Non Linear Analysis With Interface Elements of Concrete Block Masonry Under Compression

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Abstract

The main goal of this study is to evaluate a numerical model to simulate the compression test for concrete block prisms, through a constitutive model using the theory of plasticity and compare its results with those of experimental tests. For the numerical determination of the axial and lateral stress and strain of the prisms, the non linearities of the materials and the interfaces between them were considered. The numerical simulation was carried out comparing two mortar mixes, with displacement control, as in the experimental tests. For the concrete which comprised the block and the mortar of the joint a non linear material model offered by the Diana program was used, where the plasticity limit conditions are established by the combined criterion of Rankine and Drucker-Prager. This criterion is commonly employed for quasi-fragile isotropic materials, since it allows adequate representation of cracking by traction and crushing by compression. The post-peak behavior of the material under tensile followed an exponential law and, under compression, a parabolic criterion was specified for the ascendant and descendent parts of the stress diagram and the hardening parameter. The mortar was connected to the block by the interface, for which the discrete model was employed, where the cracking occurred when the normal traction exceeded the tensile strength of the material.

Keywords: Concrete blocks, structural masonry, failure mode, behavior under compression.

1 Introduction

The main deformation modes of an interface are related to kinematic phenomena, such as: localized deformation, sliding, opening and dilatance. Therefore, a greater understanding regarding the loading in failure mechanisms of masonry is required, considering a cohesive interface (before the strength peak) and a single friction model (post-peak), where the shear stresses produce geometric simulation.

MARTINS [1] carried out shear tests on hollow concrete block prisms with two levels of strength for the block and three for the settlement mortar. The concrete block prisms have a space between the middle blocks so that, during the tests, they can slide and cause shearing at the contact between the mortar and the block. Figure 1 shows the prisms and a diagram showing the set up for the tests.

ABDOU *et. al.* [2] carried out studies in which the main objective was to investigate the behavior of settlement joints under shear stress, through testing two-block prisms. A model of the interface was produced which was able to reproduce the non linearities observed in the experimental tests. The tests were carried out using two types of units (solid and hollow) for the same mortar. A piece of equipment was modified and improved to allow the tests to be carried out with mortar samples. The first tests consisted of loading and unloading cycles to characterize the displacements at the interface between the brick and the mortar (elastic, elastic-plastic), where the unloading phase allowed us to determin whether a reduction in the stiffness of the materials occurred. The

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tests also allowed the verification of a relation between an increase in vertical stress and the shear stress, as well as whether the behavior of the interface changes with the type of unit. The authors state that the failure mode of the masonry could occur in the brick (distributed cracks), in the mortar (crushing) or at the interface between the two materials. At the brick-mortar interface two failure modes are possible: failure by tensile (induces an opening of the joint) and shearing (sliding between the surfaces with friction). The values obtained in the experimental tests are summarized in Table 1.

Table 1 – Proportion by volume of cement, limestone and sand in the mortar mixes.

Brick	Characteristics	Last (Peak Values)
Solid	Cohesion (MPa)	c=1.58
	Friction Angle	tan (φ)=1.01
Hollow	Cohesion (MPa)	c=1.27
	Friction Angle	tan (φ)=1.01

GIAMBANCO & GATI [3] worked with a model for the cohesive interface of masonry blocks. This surface is bilinear, obeys the Coulomb Law and has a tensile stress as a limit. The limit functions, obtained in the stress space, are presented in Eqs. (1) and (2).

$$\phi_1(\sigma,\beta)=|\tau_n|+\sigma_n.\tan\varphi-c(\beta)=0 \quad (1)$$

$$\phi_2(\sigma,\beta)=\sigma_n-s(\beta)=0 \quad (2)$$

where φ is the internal friction angle of the material, s(β) and c(β) are the values for tensile strength and cohesion, and β is an internal variable which quantifies the inelastic behavior.

2 Simulation of Non Linear Behavior of Prisms

The adoption of the numerical model is generally based on the consideration that its results are deterministic and non probabilistic, that is, the mechanical properties are taken as averages, without considering the variability. The aim of this study is to obtain a model able to simulate numerically the prism compression tests, through a constitutive model using the theory of plasticity. Figure 2 shows a diagram of a quadrangular mesh of elements with eight nodes, submitted to a plane state of stress, displacement restrictions and loadings using the numerical model.

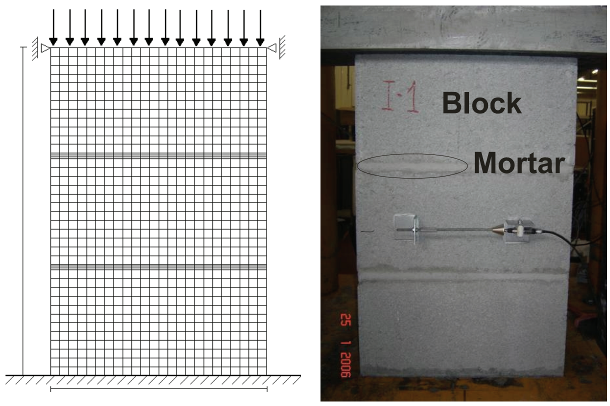

Figure 2 – Geometrical characteristics of the block-mortar set.

The linear and non-linear mechanical characteristics of the materials used in the simulation are shown in Table 2 and Table 3 ([4, 5 and 6]). They were simulated with only two mortar mixes since, in the experimental results, no differences were observed in the strength and failure mode of the prisms

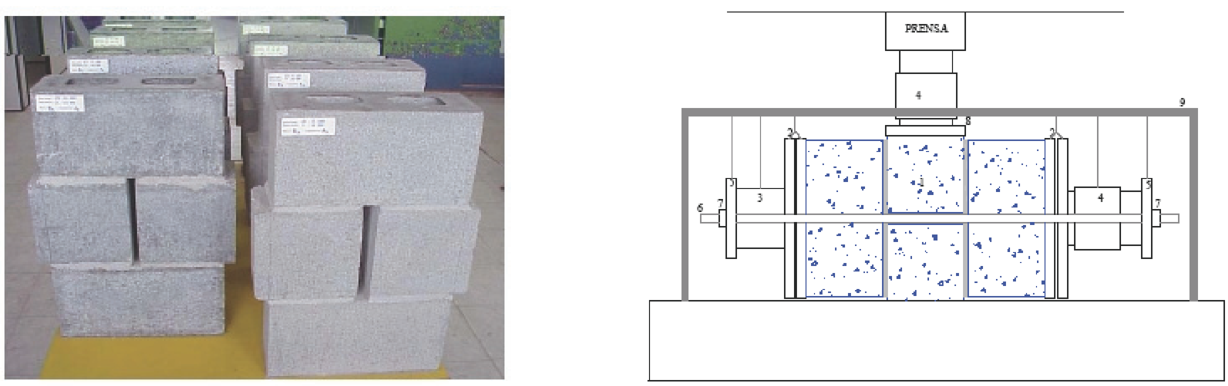

Figure 1 – *Block prisms for the shear tests with and without lateral stress and a diagram of the test carried out by Martins (2001).*

constructed with the mortar mixes II and III. The experimental results for the prisms were used, named I-1, I-2, II-1 and II-2. The properties of the materials were adjusted in each simulation. The mechanical properties of the mortars with mixes I and II were established considering the stress state in which they were found, that is, using as a reference the triaxial compression strength envelopes, the increase in the elasticity modulus of the confined mortar (E_c) and the decrease in the Poisson ratio (ν) due to the lateral confinement [7].

Table 2 – Linear mechanical characteristics of the materials.

Component	E_c (MPa)	ν	k_n (MPa/mm)	k_s (MPa/mm)
Block	16000	0.19	–	–
Mortar - I	18000	0.10	–	–
Mortar - II	14250	0.10	–	–
Interface	–	–	81	33

3 Numerical Results

3.1 Experimental results for type A prisms

The main objective of this simulation is to evaluate the axial and lateral deformability of block prisms, resulting from a change in the mortar mix (mixes I and II). The values for the elasticity modulus and Poisson ratio of the mortar given in Table 2 were obtained considering the increase in the axial and lateral stiffness due to confinement.

It was verified through the stress-strain curves, for prisms I-1 and I-2, that the axial stiffness of the numerical model was lower, that is, for the same level of vertical stress the average strain in the experimental tests were lower than those obtained numerically. Regarding the lateral strain, the numerical model managed to represent the experimental tests up to the opening of the first crack. Figures 4, 5, 6 and 7 show a comparison between the axial and lateral stress-strain curves of the prisms obtained experimentally for a mortar joint with mixes I and II and the results obtained numerically at similar positions.

The appearance of localized stress at a height half way up the prism of mix I induced cracks in the block, leading to an instantaneous increase in the lateral strain of the prism, as can be seen in Figs. 4 and 5. Thus, the prism constructed with mortar mix I did not manage to represent the lateral deformations, for stress levels above 0.6. f_c (compressive strength), but a good agreement for the stress at break point was obtained.

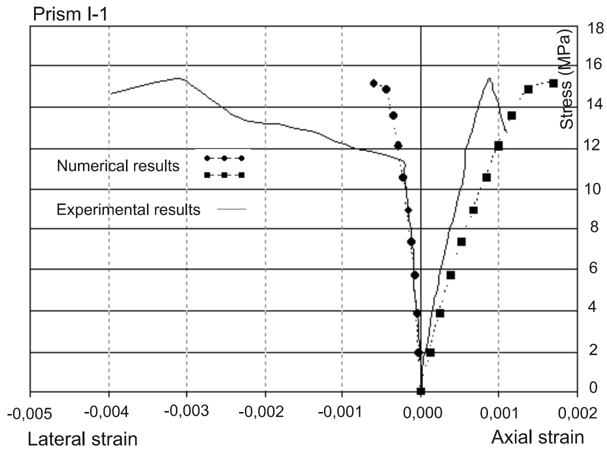

Figure 3 – Axial and lateral stress-strain curves of the prisms with mix I-1.

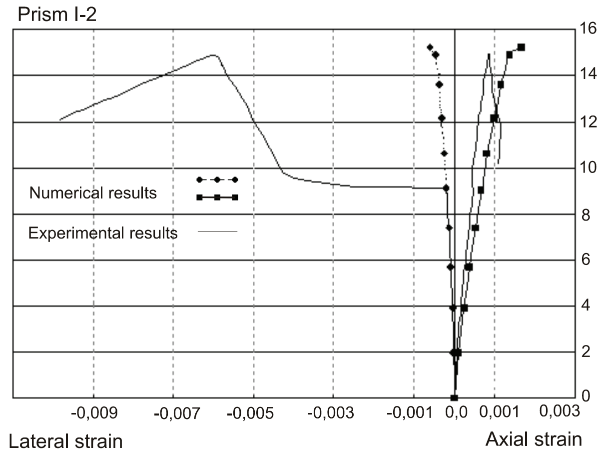

Figure 4 – Axial and lateral stress-strain curves of the prisms with mix I-2.

Table 3 – Non linear mechanical characteristics of the materials.

Component	c (MPa)	f_t (MPa)	Sin φ	Sin ψ	Gf_t (N/mm)	Gf_c (N/mm)
Block	6.5	2.13	0.15	0.0871	0.094	12
Mortar -I	7.2	2.4	0.15	0.0871	0.094	13
Mortar - II	5.2	2.0	0.15	0.0871	0.080	11
Interface	–	2.1	–	–	–	–

The prisms constructed with mortar mix II had a better approximation between the numerical and experimental results for the axial and lateral strain and the stress at break point. The failure mode observed experimentally for this type of prism began with a crushing of the mortar, and no sudden crack opening half way up the prism was observed, as occurred in the prism with mix I. Thus, there was better agreement between the lateral and axial stresses and strain at break point. Table 3 shows the comparative results for the last axial strain obtained in the experimental tests and the numerical simulations. The last deformation is taken as the loss in the total load capacity of the component, and not the appearance of the first crack. Note that there is a significant difference in the last axial strain when comparing the numerical and experimental results for the prisms I-1, I-2 and II-1.

Table 4 – Non linear mechanical characteristics of the materials.

Prism	$\varepsilon_{axial\ last}$ (Experimental)	$\varepsilon_{axial\ last}$ (Experimental)
I-1	0.00088	0.00168
I-2	0.00086	0.00168
II-1	0.00124	0.00321
II-2	0.00332	0.00321

The effect of the interface between the materials (block and mortar) on the axial and lateral stress and strain values was simulated for mortar mix II. The results obtained for the prisms not considering the interface were similar to those obtained with the interface. One explanation for this would be that the interface is being constrained, that is, non linear effects will be minimized by the acting force of compression. Table 4 shows the results for the Poisson ratio, for different stress/strength ratios, obtained using the numerical model, for the mortar mixes I and II. It can be noted from these results that there was an increase in the Poisson ratio from 0.19 to 0.36 for the settlement mortar of mix I. For mortar mix II the Poisson ratio changed from 0.19 to 0.48.

Table 5 – Average experimental results for the deformability of the prisms.

σ/f_c	*Mortar mix I*	*Mortar mix II*
	Poisson ratio	
0	0	0
0.13	0.19	0.19
0.26	0.19	0.19
0.38	0.21	0.22
0.49	0.24	0.24
0.59	0.26	0.27
0.70	0.27	0.28
0.80	0.29	0.30
0.90	0.30	0.33
0.98	0.32	0.43
1.00	0.36	0.48

Through the numerical analysis, a relation was obtained between the vertical and horizontal stresses for the mortar and the block. In the case of the mortar the type of stress was compression and for the block it was tensile. For the failure of the prisms constructed with mortar mix I, the confinement stress value for the mortar was 2.19 MPa and those for the tensile stresses of the block reached a maximum of 0.12 MPa. The prism of mix I showed a linear behavior in the increase in the confinement stress up to a σ/f_c ratio close to 0.9. Figures 8 and 9 shows the numerical results of the stresses for a specific element in the mortar and block.

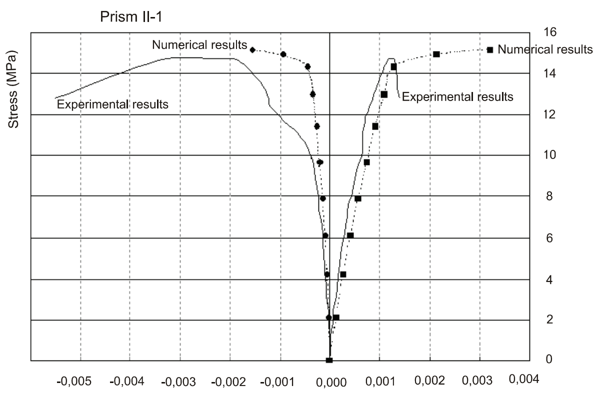

__Figure 5 –__ Axial and lateral stress-strain curves of the prisms with mix II-1.

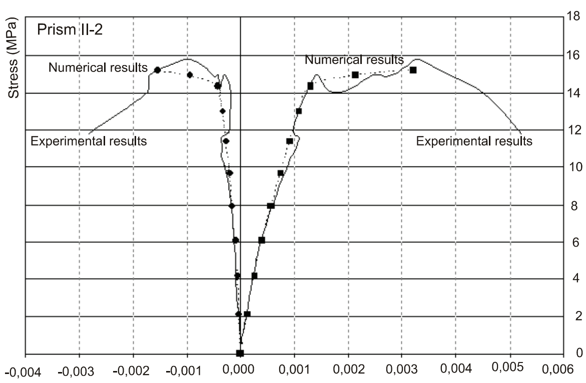

__Figure 6 –__ Axial and lateral stress-strain curves of the prisms with mix II-2.

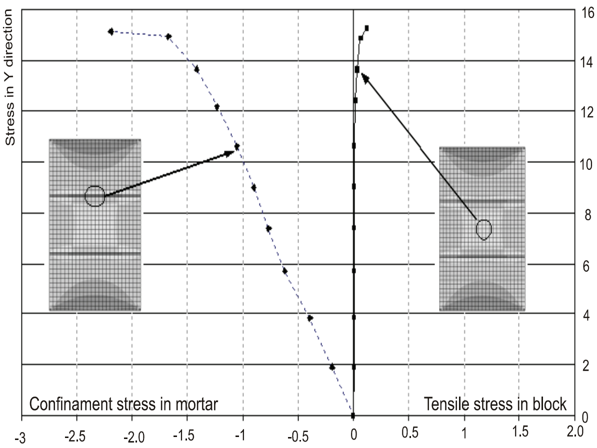

***Figure** 7 – Relation between the stresses of the numerical model for the mortar and block for mix I.*

For the failure of the prisms with mix II, the confinement stress value of the mortar was 5.9 MPa and the maximum tensile stress of the block was 0.37 MPa. The prisms of mix II had a linear variation in the increase in the confinement stresses of the mortar up to a σ/f_c ratio of 0.6. Thereafter, there was a disproportional increase in the lateral stresses, showing the strong non linear nature of the mortar set.

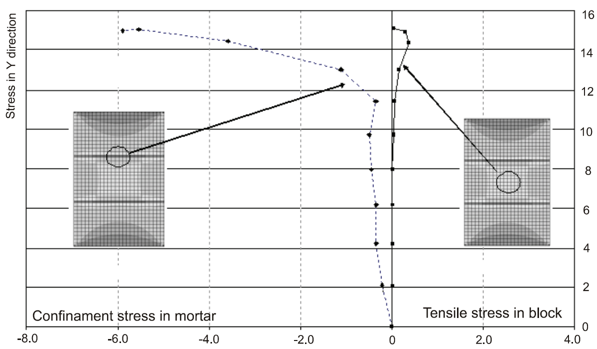

***Figure 8** – Relation between the stresses of the numerical model for the mortar and block for mix II.*

From the numerical results it was concluded that the level of tensile stress acting in the block was not sufficient to generate tensile stress leading to a failure of the concrete due to traction, which confirms that the representation of the collapse is essentially phenomenological, requiring more advanced models to properly represent the failure mode.

With the numerical results, for a selected element in the settlement mortar and in the block, a relation between the stresses and the axial and lateral strain was obtained. With these values the secant elasticity modulus was calculated, up to close to the prism failure. The relation between the ratio of elasticity modulus of the mortar to that of the block (E_{mortar}/E_{block}) and the ratio of the acting stress to the compression strength (σ/f_c) was determined, as shown in Figure 10. The lower and upper limits in Fig. 10 demarcate an area of the behavior of the stiffness ratio of the materials. The numerical results for the prisms of mix I verified the development of tensile stresses in the mortar since the elasticity modulus was higher than that of the block and, consequently, compression stresses were generated in the block. For the prisms with mix II, the block was submitted to tensile stresses throughout the loading and the mortar was under triaxial compression, since the elasticity modulus of the mortar did not reach that of the block. This leads to the conclusion that the failure modes of the prisms were differentiated, that is, for the prism with mix I there was a progressive increase in the strain in the x direction, producing stresses which lead to the material breaking by tensile. For the prism constructed with mix II, there was a greater strain of the settling joint, generating localized crushing and leading to the failure being mainly through the collapse of the joint, and the subsequent development of tensile stresses in the block.

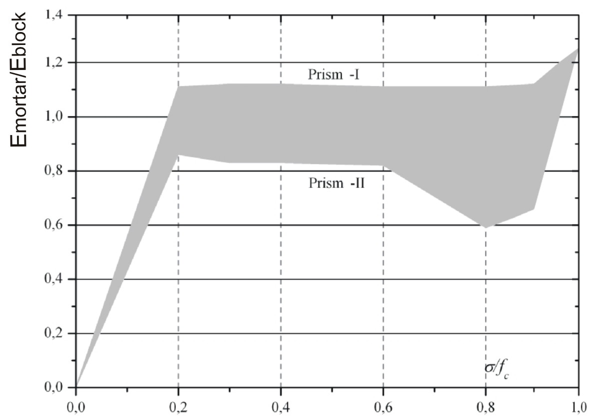

***Figure 9** – Relation between* E_{mortar}/E_{block} *and* σ/f_c *ratio.*

Figure 11 shows the deformations at failure in the x direction, considering the presence or absence of an interface between the block and the mortar. From the results it was verified that the maximum strain (ε_x) in the x direction of the prisms with an interface were lower than the strain of the prisms without an interface. The maximum strain in the x direction occurred in the middle block in all cases analyzed, due to the effect of the confinement of the plates.

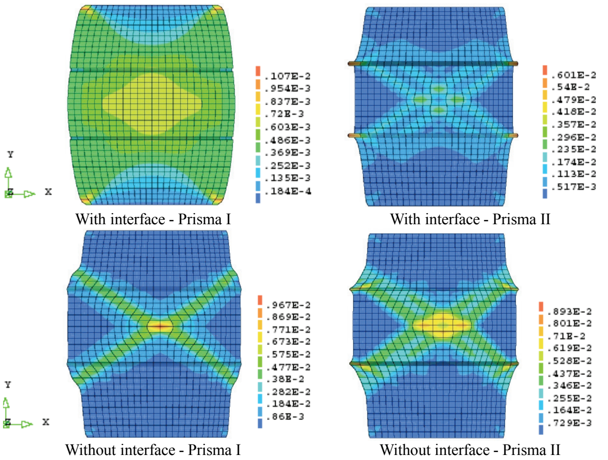

***Figure 10** – Deformation in the prisms at failure (ε_x), with and without an interface between the materials.*

4 Conclusions

The prisms constructed with mortar type I did not manage to represent the lateral strain, for stress levels above $0.60.f_c$, but there was a good agreement when compared with the stress at break point. For the prism constructed with mortar mix II, there was a better approximation between the numerical and experimental results. A sudden crack opening half way up the prism was not observed from the experimental results, as in the case of mix I. It was noted, for the three-block prisms, that the effects of considering the block-mortar interface were insignificant in terms of the deformation results. In the numerical results the prisms constructed with mortar mix I showed the development of traction stresses in the mortar, due to an increase in its rigidity and, consequently, compression stresses were generated in the block. For the prism of mix II, the block was submitted to tensile stresses during the loading and the mortar to triaxial compression. This leads to the conclusion that the failure modes of the prisms were differentiated, that is, for the prism with mix I there was a progressive increase in the deformations in the x direction, producing stresses which induce tensile in the material. For the prism constructed with mix II there were deformations in the settlement joint and localized crushing where there occurred, firstly, the collapse of the joint and then the development of tensile stresses in the block. The effect of the vertical joint on the mechanical behavior of the three-block prisms was evaluated in the prisms. Considering the results of the stress-strain diagram, there was a good approximation between the numerical model and the experimental tests, for the values of the axial strain up to stress levels of $0.6.f_c$. This occurred due to the existence of vertical joint opening, observed in the experiments with the prisms. The lateral strain of the experimental tests were greater than those obtained through numerical modeling.

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