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Analysis of deformability modulus by linear and nonlinear elastic methods in ceramic structural masonry and mortars

(Análise do módulo de deformabilidade por métodos elásticos lineares e não lineares em alvenaria estrutural cerâmica e argamassas)

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Abstract

There are studies analyzing the parameters of structural masonry strength, however few are performed evaluating the interference of the mortar in the deformability parameters. The objective of this study was to verify the theories of elasticity (Hooke's linear model and nonlinear models by Ghosh, Duffing, and Martin, Roth, and Stiehler) applied to structural masonry. Ceramic blocks were pressed and fired at 890 ºC and mortars prepared with the proportion 1:1:5:0.5:2 of cement: hydrated lime: sand: PVA binder: water. The materials were tested in compression individually and in prisms with and without the use of mortars. The results obtained with the linear elastic analysis were incoherent since the deformability modulus obtained for the mortar prisms was higher than those without mortar. Performing the analysis by nonlinear theories, it was found that the results obtained were more coherent, mainly by Duffing's theory that uses one parameter for stiffness and another for damping of the material.
Keywords: structural blocks, compressive strength, deformability, nonlinear elastic relationship.

Resumo

Existem estudos analisando os parâmetros de resistência de alvenaria estrutural, porém poucos são realizados avaliando a interferência da argamassa nos parâmetros de deformabilidade. O objetivo deste estudo foi verificar teorias de elasticidade (modelo linear de Hooke e modelos não lineares de Ghosh, de Duffing e de Martin, Roth e Stiehler) aplicados a alvenaria estrutural. Foram confeccionados blocos cerâmicos prensados e queimados a 890 ºC e argamassas na proporção 1:1:5:0,5:2 de cimento: cal hidratada: areia: cola PVA: água. Os materiais foram ensaiados à compressão individualmente e em prismas com e sem a utilização das argamassas. Os resultados obtidos com a análise linear elástica mostraram-se incoerentes uma vez que o módulo de deformabilidade obtido para os prismas com argamassa foi maior do que os sem argamassa. Realizando a análise pelas teorias não lineares, verificou-se que os resultados obtidos foram mais coerentes, principalmente pela teoria de Duffing, que utiliza um parâmetro para rigidez e outro para amortecimento do material.
Palavras-chave*: blocos estruturais, resistência à compressão, deformabilidade, relação elástica não linear.*

INTRODUCTION

Structural masonry is a constructive system that has been gaining the construction market in Brazil and the world, as it allows for a reduction in the construction period, as well as savings in the final cost of the projects [1, 2]. Despite the high acceptance in the market and the scientific scenario, the lack of some knowledge about the mechanical behavior of this type of system inhibits the application of structural masonry as a diffuse constructive model. It is worth noting that in the last years several studies have been carried out regarding the compressive strength of the structural blocks, considered the main parameter for the design of this type of masonry, lacking studies about the deformation properties that these blocks present [3, 4]. As an example of studies in structural masonry, we can mention: i) Santiago and Beck [5] performed quality control of several concrete structural block factories in different regions of Brazil, taking as parameters the compressive strength, dimensional analysis, and water absorption; ii) Mata et al. [6] verified the flexural and shear behavior in structural masonry panels using the procedures of standards ABNT NBR 15961-1:2011 [7], EN 1996-1-1:2005 [8], and ACI TMS 530:2013 [9], not checking the other properties; iii) Fortes et al. [10] studied the compressive strength of structural masonry with high strength concrete blocks; and iv) Santos et al. [11] carried out modeling by the finite element method in structural masonry intending to study the compressive strength of ceramic prisms.

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In the literature on the subject, studies on mortars used in structural masonry [12], as well as the influence of grating on the compressive strength properties of the material [13], are also highlighted. It is interesting also to highlight studies that evaluated the incorporation of residues in structural masonry, in both ceramic and concrete [14], and other studies that evaluated the productive efficiency of the system in structural masonry when compared to other methods [15], as well as environmental studies, which compare the amount of CO_2 emitted in the production and transport of the units of ceramic and concrete structural blocks comparing them with other technological ones [16]. About the use of mortars for laying structural masonry, there is also some pertinent information that is deepened in the present study. It is known that the main function of the mortar in sealing systems is to act as a bond of the parts that compose the masonry, making it monolithic [17]. Another function of great importance, which is investigated more specifically in this study, is the capacity to accommodate or receive the loads and to allow the deformations to occur without the appearance of internal tensions that would provoke the appearance of cracks. In this way, it can be considered that the mortar acts as a dilatation joint, which relieves the internal stresses of the material [18].

From another point of view, it can be considered that the mortars function as elastic support (or springs) for the blocks that make up a row of structural masonry walls. Springs are defined as any device or material, the purpose of which is to convert mechanical work into potential energy and to reconvert it back into mechanical energy. Some springs work exclusively in linear ways, obeying Hooke's law, and nonlinear springs, whose relation between load or applied stress is not proportional to the displacements or deformations suffered by the material [19, 20]. Some nonlinear elastic theories are cited below and are deepened during the analysis of the results of this study. Ghosh's theory [19] proposes that the relationship between stress and strain is not linear, but quadratic or cubic for more complex spring systems. As described, masonry mortars act as springs for the system and provide cushioning when loads are applied. However, this system is not simple, since it is composed of blocks and mortars, so it is expected that more complex theories than Hooke's law are valid for this type of material. Another interesting nonlinear theory is from Duffing [19, 20], which proposes that stresses and deformations are proportional, but depend on two distinct factors (stiffness and damping capacity), whereas classical theories such as Hooke's law propose that these two properties are related only as a function of the modulus of elasticity, which measures the stiffness of the evaluated system. It is also valid to describe Martin, Roth, and Stiehler's theory, which proposes an adjustment dependent on exponential parameters rather than the polynomial parameters presented by other authors [19, 20].

It is worth noting that although there are studies that perform numerical modeling in structural masonry [2-5], or investigate the mechanical and elastic behavior of the system as a whole or the main components of the system (mortar and block) [12, 13, 17], papers that evaluated the validity of the nonlinear elastic theories presented above were not found in the literature. This is the main novelty of this study, which evaluated the structural masonry system by different theories beyond the classical Hooke's law. In this context, the objective of this study is to understand the deformability behavior of structural masonry elements produced with pressed and fired structural masonry ceramic blocks, aiming to understand how mortars influence the mechanical behavior of loaded walls. The proposed study is important because it allows understanding the behavior of deformation of a structural material that exhibits fragile behavior. It is known that this type of structure represents less security for users of the building, since, in reinforced concrete buildings, it is easier to inspect the cracks in the material in service. In structural masonry structures, where the part of resisting efforts is performed by the wall itself, it is more difficult to perform the analysis of cracks, due to the fragility that the system presents, causing abrupt failures and without prior warnings.

MATERIALS AND METHODS

To make ceramic blocks, a kaolinite clay mass from the city of Campos dos Goytacazes-RJ, Brazil, which presented the same parameters of physical, chemical, and mineralogical characterization, indicated by other researchers who studied the same clay [21-23], was used. The ceramic blocks were produced using an Eco Master 7000 Turbo II press, with hydraulic control, 7.5 hp engine, and compression load up to 360 kN. The blocks had dimensions of 30x15x7 cm (Fig. 1) and were of the male-female model for fitting, which enabled optimization of the constructive process [24, 25]. After pressing, the structural ceramic blocks were fired at 890 °C in a Caieira-type oven. After the firing process, 6 ceramic blocks were tested in compression in an instrumented manner to obtain the modulus of elasticity of the material, as recommended by ABNT NBR 15270-2:2005 standard [26]. The blocks were cut and fitted as shown in Table I, using LVDT strain gauges (PA-06-1000BA-120L) connected to a Lynx data acquisition system. This system sent electrical signals to sensors that operated as electrical resistors and converted the variations of these resistors into deformations. These deformations were captured and interpreted by AqDados and AqDanalysis 7.0 software installed on the computer connected to the Lynx system. For the loading application, a servo-hydraulic press was used, with load control, speed control, and data acquisition cell for the applied force over time. The press used (Emic) had a load capacity of 2000 kN. Thus, it was possible to plot the stress-strain curve, from which the modulus of elasticity of the material was extracted.

The mortar used was produced in a 1:1:5:0.5:2 mass ratio of Portland cement CP III-40 RS: super lime CH III: medium sand: PVA binder: water, a composition based on literature [27, 28]. To test the material in compression and

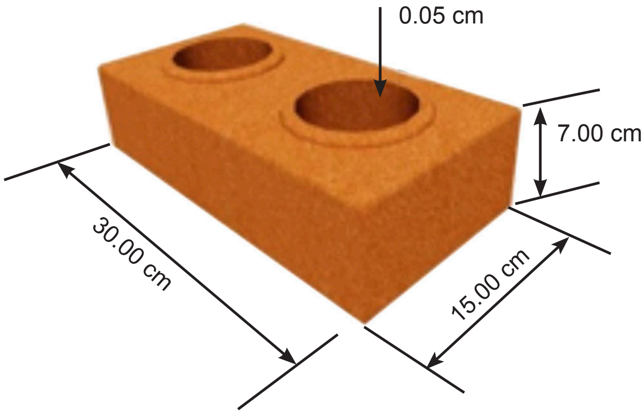

Figure 1: Illustration of the plug-in block used.
[Figure 1: Ilustração do bloco de encaixe utilizado.]

Table I - Representation of the studied models.
[Tabela I - Representação dos modelos estudados.]

Geometry	Mortar	Representation
Blocks	Without	
Prisms with whole blocks	Without	
Prisms with whole blocks	With	

to obtain the longitudinal deformation modulus, 9 prismatic 4x4x16 cm samples were used. Next, prisms were produced with the studied three-row ceramic blocks, with and without the application of the laying mortar. Table I shows the prism models used in the study. Four prisms were produced with each mortar pattern for compression testing, following the same parameters and using the same test equipment performed in the single block. Stress-strain curves were obtained for the two prism patterns under study, from which it was possible to obtain the modulus of elasticity using the classical linear theory of Hooke and other nonlinear theories, highlighted before and presented more fully ahead. It is noteworthy that the regression calculations were performed with the aid of Microsoft Excel software.

RESULTS AND DISCUSSION

Analysis of the parameters of the block and individual mortar: Fig. 2a shows the stress-strain curve for the 6 blocks tested. The compressive strength of the blocks was 4.13±0.32 MPa, and the longitudinal deformability modulus was 2.80±0.09 GPa. In addition, the blocks presented a Poisson's ratio of 0.18±0.03, and the transversal elastic modulus was 1.18±0.02 GPa. It was observed that the behavior of the material was fragile, where the rupture occurred as the appearance of previous cracks, and the elastic region was nonlinear. These facts can be justified through the crystalline structure that the ceramic blocks present. It is known that these blocks are formed by ionic bonds, and because of this, there are very few slip systems, where the movement of the dislocations can occur [29, 30]. This is due to the electrically charged nature of the ions that make up this material, which causes positions where the same charge ions are placed close to each other, causing static repulsion. These facts provoke the fracture of the ceramic materials [31, 32], and cause the occurrence of nonlinear elastic behavior, as verified in Fig. 2a. The behavior presented by the blocks makes difficult the analysis of the material, since the use of fragile structures is extremely dangerous. Thus, it is understood that analyzing only the absolute values of strength, which in this case presented an average value of 4.13 MPa, is not enough to study the structural blocks. The deformability of the blocks, which can be illustrated by parameters such as the longitudinal and transverse modulus of elasticity, should also be analyzed. These parameters of deformability were studied in prisms with two configurations: with a mortar and another without mortar. This comparison was carried out with the purpose of evaluating the effect that the mortar causes in elements of structural masonry. Fig. 2b shows the stress-strain curve obtained for the studied mortars. The compressive strength of the mortars was 2.82±0.46 MPa, while the longitudinal deformability modulus for the material was 0.88±0.02 GPa.

Analysis of the parameters of prisms with and without mortar: Figs. 3a and 3b show the stress-strain curves for the prisms produced without and with mortar, respectively. It should be noted that the raw materials without mortar had

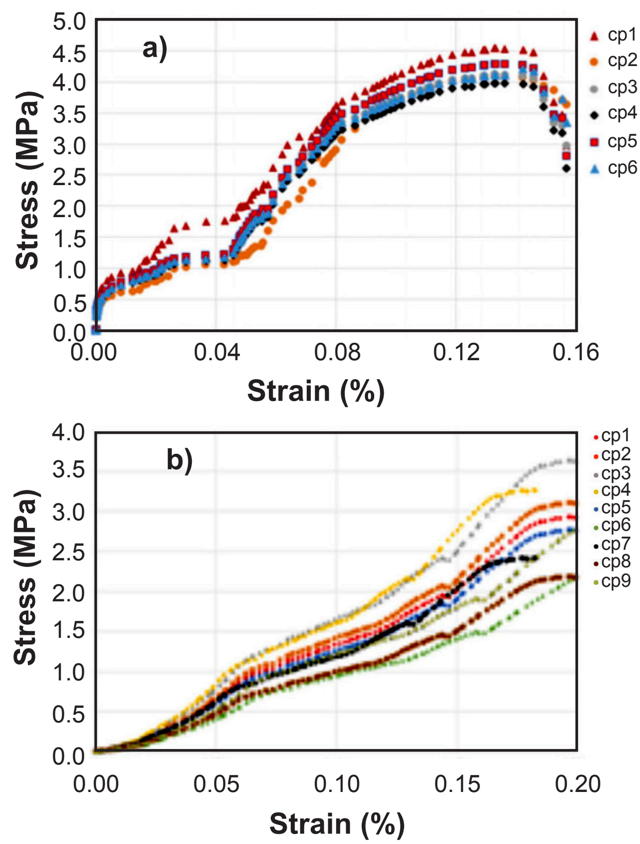

Figure 2: Stress-strain curves for the studied blocks (a) and mortars (b).
[Figure 2: Curvas tensão x deformação para blocos (a) e argamassas (b) estudados.]

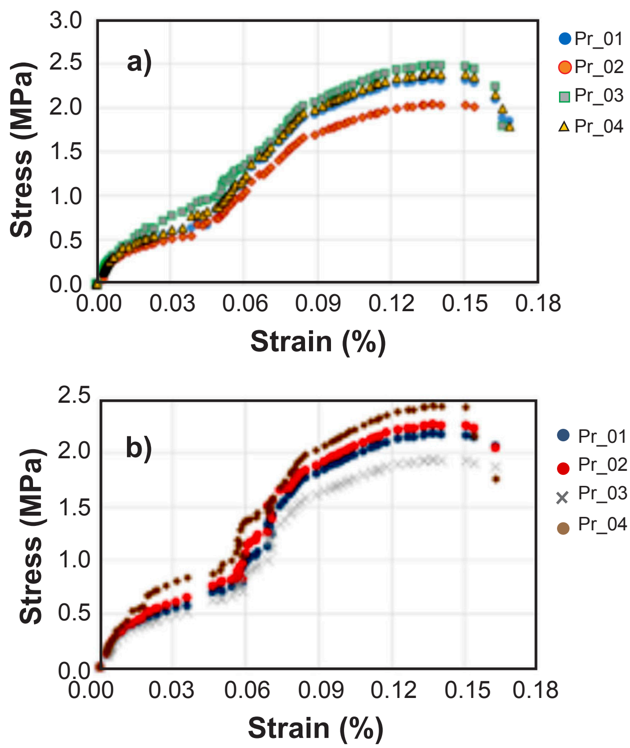

Figure 3: Stress-strain curves for prisms without (a) and with (b) mortar.
[Figure 3: Curvas tensão x deformação dos prismas sem (a) e com (b) argamassa.]

a strength of 2.21±0.08 MPa, a longitudinal deformability modulus of 1.42±0.10 GPa, and a transversal elastic modulus of 0.51±0.06 GPa. The prisms with the presence of mortar presented increases in strength (2.34±0.05 MPa), longitudinal deformability modulus (1.69±0.11 GPa), and transversal deformability modulus (0.54±0.06 GPa). This could evidence that the use of mortars in masonry prisms would cause an increase in the modulus of deformability, making the material more fragile. However, as reported in several studies [33-36], this is not the behavior presented by structural masonry walls when mortar is used. How to explain this inconsistency in the data presented?

The calculation of the deformability modulus of the prisms with mortar was performed using the theory based on Hooke's law, σ=E.ε, which assumes that this material exhibits linear elastic behavior. However, this statement is not always valid. Moreover, structural masonry walls produced with ceramic blocks (with or without mortar) are extremely fragile materials, and it is known that this type of material has practically no plastic deformation [37, 38]. Therefore, the calculation of the deformability modulus must encompass the entire region of the stress-strain plot. As discussed before, prisms presenting mortar work as elastic supports, composed precisely by mortars, as shown in Fig. 4. It is known that elastic materials, such as springs, do not necessarily present linear behavior, as discussed before. There are some theories of nonlinear elasticity, such as Ghost's, Duffing's, and Martin, Roth, and Stiehler's theories

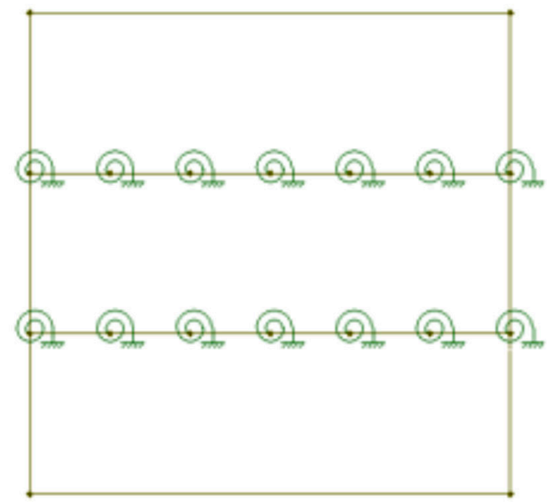

Figure 4: Representation of a prism with mortars functioning as elastic support.
[Figure 4: Representação de um prisma com argamassas funcionando como suporte elástico.]

[19, 20], which are valid for spring systems and was verified for structural masonry prisms, with and without mortar. Therefore, other ways of calculating the deformability modulus of the prisms with mortars should be used, considering that the prism has the behavior of a nonlinear spring. The main mathematical formulations that represent the behavior of nonlinear springs are described below. These formulations were applied in the study of prisms with and without mortar, performing an analysis of the deformability properties that occur in each of these theories.

The first nonlinear approach studied was Ghosh's equation (Eq. A) [39]. In this expression, it is considered that the stress does not vary linearly with the deformation, but rather they have a power-law dependence given by:

$$\sigma = K.\ \varepsilon^{P} \tag{A}$$

where σ is the stress subjected to the material, K is the stiffness to deformation, a similar concept to the deformability modulus, ε is the deformation undergone by the material, and p is an exponent related to the nonlinearity of the material, generally quadratic or cubic. It is worth mentioning that if the Ghosh equation is used with p=1, the equation proposed by Hooke's law is obtained. Thus, the difference between Hooke's equation and Ghosh's equation is the change in the order of exponent that relates stress and strain. Using the relation established by Eq. A, the following rigidities (longitudinal deformability modulus) were obtained for the prisms studied (Table II): using p=2 stiffness of 1.27±0.14 GPa for prisms without mortar and 1.22±0.11 GPa for raw materials with mortars; using p=3 stiffness of 1.24±0.09 GPa for raw materials without mortar and 1.12±0.06 GPa for prisms with mortar. It was verified that the stiffnesses obtained by both quadratic and cubic models were statistically equivalent to the use of the Ghosh's model. This is not yet the expected model for the

Table II - Deformability parameters obtained.
[Tabela II - Parâmetros de deformabilidade obtidos.]

Model studied		Prism without mortar	Prism with mortar
Hooke's law	E (GPa)	1.42±0.10	1.69±0.11
	R^2	0.693-0.712	0.705-0.723
Ghosh equation (p=2)	K (GPa)	1.27±0.14	1.22±0.11
	R^2	0.891-0.923	0.912-0.945
Ghosh equation (p=3)	K (GPa)	1.24±0.09	1.12±0.06
	R^2	0.967-0.986	0.973-0.992
Duffing equation	β (GPa)	1.67±0.14	1.38±0.11
	α (GPa)	(1.30±0.07)x10^6	(1.16±0.17)x10^6
	R^2	0.751-0.876	0.812-0.898
Martin, Roth, and Stiehler equation (A=0.38)	M	3.14±0.17	2.78±0.21
	R^2	0.570-0.662	0.592-0.703

behavior of mortar prisms, since several studies report the reduction of stiffness and better parameters of deformability in structural masonry walls with mortar [33-36]. Based on the coefficient of determination (R^2) values obtained (Table II) for the analyzes that considered Hooke's law or the Ghosh equation with p=2 and p=3, it was verified that the use of models of order higher than 1 improves the regression analysis, which proved that structural masonry prisms have a closer mechanical behavior proposed by Ghosh than the classic model established by Hooke.

Another model of nonlinear springs proposed by Duffing is given by [40-42]:

$$\sigma = \beta.\varepsilon + \alpha.\varepsilon^3 \quad \text{(B)}$$

where β represents the equivalent rigidity of the material, and α represents a nonlinear approximation to the oscillation submitted to the studied system as a result of loading and unloading. The α parameter can be defined as the damping characteristics of the studied physical system. Again, it is worth noting that for cases where α is equal to zero, the Duffing equation becomes the unidirectional Hooke's law. This equation is applied to cyclic systems, where loading and unloading occur in the mechanical systems (usually springs) studied. Therefore, it is verified that the Duffing equation proposes the addition of another constant in the equation, relating stress and deformation through two properties, the rigidity of the system and its damping capacity. Applying Eq. B in the stress-strain diagrams shown in Fig. 3, we obtained β of 1.67±0.14 and 1.38±0.11 GPa and α of (1.30±0.07)x10^6 and (1.16±0.17)x10^6 GPa for prisms without and with mortar, respectively. It was observed with the use of this model that the prisms with mortars obtained less rigidity than the raw ones without mortar. This model, therefore, followed the logic established in the literature [33-36] and can be considered as a good approximation model for the behavior of structural masonry walls, although the R^2 regression values obtained by the model were smaller than those obtained by the Ghosh's equation (Table II). About the damping capacities provided by the mortar, the mortar-free premixes had lower damping since the α values obtained were higher for this wall pattern. Thus, it is possible to understand how mortars interfere in the deformability of structural masonry walls, based on the model detailed by Eq. B. Deformability improvements should be attributed to two factors: reduction of stiffness and increased damping obtained using mortars.

The last model used to study deformability in structural masonry walls using prisms is defined by the equation of Martin, Roth, and Stiehler [43, 44]:

$$\frac{\sigma}{M} = (\varepsilon^{-1} - \varepsilon^{-2}).\, e^{A.(\varepsilon - \varepsilon^{-1})} \quad \text{(C)}$$

where M represents Young's modulus (modulus of deformability of the material), and A is a fitting parameter, ranging from 0.32 to 0.42 (usually A is adopted as 0.38). The equation proposed jointly by Martin, Roth, and Stiehler was initially used for elastomeric materials, that is, natural or synthetic polymers that have as the main characteristic the high elastic deformations when submitted to loads. A typical example of elastomer is natural rubber. Thus, it is worth noting that unlike all other theories presented, which are based on polynomial adjustments, Martin, Roth, and Stiehler's equation relates stress and strain exponentially. To calculate the parameter presented, the value of A was used as 0.38, as highlighted in other studies. The values of M obtained (Table II) were 3.14±0.17 and 2.78±0.21 GPa for the prisms without and with mortar, respectively. However, the values obtained were very high, being higher than the values obtained for the deformability modulus found for the isolated ceramic blocks. Moreover, the values were above those usually found in the literature [33-36]; therefore, the Martin, Roth, and Stiehler's model was discarded as a possible approximation to the behavior of deformability in structural masonry walls. This fact makes sense since structural masonry bonnets cannot have their deformability compared to elastomers like natural rubber. Moreover, the R^2 values obtained (Table II) were very low, indicating a weak fitting to the proposed model, mainly because of the mathematical difficulty of using Eq. C in the stress-strain curves of Fig. 3.

CONCLUSIONS

The proposed study consisted of evaluating structural deformability properties using three-row prisms with and without mortar. The ceramic blocks used were fired at 890 ºC and defined as plug-in block geometry. The mortars studied were made in a ratio of 1:1:5:0.5 of cement: hydrated lime: sand: PVA binder. Compression tests were performed on the two materials separately to obtain the strength and deformability parameters of both materials in order to verify the consistency of the obtained values. It was concluded that both materials were compatible with those commonly used in structural masonry. About the prisms, elements were made with three rows, with and without the use of mortars. The focus of the study was to obtain the deformability parameters. Using the linear relationship established by the Hooke's law, values of deformability modulus of 1.42±0.10 GPa for the prisms without mortar and 1.69±0.11 GPa for the prisms with mortar were obtained. These values were considered unsatisfactory since it does not make sense that structural masonry increases its stiffness using mortars. Thus, other elastic, nonlinear models were used to analyze the deformability parameters of the prepared prisms. Ghosh's equation was used quadratically and cubically. Although regression values higher than the Hooke's model were obtained, the analysis performed through this model was discarded since there was a statistical equivalence between the rigidity obtained for the prisms with and without mortar, a fact invalidated based on the literature. The model from Duffing showed lower regression than the Ghosh's model, but was considered satisfactory since the obtained deformability parameters were highly coherent. That is, prisms with mortar showed better deformability behavior than those without mortar. In the model detailed by the Duffing's equation, the deformability is defined in terms of stiffness, reduced for prisms with mortar. Finally, the model of Martin, Roth, and Stiehler was analyzed, which in addition to presenting low regression values because of the mathematical difficulty of the implementation of the equation, led to very high values of rigidity, leading the model to be considered incoherent. The conclusion was that the parameters of deformability of structural masonry walls produced with ceramic blocks and mortar could be defined approximately according to two parameters: rigidity and damping of the material. This behavior is defined in terms of the Duffing's equation for nonlinear elasticity.

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