ON THE SEISMIC RESPONSE OF MASONRY INFILLED RC FRAMES

Gaetano DE STEFANO
PhD Candidate
University of Salerno
Via Ponte don Melillo, 84084 Fisciano (SA), Italy
gaetano.destefano@gmail.com

Carmine LIMA
Research Assistant
University of Salerno
Via Ponte don Melillo, 84084 Fisciano (SA), Italy
*clima@unisa.it**

Enzo MARTINELLI
Assistant Professor
University of Salerno
Via Ponte don Melillo, 84084 Fisciano (SA), Italy
e.martinelli@unisa.it

Abstract

Although it is widely accepted that the interaction between masonry infill and structural members significantly affects the seismic response of reinforced concrete (RC) frames, such an interaction is generally neglected in current design-oriented seismic analyses of structures. The issue of modelling masonry infill is even more relevant in the case of seismic analysis of existing structures, as they can significantly modify both lateral strength and stiffness. As a matter of principle, accurate modelling of infill should be carried out by adopting nonlinear 2D elements. However, several design-oriented proposals are currently available in both scientific literature and engineering practice to model masonry infill by defining equivalent (nonlinear) strut elements. This paper demonstrates the OpenSEES capabilities in implementing the such models in nonlinear static and dynamic analyses.

Keywords: Infill, Nonlinear Analysis, Reinforced Concrete, Strut models.

1. Introduction

The present paper addresses the issue of simulating the influence of masonry infill on the seismic response of existing RC frames. The role of masonry infill has been observed in recent seismic events. Particularly, strength and stiffness of infill can negatively affect the global response of buildings by modifying the structural configuration in plan or elevation. However, infill are generally neglected in the current practice of design-oriented seismic analysis of structures. Two main classes of models are available for simulating the response of masonry infill in seismic analysis of RC structures: micro-models (generally very detailed finite element models) and macro-models (simplified models). Micro-models are often based on finite element analysis of infill [1]. They are generally used for analysing local mechanisms with particular reference to the ones between the RC elements and masonry panels. On the contrary, several proposals for simulating the global response of masonry infill under in seismic actions analysis consist of simpler and less time-consuming macro-models based on the assumption of equivalent struts. The identification of such models, namely the assumption of sound values for the parameters describing the structural behaviour of the above mentioned equivalent struts, is a critical aspect in macro-models. In the authors' knowledge the first contribution about defining equivalent struts for simulating the contribution of masonry infill to the lateral stiffness of RC frames dates back at the ‘60s of the last century [2]. It was particularly aimed at defining the actual width *w* of the equivalent strut depending on the relative stiffnesses of both concrete and masonry members (Figure 1). Further evolutions of such a model were presented in the following years to consider the effect of cracking in reducing the lateral stiffness of the equivalent strut [3] and better calibrating the original formula against experimental results which were made available at that time [4][5]. Moreover, the effect of partial and open infill panels was addressed in [6].

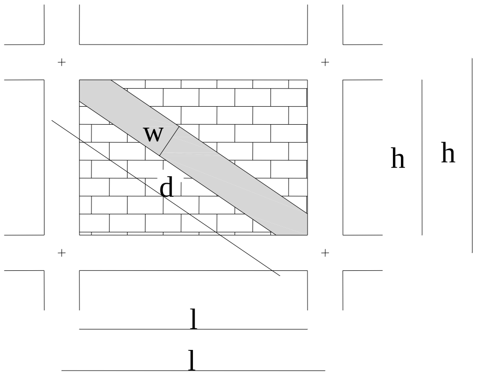


Figure 1. Geometric definition of the equivalent strut [2]

A more general relationship between the width w of the equivalent strut and the level of damage developed throughout the masonry panel was investigated experimentally in [7] and analytical relationships defining the w/d ratio of the above mentioned strut were calibrated. Simpler proposals for consistent values of the w/d ratio ranging between 0.20 and 0.25 were proposed in [8] and [9], respectively. More recently, several evolutions were proposed to the definition of equivalent stiffness to address the influence of both the stiffness of concrete frame and the possible presence of openings and windows [10]. Particularly, the influence of windows is considered by defining a reduction factor r of the equivalent strut width defined as follows on the basis of experimental observations:

$$r = 1.24 - 1.7 \cdot a \tag{1}$$

with

$$a = h_v / h = l_v / l \tag{2}$$

in which h_v and l_v denote depth and width of the window in the panel, respectively, while h and l are its vertical and horizontal dimensions.

The definition of the global force-displacement relationship which intended at simulating the behaviour of masonry infill subjected to seismic actions should be completed by introducing a credible stress-strain relationship. Two slightly different proposals are considered in the present study. Particularly, Panagiotakos and Fardis [11] proposed a trilinear relationship to describe the global strut response in terms of horizontal force-displacement response. It is defined by means of the force and displacement parameters highlighted in Figure 2a: they depend on the relevant geometric and mechanical properties of the masonry wall under consideration. The elastic stiffness of the first branch represents the behaviour of the panel without cracks and is evaluated as follows:

$$R_1 = \frac{G_w t_w l_w}{h_w} \tag{3}$$

in which G_w is the shear modulus of masonry, t_w is the thickness, l_w the length and h_w the depth of the panel, respectively. The force corresponding to the first cracking condition is evaluated through the following linear relationship:

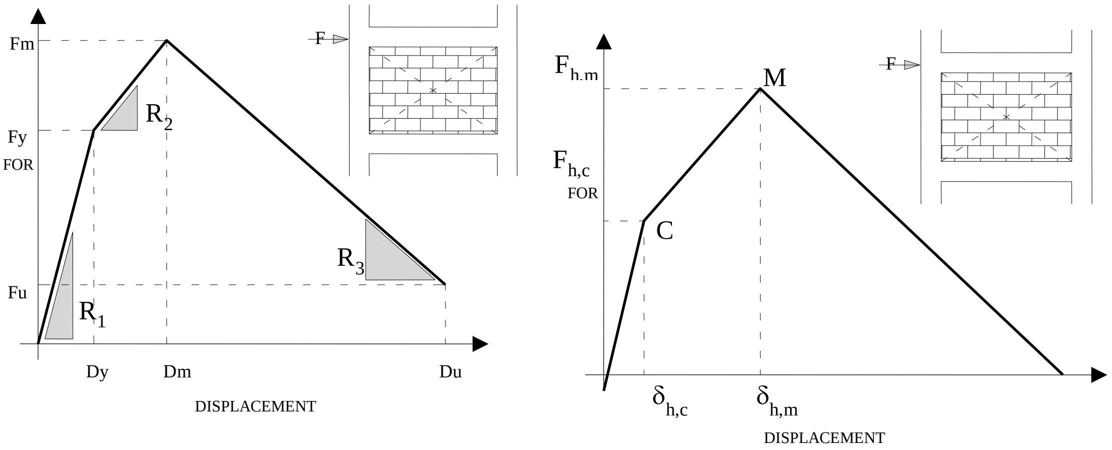
$$F_y = f_{ws} \cdot t_w \cdot l_w \quad . \tag{4}$$

while the stiffness R_2 (Figure a) can be derived as follows:

$$R_2 = \frac{E_w \cdot t_w \cdot b_w}{d_w} \tag{5}$$

where E_w is the elastic modulus of masonry; b_w is the width of the equivalent strut evaluated according to the model by Mainstone [3] and d_w is the length of the strut.

The maximum force F_m (Figure a) is equal to $1.3F_y$, while the stiffness of the third softening branch can be assumed equal to $0.5R_1$ for normal conditions and $0.1\ R_1$ in the case of very brittle masonry. Finally, he ultimate force F_u is assumed to be equal to 0.10 0.15 F_y.



a) Panagiotakos & Fardis [11] **b) Dolsek & Fajfar [12]**

Figure 2. Two alternative strut models for simulating the behaviour of masonry infill .

Dolsek and Fajfar recently proposed a slightly different model for simulating the global (horizontal) force-displacement response of masonry infill based on the results of some experimental tests carried out on a four floors masonry infilled RC structure with and without windows [12]. The initial stiffness R_1, defined as the ratio to the horizontal force ($F_{h,C}$) and the displacement ($\delta_{h,C}$) at cracking, and the maximum force $F_{h,m}$ can be evaluated according the above mentioned model by Panagiotakos and Fardis [11]. The force at cracking $F_{h,c}$ is assumed to be equal to 0.6 $F_{h,m}$ while the displacement $\delta_{h,m}$ at the maximum force $F_{h,m}$ corresponds by an interstory drift of 0.2% for panel without windows, 0.15% for panel with windows and 0.1% in the case of panels with doors. No residual force ($F_u = 0$).

2. Application to a case study

A two-storey two bay RC structure described in the scientific literature [13] is considered in this paper as a case study. It was modelled in OpenSEES [14] with the aim of performing nonlinear analyses to simulate the behaviour observed for the bare structure and predict the response of the same structure with different arrangement of masonry infill. The following subsections provide readers with the relevant information about the structural model.

2.1 Outline of the structure under consideration and its material properties

The structure under consideration was designed for gravitational load only, according the codes and general practice in use in Italy in ’70, and is described in [13]. No masonry infill are actually present on the structure. Thus, it will be firstly analysed in its “as-built” configuration (denoted as “bare structure” in the following) with the aim of calibrating the numerical models employed for structural members. Then, the possible influence of masonry infill is investigated by considering the three alternative configurations depicted in Figure 3.

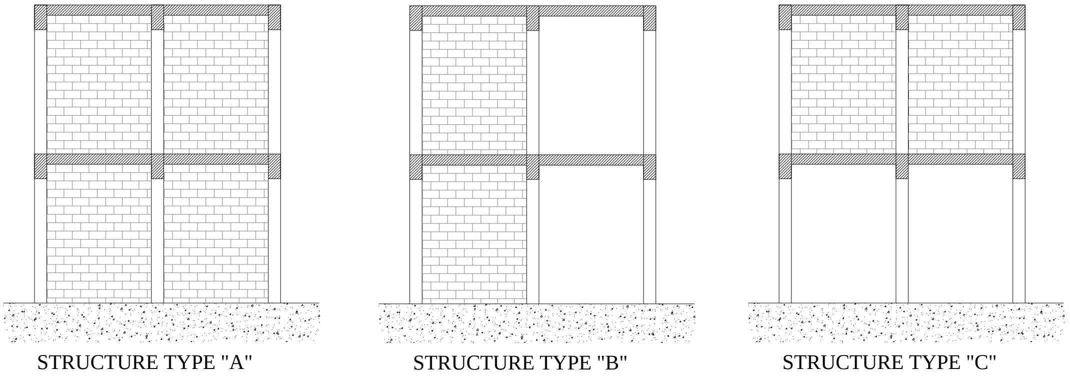


Figure 3. Alternative masonry infill distributions considered in this study

The following mechanical properties are employed for structural materials:

- Concrete R_{cm} = 22.5 MPa (f_{cm} = 19 MPa);
- AQ50-type reinforcement steel with f_{sm} = 280 MPa (smooth bars).

Masonry infill are supposed to be made out of artificial blocks of expanded clay. They are modelled by considering the mechanical properties listed below:
average compression strength f_k = 2,00 MPa, average shear strength f_{vk0} = 0,125 MPa, normal elastic modulus E_w = 1600 MPa, shear modulus G_w = 400 MPa.

2.2 Structural modelling and analysis

A nonlinear finite element (FE) model was developed in OpenSEES to simulated the structural response of the structure described in subsection 2.1 subjected to seismic excitations. The nonlinear behaviour of beam and column was simulated by employing force-based distributed plasticity elements (nonlinearBeamColumn). The transverse section of both beam and columns were discretised in 30x30 fibers, whose number was defined through a thorough sensitivity analysis.

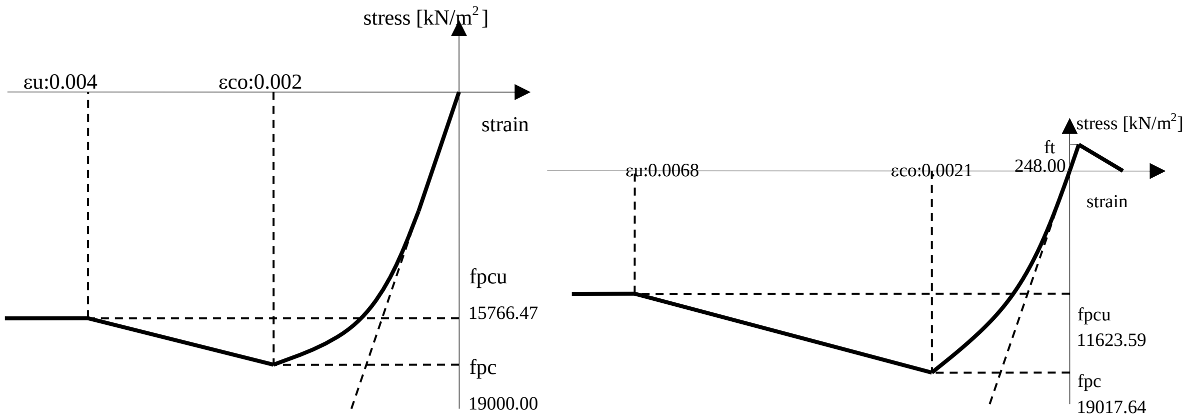


Figure 4. 1D stress-strain curves adopted for cover and core concrete.

Three different one-dimensional stress-strain laws were considered to simulate the behaviour of unconfined concrete (the cover), confined concrete (inside the area defined by transverse rebars) and reinforcing steel of longitudinal bars. Particularly, Concrete01 and Concrete 02 models (Figure 4) were employed for modelling cover and core concrete, respectively.

Moreover, an elastic-plastic behaviour with 0.1% symmetric hardening has been adopted for rebars through the so-called Steel01 stress-strain law (Figure 5).

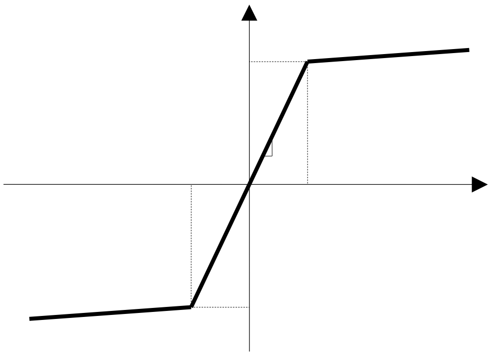


Figure 5. 1D stress-strain curves adopted for longitudinal steel reinforcing bars.

Truss elements were employed for simulating the behaviour of masonry infill in terms of both strength and stiffness. They were supposed to only sustain compressive (negative) axial forces. Stiffness degradation in both loading and unloading phases was implemented through the so-called "Pinching 4" model available in OpenSEES (Figure 6). The possible influence of openings (i.e. windows or doors) was simulated by multiplying the force values in Figure by the factor in equation (1). Figure 7 describes the geometry of the structural models implemented for both bare and masonry infilled structures.

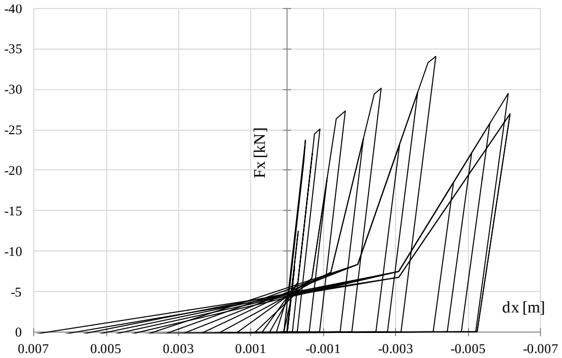


Figure 6. Skeleton curve and hysteretic behaviour simulating the behaviour of masonry-equivalent struts.

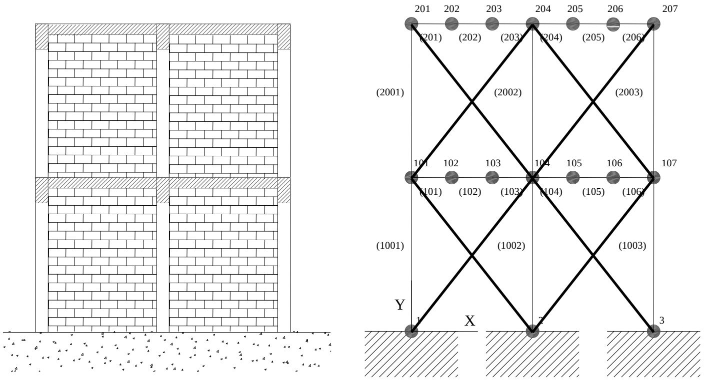


Figure 7. Geometry of structural models for either bare and infilled RC structure under consideration.

Finally, the mechanical properties adopted for structural materials are summarised in Table 3.

Table 3. Parameters of material behaviour.

Material	f_{pc} [kN/m^2]	f_{pcu} [kN/m^2]	ε_{psc0}	ε_{psu}	f_t [kN/m^2]	E_{ts} [kN/m^2]
Concrete01	19 000.00	15 766.47	0.002	0.004		
Concrete02	19 017.64	11 623.59	0.0021	0.0068	248.00	266 715.81
	f_y [kN/m^2]	E_0 [kN/m^2]	b			
Steel01	330 000	210 000 000	0.01			

3. Analysis results

The structural model described in section 2 was analysed under seismic excitation. For the sake of brevity, only the results obtained in X direction are reported in the following.

3.1 Pushover analyses

First of all, pushover analyses were carried out to understand the influence of masonry infills on the lateral strength and stiffness of the structure under consideration. Two thicknesses (namely, 12 and 20 cm) were considered for masonry and the properties of the equivalent strut were determined according to the two models outlined in Figure 2, Figure 3 describes the actual influence of the masonry infills (”Type A” distribution in Figure 3).

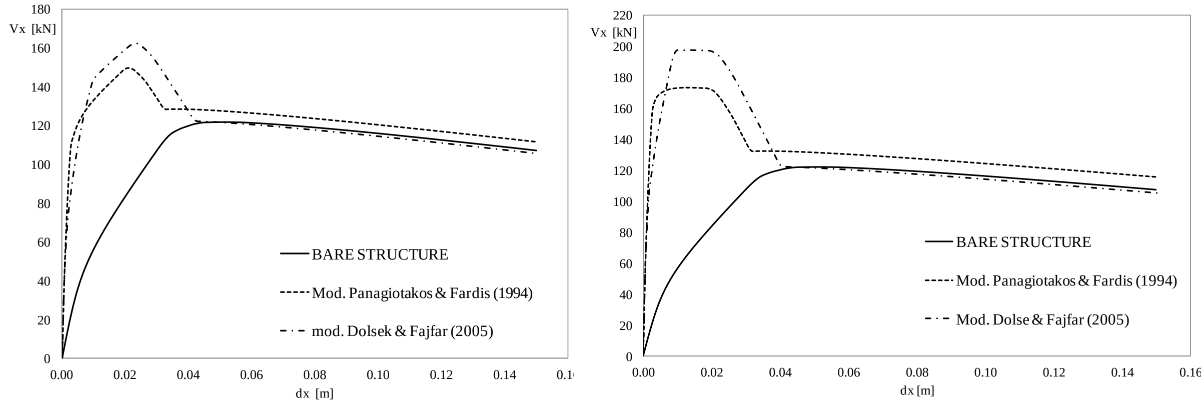


Figure 8. Capacity curves from pushover analyses: the effect of masonry thickness.

Furthermore, the effect of possible openings on the response of the structure is analysed. Figure 9 depicts the behaviour of infilled structures with variable dimensions of windows in the masonry infill. The resulting properties of the equivalent strut were determined according to the model by Dolsek and Fajfar [11] and multiplying the resulting force values by the factor defined in equation (1) with values of the “a” ratio ranging between 0.20 and 0.60.

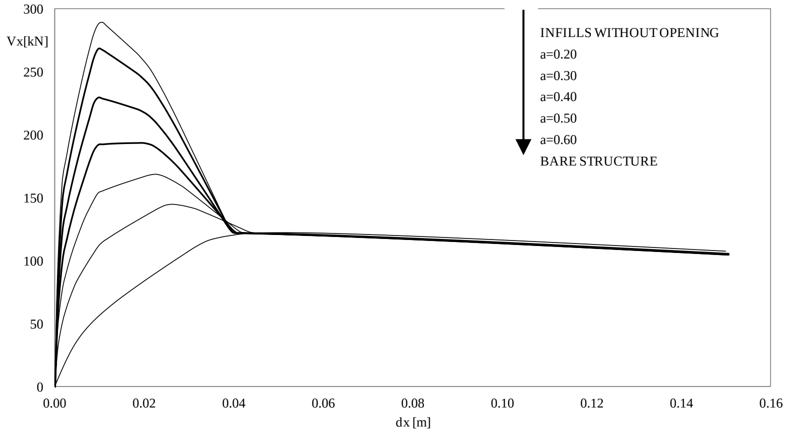


Figure 9. Capacity curves from pushover analyses: the effect of openings.

3.2 Nonlinear time-history analyses

Nonlinear time history analyses were carried out along with pushover ones with the aim of investigating the influence of masonry infill on the cyclic response of RC structures. To this end, two sets of seven natural accelerograms were selected from the European Strong Motion Database by considering two target elastic spectra whose key parameters are reported in Table 4. Figure 10 depicts both target and natural spectra for the two sets of accelerograms considered in this study.

Table 4. key parameters of the target elastic spectra for the two earthqhakes considered in this study.

	Earthquake # 1	Earthquake # 2
a_g (g)	0.334	0.261
F_0	2.400	2.364
T_C* (s)	0.364	0.346
T_B (s)	0.121	0.115
T_C (s)	0.364	0.346
T_D (s)	2.936	2.642

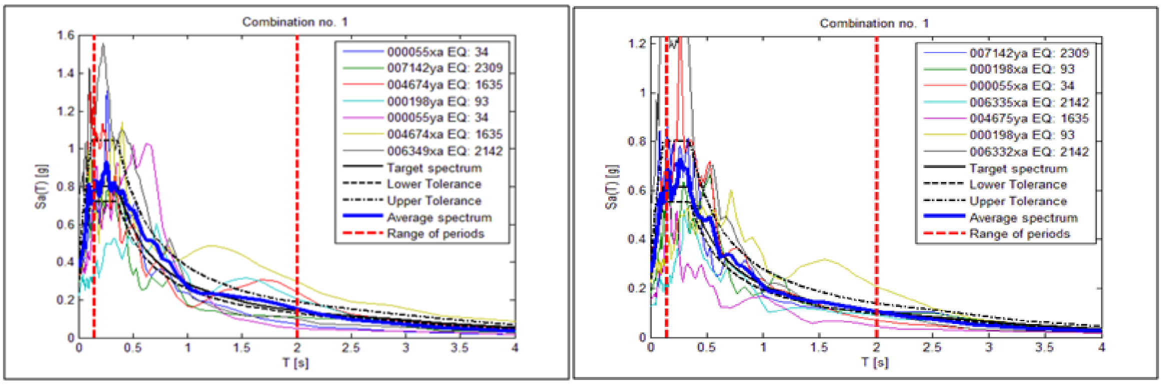
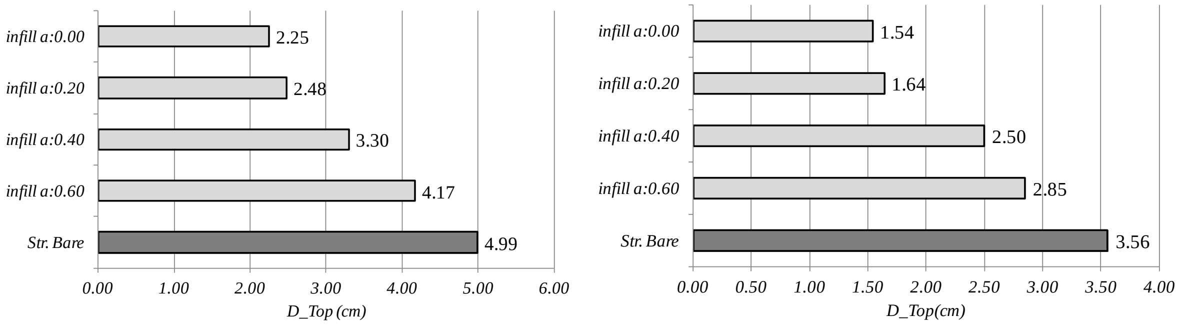


Figure 10. Target design spectra and corresponding natural ones.

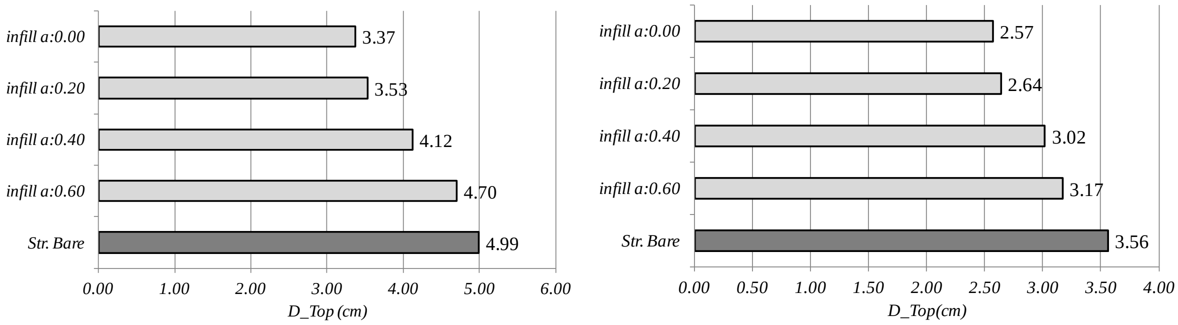
Figure 11 outlines the maximum top displacements determined for bare and for "Type A" infilled one, schematically depicted in Figure 7. It points out the significant influence of the interaction between masonry wall and reinforced concrete structural members in terms of reduction of the top displacement determined under seismic actions.



a) Earthquake #1 **b) Earthquake #2**

Figure 11. Maximum top displacement for infilled and bare structures (Structure A).

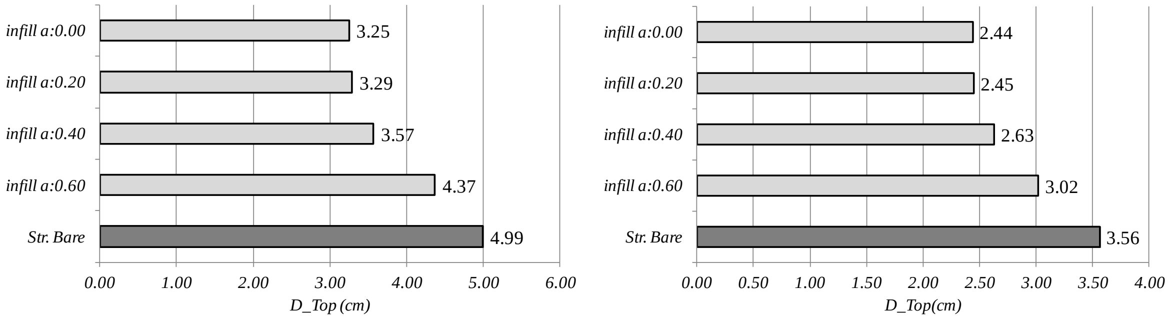
On the contrary, a much lower influence can be observed for structures with masonry infills distributed according the so called "Type B" (Figure 12) and "Type C" (Figure 13) configuration.



a) Earthquake #1 **b) Earthquake #2**

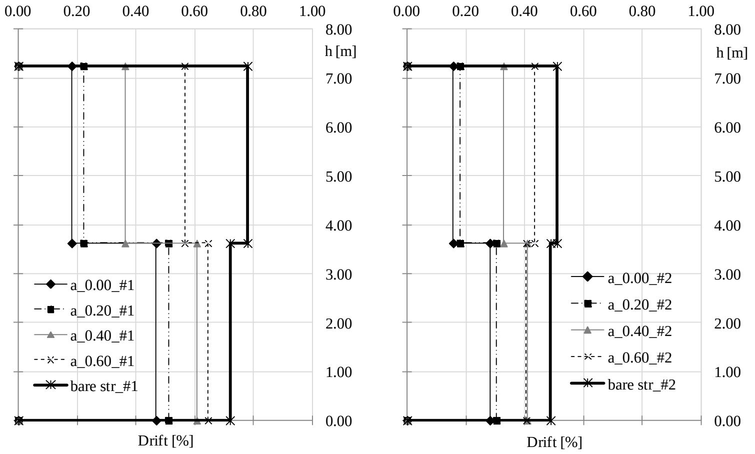
Figure 12. Maximum top displacement for infilled and bare structures (Structure B).

As expected, the effect of openings in terms of reduction of masonry strength and stiffness and, consequently, its influence on the global seismic response of structures is significantly lower in the case of “Type C” (namely “pilotis” scheme), as the whole first storey is not infilled. Thus, the maximum displacement reported in Figure 12 for structures with infill characterised by dimensional ratios a (see Eqn.(2)) ranging from 0 to 0.40 are almost equal, whereas more significant differences can be observed in the corresponding results reported in Figure 11 and Figure 12, referring to “Type A” and “Type B” structures, respectively.



a) Earthquake #1 **b) Earthquake #2**

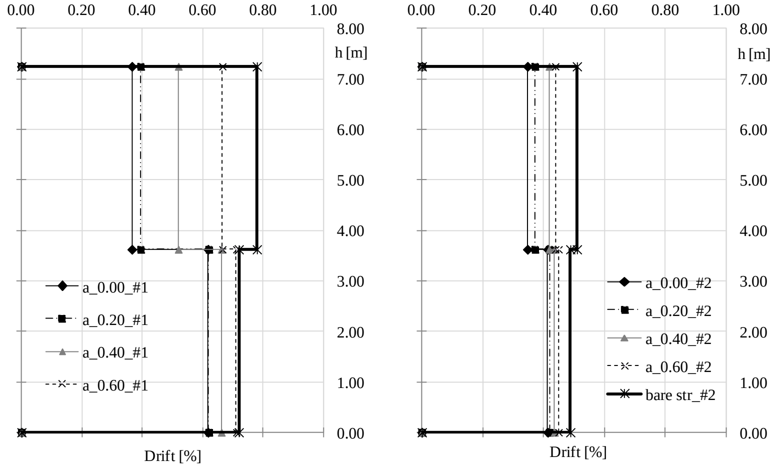
Figure 13. Maximum top displacement for infilled and bare structures (Structure C).



a) Earthquake #1 **b) Earthquake #2**

Figure 14. Average values of interstorey drifts (Structure A).

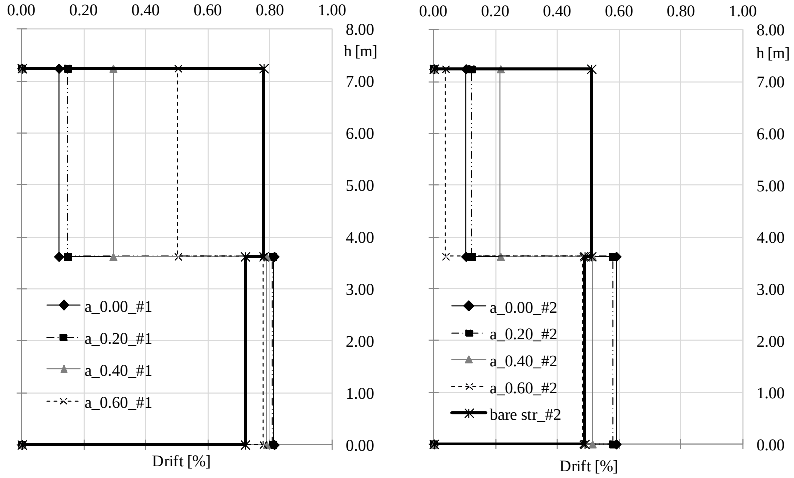
Besides the influence of masonry infill in terms of top displacement, the modification in interstorey drift distribution is also an aspect of concern in seismic analysis and assessment of existing RC buildings. Figure 14 reports the average values of interstorey drifts induced by the two sets of seven seismic signals on the so called “Type A” infilled structure; different values of the opening ratio “a” ranging from 0 to 0.60 are considered. Moreover, the corresponding values obtained on the bare structure are also reported as a reference in the same figure. The results demonstrate that, one the one hand, the absolute values of interstorey drifts are always lower in the infilled structures than in the bare one. Such a reduction is particularly relevant at the second storey, as interstorey drift of the structure infilled with full masonry walls reduces to less than one-third of the corresponding value observed for the bare one.Similar consideration could be drawn out by observing the results reported in Figure 15 for the so-called “Type B” structure. This is clearly due to the fact that both structures A and B are regular in elevation.



a) Earthquake #1 **b) Earthquake #2**

Figure 15. Average values of interstorey drifts: (Structure B).

On the contrary, the results of the analysis carried out on the so called “Type C” structure highlight a critical aspect which confirm the relevance of considering masonry infills in simulating the seismic response of RC frames. Figure 16 shows how interstorey drifts obtained at the first level for all the infilled structures are (even significantly) higher than the corresponding values determined for the bare structure. This results points out the relevant influence of masonry infills on the distribution of interstorey drift and lateral force, especially in cases of irregular distribution of such non-structural elements.



a) Earthquake #1 **b) Earthquake #2**

Figure 16. Average values of interstorey drifts: (Structure C).

Further considerations about the forces transmitted by the equivalent struts on the conventional structural members and the possible brittle failures which can occur are omitted herein for the sake of brevity.

4. Conclusions

The present paper addressed the issue of modelling the seismic response of RC frames taking into account the possible influence of masonry infill by means of "practice-oriented" numerical models implemented in OpenSEES. The key aspects of the structural behaviour of both RC structural members and masonry were firstly summarised. Particularly, the simulation of the response of masonry walls was reduced to the definition of an equivalent strut whose monotonic behaviour can be described according to analytical expressions available in the scientific literature for defining the key features of the force-displacement skeleton curve; moreover, the cyclic behaviour of such equivalent struts has been simulated by taking into account both strength and stiffness degradation (in load and unload branches).
The results obtained in the parametric analysis proposed herein confirm the importance of taking into account the role of masonry infill, as their influence cannot be otherwise quantified and simulated and can often result in unexpected effects, especially in the case of irregular distribution in elevation.

5. References

[1]. Asteris, P.G. (2003): Lateral stiffness of brick masonry infilled plane frames, J. Struct. Eng., 129 (8), 1071-1079.

[2]. Stafford-Smith B., (1966): Behaviour of square infilled frames, Journal of the Structural Division; 92 (1): 381 – 403.

[3]. Mainstone R. J., (1974): Supplementary note on the stiffness and strenght of infilled frames, Current Paper CP13/74, Building Research Establishment, London.

[4]. Klingner R. E., Bertero V. V. (1976): Infilled frames in earthquake-resistant construction, Report EERC 76-32, Earthquake Engineering Research Center.

[5]. Klingner R. E., Bertero V. V. (1978): Earthquake resistance of infilled frames, Journal of the Structural Division, vol. 104, n. ST6, pp. 973-989.

[6]. Te-Chang L., Kwok-Hung K. (1984): Nonlinear behaviour of non-integral infilled frames, Comp. and Struct., 18, 551-560.

[7]. Decanini L.D., Fantin G.E. (1986): 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.

[8]. Penelis G. G., Kappos A. J., (1997): Earthquake-resistant concrete structures, E & FN Spon, London.

[9]. Paulay and Priestley (1992): Seismic design of reinforced concrete and masonry buildings, John Wiley & Sons, New York.

[10]. Papia M., Failla A., Cavaleri L., (2002): Risposta sismica di telai tamponati in. c.a.: Modellazione e sperimentazione.

[11]. Panagiotakos, T. B., Fardis, M. N. (1994): Proposed nonlinear strut models for infill panels, 1st Year Progress Report of HCM-PREC8 Project, University of Patras.

[12]. Dolsek M., Fajfar P. (2005): Simplified non-linear seismic analysis of infilled reinforced concrete frames, Earthquake Engineering and Structural Dynamics, Vol. 34, 49-66.

[13]. Di Sarno L., Acanfora M., Manfredi G., Pecora R. (2008), Vibration control of structures under environmental loading, Proceedings of the 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China

[14]. Mazzoni S., McKenna F., Scott M.H., Fenves G.L. (2007): OpenSees Command Language Manual, Open System for Earthquake Engineering Simulation (OpenSees), Pacific Earthquake Engineering Research center.

[15]. Iervolino I., Galasso C., Cosenza E. (2010), REXEL: computer aided record selection for code-based seismic structural analysis. Bullettin of Earthquake Engineering, 8:339-362.