Acta Technica Napocensis: Civil Engineering & Architecture Vol. 55 No. 2 (2012)
Journal homepage: http://constructii.utcluj.ro/ActaCivilEng

Analytical Modelling of Masonry Infills

Diana M. Samoilă*[1]
[1] *Technical University of Cluj-Napoca, Faculty of Civil Engineering. 15 C Daicoviciu Str., 400020, Cluj-Napoca, Romania*

Received 20 August 2012; Accepted 18 September 2012

Abstract

The presence of infill walls in reinforced concrete structures can decisively influence the structure behaviour to seismic loads. There might be a positive effect - an increase of the overall stiffness and strength, but a negative effect can also appear due to effort concentration in frame members. The analytical models for masonry infill are the macro-modelling - equivalent strut method and the micro-modelling - finite element method. The study focuses on determining the width of compressed strut by means of different equations available in literature, but recommends the use of Paulay and Priestley relation. The infill influence on frame members is studied on several models, as the single-strut model, the three-strut model and finite element models. By analyzing the resulting forces in the beam and columns both as values and distribution, it has been observed that the three-strut model can estimate local effects more precisely due to frame infill interaction.

Rezumat

Prezența pereților de umplutură la structurile în cadre de beton armat poate influența decisiv comportarea structurii la acțiunea seismică. Efectul poate fi pozitiv, de creștere a rezistenței și rigidității de ansamblu, dar pot apărea și efecte negative cauzate de concentrări de eforturi în elementele cadrului. Variantele de introducere în calcul a zidăriei sunt macromodelarea - metoda diagonalei echivalente și micromodelarea - metoda elementului finit. Studiul propune determinarea lățimii diagonalei comprimate cu diferite relații existente în literatură, cu recomandarea utilizării formulei lui Paulay și Priestley. Influența peretelui de umplutură asupra elementelor cadrului este studiată pe modele diferite, atât cu zidăria reprezentată printr-o diagonală, respectiv trei diagonale echivalente, cât și prin metoda elementului finit. În urma analizei eforturilor din stâlpi și grindă, atît ca valoare, cât și ca distribuție, se observă că modelul cu trei diagonale exprimă cu mai multă exactitate efectele locale ale interacțiunii dintre peretele de zidărie și cadrul de beton.

Keywords: Masonry infill walls, equivalent strut, frame infill interaction

1. Introduction

Masonry infilled reinforced concrete frames constitute a structural system often used in many countries with relatively high seismic intensity. The seismic vulnerability of these structures has been demonstrated by the unexpected damages caused by earthquakes. Therefore, neglecting masonry infills in the design procedure is not a realistic approach.

---

* Corresponding author: Tel./ Fax.: 0744601544
E-mail address: Diana.Samoila@cfdp.utcluj.ro

Several methods have been developed on modelling infills, and they are grouped in two main categories: macro-models, based on the equivalent strut method, and micro-models, based on the finite element method. The main advantages of macro-modelling are computational simplicity and the use of structural mechanical properties obtained from masonry tests, since the masonry is a very heterogeneous material and the distribution of material properties of its constituent elements is difficult to predict. Holmes [6] was the first in replacing the infill by an equivalent pin-jointed diagonal strut. Stafford Smith [14] proposed a theoretical relation for the width of the diagonal strut based on the relative stiffness of infill and frame. Alternative proposals were given by Mainstone [10], Liaw and Kwan [8], Decanini and Fantin [4], and more recently by Paulay and Priestley [12], Durrani and Luo [5], Cavaleri and Papia [3].

In the last decades it has become clear that one single strut is not sufficient to model the complex behaviour of the infilled frame. This is because the local effects resulting from the interaction of the infill with the surrounding frame are not apparent if only the two loaded corners of the frame are connected through a single strut. As a result, bending moments and shear forces in the frame members are not modelled realistically and the location of potential plastic hinges cannot be adequately predicted. More complex macro-models were then proposed by many researchers (Crisafulli and Carr [16], Chrysostomu [16], Syrmakezis and Vartsnou [16], Andreaus [1]) based on two, three or multiple diagonal struts. Despite of increasing complexity, the main advantage of these models is the ability to reflect the actions in the frame more accurately. Micro-modelling is a more complex method based on dividing the masonry panel and the concrete frame into several elements. This modelling can provide an accurate computational representation of both material and geometrical aspects, but is too time-consuming to be used in large and practical-oriented analysis. From the first approach developed by Mallick and Severn [11] using the finite element method for the analysis of 2D infilled frames, different alternatives have been proposed by using a micro-model. Among these, we could mention Riddington and Stafford Smith [13], Liaw and Kwan [9], Dhanaskar and Page [16] or Asteris [2].

In the present study, a linear analysis of a masonry infilled concrete frame with a single storey and a single bay was carried out by modelling masonry infills through five different modelling techniques, and the results compared so as to arrive at a rational modelling scheme for masonry infilled concrete frames.

2. Determination of the equivalent strut width

The width of the equivalent diagonal strut (*w*) can be found out by using a number of expressions given by different researchers. Applying these expressions to a single-bay, single-storey example frame (Fig. 1), the study proposes a comparison of the results and indicates the most suitable relation to be used in practical design. The geometrical parameters of the frame members are presented in Table 1, and the properties of the materials are indicated in Table 2.

Table 1: Geometrical parameters of frame members

Frame element	Transverse section dimensions [m]	Transverse section area [m^2]	Moment of inertia [m^4]
Beam	$b_g x h_g$=0.5x0.25	A_g=0.125	I_g=10.4x10^{-3}
Column	$b_s x h_s$=0.5x0.5	A_s=0.25	I_s=2.6x10^{-3}

Table 2: The properties of the materials

Materials	Modulus of elasticity [kN/m^2]	Poisson coefficient
Concrete-C20/25	$E_b=30x10^6$	0.2
Masonry	$E_z=4.5x10^6$	0.19

In the following expressions *t=0.25m* is the thickness of the masonry wall and *θ=29.1^0* is the angle of inclination of the equivalent diagonal strut with the horizontal.

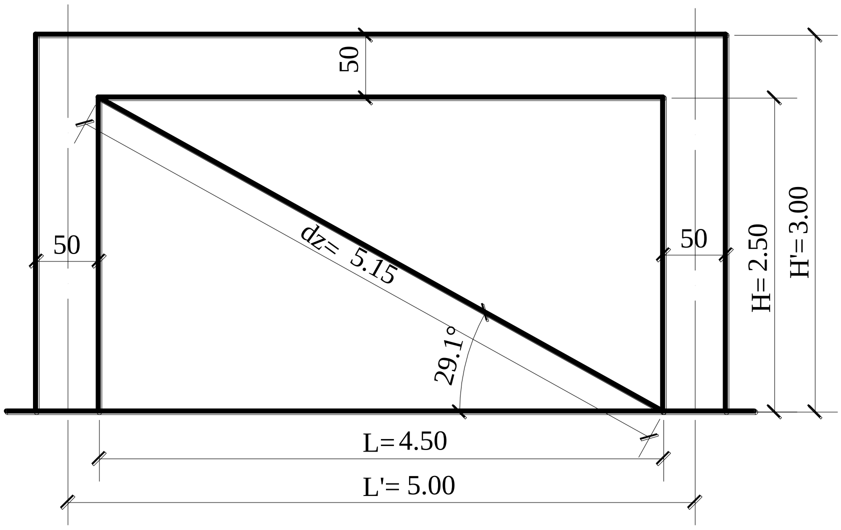


Figure 1. Masonry infilled reinforced concrete frame

- Holmes (1961) [6]

$$w = \frac{d_z}{3} = \frac{5.15}{3} = 1.72m \tag{1}$$

- Smith & Carter (1969) [15]

$$w = 0.58\left(\frac{1}{H}\right)^{-0.445}\left(\lambda_h H'\right)^{0.335 d_z \left(\frac{1}{H}\right)^{0.064}} \tag{2}$$

$$\lambda_h = \sqrt[4]{\frac{E_z t \sin 2\theta}{4 E_b I_s H}} = 0.744 \tag{3}$$

$$w = 3.25m$$

- Mainstone (1971) [10]

$$w = 0.175 d_z \left(\lambda_h H'\right)^{-0.4} = 0.65m \tag{4}$$

- Liaw & Kwan (1984) [9]

$$w = \frac{0.95 H \cos\theta}{\sqrt{\lambda_h H'}} = 1.39m \tag{5}$$

- Decanini & Fantin (1986) [4]
  - Uncracked masonry (I)

$$w = \left(\frac{0.748}{\lambda_h} + 0.085 \right) d_z = 5.61m \tag{6}$$

  - Cracked masonry (II)

$$w = \left(\frac{0.707}{\lambda_h} + 0.01 \right) d_z = 4.94m \tag{7}$$

- Paulay & Priestley (1992) [12]

$$w = \frac{d_z}{4} = 1.29m \tag{8}$$

- Durrani & Luo (1994) [5]

$$w = \gamma \sqrt{L'^2 + H'^2} \sin 2\theta \tag{9}$$

where:

$$m = 6\left[1 + \frac{6E_b I_g H'}{\pi E_b I_s L'} \right] = 7.72 \tag{10}$$

$$\gamma = 0.32\sqrt{\sin 2\theta} \left[\frac{H'^4 E_z t}{m E_b I_s H} \right]^{-0.1} = 0.226 \tag{11}$$

$$w = 1.12m$$

- Cavaleri & Papia (2003) [3]

$$w = \frac{d_z \cdot k \cdot c}{z} \frac{1}{(\lambda^*)^{\beta}} \tag{12}$$

$$\lambda^* = \frac{E_z}{E_b} \frac{t \cdot H'}{A_s} \left(\frac{H'^2}{L'^2} + \frac{1}{4} \frac{A_s}{A_g} \frac{L'}{H'} \right) = 0.537 \tag{13}$$

$$c = 0.249 - 0.0116\gamma + 0.567\gamma^2 = 0.267 \tag{14}$$

$$\beta = 0.146 + 0.0073\gamma + 0.126\gamma^2 = 0.152 \tag{15}$$

L/H is considered to be equal to *1.5*

$$z = 1 + 0.25\left(\frac{L}{H} - 1 \right) = 1.125 \tag{16}$$

F_v (vertical load) $= 13.12kN/m$

$$\varepsilon_v = \frac{F_v}{2A_s E_b} = 26.24x10^{-6} \tag{17}$$

$$k = 1 + (18\lambda^* + 200)\varepsilon_v = 1.0055 \tag{18}$$

$$w = 1.35m$$

P100/1 – 2006 [18]

$$w = \frac{d_z}{10} = \frac{5.15}{10} = 0.52m \tag{19}$$

Placing the resulting values on the same diagram (Fig. 2), one can draw the following conclusions:

1. Smith and Carter and Decanini and Fantin equations generate large values for the diagonal strut width.

2. Mainstone relation is very close to that proposed by the Romanian code, both of them being at the inferior limit.
3. The other expressions (Holmes, Liaw and Kwan, Paulay and Priestley, Durrani and Luo, Cavaleri and Papia) are comparable (values between *1.12m* and *1.72m*).
4. Paulay and Priestley relation is recommended to be used in design analysis because it gives an average value and because of its simplicity.

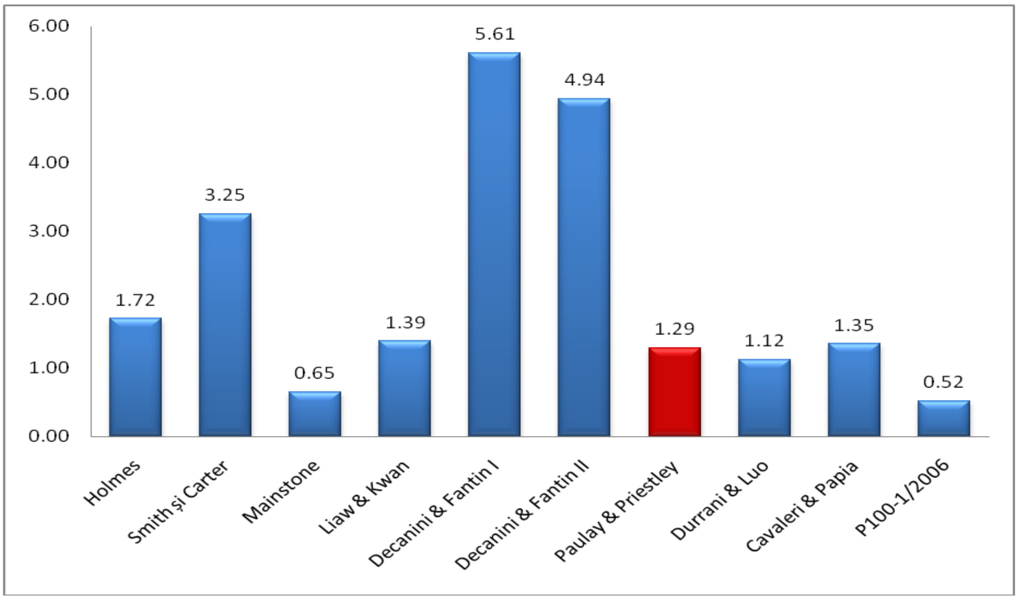


Figure 2. Equivalent strut width.

3. Infill influence on the concrete frame

A comparative study, based on the models proposed in [7], was carried out to assess a suitable model for masonry infills in RC frames. Suitability of a model is judged depending on several factors, namely, the time required and the effort involved in modelling, the ability to model lateral stiffness and the strength of infilled frame, and the ability to model failure modes in not only infills but also in frame members. The infilled frame presented above (Fig.1) was considered in the comparative study. The analysis was carried out using SAP2000 commercial software. The modelling techniques and assumptions considered in the present study are discussed in the following.

3.1 Analytical modelling

The frame was assumed to be fixed at the bottom, and the columns and beams of the frame were modelled using two-nodded frame or beam elements. Masonry infill walls were modelled as:

- equivalent diagonal struts (one strut and three struts) using two nodded beam elements;
- finite elements using shell elements.

The transfer of bending moments from frame to masonry wall was prevented by specifying the moment releases at both ends of the struts. In the case of finite element modelling only the membrane action in shell elements was considered, and bending action ignored.
The properties of the materials are those presented in Table 2.
Vertical distributed load is equal to *17.12 kN/m* and concentrated lateral load is *164kN*.

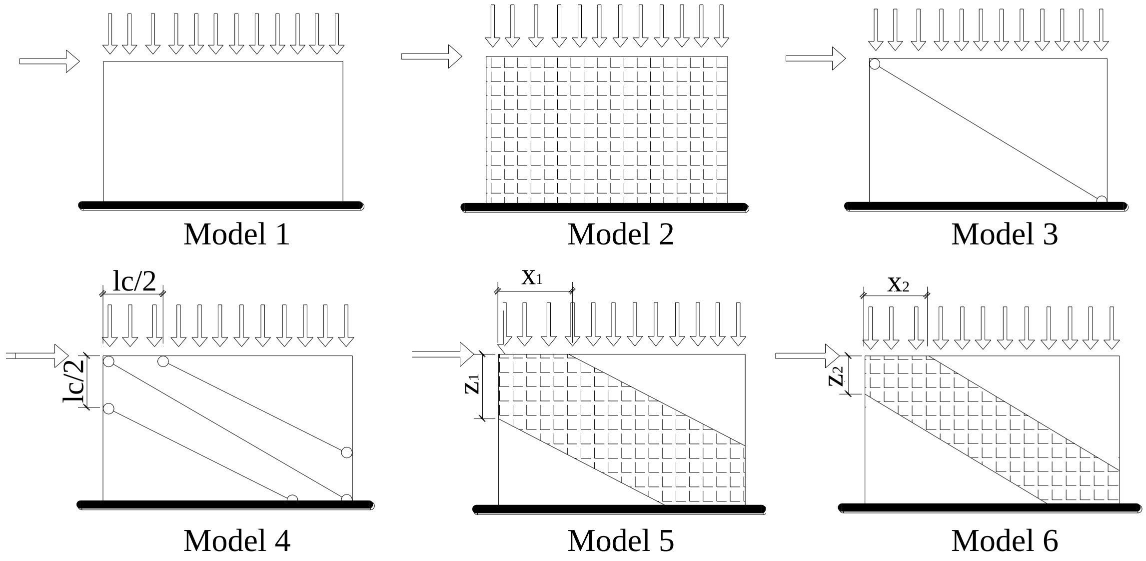


Figure 3. Different analytical models.

Six different modelling possibilities were considered, as follows:
Model 1 - bare frame model, in which the strength and stiffness of masonry infills were not considered;
Model 2 – full infill frame, with masonry modelled using finite element method;
Model 3 – masonry modelled as a single strut; the width of the strut is *1.29m*, calculated with Paulay and Priestley relation;
Model 4 – masonry modelled as three diagonal struts; the width of central diagonal strut was taken *0.645m*, which is half the strut width in Model 3 and the width of the eccentric struts is half the central strut width, *0.323m;*

- the eccentric struts were connected to the frame at the centre of the distance l_c, which is the length of contact between infill and frame members, suggested in the literature [12];

$$l_c = \frac{\pi}{2}\sqrt[4]{\frac{E_b I_S H}{E_z t \sin 2\theta}} = 1.055m \tag{20}$$

Model 5 – partially infilled frame, with masonry introduced as shell elements;
$x_1=1.40m$, $z_1=1.25m$
Model 6 - partially infilled frame, with masonry introduced as shell elements;
$x_1=1.25m$, $z_1=0.75m$
Under the effect of increasing lateral forces, the contact area between masonry infill wall and concrete frame reduces. The aim of introducing Model 5 and Model 6 is to study the effect of contact area reduction, because these models are successive fazes of Model 2.

3.2 Analysis results

Resulting forces values

It was observed that the resulting forces (obtained from envelope load case), most noticeably the bending moment, reduced considerably when the stiffness of infill was considered in the analytical model, because most of the lateral forces were then transferred to the infill wall as axial forces.
With an increase in the lateral forces acting on the frame, the area of wall in contact with the frame reduces because of the separation of the wall from the frame near the tension-diagonal joints. In other words, effective lateral stiffness of the wall, and therefore the effective width of equivalent diagonal strut reduce with the increase in the lateral forces. The effect of this on concrete columns may be considered similar to the creation of short columns because of the varying unsupported

length of columns under increasing lateral forces. Therefore, Model 2 and Model 3 may not adequately capture the actual structural behaviour because these models consider full stiffness of the infill wall irrespective of the increase of lateral forces.

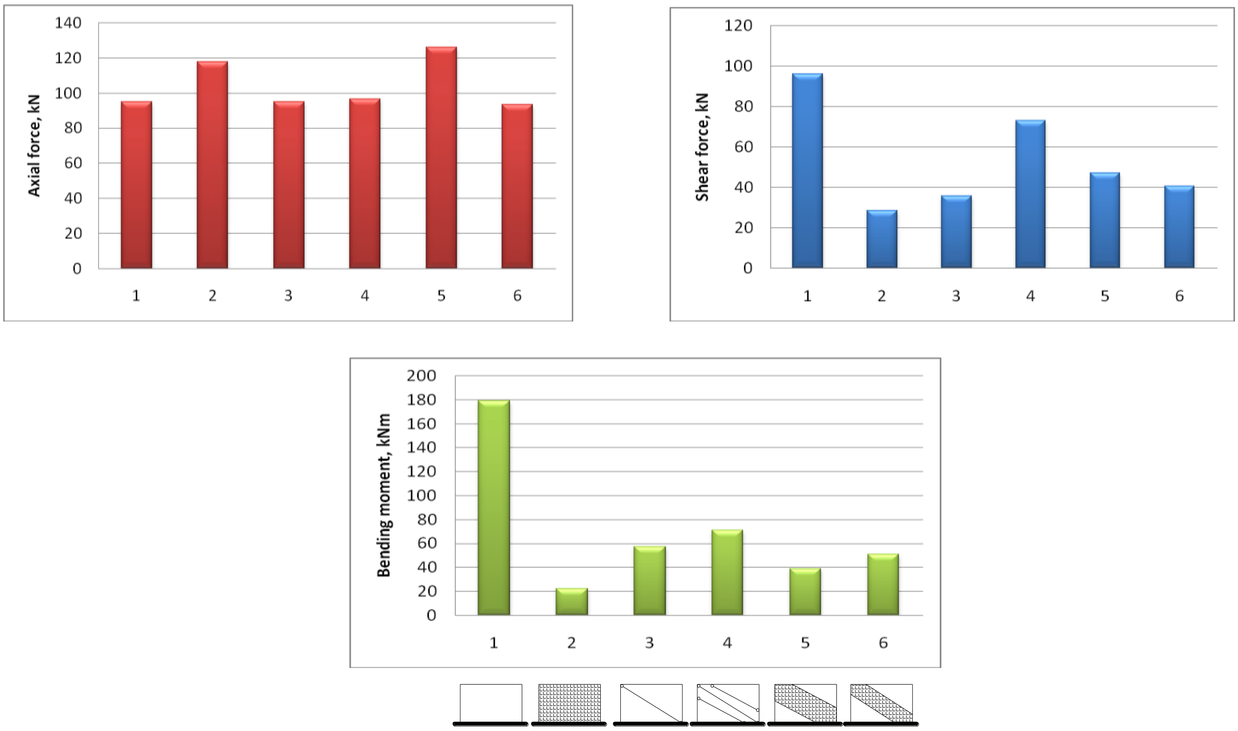


Figure 4. Resulting forces in columns.

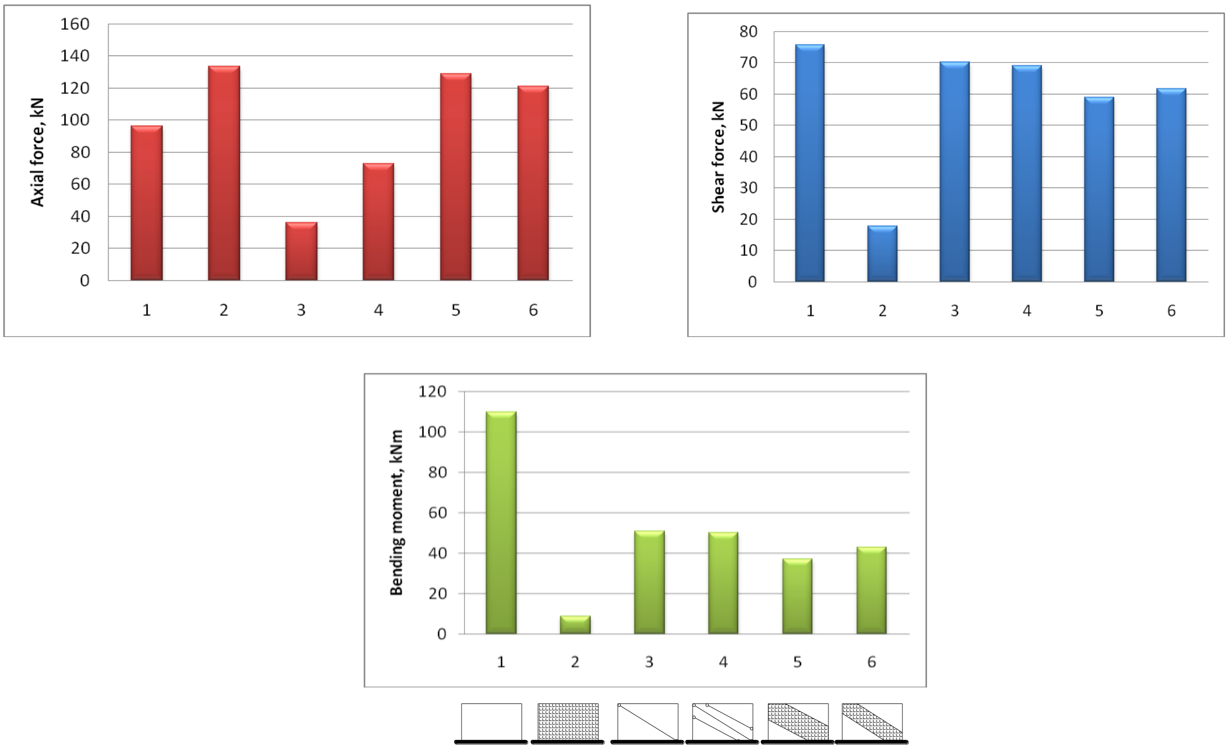


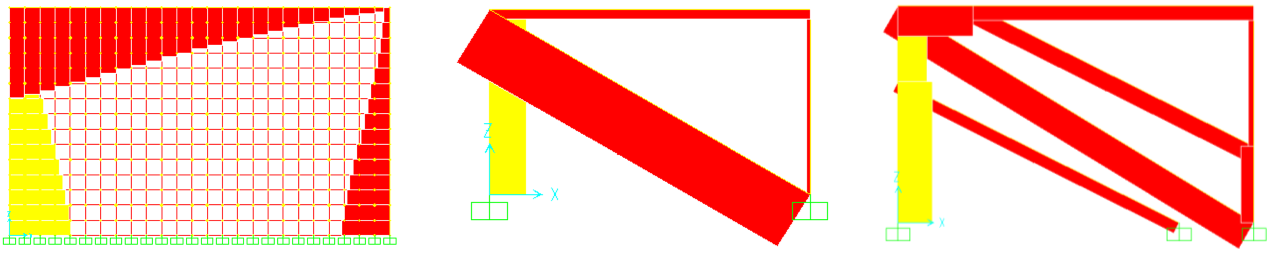
Figure 5. Resulting forces in beam.

In comparison with the results of Model 5 and Model 6 (considered to match more closely with real behaviour), the axial forces in columns, obtained by using struts models, can also be accepted because they do not have a negative effect on frame design.

Considering that the shear force in columns for the three-strut model is substantially higher than the shear obtained using the partial shell models, and the shear for Model 3 is reduced compared to the same values, the use of correction coefficients is recommended. These should be increasing coefficients for the single-strut model and reducing coefficients for the three-strut model.
Regarding columns bending moments, Model 3 and Model 4 values can be accepted because they are higher than the bending moments of partial shell models.

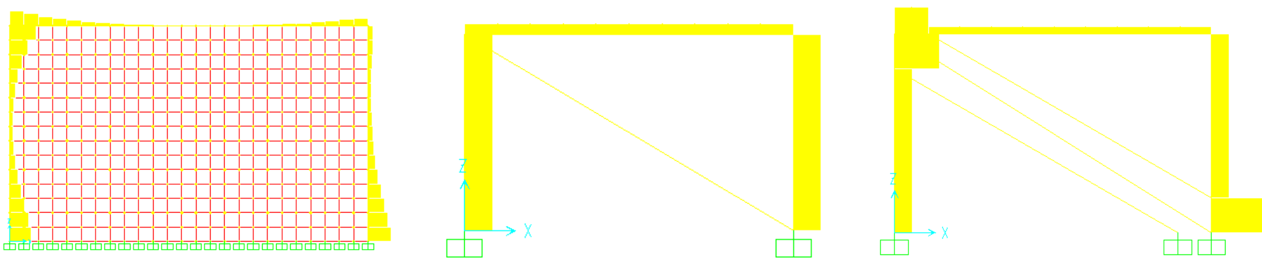
Axial forces in the beams of struts models are considerably smaller compared to axial forces in Model 5 and Model 6, but this aspect is not very important as far as the design process is concerned. Nevertheless, for a rigorous analysis, an increase of the struts models values is proposed. Shear forces and bending moments in Model 3 and Model 4 can be accepted as correct.

Resulting forces distribution



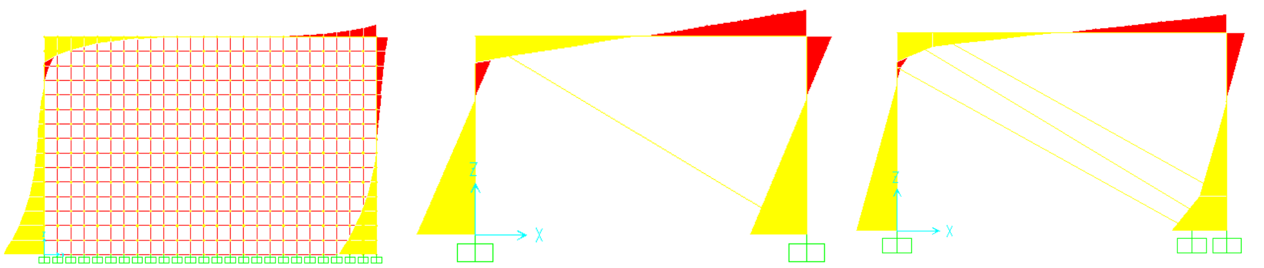
Model 2 Model 3 Model 4

Figure 6. Axial force diagrams for full shell model and for struts models.



Model 2 Model 3 Model 4

Figure 7. Shear force diagrams for full shell model and for struts models.



Model 2 Model 3 Model 4

Figure 8. Bending moments diagrams for full shell model and for struts models.

A complete image of frame infill interaction also involves studying frame efforts distribution. A comparison between the results of Model 2 (full shell), Model 3 (single strut) and Model 4 (three strut) is presented in Fig. 6, Fig. 7 and Fig. 8.

It has been observed that for the single strut model, the axial and shear force distribution is constant throughout the entire element length, which is not similar to the axial and shear force distribution in Model 2, considered closer to real behaviour. On the other hand, three-strut model reflects efforts distribution more accurately, with an increase in the length between column-beam nods and the connection points of eccentric struts. As a result, the single-strut model appears not to predict the realistic changes in efforts distribution caused by frame infill interaction.

4. Conclusions

The comparative study of different expressions for calculating the diagonal strut width reveals the Paulay and Priestley equation as the most suitable choice, due to its simplicity and because it gives an approximate average value (among those studied).

In the analysis involving analytical models for masonry infills in a single-storey, single-bay reinforced concrete frame, the single-strut model was found to be predicting the global behaviour of the system with reasonable accuracy. On the other hand, three-strut model was found to be estimating the resulting forces in the frame members more accurately when compared to that of a single-strut model.

In conclusion, the single-strut model is better to be used in analysis regarding the general behaviour of infilled frames, because it can be accepted as correct and due to its simplicity, while the three-strut model is the appropriate approach for determining the local effects of frame infill interaction.

6. References

[1] Andreaus U, Cerone M, D'Asdia P, Iannozzi F. A Finite Element model for the Analysis of Masonry Structures under Cyclic Actions. *Proceedings of the Seventh International Brick and Masonry Conference,* Melbourne, Australia, Vol 1, pp 479-488, 1985.

[2] Asteris PG. Finite Element Micro-Modeling of Infilled frames. *Electronic Journal of Structural Engineering,* 2008

[3] Cavaleri L, Papia M. A new dynamic identification technique: application to the evaluation of the equivalent strut for infilled frames. *Engineering Structures* 25, 889-901, 2003 http://www.sciencedirect.com.

[4] Decanini LD, Fantin GE. Modelos simplificados de la mamposteria incluida en porticos. Caracteristicas de rigidez y resistencia lateral en estado limite. *Jornadas Argentinas de Ingenieria Estructural,* Buenos Aires, Argentina, Vol.2, pp.817-836, 1986.

[5] Durrani AJ, Luo YH. Seismic Retrofit of Flat-slab Buildings with Masonry Infills. *NCEER workshop on seismic response in Masonry Infills,* 1994.

[6] Holmes M. Steel frames with brickwork and concrete infilling. *Proceedings of the Institution of Civil Engineers 19,* 1961.

[7] Kaushik HB, Rai D, Jain SK. A Rational Approach to Analytical Modeling of Masonry Infills in Reinforced Concrete Frame Buildings. *Proceedings of the 14th World Conference on Earthquake Engineering,* Beijing, China, 2007.

[8] Liaw TC, Kwan KH. Non-linear analysis of multistory infilled frames. *Proceedings of the Institution of*

Civil Engineers, Vol 73(2), pp 441-454, 1982.
[9] Liaw TC, Kwan KH. Nonlinear behavior of non-integral infilled frames. *Comput. Struct.* 18, 551-560, 1984.

[10] Mainstone RJ. On the Stiffness and strength of infilled frames. *Proc. Supplement, Trans. of Instn. Of Civil Engrs,* State Univ. of New York, 1974.

[11] Mallick DV, Severn RT. The behavior of infilled frames under static loading. *Proceedings of the Institution of Civil Engineers,* Vol 38, pp 639-656, 1967.

[12] Paulay T, Priestley MJN. Seismic Design of Reinforced Concrete and Masonry Buildings. *John Wiley & Sons, New York,* 1992.

[13] Riddington JR, Stafford Smith B. Analysis of infilled frames subject to racking with design recommendation. *Structural Engineer,* Vol 55(6), pp 263-268, 1977.

[14] Stafford Smith B. Behaviour of Square Infilled Frames. *Proceedings of the American Society of Civil Engineers, Journal of Structural Division,* 92, no STI, 381-403, 1966.

[15] Stafford Smith B, Carter C. A method of analysis for infill frames. *Proc. Inst. Civil Engrs,* 1969.

[16] Zybaczynski A. Cercetări asupra comportării și calculului post-elastic al structurilor de beton armat la acțiuni seismic. Teză de doctorat, Universitatea Tehnică de Construcții București, 2011.

[17] xxx CSI, SAP 2000, Ver. 14.0.0. Basic Analysis Reference Manual – Linear and Nonlinear Static and Dynamic Analysis and Design of Three-Dimensional Structures. Berkeley (CA,USA).

[18] xxx P 100-1/2006 . Cod de proiectare seismică – Prevederi de proiectare pentru clădiri. România.