EXPERIMENTAL AND NUMERICAL ANALYSIS OF BEHAVIOUR IN COMPRESSION AND SHEAR OF HANDMADE CLAY BRICK MASONRY

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Abstract

Masonry is a composite material consisting of an assemblage of brick and mortar each one with its own mechanical properties. It is one of the most predominant structural material in Peru, as well as in many parts of the world because it is a low-cost material, is a heat resistant and sound insulation, it has good mechanical properties and the material is easily available.

The Japan–Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) of the National University of Engineering from Peru was carried out several surveys about the condition of structures in various districts of Lima city in order to build a database of structural systems and structural materials used in housing buildings.

The results of this study provided information about the situation of the housing in recent years on the periphery of the city by remarking that these buildings are mostly informal. Around 70% of the housing buildings in these areas of the city are considered informal.

Regarding the brick used in informal masonry housing buildings, it has been observed that the use of handmade and tubular bricks is predominant despite not complying with all the regulations given in the Peruvian technical standards. This study develops two aspects in relation to the study of masonry buildings: the study of materials used in the outskirts of the city of Lima and the numerical analysis of the behavior of diagonal compression and axial compression that occur in masonry structures.

Compressive stress occurs in confined masonry structures due to dead and living forces, while flexion and shear effects happen owing to seismic loadings. It was observed in wall subjected to cyclic lateral loading tests carried out at CISMID that the modes of failures can be mainly generated by shear forces. Based on the previous information, it is known that diagonal cracking and slip of mortar joints are the dominant failure mechanisms of confined masonry walls.

In the present study, the results of an experimental and numerical study of the mechanical behavior of non-reinforced masonry are shown. It was carried out tests of axial compression, diagonal compression and shear direct tests on specimens made by handmade bricks used in the city of Lima.

Numerical modelling of masonry structures requires the properties of each constituent of the masonry, in this case, the constitutive relations of bricks and mortar. The parameters obtained from the above-mentioned experimental study are used for numerical modelling by means of a finite element program.

Keywords: masonry, clay brick, compressive strength, prism test, numerical analysis

1. Introduction

Masonry units or bricks are used as a structural element for construction from about 11,000 years ago, bricks are the oldest manufactured construction materials. Its simplicity, strength and durability caused its extensive use, and gave it a dominant place in history along with the stone. Pre-ceramic Neolithic farmers were the first to use them in the Levant to 9500 BC, who built homes with circular shape semi-excavated footing with stone and wall made of adobe.

In Lima City, several archaeological sites have been built in adobe, such as “Huallamarca”, which was probably a religious temple of cultural traditional Pinazo (100 BC to 200 AD) and “Huaca Pucllana” belonging to the Lima culture (200-700 AD).

Currently, masonry buildings are built in many parts of the world. It is a low cost material, has good acoustic and thermal insulation, easily available and labor is easy to obtain at each location.

In this paper, testing in handmade clay bricks and masonry specimens are shown in order to determine basic mechanical properties and define the behavior of this kind of masonry used in the city of Lima. The properties of masonry depends on the properties of bricks, type of mortar, physical properties of the sand used for the mortar, state of bricks, manpower among other.

Analysis and design of buildings require the mechanic properties of masonry, for example, the modulus of elasticity, stress-strain curves of masonry are required for detailed non-linear analysis of masonry structures.

Mathematical models of structures using masonry walls require material properties and constitutive relations of the masonry and the elements that comprise it, i.e. bricks and mortar.

2. Background

In Peru, several studies have been developing to determine the characteristics of masonry at universities and research centers. Since 1988, CISMID have performed full-scale trials tests in masonry specimens. In 1995 studies in handmade and industrial clay bricks specimens were conducted.

Since 2010, several districts in Lima have been assessed in seismic risk. These studies were conducted by CISMID requested for some national government entities. For these studies, between 25% and 30% of total blocks of each district were taken as a representative sample. Table 1 shows the percentage of houses built in masonry and type of bricks used in walls and Fig. 1.

Table 1. Percentage of houses built in masonry

District	Blocks Sample	MasonryHouses (%)	Hand made Bricks (%)
La Molina	438	95%	9%
Chorrillos	554	90%	26%
Villa El Salvador	957	89%	45%
Comas	825	91%	60%
Puente Piedra	732	80%	47%
San Juan de Lurigancho	1271	95%	44%
Cercado de Lima	403	75%	40%
Ventanilla	1080	50%	13%
Breña	126	68%	60%
Carabayllo	751	92%	56%
El Agustino	297	93%	25%
Independencia	415	93%	69%
Lurín	350	86%	35%

Fig. 1 – Masonry dwelling in Lima

3. Experimental program

In the present experimental study, handmade bricks from two factories were used, in order to differentiate their origin bricks and specimens were named as ART1 and ART2. Several experimental tests on masonry components have been carried out, starting by choose mix of mortar. Testing of mechanical properties of handmade clay bricks as we can see in Fig. 2, mortar and masonry is performed according to E070 Peruvian Standard. The masonry prisms and wallettes were built by experienced bricklayers, who selected only uncracked bricks and controlled the 10mm thick of the bed and head joints by using wood templates and plumbs. Twenty prisms for testing axial compression resistance and twenty wallettes for diagonal tension tests were conducted.

Properties of bricks

According to standard the masonry units will not have foreign matter on their surfaces or inside, such as pebbles, small shells or nodules of calcareous nature. The unit will be thoroughly cooked clay, will have a uniform color and not submit vitrification. When it is hit with a hammer or a similar object will produce a pinging sound. Masonry unit shall have no cracks, fractures, fissures or similar defects that degrade its durability or resistance. About handmade masonry units, it has noticed that do not meet some of the indications mentioned in the standard. For this reason, the units were selected, eliminating those who had deterioration thus to avoid distortion of results by this parameter.

Physical properties bricks

Suction

The suction is related to the adhesion of the union of bricks and mortar, as with excessive suction is not achieved a proper junction, because the brick absorbs fast so water from the mortar, hardening and deforming this, obtaining unions of low resistance.

The standard specifies that according to the weather conditions where the work it is located, the units should be watered for half an hour, between 10 and 15 hours before seat them. In this study, the results show that bricks have high values of suction, so in work is necessary to soak the bricks before to bed them and prevent dehydration of mortar.

Absorption

The absorption of masonry units is directly related to its resistance. To weathering, while the unit is more porous will be more absorbent; therefore, be more vulnerable to moisture from weather. The units tested meet the absorption requirements indicated in the standard, according to which the absorption of clay and silico-calcareous units not be greater than 22%.

The test results for physical properties of units are shown in Table 2.

Fig. 2 - Handmade bricks

Table 2 - Test of physical properties of brick.

ID	SUCTION ($g/200cm^2$)	ABSORPTION (%)
ART1	80.70	15.48
ART2	99.39	15.27

3.1. Mechanicals properties of bricks

3.1.1 Compressive strength in masonry units

Monotonic compression tests were carried out in ten units for each type of brick in order to determine the compression strength (f'b). For calculating the resistance, the gross area of brick has been considered. Values of 6.40 MPa for ART1 and 11.58 MPa for ART2 are obtained. The test results for compressive strength are shown in Table 3.

Fig. 3 - Compression test in bricks.

Table 3 - Compression test results in bricks.

ID	f'b (Mpa)
ART1	6.40
ART2	11.58

3.2. Properties of mortar

Three types of mortar were adopted in this study. The grain size of the fine aggregate is not within the sieve zone indicated by standard. However, no corrections are made in order to represent real conditions of construction. Three different grades of mortar were used in the study. Since compressive strength of mortar depends upon the water-cement ratio, mortar with cement-sand volumetric ratio 1:3, 1:4 and 1:5 were tested. Mortar cubes of 50 mm size (obtained for each type of mortar during the construction of the specimens) were cured in water for 28 days, and then they were tested to obtain their compressive strength. The test results for mortar are shown in Table 4.

Fig. 4 - Compression test in mortar

Table 4- Compression test result of mortar.

Type of mortar	Compressive Strenght (MPa)	Modulus of elasticity (MPa)
Mortar 1:3	22.80	18603.7
Mortar 1:4	14.50	15320.5
Mortar 1:5	9.30	13736.0

3.3. Axial Compression test of prism

Axial compression test result of prism can be used to determine the compressive capacity of a full-scale masonry wall during lateral in plane cyclic.

The samples to determinate the compressive strength of masonry are prisms made with 5 bricks as we can see Fig. 6. For each of the 2 types of bricks were prepared prisms using mortar with ratio cement: sand (1:3) cement: sand (1:4) and prisms using mortar with ratio cement: sand (1:5).

Horizontal mortar joints had a nominal thickness of 1cm. The slenderness of the specimens varies between 4 and 4.7, so we had to make the appropriate correction.

Before testing, capping with mortar, made by cement and gypsum, is applied at the bottom and top of each prism.
The tests started at an age of 28 days and compression testing was done following NTP 399.605. The test equipment is composed by a compression machine of 300 ton and a data acquisition system as we can see Fig. 7. For the measurement of deformations LVDT sensors was used.

Table 5 - Summary of compressive strength of prism, f'm

Identification	Average Compressive Strength f'm (MPa)
Mix 1:4 XV	6.89
Mix 1:5 XV	5.3
Mix 1:5 XIII	7.1
Mix 1:3 XIII	9.74

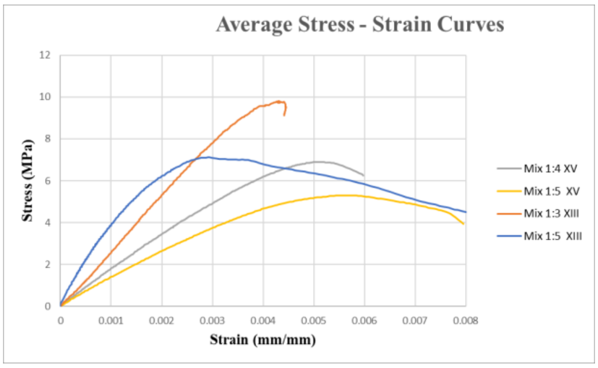


Fig. 5 - Average Stress strain curves

For data processing, inconsistent values were discarded previously. Compressive strength value of masonry, f'm, for each set of prisms was calculated by average values minus the standard deviation, according to E070 Standard. The average compressive strength for each prism was calculated as the peak load divided by the gross area of the prism. The results of the masonry prisms strength, are summarized in Table 5 and average curves for prism with each type of mortar mix are shown in Fig. 5

Based on regression analysis of data obtained from an experimental program, relationship between elasticity modulus (E) and compressive strength (f'm) of the prisms was developed as you can see in Fig. 8. and show this relationship.

For handmade bricks prism, the relationship between modulus of elasticity and compressive strength is as follow:

$$E=365.97f'm$$

Fig. 6 - Construction of prism.

Fig. 7 - Compressive strength test.

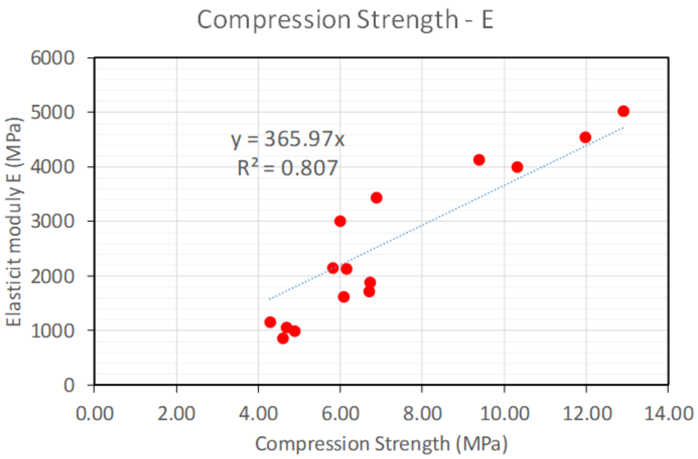


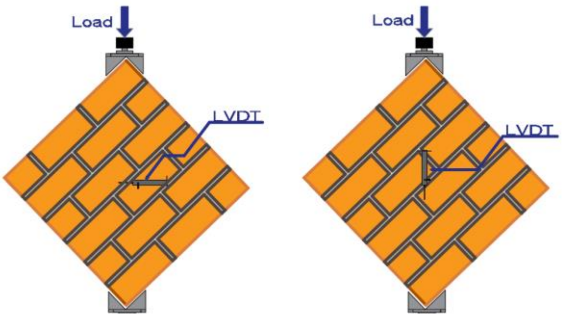
Fig. 8 - Variation of modulus of elasticity of masonry with corresponding compressive strengths for handmade bricks prisms.

(a) (b)

Fig. 9 - Type of failures in prisms. (a) Vertical cracking (b) vertical cracking and crushing.

3.4. Diagonal Tension Test

This test was developed to measure diagonal tension more precisely. The specimen is loaded in compression along one of its diagonals causing a diagonal tension failure when the specimen splitting apart parallel to load direction. Wallettes consist of six rows and each row consists of 2.5 bricks



(a) (b)

Fig. 10 - Test setup for diagonal tension test: (a) Front view (b) Back view

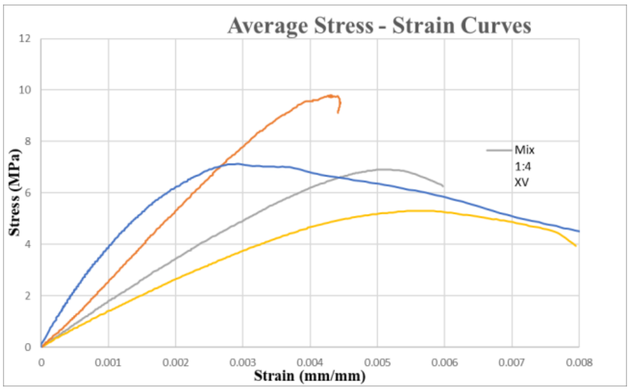


Fig. 11 - Diagonal tension test

Fig. 12 -Average Stress strain curves

It was fixed one LVDT (gauge length of 200 mm) on each side of the specimen along the diagonal in order to measure the shortening and elongation of the samples prepared. The experiment set-up of the system is shown in Fig. 10 and Fig. 11.

Table 6 - Summary of Shear Strength, V'm

Identification	**Shear Strength f'm (MPa)**
Mix 1:4 XV	0.78
Mix 1:5 XV	0.48
Mix 1:5 XIII	0.64
Mix 1:3 XIII	0.80

For processing data, inconsistent values were previously discarded. Shear stress V'm for each set was calculated by average values minus the standard deviation. The average shear stress for each specimen is calculated as the peak load divided by the gross area of the specimen. The results of the masonry shear strength are summarized in Table 6 and Fig. 12.

4. Numerical analysis

Masonry is heterogeneous and anisotropic material because of its constituents as mortar and brick. There are different possibilities to solve the problem of modelling masonry. These alternatives depend on how detailed is the modelling and the purpose of the analysis. Usually, the alternatives are classified as: detailed micro model, simplified micro model and macro model.

The first alternative to describe a masonry is the micro model (Fig. 13b). This type of modelling considers the bricks and mortar as continuum elements with defined failure criteria. The interface between bricks and mortar is modeled by special elements that represent the discontinuities. Because of the level of detail of this model, it is possible to reach more accurate result.

Simplified micro model is the second alternative, the (Fig. 13c), the bricks are kept as in the "detailed micro model", but the mortar joints and interface elements are re-defined as individual elements to represent a contact area. This means that the general geometry is maintained, but the individual elements that represent joints and interface are not able to describe the Poisson's effect of mortar over bricks. Because of this last example, some types of failure mechanisms cannot be reproduced in this type of model.

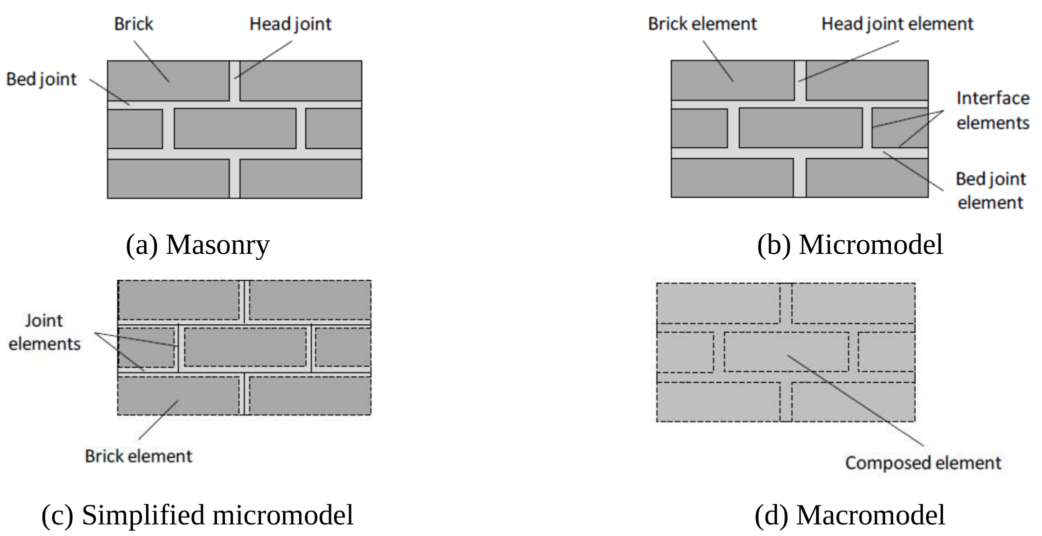
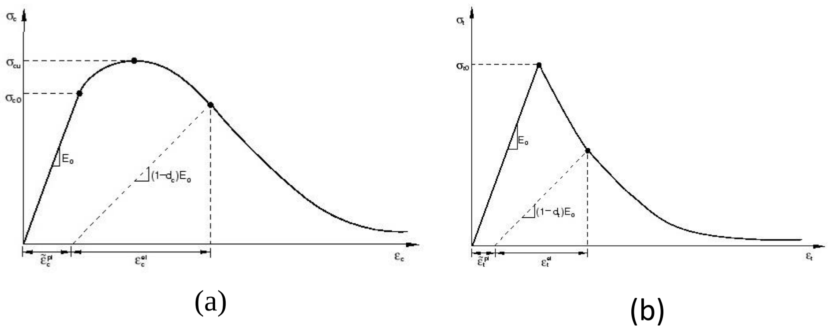


Fig. 13 – Types of modelling masonry

The last alternative is the macro model (Fig. 13d). In this case, the masonry panel is considered as a homogeneous element. Because of its characteristics, this type of model should be able to reproduce the general structural behaviour of a masonry panel but it is not able to reproduce all the types of failure mechanisms.

The damage model used in the present project is Concrete Damaged Plasticity (CDP), which is available in ABAQUS library. CDP model has been developed to predict the behavior of concrete and other quasi-brittle materials such as rock and mortar under cyclic loading. Cracks in tension or crushing in compression are the main failure modes of this model. CDP model assumes that the uniaxial compressive and tensile response of concrete is characterized by damaged plasticity (see Fig. 14).

In this study, handmade clay brick component model, meshed with element type of 3D stress linear, hex shaped with reduced integration elements (C3D8R). For interaction contact between masonry components, a friction contact element was used to be the general contact between bricks. Compression stress strain curve of brick to be used in the CDP model is the same as obtained from the experimental study for brick type ART1 (see Fig. 15), some parameter were obtained from the references. The explicit dynamic procedure has been chosen.



(a) Response of concrete to uniaxial loading in compression
(b) Response of concrete to uniaxial loading in tension

Fig. 14 - Response of concrete to uniaxial loading

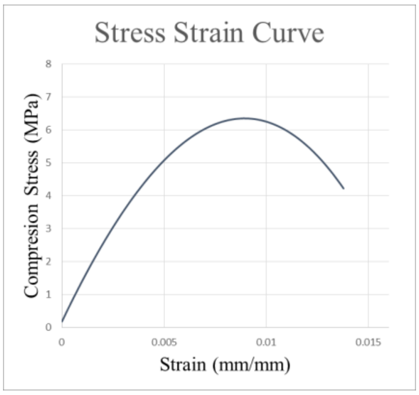
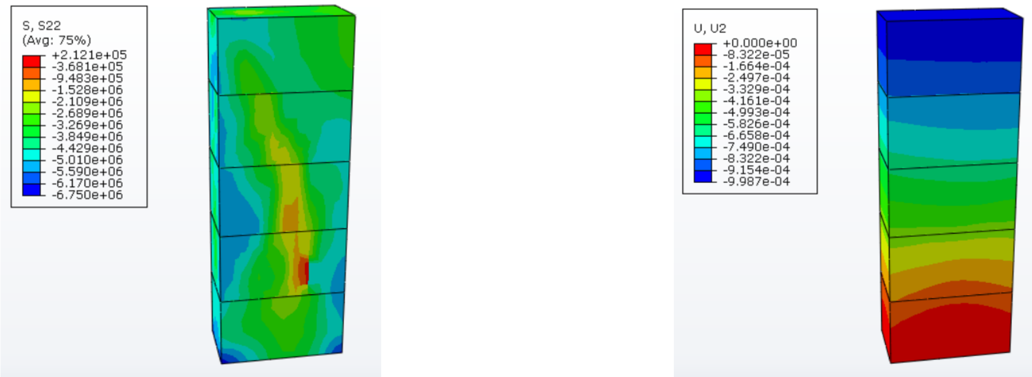


Fig. 15 – Experimental stress strain curve for brick

4.2. Numerical Analysis of Prism

For prism, the finite element simulation was under displacement control where axial displacement was applied on the top of the prism. All the degrees of freedom at the bottom of the prism were constrained. S22 represent compression uniaxial stress along axial axe of the prism, S11 represent stress in the perpendicular axe to the axial one. Fig. 16 shows state of stress generated due to application of load. Regarding to compression strength, the value obtained from numerical analysis is 5.56 MPa and the value obtained from test is 5.72 MPa. Regarding to strain at maximum compression strength, the value obtained from numerical analysis is 0.0022 and the value obtained from test is 0.0045



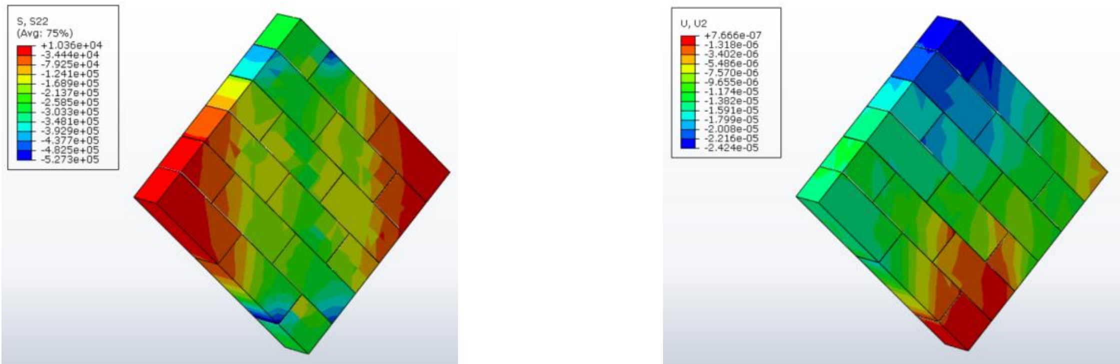
State of stress S22 results — Displacement U22 direction results

Fig. 16 – Result of numerical analysis of prism compression test

4.3. Numerical Analysis of wallettes

For wallettes, the finite element simulation was under displacement control where the displacement was applied on a steel head placed on top. Fig. 17 shows the in-plane state of stress contour generated due to application of load.

Regarding to shear strength, the value obtained from numerical analysis is 0.31 MPa and the value obtained from test is 0.36 MPa.



State of stress S22 results — Displacement U22 direction results

Fig. 17 - Result of numerical analysis of wallets diagonal tension

5. Conclusions

The handmade brick presents a high level of suction, which should be considered during the seating of units in the constructions site.

For prisms, the relationship between modulus of elasticity and compressive strength obtained experimentally is follows as:

$$E=365.97f'm$$

It can be observed that the computed values for compression strength of prism obtained with numerical analysis are in good agreement with the corresponding experimental observations. Regarding to strain at maximum compression strength, the value obtained from numerical analysis and the value obtained from test are not very close. The difference in the computed and experimental values may be attributed to values assumed for some parameter of contact element. The values of shear strength of wallet obtained with numerical analysis are in good agreement with the corresponding experimental observations.

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