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Parametric Study of Orthotropic Masonry Walls under Static and Dynamic Loading

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Abstract: The paper presents a parametric study of unreinforced and confined masonry walls with orthotropic properties under in-plane static and dynamic loading. A previously developed FEM model was extended to simulate the behaviour of the orthotropic masonry and was used to perform a series of analyses. The orthotropic behaviour of masonry is simulated with a simplified constitutive model. The influence of the orthotropy of masonry on the behaviour of two-storey walls (with different lengths and qualities of the masonry) was investigated. The results of the analysis show that the bearing capacity and the displacements of the wall, as well as the stresses in the masonry, concrete and reinforcement depend significantly on the degree of orthotropy of the masonry. As the degree of orthotropy increases, the differences in the parameters compared to isotropic masonry increase. The influence of the orthotropy of the masonry is greater under dynamic loading than under static loading. The influence of orthotropy is greater for stiff masonry than for soft masonry, and for confined masonry than for unreinforced masonry.

Keywords: numerical analysis; masonry wall; orthotropy; static and dynamic loading

1 INTRODUCTION

Masonry walls are complex anisotropic composite structures composed of masonry and reinforced concrete elements (horizontal and vertical beams, foundation etc.). The masonry is a composite material composed of brick units and mortar. Therefore, masonry walls generally always have anisotropic properties, i.e. in-plane orthotropic properties. The orthotropy of the masonry is mainly caused by vertical holes in brick units. Due to variations in the stiffness and strengths of the horizontal and vertical joints between the masonry units, additional orthotropy of masonry is exhibited. The plaster of the masonry walls additionally influences their stiffness and orthotropy, especially if it is reinforced. They mostly have higher stiffness and resistance in the vertical direction than in the horizontal direction. Fortunately, the stress of the walls in the practice are usually much greater in the vertical than in the horizontal direction.

Many different numerical models have been proposed to simulate the behaviour of orthotropic masonry under static and dynamic loads. Some of them are listed in Refs. [1-15]. Among the oldest models are those of Page et al. [1] and Dhanaeskar [2]. Andreaus [3] gave the failure criteria for masonry walls under in-plane loading. Lorenco et al. proposed several different numerical models for the analysis of masonry structures [4-6]. An orthotropic damage model for masonry structures was proposed by Berto et al [7, 8]. Calderini and Lagomarsino presented a continuum model for in-plane elastic behaviour of masonry [9]. Lishak et al. developed 2D orthotropic failure criteria for masonry [10]. A simple model for analysing unreinforced masonry shear walls under combined axial, shear and bending loading developed by Ghiassi et al. [11]. Pela et al. proposed two models for the analysis of masonry structures [12]. Penava et al. investigated the resistance clay block masonry wall using a micromodel considering anisotropy of the masonry unit [13]. Bilko and Małyszko used the orthotropic failure criterion proposed by Hoffman) as an orthotropic elastic-plastic constitutive model for masonry walls [14]. Most recently, macro-modelling of orthotropic dam341age in masonry using combination of micro-mechanics and continuum FE analysis proposed Drougkas [15].

From the presented review of the literature, it is evident that the modelling of masonry with orthotropic properties is still an actual problem due to the complexity of such constitutive models. Furthermore, there are still no such numerical model that is simple and capable to simulate the primary nonlinear effects of the masonry walls, including their orthotropy, and appropriate for extensive engineering application. Therefore, further research in this area is still welcome.

The objective of this paper is to give an answer to question: How much the orthotropic properties of the masonry affect the behaviour of the masonry walls. This paper presents a parametric study of two storey unreinforced and confined masonry walls under in-plane static and dynamic loading, in which the influence of several parameters are considered (wall length, material parameters of masonry and degree of masonry orthotropy). The innovation of the work lies in the attempt to consider the influence of the orthotropy of masonry and masonry walls on their behavior and ultimate bearing capacity under static and dynamic (earthquake) loading. The aim of the paper is to stimulate further research in this field in order to quantify the effects of anisotropy using the presented numerical model, which is based on the results of parametric analyses on the considered unreinforced and bounded masonry walls, with different ratios of wall heights and lengths.

2 NUMERICAL MODEL

2.1 Basic Numerical Model

Adopted basic numerical model [16] is presented very shortly below.

Planar 2D and 1D finite elements for spatial discretization and explicit-implicit time integration for time history analysis were adopted. The main features of this model are its simplicity and the possibility of practical application It is possible to simulate the material and geometric nonlinearities of planar concrete and masonry structures loaded in their plain. The constitutive material models are the same for static and dynamic analysis, i.e. the effect of strain rate on material characteristics is neglected.

The elastic-perfectly plastic constitutive model for concrete in compression is assumed. Modelling the opening and closing of cracks in concrete in tension-tension and tension-compression is feasible. The cracks are modelled as smeared, with fixed position. The effects of tensile and shear stiffness of cracked concrete are modelled. Reinforcement is modelled by bar elements within basic 2D elements with polygonal stress-strain relation, without slipping between the concrete and reinforcement. Using contact elements, it is possible to model penetration, separation, and slipping on the contact surface between the foundation and the ground. According to the adopted uniaxial stress-strain diagrams, contact elements are capable of transmitting normal and shear stresses.

The same constitutive model as for concrete was used for soil modelling, with appropriate material parameters.
Constitutive model for masonry in [16] does not include the effect of the orthotropy. The improved orthotropic masonry model in this paper is presented in continuation.

2.2 Ortotropic Masonry Model

A simplified orthotropic macro model of masonry is used. The main directions of orthotropy are vertical (v) and horizontal (h). Different compressive strengths (f_{mc}^v, f_{mc}^h), tensile strengths (f_{mt}^v, f_{mt}^h,), Young's modulus (E_v, E_h), limit compressive strains (ε_{mc}^v, ε_{mc}^h,) and limit tensile strains (ε_{mt}^v, ε_{mt}^h,) of masonry are defined for direction v and h. Adopted orthotropic constitutive model of masonry for normal stresses σ_m^v, σ_m^h, is presented in Fig. 1.

The failure of the masonry is defined over normal strains ε_{mc}^v, ε_{mc}^h, ε_{mt}^v, ε_{mt}^h. A small number of masonry parameters were used as the model is intended for practical application.

A measure of degree of masonry orthotropy is defined by orthotropy coefficient c_o:

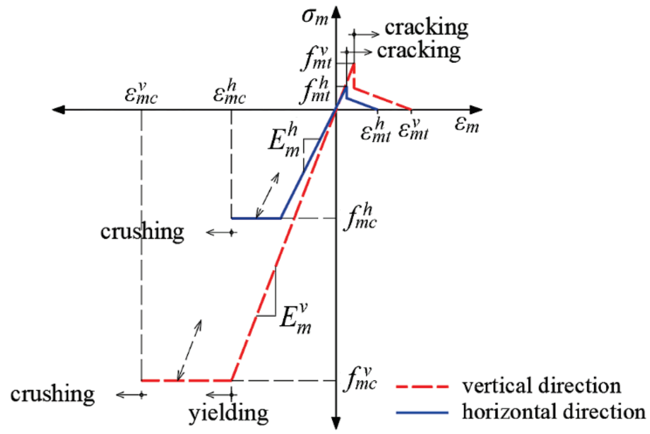
$$c_o = \frac{E_m^h}{E_m^v} = \frac{f_{mc}^h}{f_{mc}^v} = \frac{f_{mt}^h}{f_{mt}^v} = \dots \quad (1)$$

where

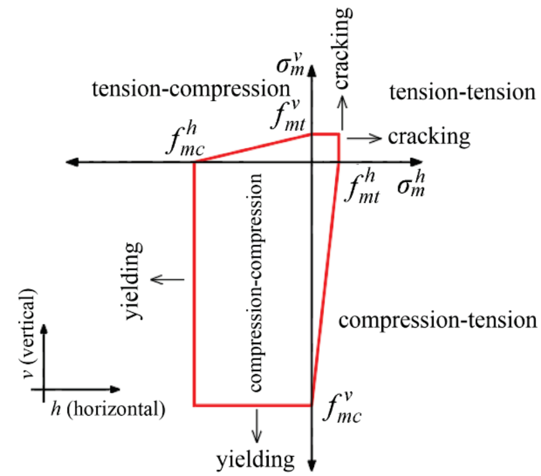
$$E_m^v \cdot \nu_m^v = E_m^h \cdot \nu_m^h \quad (2)$$

Here ν_m^v, ν_m^h are Poisson's rations in v and h directions.
The shear modulus (G) of masonry is defined by:

$$G_m = \frac{1}{\dfrac{\left(1+\nu_m^h\right)}{E_m^h} + \dfrac{\left(1+\nu_m^v\right)}{E_m^v}} \quad (3)$$



(a) 1D representation



(b) 2D representation

Figure 1 Used orthotropic constitutive model for masonry for normal stresses

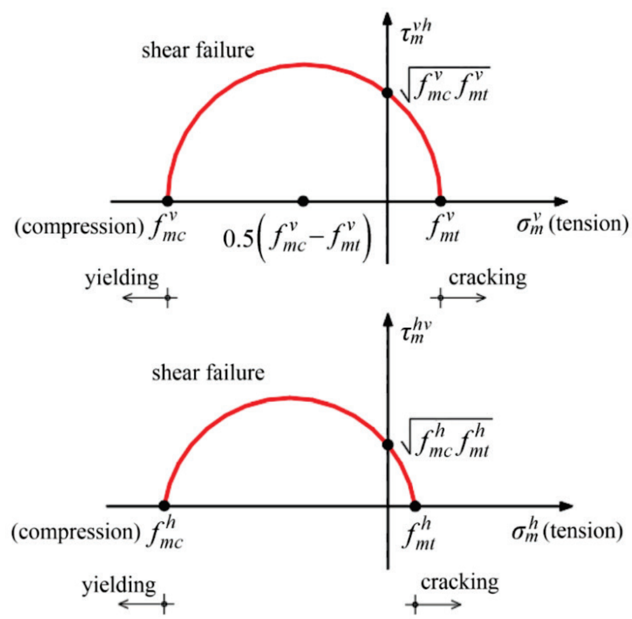


Figure 2 Used orthotropic constitutive model for masonry for shear stresses

In the model, it is assumed that the compressive strengths of the masonry in biaxial pressure are equal to its uniaxial compressive strength for a particular direction, i.e. that they do not depend on the ratio of biaxial compressive stresses. Elastic-perfectly plastic behaviour is assumed for biaxial compression, with linear unloading. The elastic behaviour is also used in biaxial tension until the tensile strength of the masonry is reached. Then the model of smeared cracks is used, which can occur in the direction perpendicular to the tensile stresses. The opening and closing of the cracks as well as the tensile and shear strength of the cracked masonry are modelled as in the concrete model [16].

The failure of the masonry due to shear stresses is also modelled (Fig. 2). The model is simple and assumes a relationship between normal (σ_m^v, σ_m^h,) and shear (τ_m^v, τ_m^h,) stresses according to circle equation.

The improved numerical model is verified by means of experimental tests [17]. The comparison of the numerical results with the experimental results is shown in Fig. 3. As can be seen, the numerical results are in good agreement with the experimental results. A more detailed description of the structural geometry, material properties and other information about the experimental tests and the validation of the improved numerical model can be found in [17].

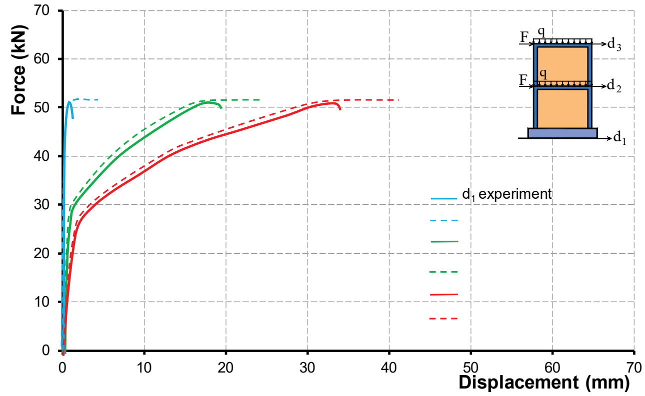


Figure 3 Validation of improved numerical model on experimental test [17]

Table 1 Scheme of the parametric study

Orthotropy coefficient c_o	Type of the wall	Material properties of the wall	Length of the wall (m)	Case
0,2 / 0,4 / 0,6 / 1	Unreinforced masonry (URM) wall	stiff masonry (S1)	3,0	/c_o/-URM-S1-3
			6,0	/c_o/-URM-S1-6
			12,0	/c_o/-URM-S1-12
		soft masonry (S2)	3,0	/c_o/-URM-S2-3
			6,0	/c_o/-URM-S2-6
			12,0	/c_o/-URM-S2-12
	Confined masonry (CM) wall	stiff masonry (S1)	3,0	/c_o/-CM-S1-3
			6,0	/c_o/-CM-S1-6
			12,0	/c_o/-CM-S1-12
		soft masonry (S2)	3,0	/c_o/-CM -S2-3
			6,0	/c_o/-CM -S2-6
			12,0	/c_o/-CM-S2-12

Table 2 Adopted material parameters of masonry for various orthotropy coefficient c_o

Parameter	Stiff masonry (S1)					Soft masonry (S2)			
	c_o = 0,2	c_o = 0,4	c_o = 0,6	c_o = 1,0		c_o = 0,2	c_o = 0,4	c_o = 0,6	c_o = 1,0
E_m^v (GPa)	5,0	5,0	5,0	5,0		1,0	1,0	1,0	1,0
E_m^h (GPa]	1,0	2,0	3,0	5,0		0,2	0,4	0,6	1,0
G_m (GPa)	0,794	1,316	1,685	2,174		0,159	0,263	0,337	0,435
f_{mc}^v (kPa)	5,0	5,0	5,0	5,0		1,0	1,0	1,0	1,0
f_{mc}^h (kPa)	1,0	2,0	3,0	5,0		0,2	0,4	0,6	1,0
f_{mt}^v (kPa)	0,15	0,15	0,15	0,15		0,03	0,03	0,03	0,03
f_{mt}^h (kPa)	0,03	0,06	0,09	0,15		0,006	0,012	0,018	0,03
Notes: *v* indicates the vertical direction; *h* indicates the horizontal direction.									

3 PARAMETRIC STUDY

The previously developed and validated numerical model was used to investigate the effects of masonry orthotropy on unreinforced (URM) and confined masonry (CM) walls with different geometries and material properties. Tab. 1 shows the schematic of the parametric study performed.

3.1 Description of the Performed Numerical Analyses

Two-storey unreinforced (URM) and confined masonry (CM) walls were considered in the analyses.

The geometry of the walls is shown in Fig. 4. The walls are 0.24 m thick and of different lengths (3.0 m, 6.0 m, 12.0 m). The reinforcement of the foundations, the horizontal and vertical ring beams and the other geometry of the walls are shown in Fig. 3.

Walls with two types of wall material properties were analysed: stiff masonry (S1) and soft masonry (S2). Soft walls have low values of modulus of elasticity and strength, while stiff walls have relatively high values. The assumed material parameters for so-called stiff and soft masonry are listed in Tab. 2. The assumed material parameters for stiff masonry are standard parameters for well-conditioned or new masonry made of clay bricks (as bricks) and single-component adhesive. The assumed basic masonry parameters for the considered orthotropy coefficient co are listed in Tab. 2. The material properties of concrete, reinforcement and contact elements used in this study are listed in Tab. 3.It is assumed that the foundations are on solid ground, with the possibility of uplifting. In addition, contact elements are used on the contact surface between the ground and foundation, in order to simulate more realistically the lifting of the foundation from the ground and the shear sliding of the foundation in relation to the ground.

The finite element discretization of the URM and CM walls is shown in Fig. 5. Due to the effectiveness of the numerical analyses, a relatively coarse mesh of finite elements was used for the wall. This has no significant impact on the conclusions of the parametric study. All nodes of finite and contact elements are free to move, only the nodes of contact elements in contact with the ground are fixed.

Table 3 Adopted basic material parameters for concrete, reinforcement and contact elements

Parameter	Concrete	Reinforcement	Contact elements
E (GPa)	30,5	210	30,5
G (GPa)	13,26	-	-
f_c (MPa)	25	560	25
f_t (MPa)	2,5	560	0

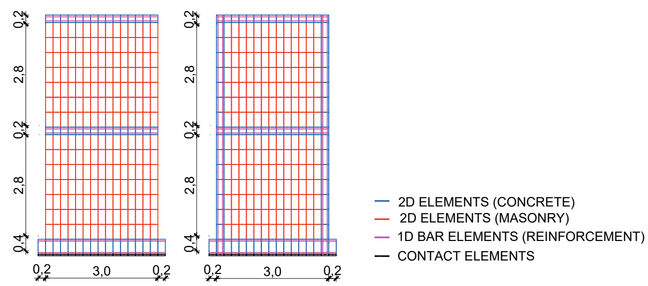


Figure 5 Finite element discretization of the walls with length of 3 m

3.2 Results

Some results of the performed parametric study of URM and CM walls are presented separately for static and dynamic loading.

3.2.1 Static analyses

In the performed static analyses the walls are firstly loaded with self - weight and constant vertical load q (q = 40 kN/m^2) and then incrementally with horizontal force F until walls failure (Fig. 4).

The ratio of ultimate load of the URM and CM walls to coefficient of orthotropy c_o is presented in Fig. 6. According to results it is evident that the ultimate load for URM walls with stiff masonry is greater than ultimate load of walls with soft masonry. It is also apparent that the longer walls have greater ultimate load than the shorter ones. The effect of orthotropy on the bearing capacity on the URM wall with soft masonry is greater than with stiff masonry.

Fig. 6 shows that the ultimate load decreases with the stiffness of the masonry. Even with a significant degree of orthotropy, the reduction in load bearing capacity is quite small compared to isotropic masonry. For walls with a coefficient of orthotropy c_o = 0.2 the reduction of ultimate load is about 10-12 %, compared to isotropic masonry (c_o = 1). The orthotropy effect of the masonry is also greater for shorter walls than for longer ones. In addition, the orthotropy effect is greater for soft masonry than for stiff masonry.

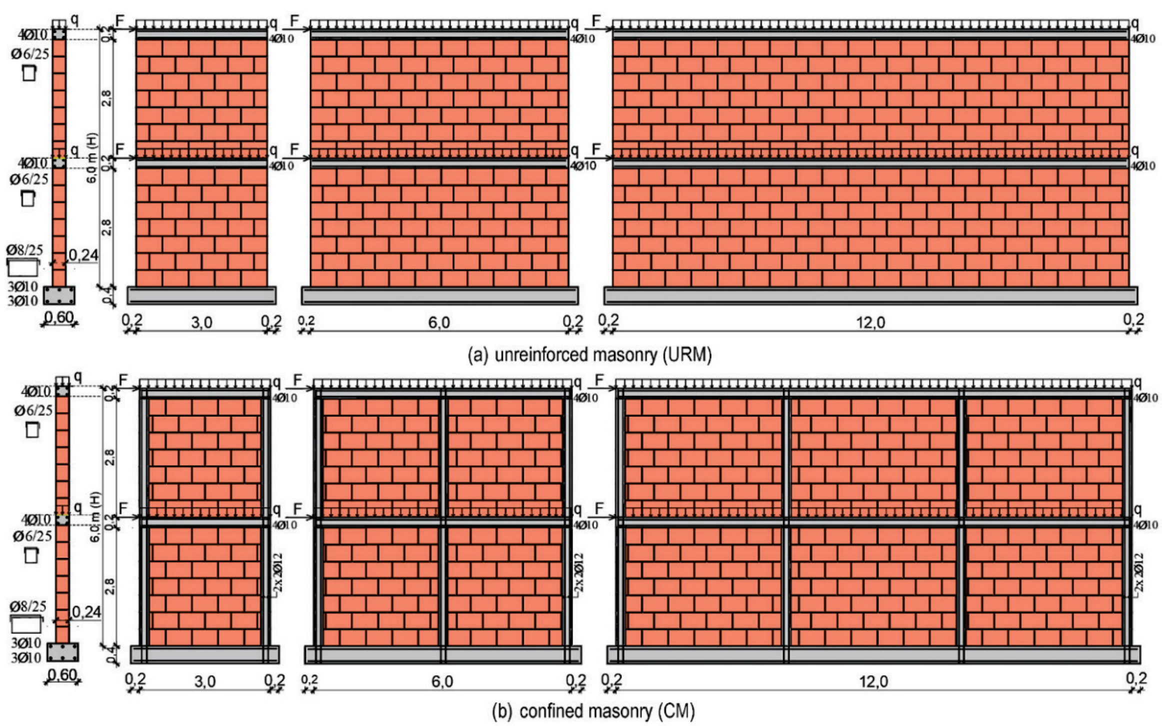


Figure 4 Geometry of considered masonry walls

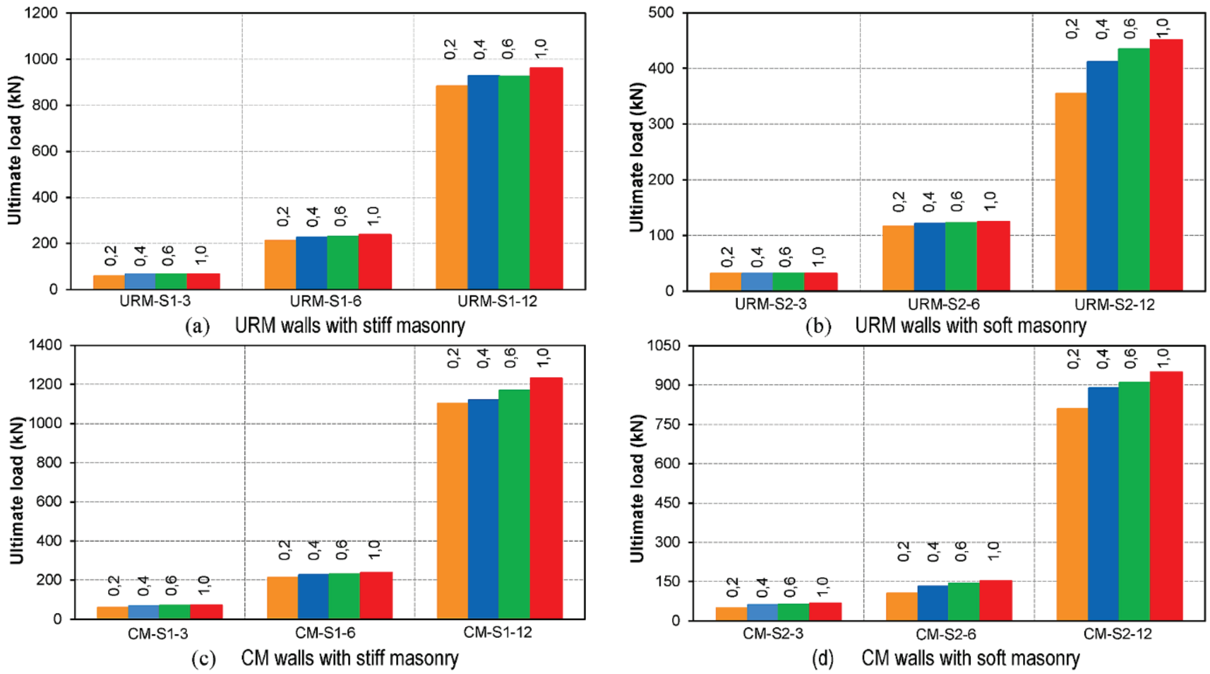


Figure 6 The ratio of ultimate load to coefficient of orthotropy c_o

The relationship between ultimate load and orthotropy coefficient c_o for CM walls is also shown in Fig. 6. Compared to URM walls, the stiffness of the masonry of CM walls has less influence on the ultimate load. Obviously, the ultimate load of the masonry is negligible, compared to the ultimate load of the horizontal and vertical concrete ring beams. It is also obvious that the CM walls have significantly smaller displacements than the URM walls.

This is to be expected, as the horizontal and vertical concrete ring beams, which form a quasi-concrete frame, make a major contribution to the overall stiffness of the wall. The effect of the orthotropy of the masonry on the displacement of CM walls is greater than for URM walls. This is due to the fact that the horizontal normal stresses in CM walls are greater than in URM walls. The effect of orthotropy is significantly greater in the shorter walls than in the longer walls because the shorter walls are more affected by shear forces (horizontal stresses) than the longer walls.

The relationship between the stresses in the masonry, in the concrete and in the reinforcement of the considered walls and the orthotropy of the masonry is analogous to the relationship between the ultimate load of the masonry and orthotropy coefficient c_o shown above.

3.2.2 Dynamic Analyses

The loading is applied in two steps, whereby in the first step the walls are loaded with the self-weight and the vertical load q, while in the second step the walls are loaded with the harmonic base excitation as shown in Fig. 7. T_1 is the first period of vibration of the elastic wall, which is initially calculated for all considered orthotropic walls. The adopted amplitude of the harmonic base excitation is 0.3g for CM walls and 0.1g for URM walls. The duration of the excitation is adapted to the stiffness of the wall and is $10 \cdot T_1$ and the total duration of the numerical analysis is $25 \cdot T_1$. In addition, a 2 % viscous damping is assumed.

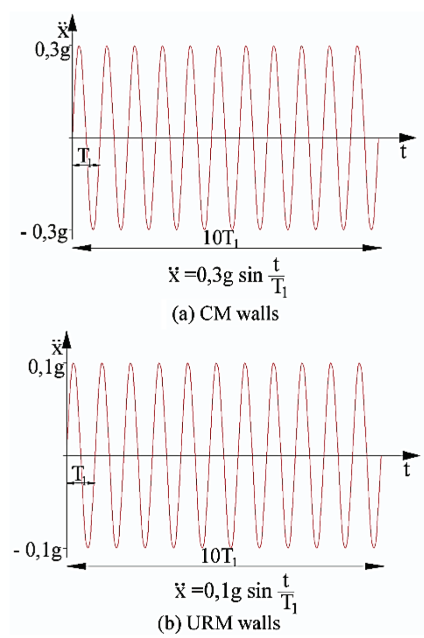


Figure 7 The adopted horizontal base excitation

Some numerical results of the dynamic analyses carried out are shown in Figs. 8-12. The horizontal displacements of the top of URM and CM walls are presented in Fig. 8. The relationship between the maximum horizontal displacement of top of the wall and the coefficient of orthotropy is presented in Fig. 9. The relationship between the maximum compressive stresses (σ_{yy}) in masonry and the coefficient of orthotropy c_o is presented in Fig. 10. The relationship between the maximum compressive stresses (σ_{yy}) in concrete and the coefficient of orthotropy c_o is presented in Fig. 11.

The relationship between the maximum tension stresses (σ_{yy}) in reinforcement and the coefficient of orthotropy c_o is presented in Fig. 12.

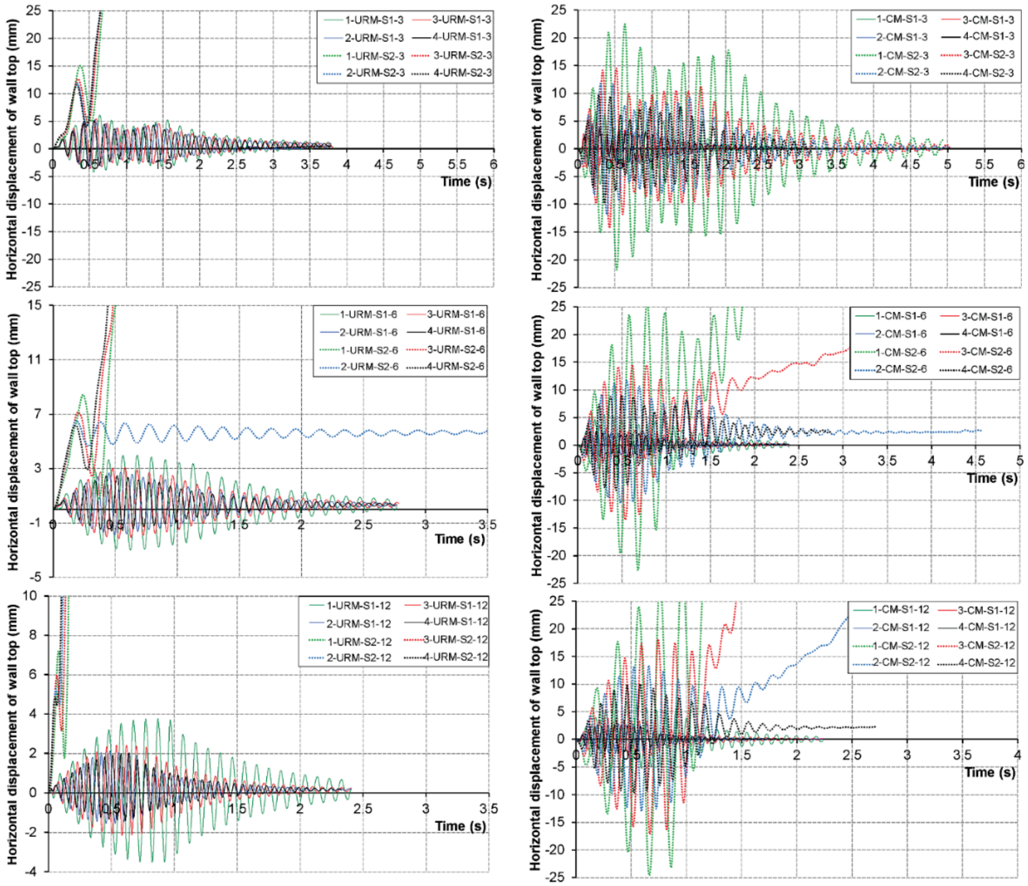
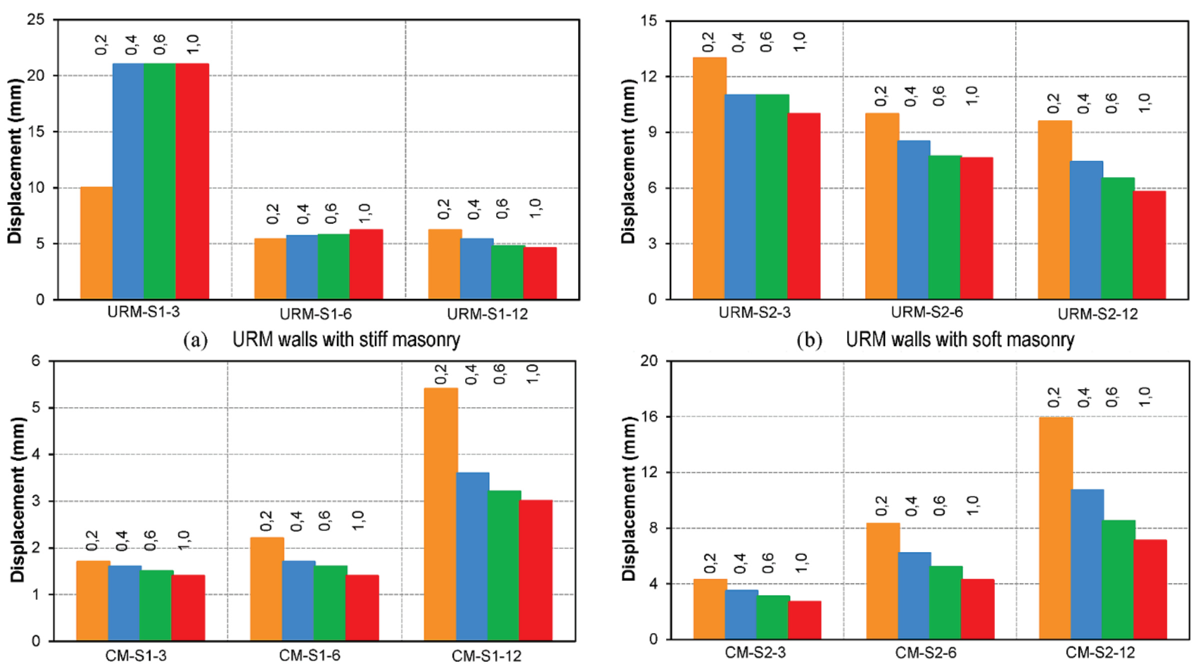


Figure 8 Horizontal displacement of the top of URM and CM walls



(a) URM walls with stiff masonry
(b) URM walls with soft masonry
(c) CM walls with stiff masonry
(d) CM walls with soft masonry

Figure 9 The ratio of maximum displacement to coefficient of orthotropy c_o

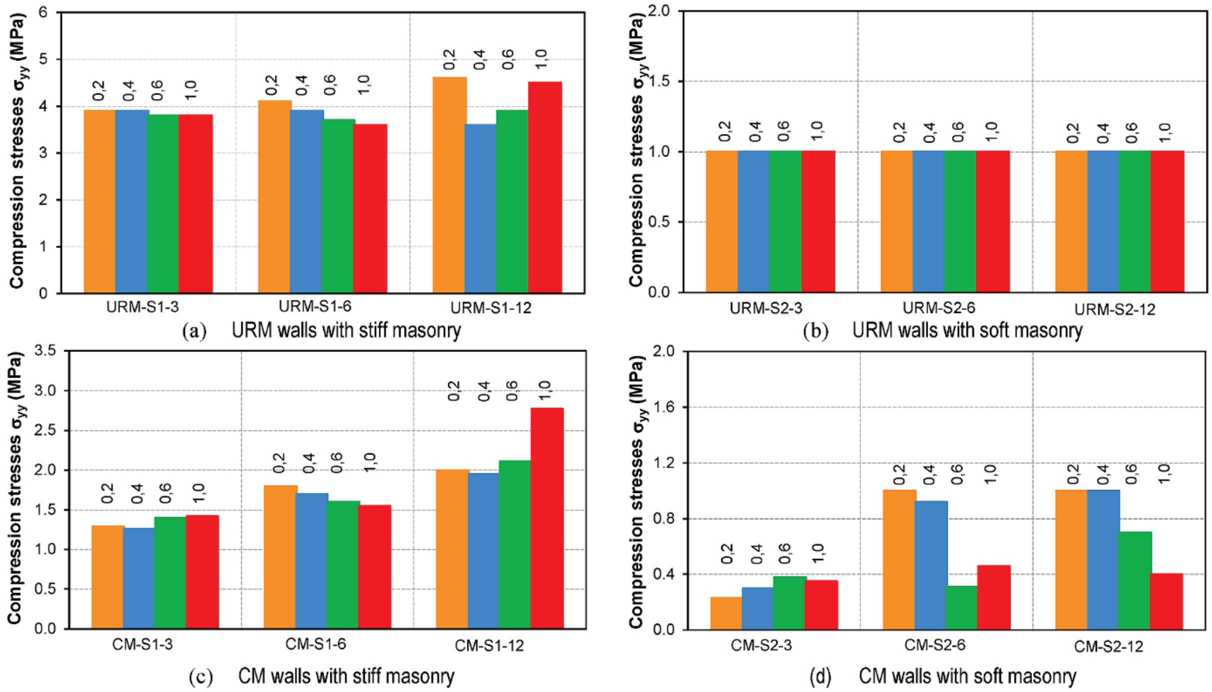


Figure 10 The ratio of maximum compressive stresses (σ_{yy}) in masonry to orthotropy coefficient c_o

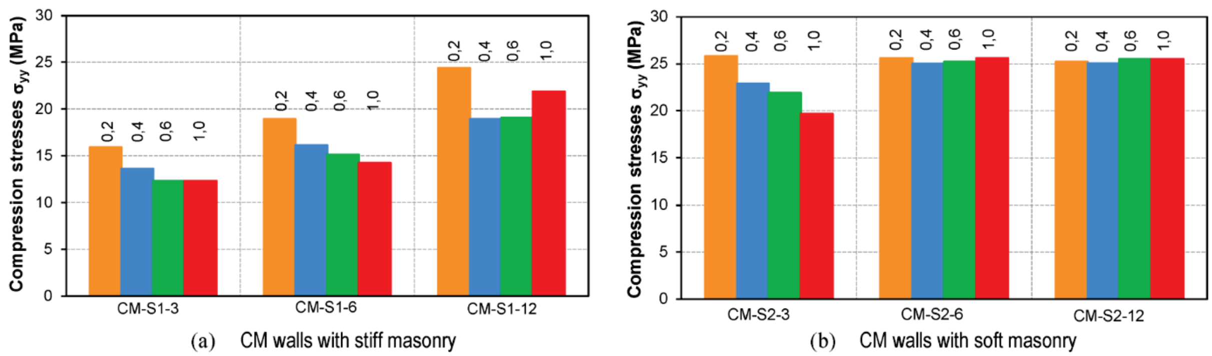


Figure 11 The ratio of maximum compression stresses (σ_{yy}) in concrete to orthotropy coefficient c_o

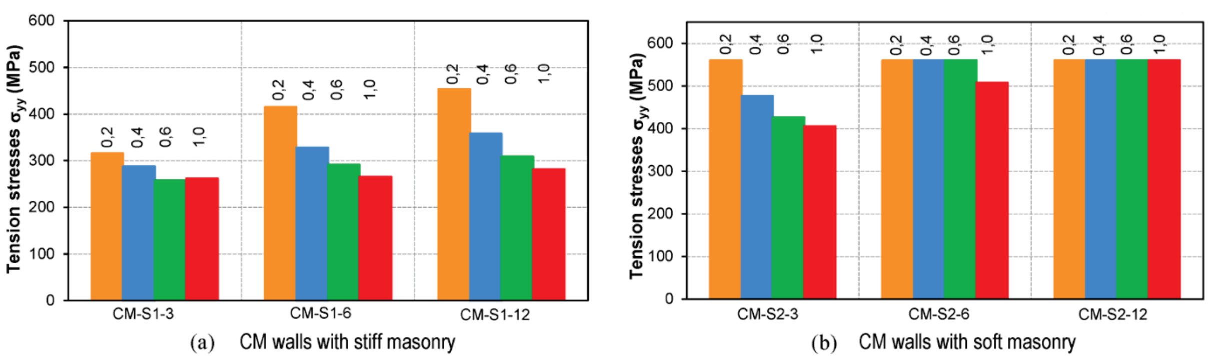


Figure 12 The ratio of between maximum tension stresses (σ_{yy}) in reinforcement to orthotropy coefficient c_o

As presented in Fig. 8-12, the displacements of the top wall, the stresses in masonry, in the concrete and in the reinforcement, as well as the ultimate load, depend on the coefficient of orthotropy c_o. With a high degree of orthotropy of the masonry (low c_o), the differences in the values of the above-mentioned parameters are greater than with isotropic masonry (c_o = 1). For the same c_o, the response of the masonry wall under dynamic loading is determined by its geometry, its type (unreinforced, confined) and the quality of the masonry (soft, stiff).

The orthotropy of the masonry also has a great influence on walls with stiff masonry, especially on longer walls. In the longer walls with soft masonry, yielding of concrete occurred in compression (the failure came through masonry). The orthotropy of the masonry has a major influence on the concrete stresses. In the longer walls with soft masonry, the steel yielded. The orthotropy of the masonry also has a strong effect on the reinforcement stresses, especially in the longer walls.

As presented in Fig. 8-12, the displacements, the stresses in masonry, concrete and reinforcement as well as the load-bearing capacity depend on the coefficient of orthotropy c_o. With a high degree of orthotropy (low c_o), the differences in the values of the above-mentioned parameters are greater compared to isotropic masonry ($c_o = 1$). For the same c_o, the behaviour of the masonry walls depends on its geometry, its type (unreinforced, encased) and its masonry quality (stiff, soft).

The effect of orthotropy on the ultimate load of masonry walls is significant, especially for confined ones. Orthotropy has a greater effect on soft masonry than on stiff masonry. Most of the URM walls failed at a harmonic base excitation with an amplitude 0,1g.

4 CONCLUSION

The numerical FE model [16] for the nonlinear static and dynamic analysis URM and CM walls under in-plane loading, which is upgraded with an orthotropic constitutive masonry model, can simulate the main material nonlinearities. However, there is still a need for further verification of the model.

The displacements and the stresses in considered URM and CM walls under static and dynamic loading, as well as ultimate load, depends on the orthotropy of the masonry. As the degree of the orthotropy increases, differences in above parameters increase in comparison to isotropic masonry. The orthotropy effect is influenced by the wall geometry, the type of the masonry wall (unreinforced, confined) and the quality of the masonry (stiff, soft). The CM walls have a greater orthotropy effect than the URM walls. The greater influence of orthotropy in CM walls compared to URM walls is explained by the additional influence of the reinforced concrete elements (horizontal and vertical beams) on their stiffness and load-bearing capacity in the horizontal direction. The orthotropy effect is greater in case of stiff masonry than soft masonry. Longer walls have a greater influence of orthotropy than shorter walls. The greater influence of orthotropy in longer walls compared to shorter walls is explained by the greater influence of shear (compared to bending) than in longer walls. The influence of the orthotropy of the masonry in the masonry walls is greater for dynamic loading (harmonic base excitation) than for static loading.

The behaviour of the orthotropic masonry walls under static loading is almost identical to that of isotropic masonry, even if there is a great degree of orthotropy. It is shown in static analyses that walls with $c_o = 0{,}2$ have approximately 10-12 % less ultimate load, than the walls with $c_o = 1{,}0$. In some cases of dynamic loading, the masonry walls with $c_o = 0{,}2$ have over 50 % less ultimate load, than walls with isotropic masonry.

This parametric study holds practical interest, because codes provide directions on evaluating the isotropic properties of masonry. In order to achieve a more realistic description of the actual complex behaviour of masonry structures, a further development of the presented numerical model is required. In this sense, it is planned to improve the numerical model by improving the simulation of different factors influencing the wall (multiaxial stress state, cyclic loading, effect of plaster, crack modelling, etc.) and developing a suitable soil model. Therefore, further numerical and experimental investigations of the behaviour of the URM and CM walls with orthotropic masonry are necessary, especially under seismic loading.

Acknowledgments

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