Proposed multi-strut macro models for structural analysis of RC infilled frames under lateral loads

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Abstract. There is knowledge of contribution to the gain of lateral stiffness and stresses distribution in structural elements provided by infill walls in RC framed structures. The non-inclusion of masonry infills in structural model not always leads to structural safety positively. The redistribution of internal forces caused by frame-masonry interaction may submit the structural elements to high stresses not predicted in design. One of the factors for not considering the masonry infill walls in the structural model is the complex behavior of the panel-frame and the dependence of several mechanical and geometric variables of the frame structure and masonry. A simple macro model to simulate the contribution of the infill walls is by an equivalent single strut. This macro model is unable to capture properly the local effects caused by the interaction between infills with columns and beams. In this case, there is the need of macro model with multiple struts. The paper intends to compare the internal forces in columns (shear forces and bending moments) and lateral stiffness in masonry-infilled RC frames obtained from proposed multi-strut macro models. These results are compared with ones obtained from a more accurate model developed by FEM capable to take into account the friction effect and slipping between masonry and frame members.

Keywords: Infilled frames, Macro models, structural analysis, Reinforced concrete.

1 Introduction

In buildings with reinforced concrete system or steel structures, the masonry normally has the role only sealing. However, it is known that the infill walls add to strength and stiffness of the building, mainly to resistance increase to horizontal loads. Yet, despite this knowledge, the structural effect of masonry is usually disregarded. Many studies have exhibited that the infill-wall account lead to better results related to stiffness, strength and energy dissipation, compared to bare frame [1-4].

There is a consensus that the non-inclusion of walls is positive by the fact that it brings a strength reserve to building. Parsekian et al. [5] mention that the wall presence in certain positions can increase significantly the stiffness in this part, changing the strain distribution.

The masonry can be simulated in different ways, like bar element, plane or solid element. The simplest way to simulate the walls is considering them like a bar element. This kind of analysis is traditionally known as Equivalent Strut Model (ESM). The classic methods often use single diagonal strut. The major difference among these models is the diagonal width gotten with different expressions found on literature. Among classic expressions of ESM it could mention Mainstone [6], Hendry [7], Liauw and Kwan [8], Paulay and Prisley [9] and Durrani and Luo [10].

For global analysis in buildings, the use of single diagonal strut presents satisfactory results when it is taking into account the walls presence. Nevertheless is unable to capture properly the shear forces and bending moments due to frame-wall interaction. In such case, the multi-struts employment brings this possibility. The multi-struts use has been addressed in literature [11-13]. Despite knowledge about masonry influence on structural behavior, there are few standards which address this issue. In this case, normally the seismic effect is emphasized [14-17]. Most standards make use of Maistone [6] model, which some authors, it provides conservative value to diagonal strut width [18-20].

The approach on standard to a masonry-frame system is recent in Brazil. The NBR 16868:2020 [21] that unify the standards for structural masonry of clay and concrete blocks treats for the first time a suggestion of calculation approach to take the lateral stiffness in concrete frames into account. Although the studies based on wall influence in structural behavior have occurred for decades, there is still no consensus about which model is more efficient.

It is intended in this paper to evaluate the shear forces, bending moments in columns and lateral stiffness of RC infilled frames subjected to lateral forces using the proposed multi-strut macro models, for two types of infill masonry. The results are compared to a plane model using Finite Element Method (FEM), that considers the friction and slipping between the masonry and the frame by contact elements (more refined), in addition to classic macro models with single diagonal strut.

2 Methodology

The models were simulated assuming simplified linear elastic analysis, according to the NBR 6118:2014 [22] and 16868:2020 [21] requirements to take into account cracking. The Ansys v.14 software was used for plane models (FEM) and the numerical routine for plane frame calculation implemented in GNU Octave was employed for macro models.

2.1 Frames description and boundary conditions

Three infilled frames of 280 cm storey height were applied. The frame members and masonry thickness are 19 cm. The frame geometry and boundary conditions are shown in Fig. 1.

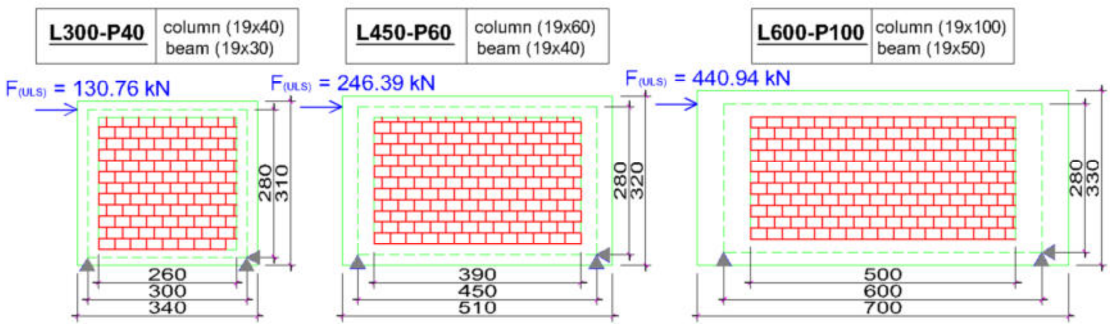

Figure 1. Infilled frames geometry and boundary conditions (dimensions in cm)

The material nonlinearity was take into account in a simplified way (NBR 6118:2014 [22] and NBR 16868:2020 [21]) for Ultimate Limit State (ULS). The secant stiffness for beams was 40% of linear-elastic flexural stiffness, whereas the secant stiffness was 80% linear-elastic flexural stiffness for columns. The masonry stiffness was reduced to 50% linear-elastic flexural stiffness.

It is assumed concrete with fck 25 MPa (beams and columns) and two masonry types. A clay masonry block with 4 MPa (more flexible) and a concrete masonry block with 12 MPa (more rigid). The Table 1 summarizes the mechanical proprieties of the materials.

Table 1. Mechanical proprieties of the materials

Material	Strength (MPa)	Modulus of elasticity for SLS (MPa)	Modulus of elasticity for ULS (MPa)	Poisson´s ratio
Concrete beams	25	24000	11200	0.20
Concrete columns	25	24000	22400	0.20
Clay prisms	2.0	1200	600	0.15
Concrete prisms	8.4	6720	3360	0.20

The applied load at the top of the frames to achieve the ULS shown in Fig 1 was found by increase of necessary load to reach the excessive deformation between floors equal to $h/850$ (h is the floor height) at Service Limit State (SLS). The assessment was made in the bare frame, including the rigid offsets modeling.

The unfavorable wind load (horizontal) for SLS must be multiplied by coefficient $\psi_2 = 0{,}3$ for quasi-permanent load combinations. For ULS, the favorable wind load is increased by $\gamma_g = 1.4$. Therefore, in a simplified way, the horizontal load to achieve the ULS is equivalent to increase the load required to reach the lateral displacement $h/850$ to $\gamma_g/\psi_2 = 1.4/0.3 = 4.67$.

The reference plane model employs mesomodeling using the PLANE182 element, besides assuming the friction effect between masonry and frame by contact element (CONTA174 and TARGE169). More details about contact element can be achieved in Silva [18].

The convergence analysis was made in plane model for the suitability of mesh size, thus the 5x5 cm mesh was appropriated. The friction assumed between masonry and structure was $\mu = 0{,}50$ (NBR 15812:2010 [23]). The cohesion factor (COHE) of 150 kN/m2 was considered for clay masonry with 4 MPa and 350 kN/m2 for concrete masonry with 12 MPa (NBR 16868:2020 [21]). The maximum shear stress (TAUMAX) was 167.5 kN/m2 for clay masonry with 4 MPa, whereas 367.5 kN/m2 for concrete masonry with 12 MPa (according to NBR 16868:2020 [21]). The normal penalty stiffness factor (FKN) was assumed the highest possible value, in order to reduce the penetration among elements.

2.2 Macro models description

Macro models with two and three diagonal struts were proposed. The position of eccentric struts was set as of the full width calculated, based on classic models of single diagonal strut. The layout for three diagonal strut models is shown in Fig. 2.

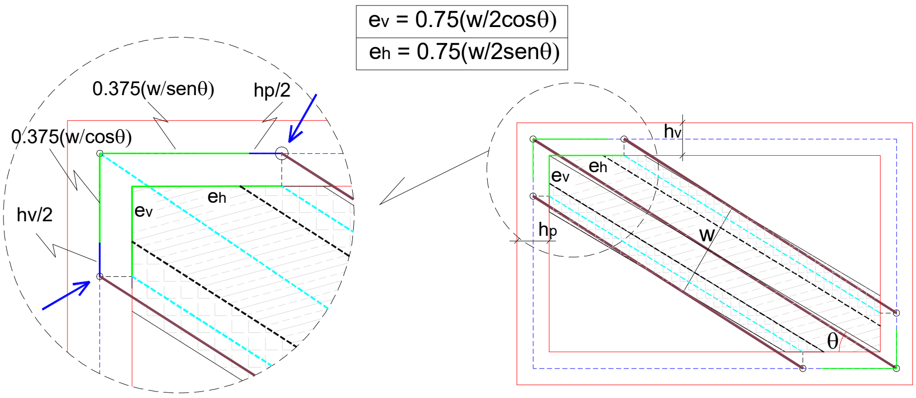

Figure 2. Position of the diagonal struts: proposed model

The parameters e_h and e_v are respectively the horizontal and vertical eccentricity (75% of contact lengths horizontal e vertical). The full width is defined by w, whereas hv and hp are beam and column height. The position of eccentric struts is transferred to structural elements axis. A traditional proposal for area division amount struts was employed: 50% of total area for central strut and 25% for eccentric struts.

For two-strut model, 50% of total area for each strut was utilized. The strut layout kept the same proposal used to three-strut model (excluding the central strut).

The NBR 16868:2020 [21] suggests the layout of compressive region of the masonry infill wall, aiming at application of resultant load for columns design. However, it does not establish clearly if for this purpose is necessary the single or multi-struts use, neither the connection point in the structure. Two layouts for strut position are presented in Fig. 3.

It was considered a single eccentric strut in the center of the compressive region (case A) and two diagonal struts in the columns at the end of compressive region (case B). The full width of diagonal struts was determined according to NBR 16868:2020 [21].

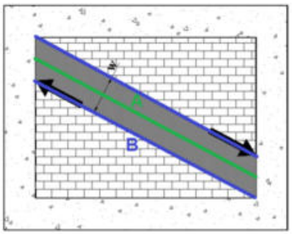

Figure 3. Layout adopted for the struts based on NBR 16868:2020 [21] suggestion

For determination of full width of diagonal struts for others macro models (single, two and three-struts), the Mainstone [6], Durrani and Luo [10] and NBR 16868:2021 [21] expressions were used. The choise of Durrani and Luo [10] method is based on the fact that some authors [18-20] show better results than Mainstone [6].

The equivalent strut width w for Mainstone [6] expression is obtained by $w = 0{,}175(\lambda H)^{-0{,}4}D$, where H is the height between beam axes (floor-to-floor height), D is the equivalent strut length. The relative stiffness λ is given by:

$$\lambda = \sqrt[4]{\frac{E_a t.sen(2\theta)}{4E_c I_p h}} \tag{1}$$

where E_a e E_c are the modulus of elasticity of masonry and concrete, t is the wall thickness. The column moment of inertia is given by I_p, h is the wall height and θ is the equivalent diagonal strut angle.

The equivalent strut width for Durrani and Luo [10] expression is obtained by $w = \gamma.sen(2\theta)D$. The non-dimensional coefficient γ is given by:

$$\gamma = 0{,}32\sqrt{sen(2\theta)}\left(\frac{H^4 E_a t}{mE_p I_p h}\right)^{-0{,}1} \quad \text{with} \quad m = 6\left(1 + \frac{6E_v I_v H}{\pi E_p I_p L}\right) \tag{2}$$

where E_p e E_v is the modulus of elastity of column and beam, respectively, I_v is the moment of inertia of beam and L is the distance between column axes.

The effective width of equivalent strut w_{ef} set by NBR 16868:2020 [21] is assumed as half of that obtained by Hendry [7] and should not be higher than a quarter of strut length D, based on Paulay and Priestley [9] expression. Hence the effective width is given by: $w_{ef} = \left(\sqrt{\alpha_H^2 + \alpha_L^2}\right)/2 \leq (D/2)$.

The parameters α_H and α_L are the vertical and horizontal contact length between frame and the masonry.

$$\alpha_H = \frac{\pi}{2}\sqrt[4]{\frac{4E_c I_p h}{E_a t_{ap}.sen(2\theta)}} \quad \text{and} \quad \alpha_L = \pi\sqrt[4]{\frac{4E_c I_v \ell}{E_a t_{ap}.sen(2\theta)}} \tag{3}$$

Finally, ℓ is the wall length and t_{ap} is twice the longitudinal walls thickness of the ungrouted hollow block or the wall thickness for brick or grouted block.

For clay masonry with 4 MPa, the longitudinal thickness of 8 mm was assumed. For the concrete masonry with 12 MPa, the longitudinal thickness of 25 mm was employed. These values are according to annex F of NBR 16868:2020 [21]).

3 Results and discussion

The maximum shear force for different macro models were compared to the maximum shear force over contact length between masonry and column supplied by plane model (FEM). The bending moment in the column base was evaluated. All evaluations were performed in left column.

Likewise, the lateral displacement obtained from macro models was compared to ones using plane model (FEM). The reading was carried out with the difference between the top and base displacement of frames, performed on the left side.

The plane model (FEM) provides axial and shear stresses. Thus the shear force and bending moment were obtained from numerical integration of stresses along the cross-sectional column. The Table 2 shows the nomenclature created for the analysis of the macro models.

Table 2. Macro models nomenclature

Model	Number of struts	Expression	Model	Number of struts	Expression
1D_M	1 strut	Mainstone	2D_N	2 struts	NBR 16868
1D_D	1 strut	Durrani and Luo	3D_M	3 struts	Mainstone
1D_N	1 strut	NBR 16868	3D_D	3 struts	Durrani and Luo
2D_M	2 struts	Mainstone	3D_N	3 struts	NBR 16868
2D_D	2 struts	Durrani and Luo	NB_1D_E	1 eccentric strut (case A)	NBR 16868
			NB_2D_P	2 struts (case B)	NBR 16868

The maximum shear force for different macro models was in relation to maximum shear force obtained by plane model (FEM). The Figure 4 shows the normalized maximum shear force provided by the different macro models.

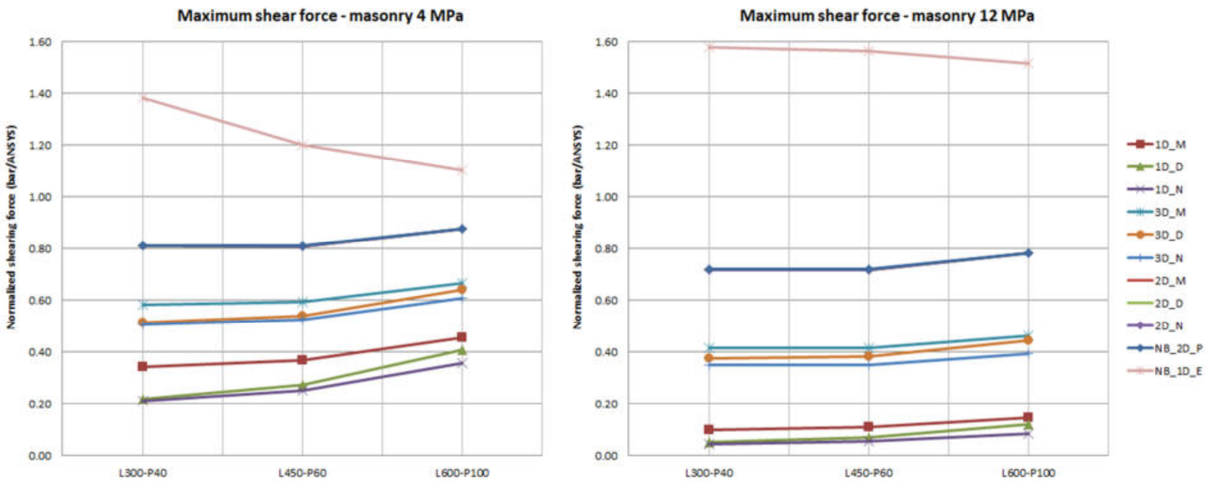

Figure 4. Normalized maximum shear force: different macro models

The results show that the classic macro models with single strut (1D_M, 1D_D and 1D_N) underestimate highly the maximum shear force over the columns compared to the others macro models.

The three-strut macro models lead to lower values for shear forces than the two-strut macro models.

Among the two-strut models, for the same frame and any expression used, the maximum shear force is virtually the same over de column. For this reason in Fig. 4, the models 2D_M, 2D_D and 2D_N are not specified, because they are covered by model NB_2D_N.

The difference among two-strut models is the length of maximum shear force. The Mainstone [6] lead to a shorter length compared to Durrani and Luo [10] and NBR 16868:2020 [21] expressions.

It was observed that two-strut models predict reasonably the maximum shear force over columns (leading to normalized shear force around 0.80 to 1.20). The increase of masonry stiffness provided slight reduction of normalized the shear forces compared to masonry more flexible.

The single eccentric strut model (NB_1D_E) was the one carried out the larger differences. For the rigid masonry, the normalized maximum shear force was clearly overestimated. As well as for the shear force, the evaluation of normalized bending moment at the column base was carried out based on plane model (FEM) as seen in Fig. 5.

The models NB_2D_P and NB_1D_E provides inappropriate values for bending moment, since they lead to the bending moment at the column much greater than reference plane model (FEM). On examining the other macro models, it is observed that choice of the expression (Mainstone [6], Durrani and Luo [10] or NBR 16868:2020 [21]) have greater influence with regard to amount of struts.

The macro models that employ the Mainstone [6] expression lead to bending moments up to 2.5 times greater compared to reference plane model (FEM).

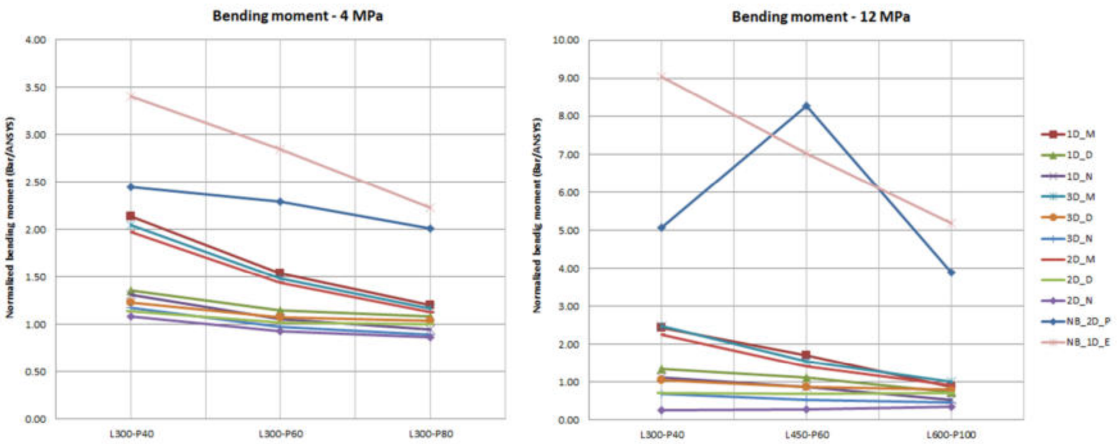

Figure 5. Normalized bending moment normalized at column base

For the flexible masonry (4MPa clay), both macro models that use Durrani and Luo [10] or NBR 16868:2020 [21] expressions present bending moment near to reference plane model (FEM). In this case, the single diagonal strut exhibit results slightly larger. The macro models with two or three-struts based to Durrani and Luo [10] expression were most suitable for masonry more rigid (12MPa concrete),

The most macro models that use Durrani and Luo [10] or NBR 16868:2020 [21] expressions present lateral displacement similar to plane model (FEM). The figure 6 shows the lateral displacement at the top of the frames regarding to different models.

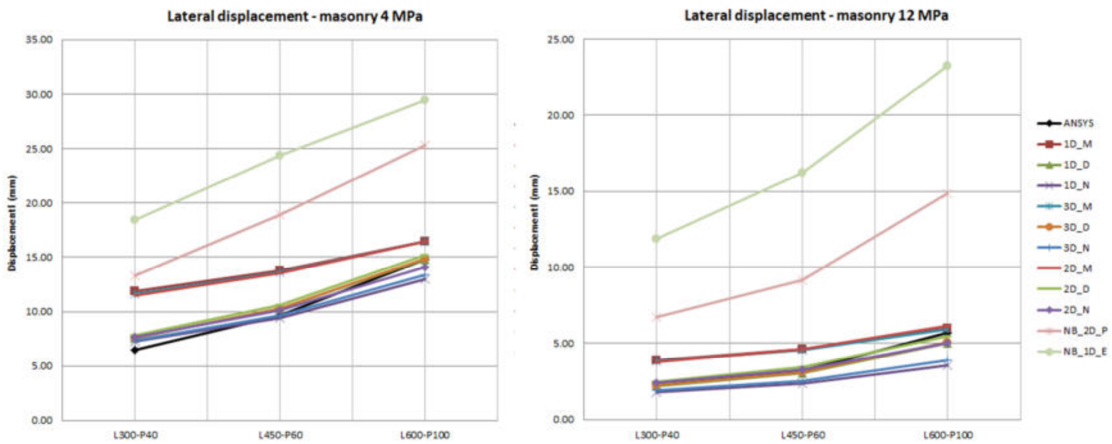

Figure 6. Lateral displacement

It is noticed that the models NB_1D_E and NB_2D_P provide displacements much higher than reference plane model (FEM). Thus these models are unsuitable for lateral stiffness analysis. The displacements obtained by the others macro models were relatively close to the plane model (FEM), there was low influence of strut numbers and masonry stiffness. The use of Mainstone [6] expression lead to more flexible infill frame model: it can be observed displacements around twice higher than reference plane model (FEM).

4 Conclusions

Shear forces and bending moments in columns were evaluated, as well as the lateral displacement in RC infilled frames. Macro models with single and multi-struts were employed and the results were compared to the reference plane model by FEM. The total area and the position of struts in the multi-strut models were established from classic models with single strut.

It was confirmed that classic single strut models underestimate the maximum shear force in columns. The shear forces of macro models with two-struts were closer to plane model related to three-struts.

The bending moment at the column base was shortly less affected by strut numbers in most cases. The choice of the expression for the calculation of total area was more relevant.

The lateral displacement of the macro models was similar to plane models (FEM). However the macro models with single eccentric strut or double struts located at the columns were few suitable for lateral stiffness assessment.

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