In-plane Behaviour of Multi-Leaf Masonry Walls Studied by Means of a Simple Rigid Block Model

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Abstract: - In this short contribution, a simplified and effective approach for studying the in-plane behaviour of multi-leaf masonry panels is proposed. Adopting an existing refined rigid block model for studying masonry panels with regular texture, which subdivides blocks into equal portions by adding new interfaces representing potential vertical cracks, the proposed approach allows for modeling two or three wall layers or leaves made of element portions having the same geometry, but with varying interface typologies and characteristics. In this way, the computational effort for studying a multi-leaf panel is limited to the post-processing phase related to interface forces determination, especially in the case of material nonlinearity. Numerical tests are performed to show the effectiveness of the approach by studying in-plane loaded masonry panels with two leaves and three leaves with rubble core.

Key-Words: - multi-leaf panels, rubble masonry, discrete element model, rigid block model, in-plane behaviour, pushover analysis.

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1 Introduction

Masonry is an ancient construction system that continues to be widely employed due to its compressive strength, aesthetic appeal, and cost-effectiveness, despite its susceptibility to damage from seismic loads, [1], [2]. Multi-leaf masonry panels are structural elements typical of historical buildings, characterized by large thickness and overall cross-section dimensions for ensuring structural strength and stability even in the case of low units and joints strength. A typical historical multi-leaf wall typology is the rubble masonry panel, characterized by external layers made of stones or bricks often arranged with a regular texture, and an inner core made of brick shards and irregular waste material connected by mortar. Current multi-leaf masonry structural elements can be characterized by an inner core with insulating properties.

The structural behavior of multi-leaf masonry walls, especially those with rubble cores, remains less thoroughly investigated compared to single-leaf or solid masonry typologies, [3]. However, the structural behaviour of this masonry typology deserves to be investigated, especially the in-plane one, since it is well-known that the best overall structural performance of masonry buildings has to favor in-plane collapse mechanisms of load-bearing walls instead of out-of-plane ones.

On one hand, several pioneering contributions, both dedicated to two-leaf walls and three-leaf walls with rubble core, mainly investigated compressive and in some cases shear behaviour with a specific focus on wall strengthening with grout injections or repointing, [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. On the other hand, research contributions can also be found dedicated to out-of-plane or, better, three-dimensional behaviour of multi-leaf masonry panels, [25], [26], some of them focusing on load-transfer mechanisms through the wall thickness, [27], [28], [29]. Numerical tools dedicated to multi-leaf masonry wall assessment, both in case of in-plane and out-of-plane actions, also with a focus on FRP strengthening, were proposed by several Italian authors, [30], [31], [32], [33], [34], [35], [36], [37].

Among the different numerical approaches proposed in literature for assessing masonry structural behaviour [38], discrete element modelling allows for a more accurate manner the contribution of joints and interfaces between stones or blocks [39], [40].

The approach proposed in this contribution starts from an existing discrete element or rigid block model [41] for studying the in-plane and out-of-plane elastic behaviour of single-leaf regular masonry. This work was extended in the field of material nonlinearity [42] and then refined by accounting for potential cracking of both mortar joints and bricks [43]. This model has been recently further upgraded considering a specific case of a multi-leaf wall, represented by a one-leaf masonry panel with external reinforcement layers, placed on both sides and over the entire panel surfaces [44].

In this contribution, the discrete model is further extended to consider generalized multi-leaf masonry walls in-plane loaded. Potentially different panel leaves can be made by bricks arranged with regular texture, but they can also be represented by a rubble material typical of historical three-leaf walls. No detachment between the leaves is assumed as a further hypothesis of the approach, whereas rigid block (or core/reinforcement) portions and elastoplastic interfaces between the portions are the main hypotheses of the model. This approach allows for minimizing the overall number of degrees of freedom of the model, since in-plane displacements are the same for all the leaves taken into consideration.

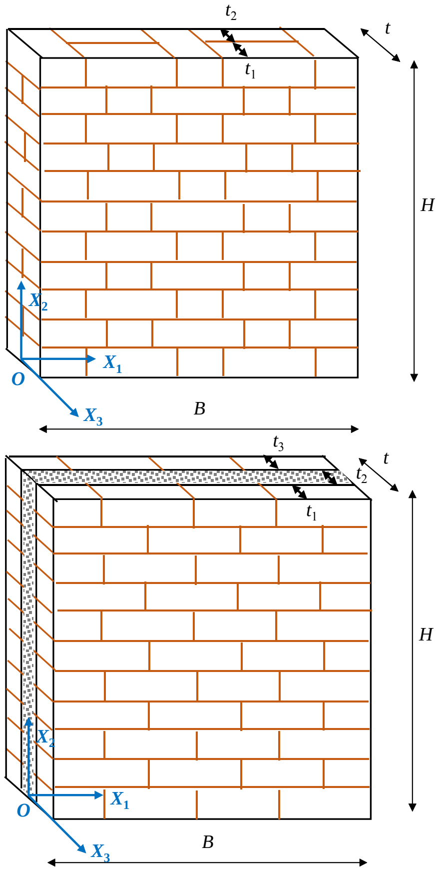

Fig. : Two-leaf masonry panel (Flemish bond case) and three-leaf masonry panel (running bond external leaves and inner core made of rubble material). *Source: created by the author*

Even if the approach represents a limited extension of existing numerical tools already proposed by the author and co-authors, this contribution is going to allow the improvement of the overall assessment of the in-plane behaviour of masonry façades taken from existing historical masonry buildings, which are typically characterized by a multi-leaf arrangement. The proposed approach will also allow the further extension of numerical tests to the field of out-of-plane behaviour.

The paper is organized as follows. The second section is dedicated to the model description and highlights the proposed computational approach. Then, the third section collects numerical tests with specimens taken from existing case studies. Finally, the fourth section is dedicated to the ending considerations and further developments of the work.

2 Rigid Block Model for Multi-Leaf Masonry Panels

A generic multi-leaf masonry wall having length B, height H, and overall thickness t is studied. For simplicity, the number of wall leaves considered in this contribution is assumed to be up to three (Figure 1). Hence, t_i with $i = 1, 2, 3$, represents the thickness of the generic layer. It is worth noting that the t_i values could not necessarily be equal. A three-dimensional coordinate system $OX_1X_2X_3$ is introduced, setting O at the bottom-left corner of the panel mid-plane, with X_1 aligned with panel length, X_2 with panel height, and X_3 with panel thickness.

The generic leaf can be made of masonry units connected by joints (Figure 2a), or can be made of a homogeneous material, such as a strengthening cementitious layer (Figure 2b) or an inner core made of brick shards meshed with mortar (Figure 2c).

2.1 Main Hypotheses and Model Kinematics

The first main hypothesis of the approach assumes the brick leaves are made of rigid blocks subdivided into equal portions. In the previous contribution by the author and co-workers, two half-block portions were proposed [44], in agreement with the approach presented in [45] with deformable quadrilateral elements. However, blocks can be subdivided into three or four portions. Then, a masonry leaf of the panel turns out to be modelled as a set of aligned rectangular or square-shaped rigid elements. Vertical interfaces between elements can be mortar (or dry) joints or inner block interfaces. Horizontal interfaces are always mortar or dry joints. Brick texture is assumed to be regular over the leaves, not necessarily coincident, but in order to have coincident block portions and coincident interface positions in the different brick leaves (Figure 3a).

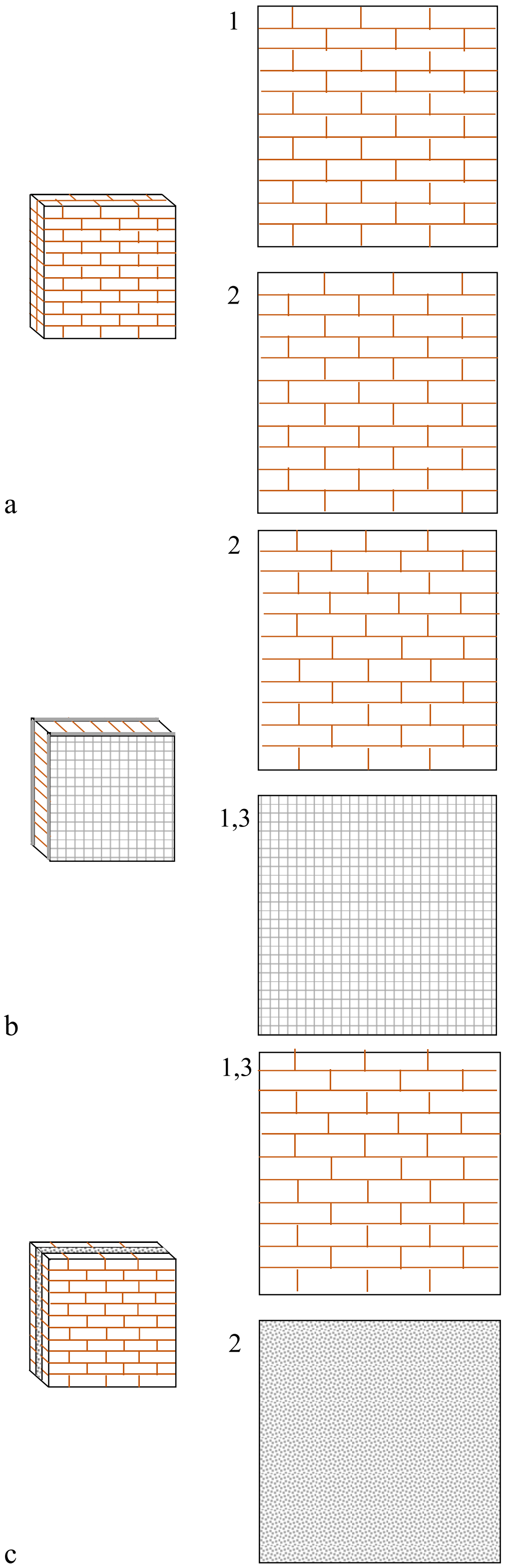

Fig. 2: Three different cases of multi-leaf masonry walls

Source: created by the author

The second main hypothesis of the approach assumes no detachment or sliding between the layers. In this manner, the geometry of the model is given by brick portion centroid positions and interface positions, which are the same for brick leaves and are extended to the potential homogeneous layers of the multi-leaf wall (Figure 3b). In this latter case, the deformability of the homogeneous material is lumped at the interface level.

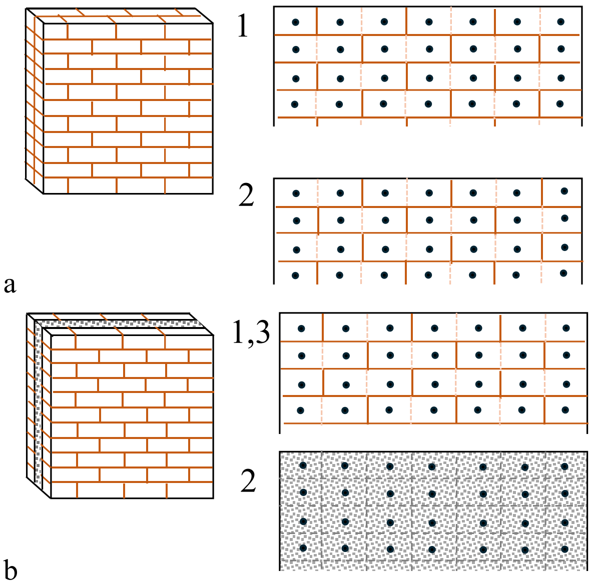

Fig. 3; Two-leaf masonry panel having leaves with different running bond texture, detail of brick subdivision into half-block portions for each layer (a). Three-leaf panel with external masonry leaves and inner core, detail of brick subdivisions for external layers and inner core discretization (b).
[Orange continuous lines = mortar (or dry) joints, orange dashed lines = inner brick potential cracks, grey dashed lines = homogeneous material subdivisions/potential cracks]

Source: created by the author

In-plane actions and displacements are considered together with the plane stress hypothesis. Then, model displacements are given by in-plane translations u_1, u_2 of the portions of the generic leaf and by the in-plane rotation ω_3 of each portion with respect to its centre. Thanks to the no-detachment hypothesis between the leaves, the overall number of degrees of freedom of the model does not increase with respect to the one-leaf case, since displacements are the same for each layer.

2.2 Interface Actions And Equilibrium

Following the approach already adopted with one-leaf panels and reinforced panels [42], [43], [44], interface actions **f** between the rigid portions of each layer depend, on one hand on relative displacements **d** between the portions, on the other hand on interface stiffness and strength. At this stage, the potentially different interface mechanical characteristics over each leaf of the panel are considered. In particular, the stiffness and strength of mortar joints are smaller than the parameters adopted for inner block interfaces, but they can be larger than the parameters chosen for simulating an inner layer typical of rubble masonry.

The actions between two generic rigid elements of each layer are normal and shear forces N, T, and a bending moment M, which depend on the relative displacements (normal, shear, rotation, respectively) between the adjacent rigid elements considered.

2.1.1 Linear Elastic Behaviour

In the elastic field, the interface force-relative displacement relationship follows a simple elastic constitutive law that accounts for the normal, shear, and bending stiffness of the interface. It is worth noting that in the case of mortar joints, stiffness values depend on the elastic parameters of mortar (elastic modulus E_m and Poisson's ratio v_m) and on interface geometry (area, inertia, and joint thickness). On the other hand, stiffness parameters for a homogeneous material, such as the inner core or a reinforcement layer, still depend on material elastic parameters (E, v), and interface dimensions. Furthermore, stiffness parameters depend on the relative distance between the centres of the elements connected by the interface, in order to account for the larger deformability of the homogeneous material with respect to thin mortar joints. Large stiffness values are finally assumed for inner brick interfaces, in order to simulate the rigid behaviour of the entire elements subdivided into two or more portions.

The sum of the forces acting at each interface for each leaf and over the entire panel must be in equilibrium with external forces. Writing the equilibrium of the multi-leaf panel in discrete form, the overall stiffness matrix turns out to be the sum of the stiffness matrices of the different leaves, which are obtained by assembling interface stiffness matrices over each leaf, pre and post-multipplied by the compatibility matrix relating interface relative displacements with the global degrees of freedom of the model, [42], [43].

2.1.2 Nonlinear Behavior

Even if different leaves are characterized by different mechanical properties, the interface nonlinear behaviour of the whole numerical model is governed in the same manner by adopting a Mohr-Coulomb yield criterion, bounded by tensile and compressive limits. Specific values of tensile strength (f_t), compressive strength (f_c), cohesion (c), friction ratio (μ), fracture energies in tension and shear (G_I, G_{II}) are assumed for each leaf of the panel. Fracture energy in compression is not considered at this stage of development of the model.

3 Numerical Tests

In this section, two numerical tests are performed to show the effectiveness of the proposed approach. Multi-leaf masonry panels subjected to in-plane gravitational loads and shear actions are considered. First, a two-leaf panel having a different block texture for each layer is studied. Then, a three-leaf panel having an inner core made of rubble material is considered.

3.1 Two-leaf Panel

A small two-leaf masonry panel is considered first. Panel overall size is taken from the specimen already studied experimentally [46], characterized by $B = H = 0.51$ m and $t = 0.25$ m, made of standard Italian bricks having size 0.25x0.12x0.55 m^3, connected by mortar joints having thickness equal to 0.01 m. The original panel was characterized by a head bond texture, with 8 rows containing 4 full bricks arranged along their thickness, hence with panel thickness coincident with block length. The proposed case study considers the panel made of two leaves with 8 rows containing 2 full bricks arranged along their length, hence with the thickness of each leaf coincident with block thickness (Figure 4).

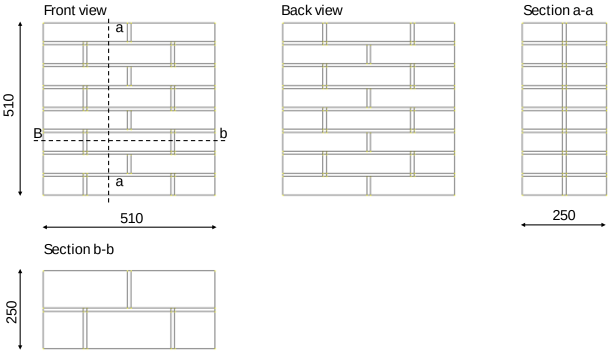

Fig. 4 Two-leaf masonry panel (dimensions in mm).
Source: created by the author

The panel is fixed at its base, and it is subjected to its self-weight and to an additional distributed vertical load on top equal to 160 kN.

Table 1 collects mechanical parameters for defining interface stiffness and strength of the model, whereas material density is assumed to be equal to 1800 kg/m^3. The numerical model is generated by subdividing each block into four equal portions, leading to 64 square-shaped elements and 112 interfaces. An increasing horizontal force at the top is applied for determining panel shear strength, which turns out to be close to 82 kN (Figure. 5).

Table 1. Mechanical parameters adopted for the interfaces (mortar joints and potential brick vertical cracks) of the two-leaf masonry wall

Parameter			
Mortar elastic modulus	E_m	1	GPa
Mortar Poisson's ratio	ν_m	0.2	-
Mortar tensile strength	f_t	0.2	MPa
Mortar cohesion	c	0.28	MPa
Mortar friction ratio	μ	0.7	-
Mortar compressive strength	f_c	4	MPa
Mortar fracture energy 1	G_I	10	N/m
Mortar fracture energy 2	G_{II}	50	N/m
Brick tensile strength	f_{tb}	1	MPa
Brick compressive strength	f_{cb}	15	MPa
Brick fracture energy 1	G_{Ib}	100	N/m
Brick fracture energy 2	G_{IIb}	1000	N/m

Source: created by the author

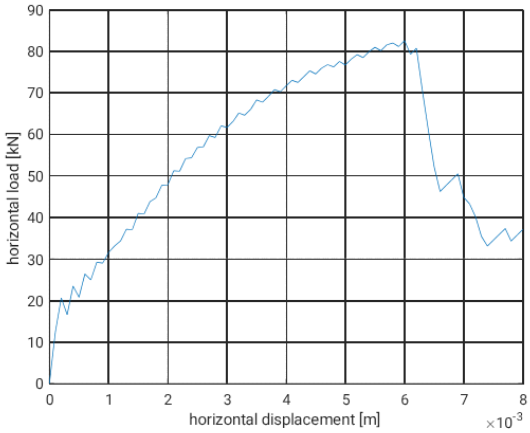

Fig. 5: Pushover curve for the two-leaf masonry panel
Source: created by the author

It is worth mentioning that the shear strength obtained with the proposed approach is in quite good agreement with the value V_u that can be obtained by applying a well-known shear failure criterion, [47]:

$$V_u = f_{tm} \, Bt / (H / B)[1 + N_{mid} / (Bt \, f_{tm})] \tag{1}$$

Which turns out to be equal to 86 kN, assuming masonry tensile strength f_{tm} as an average value between mortar and brick tensile strength (namely equal to 0.3 MPa) and considering N_{mid} as the total vertical load at panel mid height section, accounting for panel self-weight and the additional vertical load on its top.

Figure 6 shows the deformed configurations at the end of the pushover test for the two leaves, whereas Figure 7 shows the corresponding interface damage. Even if a different texture is adopted for each leaf, characterized by not aligned vertical mortar joints along wall thickness, the same crack pattern is obtained, especially with vertical cracks along the whole wall thickness involving both mortar joints and inner brick interfaces.

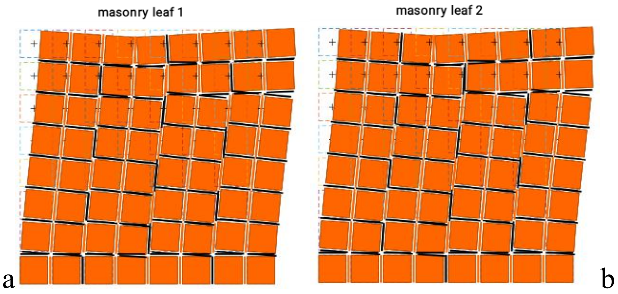

Fig. 6: Deformed configurations for the leaves of the two-leaf masonry panel
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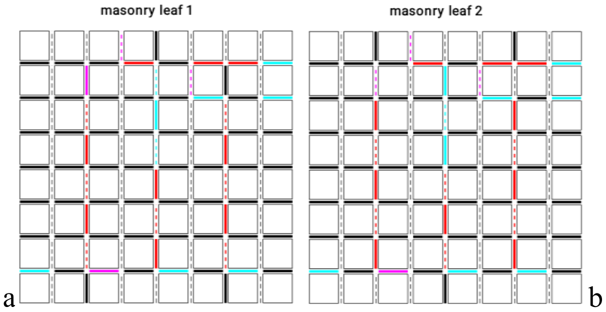

Fig. 7: Crack patterns for the leaves of the two-leaf masonry panel (failure types: cyan = tensile, red = shear, magenta = bending)
Source: created by the author

3.2 Three-leaf Panel with Rubble Inner Core

The second case study here proposed aims to reproduce a masonry wall typology typical of historical buildings, as already stated in the Introduction section, characterized by two external leaves made of blocks, and an inner core made of rubble material. In this case, an existing set of specimens already studied by means of laboratory and numerical experimental tests, [48], [49], [50], [51] is taken into consideration for the geometry and the interface typologies, whereas mechanical parameters are taken both from tests and existing literature.

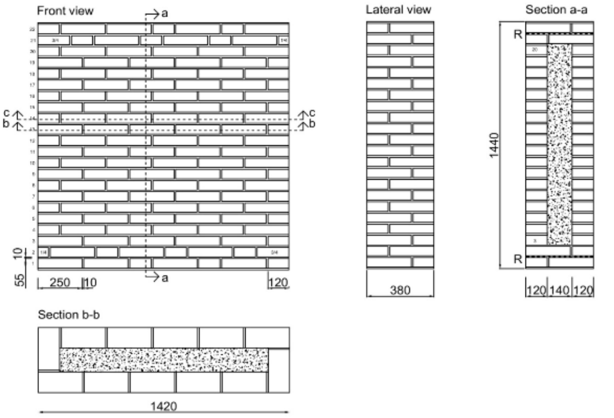

Fig. 8 Three-leaf masonry panel (dimensions in mm)
Source: created by the author

Table 2. Mechanical parameters adopted for the interfaces (mortar joints, potential brick vertical cracks, and inner core interfaces) of the three-leaf masonry wall

Parameter			
Mortar elastic modulus	E_m	1	GPa
Mortar Poisson's ratio	ν_m	0.2	-
Mortar tensile strength	f_t	0.2	MPa
Mortar cohesion	c	0.28	MPa
Mortar friction ratio	μ	0.7	-
Mortar compressive strength	f_c	10	MPa
Mortar fracture energy 1	G_I	10	N/m
Mortar fracture energy 2	G_{II}	50	N/m
Brick tensile strength	f_{tb}	1	MPa
Brick compressive strength	f_{cb}	20	MPa
Brick fracture energy 1	G_{Ib}	100	N/m
Brick fracture energy 2	G_{IIb}	1000	N/m

Source: created by the author

Panel overall dimensions are $B = H = 1.44$ m, $t = 0.38$ m. External brick leaves have the same thickness $t_1 = t_3 = 0.12$ m, which is coincident with the brick thickness. Inner core thickness is $t_2 = 0.14$ m (Figure 8). Bricks in external leaves have the same dimensions as those of the previous case study, as well as mortar joint thickness. External leaves have the same texture, with bricks arranged in a running bond pattern along their length. The panel is fixed at its base, it is subjected to its self-weight and to an additional distributed vertical load on top equal to 100 kN. Table 2 collects mechanical parameters for defining interface stiffness and strength, whereas material density is assumed to be equal to 1800 kg/m^3 for the three leaves. It is worth noting that in this case, the mechanical parameters of the interfaces of the inner core are assumed to be equal to those of mortar joints. However, the overall stiffness of the inner core layer turns out to be smaller than that of brick leaves, since stiffness parameters also account for the distance between adjacent element centres.

The numerical model is generated by subdividing each block into two equal portions, leading to 242 rectangular elements. Given that external brick leaves are coincident, a unique layer having two times the thickness of a single one is modelled, in order to reduce the overall number of interfaces, which turn out to be equal to 902.

An increasing horizontal force at the top is applied for determining panel shear strength, which turns out to be close to 250 kN (Figure 9). In this case, such a value is in quite good agreement with the corresponding one that can be obtained by applying a shear failure criterion [47], Eq (1), which is equal to equal to 267 kN, if masonry tensile strength f_{tm} is assumed as a weighted average value between mortar and brick and inner core tensile strength (namely equal to 0.4 MPa).

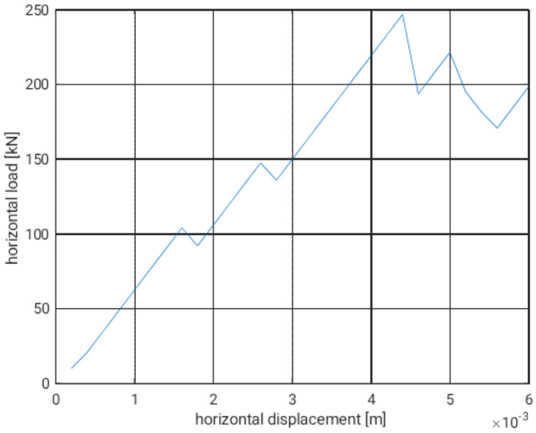

Fig. 9: Pushover curve for the three-leaf masonry panel
Source: created by the author

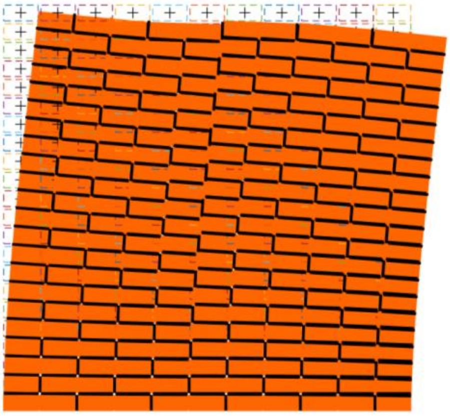

Fig. 10: Deformed configuration for the external brick leaves of the three-leaf masonry panel
Source: created by the author

Figure 10 shows the deformed configuration at the end of the pushover test for the external brick leaves, whereas Figure 11a shows the corresponding interface damage. Figure 11b shows the damage to the inner core. Due to the non-significant strength of the inner core, the same crack pattern of external leaves is obtained. In this case, due to the texture of external leaves, characterized by brick elements with a quite large length-to-height ratio, a clear diagonal crack or set of diagonal cracks is not obtained. A more diffuse shear failure of bricks and vertical mortar joints close to the central portion of the wall is observed.

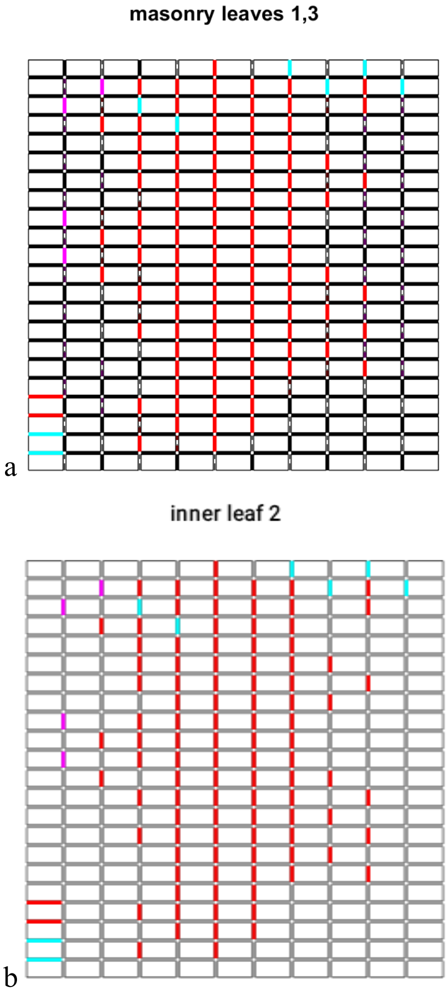

Fig. 11: Crack patterns for the leaves of the two-leaf masonry panel (failure types: cyan = tensile, red = shear, magenta = bending)

Source: created by the author

4 Conclusions

In this short contribution, a simplified and effective approach for studying the in-plane behaviour of multi-leaf masonry panels is proposed.

The model is based on an existing refined rigid block model for studying masonry panels with regular texture, which subdivides masonry bricks into equal portions by adding new interfaces representing potential vertical cracks, [43]. The proposed approach considers two and three-leaf masonry walls characterized by brick leaves with regular texture. Then, each leaf is modelled with the same geometry of rectangular or square-shaped rigid elements and horizontal and vertical interfaces. Assuming no sliding between the leaves, the overall number of degrees of freedom of the model does not increase, but the interface actions are evaluated over each leaf. In this way, the computational effort of the approach is limited to the post-processing phase related to interface forces determination, especially in case of material nonlinearity. Two numerical tests are performed to show the effectiveness of the approach by studying in-plane loaded masonry panels with two leaves and three leaves with rubble core. In the first case, the different texture of the two leaves does not influence significantly the corresponding crack pattern. This result can suggest that in case of regular texture, the specific brick arrangement of the leaves should be neglected by assuming one of the two different textures over the whole thickness of the panel. The second case study allowed to account for the presence of a weak rubble core between two brick leaves. As can be expected, the behaviour of the panel is governed by the brick leaves stronger than the core, which turns out to have the same crack pattern. In both cases, the maximum horizontal force determined during pushover tests turned out to be in quite good agreement with a well-known estimation formula, [47].

Further developments of this work will better investigate the effectiveness of the proposed approach, by comparing the results obtained with multi-leaf panels with one-leaf panels having the texture coincident with that of the first leaf, in order to evaluate differences in terms of stiffness and strength. Further case studies taken from literature will be investigated, such as three-leaf masonry panels fully made of bricks or with rubble inner core and different external brick leaves. The presence of ‘diatoni’, namely brick or reinforcing elements connecting the external leaves of a rubble masonry wall, will also be taken into consideration. Finally, the model will be further extended by considering potential sliding between the layers. This improvement will also allow to more accurately study out-of-plane loaded multi-leaf walls.

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Conflict of Interest

The author has no conflicts of interest to declare that are relevant to the content of this article.

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