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Behavior of a RC infilled frame applying the classic equivalent strut macro-model

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Abstract. There is knowledge of contribution to the gain of stiffness, stress changing in structural elements and dynamic response provided by infill walls. However it is unusual to consider the masonry in frame structures because of the complex behavior of the panel-frame and the dependence of mechanical and geometric variables of the structure and masonry. A simple macro-model to simulate the contribution of the infill walls is the replacement by equivalent single struts. The most methods are applicable to particular cases. The adjustment for multi-storey buildings shall be at the charge structural designer. The purpose of this paper is to verify the lateral stiffness and dynamic response via modal analysis of a three-story reinforced concrete frame. Two classic macro-models are used which are mentioned by most standards that approach the theme. In addition to these models, a macro-model with calibrated lateral stiffness was used. Some mass arrangements between masonry and boundary beams are simulated, in order to obtain closer frequencies to the numerical model more refined. The results are compared with the more refined plane model using FEM, including the contact effect between masonry and the frame.

Keywords: infill wall, macro-models, modal analysis, reinforced concrete.

1 Introduction

In framed structures, the masonry normally has the main role in sealing and separating the compartments of the building. But, it is known that the infill walls contribute to the strength and rigidity of the building. However, despite this knowledge, the structural effect of masonry is usually disregarded. Several studies have demonstrated that the infill-wall account in structural model brings better results than bare frame, with respect to stiffness, strength e energy dissipation [1-4] and can detect unforeseen behavior in project, compared with traditional modeling (without considering walls) [5]. Evidently, by changing of stiffness characteristics of the structure, the dynamic behavior is modified when the infill masonry is included in the structural model.

In architectural designs of buildings which require slender structural elements, the infill-wall inclusion in structural model is an alternative. However, the layout changes that need to remove structural walls are not permitted. The EC8 [6] mentions several reasons for not considering the walls in the structural behavior: (a) difficulty in understanding the mechanical interaction between frames and infill; (b) mechanical characterization of the masonry; (c) the common, but not true, consensus that disregarding masonry is a more conservative posture.

In frames under horizontal actions, the simplest way to take the masonry influence into account in the structure is to consider them as diagonal struts. This model is known as Equivalent Strut Model (ESM) and is inserted within the so-called macro modeling. There are macro-models with one or more struts. Cavalieri et al. [7] point out that more reliable macro-models present difficulties, as they require a deep knowledge of the mechanical properties of materials.

Different expressions are found in the specialized literature for calculating the equivalent strut width, essential parameter for determining the strut axial stiffness that simulates the infill walls. In the international context, standards such as TEC [8], FEMA 306 [9], CSA 304 [10] and NZS 4030 [11] are some standards cases that present methodologies for the masonry consideration, aiming at resistance to seismic loads. For the equivalent strut width, most of these standards make use of the Mainstone [12] expression, which according to some authors such as Silva [13] and Montandon [14], provides conservative values for the equivalent strut width.

A new national standard for structural masonry is being developed (NBR 16868:2020 [15]) which aims to unify the masonry standards for clay and concrete blocks. In this new standard, there is a methodology for including walls in framed structures. The macro-model suggested by the standard is that of a single strut. The equivalent strut width derive from Hendry [16] expression with upper limit of Paulay and Priestley [17] proposal. The most studies on infilled frames analized single-storey frames. However, the case of multi-storey frames has the ability to better represent the structure overall behavior.

Ozturkoglu et al. [18] report that studies on infilled frames have been extensively investigated, and that studies focused on the seismic non-linear response of partially infilled frames are scarce and consist of the analysis of single-storey, single-bay frame.

One of the simplest ways to represent the influence of walls on dynamic behavior is by using the equivalent pin-jointed diagonal strut. Various studies with an emphasis on dynamic analysis usually adopt this type of model [5, 19, 20]. However, it is emphasized the importance that the model considers the strut contribution only to the compression; therefore, the simplest model must consist of two cross-struts, in such a way that only compression is activated.

The dynamic response of framed structures, when performed, normally the masonry contributes only to the total mass of the storey, in other words, its stiffness in the dynamic performance is not considered. This simplification can lead to different modes of vibration and natural frequencies than the real ones.

Aiming to assist in discussions about macro-models, it is intended to assess lateral stiffness and dynamic response, through modal analysis, in a three-storey frame, considering the presence of infill masonry. It is intended to verify the suitability of these models for dynamic analysis.

The results of the equivalent strut model (ESM) will be compared with the results obtained by plane model using Finite Element Method (FEM), which is able to consider the interaction and friction between the masonry and the frame, contemplating the contact problem.

2 Methodology

The lateral stiffness and natural frequencies obtained by plane model (FEM) were considered as reference values and these data were compared to the results provided by the ESM models. The Ansys v.14 software was used for analysis by FEM.

2.1 Frame description

The structure consists of a three-storey reinforced concrete frame, filled with clay masonry without openings. The thickness of all structural elements (beam and column) and infill masonry are equal to 19 cm. The frame geometry and boundary conditions are show in Fig. 1.

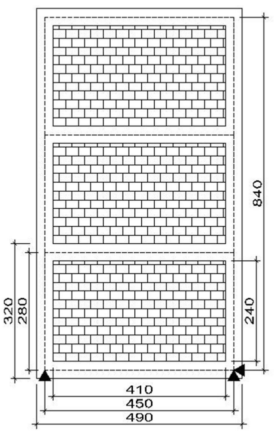

Figure 1. Frame geometry and boundary conditions

For concrete structural elements, the following values were assumed: compressive strength fck = 20 MPa, modulus of elasticity Ec = 25000 MPa [21] and Poisson coefficient ν = 0.20. Clay masonry block has a compressive strength of 1.5 MPa. Prism/block efficiency factor = 0.5 [22] was assumed. From this value, modulus of elasticity of masonry Ea = 450 MPa was obtained. The masonry Poisson coefficient was ν = 0.15. The concrete density was assumed as 2500 kg/m3 [21] and the masonry was 1400 kg/m3 [15] in all models.

2.2 ESM and plane model description

The Mainstone [12] expression is one of the most used in the literature and adopted by most standards that address methodologies for the consideration of walls. However, this expression provides conservative values for the strut width [13, 14] in relation to others found in the bibliography.

The equivalent strut width w for this model is represented by:

$$w = 0{,}175(\lambda H)^{-0{,}4} D \quad (1)$$

Where λ is the relative stiffness, H is height between beam axes (floor-to-floor distance) and D is the equivalent strut length. The relative stiffness λ is given by:

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

Where t is the wall thickness, I_p is the column moment of inertia, h is the wall height and θ is the equivalent strut angle with respect to horizontal axis.

The classic macro-model presented by Brazilian code NBR 16868:2020 [15] is based on CSA 304 standard [10]. In this model, the effective width of equivalent strut w_{ef} is assumed as half of that obtained by Hendry [16] equation and should not be longer than a quarter of strut length D, based on Paulay e Priestley [17] proposal. So effective width predicted on the NBR 16868:2020 [15] is given by:

$$w_{ef} = \frac{\sqrt{\alpha_H^2 + \alpha_L^2}}{2} \leq \frac{D}{4} \quad (3)$$

The factors α_H e α_L represent the vertical and horizontal contact length between the frame and the masonry.

$$\alpha_H = \frac{\pi}{2}\sqrt[4]{\frac{4E_c I_p h}{E_a t_{ap}.sen(2\theta)}} \quad (4)$$

$$\alpha_L = \pi\sqrt[4]{\frac{4E_c I_v \ell}{E_a t_{ap}.sen(2\theta)}} \quad (5)$$

Where I_v is the moment of inertia of the beam, 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.

Most methods that employ the ESM with single strut, consider the strut positioned at the beam-to-column connections (corners). To design the frame columns, the code NBR 16868:2020 [15] suggests the strut positioning on the columns outside beam-column joint region to account the additional shear force due the contact with infill wall. However, the standard does not provide the exact strut position. In this paper, it was considered the strut positioning on the columns at an equivalent distance to half the length w/cosθ. In addition, models were also analyzed with the traditional strut positioning (ordinary way), at the beam-to-column connections, as well as in studies developed by Medeiros at al. [23] and Queiroz [24].

The Fig. 2 represents the plane model (FEM) and ESM with concentric and eccentric single strut, applying to infilled frame in study.

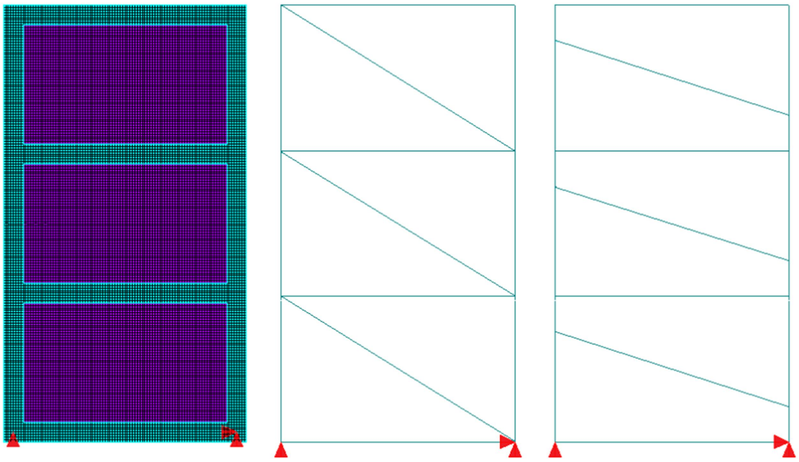

Figure 2. Plane model and ESM with concentric and eccentric single strut

The reference plane model uses mesomodeling techniques, employing the PLANE182 element for beams, columns and walls, besides considering the friction effect between masonry and frame by contact element (CONTA172 and TARGE169). More details on the discussion about contact problem can be found in Silva [13], Montandon [14] and Queiroz [24].

On bar models were applied the BEAM3 element (2-D elastic beam, 3 DOF) for beams and columns, whereas the element LINK10 (3-D spar element, Tension-only or compression-only spar) was used for diagonal struts. The LINK10 element was activated to compression-only.

A convergence analysis was carried out on the FEM model with a view to the suitability of the mesh size adopted for the plane model. The convergence analysis was made through static analysis. In this case, the 5x5 cm mesh was appropriated.

On FEM model, the friction between masonry and structure was $\mu = 0{,}70$ (value suggested by FEMA 306 [9]). A cohesion factor (COHE) of 18750 N/m2 was considered (concerning masonry shear strength) and maximum shear stress (TAUMAX) of 76000 N/m2.

The stiffness of rigid offsets was calibrated from static analysis such that the lateral bare frame stiffness was the same in plane model. In the case analyzed the rigid offsets height amount to 20.5% interstory height and frame width.

It was tested a bar model with calibrated stiffness (Model A), whose strut width of the infilled frame achieved lateral stiffness equivalent to plane model. The lateral stiffness of the infilled frame by plane model (FEM) was assessed through static horizontal force at top of the structure. The lateral stiffness obtained was 6.48 kN/mm.

Considering that the masonry is supported on the beams, thus, a more approximate way of mass distribution of the walls is to consider part of its mass on the compression strut and the portion of the masonry outside the strut on the beams. For this proposal, cases were simulated adopting the model with two cross-struts, considering the mass outside the strut area distributed over the frame beams (Fig. 3).

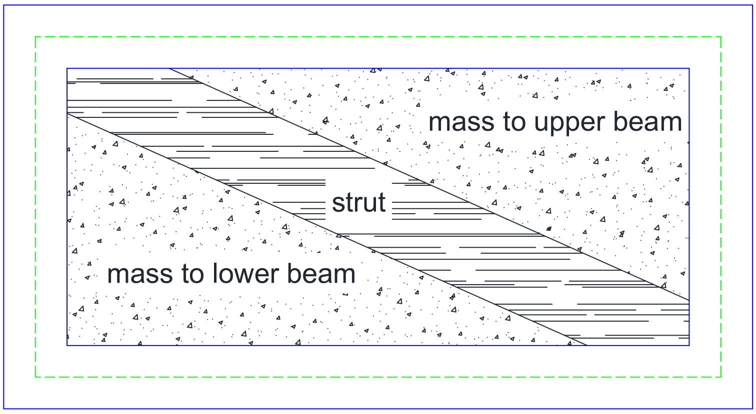

Figure 3. Mass distribution of masonry to the frame beams

3 Simulations and discussions

3.1 Bare frame

Natural frequencies obtained by plane model (FEM) were considered as reference values and these were compared with bar models results. The initial assessments between the plane model and bar models were carried out using the bare frame (without infill walls).

The first three vibration modes were analyzed related to bend shape (horizontal displacements).

This kind of simulation aimed to calibrate the results among models (plane model and bar model). Not putting frame-infill sliding and stress effects, the stiffness and natural frequencies should be very close. In this context, the rigid offsets influence was also assessed. The frequencies obtained in these models were compared to reference plane model. The results are shown in Tab. 1.

Table 1. Modal analysis in bare frame

	FEM Model	Model VZ-N		Model VZ-R	
Mode	Freq. (Hz)	Freq. (Hz)	*Dif.*	Freq. (Hz)	*Dif.*
1	5,240	4,993	*4,71%*	5,231	*0,17%*
2	18,042	17,274	*4,26%*	18,125	*-0,46%*
3	35,407	33,942	*4,14%*	35,893	*-1,37%*

The Model VZ-N refers to the bare frame model without rigid offsets, while the Model VZ-R considers the rigid offsets in the frame.

The first three modes frequencies were similar for all models. The model with rigid offsets was carried the smallest differences compared with model plane. Thus, the modal analyses considering the presence of masonry were carried out using Model VZ-R.

3.2 Infilled frame

The assessment of mass arrangement influence between struts and beams was carried out in model with calibrated strut (Model A). The Table 2 presents the results of the modal analysis considering the mass arrangement between struts and beams. The first three vibration modes were assessed, associated to bend shape with horizontal displacement.

Table 2. Modal analysis in infilled frame considering the mass arrangement

	FEM Model	Model A1		Model A2		Model A3	
Mode	Freq. (Hz)	Freq. (Hz)	*Dif.*	Freq. (Hz)	*Dif.*	Freq. (Hz)	*Dif.*
1	7,956	6,741	*15,27%*	6,924	*12,97%*	7,416	*6,79%*
2	24,828	21,862	*11,95%*	21,930	*11,67%*	21,446	*13,62%*
3	45,221	40,120	*11,28%*	34,838	*22,96%*	24,170	*46,55%*

The Model A1 considered the whole masonry mass spread over the struts. The Model A2 adopted part of masonry mass equivalent to strut area spread over the struts. The parts out of struts were spread over between the upper and lower beams. The Model A3 counted a minimal masonry mass for struts and the masonry mass was spread over the lower beams.

For the first two modes, the change in the masonry mass distribution did not bring significant difference in natural frequencies for ESM regarding the plane model. For first mode, the Model A3 was closer to plane model, however to the other frequencies, it was the model with the greatest percentage differences compared with plane model. On the whole, the Model A1 and Model A2 reached similar results for first two modes, for third mode, the Model A1 was closer than plane model.

Regarding that first vibration modes are of greater importance, further investigations were performed with Mainstone [12] and NBR 16868:2020 [15] models, adopting the masonry mass distribution used in A3.

The strut width obtained by the NBR 16868:2020 [15] model is 118.77 cm, whose lateral rigidity of the frame adopting the struts at the corners is 6.88 kN/mm (stiffness 6.17% higher than plane model). For eccentric struts, the lateral stiffness decrease to 4.48 kN/mm (stiffness 30.86% less than plane model). The Mainstone [12] model supplies a strut width of 61.99 cm and lateral stiffness of 4.98 kN/mm (stiffness 23.15% less than plane model). The Table 3 presents the natural frequencies in analyzed models.

Table 3. Modal analysis of the infilled frame using ESM

	FEM Model	Model B3		Model C3		Model D3	
Mode	Freq. (Hz)	Freq. (Hz)	*Dif.*	Freq. (Hz)	*Dif.*	Freq. (Hz)	*Dif.*
1	7,956	6,277	*21,10%*	7,737	*2,75%*	*5,938*	*25,36%*
2	24,828	19,418	*21,79%*	21,447	*13,62%*	*19,041*	*23,31%*
3	45,221	24,168	*46,56%*	24,171	*46,55%*	*25,080*	*44,54%*

The Model B3 represents the Mainstone [12] model with two cross-struts. The Model C3 refers to NBR 16868:2020 [15] model with two cross-struts and concentric struts, while the Model D3 employs eccentric struts.

The Model C3 achieved frequencies nearer to the plane model when compared to models with eccentric strut (D3) and that uses Mainstone [12] expression (B3).

When observing the first three vibration modes, the Model C3 leaded to the best results. The strut position out of beam-to-column joint region did not achieve satisfactory results to natural frequencies prediction.

Although the eccentric strut methodology is recommended by NBR 16868:2020 [15] to consider the additional shear force on the columns due to the contact with infill wall, it was less suitable to modal assessment conducted.

It is suggested to carry out studies on the proposal model by NBR 16868:2020 [15], considering different eccentricities for the strut position. This methodology aims a model that leads suitable results to predict the internal forces for all members (that it was not realized in this research), in addition to providing good results in the assessment of dynamic behavior.

4 Conclusions

A three-storey frame in reinforced concrete filled with ceramic masonry was simulated. The study aimed in assessment the lateral stiffness and dynamic response (modal analysis). Classic macro-models were employed and the findings were compared to plane model more detailed by Finite Element Method (FEM).

The importance of considering the rigid offsets was confirmed through bare frame. The mass distribution influence of the wall inside in the infilled frame exhibited low interference for first and second vibration modes, in contrast there was some influence for third mode.

Among classic macro-models evaluated, the proposal method by Brazilian code for structural masonry with concentric struts conducted to the lateral stiffness closer than plane model, as well as natural frequencies more similar to reference FEM model.

The eccentric strut used did not produce adequate results. Since this model type is appropriated to obtain the additional shearing force in the columns due to contact with masonry, it is intended to continue the researches, aimed satisfactory results in static and dynamic analysis.

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References

[1] C. V. R. Murty and S. K. Jain, "Beneficial influence of masonry infill walls on seismic performance of RC frame buildings". In: Proceedings, *12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 2000.

[2] P. B. Shing and A. B. Mehrabi, “Behaviour and analysis of masonry-infilled frames”. *Progress in Structural Engineering and Materials*, vol. 4, n. 3, pp. 320-331, 2002.
[3] G. Uva, D. Raffaele, F. Porco and A. Fiore, “On the role of equivalent strut models in the seismic assessment of infilled RC buildings”. *Engineering Structures*, vol. 42, pp. 83-94, 2012.
[4] C. Zhai, X. Wang, J. Kong, S. Li and L. Xie, “Numerical Simulation of Masonry-Infilled RC Frames Using XFEM”. *Journal of Structural Engineering*, vol. 143, n. 10, pp. 04017144, 2017.
[5] G. Magenes, S. Pampanin, “Seismic reponse of gravity-load design frames with masonry infills”. In: Proceedings, *13th World Conference on Earthquake Engineering*, Vancouver, Canada, 2004.
[6] Code, Price. "Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings". *Brussels: European Committee for Standardization*, 2005.
[7] L. Cavaleri, M. Papia, G. Macaluso, F. Di Trapani and P. Colajanni, “Definition of diagonal Poisson’s ratio and elastic modulus for infill masonry walls”. *Materials and structures*, vol. 47, n. 1-2, pp. 239-262, 2014.
[8] Turkish Code for Buildings in Seismic Zones -TEC. “Turkish Seismic Code”. *The ministry of public works and settlement*, Ankara, Turkey, 2007.
[9] Federal Emergency Management Agency. “FEMA 306: Evaluation of earthquake damage concrete and masonry wall buildings”. *Basic Procedures Manual*, Washington, DC, 1998.
[10] Canadian Stardards Association. “S304 – Design of masonry structures.” Ontario. 2014.
[11] Standards New Zealand - NZS. “Design of reinforced concrete masonry structures”. *NZS 4230-04*, Wellington, New Zealand, 2004.
[12] R. J. Mainstone, “Supplementary note on the stiffness and strengths of infilled frames”. *Building Research Station*, Garston, UK, 1974.
[13] L. R. da Silva, “Modelagem de pórticos de concreto armado preenchidos com a consideração de aberturas nos painéis de alvenaria”. Dissertação (Mestrado em Engenharia Civil) – Universidade Federal de Santa Maria, Santa Maria, 2014.
[14] G. A. Montandon, “Modelos estruturais para a análise de pórticos preenchidos com blocos cerâmicos em edifícios de concreto armado”. Dissertação (Mestrado em Engenharia Civil) – Universidade Federal de Uberlândia, Uberlândia, 2018.
[15] Associação Brasileira de Normas Técnicas. NBR 16868 “Alvenaria estrutural – Parte 1: Projeto”. Rio de Janeiro, 2020.
[16] A. W. Hendry, “Structural brickwork”. *Halsted Press*, 1981.
[17] T. Paulay and M. J. N. Priestley, “Seismic design of reinforced concrete and masonry buildings”. New York: John Wiley & Sons Inc., 1992.
[18] O. Ozturkoglu, T. Ucar, And Y. Yesilce, “Effect of masonry infill walls with openings on nonlinear response of reinforced concrete frames”. *Earthquakes and Structures*, vol. 12, n. 3, pp. 333-347, 2017.
[19] T.-C. Liauw, “Tests on multistory infilled frames subject to dynamic lateral loading”. In: *Journal Proceedings*, vol. 76, n. 4, pp. 551-564, 1979.
[20] F. J. Crisafulli and A. J. Carr, “Proposed macro-model for the analysis of infilled frame structures”. *Bulletin of the New Zealand Society for Earthquake Engineering*, vol. 40, n. 2, pp. 69-77, 2007.
[21] Associação Brasileira de Normas Técnicas. NBR 6118 “Projeto de estruturas de concreto - Procedimento”. Rio de Janeiro, 2014.
[22] Associação Brasileira de Normas Técnicas. NBR 15270 “Componentes cerâmicos - Blocos e tijolos para alvenaria. Parte 1: Requisitos”. Rio de Janeiro, 2017.
[23] W. A. Medeiros, G. A. Parsekian, R. M. da Silva, A. B. C. de Grandi, “Avaliação da contribuição da alvenaria participante na rigidez lateral de pórticos pré-moldados de concreto”. *Revista Concreto & Construções*, Ed. 90, Abr – Jun, pp. 95-102, 2018.
[24] L. F. de Queiroz, “Alvenarias participantes: consideração e efeitos em edifícios de concreto sob ações horizontais”. Dissertação (Mestrado em Engenharia Civil) – Universidade Federal de Uberlândia, Uberlândia, 2020.