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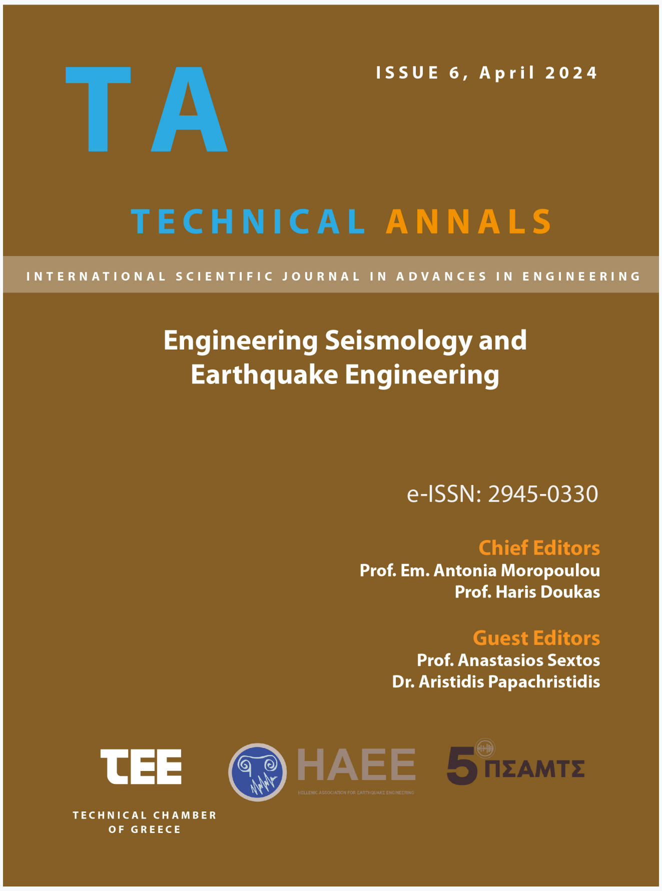

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Preliminary evaluation of predictions from compressive strength models for masonry

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Abstract. Compressive strength is the most essential design parameter of load-bearing masonry structures. The performance of masonry under compression depends on numerous parameters and is linked to the properties of its component materials, which enclose high variability, and to its geometrical characteristics and interlocking arrangement. Available predictive models are usually based only on few variables and therefore their estimates are liable to uncertainties. In this paper, the performance of four existing models for the estimation of the compressive strength of masonry made of solid units, is evaluated. To this end, experimental data from tests on single-layered specimens made of solid clay bricks, and subjected to monotonic compression, were collected from the literature. The predictions of the four models are compared to the experimental strength of the masonry specimens. The performance of each model is assessed through statistical analysis indices. From the analysis, it is concluded that the examined predictive models overestimate the masonry specimens with experimental strength less than 5 MPa.

Keywords: masonry, compression, models.

1 Introduction

Load-bearing masonry systems comprise a significant part of the building stock mainly in rural areas, but also in large urban centers around the world. Moreover, masonry structures represent the main method of construction of architecturally noteworthy structures of the world's cultural heritage. Even today, use of masonry remains a popular option for satisfying housing needs. The layout of load-bearing masonry buildings is realized with various structural configurations and numerous materials, such as natural or artificial masonry units (solid, perforated or frogged) and binding mortars of different composition, depending on the design requirements, the traditional construction practice and the local materials of each region.

The primary mechanical property of load-bearing masonry in structural design is its compressive strength. As a consequence, research on the compressive behavior of masonry has been very popular among researchers for the past decades. The complexity of the stress transfer mechanisms developed in masonry subjected to compression and the numerous factors that affect its ultimate failure stress, have been discussed since early 1900’s.

The principal factors that have been determined to affect the masonry compressive behavior are the mechanical properties of its components [1 – 4], the thickness of the mortar joints [5, 6], the ratio with which the two materials participate in the masonry [7], and the bond properties between the two materials [8]. Also, the role of the slenderness ratio of the masonry, (h/t), the quality of construction and the interlocking arrangement of its units in compressive strength are also emphasized in several studies.

However, available models for estimating the compressive strength of masonry are expressed as a function, mainly, of the compressive strength of the units and mortar. Consequently, a large scatter in their predictions is typically observed. In the following sections, a preliminary assessment of the reliability of four predictive models proposed in Standards and by researchers is carried out, based on experimental results from compression tests available in the published literature.

2 Experimental Data

To evaluate the models, results were collected from compression tests under monotonic loading, on rectangular and square single-layered masonry prisms and rectangular single-layered wallettes, made of solid clay bricks and mortars of different composition (Figure 1). In total, 57 datasets of prism specimens and 29 datasets of wallette specimens that failed in compression, were gathered and analyzed. Each dataset consists of 3 or more specimens with the same characteristics. The datasets are derived from four experimental studies [7, 9 – 11], in which 234 prism and 92 wallette specimens, were constructed.

Constituent Materials. The dimensions of the clay bricks used to construct the masonry specimens range from 100 to 228 mm in length, 96 to 112 mm in width, and 50 to 78 mm in height, while the joint thicknesses range from 10 to 18 mm for horizontal joints and from 10 to 12 mm for the vertical.

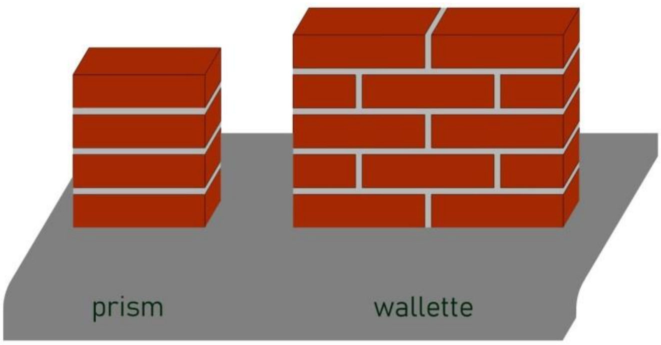

Fig. 1. Schematic illustration of prisms and wallettes

As binding material cement mortars, cement-lime mortars and lime mortars, with different composition proportions and a wide range of compressive strength were applied. Specifically, the compressive strength of the two components in the research programs considered range from 6.68 to 120.00 MPa for the clay bricks and from 0.69 to 48.00 MPa for the mortar, as shown per type of specimen in Table 1. Table 2 displays the number of datasets divided in sub-ranges of compressive strengths for the units and mortar of the collected database.

Table 1. Range of compressive strength of units and mortars per type of specimen

Component		Prisms	Wallettes
		Compressive Strength (MPa)	
Units	min	6.68	
	max	120.00	
Mortars	min	0.69	4.00
	max	48.00	48.00

Table 2. Datasets categorized by compressive strength of each material

		Compressive Strength of Units (MPa)			
Type of specimen		≤ 25	> 25, ≤ 50	> 50, ≤ 75	> 75
Prism	Number of datasets	31	12	10	4
Wallette		18	4	5	2
		Compressive Strength of Mortar (MPa)			
Type of specimen		≤ 5	> 5, ≤ 15	> 15, ≤ 30	> 30
Prism	Number of datasets	12	23	11	11
Wallette		4	12	6	7

Masonry Specimens. The masonry specimens consist of 2 to 8 and 2 to 6 layers of clay bricks in height, for the prisms and wallettes, respectively, assembled with full mortar joints. Their height-to-thickness ratios (h/t) range from 1.15 to 5.00 for the prism specimens and from 1.15 to 3.65 for the wallettes. Table 3 illustrates the ranges of strength and geometrical characteristics of the two types of masonry specimens included in the collected experimental data.

Table 3. Range of strength and geometrical characteristics of masonry specimens

Property		Prisms	Wallettes
Compressive Strength (MPa)	min	1.22	1.10
	max	39.80	46.70
Length (mm)	min	100	210
	max	228	430
Thickness (mm)	min	96	96
	max	112	100
Height (mm)	min	110	110
	max	500	350

3 Predictive Models

In this section, are presented the equations included in the European (EN 1996–1–1) [12] and American (TMS 602 – 11/ACI 530.1 – 11/ASCE 6 – 11) [13] Standard, as well as two more models which have been proposed by T.P. Tassios [14] and G. Rossi [15]. It is further stated that the model of T.P. Tassios [14], is also adopted by the Greek Code for the assessment and structural interventions of masonry structures [16].

European Standard EN 1996-1-1 [12]. The model is utilized for the design of masonry structures with binding material mainly of cement mortars, in which the arrangement of the units in height is implemented in regular layers. For masonries constructed from solid unit blocks with general-purpose mortar, the compressive strength results from equation (1):

$$f_{\mathrm{mod}} = 0.55 \cdot f_b^{0.7} \cdot f_m^{0.3} \tag{1}$$

where f_{mod} is the compressive strength of masonry [MPa], f_b is the compressive strength of units [MPa] and f_m is the compressive strength of mortar [MPa].

American Standard [13]. The equation provided by the American Standard TMS 602 – 11/ACI 530.1 – 11/ASCE 6 – 11 (TMS/ACI/ASCE) for predicting the compressive strength of masonry, is based on the compressive strength of units and the type of mortar applied. According to this model, the compressive strength of the masonry is calculated as follows:

$$f_{\mathrm{mod}} = A \cdot (400 + B \cdot f_b) \tag{2}$$

where f_{mod} is the compressive strength of masonry [psi], f_b is the compressive strength of units [psi], A is a factor equal to 1 for masonry constructed under supervision and B is a factor equal to 0.2 for lime-cement mortar type N and 0.25 for lime-cement mortar type S or M, as defined in the Standard. For the mortars of the specimens of this paper, type S/M is assumed for mortar's compressive strength equal to or greater than 10 MPa and type N for compressive strength less than 10 MPa. It is recalled that 1 psi is equal to 0.0068947573 MPa.

Model T.P. Tassios [14]**.** The proposed relationship links the compressive strength of the masonry, with the ratio of the joint thickness to the height of the units, the compressive strength of the units and, if applicable, the compressive strength of the mortar. The strength of masonry is calculated from equation (3):

$$f_{\text{mod}} = \begin{cases} [f_m + 0.40 \cdot (f_b - f_m)] \cdot (1 - 0.8 \cdot \sqrt[3]{\alpha}), \text{ for } f_b \succ f_m \\ f_b \cdot (1 - 0.8 \cdot \sqrt[3]{\alpha}), \text{ for } f_b \prec f_m \end{cases} \tag{3}$$

where f_{mod} is the compressive strength of masonry [MPa], f_b is the compressive strength of units [MPa], f_m is the compressive strength of mortar [MPa] and α is the ratio of the horizontal mortar joints thickness to the height of the units.

Model G. Rossi [15]**.** Guido Rossi proposes a logarithmic relationship to predict the compressive strength of masonry constructed with solid or perforated – with vertical or horizontal holes – units and different mortar arrangements. For masonry consisting of solid units and mortar of general application, the compressive strength is expressed by equation (4):

$$f_{\text{mod}} = \frac{S}{A} \cdot \frac{f_b}{\alpha} \cdot \log(10 \cdot f_m + 5) \tag{4}$$

where f_{mod} is the compressive strength of masonry [MPa], f_b is the compressive strength of units [MPa], f_m is the compressive strength of mortar [MPa], S is the total area of the units that is filled with the mortar of the horizontal joints [cm^2], A is the total horizontal area of the units, resulting from the product of their width over their length, without removing potential holes [cm^2] and α is a factor as follows: α = 5 for solid units with compressive strength f_b > 10 MPa, while α = 4 for f_b < 10 MPa.

4 Statistical Analysis Indices

In this work statistical indices based on the ratio of the estimated, f_{mod}, to the experimental, f_{exp}, masonry strength ($f_{\text{mod}} / f_{\text{exp}}$) are used for the evaluation of the predictive models. More precisely, the statistical indices calculated are: the mean, the coefficient of variation and the average absolute error of estimation. The relationships of those indices are discussed in the next two subsections.

Mean and coefficient of variation. Mean, designates the average of the ratios $f_{\text{mod}} / f_{\text{exp}}$ as shown in equation (5). For mean values greater than unity the experimental strength is overestimated, which demonstrates that the model predictions are unsafe. For ratios $f_{\text{mod}} / f_{\text{exp}} < 1$, the model is safe. Too low values imply that the model tends to underestimate the actual compressive strength of the specimen.

The coefficient of variation, COV, is calculated from equation (6). It is noted that lower values of COV indicate better predictive capacity of the model. The $mean$ and the coefficient of variation of the ratios of the two variables (COV), are calculated by the relations:

$$mean = \frac{1}{n} \cdot \sum_{i=1}^{n} (f_{\text{mod},i} / f_{\text{exp},i}) \tag{5}$$

$$COV = \frac{\sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} [(f_{\text{mod},i} / f_{\text{exp},i}) - \frac{1}{n} \cdot \sum_{i=1}^{n} (f_{\text{mod},i} / f_{\text{exp},i})]^2}}{\frac{1}{n} \cdot \sum_{i=1}^{n} (f_{\text{mod},i} / f_{\text{exp},i})} \tag{6}$$

where $mean$ is the average value of the ratios $f_{\text{mod},i} / f_{\text{exp},i}$ of a database with n datasets, $f_{\text{mod},i}$, $f_{\text{exp},i}$ are the estimated and the experimental compressive strength, respectively, of a dataset with index i and COV is the coefficient of variation for the datasets considered.

Average absolute error of estimation. The index of average absolute error (Average Absolute Error – AAE) [17, 18], expresses – on average – the relative error between the estimated and experimental masonry compressive strength of a database, as a percentage of the experimental strength. The relation that provides the average absolute error of the estimation is defined as shown in equation (7):

$$AAE = \frac{\sum_{i=1}^{n} \left| \frac{f_{\mathrm{mod},i} - f_{\exp,i}}{f_{\exp,i}} \right|}{n} \qquad (7)$$

where AAE is the average absolute error of estimation, $f_{\mathrm{mod},i}$, $f_{\exp,i}$ are the estimated and the experimental compressive strength, respectively, of an $-i$ dataset and n is the number of datasets included in the database.

5 Results

The compressive performance of the two types of specimens is, as expected, different. The presence of vertical joints in the wallettes increases their horizontal deformation during compression and as a consequence reduces quite frequently their ability of resistance. For this reason, the evaluation of the design models is carried out separately for the two types of specimens.

Figure 2 demonstrates the comparison between experimental strengths, $f_{\exp}$, and estimated strengths, f_{mod}. The circular points represent the prism specimens and the diamonds the wallettes. The points on the bisector correspond to $f_{\mathrm{mod}} = f_{\exp}$. The points in the diagrams included between the bisector and the upper dashed line correspond to overestimation of the model up to 20%. Similarly, the points included below the bisector and between the lower dashed line indicate that the model underestimates up to 20% the experimental strength of specimens.

Table 4 presents the results of the statistical analysis indices shown in section 4, which qualitatively capture the degree of reliability of the predictions of the models of section 3, for the two types of specimens.

As demonstrated in Fig. 2, the predictive models tend to overestimate the compressive strength of prisms and wallettes with experimental strength lower than 5 MPa. For greater experimental strengths, EN 1996-1-1 estimations are better for wallettes in comparison to prism specimens.

For this range of compressive strengths, the predictions of TMS 602 model are, mainly, conservative. The model significantly underestimates the experimental strengths of both types of specimens constructed with units and mortars of very high compressive strength. That is probably due to the equation of the American Standard which ignores the compressive strength of mortar and its contribution to masonry's strength.

In contrast, specifically for prism and wallette specimens which are constructed with masonry units of very high compressive strength, the estimations of the Rossi model are in general much higher from experimental strengths.

The model Tassios, results quite good estimated strengths for both types of wall specimens, as shown from the diagrams of Fig. 2 and the statistical indices in Table 4.

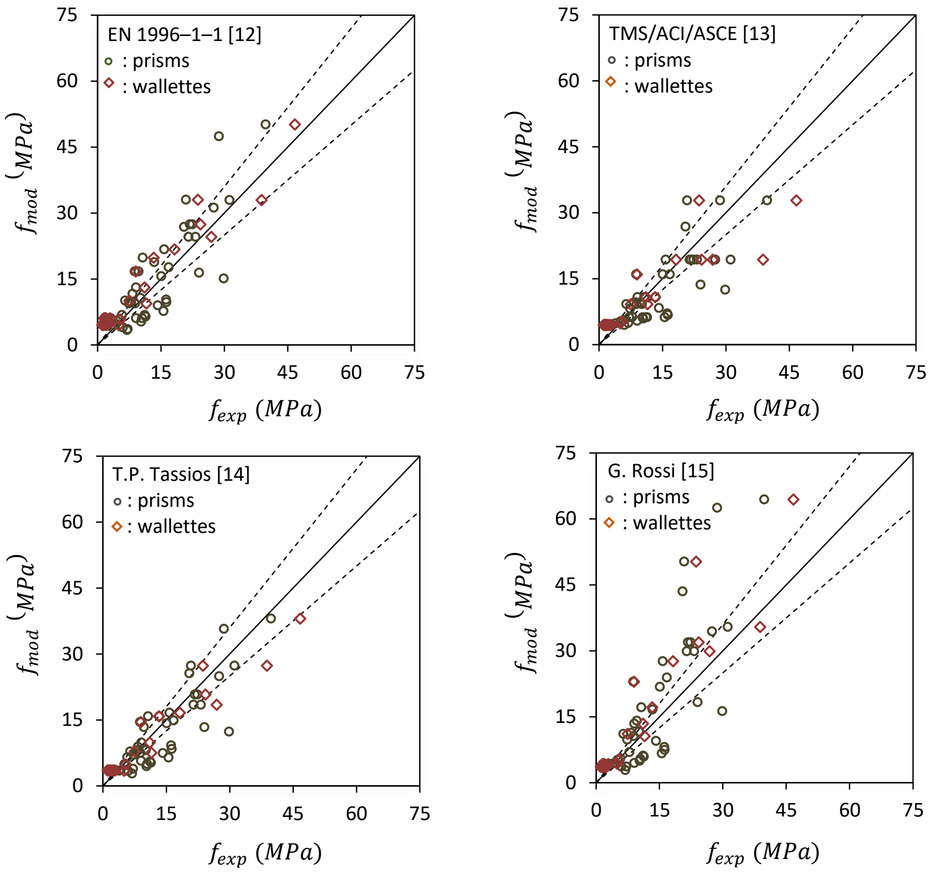

Fig. 2. Comprarison between experimental strengths $f_{\exp}$ and estimated strengths f_{mod}

Table 4. Statistical indices for the database per type of specimen (P: Prisms, W: Wallettes)

Models	$\sum_{i=1}^{n}(f_{\mathrm{mod},i}/f_{\exp,i})$				*AAE*	
	mean		*COV*			
	P	W	P	W	P	W
EN 1996–1–1 [12]	1.54	2.20	0.59	0.49	0.75	1.24
TMS/ACI/ASCE [13]	1.33	1.93	0.63	0.53	0.61	1.06
T.P. Tassios [14]	1.18	1.62	0.54	0.47	0.48	0.75
G. Rossi [15]	1.42	1.89	0.49	0.37	0.66	0.91

6 Conclusions

In this paper the reliability of four models to predict the compressive strength of masonry specimens consisting of solid clay bricks and different types of mortars, is examined. For that purpose an experimental database of compression tests, under monotonic loading, on prism and wallette specimens, was assembled.

The processing of the data was carried out by type of specimen. From the analysis of the results the following conclusions are drawn for the sample of the database presented in this paper:

- The predictive models significantly overestimate the compressive strength of masonry specimens with experimental strength lower than 5 MPa for both types of specimens.
- The estimated strengths of the model calculated according to EN 1996–1–1, for the masonry specimens with experimental strength greater than 5 MPa, are placed better in the comparison diagrams for the wallettes than for the prism specimens.
- The predictions of TMS 602 model, for the specimens with experimental strength greater than 5 MPa, are in general conservative.
- The estimations of Tassios model result in quite good estimated strengths and statistical indices for both types of wall specimens.
- The model proposed by Rossi mainly overestimates the experimental strengths of both prism and wallette specimens.

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