ANALYSIS OF MASONRY PANELS USING AN EQUIVALENT HOMOGENEOUS MATERIAL

S. C. Peleteiro(1); M. R. S. Correa(2); M. A. Ramalho(3)

ABSTRACT

Masonry can be considered as a nonhomogeneous continuous media with mechanical orthotropic characteristics. It is considered as a periodic composite continuum, composed of two different materials (brick and mortar) arranged in a periodic manner. The homogenisation theory for periodic media allows for the overall behaviour of masonry to be derived from the behaviour of the constitutive material. By means of a homogenisation process, a fictitious material can be defined whose mechanical properties are equivalent to the average characteristics of a given nonhomogeneous material. The aim of this paper is to numerically derive the in-plane elastic characteristics of masonry using the ANSYS software program. Panels of different geometry were analysed and it was verified that the results agreed well with the values reported by other authors.

Key words: Masonry, homogenisation, finite element, brick, mortar, behaviour.

(1) Graduate Student e-mail: scampana@sc.usp.br
(2) Senior Lecturer e-mail: marcio@engmail.newcastle.edu.au
(3) Senior Lecturer e-mail: ramalho@sc.usp.br

São Paulo University – São Carlos Engineering School
Structures Engineering Department
Av. Trabalhador São Carlense, 400
CEP 13566-590 São Carlos, SP, Brazil

INTRODUCTION

Masonry can be considered as a continuous nonhomogeneous media with mechanical orthotropic characteristics. It is considered a composite continuum consisting of two different materials, blocks and mortar, arranged periodically. According to ANTHOINE (1995), it is possible to use the theory of homogenisation for periodic media to determine the behaviour of masonry from the behaviour of its constituent materials. By means of a homogenisation process, one can define a fictitious material whose mechanical properties are equivalent to the average characteristics of a given nonhomogeneous material.

Admitting that nonhomogeneities are small in comparison to the dimensions of the structure and treating it as a composite material consisting of blocks and mortar, it seems natural to consider masonry as a homogeneous material.

According to LOURENÇO & ROTS (1997), the issue of describing the behaviour of masonry in terms of average stresses and average strains can basically be approached in two ways. One approach is to gather, collate and interpret extensive experimental data and to define analytical expressions for an orthotropic macro-constitutive law that apparently fits the experimental data. This approach is necessary because, as yet, little is known about the behaviour of masonry. The results of this approach are limited to the conditions under which the data are obtained.

The second approach is to use approximate homogenisation techniques, which consist of obtaining a macro-constituent law based on the micro-constitutive laws and the geometry of the composite material. Hence, the macro-constituent law is not actually implemented or even exactly known. Knowledge of this relation allows one to understand the behaviour of masonry and, thus, alterations of its geometry can be numerically manipulated without the need for new tests. The latter approach is interesting because it is common to use blocks of different geometry and mortar with different thicknesses. Research focusing on the possible use of homogenisation techniques for the analysis of masonry structures has, therefore, become increasingly popular in the last decade.

One of the first articles about the subject was introduced by PANDE et al. in 1989, who used an "equivalent” material approach to compute the elastic properties of masonry walls. A stacked brick-mortar system is introduced composed of a series of parallel layers that behave elastically. This is extended to allow an equivalent homogeneous elastic material to represent masonry with two sets of mortar joints (bed and head joints). The process consists of two steps: in the first step, horizontal homogenisation is performed, including the blocks and the vertical joints. In the second, vertical homogenisation is carried out, joining the previously homogenised material with the horizontal joints (Figure 1). Expressions for the elastic properties of the equivalent material are derived in terms of the elastic properties of the block and mortar and considering the mortar's relative thickness.

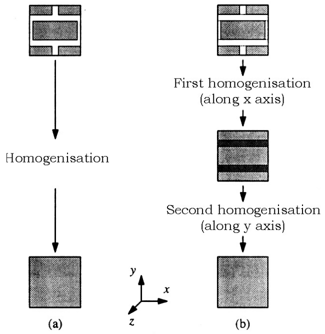


Figure 1 – Two-step homogenisation
Adapted from LOURENÇO (1996)

In 1992, PIETRUSZCZAK & NIU proposed a mathematical formula to describe the average mechanical properties of structural masonry. These authors regarded a typical element of structural masonry as a composite medium whose average macroscopic properties can be identified. Thus, they provided a general three-dimensional formula, using it to estimate the average macroscopic properties of the system. Their article also reported on an investigation of the phenomenon of progressive failure of brickwork, demonstrating that the failure mechanism consists of a formation of macrocracks in bricks or a ductile/brittle failure of the bed joints. The properties of the vertical joints have a very limited effect on the macroscopic failure. Thus, for practical purposes, the vertical joints can be assumed to have isotropic linearly elastic characteristics.

PAPA & NAPPI (1993) presented a material model based on a homogenisation procedure for the analysis of masonry structures. This model considers masonry as a composite material and its global mechanical properties are determined as a function of the properties of its components, i.e., the blocks (admitted as brittle elastic) and the mortar (admitted as subject to damage). The method consists of two steps. The first step consists of vertical homogenisation, including the bricks and vertical joints as well as the bricks and bed joints. The second step consists of horizontal homogenisation based on the materials previously obtained. The failure predicted by this theoretical approach is in agreement with the results of experimental research.

In 1995, ANTHOINE presented a study in which the theory of homogenisation of periodic media is applied more strictly to determine the characteristics of masonry. According to the author, similar procedures have been used by many researchers, albeit in a more general, indefinite manner. The article gives a description of the theory of homogenisation for periodic means implemented in a single step on the real geometry of masonry (mortar pattern and wall thickness). The results obtained are compared with analyses based on existing simplified methods, constituting a basis of reference to evaluate the relevance of some of the approaches commonly found in the literature. An important result is the numerical applications the author proposes, which demonstrate that varying joint patterns, disregarding vertical joints or assuming plane stress provides fairly reasonable estimates of the global elastic behaviour of masonry.

LOURENÇO & ROTS (1997) evaluated the performance of the homogenisation process in two steps, based on the assumption of layered materials. They analysed the processes adopted by PANDE et al. (1989) and PAPA (1990) and discussed the effectiveness of homogenisation techniques in the analysis of masonry structures. According to these authors, the greatest advantage of homogenisation is that, once the properties of the constituents are known, the composite behaviour of the material can be predicted without the need for costly and, in the case of masonry, extensive tests. This would mean that changes in geometry, i.e., the dimensions of bricks and the thickness of joints or geometrical arrangements, could be manipulated entirely numerically. The authors demonstrated that two-step homogenisation can be used to determine the linear characteristics of masonry.

LUCIANO & SACCO (1997) presented a damage model for old masonry based on a variational formulation for the problem of periodicity. A numerical procedure to determine the elastic properties of complete and damaged material was developed. The evolution of damage to masonry, considering the exact geometry and the representatives of the composite mechanical properties, was obtained. It was assumed that damage is caused by coalescence and growth of fractures only in the mortar. A representative elementary volume was chosen, and eight possible states of damage and intact material for the masonry were identified. The theory of homogenisation for materials with periodic microstructures was used to define the overall module of the uncracked and cracked masonry. The damage model thus obtained is apparently simple and serves to identify the behaviour of regular masonry. The effectiveness of the proposed damage model has been tested by developing a simple structural application.

DE BUHAN & DE FELICE (1997) presented a continuous model to assess the ultimate failure of masonry as a homogeneous material. It was demonstrated that a macroscopic resistance criterion for the masonry, described as a group of regular blocks separated by mortar joints in its interfaces, can be built based on the homogenisation technique implemented within the framework of the yield design theory. The authors point out that the validity of the proposed model, in the manner in which it was applied in the article, is entirely dependent on the characteristics of the length of the heterogeneity (in the article, the dimension of the representative elementary volume). This dimension must be small in relation to the structure’s other dimensions, e.g., the length of the wall.

LEE et al. (1998) presented numerical investigations of structural masonry walls subjected to uniform plane stress/strain using several homogenisation techniques. The structural masonry was considered as a material composed of blocks and horizontal and vertical joints. A perfect connection was assumed among the constituent materials. Two homogenisation techniques, based on strain energy, were applied to determine the module of equivalent elasticity of the masonry. The structural relation of the constituent materials is deduced to relate the stresses and strains in the constituent materials with the stresses and average strains in the masonry. The masonry's traction tension resistance was determined based on the flaw of one of the constituent materials. It was demonstrated that the traction tension resistance is a function of the elastic parameters of the block and the mortar and of the traction resistance of the mortar.

DETERMINATION OF THE ELASTIC CHARACTERISTICS OF MASONRY

A comparison was made between the elastic properties defined numerically and the properties obtained using the method proposed by PANDE et al. (1989) for a masonry cell (figure 2). Pande's process consists of two steps. Horizontal homogenisation was carried out in the first step, including the blocks and the vertical joints, while vertical homogenisation was performed in the second step, including the material homogenised previously with the horizontal joints. For the numerical determination of the average elastic characteristics of masonry, a cell was modelled using the ANSYS software program. A quadrilateral element called PLANE42 was adopted. The element was defined by 4 nodes with 2 degrees of freedom at each node, with translations in the nodal x and y directions.

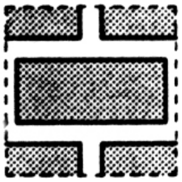


Figure 2 – Typical cell of masonry
Adapted from LOURENÇO (1996)

In this study, the block and the mortar were considered to have a linear isotropic behaviour. The properties adopted for the block were constant and the ratio between the module of elasticity of block and mortar varies from 1,1 to 11. The properties of the materials employed are shown in Table 1.

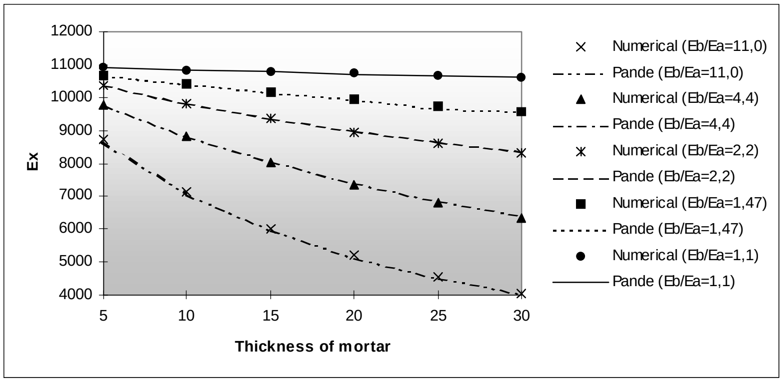
Table 1: Material Properties

YOUNG'S MODULE – Eb	11000 N/mm^2
COEFFICIENT OF POISSON (BLOCK) - ν_b	0,25
COEFFICIENT OF POISSON (MORTAR) - ν_m	0,20
WIDTH OF BLOCK – LB	225 mm
HEIGHT OF BLOCK – HB	75 mm
THICKNESS OF BLOCK – Th	100 mm

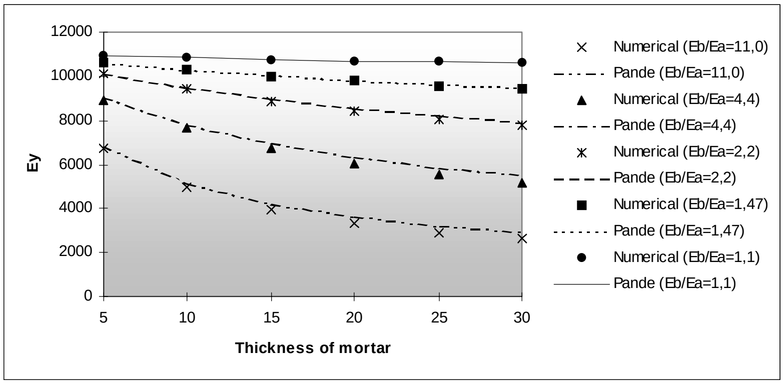
To numerically determine the module of elasticity of the equivalent material, the masonry's block and mortar properties were modelled separately. To determine the module of elasticity in a given direction, for example the x axis, the masonry cell was subjected to uniform loading along this direction. The average strain of the cell's faces in the x direction was then determined.

Assuming that the strain of the equivalent material is the same as that of the basic cell, i.e., the two systems contain the same strain energy, Young's module of the cell was calculated in the x direction. The ν_{xy} coefficient of Poisson was obtained based on the average strains of the cell's faces in the y direction. The same procedure was used for the y direction.

For the sake of comparison, the values of the elastic constants, Ex and Ey, obtained by both PANDE's method and numerically, are presented in graphs 1 and 2, respectively.



Graph 1 – Ex homogenised/numerical x Thickness of mortar



Graph 2 – Ey homogenised/numerical x Thickness of mortar

Graphs 1 and 2 show the values of Ex and of Ey obtained numerically and those obtained by Pande's method. As can be seen, these values are quite similar. It was, therefore, concluded that both methods could be used to homogenise masonry without reaching significantly different values.

EXAMPLE - Uniformly distributed horizontal load

In this example, a 1970,0 mm long, 1106,0 mm high masonry wall (nine blocks in length and eighteen blocks in height) is analysed. The wall is subjected to a uniform horizontal load distributed along its top, as shown in figure 3. The load is applied in the direction of the x axis and a very rigid beam is used to distribute the load uniformly along the wall. A force of F=1,0 MN is applied.

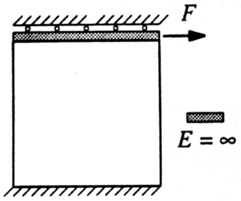


Figure 3 – Uniformly distributed horizontal load
Adapted from LOURENÇO (1996)

A 210 x 52 x 100 mm block with 10 mm thick mortar joints was used. For purposes of comparison, three models were considered, i.e., a continuous model, in which block and mortar were modelled separately using a 4-node quadrilateral element (PLANE42), and two homogenised models, in which the wall was modelled as an orthotropic material using the same element. The properties of one homogenised model were obtained using PANDE's equations (1989) while those of the other model were determined numerically. Young's module of the block (Eb) was 20000,0 N/mm^2 and Poisson's ratio (ν_b) was equal to 0,15. The mortar for Young's module (Em) was 2000,0 N/mm^2 and Poisson's ratio (ν_m) was 0,125. The orthotropic properties of both models are given in table 2.

Table 2 – Orthotropic properties

Material Properties	PANDE et al.	Numerical
Ex	12320,0	12691,7
Ey	8164,1	7893,7
ν_{xy}	0,113	0,128
G_{xy}	3160,5	3356,3

Figure 4 shows the results obtained for displacement in the x direction with the three adopted models. It can be seen that the two homogenised models are in good agreement with the continuous model. The values obtained for displacement are very close.

The results obtained for stresses (σ_x, σ_y and τ_{xy}) are presented in figures 5, 6 and 7. As can be seen, the overall behaviour of the homogenised structure is in good agreement with the continuous model. An analysis of the results indicates that there is a uniform distribution of stresses in the walls. Indeed, an overall analysis of the homogenised model indicates that its behaviour is very close to the continuous model, with the added advantage of faster modelling and shorter processing time.

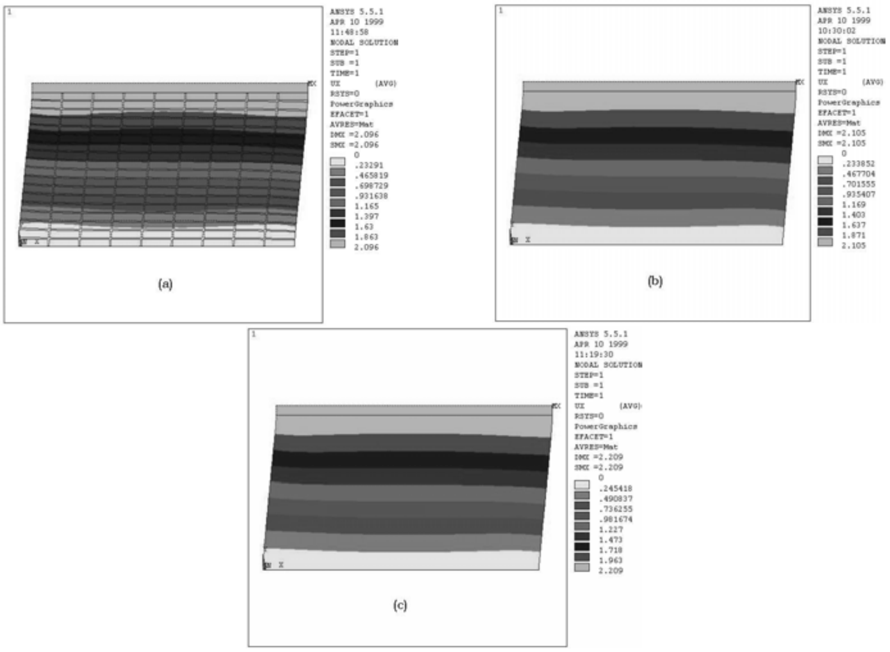


Figure 4 - Displacements: (a) continuous model; (b) numerical homogenisation; (c) homogenisation of PANDE et al.

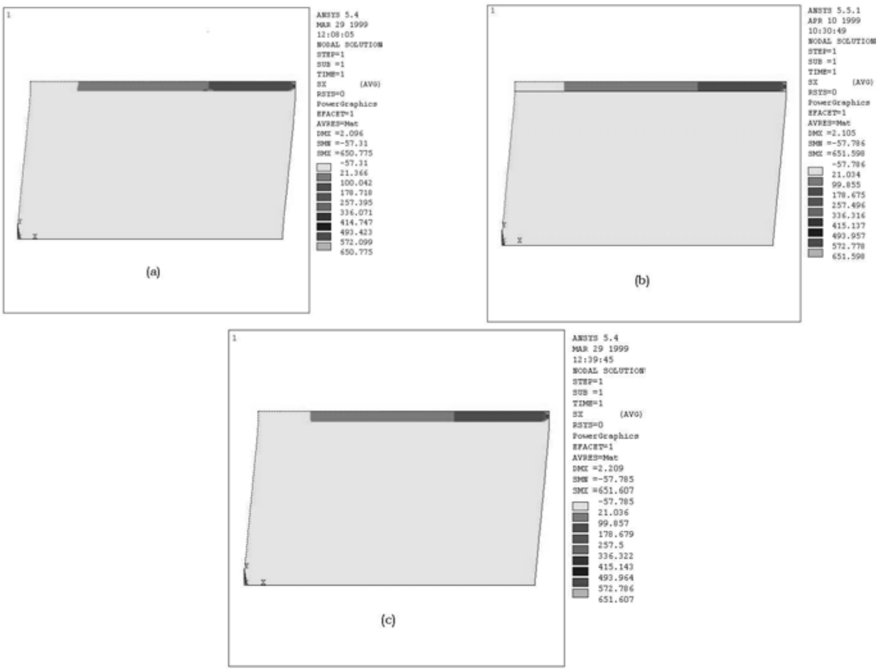


Figure 5 - Stresses σ_x: (a) continuous model; (b) numerical homogenisation; (c) homogenisation of PANDE et al.

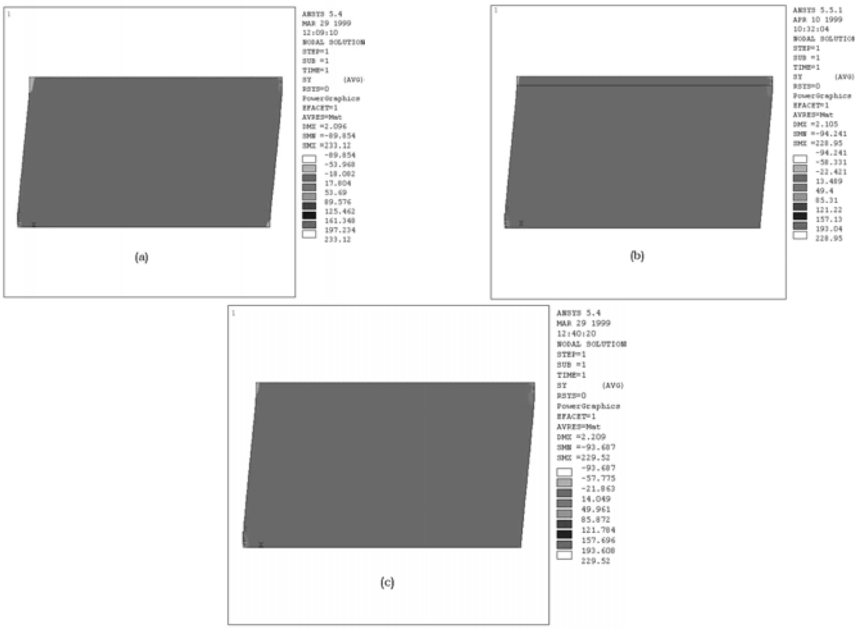


Figure 6 - Stresses σ_y: (a) continuous model; (b) numerical homogenisation; (c) homogenisation of PANDE et al.

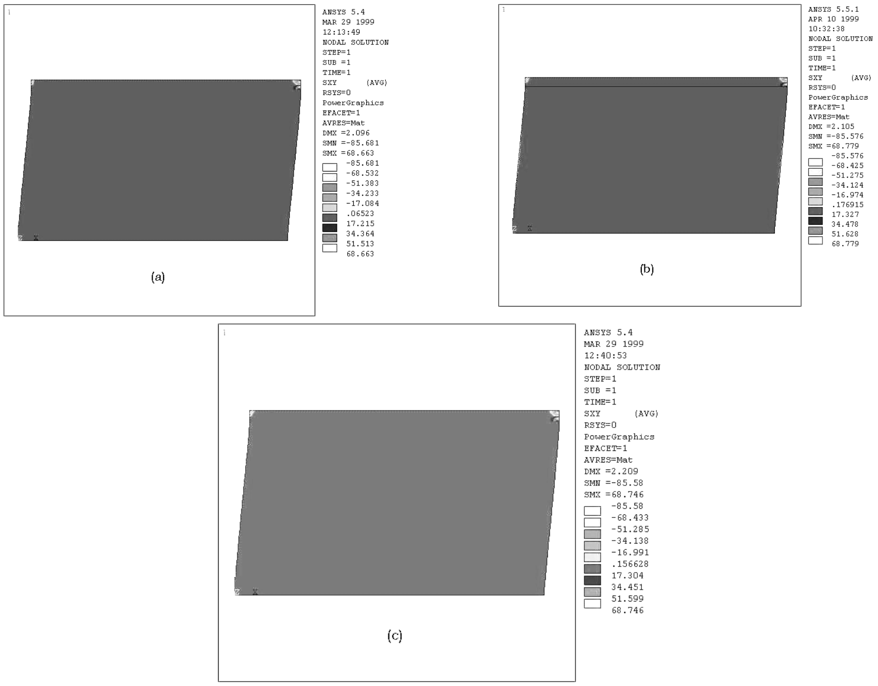


Figure 7 - Stresses τ_{xy}: (a) continuous model; (b) numerical homogenisation; (c) homogenisation of PANDE et al.

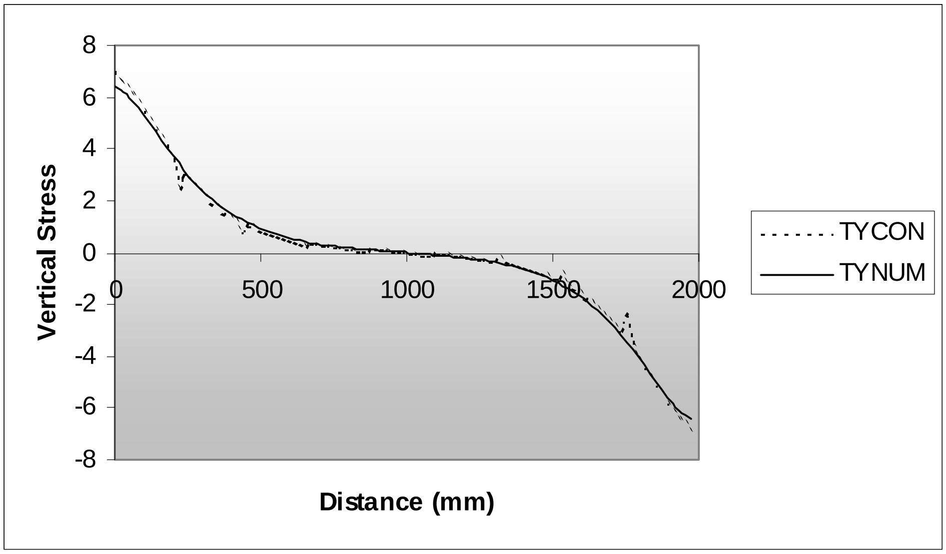


Figure 8 - Vertical stress (σ_y) in the wall (y=274)

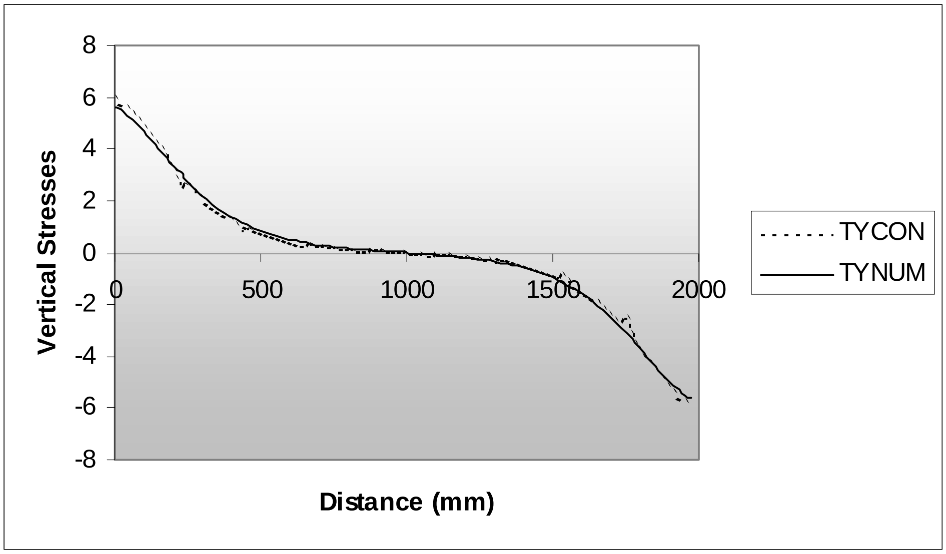


Figure 9 – Vertical stress (σ_y) in the wall (y=305)

Figure 8 illustrates the variation of vertical stresses (σ_y) in a line located 274 mm from the base of the wall, where the layers of block and mortar are alternated. Figure 9 shows the variation of vertical stresses (σ_y) in a line located 305 mm from the base of the wall, where there is a vertical layer of mortar. As can be seen, despite the fact that the homogenised model is in good agreement with the continuous model in terms of overall behaviour, there are differences in terms of local behaviour, even in a linear analysis. In the continuous model, tension peaks can be observed at certain points, mainly in the mortar, which is not the case in the homogenised model. Therefore, for analyses of peak stresses, the homogenised model does not appear to be a good alternative.

CONCLUSIONS

Masonry can be interpreted as a macroscopically orthotropic material whose mechanical properties can be determined by a homogenisation procedure based on its components' properties.

This study demonstrated that the homogenisation procedure is in excellent agreement with the behaviour of the detailed modelling, with additional advantages such as easy modelling of the structure and shorter processing time.

It was also demonstrated that, in the case of linear analyses, in which the main objective is to analyse of a structure’s global behaviour, the homogenisation procedure is a viable and simple alternative to calculate the linear characteristics of masonry. However, for purpose of microscopic analyses, analyses of tension concentrations in specific points of the structure, and in the presence of non-linear behaviour, homogenisation is not the best alternative. The technique is likely to produce significant errors, at least locally, for which reason it is not a good option in its present form.

REFERENCES

ANTHOINE, A. (1995). International Journal of Solids and Structures, v.32, n.2, p.137-163.

DE BUHAN, P.; DE FELICE, G. (1997). Journal Mech. Phys. Solids. v.45, n.7, p.1085-1104.

LEE, J.S.; PANDE, G.N.; KRALJ, B. (1998). Materials and Structures, v.31, p.473-479, Aug-Sep.

LOURENÇO, P.B. (1996). Computational strategies for masonry structures. Netherlands, Delft University Press.

LOURENÇO, P.B.; ROTS, J.G. (1997). Masonry International, v.11, n.1, p.26-32.

LUCIANO, R.; SACCO, E. (1998). European Journal of Mechanics – A/Solids, v.17, n.2, p.285-303.

PANDE, G.N.; LIANG, J.X.; MIDDLETTON, J. (1989). Computers and Geotechnics, v.8, p.243-265.

PAPA, E. (1990). About damage mechanics with particular reference to masonry (in Italian). Dissertation, Politecnico de Milano

PAPA, E.; NAPPI, A. (1993). Masonry International, v.7, n.1, p.18-24

PIETRUSZCZAK, S.; NIU, X. (1992). International Journal of Solids and Structures. V.29, n.5, p.531-546.