A numerical model of the behavior of the resistance to compression in prisms of solid masonry

N Afanador García¹, K A Farelo Alvarez¹, and F Calderon¹
¹ Grupo de Investigación en Ingeniería Civil, Universidad Francisco de Paula Santander, Seccional Ocaña, Colombia
E-mail: nafanadorg@ufpso.edu.co, faucalderonser@gmail.com

Abstract. This research work presents an experimental and numerical analysis of three-dimensional behavior to the compression of masonry prisms with solid brick, in pieces built-in artisanal ovens used in the municipality of Ocaña, Colombia, with the objective to determining deterministically the resistance to uniaxial compression and determine numerical models for structural design purposes. The experimental methodology consisted of determining statistically for solid clay brick units, the initial rate of absorption, final absorption, rupture modulus and resistance to uniaxial compression, and in masonry prisms, to uniaxial compression resistance and modulus of elasticity. The behavior observed in the uniaxial compression test in masonry prisms were validated in a commercial code of finite element modeling. The efficiency of the model makes it possible to predict the uniaxial compressive strength of masonry prisms in solid bricks built in artisan ovens. Allowing to reduce the number of tests in the future and perform probabilistic analysis.

1. Introduction
Masonry constructions constitute an important part of the existing buildings in the city, especially 1 and 2 story houses and buildings of great historical value. The masonry walls are designed mainly to resist vertical loads, and horizontal forces due to seismic events, generating different stress in the plane and out of the plane in these walls. The behavior and pathology of the damage caused due to seismic loads is varied [1]. The most frequent type of failure is the formation of vertical cracks produced in the units by transverse deformations. These faults are highly influenced by the strength of the glues mortar [2].

The use of solid clay bricks built in artisanal ovens is widely used in construction, but due to its construction, it presents high dispersion in its mechanical properties, which does not allow to infer basic parameters of structural design, such as resistance to uniaxial compression and modulus of elasticity in masonry prisms. This is also influenced by the heterogeneity of the prism, given the materials involved [3].

To solve the problem of prism heterogeneity, homogenization techniques have been developed to replace a heterogeneous material with homogeneous material, equivalent in the usual load range [4]. There are homogenization techniques to solve the problem of the heterogeneity of the materials and to represent the structural behavior of the masonry prisms, taking advantage of the periodic configuration of the materials [5]. It [6] obtained homogenization parameters by masonry walls using bricks produced by industrial processes to determine the interrelation
between structural masonry walls arranged orthogonally using finite element models. [7] was the first to use interface elements to model the non-linear behavior of mortar joints, and considered bricks as homogeneous isotropic elastic elements, joined by interface elements, which the fault in the joints between the mortar and the bricks. Other researchers have proposed a brick-mortar interface model by discretizing the unit cell by giving periodicity to the structure using triangular finite elements of flat tension for bricks and finite interface elements for the mortar joints [8]. A finite element model for masonry prisms using 3D solid45 element, with eight nodes, three degrees of freedom per node in the x, y and z directions was used [9]. It was used to establish a numerical model that allows an experimental saving and estimate the stress-strain behavior in masonry prisms.

2. Method
The mechanical properties of solid brick clay units such as compression resistance, rupture modulus, absorption of initial rate and by immersion 24 h were determined, as well as the resistance to compression and fluidity of glue mortars used. Finally the resistance to the uniaxial compression of masonry prisms in solid clay bricks was determined. The uniaxial compressive strength ($f'_{cu}$) in units of solid clay brick is calculated as the ratio between the maximum load ($P_{\text{max}}$) applied and the average of the upper and lower surface area ($A$). The rupture module (RM) is an important property as a criterion of durability and to understand the failure mechanism of the masonry when compression and bending stresses are requested. The brick was subject to a point load in the center of the piece with a loading speed of less than 1.3 mm/min [10]. By registering the fault load and replacing in the Equation (1), the rupture module (RM) is obtained.

$$RM = \frac{3P_{\text{max}}L}{2bd^2}$$  \hspace{1cm} (1)

Where, $P_{\text{max}}$=maximum breaking load (N), $L$ = distance between supports (mm), $b$ = net width of the sample in the failure plane (mm), $d$ = depth of the sample in the fault plane (mm). The variable initial rate of absorption (IRA) was taken into account given that it affects the behavior of the cement mortar as its adherence to the brick. Low adhesion affects the strength of the mortar and the compressive strength of the brick prism. The IRA is defined by Equation (2).

$$IRA = \frac{\text{Final mass} - \text{dry mass}}{\text{Area de contact with water}}$$ \hspace{1cm} (2)

Wherein, the dry mass corresponds to the mass before being in contact with a sheet of water of approximately 3 mm in g, the final mass corresponds to the wet mass after 1 minute of being in contact with the sheet of water in g. The area of contact with water is the area of the exposed brick with the water sheet, i.e. $A$ (mm$^2$). The increase in mass by free absorption of water determined by the immersion for 24 hours at ambient temperature of pieces of solid clay brick. The absorption is defined by Equation (3).

$$\text{Absorption} = \frac{\text{Saturated mass}_{24h} - \text{dry mass}}{\text{Dry mass}}$$ \hspace{1cm} (3)

Where, Saturated mass$_{24h}$ represents saturated mass after immersion in water and dry mass is the dry mass. The resistance to compression of the mortar cube ($f'_{cm}$) and the masonry prism ($f'_{m}$) calculated as $P_{\text{max}}/A$ [10], where $P_{\text{max}}$ represents the maximum applied load and $A$ the average area of the upper and lower surfaces. The fluidity is a property of the mortar and measured in the laboratory, this consists of measuring the increase in diameter (%) of a
truncated cone of mortar, when placed on a flow Table which rises 12.5 mm and is dropped 25 times in 15 seconds [15].

The masonry prism composed of two materials with different properties; relatively soft cement mortar and stiff fired-clay brick, see Figure 1(a). Figure 1(a) is schematically represented the geometry of the prism and the arrangement of the displacement measurement devices, see Figure 1(b); devices arranged on both sides of the prism to minimize dispersion. When the prism is subjected to a uniaxial compressive force, the mortar has a tendency to expand laterally more than the brick. Because the mortar and brick bonded together chemically and mechanically, the mortar is confined laterally by the brick [2].

![Figure 1. Masonry prism in uniaxial compression test.](image)

To model the cement mortar and solid clay brick units were used solid element: 22-node hexahedron, see Figure 2(a), 12-node tetrahedral, Figure 2(b) and 15-node prisms, Figure 2(c), were used to calibrate the elements and different sizes of mesh of the finite element. Measured properties of brick and mortar were used as input to a numerical model. The prism strengths and deformations calculated using this model were then compared with experimental results.

![Figure 2. Types of element shapes second-order structural solid element used in finite element mesh calibration.](image)

2.1. Experimental test
A compression experimental program in masonry prism was carried out in order to determine the numerical model that appropriately describes the compression behavior of masonry prism. Initially, tests were carried out on the materials used in the prism separately, such as resistance to compression in solid ceramic bricks manufactured manually and cement mortar
and complementary tests, such as initial absorption rate (IAR) and absorption 24 hours in solid ceramic bricks manufactured manually were made. The population is constituted by 16 artisanal ovens (N = 16), located in the municipality of Ocaña, North of Santander, Colombia. The method used to determine the sample size (n) for a population with similar characteristics was the simple random sampling method [11], whose result was n = 5 artisanal ovens, which were identified as the makers 1, 3, 4, 13, 16. As a first step, the compression strength of solid ceramic brick units (f’cu) was obtained for a rectangular geometry and a sample of 5 quasi-static tests per maker, performed in load control at 0.3 MPa/s [12]. Both characterization and compression tests were conducted in a servo-hydraulic machine with a maximum loading capacity of 100 t. The machine was equipped with two compressive steel plates and a spherical seat in the upper part in order to align the load with the actuator axis.

The results of area (A), maximum lead to compression (Pmax) and f’cu (Pmax/A) are indicated in Table 1 together with the respective variation coefficients (CV). In general, the A, Pmax and f’cu have an average representative of the data set and can be considered as a homogeneous set (CV < 20%) for each maker. The variability of the f’cu with respect to the average for each maker is less than 10%, except for the manufacturer 16, which has greater variability than that found in the other makers, in addition to having the lowest f’cu.

**Table 1.** Average results of the uniaxial compressive strength test in masonry units by maker.

| Maker | A (mm²) | Pmax (N)     | f’cu (MPa) |
|-------|---------|--------------|------------|
| 1     | 26,028.2 (1.7) | 463,950.0 (10.3) | 17.8 (9.4) |
| 3     | 26,806.6 (1.8) | 263,338.3 (10.4) | 9.8 (9.5)  |
| 4     | 27,609.4 (1.2) | 400,951.2 (7.0)  | 14.5 (8.0) |
| 13    | 27,761.6 (1.0) | 320,590.0 (6.5)  | 11.6 (6.9) |
| 16    | 28,903.2 (2.1) | 190,003.5 (16.2) | 6.6 (16.9) |

(%) Coefficient of variation.

The dispersion of the f’cu in the maker 13 is the lowest of the sample taken and the data have good behavior around of the median value, indicating that the data are between the first quartile and the third quartile (Q3-Q1). Other makers present results in the first and fourth quartiles (Q1, Q4), indicating this greater variability in the results. The maker 1 has the highest average of the sample and the makers 1, 3, and 4 the Q3 > Q2. The average values of Pmax and RM found by maker in the test of bending in solid clay bricks are registered in Table 2.

**Table 2.** Average results of the concrete rupture modulus test in solid clay bricks by maker.

| Maker | Pmax (N) | RM (MPa) |
|-------|----------|----------|
| 1     | 2,973.6 (30.3) | 1.3 (32.9) |
| 3     | 4,776.1 (86.7) | 2.2 (93.9) |
| 4     | 2,685.2 (15.8) | 1.3 (21.3) |
| 13    | 1,980.3 (48.4) | 1.0 (51.5) |
| 16    | 1,164.8 (13.6) | 0.5 (16.3) |

(%) Coefficient of variation.
There is a lot of variability of the $P_{\text{max}}$ results with respect to the average value for maker 1, 3 and 13 with CV > 30% possibly due to faults in the cooking process when using artisan ovens. The average values of RM correspond to that obtained by [13] with a RM = 0.97 MPa, and taking into account that the bend resistance varies between 10% and 30% of the $f_{\text{cu}}$ according to [14], the results correspond as expected. The IAR tests were carried out taking into account [10] and the results found are presented in Table 3. IAR values of 0.4 (g/cm$^2$/min) with IAR variability levels of 19.3% with respect to the average value is high and will influence the behavior of the cement mortar and the masonry prism. The results obtained from the absorption test for the sample are given in Table 3.

**Table 3.** Average results of the initial absorption rate test by maker.

| Maker | Dry Mass (g) | Final Mass (g) | IAR (g/cm$^2$/min) |
|-------|--------------|----------------|--------------------|
| 1     | 2,858.6 (2.7) | 2,913.0 (2.8) | 0.2 (26.9)         |
| 3     | 3,186.4 (1.9) | 3,293.2 (2.3) | 0.4 (19.3)         |
| 4     | 3,098.6 (2.1) | 3,204.8 (1.8) | 0.4 (12.0)         |
| 13    | 3,115.8 (1.5) | 3,202.4 (1.8) | 0.3 (50.2)         |
| 16    | 2,995.6 (1.5) | 3,038.8 (1.2) | 0.2 (35.2)         |

(%) Coefficient of variation.

Makers 3 and 4 have the highest rates of initial absorption with IAR = 0.4 with 12.0 < CV < 19.3 meanwhile the maker 13 has the highest variability of the IAR with respect to the average value, and a IAR = 0.3 slightly higher. The absorption by immersion 24 h was determined using the Equation (3). The results obtained from the absorption for the sample used show low variability with respect to the average value of the absorption by maker, see Table 4. It has a high percentage of water absorption of up to 26.8%, that is, the sample of the maker 16 had an increase of 739.8 g in 24 h.

**Table 4.** Average results of the immersion absorption test by maker.

| Maker | Dry Mass (g) | Saturated Mass $24h$ (g) | Absorption (%) |
|-------|--------------|--------------------------|----------------|
| 1     | 2,865.4 (2.8) | 3,316.8 (3.6) | 15.7 (10.3) |
| 3     | 3,207.6 (4.0) | 3,687.0 (4.1) | 15.0 (3.1) |
| 4     | 3,094.2 (0.7) | 3,611.0 (1.3) | 16.7 (4.3) |
| 13    | 3,146.0 (1.0) | 3,732.2 (1.1) | 18.6 (2.6) |
| 16    | 2,967.0 (2.0) | 3,760.8 (1.4) | 26.8 (3.2) |

(%) Coefficient of variation

Finally, tests of resistance to compression in cement mortars cubes of 50 mm sideways were made to the mortar used in the prisms of solid clay masonry. The cement mortar used in the construction of the masonry prisms is type N con volume proportion of cement:sand was 1:6 with the average value of $f'_{\text{cp}} = 13.2$ MPa and CV = 19.7%, while the average value of the fluidity
was 91.4% and CV = 12.1%. Finally, the average values of the uniaxial compression tests in solid clay masonry prisms for each maker, presented in the Table 5. The maker 16 presents the most unfavorable averages for the following mechanical properties: $f'_cu$, RM, absorption, $f'_m$ and $E_m$, additionally the CV are high by $E_m$, especially for makers 4 and 18.

| Maker | $f'_m$ (MPa) | $E_m$ (MPa) |
|-------|---------------|-------------|
| 1     | 6.6 (3.6)     | 12.0 (18.6) |
| 3     | 4.9 (10.5)    | 7.5 (16.1)  |
| 4     | 5.1 (12.7)    | 14.0 (79.2) |
| 13    | 4.3 (11.2)    | 8.1 (22.5)  |
| 18    | 3.2 (11.9)    | 5.6 (52.6)  |

Table 5. Average results of the resistance to the uniaxial compression ($f'_m$) and modulus of elasticity of the masonry prism ($E_m$).

(%) Coefficient of variation

2.2. Numerical implementation

A numerical model is built to predict behavior of uniaxial compression of solid clay masonry prisms, a set of properties used for numerical modeling, see Table 6. For the numerical model, the minimum values of $f'_cu$, $f'_cp$, $E_{cu}$ and $E_{cp}$ were considered to reduce the confinement effect at the time of the test and to avoid overestimating the mechanical properties of the material.

| Parameter | Brick | Mortar |
|-----------|-------|--------|
| $\rho$ (g/mm$^2$) | 158.00 | 254.00 |
| E (MPa)   | 526.40 | 137.20 |
| $\nu$     | 0.33   | 0.29   |
| $f'$ (MPa) | 12.06  | 4.03   |

Table 6. Parameters used in the finite element model.

Where $\rho$ represents the density, $E$ is the modulus of elasticity, $\nu$ is the Poisson’s coefficient and $f'$ corresponds to the compressive strength of the material. It was determined that the type and size of the finite element was a Hexaedral of 9 mm without loss of precision. A comparison between the behavior $\sigma$-$\epsilon$ ($\sigma$, stress; $\epsilon$, strain) of the experimental results and the numerical model using Ansys version 18 is illustrated in Figure 3. The finite element model is a micro model that took into account the mechanical properties of brick and cement mortar. The behavior $\sigma$-$\epsilon$ of the model corresponds to the lower limit of the one found experimentally and corresponds to the properties adopted for the material [9] and [16, 3].
3. Discussion
The IARs found are similar to those found by [13], although the sample has maximum values of $0.4 \text{ g/cm}^2/\text{min}$ for makers 3 and 4, considered high for this test. Some average values per maker exceed the initial maximum absorption rate [10] of $0.25 \text{ g/cm}^2/\text{min}$, with values of 0.3 with CV = 50.2% and 0.4 with CV = 19.3% and 12.0% for makers 13, and 3 and 4 respectively. These results indicate problems in the cooking and possibly in the selection of the materials for the elaboration of solid clay brick units. Recent investigations on the behavior $\sigma$-$\epsilon$ of massive clay masonry prisms subjected to uniaxial compression, homogenize the two materials (brick and mortar cement) in a single material that takes into account the properties of the materials that make up the prism.

4. Conclusion
Makers located in the municipality of Ocaña, North of Santander, Colombia, generally offer a solid clay brick with regular capacities to withstand compression, bend and high water absorption contents. A brick with a high level of water absorption negatively affects the $f'_{cp}$ and the brick-mortar bond. The $f'_m$ and $E_m$ for each of the makers are low compared to that obtained by other researchers. Homogenization techniques should be applied to avoid the effect of confinement in compression tests on bricks and cement mortars. Problems in the cooking process of the solid brick are evident in the high level of water absorption and low resistance to the $f'_{cp}$ and in the RM, in addition to the lack of skilled labor, which allows selecting the right material and the best mix of materials.

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