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COMPUTATIONAL IMPLEMENTATION OF AN IMPROVED MASONRY PANEL ELEMENT

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Abstract

The analysis of confined masonry and infilled frames structures is very complex and highly nonlinear due to the interaction between the masonry panel and the surrounding reinforced concrete frame. The equivalent strut model can be used to represent, in a very simplified approach, the effect of the masonry wall. This model may properly represent the global stiffness and resistance of the structure but it is not able to capture local effects, such as the flexural and shear demands in the columns of the frame. On the other hand, refined finite elements models can represent in detail all aspects of the nonlinear response, but they require a high computational cost and their application to large structure can be difficult.

This paper presents a macro-model in the form of a twelve-node panel element, which internally includes six diagonal struts. The proper adjustment of the mechanical properties of the struts allows representing the global behavior of the structure and the local effects induced in the different elements of the model. In this way, different type of failure in the masonry panel and in the frame can be considered, such as the horizontal sliding failure of the masonry or the premature shear failure in the columns.

In order to facilitate the practical application of the new panel element, the model has been implemented in the open-source software OpenSees, including a precise hysteretic strain-stress relationship to represent the nonlinear axial behavior of the masonry struts in term of both stiffness and strength. The numerical results show a good agreement with experimental data available in the literature. The proposed macro-model, due to its capabilities, can be used for the analysis of large structures, such as multi-story buildings.

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Keywords: Masonry panel, Strut model, Macro-model

1. Introduction

The evaluation of the seismic performance of confined masonry and infilled reinforced concrete frame structures present significant difficulties and limitations despite the numerous efforts reported in the literature for decades. In many cases, the infill is often treated as nonstructural elements for lateral actions and is omitted in the analysis models. The uncertainly associated with the interaction of the infill and the surrounding frame, the different failure modes of the masonry, the variability of the materials components for masonry and construction methods are the principal problems to be considered for the analysis of this type of structures.

The computational modeling techniques used for the analysis of infilled frames and confined masonry structures can be divided in two categories: (i) micro-models and (ii) macro-models. The first of them is based on the precise representation of the complete masonry panel using nonlinear finite elements with different degree of refinement, ranging, for example, from refined models in which masonry units, mortar joints and unit-mortar interfaces are explicitly represented to models using a continues representation of masonry as an equivalent material Some of these models are used for Mehrabi and Shing [1], Laurenco [2], Stavridis and Shing [3], Lang and Benzoni [4]. The complexity of the constitutive models incorporated in finite element analysis, involving intensive computational effort, hinders their application in the analysis of large structures. On the other hands, macro-models make use of the concept of compression strut to provide a simple and efficient tool, able to represent the global response of the infill panel and its interaction with the surrounding frame. This concept is widely used and has many variations in the definition of the struts. Some authors as Holmes [5] and Mainstone [6] considered a single strut connecting the corners nodes along each diagonal. There are models with two struts but they are still connected to one node in the corner of the frame, Crisafulli [7]. It has been well established by Torrisi [8], Torrisi and Crisafulli [9], modelling different infilled frames and confined masonry walls with nonlinear finite elements, that the contact zone between the masonry panel and the external frame is not a node but a finite zone. In addition, the finite dimension of the contact zone introduce forces in the frame and there is a degradation of the compression zone along the diagonal panel, which changes the resistance and stiffness of the structure. Moreover, the interface conditions between the panel and the frame modifies the initial and final behavior of the wall, as is shown in Torrisi [8], Torrisi and Crisafulli [10, 11]

The aim of this paper is to present the implementation of an improved macro-model developed by Torrisi [8] in the open source software OpenSees [12]. The proposed macro-model is a twelve-node panel element, which can be used to analyze large structures, such as multi-story buildings, taking into account the different failure modes of the masonry panel, the interaction with the surrounding frame and the degradation of the struts as it is observed in real structures.

2. Description of the macro-model

The macro-model for infill panels, developed by Torrisi [8] is represented with a twelve-node element (with four nodes in each edge in order to allow the proper connection to the column macro-element) and its formulation considers six masonry struts (three in each direction), as shown in Fig. 1. It has been shown that the multi-strut formulation is able not only to estimate the lateral stiffness and the strength of the structure but also to represent the bending moment, shear and axial forces induced in the RC frame as result of the interaction with the masonry panel, Crisafulli [7], Torrisi [8].

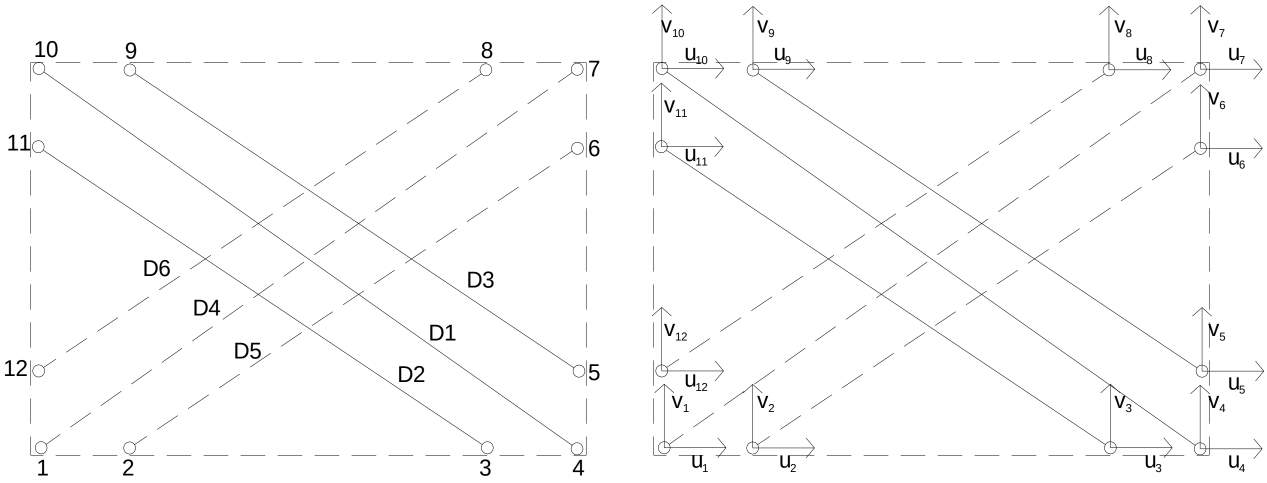


Fig. 1 – Macro-element for masonry panel: (a) nodes and struts, (b) degrees of freedom

The material used by each strut was developed by Crisafulli [7] and the envelope curve and hysteretic rule number is shown in Fig. 2. The maximum compression stress for the material model is defined by the failure theory for masonry proposed by Torrisi [8].

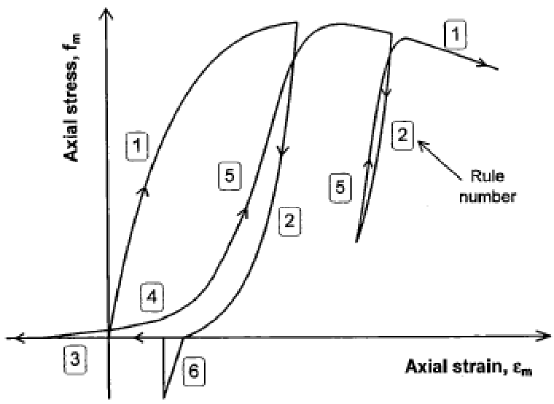


Fig. 2 – Hysteretic model used by the struts

The macro-model presented was developed taking into account the contact zones between the infill panel and the surrounding frames, as the finite element models showed [8]. Also, in confined masonry walls, the initial behavior, previous the strut behavior is monolithic due to the bond between the panel and the frame [8], [10], [11], [12], Fig. 3, this effect is considered in the model with the tension behavior of the strut. The value of tension strength can be set up as the minimum value corresponding to the tension strength of the masonry or the bond strength between the panel and the frame. This last value increases when the toothed Wall is used.

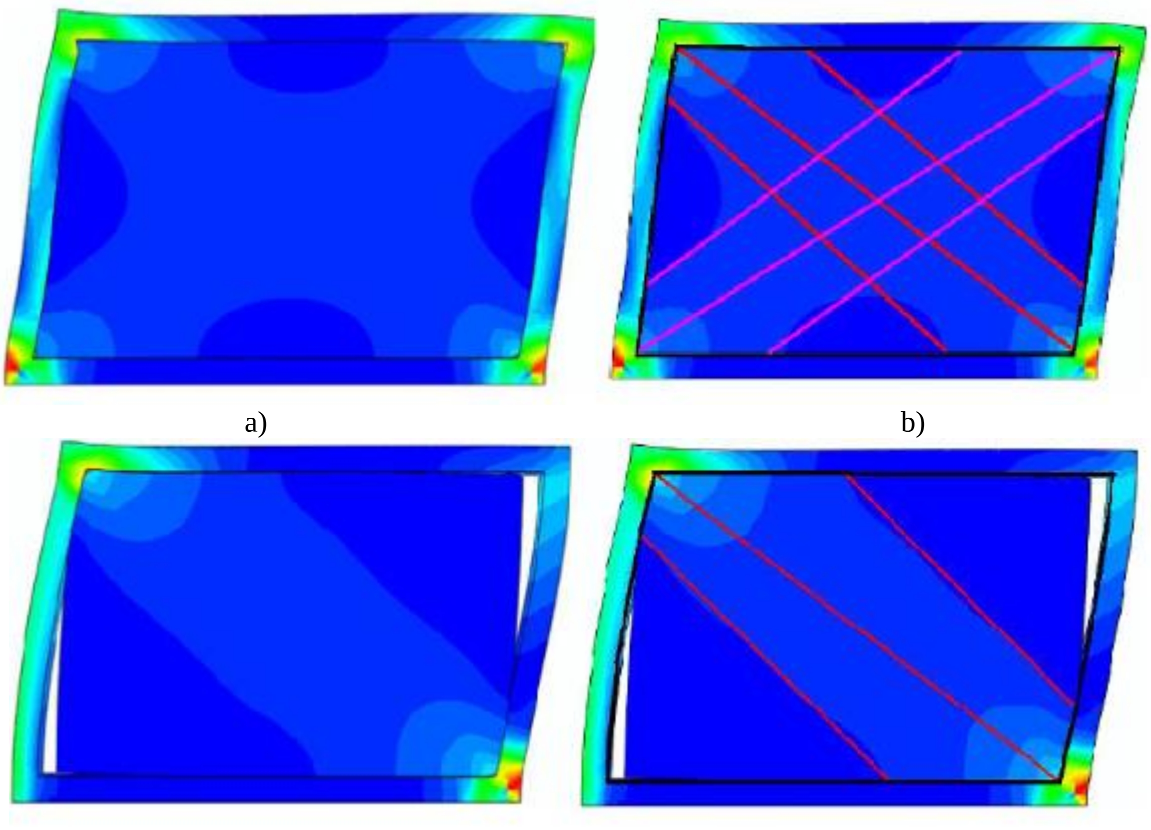


Fig. 3 – Deformed shape and Von Misses stresses in a finite element model of a confined masonry wall (a) at the initial stage, and (b) Initial stage with justification for three struts, c) after separation, d) after separation with struts [8]

Some analytical results of walls modeled with nonlinear finite elements shown that the initial compressed zone in the panel degrades as the strains increases [8], due to this effect the macro-model is able to consider the differences in degradation between the central and lateral struts. In many cases, the central strut degrades faster than the lateral strut and then, the strength and stiffness of the wall decreases. This effect is shown in Fig. 4.

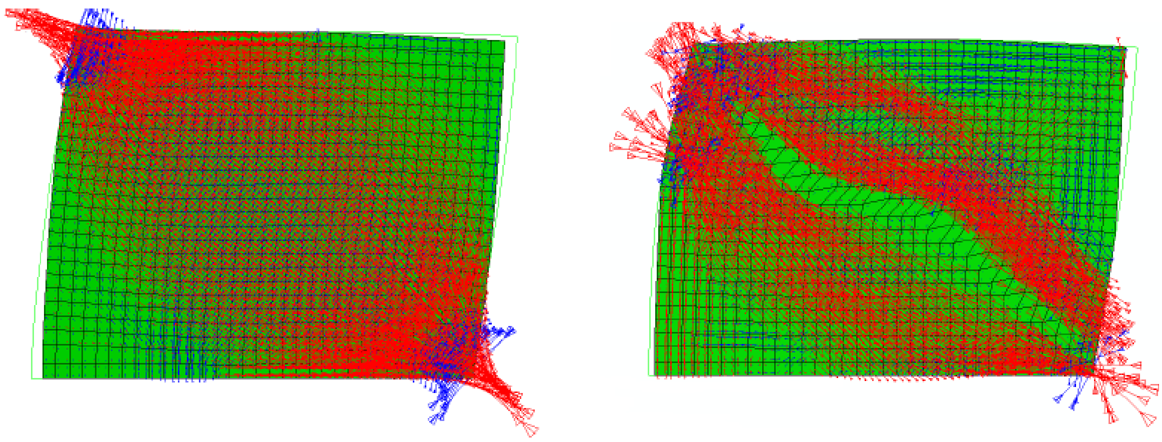


Fig. 4 – Principal stresses at (a) maximum shear and (b) post maximum point. [8]

The degradation of the struts is defined by the two values of strains, ε1 at which degradation starts, ε2, where degradation ends with and a residual value of area a2 (as percent of initial area a1). This values can be different for the central (D1 and D4) and lateral struts (D2, D3, D5 and D6), see Fig. 1.

The model was implemented into the open source software OpenSees [12] together with the material for masonry. There are two panels implemented, the 2D version for planar structures and a 2D panel for 3D structures. The definition of the panel is made with the following variables:

Element Masonrpan12 $elnum $node1…$node12 $mat1 $mat2 $th $wr $w1

Where, *$elnum* is the element number, *$node1…$node12* are the twelve nodes of the panel, *$mat1* is the material number for the central strut, *$mat2* is the material number for lateral struts, *$th* is the thickness of the panel, *$wr* is the percent of the central diagonal to define the total area of the struts and *$w1* is the percent of the total area corresponding to the central strut. The definition of the area degradation is made the material definition because the *$mat1* have the material for the central strut with the degradations characteristics for this strut and *$mat2* has the definition for lateral struts and the degradations characteristics for these struts.

A large discussion about the values for *$wr* and *$w1* and the effect on the global response is described in Torrisi [8], but typically values for *$wr* are ranging from 0.1 to 0.3 and the value range for *$w1* is from 0.3 to 0.6. The contact zone between the panel and the frame in the columns and beams id given by the position of the internal nodes of the panel (2, 3, 5, 6, 8, 9, 11and12). The length of this zone modifies the shear forces and bending moments introduced by the panel into the surrounding frame. The finite longitude of the contact zone depends of the relative stiffness of the panel and the frame and some expressions for estimating this longitude are given in Crisafulli [7] and a discussion about the effect on the global and local response is made in Torrisi [8]. Typically values used for the most of the walls ranging from 0.1 to 0.3 of the column height.

3. Comparison with experimental results

The macro-element panel was implanted into OpenSees and was tested with some experimental results. The panel element was developed to work together with a column macro-element to take into account the nonlinear beaviour of the frame due to axial, shear and flexure [8], [11], [13]. This element has not been yet implemented into OpenSees but the nonlinear beam-column element of the program is used. This element has a similar behavior, but not the same, as the macro-element column developed.

The analytical results obtained with the macro-element panel are compared with experimental results from different authors. The first results are from Aguilar and Alcocer [14] and are for the wall M01. The dimensions of the wall are shown in Fig. 5 and the results of the analytical model and experimental model are presented in Fig. 6. This model was also compared with results of the discrete element method, presented by Lang et al [15].

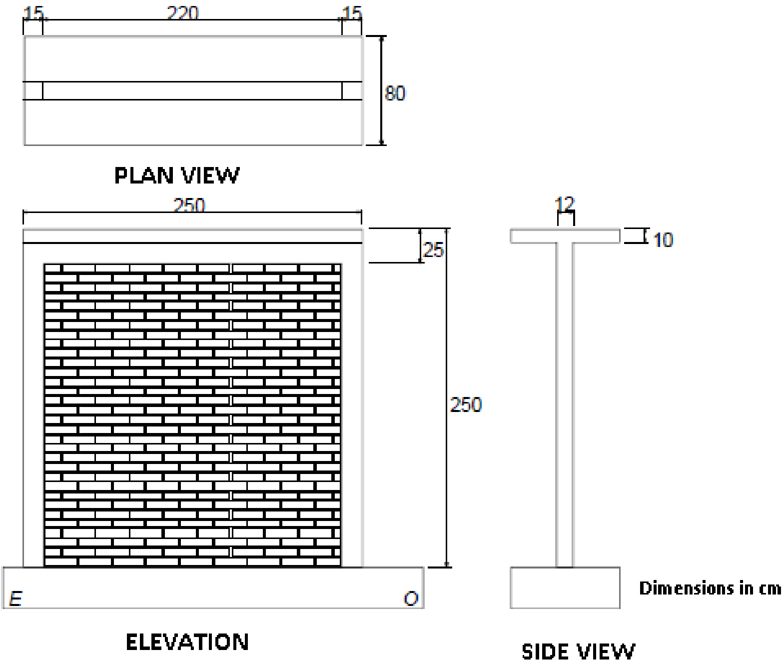


Fig. 5 – Wall M01 from Aguilar and Alcocer. [13]

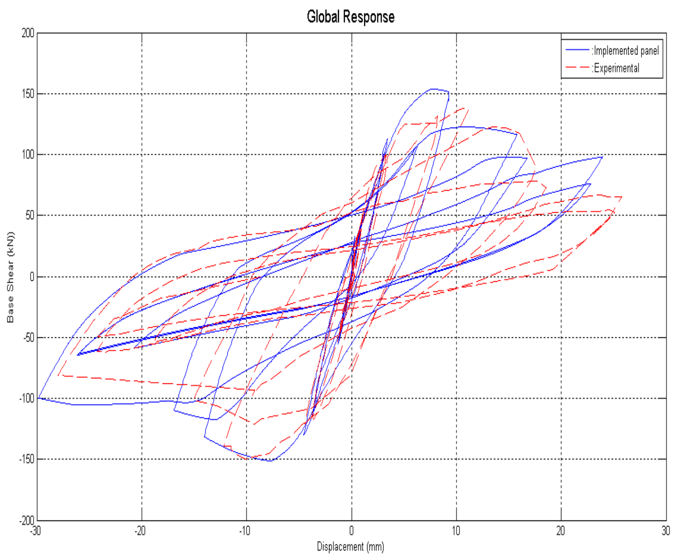


Fig. 6 – Comparison of experimental and analytical results from Wall M01 [13].

The next comparison was for the wall tested by Pires and Carvalho [16] and was denominated M2. The Fig. 7 shows the dimensions of the wall the analytical and experimental results are shown in Fig. 8.

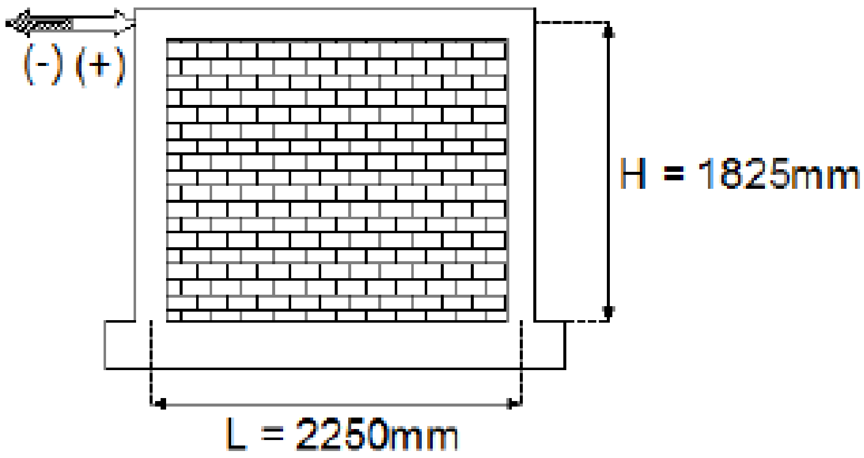


Fig. 7 – Wall M2 from Pires and Carvalho. [16]

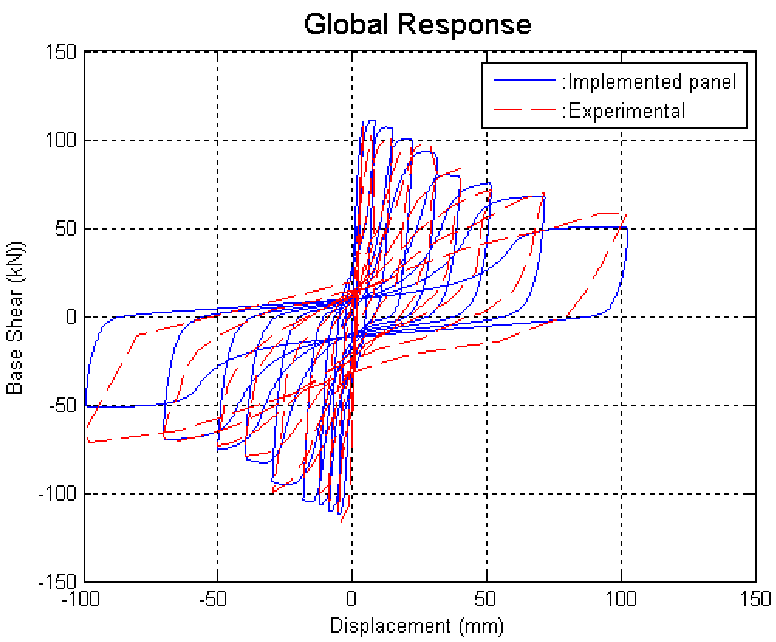


Fig. 8 – Comparison of experimental and analytical results from Wall M2 [16].

Another comparison is presented, using the experimental results obtained by Crisafulli [7] for a confined masonry wall (specimen 1). Figs. 9 and 10 show the dimensions and results for this wall, respectively. In Fig. 10a the results show a symmetric response of the model where the positive part has a good agreement but the negative part is not so accurate, but in Fig. 10b, the negative part show a good agreement in the results although the positive part has more difference in the results. This is because the analytical results are symmetric but the experimental response was not the same in the positive and negative direction due to accidental imperfections in the model. If the model is symmetric and the loading protocol is also symmetric the analytical result will be always symmetric.

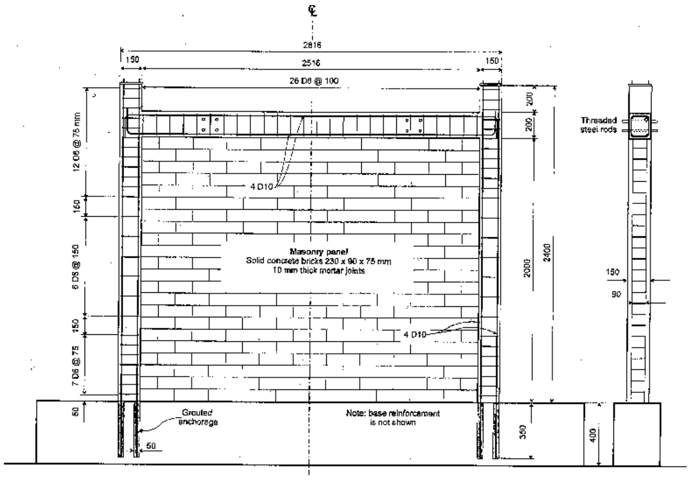
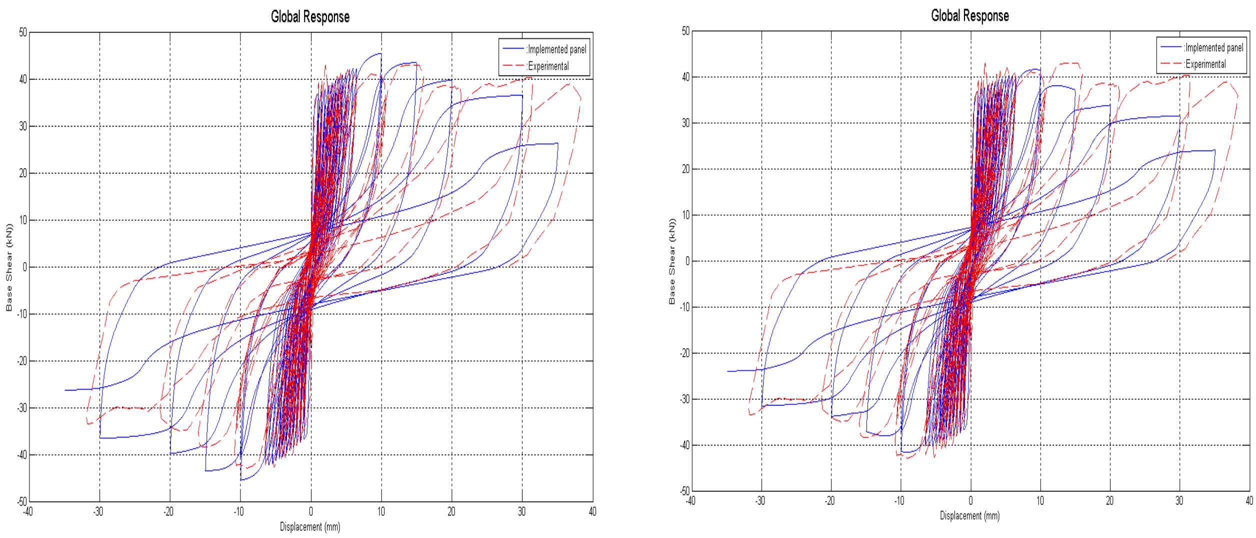


Fig. 9 – Specimen 1 from Crisafulli. [7]



a) b)

Fig. 10 – Comparison of experimental and analytical results from Specimen 1 [7].

Finally, the three story wall tested by Koutas et. al. [17] is modeled with the improved panel. The wall is shown in Fig. 11 and the results are shown in Fig. 12.

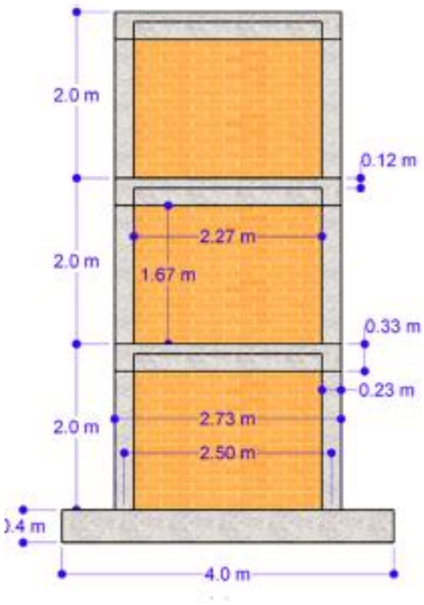


Fig. 11 – Wall U3 from Koutas et. al. [17]

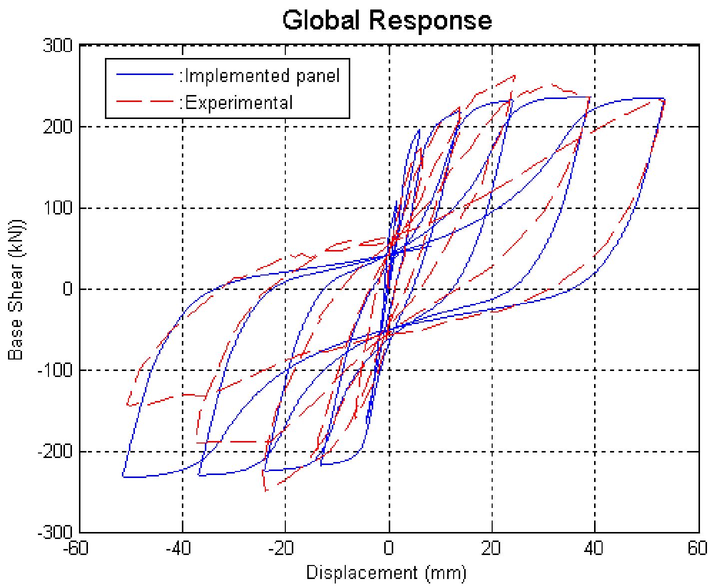


Fig. 12 – Comparison of experimental and analytical results from Wall U3 [17].

The analytical results agree very well with the experimental data in terms of maximum strength, stiffness and degradation of strength and stiffness in all the walls tested.

A resume of the principal variables used in the analysis of the models are presented in the Table 1. All the variables were previously defined.

Table 1 – Values for variables used in analysis

Model	z [m]	f'$_m$ [MPa]	E'$_m$ [MPa]	ε_1	ε2	%Area	w_r	w_1
Alcocer	0.75	1.95	728.5	0.0015	0.0035	0.50	0.650	0.25
Crisafulli	0.35	1.20	1150.0	0.0004	0.0040	0.60	0.125	0.40
Koutas	0.40	2.14	855.0	0.0005	0.0800	0.80	0.125	0.35
Pires	0.35	0.98	194.0	0.0001	0.0108	0.65	0.390	0.30

All the examples presented previously represented plane structures (two-dimensional models). However, the proposed panel-element can be also implemented in three-dimensional models.. As an example, Fig. 13 shows a simple 3D structure with two confined masonry walls along the X and Y axis, which was analyzed under dynamic load (real earthquake) in direction Y. The results, in terms of base shear vs. top displacement are shown in Fig. 14.

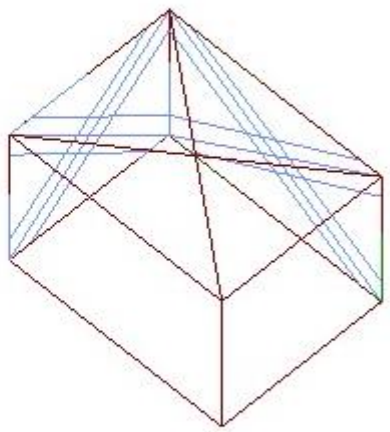


Fig. 13 – Simple 3D model

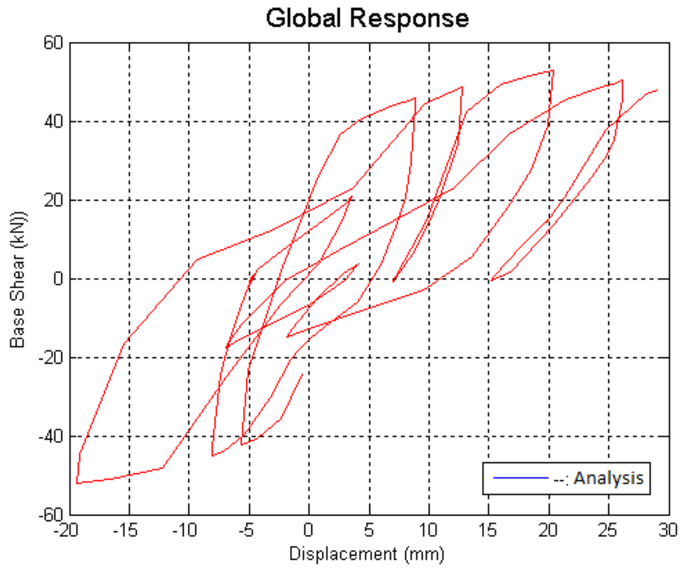


Fig. 14 – Dynamic response of 3D model.

The Base shear vs. top displacement presented in Fig. 14 shows a stable response of a 3D-model with confined masonry panels represented by the new element described previously in this paper. The total response shows an increasing envelope strength and degradation in the unloadings. The pinching effect is more visible in the last cycles and not in the initial ones.

4. Conclusions

The paper presents the implementation in OpenSees of an improved masonry panel element for the analysis of confined masonry and infilled frames. The macro-element is a six strut-twelve nodes element, which allows having different rates of degradation for the area struts and the free choice of distribution of the total area of the strut between lateral and central struts. Also, the element can represent the initial behavior of the wall and the degradation in stiffness and strength after the pick load.

The comparison with experimental results indicates that the proposed macro-model, if properly calibrated, is able to represent the complex nonlinear response of these type of structures. The macro-element can be used in 3D models, which allows the analysis of large structures, such as buildings, under static and dynamic loading.

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