Earthquakes and Structures, *Vol. 12, No. 3 (2017) 333-347*
DOI: https://doi.org/10.12989/eas.2017.12.3.333

Effect of masonry infill walls with openings on nonlinear response of reinforced concrete frames

Onur Ozturkoglu*[1], Taner Ucar[2a] and Yusuf Yesilce[1b]

[1]*Deparment of Civil Engineering, Dokuz Eylul University, 35160, Buca, Izmir, Turkey*
[2]*Department of Architecture, Dokuz Eylul University, 35160, Buca, Izmir, Turkey*

(Received November 9, 2016, Revised January 21, 2017, Accepted March 9, 2017)

Abstract. Masonry infill walls are unavoidable parts of any building to create a separation between internal space and external environment. In general, there are some prevalent openings in the infill wall due to functional needs, architectural considerations or aesthetic concerns. In current design practice, the strength and stiffness contribution of infill walls is not considered. However, the presence of infill walls may decisively influence the seismic response of structures subjected to earthquake loads and cause a different behavior from that predicted for a bare frame. Furthermore, partial openings in the masonry infill wall are significant parameter affecting the seismic behavior of infilled frames thereby decreasing the lateral stiffness and strength. The possible effects of openings in the infill wall on seismic behavior of RC frames is analytically studied by means of pushover analysis of several bare, partially and fully infilled frames having different bay and story numbers. The stiffness loss due to partial opening is introduced by the stiffness reduction factors which are developed from finite element analysis of frames considering frame-infill interaction. Pushover curves of frames are plotted and the maximum base shear forces, the yield displacement, the yield base shear force coefficient, the displacement demand, interstory drift ratios and the distribution of story shear forces are determined. The comparison of parameters both in terms of seismic demand and capacity indicates that partial openings decisively influences the nonlinear behavior of RC frames and cause a different behavior from that predicted for a bare frame or fully infilled frame.

Keywords: partially infilled RC frames; stiffness reduction factor; nonlinear behavior; pushover analysis; capacity; seismic demand

1. Introduction

Masonry infill walls made of various types of bricks and aerated concrete, are widely used in reinforced concrete (RC) structures in the form of interior or exterior partition walls. RC frames with masonry infill are commonly used structural systems in many parts of the world and it seems that infill walls will maintain their functional role in future construction practice. The mechanical in-plane contribution of masonry infill wall on seismic performance of RC frames is generally neglected in structural analysis and current design process, and infill walls are considered as vertical loads acting on beams and slabs.

The observations of post-earthquake damages on RC buildings have clearly shown that the presence of infill wall may significantly affect the seismic behavior of buildings by causing severe earthquake induced damages both in infill wall and frame members. The infill wall clearly interacts with the bounding RC frame when the structure is subjected to earthquake excitation since the infill wall is not isolated from the frame and a load transfer mechanism is developed at wall plane. This interaction of infill wall with the bounding frame may decisively influence the global response of the structure, both in terms of seismic demand and capacity, and cause a different behavior from that predicted for a bare frame. The possible contribution to strength and lateral stiffness, and the expected brittleness of the infill wall may decisively influence the modal characteristics and the failure modes of the structure. However, it is not easy to create a realistic and simple mathematical model for infill wall due to its inherent nonhomogeneous and anisotropic structure, and the complexity of the problem considering frame-wall interaction.

In addition to controversial issues related with complex composite behavior of masonry-infilled frames, infill walls usually have functional openings, such as doors and windows, which are expected to affect the seismic response of infilled frames thereby decreasing the lateral stiffness and strength. The percentage of the opening, the aspect ratio and the position of the opening in the infill wall are essential parameters reflecting the effect of the partial openings. The predicted behavior of infilled frames with openings in infill wall may differ in comparison to bare or fully infilled frames and due to lack of rational approach in modelling of openings, partially infilled RC frames are still topic of interest (Dolsek and Fajfar 2008, Kakaletsis and

*Corresponding author, Research Assistant (Ph.D. student)
E-mail: onur.ozturkoglu@deu.edu.tr
[a]Assistant Professor
E-mail: taner.ucar@deu.edu.tr
[b]Associate Professor
E-mail: yusuf.yesilce@deu.edu.tr

ISSN: 2092-7614 (Print), 2092-7622 (Online)

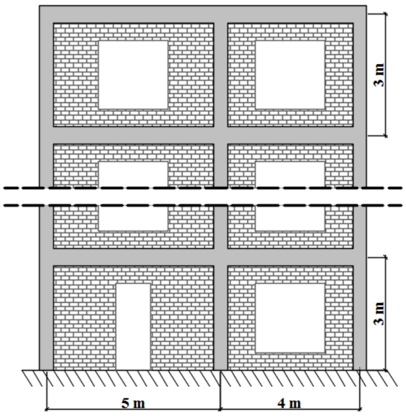
Karayannis 2008, 2009, Mohebkhah *et al*. 2008, Mondal and Jain 2008, Kose 2009, Tasnimi and Mohebkhah 2011, Asteris *et al*. 2011a, Mohammadi and Nikfar 2013, Asteris *et al*. 2015, Martinelli *et al*. 2015).

Seismic behavior of masonry infilled structures is extensively investigated under static and/or dynamic loads. There are many analytical and experimental studies where infill walls generally without openings and rarely with openings are modelled by using various approaches. The studies on this topic began with Polyakov (1950). It is often seen that, infill walls are modelled by equivalent compression strut approach (Madan *et al.* 1997, Kaushik *et al.* 2008, Kose 2009, Uva *et al*. 2012, Akpınar and Binici 2013, Ricci *et al*. 2013, Lima *et al*. 2014, Liu *et al.* 2014, Rathod and Dyavanal 2014, Ercolino *et al*. 2016) and this approach is specified in some current seismic design codes and international documents and standards. (Eurocode 6 1996, FEMA-306 1998, FEMA-356 2000, TSDC 2007). Besides, infill walls (Dorji and Thambiratnam 2009, Asteris *et al*. 2013, Allouzi *et al.* 2014, Koutromanos and Shing 2014, Fenerci *et al*. 2016) and infill walls with openings at wall plane (Asteris 2003, Kakaletsis and Karayannis 2008, Asteris *et al.* 2011a, Pradhan *et al.* 2012, Andrei 2014) are considered in structural analysis with finite element approach at some studies. Also, experimental studies about partially and fully infilled frames commonly exist in scientific literature (Mehrabi *et al*. 1996, Mosalam *et al.* 1997, Kakaletsis and Karayannis 2008, Pujol *et al.* 2008, Asteris *et al.* 2011b, Koutromanos *et al*. 2011, Valente 2012, Kuang and Zhang 2014, Emami and Mohammadi 2016, Fenerci *et al*. 2016). Nonlinear analysis of infilled frames and the influence of infill panels on nonlinear seismic response are still topics of current interest (Caprili *et al*. 2012, Fiore *et al*. 2012, Cavaleri and Trapani 2014, Haris and Hortobágyi 2015, Porco *et al*. 2015, Yuen and Kuang 2015, Bolhassani *et al*. 2016).

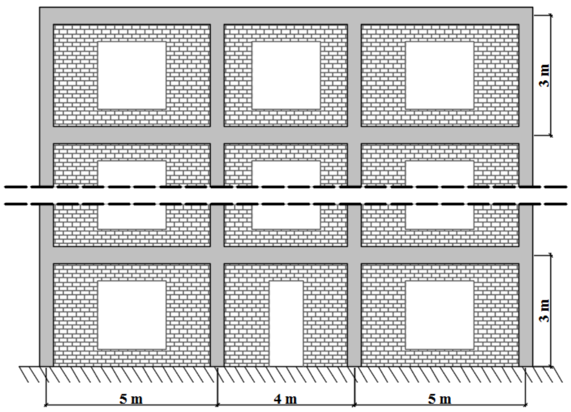
Although infill walls have been extensively investigated, studies deal with nonlinear seismic response of partially infilled RC frames are very limited and generally consist of analytical or experimental investigation of one-story, one-bay generic frames. In this paper, the possible effects of partially infilled walls on nonlinear seismic behavior of RC frames is analytically studied by means of pushover analysis of several RC frames having different bay and story numbers. First, bare frames reflecting the current engineering practice are considered in analyses. Then, infill walls are defined using the equivalent compression strut concept but openings are not considered (fully infilled frames). And finally, both infill walls and partial openings are considered in mathematical model of frames (partially infilled frames). Totally 36 analytical models are created. Equivalent strut widths obtained for fully infilled walls are multiplied with a stiffness reduction factor in order to reflect the presence of opening. Stiffness reduction factors accounting for frame-wall interaction are originally developed for each bay having different characteristics (i.e., different wall lengths and heights; dimensions of columns; different shapes, positions and sizes of openings) where infill walls are modeled with finite elements. In order to define nonlinear behavior of infill walls, axial force-displacement relationships obtained for different positions and percentages of opening are assigned to equivalent compressive strut. The base shear force capacity, the yield base shear force, the yield displacement and the top displacement demand of frames are determined. Consequently, the distribution of story base shear forces, the lateral displacement profile and the intersory drift ratios corresponding to top displacement demand of frames for different infill wall configurations are obtained. The discussion and comparison of above mentioned parameters emphasize that partial openings in the infill walls have considerable effects on nonlinear seismic response of RC frames.

2. Description of frames

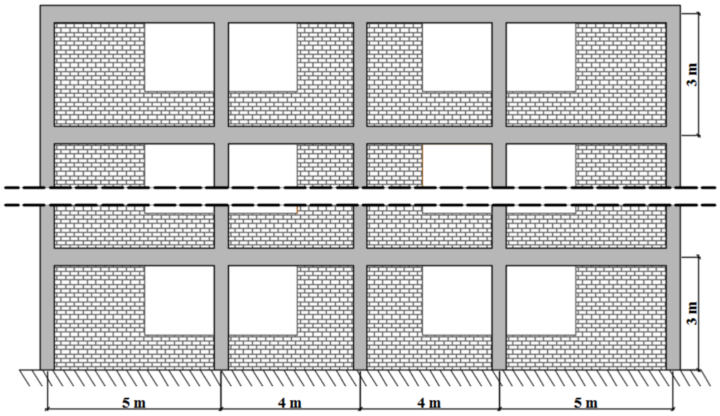
In order to investigate the possible effects of partially infilled walls to nonlinear seismic behavior of RC frames; partially infilled frames that have three, four, five, six stories and two, three, four bays are selected. Material properties are assumed to be 20 MPa for the concrete compressive strength and 420 MPa for the yield strength of reinforcement steel. Frames are assumed to be located on seismic zone 1 and the site condition is chosen as Z3 according to Turkish Seismic Design Code (TSDC 2007). According to the average of shear wave velocity in the first 30 m of the soil (V_{S30} values), soil profile type definitions of Z3 may be considered as the counterparts of soil profile types S_D in UBC-97 (UBC 1997) and C in Eurocode 8, or EC8, (CEN 2004). The selected frames are 2D modeling of an external frame of a 3D structure having symmetrical stiffness distribution in both directions and uniformly distributed mass over the plan and the magnitudes of gravity loads are determined accordingly. Live load participation factor (n) is taken as 0.30 and floor weights and related masses, which are considered in seismic calculations, are determined as the combination of dead loads and 30% of live loads. RC moment resisting frames are designed and detailed to satisfy the requirements of TSDC (2007) considering both gravity and seismic loads and as well as TS500 (2000). In TSDC (2007) the design seismic forces are specified in terms of story shear forces as a function of building period (T) and soil conditions. The design base shear force is calculated in accordance with the elastic design spectrum and it is reduced depending on the characteristics of the structural system by the earthquake response reduction factor ($R_a(T)$) in order to account for inelastic deformations. The reduced base shear force is distributed over the height of the structure in accordance with equivalent static lateral load procedure. The design internal forces are determined considering some typical design load combinations including both gravity loads and seismic loads. The RC design of frames is performed using the structural analysis program SAP2000 (2016). Rectangular beams and square columns are considered in the design. Beam dimensions are 25×50 cm in all frames; column dimensions are 40×40 cm for three- and four-story frames, 45×45 cm for five-story frames and 50x50 cm for six-story frames.



(a) Two-bay frames



(b) Three-bay frames



(c) Four-bay frames

Fig. 1 Partially infilled RC frames

Infill walls that have door or window openings are located at each bay of frames. Typical size of door openings is assumed to be 1×2.5 m while it is taken as 2×2 m for window openings. The thickness of infill wall is assumed to be 20 cm in all analytical models. Considering the stress-strain relations of brick infill and mortar, the elastic modulus of infill wall is calculated as 1661 MPa in accordance with Kaushik *et al*. (2007). Partially infilled RC frames having different number of bays and stories are shown in Fig. 1. Opening layouts are constant for frames having the same bay number.

Table 1 list the abbreviation of RC frames according to their bay/story numbers (e.g., 2B3S) and presence of infill and opening (e.g., 1 stands for a bare frame, 2 stands for a partially infilled frame and 3 stands for a fully infilled frame).

Table 1 Abbreviation of frames

Number of Bay	Number of Story	Bare Frame	Partially Infilled Frame	Fully Infilled Frame
2	3	RCF_2B3S-1	RCF_2B3S-2	RCF_2B3S-3
	4	RCF_2B4S-1	RCF_2B4S-2	RCF_2B4S-3
	5	RCF_2B5S-1	RCF_2B5S-2	RCF_2B5S-3
	6	RCF_2B6S-1	RCF_2B6S-2	RCF_2B6S-3
3	3	RCF_3B3S-1	RCF_3B3S-2	RCF_3B3S-3
	4	RCF_3B4S-1	RCF_3B4S-2	RCF_3B4S-3
	5	RCF_3B5S-1	RCF_3B5S-2	RCF_3B5S-3
	6	RCF_3B6S-1	RCF_3B6S-2	RCF_3B6S-3
4	3	RCF_4B3S-1	RCF_4B3S-2	RCF_4B3S-3
	4	RCF_4B4S-1	RCF_4B4S-2	RCF_4B4S-3
	5	RCF_4B5S-1	RCF_4B5S-2	RCF_4B5S-3
	6	RCF_4B6S-1	RCF_4B6S-2	RCF_4B6S-3

3. Determination of stiffness reduction factor

The possible effects of opening on the lateral stiffness of the partially infilled frames may be introduced by using stiffness reduction factors (k). In this paper, a new approach is developed to determine stiffness reduction factor. Accordingly, stiffness reduction factors of partially infilled frames considering the shape, the size and the position of the opening are derived by means of finite element analysis carried in the elastic region for monotonic loading. First, one-story one-bay bare frame is horizontally loaded at the top and the lateral stiffness of the bare frame (k_{bare}) is obtained by dividing the applied load (P) to lateral top displacement of bare frame (Δ_{bare}) (Eq. (1))

$$k_{bare} = \frac{P}{\Delta_{bare}} \tag{1}$$

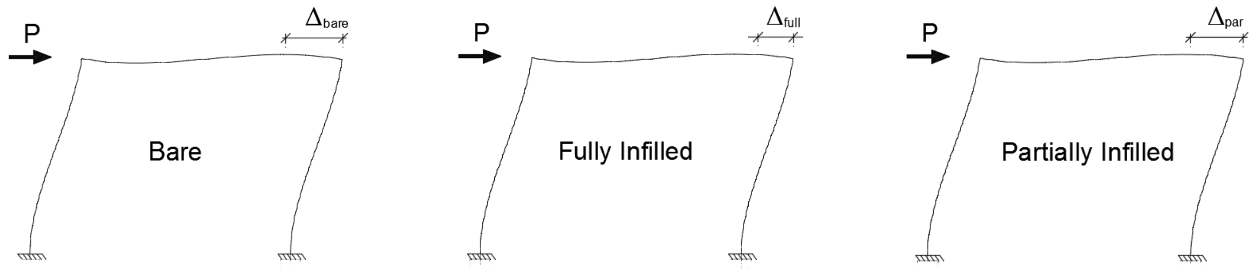


Fig. 2 Determination of lateral stiffness of frames

Then, the fully infilled frame is horizontally loaded at top and the resultant lateral displacement (Δ_{full}) is determined. Accordingly, the lateral stiffness of fully infilled frame (k_{full}) is calculated as in Eq. (2)

$$k_{full} = \frac{P}{\Delta_{full}} \tag{2}$$

Finally, the partial openings are created by erasing the related finite elements from fully infilled frame and the lateral stiffness of the partially infilled frame (k_{part}) is obtained as

$$k_{part} = \frac{P}{\Delta_{part}} \tag{3}$$

where, Δ_{part} is the lateral top displacement of partially infilled frame. Fig. 2 describes the methodology used to determine the lateral stiffness of a partially infilled one-story one-bay frame.

Since infill walls have smaller thickness in comparison to their height and length, they are considered as two dimensional shell elements at finite element modeling technique, which is a widely used tool in modelling of infill walls (Mohebkhah *et al.* 2008, Mondal and Jain 2008, Stavridis and Shing 2010, Moaveni *et al.* 2013). Partial openings in infill wall can easily be created at analytical model by erasing related finite elements (i.e., small pieces of shell elements). In finite element modelling, thickness and elastic modulus of shell element is taken to be equal to thickness and elastic modulus of infill wall. Size of finite elements are selected carefully to define exact sizes of openings. Additionally, RC frame-infill wall interaction is a crucial issue in modeling of infill walls. In this study, frame-wall interaction is modelled by defining gap elements between the bounding frame and infill wall, which transfer only compression loads. The stiffness of gap element (k_g) is calculated as

$$k_g = \frac{t_{inf} \cdot a \cdot E_{me}}{r_{inf}} \tag{4}$$

where, t_{inf} and E_{me} are thickness and elastic modulus of infill wall, a and r_{inf} are width and length of equivalent compression strut. Modelling of bounding frame-infill wall interaction by using gap elements is shown in Fig. 3.

The lateral stiffness of infill walls without openings ($k_{full,i}$) and with openings ($k_{part,i}$) can be calculated by subtracting the lateral stiffness of bare frame from fully and partially infilled ones, respectively

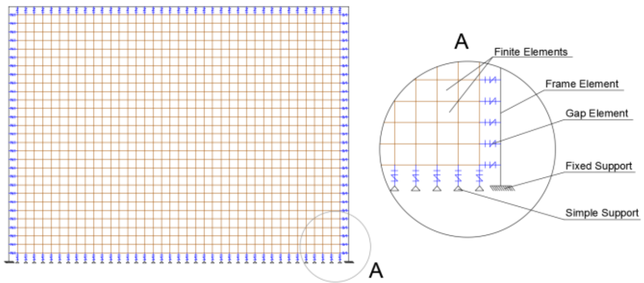


Fig. 3 Modelling of frame-infill wall interaction

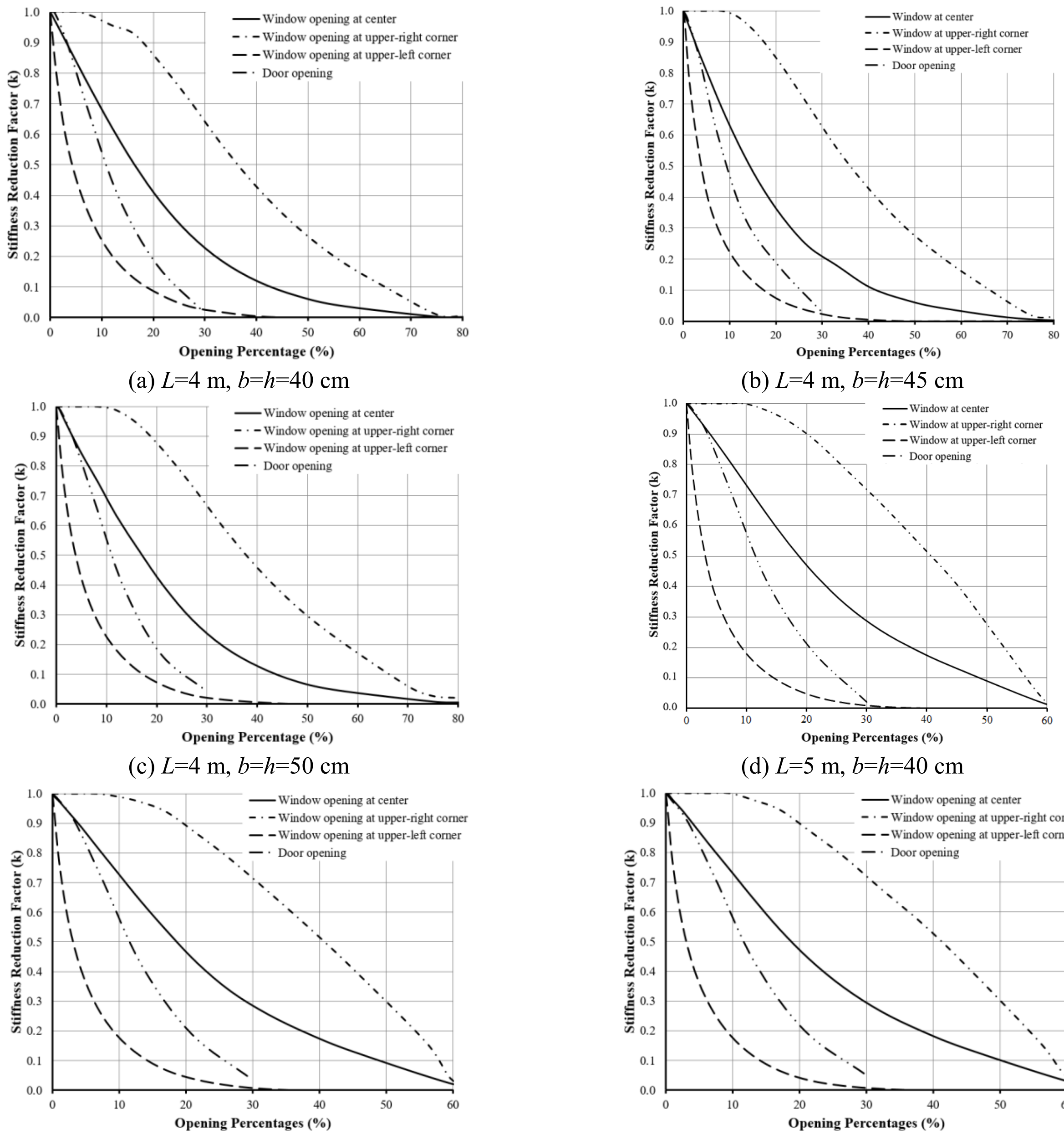
$$k_{full,i} = k_{full} - k_{bare} \tag{5}$$

$$k_{part,i} = k_{part} - k_{bare} \tag{6}$$

Consequently, the stiffness reduction factor (k), which accounts for the effect of the opening on the stiffness, is obtained by dividing the lateral stiffness of infill with partial opening ($k_{part,i}$) to the lateral stiffness of infill without partial opening ($k_{full,i}$)

$$k = \frac{k_{part,i}}{k_{full,i}} \tag{7}$$

Fig. 4 shows the variation of the stiffness reduction factor of an infill wall with partial opening in relation to opening percentage obtained for every different bay lengths (L), different columns dimensions (b, h) and different opening conditions. Some of the resultant stiffness reduction factors may be verified by the stiffness reduction factors of partially infilled RC frames obtained by Asteris (2003) where stiffness reduction factors of infilled RC frames in relation to opening percentage for different positions of opening are provided. The stiffness reduction factors of the present work directly reflect the contribution of the infill walls with different opening positions and percentages. Accordingly, when the lateral stiffness of bare RC frame is subtracted from the lateral stiffness of infilled RC frame of Asteris (2003) a reasonable agreement can be obtained for the similar opening positions and percentages. Although they are not identical due to different infill wall thickness, different story height and some different material properties, the variation of stiffness reduction factor for the frame having bay length L=4 m, column dimension b=h=40 cm and window opening at center (the solid black curve of Fig. 4(a)) matches quite well with stiffness reduction factor



(a) *L*=4 m, *b*=*h*=40 cm (b) *L*=4 m, *b*=*h*=45 cm

(c) *L*=4 m, *b*=*h*=50 cm (d) *L*=5 m, *b*=*h*=40 cm

(e) *L*=5 m, *b*=*h*=45 cm (f) *L*=5 m, *b*=*h*=50 cm

Fig. 4 Stiffness reduction factors

of Asteris (2003) for opening upon compressed diagonal.

When opening percentage is increased a decrease in stiffness reduction factor is observed. The position of opening substantially effects the decrease in the stiffness reduction factor, and also the variation of stiffness reduction factor with respect to opening percentage. If lateral load acts for right direction, openings located at the upper-left corner of the load transfer mechanism, where load transfer initiates in infill wall, have the maximum effect on the stiffness of frames. For small opening percentages, opening located at the upper-right corner, where the load transfer is considerably low, does not reduce the stiffness of frames. Opening at upper-right corner starts being effective when the opening percentage exceeds 20. The effect of central openings in infill wall is between the effects of openings located at upper-left corner and upper-right corner. Partially infilled walls may not be considered in analyses when the opening ratio exceeds 30% in case of opening position at upper-left corner and exceeds 60% for central openings and openings located at upper-right corner. It can be concluded that the higher value in stiffness reduction occurs when the opening is located at the upper-left corner and the lower value in stiffness reduction are observed in case of opening located at the upper-right corner.

According to the presented approach, the stiffness reduction factors of the study directly reflect the contribution of the infill walls with different opening positions and percentages. The obtained stiffness reduction factors can be used to modify the width of equivalent compression strut and accordingly the main parameters reflecting the effect of the opening are introduced to nonlinear analysis.

4. Modification of equivalent diagonal strut width

In nonlinear analyses of the study, the infill wall with partial openings is modeled by means of an equivalent compression strut, which is the most common approach of modeling infills. In this approach, infill walls are considered in analytical model as one or more strut that defined at load transfer direction. Thickness and elastic modulus of equivalent compression strut is taken to be equal to the thickness and elastic modulus of infill. The width of equivalent compression strut (a) is calculated by Eqs. (8)-(9) (FEMA-356 2000)

$$\lambda = \sqrt[4]{\frac{E_{me} \cdot t_{inf} \cdot sin(2\theta)}{4 \cdot E_{fe} \cdot I_{col} \cdot h_{inf}}} \tag{8}$$

$$a = 0.175 \cdot (\lambda \cdot h_{col})^{-0.4} \cdot r_{inf} \tag{9}$$

where λ is a parameter that indicates relative stiffness of the infill wall and frame, E_{me} and E_{fe} are the elastic modulus of infill and frame elements, h_{inf} and t_{inf} are the height and the thickness of infill wall, θ is the angle between equivalent compression strut and horizontal plane, I_{col} and h_{col} are the moment of inertia and the height of the column and r_{inf} is the length of equivalent compression strut, respectively. Some parameters using in determining of equivalent compressions strut width are shown in Fig. 5.

The presence of prevalent partial openings within the infill wall may decisively reduce the stiffness of infill wall. Therefore, when infill wall with partial openings are modeled by the common equivalent compression strut approach, strut width should be multiplied by a stiffness reduction factor, which ranges from zero (infill does not exist) to one (fully infilled). Accordingly, in case of a partial opening in the infill wall the width of the equivalent compression strut (a_m) is given by Eq. (10)

$$a_m = k \cdot 0.175 \cdot (\lambda \cdot h_{col})^{-0.4} \cdot r_{inf} \tag{10}$$

The equivalent diagonal strut widths and the modified equivalent diagonal strut widths of partially infilled frames are presented at Table 2 and Table 3 together with opening percentages and stiffness reduction factors. Considering the shape, the percentage and the position of the opening, the values of stiffness reduction factor are determined form the related graphics of previous section.

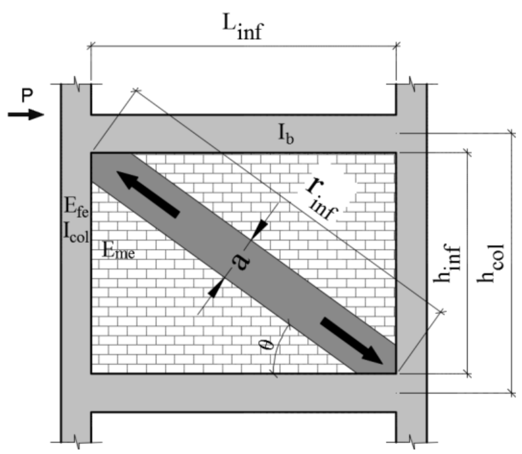


Fig. 5 Equivalent diagonal strut for modelling of infill wall

Table 2 Equivalent compression strut widths (L=4 m)

	Window Opening at Center	Window Opening at Upper-Right Corner	Window Opening at Upper-Left Corner	Door Opening
b=h=40 cm				
a (fully infilled)	528 mm	528 mm	528 mm	528 mm
Opening Percentage	33%	33%	33%	21%
k	0.18	0.56	0.02	0.17
a_m (partially infilled)	95 mm	296 mm	11 mm	90 mm
b=h=45 cm				
a (fully infilled)	548 mm	548 mm	548 mm	548 mm
Opening Percentage	33%	33%	33%	21%
k	0.18	0.55	0.01	0.17
a_m (partially infilled)	99 mm	301 mm	6 mm	93 mm
b=h=50 cm				
a (fully infilled)	566 mm	566 mm	566 mm	566 mm
Opening Percentage	33%	33%	33%	21%
k	0.19	0.59	0.01	0.17
a_m (partially infilled)	108 mm	334 mm	6 mm	96 mm

Table 3 Equivalent compression strut widths (L=5 m)

	Window Opening at Center	Window Opening at Upper-Right Corner	Window Opening at Upper-Left Corner	Door Opening
b=h=40 cm				
a (fully infilled)	637 mm	637 mm	637 mm	637 mm
Opening Percentage	27%	27%	27%	17%
k	0.34	0.78	0.02	0.19
a_m (partially infilled)	217 mm	497 mm	13 mm	121 mm
b=h=45 cm				
a (fully infilled)	662 mm	662 mm	662	662
Opening Percentage	27%	27%	27%	17%
k	0.33	0.78	0.02	0.19
a_m (partially infilled)	219 mm	516 mm	13 mm	126 mm
b=h=50 cm				
a (fully infilled)	684 mm	684 mm	684	684 mm
Opening Percentage	27%	27%	27%	17%
k	0.34	0.78	0.01	0.20
a_m (partially infilled)	233 mm	534 mm	7 mm	137 mm

4.1 Force-displacement relationships of diagonal struts

Infill walls behave linearly and elastically under very

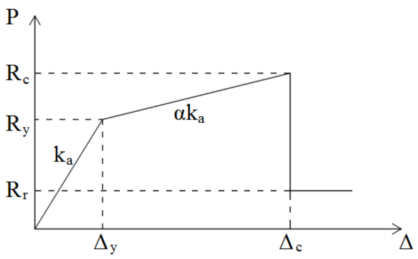


Fig. 6 Force-displacement relationship of equivalent compression strut

low loads. However, with increasing magnitude of loads, infill walls crack and start to behave nonlinearly. Since it is a complex phenomenon, several different proposals have been made for nonlinear force-displacement [F-Delta] relationship of the diagonal struts representing the infill. In this study, F-Delta relationship suggested by Tsai and Huang (2011) is used for defining nonlinear behavior of infill walls. Fig. 6 shows the backbone curve of F-Delta relationship that is assumed.

The strength of equivalent compression strut (R_c) is calculated by Eq. (11)

$$R_c = a \cdot t_{\inf} \cdot f'_{me90} \tag{11}$$

where f'_{me90} is the horizontal expected strength of infill. The corresponding displacement (Δ_c) is determined as

$$\Delta_c = \varepsilon'_m \cdot r_{\inf} \tag{12}$$

where ε'_m is the maximum strain of infill. The compression cracking force (R_y) is given by Eq. (13)

$$R_y = \frac{R_c - \alpha \cdot k_a \cdot \Delta_c}{1 - \alpha} \tag{13}$$

where α is the post-stiffness ratio (α=0.2) and k_a is the axial compressive stiffness of the strut which is obtained from Eq. (14). The corresponding displacement of cracking force is calculated as $\Delta_y = R_y/k_a$. The residual strength of strut (R_r) is assumed to be 30% of the yielding force

$$k_a = \frac{t_{inf} \cdot a \cdot E_{me}}{r_{inf}} \tag{14}$$

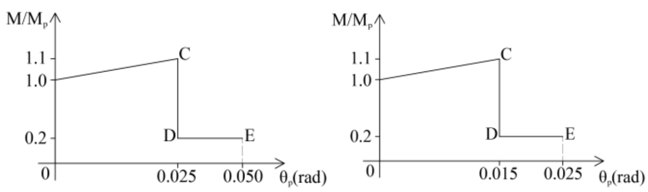
5. Pushover analysis of frames

The effect of openings on seismic response of brick-masonry infilled RC frames has been analytically studied by means of nonlinear static analysis, or so-called pushover, which has become a common tool for evaluating the seismic response of structures in recent years. Nonlinear mathematical model of 36 RC frame are created in SAP2000 (2016) environment considering the same material properties used in the design of RC frames. The infill walls without or with window and door openings are considered in analytical model as an equivalent compression strut which is placed between the beam-column joints. Section and nonlinear properties determined for different shape, position and percentage of openings are assigned to diagonal struts. The initial effective stiffness values of structural elements are reduced according to TSDC (2007) in order to account for cracking in sections during the inelastic response. Accordingly, the effective flexural stiffness of beams is taken as 40% of the uncracked stiffness of the section. The effective flexural stiffness of columns ($(EI)_e$) is taken to be between 40% and 80% of the uncracked stiffness ($(EI)_o$) according to the level of axial load (i.e., if $N_D/(A_c f_c) \leq 0.10$ then $(EI)_e = 0.40(EI)_o$ and if $N_D/(A_c f_c) \geq 0.40$ then $(EI)_e = 0.80(EI)_o$). For $N_D/(A_c f_c)$ between 0.10 and 0.40, a linear interpolation is performed, where N_D is axial load, A_c is cross sectional area of the column and f_c is concrete compressive strength. Effective natural vibration periods obtained from modal analysis of frames are given in Table 4. According to this table, it can be concluded that infill walls enhance the lateral stiffness of frames and moreover, partial openings in the infill wall reduce the stiffness of frames since natural periods lengthen when compared to periods of fully infilled ones.

Nonlinear behavior of columns and beams is considered by adopting a lumped plasticity model. Plastic hinges are assigned at both ends of elastic beam and columns. Bending moment-rotation envelopes of plastic hinges defining behavior under monotonically increasing deformation is determined in accordance with FEMA-356 (2000) (Fig. 7). In this figure, M/M_p is normalized bending moment and θ_p is plastic rotation of beam or column. Geometric nonlinearity is not taken into consideration and capacity curves are obtained by conducting a displacement controlled pushover analysis in SAP2000 (2016). An

Table 4 Effective natural periods of frames

Frame		Natural Periods (s)		
Number of Bay	Number of Story	Bare Frame	Partially Infilled Frame	Fully Infilled Frame
2	3	0.56	0.45	0.30
	4	0.74	0.58	0.39
	5	0.84	0.68	0.47
	6	0.95	0.77	0.56
3	3	0.59	0.44	0.31
	4	0.78	0.57	0.39
	5	0.88	0.68	0.48
	6	0.99	0.77	0.56
4	3	0.58	0.42	0.30
	4	0.75	0.54	0.39
	5	0.85	0.65	0.47
	6	0.96	0.73	0.55



(a) Beam (b) Column

Fig. 7 Bending moment-plastic rotation envelopes for frame members

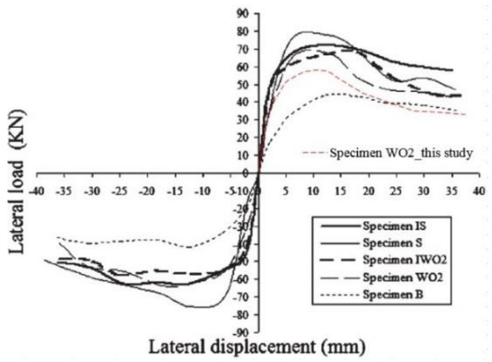


Fig. 8 Validation of the adopted model for Specimen WO2 of Kakaletsis and Karayannis (2008)

invariant lateral load pattern corresponding to the first-mode shape is used in pushover analyses.

In scientific literature there exist substantial experimental studies on seismic behavior of RC and steel one story, one bay infilled frames having different shapes, positions and sizes of openings (Mosalam *et al.* 1997, Kakaletsis and Karayannis 2007, Kakaletsis and Karayannis 2008, Asteris *et al.* 2011b, Koutromanos *et al.* 2011). In order to investigate the nonlinear behavior of infilled RC frames with openings the adopted macro-model is validated with the experimental study of Kakaletsis and Karayannis (2008). Accordingly, the analytical model of test specimen WO2 of Kakaletsis and Karayannis (2008) is created in SAP2000 (2016) and lateral load-lateral displacement curve of the adopted model for Specimen WO2 is obtained. A reasonable agreement between the results is achieved (Fig. 8). The ratio of the maximum lateral load obtained by the authors to the maximum lateral load obtained by Kakaletsis and Karayannis (2008) is 88% while the ratio of the corresponding lateral displacements is 85%.

After the validation of the adopted model, pushover analysis of the considered frames is conducted. Base shear is plotted as a function of the top displacement in order to obtain the pushover curve and the resultant pushover curves are presented in Fig. 9. Unstable results are obtained from pushover analysis of frames that have hinges with negative slope at any step of the analysis and therefore capacity curves of some models end up with relatively small values of lateral displacement. The detailed information about this topic can be found in SAP2000's help menu (see "Hinge unloading method"). In case of this problem in some models, the results of the performed analyses are reasonably sufficient in order to interpret the nonlinear behavior of partially infilled RC frames.

Pushover curves increase linearly at small values of lateral top displacement. When plastic hinges form, base shear force-top displacement relationship becomes a curve having decreasing slope. First plastic deformations occur at the infill walls of the first stories at small values of lateral top displacement. With a further increase in lateral displacement, plastic deformations concentrate first at some beam ends and then at the base of first story columns when the infill walls of the first stories exceed their capacities. Pushover curves reach their peak values in terms of base shear force when all infill walls in first few stories collapse. In the case of the partially and fully infilled frame, the maximum force is reached at a relatively small top displacement. With a further increase in lateral displacement, infill walls start to degrade and in a case of fully infilled frame, a substantial reduction in strength occurs after the infill walls of the first story completely collapse. This reduction is not so apparent in partially infilled frames. After this strength degradation due to gradual failure of infill wall, the pushover curve becomes almost parallel to horizontal axis, which indicates that the behavior of infilled frames become identical to behavior of bare frames. In the top stories the infill walls remain in the elastic range or exceed their compression cracking force while the RC frame is near collapse. Story mechanism occurs in some frames while a global failure mechanism is achieved in many frames. No significant change in plastic hinge formation sequence at RC members is observed due to existence of infill wall or positon and percentage of the partial opening. However, the initial stiffness of fully infilled frames is higher than the initial stiffness of other frames. Moreover, stiffness values of partially infilled frames are between the stiffness values of fully infilled and bare frames.

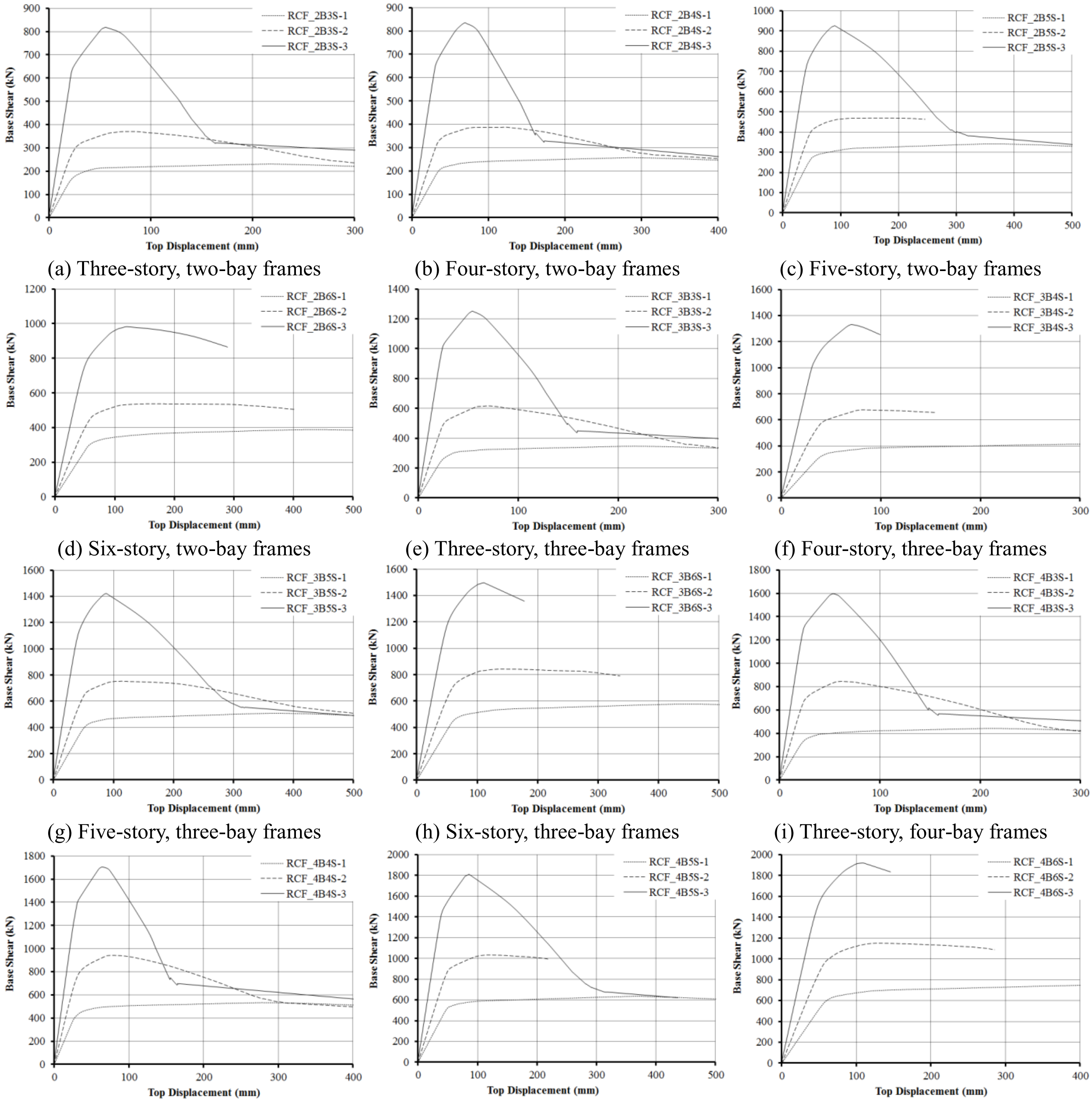
5.1 The maximum base shear force

The maximum base shear force values obtained from pushover analysis of frames are shown in Table 5. In this table, the base shear force values of partially and fully infilled frames are given with respect to the base shear force values of bare frames, which makes easier the comparison of the results and reflects the effect of partial openings in terms of the maximum base shear force.

The results of Table 5 indicate that, the average of the maximum base shear forces of fully infilled and partially infilled frames are 3.03 and 1.59 times larger than that for the bare frames, respectively. It can be concluded that the presence of masonry infill substantially increases the strength of the frame while partial openings decrease the base shear force capacity of the frame. Furthermore, the

Table 5 The maximum base shear force values of frames

Frame		**Maximum Base Shear (kN)**	**Infilled Frame/Bare Frame Base Shear Ratio**	
Number of Bay	**Number of Story**	**Bare Frame**	**Partially Infilled Frame**	**Fully Infilled Frame**
2	**3**	231	1.60	3.45
	4	257	1.50	3.25
	5	341	1.37	2.72
	6	389	1.38	2.52
3	**3**	347	1.78	3.61
	4	414	1.64	3.22
	5	509	1.48	2.79
	6	577	1.46	2.59
4	**3**	443	1.91	3.60
	4	533	1.77	3.20
	5	635	1.63	2.85
	6	750	1.54	2.56



(a) Three-story, two-bay frames (b) Four-story, two-bay frames (c) Five-story, two-bay frames

(d) Six-story, two-bay frames (e) Three-story, three-bay frames (f) Four-story, three-bay frames

(g) Five-story, three-bay frames (h) Six-story, three-bay frames (i) Three-story, four-bay frames

(j) Four-story, four-bay frames (k) Five-story, four-bay frames (l) Six-story, four-bay frames

Fig. 9 Pushover curves of frames

effect of infill walls and the partial openings in infill walls on the maximum base shear force of frames increase with increasing number of bays and decrease with increasing number of stories.

5.2 Yield displacement and yield base shear force

The global yield point, which is an important parameter in earthquake resistant design, is determined for each frame model. Although there exist some approaches based on idealization of pushover curve with multilinear curves in order to determine the global yield point of infilled frames, there is no universal consensus. So, in this study, the criterion used to define the global yield point is specified as the lateral displacement where yielding occurs at some structural members (the point where a clear departure from linear elastic behavior occurs) and it is monitored from the pushover analysis for each frame. First, the yield displacement is determined and the corresponding base shear force is obtained from the pushover curve. Consequently, yield drift ratios (δ_y/H) and yield base shear force coefficients (V_y/W) of frames are given in Table 6, where δ_y is the yield displacement, V_y is the yield base shear force, H is the total height and W is the seismic weight of frame, respectively.

Infill walls considerably increase the yield base shear force, or the yield base shear force coefficient of frames, while partial openings in the wall decrease the yield base shear force in comparison to fully infilled ones. For frames having the same number of bays and stories, the average yield base shear force coefficients of partially and fully infilled frames are 1.90 and 3.56 times larger than the yield base shear force coefficient of bare frames, respectively. The contribution of infill walls to the yield base shear force coefficients increases with increasing number of bays and decreases with increasing number of stories. Fully infilled frames yield at larger lateral displacement values in comparison to bare frames. On the other hand, the biggest yield drift ratios are obtained for partially infilled frames. This result can also be concluded from the comparison of pushover curves of partially infilled frames to pushover curves of fully infilled or bare frames.

The variation of yield base shear force coefficient with effective period is shown in Fig. 10. The spectral variation of the yield base shear force coefficient of TSCD (2007) is also plotted and base shear force capacities of frames are compared with code requirements. Shown with a solid line in Fig. 10 is the variation of V/W as a function of period obtained from the inelastic design acceleration spectrum of TSDC (2007). The inelastic (reduced) acceleration response spectrum is directly obtained from the linear elastic acceleration spectrum by dividing the spectral acceleration coefficient $A(T)$ to earthquake response reduction factor $R_a(T)$. All frames satisfy the minimum base shear force capacity requirement of TSDC (2007), while the fully infilled frames have the highest yield base shear force coefficient. Base shear force capacity of frames decreases as the opening ratio increase (i.e., as effective period of frames lengthens.). Frames having the same number of stories and the same infill conditions (bare, partially infilled and fully infilled) fall into the groups of threes at Fig. 10, which means these frames have reasonable close natural periods and base shear force coefficients.

Table 6 Yield drift ratios and corresponding base shear force coefficients

Frame		Bare Frame		Partially Infilled Frame		Fully Infilled Frame	
Number of Bay	Number of Story	$\frac{\delta_y}{H}\cdot 10^{-3}$	$\frac{V_y}{W}$	$\frac{\delta_y}{H}\cdot 10^{-3}$	$\frac{V_y}{W}$	$\frac{\delta_y}{H}\cdot 10^{-3}$	$\frac{V_y}{W}$
2	3	3.78	0.213	5.44	0.374	3.92	0.768
	4	3.67	0.177	4.25	0.293	4.00	0.616
	5	3.27	0.174	4.40	0.286	4.20	0.549
	6	3.17	0.161	4.72	0.272	4.33	0.489
3	3	3.00	0.190	4.89	0.401	4.44	0.806
	4	3.42	0.171	5.17	0.338	3.75	0.616
	5	3.47	0.169	5.00	0.301	4.33	0.552
	6	3.44	0.160	5.06	0.281	4.33	0.485
4	3	2.67	0.184	4.33	0.426	4.22	0.807
	4	3.25	0.163	4.50	0.327	3.92	0.606
	5	2.93	0.156	5.07	0.321	2.27	0.556
	6	3.28	0.144	4.50	0.297	4.17	0.490

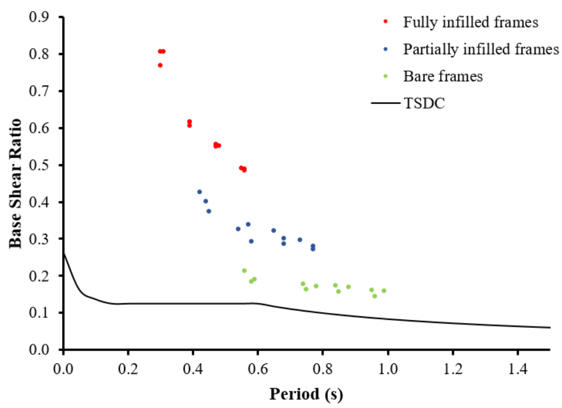


Fig. 10 Variation of yield base shear force coefficient with effective period

5.3 Displacement demand and corresponding base shear force

Lateral displacement demand of frames is determined in accordance with the procedure given in TSDC (2007). According to TSDC (2007), if the fundamental period of the structure is greater than the T_B corner period of the demand spectrum then equal displacement rule is employed, otherwise an equal energy approach is used. The equal displacement approximation implies that the peak displacement of moderate and long-period non-degrading systems is proportional to the ground motion intensity and the total displacement experienced by moderate and long-period structures that undergo inelastic response is, on average, the same as structures of the same period, responding in an elastic manner. This rule is an efficient and accurate approach to estimate the displacement demand of elastic-perfectly plastic SDOF systems. However, the well-known equal displacement rule does not hold for all types of structures (Ruiz-Garcia and Miranda 2005). Recent studies examined the effects of combined stiffness degradation and strength degradation have concluded that for moderate and long-period degrading systems peak displacements are, on average, similar to those experienced by elastoplastic or bilinear strength hardening systems and these effects are found to be significant for short-period systems (FEMA P440A 2009).

First, the resultant pushover curves are converted into

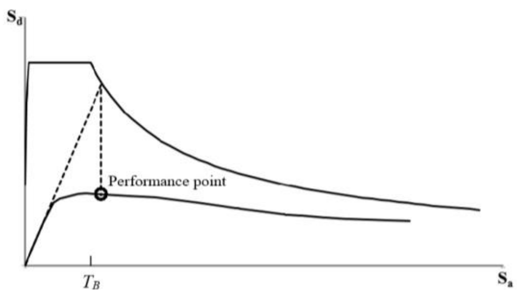
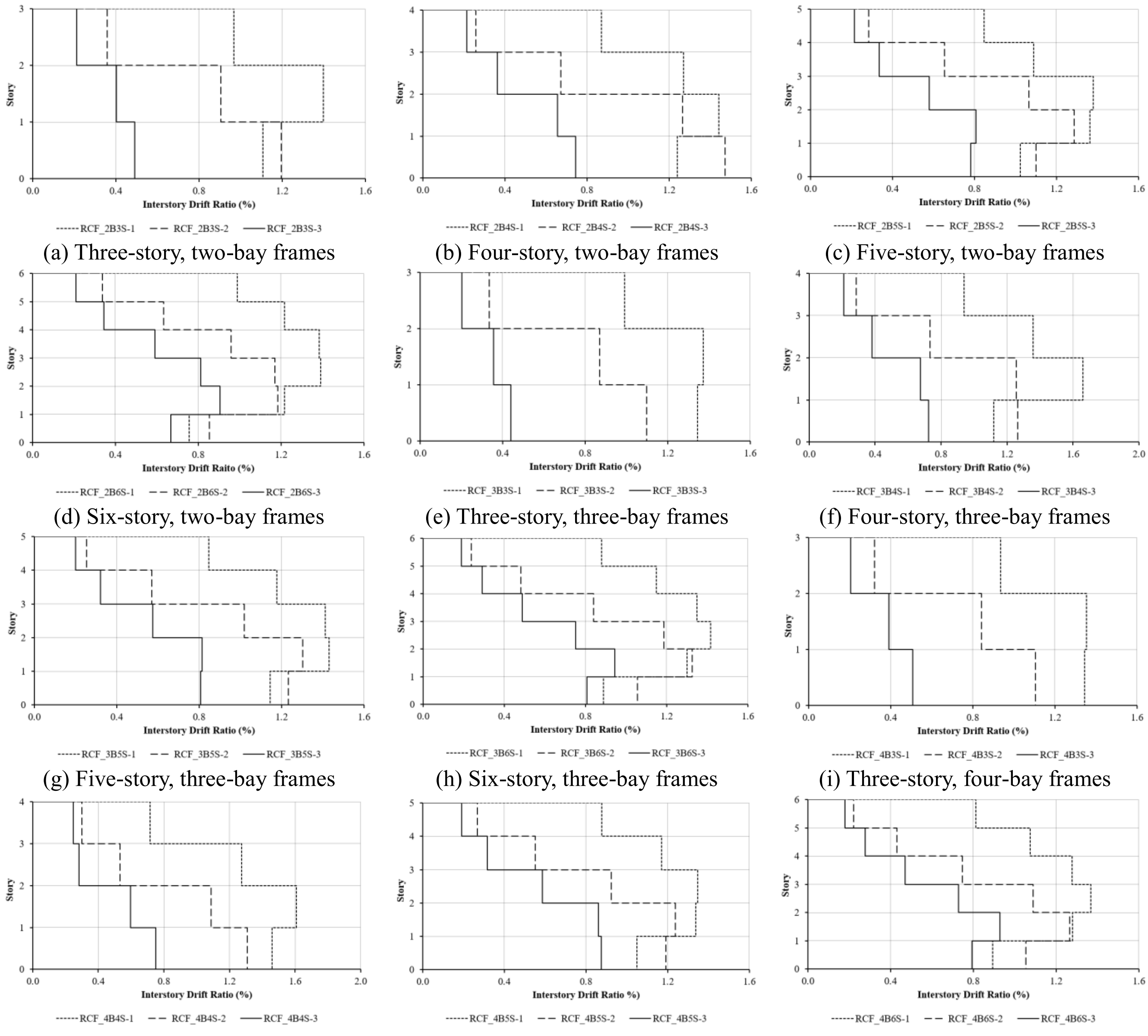


Fig. 11 Determination of displacement demand of equivalent SDOF system



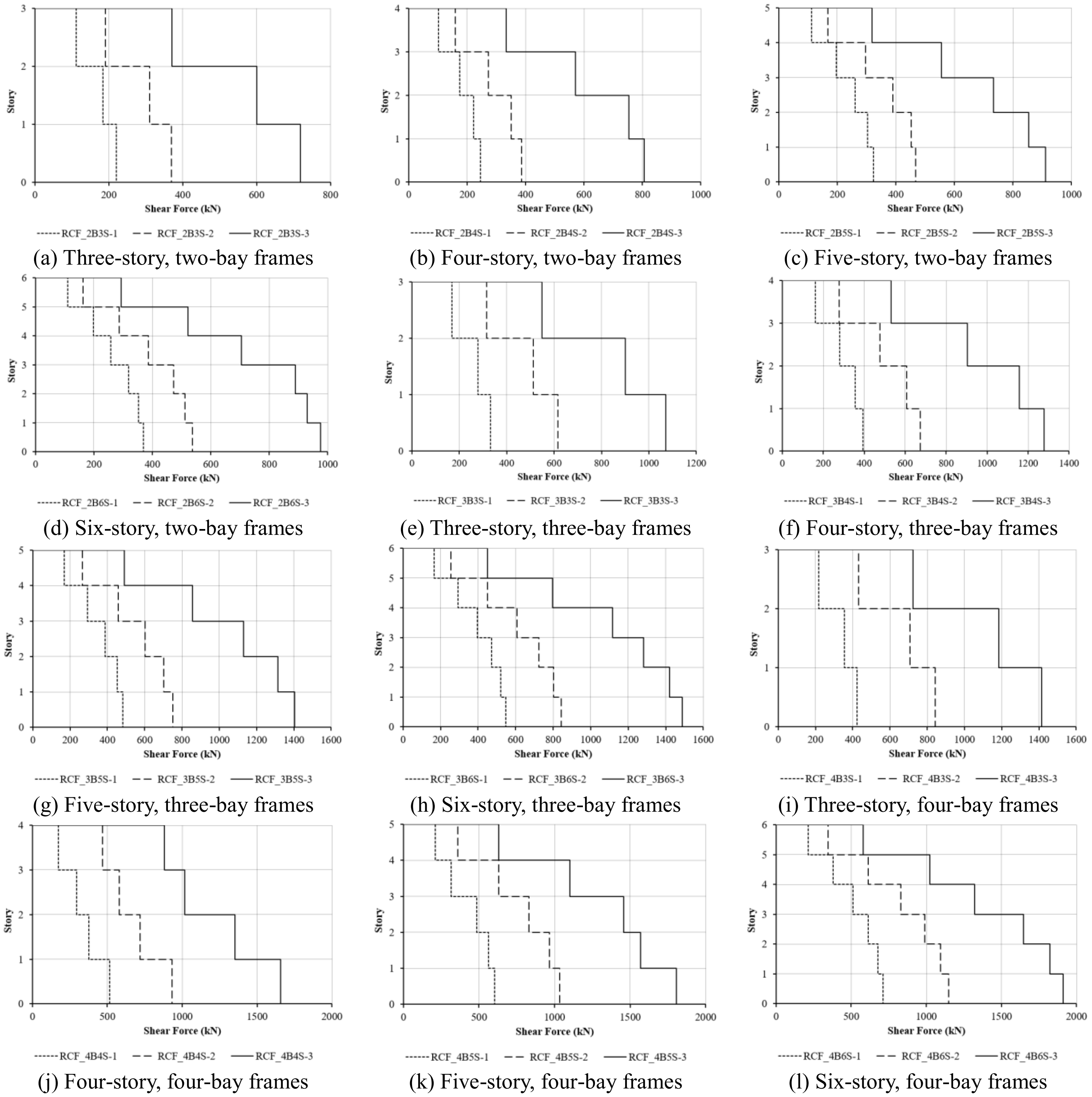
(a) Three-story, two-bay frames (b) Four-story, two-bay frames (c) Five-story, two-bay frames
(d) Six-story, two-bay frames (e) Three-story, three-bay frames (f) Four-story, three-bay frames
(g) Five-story, three-bay frames (h) Six-story, three-bay frames (i) Three-story, four-bay frames
(j) Four-story, four-bay frames (k) Five-story, four-bay frames (l) Six-story, four-bay frames

Fig. 12 Interstory drift ratios of frames

the spectral format by making the adjustments on the pushover curve by the modal mass coefficient and the modal participation factor of the first natural mode of the frames. The demand curve is represented by 5% damped design earthquake response spectrum. Then, the corresponding seismic demand and capacity spectra are presented in spectral format for comparison (Fig. 11) and intersecting the line representing the initial slope of the pushover curve with the demand and the capacity spectra, the performance point of each frame is determined. Finally, these spectral quantities are back transferred to a lateral top displacement and a base shear force by using the basic transformation equations of structural dynamics.

Table 7 lists the resultant displacement demands (δ_d) and the corresponding base shear forces (V_d) of frames. The largest top displacement demands are obtained for bare frames, due to their low stiffness in comparison to fully infilled and partially infilled frames. The average of the top displacement demands of partially and fully infilled frames are obtained to be 29% and 58% less than those for the bare frames, respectively. However, the presence of partial openings on the infill wall considerably reduces the displacement demand of the frames. The characteristic effect of infill walls and partial openings on top displacement demand decreases with increasing number of story. Due to the same reason, the lateral strengths of fully infilled frames are substantially higher than those of other models under the same seismic demand, while partial opening also reduce the corresponding base shear forces. The average of the calculated base shear forces of fully and partially infilled frames are 3.07 and 1.68 times higher than the average base shear forces of bare frames.

In order to investigate the effect of partial openings on lateral displacement profile of frames, the interstory drift



(a) Three-story, two-bay frames (b) Four-story, two-bay frames (c) Five-story, two-bay frames

(d) Six-story, two-bay frames (e) Three-story, three-bay frames (f) Four-story, three-bay frames

(g) Five-story, three-bay frames (h) Six-story, three-bay frames (i) Three-story, four-bay frames

(j) Four-story, four-bay frames (k) Five-story, four-bay frames (l) Six-story, four-bay frames

Fig. 13 Story shear forces

ratios corresponding to the displacement demand of frames are presented in Fig. 12. At top displacement demands of partially infilled frames, all infill walls in the first stories collapsed. Accordingly, lateral displacements and interstory drift ratios obtained at the first stories of all partially infilled frames are found to be close to those values of bare frames. Since infill walls at the upper stories of the frames still do not collapse and continue to restrict displacement of these stories, the differences between the lateral displacements of bare, partially infilled and fully infilled frames are more explicit. Story displacements and interstory drift ratios of fully infilled frames are significantly smaller than those of partially infilled and bare frames at each story. Due to absence of partial openings that influence the lateral stiffness of frames, the interstory drift ratios of partial infilled frames are generally found to be between the interstrory drift ratios of bare frames and fully infilled frames.

5.4 Distribution of story shear forces

In order to investigate the effect of partial openings on distribution of story shear forces, frames are pushed up to inelastic displacement demands and the corresponding story shear forces are determined. The distribution of story base shear forces of the frames is presented in Fig. 13.

As expected, infill walls considerably enhance the shear force of each story. Story shear forces of partially infilled

Table 7 Displacement demands and corresponding base shear forces

Frame		Bare Frame		Partially Infilled Frame		Fully Infilled Frame	
Number of Bay	Number of Story	δ_d (mm)	V_d (kN)	δ_d (mm)	V_d (kN)	δ_d (mm)	V_d (kN)
2	3	104.25	219.78	73.75	369.85	33.19	718.45
	4	144.70	245.23	110.09	386.83	59.36	806.48
	5	171.01	323.98	131.72	467.63	81.53	910.73
	6	208.69	369.80	154.11	537.02	105.91	974.97
3	3	111.26	331.34	69.11	616.65	30.00	1072.36
	4	152.40	394.20	106.18	672.93	59.70	1278.32
	5	180.31	483.22	131.44	750.51	81.58	1403.55
	6	209.60	547.68	153.89	842.63	104.21	1488.14
4	3	109.05	423.70	69.02	842,94	33.13	1415.00
	4	151.71	514.84	96.81	930.92	56.34	1655.80
	5	173.41	602.03	125.16	1032.20	84.97	1806.66
	6	201.24	711.23	144.25	1148.43	101.32	1911.28

frames are between those obtained for bare frames and fully infilled frames. Although, story base shear forces of partially infilled frames are found to closer to story base shear forces of bare frames. Also, it is observed that, infill walls and partial openings do not affect the ratio of interstory base shear forces. So, the normalized base shear force distribution remains the same.

6. Conclusions

The effects of partially infilled frames on nonlinear seismic behavior of RC frames is investigated by means of pushover analyses of moment resisting RC frames having different number of bays and stories. Totally, 36 nonlinear analytical models of bare, partially infilled and fully infilled frames are created. The effect of partial opening is introduced by the stiffness reduction factors which are developed from finite element analysis of frames considering the interaction of bounding frame with the infill wall. Pushover curves of frames are plotted and a comparison in terms of some demand and capacity related parameters is made.

The position of partial openings in infill wall significantly affect the lateral stiffness of the frame. Openings where load transfer initiates in infill wall have the maximum effect on the stiffness of the frames. On the other hand, openings, where the load transfer is considerably low, reduce the stiffness of frames slightly. Initial stiffness of fully infilled frames is higher than the initial stiffness of partially infilled and bare frames. The increase in stiffness of frames due to presence of infill walls cause a significant decrease in natural periods. Additionally, partial openings in infill wall reduce this effect.

It can be concluded that fully infilled and partially infilled frames behave like a bare frame when infill walls have completely collapse. The average of the maximum base shear forces of fully infilled frames is three times larger than that for the bare frames, while the same ratio is one and a half, on average, for partially infilled frames. Infill walls and partial openings also affect the yield base shear at force of frames. The highest yield base shears are obtained fully infilled frames, while the lowest yield base shear forces are obtained for bare frames.

The smallest displacement demands are calculated for fully infilled frames while the corresponding base shear force of fully infilled frames is the highest. The largest top displacement demands and the lowest values of corresponding base shear forces are obtained from the bare frames. The displacement demand and capacity base shear force of partially infilled frames are found to be between the values of bare and fully infilled frames. Moreover, infill walls and partial openings have considerable influence on story displacements and interstory drift ratios.

Story base shear forces corresponding to inelastic displacement demand of partially infilled frames are generally closer to story base shear forces of bare frames. The presence of partial openings in infill wall do not affect the ratio of interstory base shears and the distribution profile of normalized base shear forces remains the same.

The main findings of the present study indicate that, the presence of partial openings in infill wall substantially influences the quantity of each considered response parameter. In addition, the position and the percentage of the opening are found to be essential parameters reflecting the effect of opening. In general, seismic response parameters of partially infilled frames remain between those obtained for bare frames and fully infilled frames. The presence of partial openings decisively influences the nonlinear behavior of RC frames, both in terms of seismic demand and capacity, and cause a different behavior from that predicted for a bare frame or fully infilled frame.

References

Akpınar, U. and Binici, B. (2013), “The effect of infill wall collapse on the deformation estimations of reinforced concrete frames”, *J. Civ. Eng. Sci.*, **2**(3), 171-177.

Allouzi, R., Irfanoglu, A. and Haikal, G. (2014), “Non-linear finite element modeling of RC frame-masonry wall interaction under cyclic loadings”, *Tenth U.S. National Conference on Earthquake Engineering*, Anchorage, Alaska, July.

Andrei, Z. (2014), “Influence of openings on the behavior of masonry infill frames”, *2nd International Conference on Advances in Engineering Sciences and Applied Mathematics*, Istanbul, May.

Asteris, P.G. (2003), “Lateral stiffness of brick masonry infilled plane frames”, *J. Struct. Eng.*, **129**(8), 1071-1079.

Asteris, P.G., Chrysostomou, C.Z., Giannopoulos, I.P. and Smyrou, E. (2011a), “Masonry infilled reinforced concrete frames with openings”, *III ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Corfu, Greece, May.

Asteris, P.G., Kakaletsis, D.J., Chrysostomou, C.Z. and Smyrou, E.E. (2011b), “Failure modes of in-filled frames”, *Electronic J. Struct. Eng.*, **11**(1), 11-20.

Asteris, P.G., Cotsovos, D.M., Chrysostomou, C.Z., Mohebkhah, A. and Al-Chaar, G.K. (2013), “Mathematical micromodeling of infilled frames: State of the art”, *Eng. Struct.*, **56**, 1905-1921.

Asteris, P.G., Repapis, C.C., Tsaris, A.K., Trapani, F.D. and Cavaleri, L. (2015), "Parameters affecting the fundamental period of infilled RC frame structures", *Earthq. Struct.*, **9**(5), 999-1028.

Bolhassani, M., Hamid, A.A., Johnson, C. and Schultz, A.E. (2016), "Shear strength expression for partially grouted masonry walls", *Eng. Struct.*, **127**, 475-494.

Caprili, S., Nardini, L. and Salvatore, W. (2012), "Evaluation of seismic vulnerability of a complex RC existing building by linear and nonlinear modeling approaches", *Bull. Earthq. Eng.*, **10**(3), 913-954.

Cavaleri, L. and Trapani, F.D. (2014), "Cyclic response of masonry infilled RC frames: Experimental results and simplified modeling", *Soil Dyn. Earthq. Eng.*, **65**, 224-242.

CEN (2004), Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, European Committee for Standardization, Brussels, Belgium.

Dolsek, M. and Fajfar, P. (2008), "The effect of masonry infills on the seismic response of a four-storey reinforced concrete frame-a deterministic assessment", *Eng. Struct.*, **30**(7), 1991-2001.

Dorji, J. and Thambiratnam, D.P. (2009), "Modeling and analysis of infilled frame structures under seismic loads", *Open Constr. Build. Technol. J.*, **3**, 119-126.

Emami, S.M.M. and Mohammadi, M. (2016), "Influence of vertical load on in-plane behavior of masonry infilled steel frames", *Earthq. Struct.*, **11**(4), 609-627.

Ercolino, M., Ricci, P., Magliulo, G. and Verderame, G.M. (2016), "Influence of infill panels on an irregular RC building designed according to seismic code", *Earthq. Struct.*, **10**(2), 261-291.

Eurocode 6 (1996), Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures, European Committee for Standardization, Brussels, Belgium.

FEMA-306 (1998), Evaluation of earthquake damaged concrete and masonry wall buildings, Federal Emergency Management Agency, Washington, D.C.

FEMA-356 (2000), Prestandard and commentary for the seismic rehabilitation of buildings, Federal Emergency Management Agency; Washington, D.C.

FEMA P440A (2009), Effects of strength and stiffness degradation on seismic response, Federal Emergency Management Agency, Washington, D.C.

Fenerci, A., Binici, B., Ezzatfar, P., Canbay, E. and Ozcebe, G. (2016), "The effect of infill walls on the seismic behavior of boundary columns in RC frames", *Earthq. Struct.*, **10**(3), 539-562.

Fiore, A., Porco, F., Raffaele, D. and Uva, G. (2012), "About the influence of the infill panels over the collapse mechanisms actived under pushover analyses: Two case studies", *Soil Dyn. Earthq. Eng.*, **39**, 11-22.

Haris, I. and Hortobágyi, Z. (2015), "Comparison of experimental and analytical results on masonry infilled RC frames for cyclic lateral load", *Periodica Polytechnica*, **59**(2), 193-208.

Kakaletsis, D.J. and Karayannis, C.G. (2008), "Influence of masonry strength and openings on infilled R/C frames under cycling loading", *J. Earthq. Eng.*, **12(**2), 197-221.

Kakaletsis, D.J. and Karayannis, C.G. (2009), "Experimental investigation of infilled reinforced concrete frames with opening", *ACI Struct. J.*, **106(**2), 132-141.

Kaushik, H.B., Rai, D.C. and Jain, S.K. (2007), "Stress-strain characteristics of clay brick masonry under uniaxial compression", *J. Mater. Civ. Eng.*, **19**(9), 728-739.

Kaushik, H.B., Rai, D.C. and Jain, S.K. (2008), "A rational approach to analytical modeling of masonry infills in reinforced concrete frames buildings", *The 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Kose, M.M. (2009), "Parameters affecting the fundamental period of RC buildings with infill walls", *Eng. Struct.*, **31**(1), 93-102.

Koutromanos, I. and Shing, P.B. (2014), "Numerical modeling of masonry infilled reinforced concrete frame buildings", *Encyclopedia Earthq. Eng.*, 1-15.

Koutromanos, I., Stavridis, A., Shing, P.B. and Willam, K. (2011), "Numerical modeling of masonry-infilled RC frames subjected to seismic loads", *Comput. Struct.*, **89**(11-12), 1026-1037.

Kuang, J.S. and Zhang, H. (2014), "Shake table tests of infilled RC frames with different column-to-infill connections", *Second European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey, August.

Lima, C., Stefano, G.D. and Martinelli, E. (2014), "Seismic response of masonry infilled RC frames: practice-oriented models and open issues", *Earthq. Struct.*, **6**(4), 409-436.

Liu, L., Wu, Z. and Sun, H. (2014), "The influence of infill walls on RC frames under seismic excitation", *Arch. Eng.*, **2**(4), 68-72.

Madan, A., Reinborn, A.M., Mander, J.B. and Valles, R.E. (1977), "Modeling of masonry infill panels for structural analysis", *J. Struct. Eng.*, **123**(10), 1295-1307.

Martinelli, E., Lima, C. and De Stefano, G. (2015), "A simplified procedure for nonlinear static analysis of masonry infilled RC frames", *Eng. Struct.*, **101**, 591-608.

Mehrabi, A.B., Shing, P.B., Schuller, M.P. and Noland, J.L. (1996), "Experimental evaluatıon of masonry infılled RC frames", *J. Struct. Eng*., **122**(3), 228-237.

Moaveni, B., Stavridis, A., Lombaert, G., Conte, J.P. and Shing, P.B. (2013), "Finite-element model updating for assessment of progressive damage in a 3-story infilled RC frame", *J. Struct. Eng.*, **139**(10), 1665-1674.

Mohammadi, M. and Nikfar, F. (2013), "Strength and stiffness of masonry-infilled frames with central openings based on experimental results", *J. Struct. Eng.*, **139**(6), 974-984.

Mohebkhah, A., Tasnimi, A.A. and Moghadam, H.A. (2008), "Nonlinear analysis of masonry-infilled steel frames with openings using discrete element method", *J. Constr. Steel Res.*, **64**(12), 1463-1472.

Mondal, G. and Jain, S.K. (2008), "Lateral stiffness of masonry infilled reinforced concrete (RC) frames with central opening", *Earthq. Spectra*, **24**(3), 701-723.

Mosalam, K.M., White, R.N. and Gergely, P. (1997), "Static response of infilled frames usıng quasi-static experimentation", *J. Struct. Eng.*, **123**(11), 1462-1469.

Polyakov, S.V. (1950), "Investigation of the strength and of the deformational characteristics of masonry filler walls and facing on framed structures", *Construction Industry Instıtute*, **3**.

Porco, F., Fiore, A., Uva, G. and Raffaele, D. (2015), "The influence of infilled panels in retrofitting interventions of existing reinforced concrete buildings: a case study", *Struct. Infrastruct. Eng.*, **11**(2), 162-175.

Pradhan, P.M., Pradhan, P.L. and Maskey, R.K. (2012), "A review on partial infilled frames under lateral loads", *Kathmandu University J. Sci., Eng. Technol.*, **8**(1), 142-152.

Pujol, S., Climent, A.B., Rodriguez, M.E. and Pardo, L.P.S. (2008), "Masonry infill walls: an effective alternative for seismic strengthening of low-rise reinforced concrete building structures", *The 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Rathod, P. and Dyavanal, S.S. (2014), "Seismic evaluation of multistorey RC building with openings in unreinforced masonry infill walls with user defıned hinges", *Proceedings of 08th IRF International Conference*, Bengaluru, India, July.

Ricci, P., Verderame, G.M. and Manfredi, G. (2011), "Analytical investigation of elastic period of infilled RC MRF buildings", *Eng. Struct.*, **33**(2), 308-319.

Ruiz-Garcia, J. and Miranda, E. (2005), "Performance-based assessment of existing structures accounting for residual displacements", Report No. 153, John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

SAP2000 (2016), Integrated Structural Analysis and Design Software, Ver.16.0.0, Computer and Structures Inc., USA.

Stavridis, A. and Shing, P.B. (2010), "Finite-element modeling of nonlinear behavior of masonry-infilled RC frames", *J. Struct. Eng.*, **136**(3), 285-296.

Tasnimi, A.A. and Mohebkhah, A. (2011), "Investigation on the behavior of brick-infilled steel frames with openings, experimental and analytical approaches", *Eng. Struct.*, **33**(3), 968-980.

Tsai, M. and Huang, T. (2011), "Numerical investigation on the progressive collapse resistance of and RC building with brick infills under column loss", *World Academy Sci. Eng. Technol.*, **7**(1), 27-34.

TSDC (2007), Turkish seismic design code, Ministry of Public Works and Settlement; Ankara, Turkey.

TS500 (2000), Requirements for design and construction of reinforced concrete structures, Turkish Standards Institution; Ankara, Turkey.

UBC (1997), Uniform building code, International Conference of Building Officials; Whittier, California, USA.

Uva, G., Porco, F. and Fiore, A. (2012), "Appraisal of masonry infill walls effect in the seismic response of RC framed buildings: A case study", *Eng. Struct.*, **34**, 514-526.

Valente, M. (2012), "Seismic performance assessment of a masonry infilled ductile RC structure", *Int. J. Eng. Technol.*, **4**(6), 701-704.

Yuen, Y.P. and Kuang, J.S. (2015), "Nonlinear seismic responses and lateral force transfer mechanisms of RC frames with different infill configurations", *Eng. Struct.*, **91**, 125-140.

CC