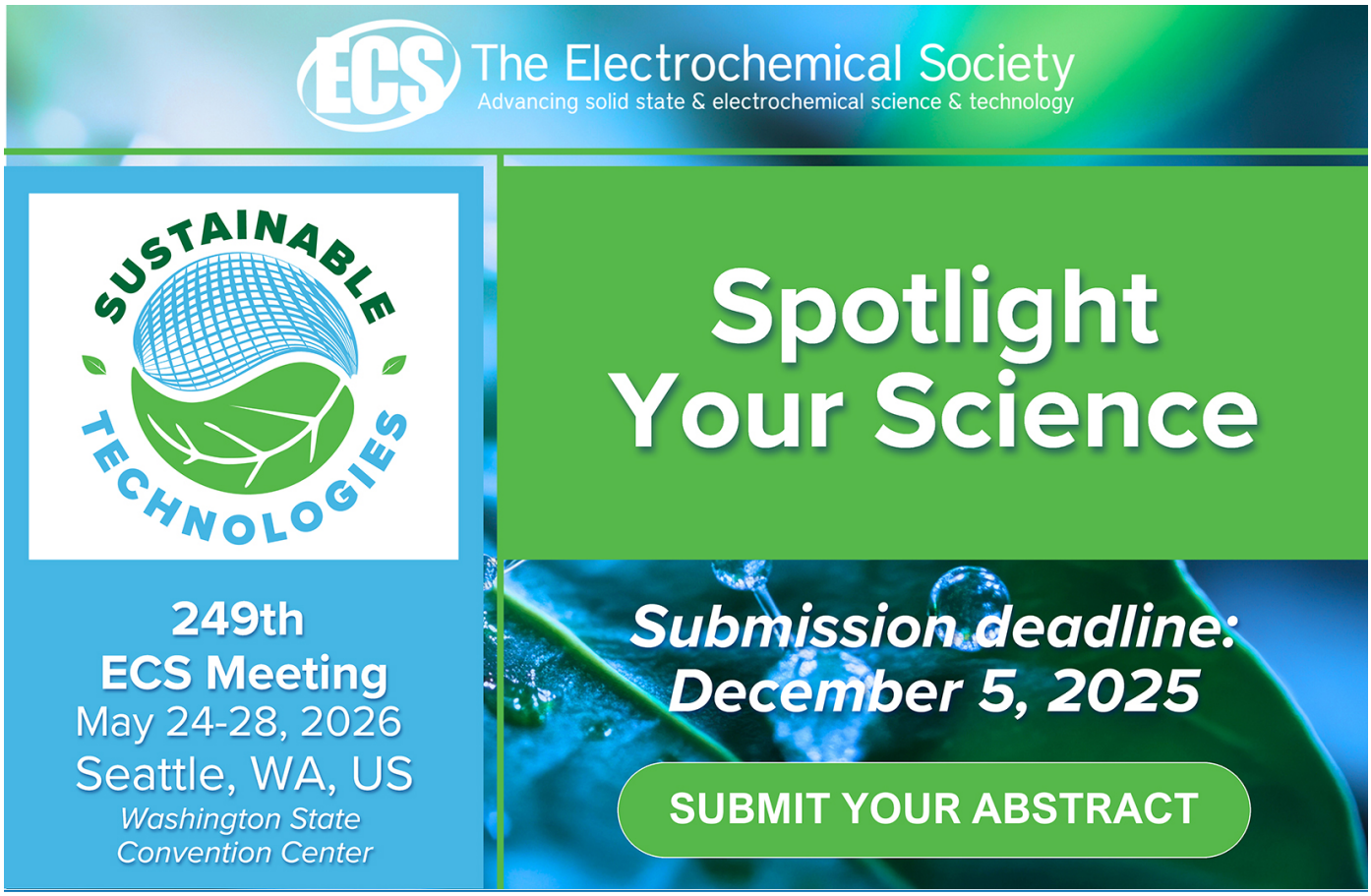
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In-plane behavior of clay blocks externally reinforced

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Abstract. The objective of this research work was to determine the resistance to cutting of clay block walls of size 1.20 $m \times 1.20$ m without and with external reinforcement. Blocks of width equal to 0.10 m were used for four manufacturers, one located in Ocaña, Colombia, and three more established in San José de Cúcuta, Colombia. Reinforcement with electrowelded mesh is an alternative to reduce the seismic vulnerability of homes in areas of intermediate and high seismic risk. Ocaña, Colombia, is located in an intermediate seismic hazard zone and therefore the use of simple masonry in homes is not allowed. This made it necessary to determine the mechanical properties of the clay block pieces, such as compressive strength, compressive strength of the bonding mortar, compressive strength of clay block prisms, diagonal tensile strength, modulus of elasticity and shear modulus of reinforced and unreinforced walls. The tests were carried out on a universal machine with a compression capacity of 100 t, a tensile capacity of 60 t class B with a precision of $0.1\% \pm 0.05$ mm. This research established the physical parameters of the clay block prisms and the physical behavior of shear deformation vs. Shear stress without and with exterior reinforcement, necessary to establish physical models of structural reinforcement of houses vulnerable to seismic movements, and with this avoid human losses.

1. Introduction

Unreinforced masonry is one of the most widely used non-structural systems in Latin America; one-, two-, and three-story houses are built without proper seismic precautions and have generated human losses in recent years, mainly due to the use of this type of unreinforced masonry (URM). Despite advances in seismic engineering in recent years, URM buildings are the main cause of human and economic losses during seismic events, as observed during the earthquakes of Ankara [1] and Oaxaca [2]. During an earthquake, horizontally perforated fired clay block walls (HPFCB) are subject to both in-plane and out-of-plane loads. URM walls are very weak in out-of-plane flexural action due to the extremely low tensile strength of the mortar-brick interface and resist primary lateral loading in in-plane action. This makes the URM vulnerable to seismic action and must be controlled to avoid claims of lives.

The door and window openings in the walls are sources of weakness in the in-plane action of the walls; openings result in a reduction of the effective cross-sectional area of walls resisting lateral loads. The columns (wall section without openings) between door and window openings

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are the most critical components resisting in-plane forces; these are subject to higher stresses than the wall portions above and below the openings. Depending on the critical action, the columns may fail in sliding shear, diagonal cracking, toe crushing, or rocking failure modes [3–8]. Masonry has predefined planes of weakness along the mortar-brick joints; for low-rise buildings with low normal (vertical) stress at the bond joints, sliding is the main failure mode, since masonry provides resistance against sliding failure primarily through friction at the joint. Columns have a higher vertical load and may fail in diagonal shear as a result of the combination of vertical and lateral loads; cracks follow the plane of principal stresses exceeding the tensile strength in the plane of the masonry.

Reinforcement of masonry walls using externally bonded or embedded near-surface welded mesh (WME) is the simplest and most cost-effective way to reinforce URM buildings [9–11]. Research carried out by the latter three investigators showed that the lateral load capacity improved and the damage mechanism was transformed from the mixed compression-flexion-shear mode to a bending-rocking mode. Among several tests, this research carried out the diagonal tension test; 24 walls were built, 8 without external reinforcement and 16 externally reinforced with $150 \times \ mm \times 150\ mm \times 3.5\ mm \times 3.5\ mm$ electro-welded mesh. The tests were carried out until failure, showing diagonal tensile failure in both types of walls, without and with external reinforcement [6, 12].

2. Materials and methods

To estimate the in-plane resistance of the walls, a sample of HPFCBs commercialized in the municipality of Ocaña, Colombia, was taken for the characterization of their mechanical properties. In this work, the manufacturers are identified as F1 to F4 that is, F1, F2, F3, and F4.

As established in the Colombian technical norm (NTC), NTC 4017 [13], geometric measurements of the block are made, then the drying is done using a muffle furnace, subjected to temperatures between 110 ^oC and 115 ^oC for a time not less than 24 hours. After the drying process, two successive weightings are carried out at 2-hour intervals, verifying that there is no loss of mass greater than 0.2% of the last weight of the sample previously determined. After drying, the specimens are stored without stacking them in a room with a controlled temperature of 24 $^oC \pm 8\ ^oC$ and a relative humidity between 30% and 70%; once the units are cooled, the process of gypsum plastering is started on the two opposite load faces of each sample without exceeding 3.2 mm.

The plaster samples should have at least 24 h before being tested. At the time of testing, the units should be placed in such a position that the load is applied in the direction in which they will be put into service. The samples are centered under a 20 mm thick steel sheet, attached to a previously calibrated 20 t hydraulic jack, which in turn is connected to a muffle furnace multiplexer, which is connected to a computer that translates the information into numerical data.

3. Results

Table 1 shows the results of the test, where f'_{cu} represents the compressive strength in masonry units, while $\bar{f'_{cu}}$ is the average value of the strength. Table 1 shows the compression results of the H-10 masonry pieces, whose maximum value was for manufacturer 4 with $\bar{f'_{cu}} = 59.85$ kgf/cm^2 and whose minimum value was for manufacturer 3 with $\bar{f'_{cu}} = 44.65$ kgf/cm^2.

The coefficients of variation are similar except that of the manufacturer F3 since it presents a value of 59.11 kgf/cm^2. The compressive strength in horizontally perforated clay blocks does not differ between manufacturers, that is, they are similar, otherwise with the other manufacturers. A representation of the data in a graphical way that allows observing the variation between the extreme and average values can be observed in the BoxPlot diagram, see Figure 1.

Table 1. Average compressive strength of horizontally perforated fired clay units by manufacturer.

Manufacturer	Area (cm^2)	f'_{cu} (kgf/cm^2)	$\bar{f'_{cu}}$ (kgf/cm^2)
F1	285.05	62.88	58.56 (13)
	283.38	58.53	
	279.89	46.68	
	282.49	67.20	
	282.15	57.50	
F2	303.72	46.36	47.65 (11)
	306.66	54.25	
	303.60	50.54	
	308.28	45.68	
	310.57	41.42	
F3	291.10	41.12	44.82 (18)
	292.05	40.78	
	292.73	41.03	
	282.35	42.04	
	283.41	59.11	
F4	301.77	68.41	59.85 (12)
	299.38	56.38	
	302.16	64.66	
	300.31	49.92	
	300.62	59.89	
Average			52.66 (14)

() Coefficient of variation, %

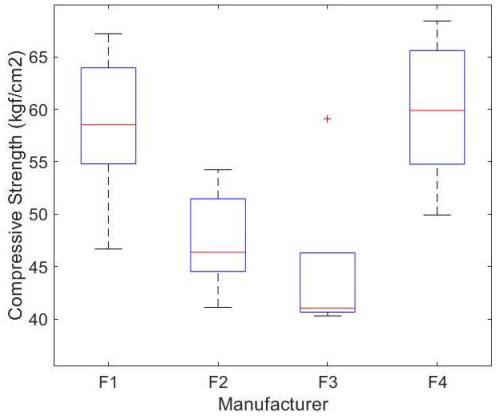


Figure 1. Compressive strength in units per manufacturer.

The results of manufacturers F1 and F4 are similar, while manufacturer F3 presents an atypical value (59.11 kgf/cm^2), which when neglected makes the average value decrease to 41.24 kgf/cm^2, this being the manufacturer with the lowest compression capacity. These results indicate that the manufacturer F3 has significantly the lowest resistance to compression, and

also has the highest dispersion. This may be due to problems in the mixture of clays and silts, lack of cooking, low temperatures, among others.

Twelve compression tests were performed on masonry prisms, 3 per manufacturer with double linear variable differential transformer (LVDT), one per face to avoid load distortion. Three compressive strength tests were carried out on glue mortar cubes($f'cp$) per manufacturer, with an average value of 13.83 MPa with a standard deviation of 0.91 MPa, a coefficient of variation of 6% and a flow rate of 93.25%.

The results of the compression test on HPFCB masonry prisms are shown in Table 2, where f'^{Exp}_m represents the compressive strength in masonry prisms obtained experimentally, $\bar{f}'^{Exp}_m$ corresponds to the average value of f'^{Exp}_m, E^{Exp}_m is the modulus of elasticity of the masonry obtained from the stress-strain curve of the compressive strength test of H-10 masonry prisms obtained from the slope of the secant taken from the points $0.05f'_m$ to $0.33f'_m$ and $\bar{E}^{Exp}_m$ represents the average value value of E^{Exp}_m.

Table 2. Compressive strength and modulus of elasticity of horizontally perforated fired clay masonry prisms by manufacturer.

Manufacturer	f'^{Exp}_m (MPa)	$\bar{f}'^{Exp}_m$ (MPa)	E^{Exp}_m (MPa)	$\bar{E}_m Exp$ (MPa)
F1	6.33 6.41 6.34	6.36 (1)	410.74 415.93 6491.50	2439.39
F2	5.47 5.63 5.34	5.48 (3)	264.87 1753.85 3724.67	1914.46
F3	6.33 5.97 5.11	5.92 (13)	8306.68 2526.22 487.87	3773.59
F4	6.33 7.86 7.49	7.29 (9)	2566.79 5078.30 4926.48	4190.52
Average		6.26 (7)		3079.49

() Coefficient of variation, %

The manufacturer with the highest average prism compressive strength is F4, while F2 is the manufacturer with the lowest $\bar{f}'^{Exp}_m$. The highest average modulus of elasticity obtained from experimental data is the manufacturer F4 with 4190.52 MPa and the lowest corresponds to the manufacturer F2; there is a direct relationship between f'_m and E_m.

A test program was carried out to investigate the in-plane capacity of URM and the improvement of its shear capacity and ductility [14] after strengthening with WME. Eight HPFCB walls of dimensions 1.20 m × 1.20 m URM and 16 HPFCB walls strengthened with WME of 150 mm × 150 mm × 3.5 mm × 3.5 mm subjected to diagonal compressive loading (in plane shear) were tested. The wires in the wire mesh were oriented perpendicular and parallel to the bed joints of the masonry. The mortar used for plastering the prisms and the 1.20 m×1.20 m walls was made using a 1 : 4 dosage, with an average compressive strength (f'_{cp}) of 18.45 MPa, a coefficient of variation of 20 % and a flow percentage of 89.63%. The average compressive strength of the mortar used for plastering all the walls of the 4 manufacturers is 13.17 MPa, with a coefficient of variation of 9% and a flow percentage of 99.13%.

The results obtained from the diagonal compression test on HPFCB walls without external reinforcement are shown in Table 3. Where τ represents the shear stress, $\bar{\tau}$ corresponds to the average shear stress, γ is the shear deformation, G_m represents the shear modulus of the wall and $\bar{G}_m$ corresponds to the average shear modulus of the masonry wall. This research determined the shear modulus in horizontally perforated fired clay block walls, essential for modeling URM buildings, whose value is $\bar{G}_m = 480.11\ MPa$ for unreinforced HPFCB with a coefficient of variation of 38%, see Table 3.

Table 3. Shear stress and modulus of rigidity in unreinforced H-10 horizontally perforated masonry walls.

Manufacturer	Dimension (m)	τ (kPa)	$\bar{\tau}$ (kPa)	γ (mm/mm)	G_m (kPa)	$\bar{G}_m$ (kPa)
F1	1.20x1.20 1.20x1.20	515.27 805.01	660.14	5.57 5.74	414.06 308.92	361.49 (21)
F2	1.28x1.28 1.28x1.28	748.08 590.15	669.12	2.36 0.83	361.79 699.24	530.51 (45)
F3	1.26x1.26	539.23	539.23	1.93	549.13	549.13
F4	1.25x1.25 1.26x1.26	860.21 833.02	846.62	1.45 3.16	639.43 319.16	479.30 (47)
Average			678.78			480.11(38)

Table 4 shows the results obtained from the diagonal compression test on reinforced BACPH walls. It is observed an increase in the shear stress and in the shear modulus, maintaining the dispersion in the data in a similar way. In the mathematical models that represent the buildings, physical-mechanical parameters that characterize the material are necessary; one way to obtain the modulus of elasticity (E) is through the shear modulus (G), according Equation (1) [15].

$$E = G(1 + \mu), \tag{1}$$

where, E corresponds to the modulus of elasticity and μ is the Poisson's ratio = 0.16, that is, the modulus of elasticity for buildings constructed with externally reinforced horizontally perforated clay blocks (E) corresponds to $767.39(1 + 0.16) = 890.17\ kPa$.

Table 4. Shear stress and modulus of stiffness in reinforced H-10 horizontally perforated masonry walls.

Manufacturer	Dimension (m)	τ (kPa)	$\bar{\tau}$ (kPa)	γ (mm/mm)	G_m (kPa)	$\bar{G}_m$ (kPa)
F1	1.20x1.20	936.89	936.89	1.15	437.46	437.46
F2	1.28x1.28 1.25x1.25	1375.50 1538.54	1457.02	1.70 2.87	1068.30 507.90	788.10 (50)
F3	1.27x1.27 1.25x1.25	1726.57 1704.83	1715.70	2.36 1.53	1064.69 995.88	1030.29 (5)
F4	1.27x1.27 1.27x1.27	1466.44 1466.44	1646.33	2.99 3.10	1114.93 512.47	813.70 (52)
Average			1438.99			767.39 (36)

4. Conclusions

There is an important increase in the modulus of elasticity for externally reinforced horizontally perforated fired clay block walls with respect to unreinforced walls of about 60%, but the most important factor is obtaining the physical parameters that allow the modeling of reinforced buildings. This work opens the door to the reinforcement of unreinforced masonry buildings in intermediate and high seismic hazard zones.

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