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EVALUATION OF MASONRY WALLS INTERSECTIONS BEHAVIOR USING SPECIAL AND ORDINARY BLOCKS

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Abstract. Connections are usually critical regions in all kind of structures. The transmission of stresses between structural elements is in general the main issue. It is common in load-bearing masonry structures to build the intersections of walls through the interlocking of units. This paper aims to evaluate the behavior of masonry walls intersections built with two different blocks configurations: applying only ordinary concrete blocks with two cells and applying special concrete blocks with three cells. Two approaches are considered to evaluate the masonry intersections: specimens subjected only to vertical loads and specimens subjected to the combination of vertical and horizontal loads. A numerical study using a 3D-model is performed through the software DIANA® based on the Finite Element Method. Masonry walls are modeled using the micro-modeling which considers a discontinuous assembly of units connected by joints simulated by appropriate constitutive laws. Normal and shear stresses in interfaces are presented as well as the deformed shape of specimens.

1 INTRODUCTION

Masonry is one of the most antique structural systems in the world. However, it has been lost prestige with the advance of other structural systems such as reinforced concrete and steel. This was to certain extent the result of scarce or even absence of rules, recommendations and design methods available for masonry. On the other hand, masonry has advantages other than good performance as structural system such as durability, fire resistance and thermal and acoustic reasonable behavior.

In load-bearing masonry buildings, walls are the main structural elements that assure the structural stability. These walls are often subjected to lateral loads from wind or, in zones of moderate or high seismicity, from seismic actions, meaning that structural systems have to be designed to resist these types of loading. Besides lateral loads, the walls are submitted to vertical loads since they constitute the main supports of slabs, vaults and domes, meaning that a complex stress state develops in masonry walls.

In masonry buildings the walls are generally restrained in three or four sides: at upper and bottom edges by slabs/wood diaphragms and at lateral edges by perpendicular walls. Abrams (1986) and Modena *et al.* (2004) tested two-story reinforced masonry building systems in a natural scale, which enabled to simulate the real connection between the structural elements. Nevertheless, these types of specimens are expensive and need special apparatus to be tested. Therefore, single walls are the most common system for masonry wall testing, see Figure 1a. Thus, there has been considerable research works focused on the analysis of the behavior of single masonry walls (Abrams, 1986; Shing *et al.*, 1989; Tomaževič, 1999; Voon and Ingham, 2006; Haach *et al.*, 2010). Lateral restraints of masonry walls in a building can be simulated by flanged panels (Yoshimura *et al.*, 2003; Modena *et al.*, 2004) as shown in Figure 1b.

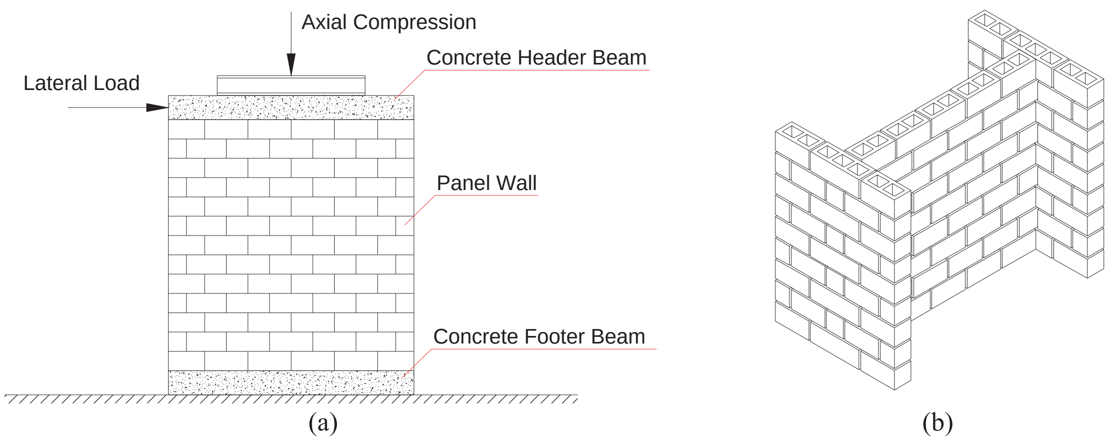


Figure 1: Masonry specimes commonly used: (a) single masonry walls and (b) flanged masonry walls.

The consideration of masonry walls connections to guarantee the transference of stresses is a great issue in masonry building design. In case of the distribution of vertical loading, in general, vertical loads applied to slab may be distributed between the walls through the yield lines proceeding. However, it is observed by some authors (Stockbridge, 1967; Sinha and Hendry, 1979; Hendry, 1998; Cappuzo Neto, 2000; Corrêa and Page, 2001; Ramalho and Corrêa, 2003; Côrrea and Ramalho, 2004; Cappuzo Neto, 2005) that there is a tendency of homogenization of the vertical loads between all the walls in the inferior floors in a multi-story masonry building. That means the taller is the building, the greater is the homogenization of the load. In case of the horizontal loading distribution, the connection of walls leads to an increase of the second moment of area of the masonry panels, consequently increasing the lateral strength. However, the homogenization of the vertical loading and the improvements on the lateral behavior of masonry walls are only possible if the connection between the walls are ensured. In unreinforced masonry the connection of walls in general is made through the interlocking of the units. The interlocking of units can be reached using ordinary or special blocks.

2 SPECIAL AND ORDINARY BLOCKS

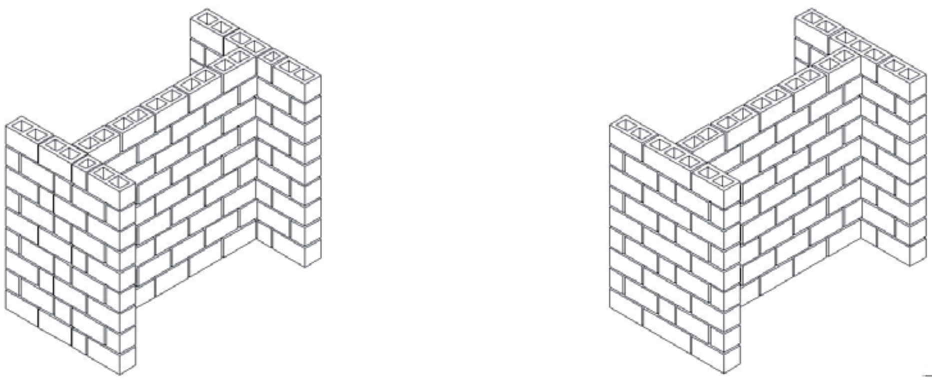
Masonry can be defined as a composite material where units are laying on top of each other joined with mortar. There are many different sizes and textures masonry units to fit any application. In Brazil, it is common to use concrete blocks for load-bearing masonry walls as presented in Figure 2; the dimensions of these blocks are defined by NBR 6136 (2006).

(a) (b)

Figure 2: Masonry units: (a) ordinary blocks and (b) special blocks.

Units can be oriented and positioned in the wall in several manners creating different bond patterns. Running bond is the more common pattern of units in load-bearing masonry buildings and it consists of overlapping units in adjacent courses. The aforementioned overlapping produces the interlocking of units enhancing the structural behavior of masonry.

Maintaining the masonry patterns on a straight wall is relatively easy; however, some issues can occur in connections of the walls. The interlocking of units is reached in four courses when only ordinary blocks are used in masonry connections, see Figure 3a. On the other hand, the interlocking of units is reached in two courses when special blocks are used in masonry connections, see Figure 3b. However, special blocks have higher weight than ordinary blocks, which hinders the laying of this type of unit.



(a) (b)

Figure 3: Masonry connections: (a) with ordinary blocks and (b) with special blocks.

Therefore, this paper aims to evaluate the behavior of unreinforced masonry walls intersections using special and ordinary blocks in the unit interlocking. In this way, this work intends to analyze the behavior of the connection of walls when subjected to vertical and/or lateral loading.

3 EXPERIMENTAL DETAILS

The numerical model used in this study was validated from the experimental result of in-plane test carried out on an unreinforced concrete block masonry wall. The experimental test consisted of in-plane cyclic test on a cantilever wall following the typical test setup shown in Figure 4, used for masonry walls under combined vertical and horizontal loads (Vasconcelos and Lourenço, 2009). The testing procedure was divided in two phases. First, the vertical load was applied at a rate of 0.25kN/s up to a vertical stress equal to 0.56 MPa which was kept constant during the test. After that, horizontal displacements were imposed to the walls until the failure. The cyclic tests were carried out under displacement control at a rate of 70 μm/s by means of an external LVDT connected to the horizontal actuator.

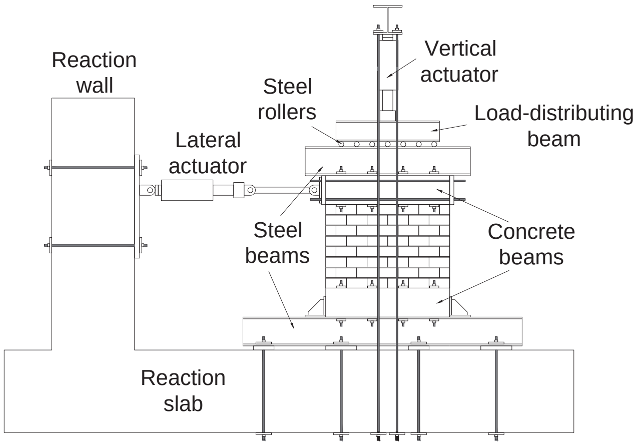


Figure 4: Test setup used in experiment

The dimensions of the tested masonry walls were 1206mm x 800mm x 100mm. Hollow concrete units of 201mm(length) x 93mm(thickness) x 100mm(height) in half-scale were considered in the experimental test. These units have two cells with 60mm x 70mm and one small cell in the middle of the unit with 15mm x 70mm. The percentage of holes in the block is roughly 46%, which, according to Eurocode 6 (2005) indicates that the units belong to Group 2.

Reinforced concrete beams were placed at the bottom (280 mm x 280 mm x 1400 mm) and at the top (280 mm x 280 mm x 1200 mm) of the walls in order to ensure an uniform distribution of the applied vertical and horizontal loads. The displacements of the wall under cyclic loading were measured by means of a set of LVDTs. A more detailed overview of the experimental results can be found in Haach *et al.* (2010).

4 NUMERICAL MODELING

The numerical model applied to study masonry walls under in-plane loading was defined using the software DIANA®. The micro-modeling approach was chosen for the modeling since it includes all the basic failure mechanisms that characterize masonry, enabling the detailed representation of resisting mechanisms of the walls. In the numerical analysis only monotonic loading was considered. Newton-Raphson iteration procedure was used with displacement control and an energetic convergence criterion with a tolerance of 10^{-3}.

Firstly, the validation of the numerical model was carried out based on the experimental result as previously commented. In a second phase, a parametric analysis was performed in masonry walls using units with actual dimensions (400mm x 200mm x 200mm) and considering either ordinary or special blocks.

4.1 Geometrical Properties

Unreinforced masonry walls with H-section were considered in numerical analysis, as presented in Figure 5. The walls had 2800mm of height and 2800mm of length height resulting in an aspect ratio of 1.0. The walls were modeled with a flange of 1800 mm of length representing the connection between walls. An upper concrete beam with 400 mm of height was modeled in order to provide a better distribution of the loads as in the case of the experiment. On the other hand, the bottom concrete beam was not included since its consideration does not influence the masonry wall behavior.

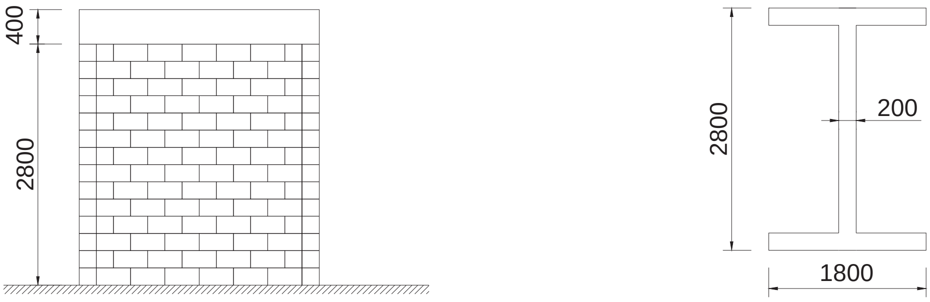


Figure 5: Geometry of masonry walls used in numerical study.

4.2 Material Properties

In the micro modeling approach all constituent materials of the masonry walls, with distinct mechanical properties, are independently described. Distinct material models were used to represent the behavior of the concrete of the top beam, concrete masonry units, vertical and horizontal joints and the potential cracks in the middle of the units. The mechanical properties used in the description of the material models were obtained from experimental tests carried out on materials and masonry assemblages, Haach (2009).

Isotropic elasticity was adopted for the upper concrete beam since the stresses developed in this element are very small and thus linear stress-strains relationship is valid. An elastic modulus equal to 30 GPa was used for the concrete of beams, corresponding to a concrete compressive strength of nearly 30 MPa.

An interface cap model with modern plasticity concepts proposed by Lourenço and Rots (1997), and further enhanced by Van Zijl (2004), was used for interface elements describing the masonry joints. The interface material model is appropriate to simulate fracture, frictional slip as well as crushing along material interfaces, which are the possible failure modes of the masonry unit-mortar interfaces. Among the mechanical properties used for the definition of the yield functions in tension, compression and shear of the unit-mortar interfaces are the normal and transversal stiffness of bed joints (k_n = 11 N/mm^3 and k_s = 48 N/mm^3, respectively). The normal stiffness was defined by fitting the numerical to experimental results obtained in the masonry walls. The shear stiffness was obtained through the results of the shear tests carried out on triplet specimens to characterize the shear behavior of concrete unit-mortar interface (Haach, 2009).The yield function with exponential softening for the tension cut-off model requires the knowledge of the tensile bond strength of bed joints (f_t = 0.33 MPa) and the mode I fracture energy (G_f^I = 0.017 N/mm). The tensile bond strength was obtained from the experimental results of flexural tests of masonry specimens loaded in the direction parallel to bed joints (Haach, 2009). Due to the difficulty of obtaining mode I fracture energy of the unit-mortar interface this mechanical property was defined by fitting the numerical to experimental results obtained in the masonry walls.

The shear behavior of the unit-mortar interfaces is represented by the Coulomb failure criterion. The definition of this function is made through the knowledge of the cohesion (c = 0.42 MPa), friction coefficient (μ = 0.49), the dilatancy coefficient ($\tan\psi$ = 0.52), and the shear fracture energy (G_f^{II} = 0.1 N/mm). In order to capture the cohesion softening and the friction softening the residual friction coefficient (μ_{res} = 0.43) should be obtained. All the parameters were obtained from the tests carried out on triplet specimens (Haach, 2009). In the model, the dilatancy is considered to be dependent on the normal confining stress and on the shear slipping. Thus, for the correct definition of the dilatancy, the confining normal stress at which the dilatancy becomes zero (σ_u = 1.35 MPa) and the dilatancy shear slip degradation coefficient (δ = 1.64), were also obtained by experimental analysis. Vertical and horizontal mortar joints were represented by the same material model using the same properties' values.

According to Lourenço and Rots (1997), it is useful to model potential cracks in units in order to avoid an overestimation of the collapse load and of the stiffness. Thus, potential cracks placed at the middle length of units were considered through interface elements with a discrete cracking model. High stiffness should be considered for this interfaces according to Lourenço and Rots (1997) (k_n = 106 N/mm^3 and k_s = 106 N/mm^3, respectively). In addition, an exponential softening behavior was adopted for the tensile behavior of these interfaces with the tensile bond strength (f_t = 3.19 MPa) obtained in uniaxial tensile tests carried out on the concrete units (Haach, 2009) and the mode I fracture energy (G_f^I = 0.06 N/mm) obtained from the experimental results of Mohamad (2007) in concrete blocks with similar raw materials composition. The constitutive law for discrete cracking in DIANA® is based on a total deformation theory, which expresses the tractions as a function of the total relative displacements.

The non-linear behavior of the concrete masonry units was represented by a Total Strain Crack Model based on a fixed stress-strain law concept available in the commercial software DIANA®. It describes the tensile and compressive behavior of the material with one stress-strain relationship in a coordinate system that is fixed upon crack initiation. Exponential and parabolic constitutive laws were used to describe the tensile and compressive behavior of concrete masonry units respectively. The mechanical properties needed to describe this material model are the elastic modulus of concrete units (E = 9.57 GPa), the Poisson's ratio of concrete units (ν = 0.20), the tensile strength of concrete units (f_{tu} = 3.19 MPa), the fracture energy of units under tension (G_{fu}^I = 0.06 N/mm) and the shear retention factor (β = 0.01). Due to the impossibility of obtaining the post-peak behavior in tension of the three cell concrete units, the values of fracture energy in tension were evaluated from the experimental results obtained by Mohamad (2007) in concrete blocks with similar raw materials composition. In this study, compressive strength of units and fracture energy of units under compression were considered equal to compressive strength of masonry and fracture energy of masonry under compression (f_{cu} = 5.95 MPa and G_{cu}^I = 5.00 N/mm, respectively). The shear behavior during cracking was described through a shear retention model defined by a constant value.

4.3 Mesh

The mesh was composed of continuum and interface elements to represent respectively the masonry units and the masonry joints, see Figure 6. Four-node isoparametric plane curved shell elements with Gauss integration scheme were adopted to simulate the units (Q20SH - DIANA®), see Figure 7a. Each masonry unit was modeled with two continuum elements. Potential vertical cracks of the units were introduced at mid length of the units. The joints were lumped into the concrete units and the unit-mortar interface was represented by an interface element (N6IF - DIANA®) between two nodes in a three-dimensional configuration, see Figure 7b.

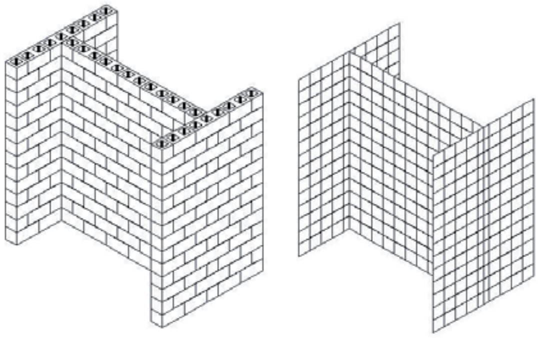
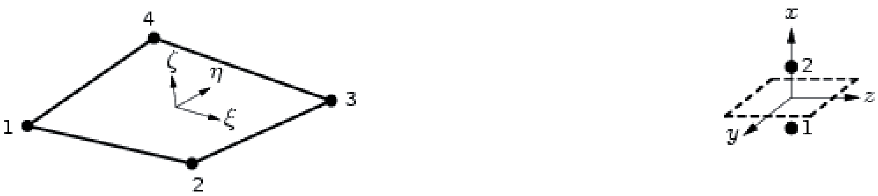


Figure 6: Example of mesh applied to the masonry walls.

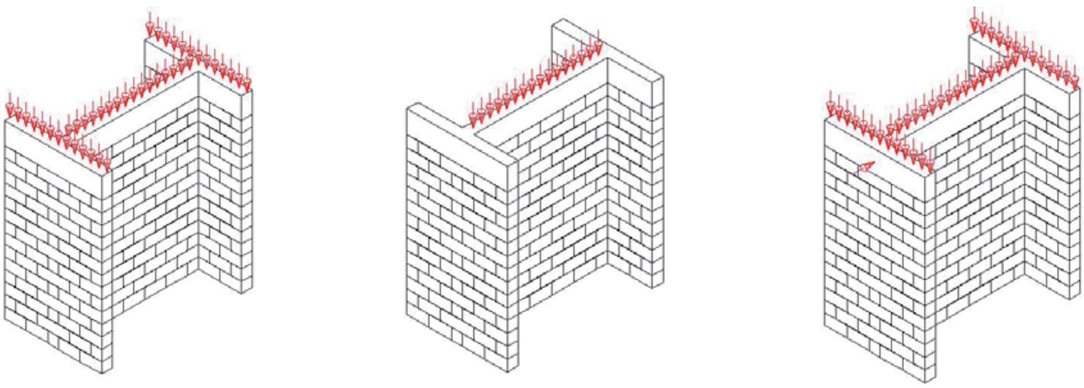


(a) (b)

Figure 7: Elements used in numerical modeling (DIANA®).

4.4 Loading and Boundary conditions

In the numerical modeling only monotonic loads were applied on specimens since the interface elements do not support cyclic loads. Three types of loading were applied to masonry specimens in order to evaluate the behavior of the wall intersections: vertical loading combined with lateral loading, uniform vertical loading and vertical loading only in the central wall, which means without vertical loading on the flanges, see Figure 8.



(a) (b) (c)

Figure 8: Application of loading on masonry specimens: (a) uniform vertical loading, (b) vertical loading only in the central wall and (c) vertical loading combined with lateral loading.

For the specimens subjected to vertical loading combined with lateral loading, as in the case of the experiment, the axial load was applied in the first step and then was kept constant onwards. After that, horizontal displacements were imposed to the walls until the failure occurred. Two axial loading levels (0.40 MPa and 0.60 MPa) were applied to the masonry walls in order to ensure the occurrence of different failure modes. For specimens subjected to uniform vertical loading and vertical loading only on the central wall, the load was applied in only one step up to the failure.

As boundary conditions, the continuum elements representing the masonry units located at the base of wall were connected to interface elements which were fully fixed in order to represent the fixed base of the masonry walls. The upper beam was connected to the wall through interface elements modeled with linear behavior and infinite stiffness to simulate a perfect bond between these two elements, as observed in the experimental test.

5 RESULTS AND DISCUSSION

A general overview of the results obtained in numerical analysis is presented in this section. Force-displacement diagrams, failure modes and the distribution of normal and shear stresses are some of the aspects under analysis.

5.1 Validation of Numerical Model

A numerical modeling only makes sense if it corresponds to the actual model. Therefore, the first step of the numerical analysis comprises the calibration of the numerical model defined for the masonry shear walls, which is achieved from the comparison between experimental and numerical results. This enables the use of a reliable model for the envisaged parametric study. The comparison between the cyclic force-displacement diagram obtained in the experimental test with the numerical monotonic envelop reveals that a reasonable agreement was attained between both approaches, see Figure 6.

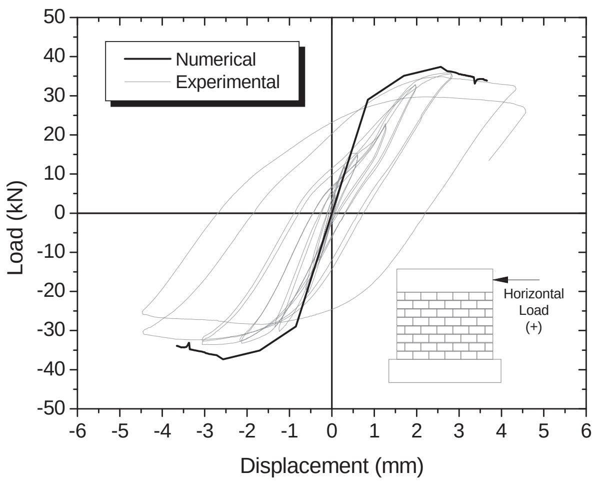
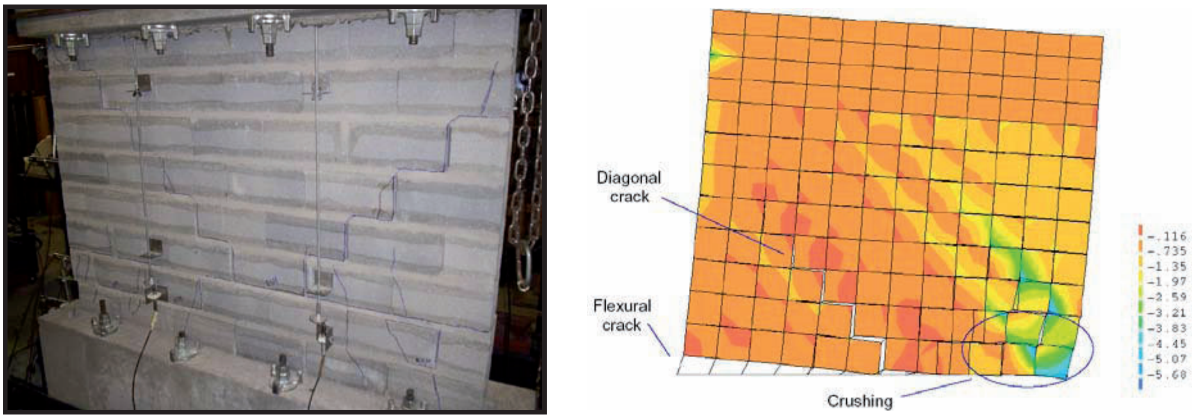


Figure 2: Comparison between experimental and numerical results (force-displacement diagram).

Concerning the failure mode, the numerical modeling agrees reasonably well with the experimental results in spite of the monotonic loading considered in numerical modeling. As shown Figure 7, the numerical results represented the three main crack patterns developed during the experimental behavior of the wall, namely flexural cracking, diagonal cracking and crushing at the bottom of the wall. In the experimental test, after the diagonal crack and crushing at the bottom corner occurred, the upper part of the wall slided over the diagonal crack. Some penetrations of the elements in the compressed corner during the sliding were observed in the numerical modeling.



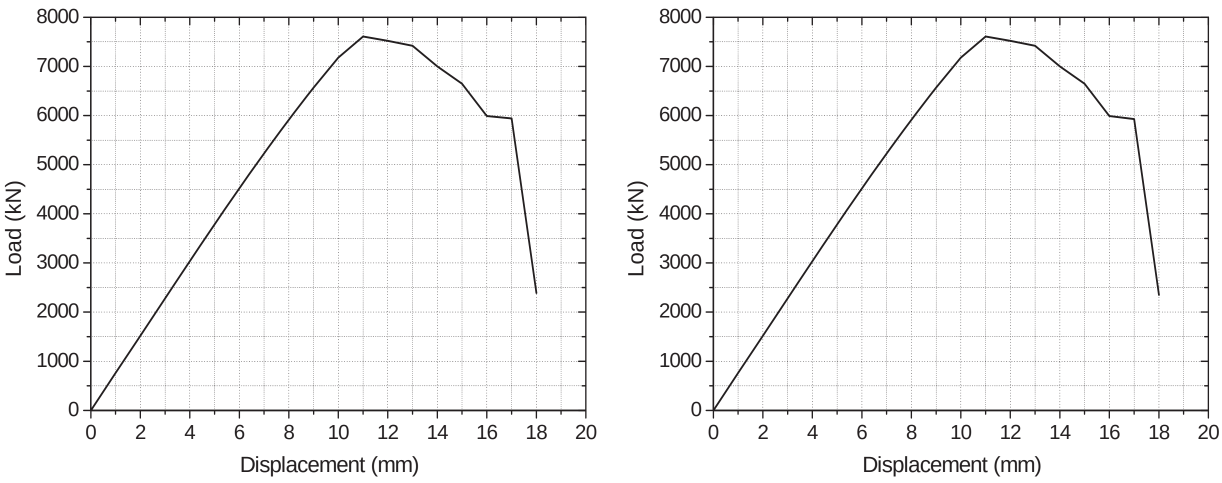
(a) (b)

Figure 3: Comparison between experimental and numerical results (failure mode).

In general the results of numerical modeling showed a reasonable agreement with the experimental results, meaning that it represents satisfactorily well the lateral in-plane behavior of the masonry walls. This indicated that the numerical model is adequate to accurately proceed with the parametric study.

5.2 Uniform vertical loading

Negligible differences could be observed in the behavior of masonry walls subjected to uniform vertical loading using special or ordinary blocks. Force *vs.* Displacement diagrams were the same for both types of blocks, see Figure 7.



(a) (b)

Figure 7: Force *vs.* Displacement diagram for specimens with uniform vertical loading: (a) special blocks and (b) ordinary blocks.

The same behavior could be observed in the case of shear stresses on the vertical interface between the central wall and the flanges, see Figure 8. Due to the uniform vertical loading applied to the wall, these stresses are practically neglegible except at the extremities of the specimens due to the perturbation caused by the load application at the top and the fixed conditions at the base.

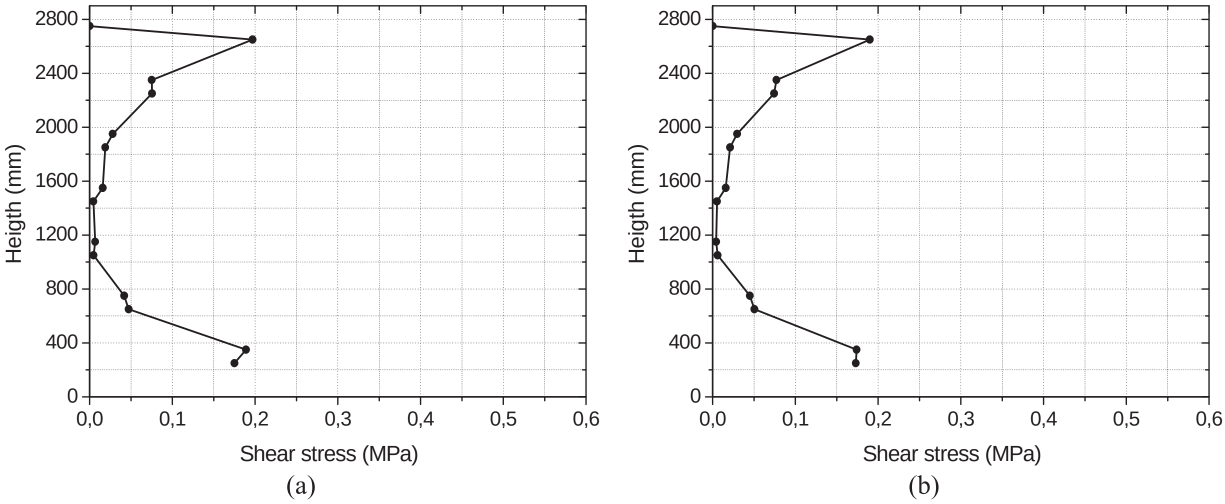


Figure 8: Shear stresses on the interface between central wall and flanges of specimens with uniform vertical loading (σ = 4.68 MPa): (a) special blocks and (b) ordinary blocks.

Some small differences could be observed in the case of normal stresses on the base of the walls. The stresses on the extremities of the central wall presented a small reduction for special blocks and a more uniform distribution of normal stresses on the middle of wall, see Figure 9. Flanges of masonry walls modeled with special blocks exhibited symmetric normal stresses distribution. On the other hand, an increase on the normal stresses in the region of the head joint in the case of the masonry walls modeled with ordinary blocks could be observed, see Figure 10. In brief, the differences between the behaviors of the masonry walls modeled with special or ordinary blocks were negligible in the case of uniform vertical loading.

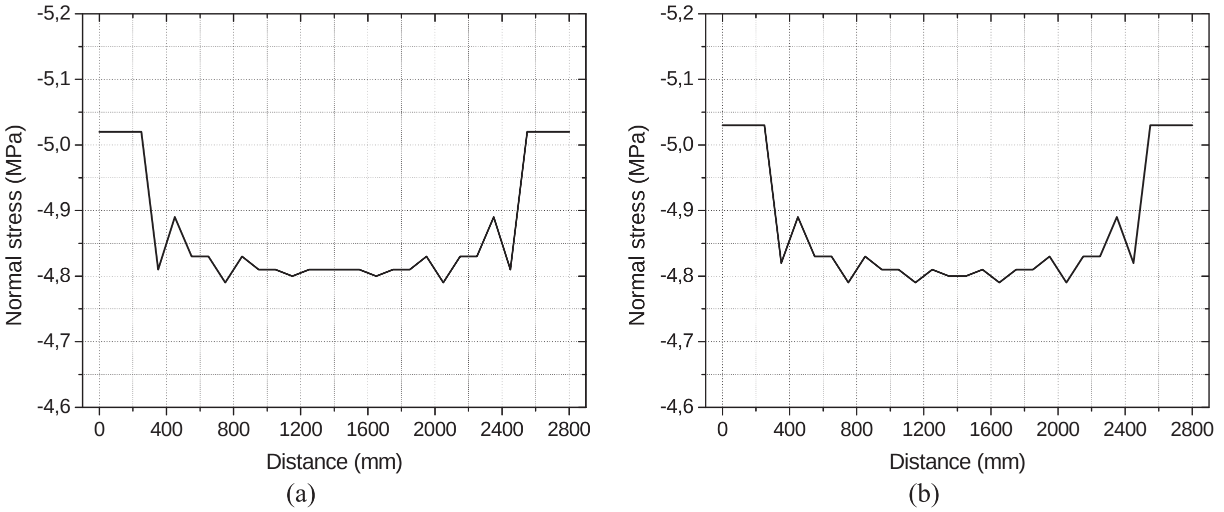
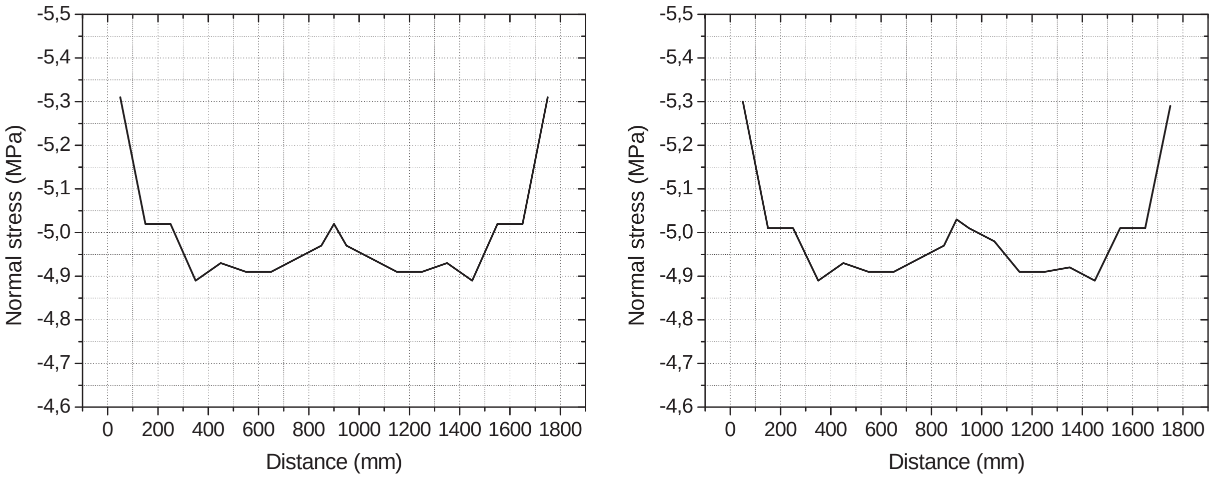


Figure 9: Normal stresses on the base of central wall of specimens with uniform vertical loading (σ = 4.93 MPa): (a) special blocks and (b) ordinary blocks.

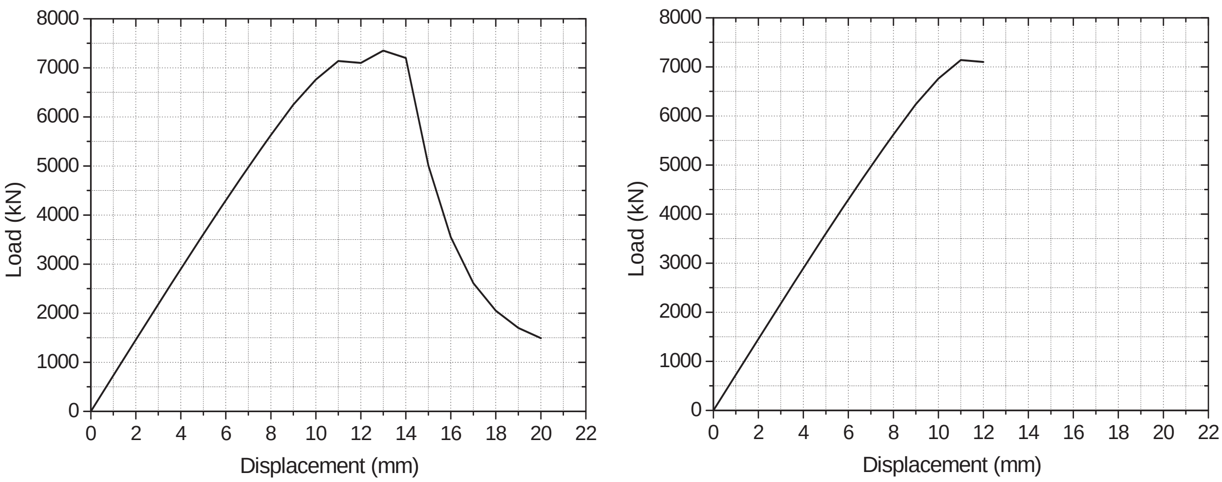


(a) (b)

Figure 10: Normal stresses on the base of flanges of specimens with uniform vertical loading (σ = 4.93 MPa): (a) special blocks and (b) ordinary blocks.

5.3 Vertical loading applied only in the central wall

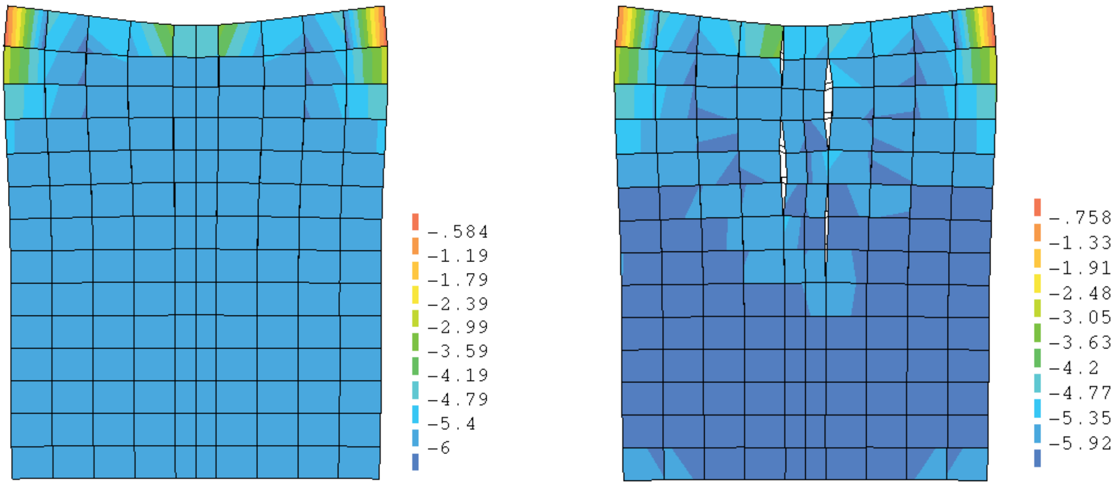
The application of the vertical loading only on the central wall mobilized the resistance mechanisms of the interface between the central wall and the flanges of the masonry panel. It is clear the difference between the force-displacement diagrams for masonry walls using special blocks and ordinary blocks, see Figure 11. The ultimate force for both assemblies was very similar; however the ordinary blocks exhibited a very fragile behavior.



(a) (b)

Figure 11: Force *vs.* Displacement diagram for specimens with uniform vertical loading: (a) special blocks and (b) ordinary blocks.

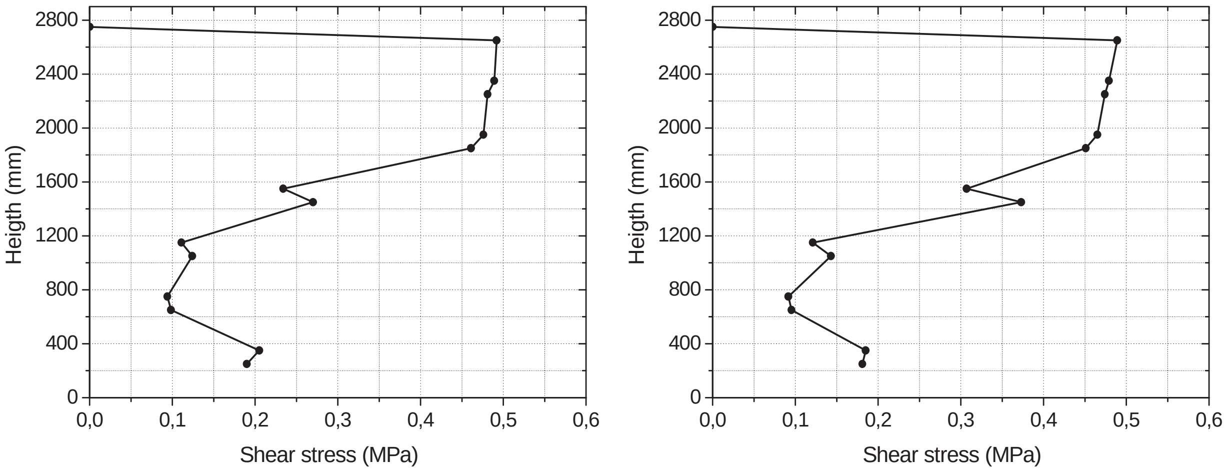
The failure modes for both assemblies were quite different, see Figure 12. The masonry walls modeled with ordinary blocks reached a limit of loading where the head joints of the flanges opened due to the high tensile stresses. In these masonry walls, the interlocking of blocks was reached in four courses, which creates a continuum head joint of three successive courses and a corresponding plane of weakness. In masonry walls modeled with special blocks, the interlocking of blocks was reached in two courses, ensuring an extra resistance to the tensile stresses and a gradual degradation.



(a) (b)

Figure 12: Failure mode for specimens with uniform vertical loading: (a) special blocks and (b) ordinary blocks.

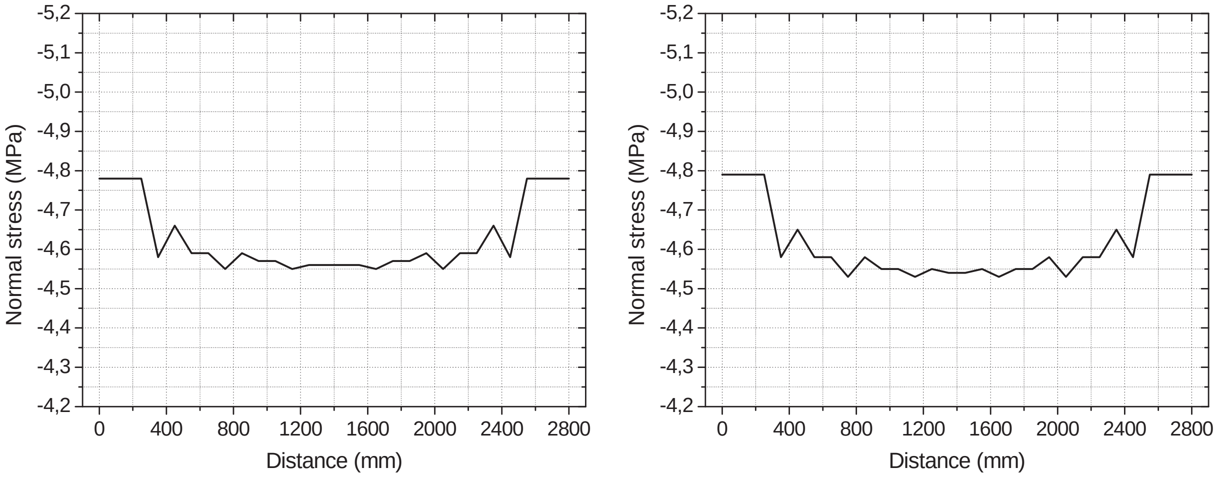
Figure 13 shows that the shear stresses in masonry walls subjected to vertical loading applied only on the central wall are higher than in masonry specimens subjected to a uniform vertical loading (Figure 8). As previously commented, in masonry walls subjected to vertical loading applied only in the central wall, resistance mechanisms of the interface of walls are mobilized in order to distribute the normal stresses for whole section of the masonry wall. In this case could be observed lower shear stresses were developed through the height of wall in specimens modeled with special blocks than in specimens modeled with ordinary blocks. However, this difference was around 4%.



(a) (b)

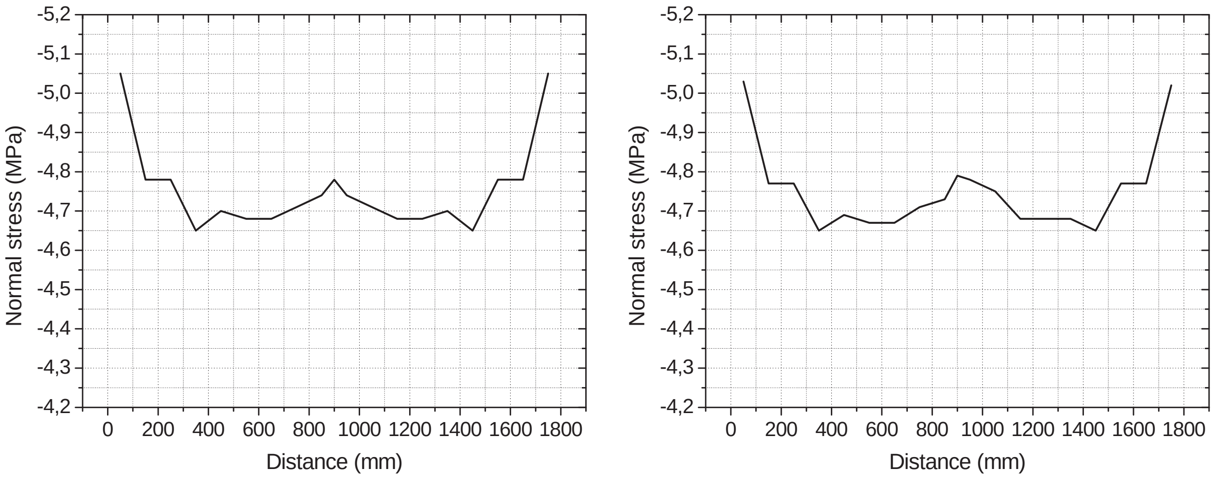
Figure 13: Shear stresses on the interface between central wall and flanges of specimens with uniform vertical loading (σ = 4.68 MPa): (a) special blocks and (b) ordinary blocks.

Regarding the normal stresses on the base of masonry walls, the same differences observed in the specimens with uniform vertical loading could be observed in those with vertical loading applied only on the central wall, see Figure 14 and Figure 15.



(a) (b)

Figure 14: Normal stresses on the base of the central wall of specimens with uniform vertical loading (σ = 4.68 MPa): (a) special blocks and (b) ordinary blocks.

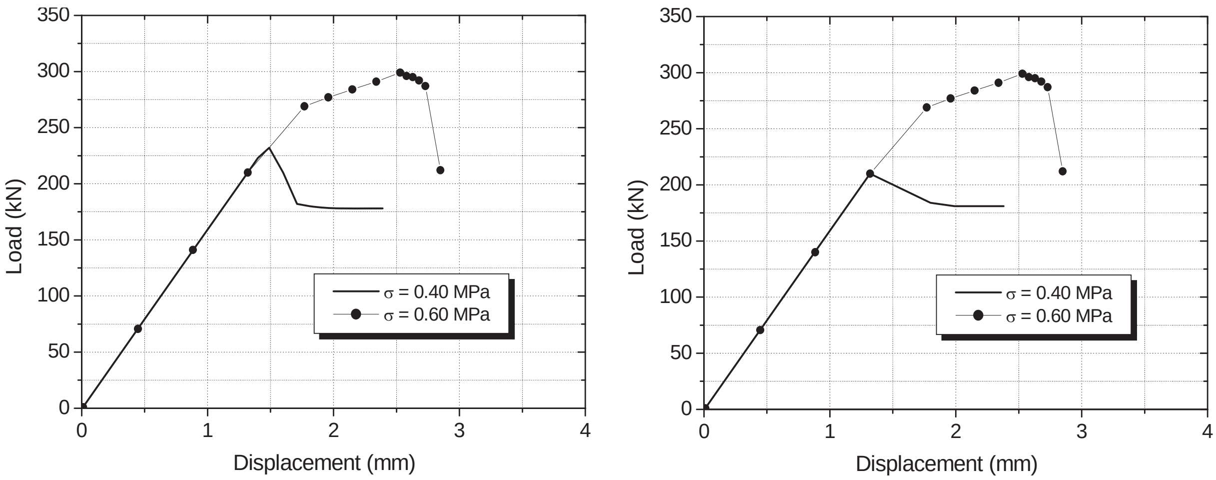


(a) (b)

Figure 15: Normal stresses on the base of the flanges of specimens with uniform vertical loading (σ = 4.68 MPa): (a) special blocks and (b) ordinary blocks.

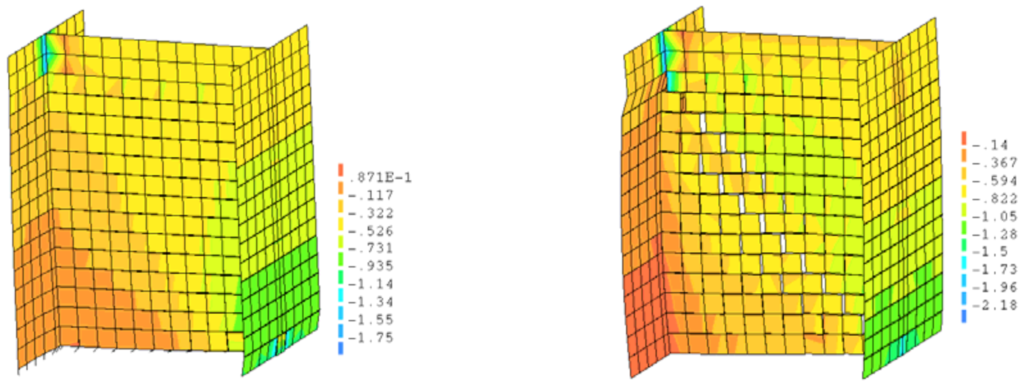
5.4 Vertical loading combined with lateral loading

The behavior of the masonry walls subjected to vertical loading combined with lateral loading was not influenced by the use of special or ordinary blocks in the vertical interface of the walls. The masonry walls modeled with both units, special or ordinary blocks, exhibited a very similar behavior. Specimens subjected to a pre-compression equal to 0.60 MPa failed by shear reaching a higher ultimate force, while specimens subjected to a pre-compression equal to 0.40 MPa failed by rocking, see Figure 16 and Figure 17. The results indicated that the combined vertical and lateral loadings produced the higher values of shear stress in the interface between central wall and flanges with a small variation due to the increase of the pre-compression, see Figure 18.



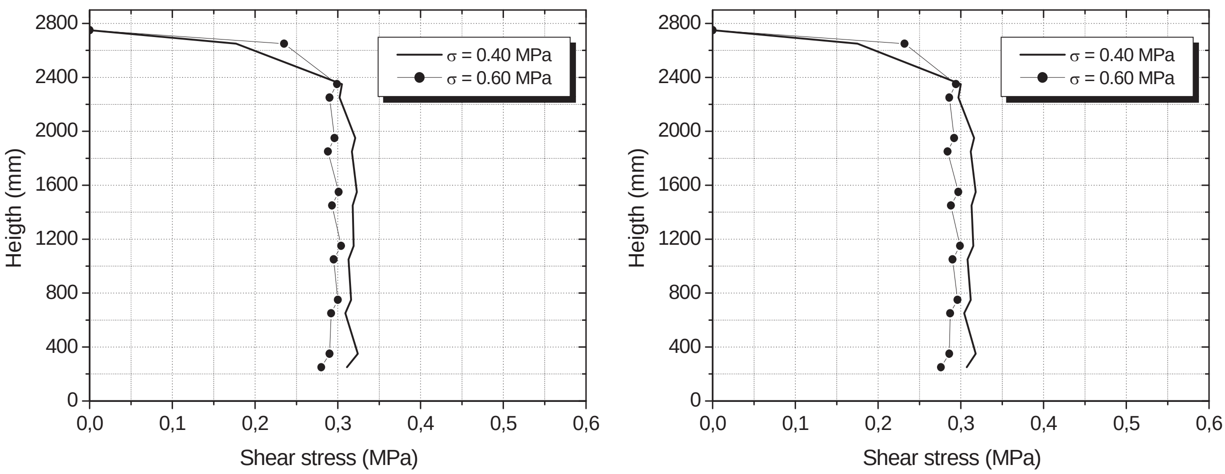
(a) (b)

Figure 16: Force *vs.* Displacement diagram for specimens with uniform vertical loading: (a) special blocks and (b) ordinary blocks.



(a) (b)

Figure 17: Failure mode for specimens with vertical loading combined with lateral loading: (a) σ = 0.40 MPa and (b) σ = 0.60 MPa.



(a) (b)

Figure 18: Shear stresses on the interface between central wall and flanges of specimens with uniform vertical loading (H=210 kN): (a) special blocks and (b) ordinary blocks.

No differences were observed in normal stresses on the base of the masonry walls subjected to vertical loading combined with lateral loading in comparison to the specimens subjected to uniform vertical loading and vertical loading applied only in the central wall, see Figure 19 and Figure 20. This behavior can be explained by the low level of the normal stresses in the case of masonry walls subjected to vertical loading combined with lateral loading, since their failure modes were rocking and diagonal cracking. Masonry walls can present other failure modes; thus, an evaluation of the influence of the use of special or ordinary blocks in the intersection of masonry walls with other geometries should be performed in order to observe other failure modes.

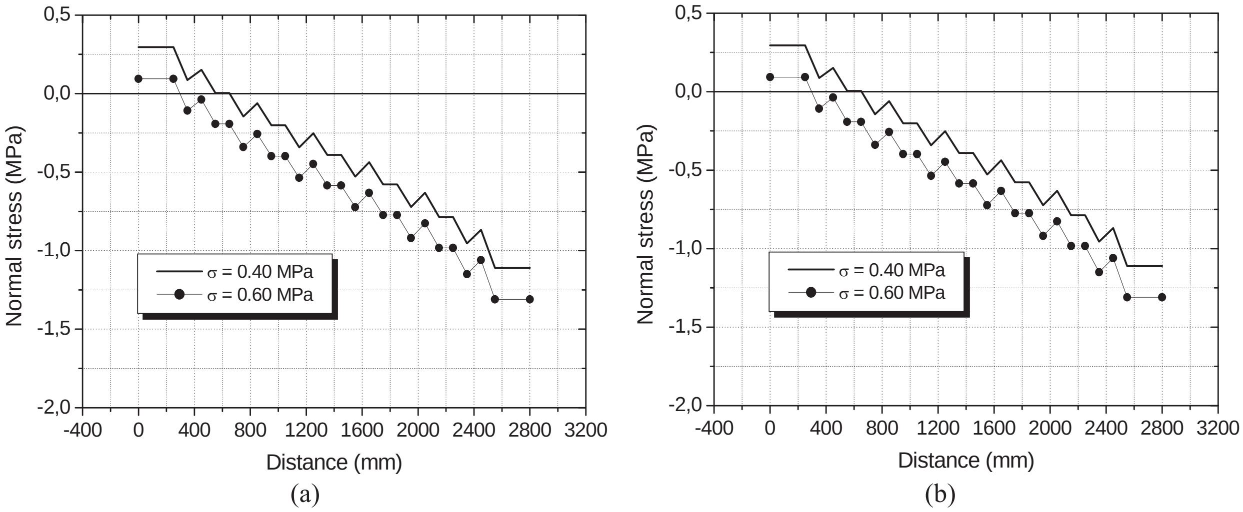


Figure 19: Normal stresses on the base of central wall of specimens with uniform vertical loading (H=210 kN): (a) special blocks and (b) ordinary blocks.

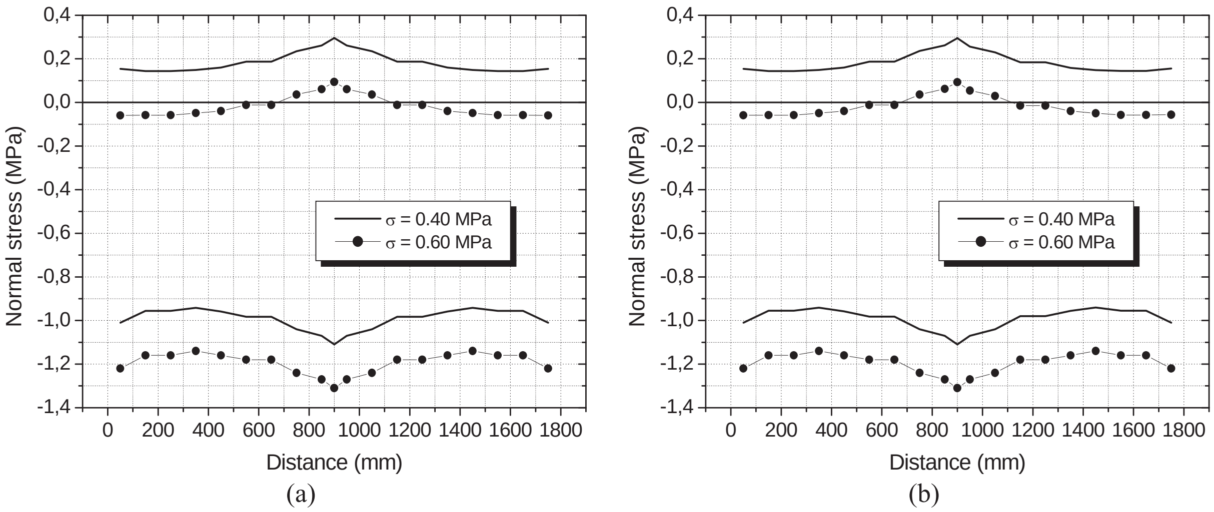
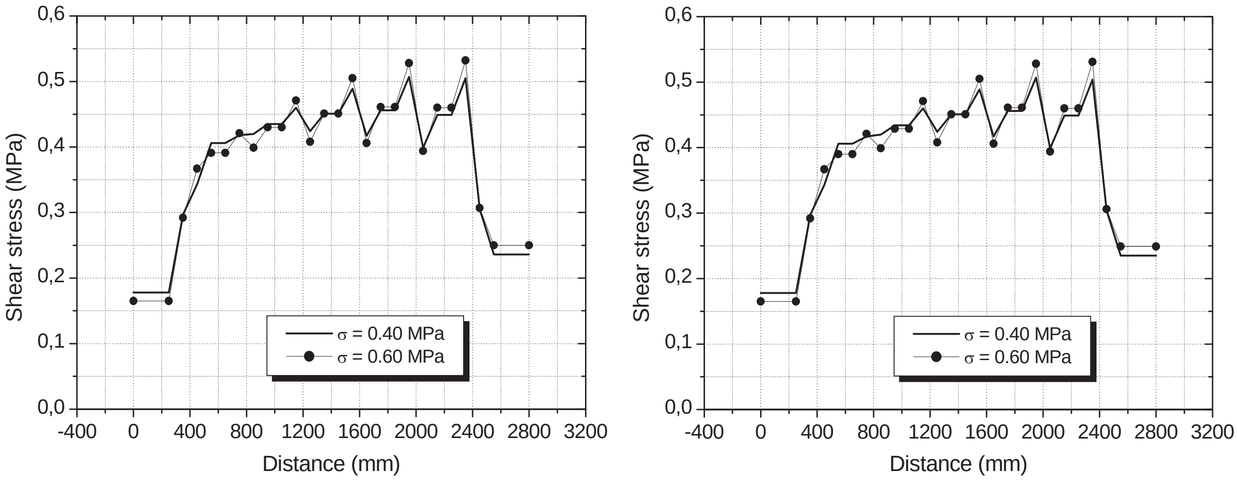


Figure 20: Normal stresses on the base of the flanges of specimens with uniform vertical loading (H=210 kN): (a) special blocks and (b) ordinary blocks.

No differences were also observed in shear stresses on the base of masonry walls subjected to vertical loading combined with lateral loading, see Figure 21.



(a) (b)

Figure 21: Shear stresses on the base of the central wall of specimens with uniform vertical loading (H=210 kN): (a) special blocks and (b) ordinary blocks.

6 CONCLUSIONS

In brief, the use of special blocks or ordinary blocks on the intersection of masonry walls seemed to produce a small influence in the behavior of the walls.

When vertical loading was applied only on the central wall, more significant differences could be observed, mainly in the failure mode. In this case, the masonry walls modeled with ordinary blocks presented some continuum head joints which produced planes of weakness due to the assembly of units in order to ensure some interlocking of units. These differences could be observed only when the walls reached high values of normal stresses.

In the case of masonry walls subjected to combined vertical and lateral loadings no differences were observed in the behavior of specimens modeled with special or ordinary blocks. However, all specimens failed with low normal stresses.

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REFERENCES

Abrams, D.P., “Lateral resistance of a two-story block building”, *Proceedings of ASCE Structures Congress*, New Orleans, USA, pp. 41-57, 1986.

BRAZILIAN TECHNICAL STANDARDS ASSOCIATION (ABNT). NBR 6136, Hollow concrete blocks for concrete masonry – Requirements, Rio de Janeiro, 2006.

Capuzzo Neto, V.. Estudo teórico e experimental da interação de paredes de alvenaria estrutural submetida a ações verticais, *MSc Thesis*, School of Engineering of São Carlos, University of São Paulo, São Carlos, 111p., 2000. (in Portuguese)

Capuzzo Neto, V.. Interação de paredes de alvenaria estrutural cerâmica sob ações verticais, *PhD Thesis*, School of Engineering of São Carlos, University of São Paulo, São Carlos, 322p., 2005. (in Portuguese)

Corrêa, M. R. S; Page, A. W.. The interaction of load-bearing masonry walls subjected to vertical loads: *Research Report N° 218.12.2001*, Callaghan: The University of Newcastle, 61p., 2001.

Corrêa, M.R.S; Ramalho, M.A.. A Simple Finite Element Based Model for Evaluating the Interaction of Load Bearing Walls Subjected to Vertical Loading, *Construction & Building Materials*, v. 18, p. 77-89, 2004.

EUROPEAN STANDARD. EN 1996-1-1, Eurocode 6: Design of masonry structures, 2005.

Haach, V. G., "Development of a design method for reinforced masonry subjected to in-plane loading based on experimental and numerical analysis", *PhD Thesis*, University of Minho, Guimarães, Portugal, 2009. (In Portuguese). Available from www.civil.uminho.pt/masonry.

Haach, V.G.; Vasconcelos, G.; Lourenço, P. B., "Experimental analysis of reinforced concrete block masonry walls subjected to in-plane cyclic loading", *Journal of Structural Engineering*, V. 136(4), pp. 452-462, 2010.

Hendry, A.W.. "Structural Masonry", *MacMillan Press LTDA*, London, UK, 1998.

Lourenço, P.B.; Rots, J.G., "Multisurface interface model for analysis of masonry structures", *Journal of engineering mechanics*, V.123(7), pp. 660-668, 1997.

Modena, C., Porto, F., Valluzzi, M.R., "Reinforced and rectified clay block masonry", *Proceedings of 6th National Congress of Seismology and Seismic engineering*, Guimarães, Portugal, pp. 155-177, 2004.

Mohamad, G., "Mechanism failure of concrete block masonry under compression", *PhD Thesis*, University of Minho, Guimarães, Portugal, 2007. (In Portuguese). Available from www.civil.uminho.pt/masonry.

Ramalho, M.A.; Corrêa.M.R.S., "Projetos de edifícios de alvenaria estrutural", *Pini*, São Paulo, 2003. (in Portuguese).

Shing, P. B.; Noland, J. L.; Klamerus, E., Spaeh, H., "Inelastic behaviour of concrete masonry shear walls", *Journal of Structural Engineering*, V.115(9), pp. 2204-2225, 1989.

Sinha, B. P.; Hendry, A. W.. Compressive strength of axially loaded brick walls stiffened along their vertical edges. *Proceedings of 5th International Brick Masonry Conference*, Washington, pp. 254-261, 1979.

Stockbridge, J. G.. A study of High-Rise load bearing brickwork in Britain. *PhD Thesis*, University of Edinburgh, Edinburgh, 1967.

Tomaževič, M., "Earthquake-resistant design of masonry buildings", *Imperial College Press*, London, 1999.

Van Zijl, G.P.A.G., "Modeling masonry shear-compression: Role of Dilatancy highlighted", *Journal of engineering mechanics*, V.30(11), pp. 1289-1296, 2004.

Vasconcelos, G., Lourenço, P.B., "In-plane experimental behaviour of stone masonry walls under cyclic loading", *Journal of Structural Engineering*. V.135(10), pp. 1269-1277, 2009.

Voon, K.C., Ingham, J.M., "Experimental In-Plane shear strength investigation of reinforced concrete masonry walls", *Journal of Structural Engineering*, V.132(3), pp. 400-408, 2006.

Yoshimura, K., Kikuchi, K., Kuroki, M., Nonaka, H., Kim, K.T., Matsumoto, Y. Itai, T., Reeznag, W., Ma, L., "Experimental study on reinforcing methods for confined masonry walls subjected to seismic forces", *Proceedings of 9th North American Masonry Conference*, Clemson, South Carolina, USA, 2003.