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Micro modelling of masonry walls by plane bar elements for detecting elastic behavior

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Abstract. Masonry walls are amongst the oldest building systems. A large portion of the research on these structures focuses on the load-bearing walls. Numerical methods have been generally used in modelling load-bearing walls during recent years. In this context, macro and micro modelling techniques emerge as widely accepted techniques. Micro modelling is used to investigate the local behaviour of load-bearing walls in detail whereas macro modelling is used to investigate the general behaviour of masonry buildings. The main objective of this study is to investigate the elastic behaviour of the load- bearing walls in masonry buildings by using micro modelling technique. In order to do this the brick and mortar units of the masonry walls are modelled by the combination of plane truss elements and plane frame elements with no shear deformations. The model used in this study has fewer unknowns then the models encountered in the references. In this study the vertical frame elements have equivalent elasticity modulus and moment of inertia which are calculated by the developed software. Under in-plane static loads the elastic displacements of the masonry walls, which are encountered in literature, are calculated by the developed software, where brick units are modelled by plane frame elements, horizontal joints are modelled by vertical frame elements and vertical joints are modelled by horizontal plane truss elements. The calculated results are compatible with those given in the references.

Keywords: computational mechanics; finite element method (FEM); historical bridges/buildings; masonry structure; static analysis

1. Introduction

Masonry buildings are the oldest buildings that are considered to be significant in history. Considering the entire course of history it might be said that dwellings were generally built using masonry walls. A large portion of the research on these structures focuses on the load-bearing walls which emerge as one of the important components of masonry buildings. The load-bearing systems of such buildings are comprised of walls which are made of stones, bricks or earth blocks. In the masonry walls such elements are generally held together with mortar which has high compressive strength but negligible tensile strength.

There are two basic systems for modeling masonry walls; macro modeling and micro modelling. Macro modelling is preferred if the behavior of the whole building is to be investigated and the walls are represented by simple elements. If only the behavior of the wall is to be investigated micro modelling is preferred where brick units and mortar are also modelled. The preference between the two basic systems of modelling is related to the total number of unknowns and the analysis capacity. In macro modelling the entire wall is modelled by using few elements where as in micro modelling every brick and mortar joints are modelled by using different elements.

2. Modelling techniques used in masonry building elements

Modelling of concrete buildings using finite element method provides successful results. But the same cannot be stated for masonry buildings, where both the elements and the premises used in the modelling of masonry buildings are quite different. Although heterogeneous materials (at least concrete and steel reinforcement bar) are used in reinforced concrete buildings it is possible to model the structural component with the same finite elements based on the valid premises of the models (Ural 2009). But in masonry buildings things are rather different. Modelling the load-bearing wall elements in the structural analysis of masonry buildings is extremely important when finite element method is used. The solution time may be increased due to the large number of variables and large system rigidity matrix in finite element method which can be used in both linear and nonlinear analyses (Ural and Doğangün 2007). A very important step to overcome this problem was taken by Lourenço (1996) who introduced the homogenisation technique. Through homogenisation the wall element composed of masonry units and mortar can be represented as a single material. In walls, which are probably the most important components of masonry buildings, the use of masonry units such as stones, bricks and lightweight concrete blocks along with mortar has various structural characteristics which impedes modelling with the same type of finite element and homogenisation. Thus, an acceptable and realistic modelling technique is necessary. Otherwise masonry units and mortar should be separately modelled. In

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this modelling masonry units and interfacial elements are separately modeled so the number of variables becomes very high (Ural 2009).

2.1 Macro modelling

The interaction between masonry units and mortar is generally neglected when the behavior of the whole building is studied. Such modelling is known as macro modelling (Fig. 1). In macro modelling the analyzed building is studied in partitions of a certain size. Each macro element is either a whole wall or a wall segment in cavity walls with openings. The model is not suitable for small details of the building or the elements. In modelling of masonry buildings some models that reduce the degree of freedom and the time used for calculation using macro elements for the analysis of the behavior of entire building were developed (Lagomarsino 1998, Gallasco *et al*. 2004, Casolo and Peña 2007, Chen *et al*. 2008, Brencich and Caliò *et al*. 2012). Each macro element is either a wall or a wall fragment in cavity walls (Fig. 1(b)).

There are also simplified and rough modelling methods such as equivalent frame system for masonry buildings (Roca *et al*. 2005, Belmouden and Lestuzzi 2009, Demirel 2010, Sima *et al*. 2011). For modelling of masonry buildings Demirel (Demirel 2010) uses nonlinear bar frame models which are constructed through assigning lumped plastic joints to masonry building models that were built using isotropic and coherent equivalent bar elements. With a similar approach Sabatino and Rizzano (2010) have obtained results close to macro modeling with equivalent frame method comparing their equivalent frame model with macro modeling method (Fig. 2). In another work, Kheirollahi modelled the masonry structures by using shell element (Kheirollahi 2013)

2.2 Micro modelling

Micro modelling approach has been accepted in the world of science following macro modelling with macro elements. Especially Lourenço (1996) developed a numerical model for micro modelling during his doctoral studies where he uses shear, cracking and failure mechanisms together. Lourenço (1996) defines three methods for modelling masonry walls in his study; macro modelling (Fig. 3(c)), simplified micro modelling (Fig. 3(b)) and detailed micro modelling (Fig. 3(a)).

Casolo (2004, 2009) has made the micro modelling of masonry walls with rigid rectangular elements with two normal springs and a shear spring on each side which are also used for controlling the rotation of the brick unit. (Fig. 4).

Berto *et al*. (2005) who used micro modelling technique during the modelling phase have conducted 2D and 3D analyses for investigating the behavior of masonry prisms under axial pressure. They have taken into consideration lean mortar - strong brick and pup - strong mortar properties.

Chaimoon and Attard (2006) who have developed a formula for determining the behavior of masonry wall elements in case of shear and compression breakage have used a simplified micro modelling technique in their study in which they have used triangle finite elements.

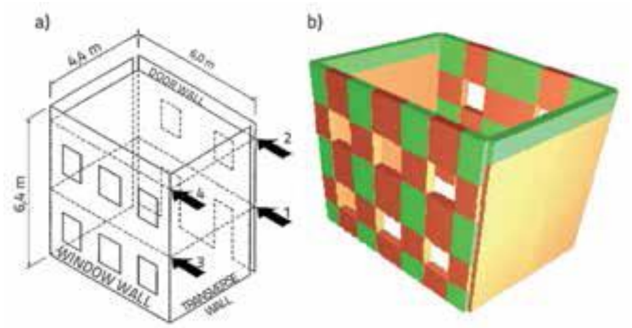

Fig. 1 Modelling of masonry buildings using macro elements (Gallasco *et al.* 2004), (a) Schematic representation of the building and (b) modelling with macro elements

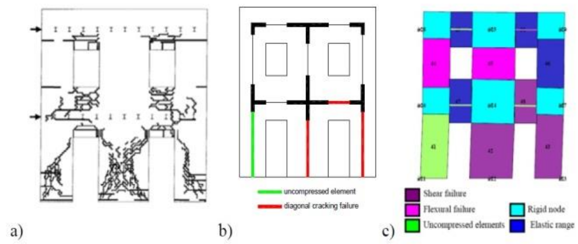

Fig. 2 Equivalent frame model (Sabatino and Rizzano 2010), (a) Sample wall, (b) Equivalent frame model and (c) Macro model

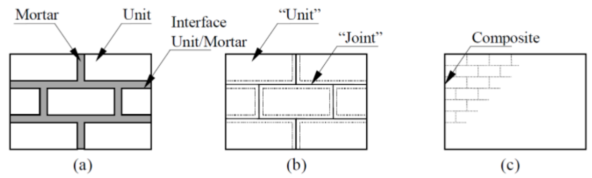

Fig. 3 Masonry wall modelling, (Lourenço 1996), (a) Detailed Micro Modelling, (b) Simplified Micro Modelling and (c) Macro Modelling

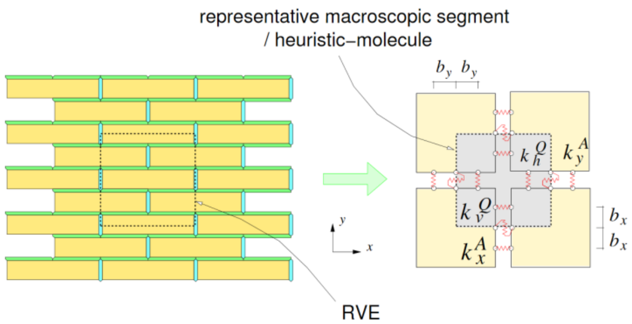

Fig. 4 Heuristic representation of the correspondence between an RVE (representative volume element) of the composite material and the representative macroscopic segment, or heuristic molecule, made of rigid masses and springs (Casolo 2009)

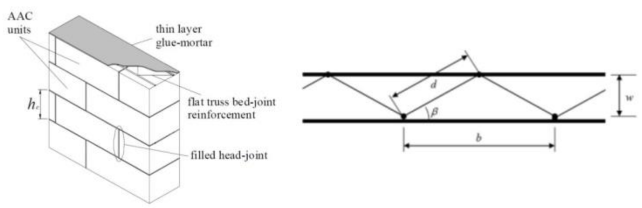

Fig. 5 Modelling bed joints using truss elements (Mandilora *et al*. 2012)

They have accepted that bricks and mortar had elastic behaviors while the brick-mortar interface had post-elastic behavior.

Mandilora *et al*. (2012) modelled walls using micro modelling technique in their study. Their modelling technique in Fig. 5 shows how they modelled the bed joint mortar which vertically joins bricks using truss elements.

Sattar (2013) who has used both micro and macro modelling in his doctoral dissertation has modelled masonry walls with micro modelling while he modelled masonry elements as two solid parts; bed joints as horizontal truss elements and head joints as vertical truss elements (Fig. 6). Moreover, Sattar also investigates the behavior of concrete frame elements which do not have infilled walls.

Considering the used modelling technique it might be asserted that macro modelling and equivalent frame modelling are used for modelling of the whole building while micro modelling is merely used for modelling a certain part of the building using present technological facilities. Hence micro modelling is used for modelling the structural elements of masonry buildings especially load-bearing walls.

It has been observed that detailed micro modelling technique is not commonly used in large systems although it is an efficient way for modelling realistic behaviors of masonry walls. Accordingly, research has concentrated on developing various modelling techniques aimed at providing faster solutions for large buildings in lower capacity computers. Simplified micro modelling technique is one of the mentioned methods (Ural 2009). In simplified micro modelling the sizes of the masonry units are enlarged by half the thickness of the mortar neglecting it and the masonry units are separated from each other with average interfacial lines as shown in Fig. 3(b) (Ural and Doğangün 2009).

In detailed micro modelling all the mechanical properties of bricks and mortar that make up the masonry wall are separately considered.

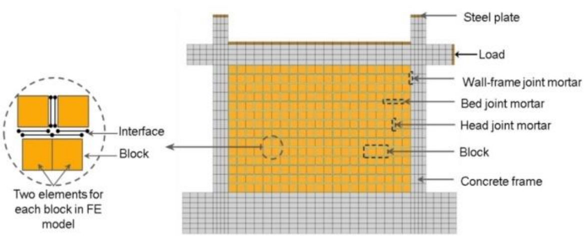

Fig. 6 Micro modelling with truss and solid elements (Sattar 2013)

In this approach, it is assumed that the cracks in the masonry wall would occur in the interface between the masonry unit and the mortar (Ural and Doğangün 2007). In another study the researchers worked on inelastic behavior of masonry walls under shear (Ural and Doğangün 2012). Significant studies on detailed micro modelling carried out by Zucchini and Lourenço (2002), Pina and Lourenço (2004), Milani *et al*. (2005a, b).

3. Modelling masonry walls with bar elements

In this study brick and mortar units are modelled separately and then combined. In the most general terms, the brick elements are modelled as frame elements and the mortar units are grouped as horizontal and vertical joints; the horizontal joints are modelled with vertical frame elements including the height of the bricks and the vertical joints are modelled with horizontal truss elements. In this way, the masonry wall is modelled with bar elements as a two-dimensional frame-truss hybrid system (Kafkas 2015).

Each brick element is modelled as three rigidly connected frame elements (Fig. 7(c)). It is accepted that these frame elements are positioned in the middle of the bricks thus they have the matching sizes to the given dimensions as shown in the figure (Fig. 7(c)). The area, moment of inertia, and the length of the frame element are calculated based on the cross-sectional properties of the brick element. The elasticity modulus is determined according to the type of material used.

In Fig. 7 'h_t'is the height, 'b_t'is width and 'L_t' is the length of the brick. In relation (1) the cross-sectional area 'A_t' of the bar element, in relation (2) the moment of inertia 'I_t' of the bar element and in relation (3) the length 'l' of the bar element are defined where 'dg' is mortar width.

$$A_t = b_t * h_t \quad (1)$$

$$I_t = b_t * h_t^3 / 12 \quad (2)$$

$$l = (L_t - dg) / 2 \quad (3)$$

The mortar units are grouped as horizontal and vertical joints; the horizontal joints are modelled with vertical frame elements including the height of the bricks and the vertical joints are modelled with horizontal truss elements. The system has one horizontal truss element for the vertical joint and one vertical frame bar element for the horizontal joint (Fig. 8).

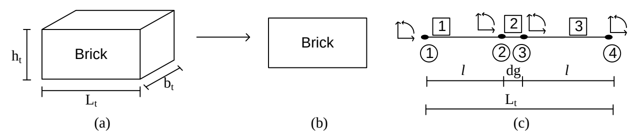

Fig. 7 Micro modelling of brick with bar element (frame element) (Kafkas 2015)

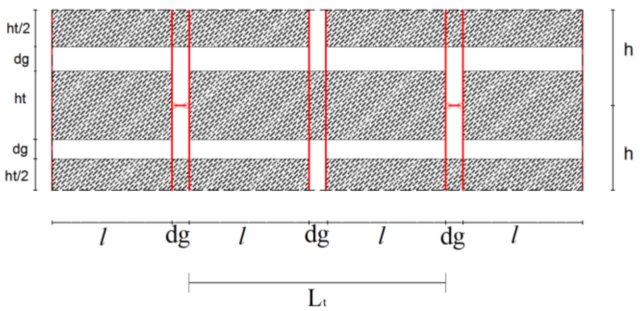

Fig. 8 Modelling of mortar units with frame and truss elements (Kafkas 2015)

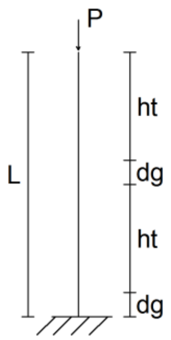

Fig. 9 Vertical frame element model with axial load (Kafkas 2015)

The area of the elements that represent the mortar units are calculated through the proration of the area of the mortar on the brick for each element. Considering the dimensions in Fig. 7(a). the cross-sectional area A_{hy} and the equivalent moment of inertia I_{hy} of the vertical frame element, that represent the horizontal joint, are defined in relation (4) and the cross-sectional area A_{hd} of the horizontal truss element, that represent the vertical joint, is defined in relation (5). In relation (4) β is a coefficient which is calculated from relation (10) on the basis of the number of vertical bricks.

$$A_{hy} = (L_t * b_t)/4$$
$$I_{hy} = \beta * I = \beta * ((L_t/4)^3 * b_t)/12 \quad (4)$$

$$A_{hd} = h_t * b_t \quad (5)$$

The lengths of the elements that represent the mortar units are calculated on the basis of the length and height of the brick elements and the horizontal and vertical thickness of the joints. The length of the horizontal truss element is equal to joint width *dg*, the length of the vertical frame element h can be calculated as follows depending on the geometry of the model

$$h = h_t + dg \quad (6)$$

The modulus of elasticity for the horizontal truss element, that represents the vertical joint, is chosen on the basis of the elasticity modulus of the mortar element. For the vertical frame element, that represents the horizontal joint, since the calculated bar length of it remains partially in the brick element and partially in the mortar element, then an equivalent elasticity modulus E_e has to be calculated. If the vertical frame element is taken as a single bar unit and an axial load *P* is applied the elongation or shortening deformations can be calculated using Hooke's Law (Fig. 9.).

The change in the length of the vertical frame element in Fig. 9 which is constructed from two bricks and two layers of mortar can be calculated as follows according to Hooke's Law

$$\Delta = P * L / E_e * A_{hy} \quad (7)$$

The change in length can also be calculated as follows given that E_t is the elasticity modulus of the brick, E_h is the elasticity modulus of the mortar and A_{hy} is the cross-sectional area of the bar

$$\Delta = (P * 2 * h_t / E_t * A_{hy}) + (P * 2 * dg / E_h * A_{hy}) \quad (8)$$

The equivalent elasticity modulus of the bar can be calculated using the Eqs. (7) and (8)

$$E_e = E_t * E_h * (h_t + dg)/(h_t * E_h + dg * E_t) \quad (9)$$

The vertical frame element model, that is given in Fig. 10, will be used to calculate the coefficient β,which is used in definition (4).The vertical frame element in Fig. 10 has cross-sectional area A_{hy}, equivalent moment of inertia I_{hy} and measures 3h in length. The load *P* is applied horizontally to this vertical frame element and the top of the element horizontally displaces by δ amount. It is considered that the moment of inertia of the composite pillar is equal to *I* and it is composed of three joints and three bricks. It is expected that the horizontal load *P* which affects this composite pillar should also have the same δ horizontal displacement. To achieve this, the displacement energy stored in both models, which stems from bending, is calculated and then equated as shown in relations (10). Since $I_{hy}=\beta.I$, then coefficient β for the vertical frame element shown in Fig. 10 can be calculated from relation (10). Similarly, the β coefficients of the other vertical frame elements can be calculated.

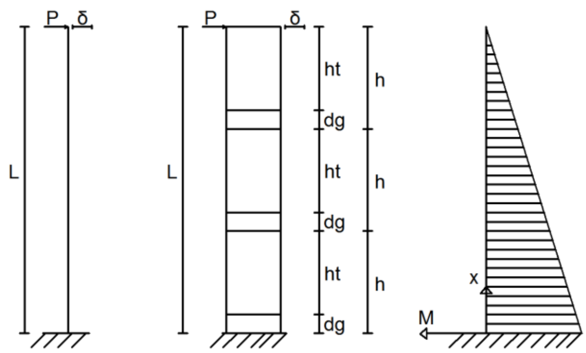

Fig. 10 Vertical frame element model and composite pillar with horizontal load (Kafkas 2015)

$$\int_0^{3h}\frac{M^2}{2E_e\beta I}dx=\int_0^{dg}\frac{M^2}{2E_hI}dx+\int_{dg}^{h}\frac{M^2}{2E_tI}dx+\int_{h}^{h+dg}\frac{M^2}{2E_hI}dx+\int_{h+dg}^{2h}\frac{M^2}{2E_tI}dx+\int_{2h}^{2h+dg}\frac{M^2}{2E_hI}dx+\int_{2h+dg}^{3h}\frac{M^2}{2E_tI}dx \tag{10}$$

Mortar and masonry unit elements of load-bearing walls, which are under in-plane static loads, are modelled by using the bar elements of the plane frame-truss hybrid system. In this modelling there are free nodes which are four times as many as the brick elements in the wall. In this modelling there are also three frame elements for each full brick element in the wall and also there is one frame element for half a brick element at the wall ends. The mortar units are modelled using four vertical frame elements for each horizontal joint and a horizontal truss element for each vertical joint in the wall (Figs. 11 and 12).

While modelling a wall using bar elements the number of nodes, the number of bars and the degree of freedom are calculated by using relations (11-17).

Here; *yts* is the number of horizontal bricks, *dts* is the number of vertical bricks, L_d is the length of the wall, h_d is the height of the wall, L_t is the length of the brick, h_t is the height of the brick, *dg* is the horizontal-vertical joint thickness, *ds* is the number of nodes, *çcs* is the number of frame elements, *kcs* is the number of truss element, *cs* is the number of bars and *sd* is the degree of freedom of the model.

$$yts=(L_d+dg)/(L_t+dg) \tag{11}$$

(round up the fractions)

$$dts=h_d/(h_t+dg) \tag{12}$$

(omit the fractions)

$$ds=(yts*4)*(dts+1) \tag{13}$$

$$ccs=[yts*dts*3-(dts/2)]+[yts*dts*4] \tag{14}$$

$$kcs=(yts-1)*dts+(dts/2) \tag{15}$$

$$cs=ccs+kcs \tag{16}$$

$$sd=yts*dts*4*3 \tag{17}$$

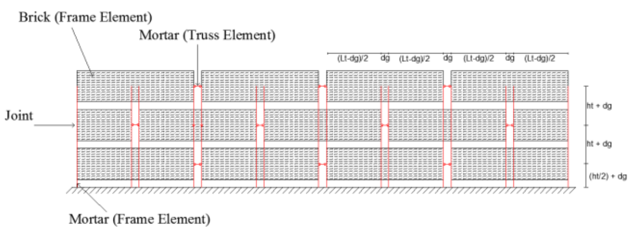

Fig. 11 Micro modelling bricks and mortar using frame and truss elements (Kafkas 2015)

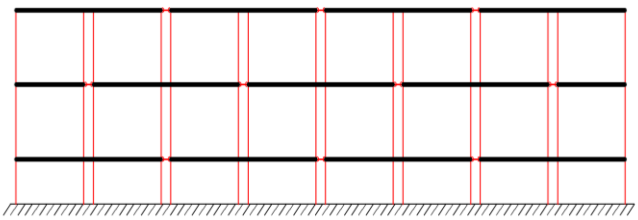

Fig. 12 Representation of the micro model (Kafkas 2015)

Using relations (11-17) the following results are obtained for the model if a wall, which is 329 cm. wide and 290 cm. high, is composed of 29×19×13.5 (cm^3) bricks with mortar width 1 cm.

Number of horizontal bricks; (*yts*) = 330/(29+1) = 11

Number of vertical bricks; (*dts*) = 290/(13.5+1) = 20

Number of nodes; (*ds*) = (11×4) * (20 + 1) = 924

Number of bars; (*cs*) = (11 * 20 * 3 – 20 / 2) + [(11 – 1) *20 + 20 / 2] + (11 * 20 * 4) = 1.740

Degree of freedom; (*sd*) = 11 * 20 * 4 * 3 = 2.640

4. Application of Lourenço masonry wall model

Lourenço's (1996) wall model is composed of 18 rows of 210×52×100 (mm^3) bricks and 10 (mm) thick layer of mortar. The loading types and recorded displacements are presented in Fig. 13. All load values are taken as 1.000 kN. For load-(a) and for load-(b) the load is applied on the overlying upper rigid block while for the other two loadings the load is applied to the middle of the upper rigid block. Ural (2009) used the elasticity moduli for this wall as 20.000 N/mm^2 for brick blocks and 2.000 N/mm^2 for mortar. In this study the same values are used in the modelling. Four different loads are applied to the model constructed by both Lourenço (1996) and Ural (2009) and the displacements *d*, which are shown in Fig. 13, are calculated.

The calculated displacement *d* values under the loads are comparatively presented in Table 1. In the table the last column YDPro represents the findings of the model considered in this study. The total deformations of the model used in this study under each loading case are presented in Figs. 14-17.

Table 1 Comparative displacement values

	Lourenço (1996)	LUSAS Ural (2009)	FEMMAS-L Ural (2009)	YDPro (This study)
	d (mm.)	*d* (mm.)	*d* (mm.)	*d* (mm.)
Load-(a)	5.39	5.413	5.413	5.6291
Load-(b)	1.35	1.359	1.3588	1.3361
Load-(c)	12.41	13	12.996	12.7928
Load-(d)	3.82	3.85	4.62	5.27

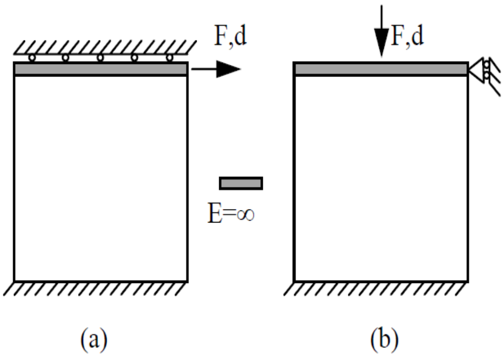

Fig. 13 Loading types of the model (Lourenço 1996, Ural 2009)

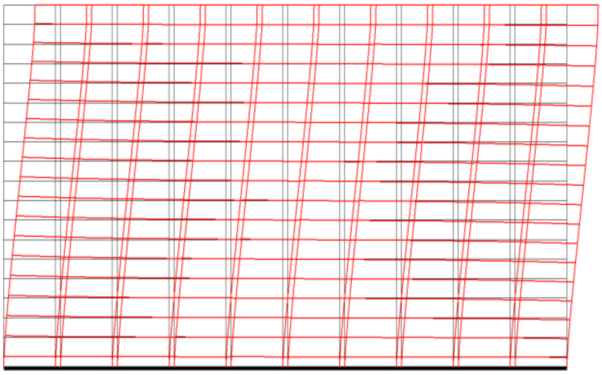

Fig. 14 Deformation under load-(a) (Kafkas 2015)

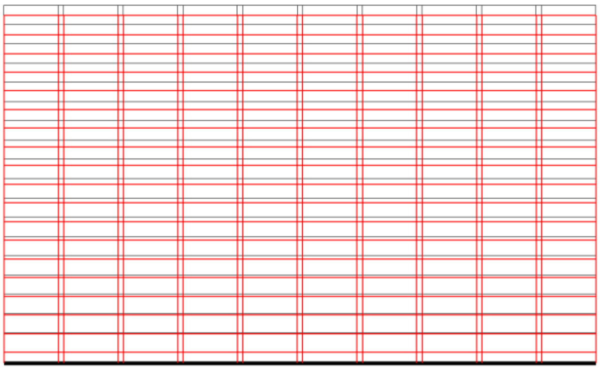

Fig. 15 Deformation under load-(b) (Kafkas 2015)

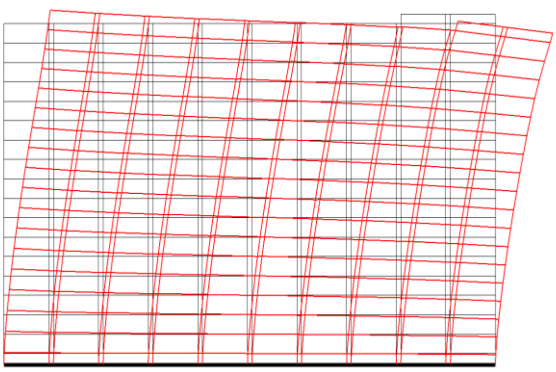

Fig. 16 Deformation under load-(c) (Kafkas 2015)

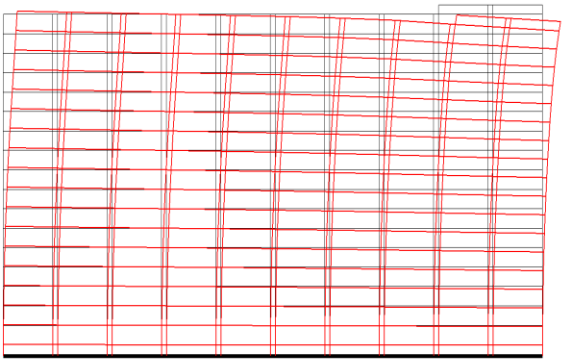

Fig. 17 Deformation under load-(d) (Kafkas 2015)

5. Conclusions

Masonry buildings had been existed in different parts of the world since time immemorial. Yet, the number of studies that focus on the modelling of masonry buildings is relatively low when compared with reinforced concrete and steel buildings. In literature the most widely known and applied modelling techniques for the masonry buildings are found to be macro and micro modelling. Although detailed micro modeling technique looks more realistic, it is generally impossible to analyze the whole building using micro modelling due to very large number of equations and unknowns. It is important to reduce the number of variables and model the masonry buildings for attaining a full analysis of the entire building.

In this study, vertical frame elements with equivalent elasticity modulus and equivalent moment of inertia are used for horizontal joints whereas horizontal truss elements are used for vertical joints and frame elements used for bricks to construct a modelling technique close to micro modelling. Modelling the masonry units with frame and truss elements means less nodes and equations. In this model the shear deformation is not considered for the frame elements. The Lourenço masonry wall example is analyzed in terms of its elastic behavior through the developed software. It is observed that the findings obtained after the analyses are compatible with the experimental and analytical results in the literature. It might be asserted that the modelling technique that is developed using the frame and truss elements, where for the vertical frame elements the equivalent elasticity modulus and moment of inertia, can be satisfactorily used for determining the elastic behavior of masonry walls. The mentioned software is under developing in order to be able to analyze the non-elastic behavior of masonry buildings, as well. Different researchers working on the subject would be beneficial in order to achieve more realistic and economical solutions to the problem.

References

Belmouden, Y. and Lestuzzi, P. (2009), "An equivalent frame model for seismic analysis of masonry and reinforced concrete buildings", *Constr. Build. Mater.*, **23**(1), 40-53.

Berto, L., Saetta, A., Scotta, R. and Vitaliani, R. (2005), "Failure mechanism of masonry prism loaded in axial compression", *Comput. Aspects, Mater. Struct.*, **38**(2), 249-256.

Brencich, A. and Lagomarsino, S. (1998), "A macro-element dynamic model for masonry shear walls", (Eds., Pande G *et al*.) Comp. meth. instruct. masonry, 4, E&FNSpon, 67-75.

Caliò, I., Marletta, M. and Pantò, B. (2012), "A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings", *Eng. Struct.*, **40**, 327-338

Casolo, S. (2004), "Modelling in-plane micro-structure of masonry walls by rigid", *Int. J. Solids Struct.*, **41**(13), 3625-3641.

Casolo, S. (2009), "Macroscale modelling of micro-structure evolution damage by a rigid body and spring model", *J. Mech. Mater. Struct.*, **4(**3), 551-570.

Casolo, S. and Peña, F. (2007), "Rigid element model for in-plane dynamics of masonry walls considering hysteretic behaviour and damage", *Earthq. Eng. Struct. D.*, **36**(8), 1029-1048.

Chaimoon, K. and Attard, M.M. (2006), "Modeling of unreinforced masonry walls under shear and compression", *Eng. Struct.*, **29**(9), 2056-2068.

Chen, S.Y., Moon, F.L. and Yi, T. (2008), "A macro-element for the nonlinear analysis of in-plane unreinforced masonry piers", *Eng. Struct.*, **20**(8), 2242-2252.

Demirel, İ.O. (2010), "A nonlinear equivalent frame model for displacement based analysis of unreinforced brick masonry buildings", MSc. Thesis, METU, Ankara, Turkey.

Galasco, A., Lagomarsino, S., Penna, A. and Resemini, S. (2004), "Non-linear seismic analysis of masonry structures", *Proceedings of the 13th World Conference on Earthquake Engineering*, Paper No. 843, Vancouver, Canada.

Kafkas, U. (2015), "Micro modeling of masonry wall elastic behavior by plane bar members", MSc. Thesis, Dumlupinar University, Kütahya, Turkey. (in Turkish)

Kheirollahi, M. (2013), "Equivalent frame model and shell element for modeling of inplane behavior of Unreinforced Brick Masonry buildings", *Struct. Eng. Mech.*, **46**(2), 213-229.

Lourenço, P.B. (1996), "Computational strategies for masonry structures", PhD Thesis, Delft University of Technology, Delft, Netherlands.

Mandirola, M., Penna, A., Rota, M. and Magenes, G. (2012), "Experimental assessment of the shear response of autoclaved aerated concrete (AAC) masonry with flat truss bed-joint reinforcement", *Proceedings of the 15th International Brick and Block Masonry Conference*, Florianópolis, Brazil.

Milani, G., Lourenço, P.B. and Tralli, A. (2005a), "A micro mechanical model for the homogenized limit analysis of out-of-plane loaded masonry walls", *Proceedings of the 10th International Conference on Civil*, Structural Environmental Engineering Computing, Rome, Italy.

Milani, G., Lourenço, P.B. and Tralli, A. (2005b), "A simple homogenized micro mechanical model for the analysis at the collapse of out-of-plane loaded masonry walls", *Proceedings of the 17th Congresso AIMETA di Meccacica Teorica e Applicata*, 1-12, Frenze, Italy.

Pina-Henriques, J. and Lourenço, P.B. (2004), "Masonry micro modeling adopted a discontinuous framework", *Proceedings of the 7th International Conference on Computational Structures Technology*, Lisbon, Portugal.

Roca, P., Molins, C. and Marí, A.R. (2005), "Strength capacity of masonry Wall structures by the equivalent frame method", *J. Struct. Eng.*, ASCE, **131**(10), 1601-1610.

Sabatino, R. and Rizzano G. (2010), "Nonlinear static analysis of masonry structures simplified equivalent frames and accurate models", *Proceedings of the 14th European Conference on Earthquake Engineering (ECEE)*, Macedonia.

Sattar, S. (2013), "Influence of masonry infill walls and other building characteristics on seismic collapse of concrete frame buildings", PhD Thesis, University of Colorado, Colorado, USA.

Sima, J.F., Roca, P. and Molins, C. (2011), "Nonlinear response of masonry wall structure subjected to cyclic and dynamic loading", *Eng. Struct.*, **33**(6), 1955-1965.

Ural, A. (2009), "Investigating linear and nonlinear behaviors of masonry structures", PhD Thesis, Karadeniz Technical University, Trabzon, Turkey. (in Turkish)

Ural, A. and Doğangün, A. (2007), "Evaluating the seismic performance of masonry structures using with micro modeling strategy", *Proceedings of the International Earthquake Symposium 2007*, Kocaeli, Turkey. (in Turkish)

Ural, A. and Doğangün, A. (2009), "Parameter effects on shear capacity of masonry walls; Unsupported length aspect", *e - J. New World Sciences Academy 2009*, **4**(3), 340-350. (in Turkish)

Ural, A. and Doğangün, A. (2012), "Crack development depending on bond design for masonry walls under shear", *Struct. Eng. Mech.*, **44**(2), 257-266.

Zucchini, A. and Lourenço, P.B. (2002), "A micro mechanical model for the homogenization of masonry", *Int. J. Solids Struct.*, **39**(12), 3233-3255.

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