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ANALYSIS OF UNIAXIAL COMPRESSION BEHAVIOR OF HOLLOW CONCRETE BLOCK MASONRY: EXPERIMENTAL AND ANALYTICAL APPROACHES

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Abstract. This article focuses on the uniaxial compression behavior of concrete hollow brick masonry assembly. This study was performed both by experimental and analytical approaches. In the first experimental part, the compression tests were done according to the European standard EN1052-1. It is highlighted from the tests that this concrete hollow brick masonry is a very high dispersive material and that the compression behavior of this masonry is similar and depends principally on that of bricks. In addition, the vertical splitting failure modes reflect the effect of "expanding/restraining" for this type of masonry and the elastic properties determined from these tests are comparable with the values found in the literature. Then, in the analytical approach, the simple calculations were done by different existed models to predict the compressive strength of masonry prism. A comparison of the results obtained by using these models with those of experimentation shows that only the model which takes into account the effect of vertical joints is mostly adapted for the safe design of this masonry prism under uniaxial compression load.

Keywords: hollow concrete masonry, compressive behavior, analytical models.

1. INTRODUCTION

Hollow concrete masonry structure has been widely used in most types of building construction in the world because of its low cost, good sound and heat isolation properties, locally available material and ease of construction. However, the comprehension of this masonry material is still limited and it is necessary to contribute to the research data the behavior of this type of masonry. In addition, there are some existed models to predict the compressive strength of masonry prism but there was not any verification of these models for the case of hollow concrete brickwork. One important part of this study is therefore to verify the adaptation of existed models to estimate the strength of hollow concrete masonry prism under uniaxial compression stress. This verification helps to understand profoundly the compressive mechanical behavior of this type of masonry.

The first part of this present work addresses on the experimental study of compression behavior of hollow concrete brickwork. For the compressive behavior of brick-mortar combination, many studies have been conducted by performing tests on masonry prisms following the recommendation EN1052-1 (1998) ([1-5]) or the recommendation ASTM E474 ([4], [6], [7], [8]). The specimens prepared according to latter contains only horizontal mortar joints whereas there are both horizontal and vertical mortar joints in the specimens prepared according to the former recommendation. The specimens for the compression test in this study are therefore prepared base on this latter recommendation because it seems more representative of ordinary masonry in the reality. Based on these tests, some mechanical properties of masonry component were determined in accepting some assumptions.

The second part constitutes an analytical interpretation of the experimental results. For this purpose, a bibliographic review of existed models was first performed by analyzing the principle, the hypotheses, and the formulation of different models and the field of application of each model. The calculation in applying those existed models with the masonry components' properties determined from the experimental part was then done to estimate the compressive strength of masonry prism. A comparison of the analytical results with those obtained from the experimentation helps to better understand the compression behavior of the masonry of hollow concrete bricks.

2. EXPERIMENTAL INVESTIGATION

2.1. Material constituents

The bricks used in the present study are halved lengthwise of hollow concrete brick; class B40 (the characteristic compressive strength is 4MPa) whose dimension is 500x200x75 mm^3. The dimension of brick unit is therefore 250x200x75 mm^3. The uniaxial compressive test was performed at laboratory and shows that the average compressive strength of these bricks is 6.5 MPa.

The mortar used in our study is a Portland cement-based mortar (CEM I 52.5 – according to the Eurocode 6), the formulation of which is shown in Table 1.

Table 1. Mortar formulation.

Type	Proportions		
	Cement	Sand 0/4	Water
Mortar based on CEM I 52,5	1	3	0.5

The uniaxial compressive tests and flexural tests were performed at our laboratory with nine prismatic specimens measuring 40x40x160 mm3 manufactured according to the European standard (EN 1015-11). These tests were done on 3 specimens after 31 curing days with the result of average compressive strength equals to 48 MPa.

2.2. Uniaxial compression tests of masonry prism

2.2.1. Specimens

The specimens are prepared according to the standard EN1052-1, each specimen contains four bricks (described above) in height and two bricks along the width. The bricks are connected by mortar with the average thickness of 10mm (h_{mor} = 10 mm). The total dimensions of the masonry specimens are about 510x830x75 mm^3, **Figure 1**.

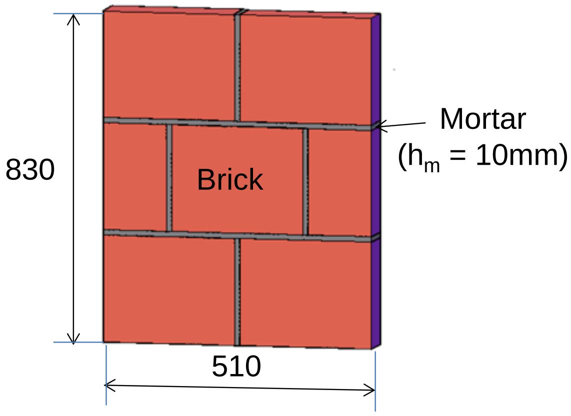

Figure 1. Geometry of the masonry specimens used for uniaxial compressive tests.

2.2.2. Test set-up

The uniaxial compression test set-up consists of two rigid steel profiles: the first one is fixed in the lower part on which the masonry specimen is placed, and the second one is placed on the upper face of masonry specimen. The vertical load is applied by a mean of hydraulic actuator (20 tons) and measured by a loadcell, **Figure 2**.

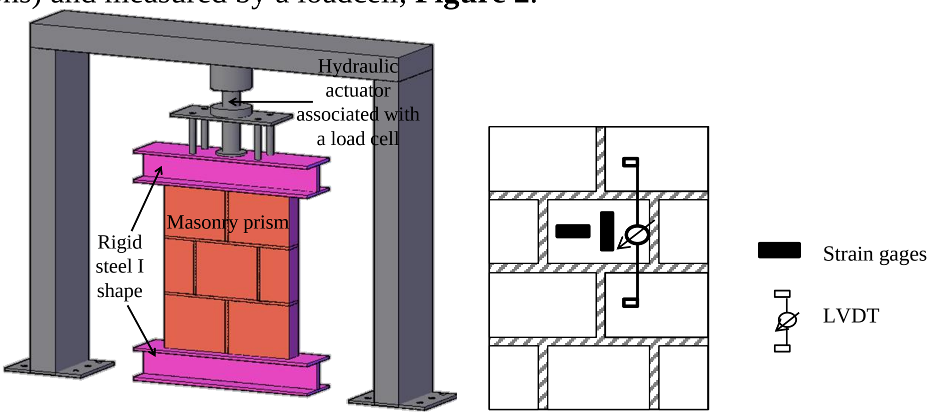

Figure 2. The test set-up and the instrumentations used in the uniaxial compressive test of masonry prism.

In order to characterize the compression behavior of the masonry and indirectly its constituent elements, LVDT displacement sensors (± 10 mm) are centrally placed (on both two faces) along the vertical direction in systematic including two mortar joints in this measurement length. In addition, the strain gages are glued to the central brick's faces.

The test is performed by displacement control with the speed of 0.05 mm/minute. Three masonry specimens were tested where two of which (E1 and E2) were tested by monotonic loading and the rest one (E3) was tested by a charge – discharge cyclic loading.

2.2.3. The failure mode of hollow concrete brick masonry prism under compressive stress

The failure of these concrete hollow brick masonry prisms under uniaxial compression test is characterized by the vertical cracks (vertical splitting) through the bricks due to tensile stress accompanied with crushing of bricks, **Figure 3**. The vertical splitting failure mode shows in the present case; the mortar is less stiff than the bricks. Indeed, under the uniform compressive stress, the mortar tends to expand laterally outside. However, the connection between mortar and brick tends to limit this expansion. As a result, the mortar is in a state of biaxial compressive stress while a state of bi-axial tensile stress occurs at the brick element. It seems that the failure of the masonry prism occurs simultaneously when the tensile stress in the brick reaches its ultimate tensile strength.

Figure 3. The failure modes of masonry prism under uniaxial compression test.

2.2.4. Compression behavior of hollow concrete brick masonry prisms and determination of material properties

The compression behavior of hollow concrete brick masonry prism is represented by the relation curve between the compressive stress (σ) and the vertical strain of prism (ε_M^v), the continuous curves in **Figure 4**. It is important to note that the vertical strain is the average value calculated from the displacement recorded by the LVDT displacement sensors which are disposed on two prism's faces.

It should be emphasized that the compression behavior of this hollow concrete brick masonry prism is quite fragile up to the peak which corresponds to the collapse of the prisms. In addition, in comparison between the behavior curves of the prisms and that of bricks which obtained through the strain gages glued to the central bricks (the discontinuous curves and continuous curves in **Figure 4**, it is founded that the compression behavior of the prisms is similar and primarily decided by that of bricks. However, the stiffness of the prisms is a little smaller than that of bricks. This result could be explained by the presence of mortar joints which are softer than those of bricks in the prisms that are consistent with the mechanical failure observed above.

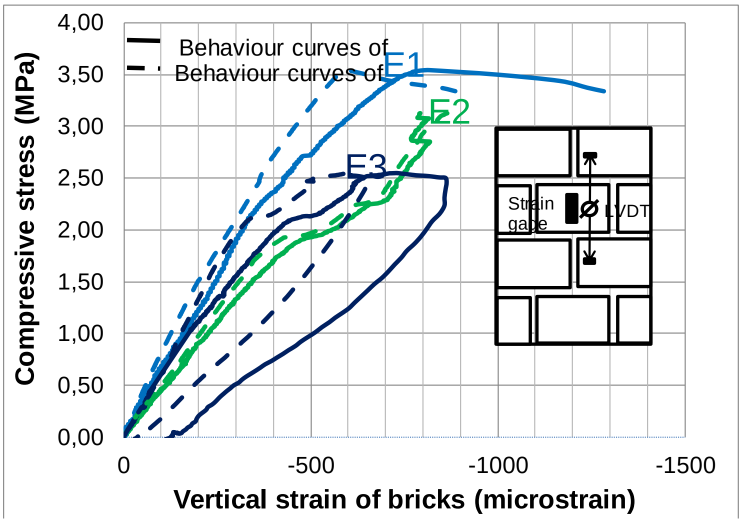

Figure 4. Comparison of the behavior curves between prisms and bricks.

Additionally, through these tests, some mechanical parameters can be determined. According to Mohamad et al. [7], the Young modulus of the "homogenized masonry" material, E_M (the brick, E_b, respectively) can be determined by measuring the secant slope between the stresses at 5% and 33% of the maximum compressive strength, while the Young modulus of mortar (E_{mor}) can be indirectly determined from that of brick and masonry by the following formula:

$$E_{mor} = \frac{E_M \times E_b}{\alpha\left(E_b - E_M\right) + E_b} \tag{1}$$

Where: α is the ratio between the total height of bricks to that of mortar along the measurement height of LVDT sensor.

The compressive strength of the prisms (f_M) should be the peak of these curves, exception the case of E3 prism because this test is undergone by a charge/discharge cycle. The Poisson's ratio of the bricks can be also estimated from the relation curve between the horizontal and vertical strain of brick (**Figure 5**). All the results calculated are represented in **Table 2.**

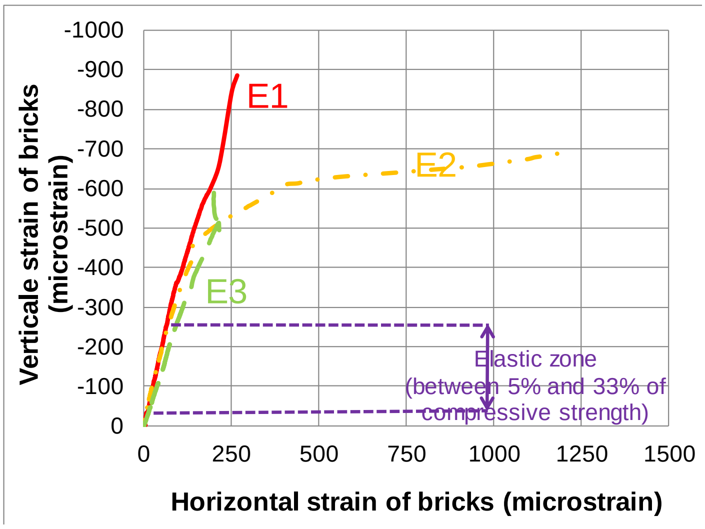

Figure 5. The relation curves between the horizontal and vertical strain of bricks.

The results obtained are in range of values comparable to those founded in the literature: the Young modulus of hollow concrete bricks of the same class B40 was found equal to 5567 MPa following uniaxial compression tests on masonry prisms made up of two bricks [9]. The average compressive strength of the homogeneous masonry material found in this study is 3.45 MPa is approximately 55% of the average compressive strength of bricks used. This result is closed to the results found in the literature where the ratio between the compressive strength of homogeneous masonry and that of brick varies from 0.6 to 0.68 ([11]).

Table 2. Material properties of masonry prisms and bricks.

Prism	Young modulus E (Mpa)			Poisson ratio of brick	Compressive strength of masonry (Mpa)
	Masonry prism (E_M)	Brick (E_b)	Mortar (E_{mor})		
E1	6250	7500	1650	0.28	3.63
E2	4550	4680	3020	0.33	3.27
E3	5900	6000	4550	0.28	-
Average	**5567**	**6060**	**3070**	**0.3**	**3.45**
Standard deviation	**733 (13%)**	**1152 (19%)**	**1184 (39%)**	**0.02 (8%)**	**0.17 (5%)**

The important value of standard deviation in Table 2 reflects a high dispersion of this material which has also been noted in the literature ([6], [7]). This high standard deviation can be justified by the simplicity of the analytical approach and in the fact that the study is based on deformations measured at the surface. Finally, the dispersion affecting the constituent materials is not negligible.

These mechanical properties will be used in the following part to evaluate the compressive strength of masonry prism.

3. VERIFICATION OF EXISTED ANALYTICAL MODELS FOR ESTIMATING THE COMPRESSIVE STRENGTH OF HOLLOW CONCRETE BLOCK MASONRY PRISM

3.1. Analytical models

3.1.1. Theoretical models

For the theoretical models, it was accepted that the failure of masonry under uniaxial compressive stress is mainly resulted by the interaction between brick and mortar

According to Hendry [11] in assuming the compatibility of deformations between the components, the difference in the rigidity of brick and mortar, under the uniaxial compression load, leads to a stress state characterized by biaxial compression/traction in the brick and triaxial compression in the mortar, **Figure 6**. This is common when the mortar is softer than bricks.

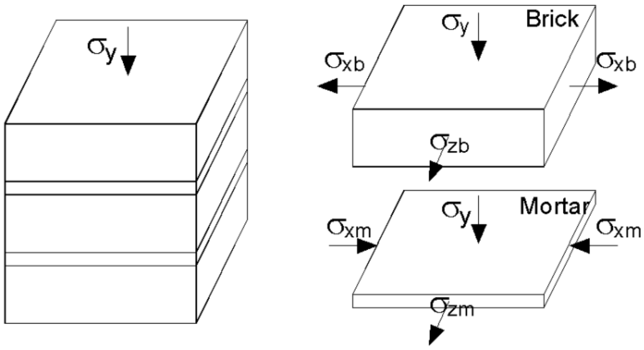

Figure 6. State of stress in brick and mortar under uniaxial compression [11].

Based on these assumptions, several models have been developed

➢ **Model proposed by HILSDORF [12]**

In the study of Hilsdorf represented in [12], the main hypothesis adopted was that the failure of the mortar was synonymous with the failure of the masonry.

The author assumed that the failure of brick respects Mohr-Coulomb criterion and it is proposed that the crushing of mortar and the tensile cracking of bricks occur simultaneously leading to the failure of masonry prism.

Accepting those assumptions, the compressive strength of masonry prism (f_M) is calculated by the following formula in introducing a coefficient U_n (variant from 1.1 to 2.5) in order to take into account the effect of stress non-uniformity:

$$f_M = \frac{f_{c,b}}{U_n} \times \frac{f_{c,b} + \gamma f_{c,\mathrm{mor}}}{f_{\mathrm{t},b} + \gamma f_{c,\mathrm{b}}} \quad \text{with } \gamma = 4.1 \frac{h_{mor}}{h_b} \tag{2}$$

➢ **Model proposed by Francis et al. [13]**

This model is based on that of Hilsdorf above. However, it is proposed that the failure of masonry prism is controlled by the tensile cracking of brick, which is proposed to respect the Mohr-Coulomb criterion. The compressive strength of the masonry prism is calculated by the following expression:

$$f_M = \frac{1}{\left(1 + \frac{\phi\left(\beta \nu_{mor} - \nu_b\right)}{\alpha\beta\left(1 - \nu_{mor}\right)}\right)} \times f_{c,b} \tag{3}$$

Where: $\alpha = \frac{h_b}{h_{mor}}$; $\beta = \frac{E_b}{E_{mor}}$; $\phi = \frac{f_{c,b}}{f_{t,b}}$

➢ **Model proposed by Lateb [14]**

This model is based on the same principle as proposed by Hendry [11] in Figure 6. However, it takes into account the influence of mechanical and geometric characteristics of vertical joint. In addition, it is assumed that the failure of specimen is guaranteed by the tensile failure of brick.

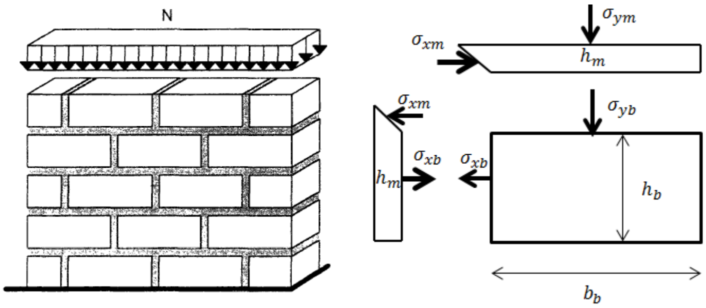

Figure 7. Assumption on the state of stress in bricks and in mortar joints [14].

From the principle of the brick/mortar interaction where bricks are considered more rigid than mortar, the horizontal mortar tends to deform laterally much more than bricks. With this lateral deformation, the vertical joint is subjected to horizontal stress which tends to separate the bricks while the horizontal joint is confined. It causes therefore the tensile stress in brick, **Figure 7**.

The compressive strength of masonry prism is calculated by the following formula:

$$f_M = \frac{b_b}{(b_b + h_{mor})} \times \frac{f_{t,b}}{M + \nu_b} \tag{4}$$

Where: $M = \dfrac{(\beta \nu_{mor} - \nu_b)}{\left(1 + \beta\left(\dfrac{h_{mor}}{b_b} + \dfrac{h_b}{h_{mor}}\left(1 + \dfrac{h_{mor}}{b_b}\right)\right)\right)} \times f_{c,b}$ and $\beta = \dfrac{E_b}{E_{mor}}$

3.1.2. Empirical models

➢ **Model proposed by Khoo & Hendry [15]**

Khoo and Hendry **[15]** proposed, from their experimental study, another empirical formula to assess the compressive strength of masonry prism:

$$A(f_M)^3 + B(f_M)^2 + C(f_M) + D = 0 \tag{5}$$

Where:

$$A = 0.2478 f_{t,b}\left(\frac{1}{f_{c,b}}\right)^3 - 0.0018\alpha\left(\frac{1}{f_{c,mor}}\right)^2$$

$$B = 1.2781 f_{t,b}\left(\frac{1}{f_{c,b}}\right)^2 - 0.0529\alpha\left(\frac{1}{f_{c,mor}}\right)$$

$$C = 2.2064 f_{t,b}\left(\frac{1}{f_{c,b}}\right) + 0.1126\alpha$$

$$D = 0.9968 f_{t,b} + 0.1620\alpha f_{c,mor}$$

With: $\alpha = \dfrac{h_b}{h_{mor}}$

➢ **Model proposed in Eurocode 6**

Eurocode 6 proposed an empirical formula for calculating the compressive strength of masonry prism according to the mechanical characteristics of its components:

$$f_M = K . f_{c,b}^{0.7} \cdot f_{c,mor}^{0.3} \tag{6}$$

Where: K, constant which takes into account the classification group of masonry elements (between 0.4 and 0.6)

3.1.3. Comments

Despite the physical “expanding/restraining” phenomena highlighted in numerous works in the literature linked to considerations of differentiated deformations of the constituent elements, all the forecast expressions are based on criteria in resistance. However, in the elastic domain the recourse to rigidities of the constitutive elements (Francis et al. [13], Lateb [14]) constitutes a comparable approach, still it is advisable to identify precisely the required properties.

Among the theoretical models, the hypothesis that the crushing failure of mortar occurs simultaneously with the tensile failure of brick in Hilsdorf's model [12] leads to a formula where the compressive strength of masonry prism depends, among other factors, on the compressive strength of mortar which can be questionable if this latter characteristic is determined from compression tests on mortar prisms (different from that of mortar in the assembly). However, even if the other two models (Francis et al. [13], Lateb [14]) assumed that the rupture of masonry prism is caused by the splitting failure of the brick under tensile stress (resulted by the interaction between brick and mortar), the model proposed by Lateb [14] is established by taking into account the effect of vertical mortar joints, which seems more appropriate for the case where the test specimens consist both of horizontal joints and vertical joints.

The formulas proposed by Khoo & Hendry [15] and Eurocode 6 are simply empirical formulas of which, little information on physical behavior (brick/mortar interaction phenomenon) is obtained in comparison to other analytical models, although they give a basic value for establishing values for design codes.

3.2. Evaluation of strength of masonry prism under uniaxial compression

In this part, the compressive strength of masonry walls under uni-axial compression is evaluated from the simplified models described above and compared with those obtained experimentally. This evaluation is based on values of the mechanical properties of the components (bricks and mortar). Some of these mechanical properties were experimentally determined above such as the compressive strength of mortar ($f_{c,mor}$) and of brick ($f_{c,b}$); Young's modules of brick (E_b) and mortar (E_{mor}); the Poisson coefficient of brick (ν_b).

The tensile strength of brick ($f_{t,b}$) is considered to be equal to 10% its compressive strength (according to A. Brenich et al. [16]). The Poisson coefficient of mortar is proposed equal to that of brick.

The compressive strengths of masonry prism calculated according to different simplified models above are presented in Table 3.

Table 3. Evaluation of compressive strength of masonry prism according to different models.

Model	Formula	Analytical results	Error
Hilsdorf [12]	$f_M = \frac{f_{c,b}}{U_n} \times \frac{f_{c,b} + \gamma f_{c,\mathrm{mor}}}{f_{\mathrm{t},b} + \gamma f_{c,\mathrm{b}}}$	**35.73 (MPa)**	**(+936%)**
Francis et al. [13]	$f_M = \frac{1}{\left(1 + \frac{\phi(\beta \nu_{mor} - \nu_b)}{\alpha\beta(1-\nu_{mor})}\right)} \times f_{c,b}$	**5.25 (MPa)**	**(+52%)**
Lateb [14]	$f_M = \frac{b_b}{(b_b + h_{mor})} \times \frac{f_{\mathrm{t},b}}{M + \nu_b}$	**2.04 (MPa)**	**(-41%)**
Khoo and Hendry [15]	$A(f_M)^3 + B(f_M)^2 + C(f_M) + D = 0$	**26.13 (MPa)**	**(657%)**
Eurocode6	$f_M = K.f_{c,b}^{0.7}.f_{c,mor}^{0.3}$	-	

It is emphasized that the formula proposed by Eurocode 6 which is empirical in nature is not applicable in this case since the compressive strength of the mortar (50MPa) greatly exceeds the maximum value allowed by this code (20MPa).

It should also be noted that the results obtained by the models of Hilsdorf [12] and Khoo and Hendry [15] significantly overestimate the experimental value (from 657% to 936%). This is explainable because in these models, the compressive strength of prism is calculated with the compressive strength of mortar determined from the tests of mortar prism which does not faithfully reflect that of mortar in masonry assembly.

Two other models (Francis et al. [13] and Lateb [14]) consider the elastic properties of the components (stiffness ratio between brick and mortar) and take into account the compressive strength of the brick rather than that of the mortar. This leads to the values closer to those obtained experimentally because the elastic properties of the components used in this model are determined experimentally from uniaxial compression tests on masonry prism. However, only the model of Lateb [14], which takes into account the vertical joint effect, tends to give an underestimated value.

3. CONCLUSION AND PERSPECTIVES

This study contributes data to hollow concrete block masonry prism under uniaxial compressive stress with several findings as follow:

From the experimental tests, it is found that bricks play a "principal role" in the compression behavior of hollow concrete block masonry prism. In addition, it is necessary to insist on the high dispersion of this type of masonry which could not be ignored especially in designing calculation or in modeling. Furthermore, the vertical splitting type breaking modes reflect the "expanding/restraining" effect for this case of masonry.

The verification of different existed models was done and confirmed that the compressive strength of this hollow concrete masonry prism is principally based on the splitting failure of brick. However, only the model which takes into account the effect of vertical mortar joints seems to be adapted for the safe design of this masonry prism under uniaxial compressive stress when it gives an underestimated value.

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