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Experimental investigation of infilled r/c frames with eccentric openings

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Abstract. The influence of masonry infills with eccentric openings on the seismic performance of reinforced concrete (r/c) frames that were designed in accordance with current code provisions are investigated. Eight 1/3-scale, single-story, single-bay frame specimens were tested under cyclic horizontal loading up to a drift level of 4%. In all examined cases the shear strength of columns was higher than the cracking shear strength of solid infill. The parameters investigated include the shape and the location of the opening. Assessment of the behavior of the frames is also attempted, based on the observed failure modes, strength, stiffness, ductility, energy dissipation capacity and degradation from cycling loading. Based on these results there can be deduced that masonry infills with eccentrically located openings has been proven to be beneficial to the seismic capacity of the bare r/c frames in terms of strength, stiffness, ductility and energy dissipation. The location of the opening must be as near to the edge of the infill as possible in order to provide an improvement in the performance of the infilled frame.

Keywords: infilled r/c frames; masonry infills; openings; cycling loading; experiments.

1. Introduction

Masonry infills can be frequently found in r/c frame structures in the form of interior or exterior partition walls. The frames are generally well-engineered under gravity loads and strong earthquake loads, in accordance with the state-of-knowledge of the day, whereas the infill panels are invariably considered to be "nonstructural". However, the load-resistance mechanisms of an infilled frame is quite complex, involving the interaction of the frame and the infill and there is an uncertainty of how the brick walls interact with the structural r/c frames. Although the infills often control the global seismic response and performance, there are no code provisions or rational guidelines available for design and safety assessment of such structures. Besides, reported damage from earthquakes to brick-infilled r/c framed buildings ranges from very minor to significant. The behavior of infilled frames

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under lateral loads has been a subject of many debates for the past five decades.

It is important to recognize that many behavior problems with infilled frames arise from discontinuities of infill, resulting from soft stories or checkered patterns, leading to a high concentration of forces to be transferred among components. Other impediments to reliable modelling generalizations of infilled-frame systems are the large variation in construction practice over different geographic regions and changes of materials over time. Early infilled-frame construction, generally, consisted of clay brick (or sometimes stone masonry) and steel frames. With time, concrete frames became popular and concrete masonry units or solid (poured) concrete were used for the infill panels.

Early studies on the interaction between infill panels and the frames of buildings under lateral loading were mostly concerned with the monotonic lateral-strength capacity of infilled frame systems. The infill walls were commonly modelled as diagonal struts which can transfer only the compressive force between the diagonally opposite joints (FEMA 306 1999). Analytical models of the infill presented so far, have some disadvantages, such as the inability to model reliably the descending branch of the envelope, after the failure of the infill and the degradation of the infill due to cyclic loading, and the inability to take into account the influence of the mode of failure of both infill and frame. Early equivalent-strut methods, used an equivalent single strut to represent infill behavior. It was later realized that such a simplification did not accurately capture all facets of frame-panel interaction and several multiple-strut methods of analysis have been proposed (Mander *et al.* 1994, Gergely *et al.* 1994). In spite of these attempts to enhance infilled frame analysis using a multiple-strut approach, there are still drawbacks - principally the inability to model force transfer-slip at the frame-panel interfaces. Nonlinear finite element analysis, however, has been used when such a refinement is required (Shing *et al.* 1994, Mosalam *et al.* 1994). Nevertheless difficulties remain, mostly due to computational limitations, on analyzing more than one panel at a time.

Early research that investigated the seismic performance of infilled-frame specimens, using reversed cyclic loading, mostly focused on developing improved seismically-resistant design, analysis, and construction techniques for new structures. Mehrabi *et al.* (1996) have investigated the influence of masonry infill panels on the seismic performance of r/c frames that were designed in accordance with current code provisions. Both simple analytical models and inelastic finite-element analysis methods have been developed and validated by experimental results. One-bay masonry infilled frames tested under cyclic loading (C3ES Report 1995) and four-storey building tested under pseudo-dynamic loading (Negro *et al.* 1995, Fardis 1996) have been used by Combescure and Pegon (2000) for the validation of the so called two level modelling of the seismic performance of infilled frame structures, used in a complementary way – the local level, where the properties of each constituent are considered, and the global level, where each structural element has its own constitutive law and geometric support. The effect of masonry infills on the global seismic response of reinforced concrete structures is studied through numerical analyses by Fardis and Panagiotakos (1997). The authors have focused their research on the aspects of the effect of shortening of the natural period by the infilling and the effects of the irregularities of infills in elevation. Results of pseudo-dynamic tests of scale infilled r/c frame structures have been used by Bertero and Brokken (1983), Papia *et al.* (2002), Dolsek and Fajfar (2002) to determine the force against displacement envelopes and the hysteretic behavior of the usual model for infill that consists of two equivalent diagonal struts, which only carry compressive loads.

In spite of the general success of modelling infilled frames with solid panels, major difficulties still remain unresolved regarding the modelling approach of infilled frames with openings. Such frames, in practice, are commonplace and are perhaps the norm rather than the exception. From a broad survey of the available experimental results on the behavior of individual infilled frames under in-plane cyclic lateral loading, static or dynamic, as well as of the available models of the behavior that can be found in CEB (1996), it can be concluded that only a limited amount of research has been undertaken on infilled frames with openings. According to Fiorato *et al.* (1970), presence and size of openings are among the important influential parameters affecting strength and stiffness. Openings, interface gaps, and other discontinuities may affect development of a compression diagonal. Mallick and Garg (1971) investigated the effect of possible positions of openings on the lateral stiffness of infilled frames. The square frames, tested by the authors, were made of steel, while the infills were made of high-alumina cement mortar. In both series of the performed tests (one with infills provided with shear connectors, the other without shear connectors), a considerable decrease in lateral stiffness was recorded in cases of openings located close to the loaded ends of the compressed diagonal. On the contrary, the presence of relatively small openings ($L/4 \times L/4$) at the centre of infills, did not cause a considerable decrease in the stiffness of infilled frames. From the results obtained by Dawe and Young (1985), it seems that the negative effect of the doorway on the stiffness of the infilled frame is more pronounced for a symmetrically located opening. However, in the case of large amplitude cyclic actions, where the eccentricity of an opening is favourable, during one loading direction, and unfavourable, during the opposite direction, it seems that the symmetrical location is preferable. However the authors did not observe any significant reduction of the ultimate strength of their infilled frames in the presence of openings.

Other strength analysis recommendations have been made for infills with wide openings, but these have not been substantiated by experimental studies. Freeman (1994) has proposed a lateral force resisting system of an existing brick infill steel frame building, based on some representative load paths. Hamburger *et al.* (1993) has developed a methodology for evaluating the seismic adequacy of steel-frame buildings with masonry walls in which, using braced-frame models directly incorporating masonry struts, indicate structural stiffness comparable to that predicted by finite elements. For global building analysis purposes, the approach of diagonally concentric equivalent struts has been recently adopted by FEMA 356 (2000), that may be used to incorporate infill panel stiffness into analytical models for perforated infill panels (e.g., infills with window openings), provided that the equivalent stiffness of the infill is determined, using appropriate analysis methods (e.g., nonlinear finite element procedures such as discussed by Kariotis *et al.* 1994) in a consistent fashion with the global analytical model. Analysis of local effects, however, must take into account various possible stress fields that can potentially develop within the infill. Theoretical work and experimental data for determining multiple strut placement and strut properties, however, are not sufficient to establish reliable guidelines; the use of this approach requires judgment on a case-by-case basis.

Among the more notable methods of intervention in case of repair and strengthening of buildings, before and after an earthquake, is the addition of infilled walls (Dritsos 2005). Resent results from ongoing experimental research programs concerning less stiff interventions, by placing brick masonry walls, indicate that the technique has proved to be very efficient in increasing the stiffness and enhancing the seismic behavior of the whole building (Karayannis *et al.* 2005). For cases where the infilled masonry walls have window or door openings, experimental results have shown that the effectiveness of the technique was significantly reduced (Kakaletsis and Karayannis 2003). However, from these authors' results, it can be recognized that by choosing special positions for openings, the reduction in the effectiveness of the technique can be small.

In this paper, experimental results are presented from tests that were carried out on the interaction of infills and r/c frames under cyclic loading to find the effect of windows and doors on the hysteretic characteristics of infilled frames, and study the relative merits and demerits of different positions for windows and doors. Results from this study allow better evaluation of the structural behavior of masonry infill-frame structures, under earthquake loading, and investigate the potential of utilizing masonry infills with openings to improve the seismic resistance of buildings.

2. Experimental program

2.1 Test specimens

The experimental program as shown in Table 1 consisted of testing eight single-story, one-bay, 1/3-scale specimens of reinforced concrete frames. Each frame confined a clay brick infill with

Table 1 Test specimens

Specimen notation	Opening shape		Opening size *la*/*l*	Opening location *x*/*l*		
	Window	Door	0.25	0.17	0.33	0.50
B	Bare	Bare	-			
S	Solid	Solid	-			
WO2	■		■			■
WX2	■		■		■	
WX1	■		■	■		
DO2		■	■			■
DX2		■	■		■	
DX1		■	■	■		

where *l* is the length of masonry infill, *la* is the width of opening, *x* is the distance between opening centre-north edge of infill

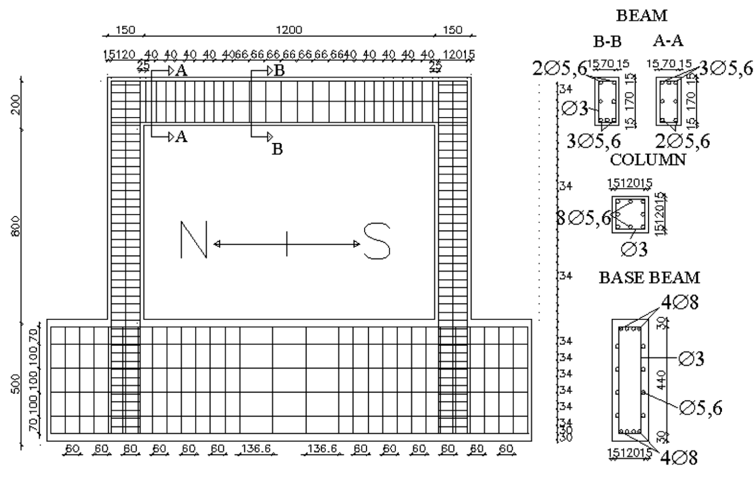


Fig. 1 Reinforcement detailing of the R/C frame model (mm)

openings. Two parameters were examined, the opening shape and the opening location within the frame. The description of the specimens is: A bare frame and a frame with solid infill (pilot specimens), three specimens with window shape opening at various locations and three specimens with door shape opening at various locations too.

The design details for the bare frame (reference frame) are shown in Fig. 1. The beam and the column cross sections were 100×200 mm and 150×150 mm respectively. The above dimensions corresponds to one third (1/3) scale of the prototype frame sections, 300×600 mm for the beam and 450×450 mm for the column. The column had closer ties throughout the length. The beam had more shear reinforcement in the critical regions. Each beam-to-column joint had five horizontal stirrups to prohibit brittle shear failure. The longitudinal reinforcement diameter $\Phi5.60$ mm and stirrups diameter $\Phi3$ mm of the frame members corresponds to one third (1/3) scale of $\Phi18$ mm and $\Phi10$ mm reinforcement diameters respectively of the prototype frame. At the specimens, low strength plain bars were used, although the rule for the construction practice is to use high strength deformed bars. The examining reinforced concrete frame, represents the typical ductile concrete construction, which is used in Greece according to the current codes and standards.

Masonry infill in the model had a height of 800 mm and a length of 1200 mm, as shown in Figs. 2(a) and 2(b), representing an exterior partition wall of the prototype structure with a height of 2.40 m and a length of 3.60 m (height against length ratio $H/l = 1/1.50$). In the experiments a brick

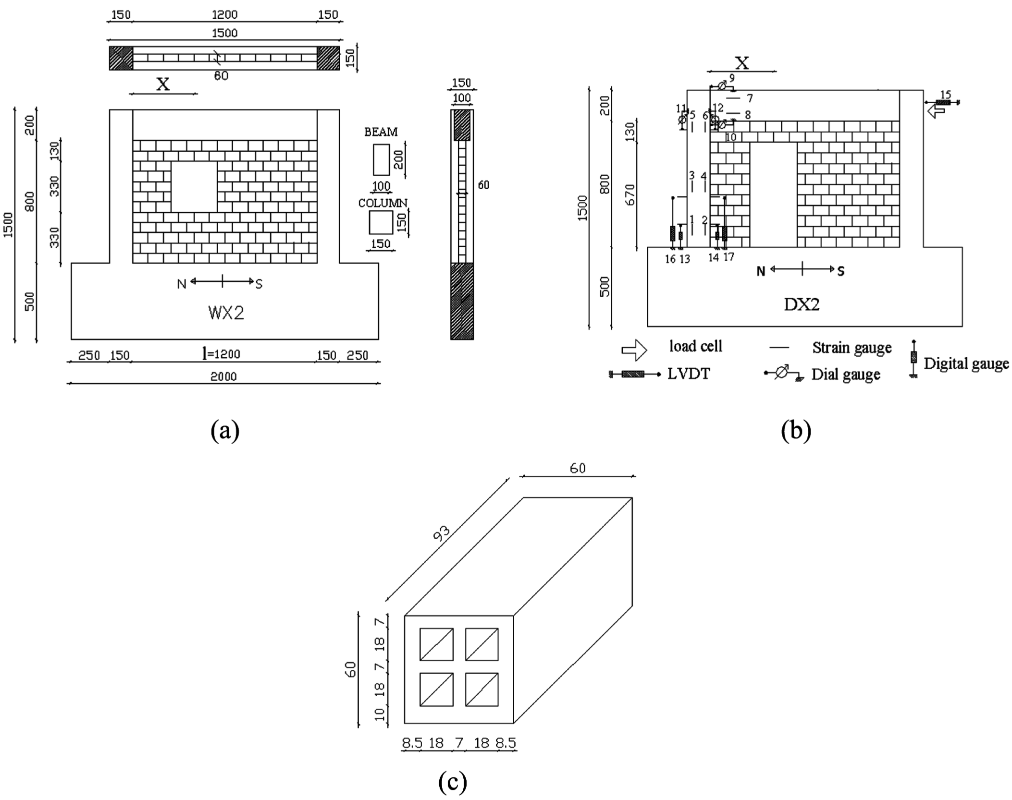


Fig. 2 Description of infilled frame specimens and instrumentation; (a) window opening (mm), (b) door opening (mm), (c) brick unit (mm)

with dimensions 60 × 60 × 93 mm was used and obtained by cutting a certain brick with dimensions 60 × 90 × 185 mm. The experimental brick unit corresponds to one third (1/3) scale of the prototype brick unit with dimensions 180 × 180 × 300 mm, which is used in exterior partition walls. Brick shape is shown in Fig. 2(c). The mortar joints were not scaled. A representative mortar mix was used for the infills contained the portions 1:1:6 (cement: lime: sand) and produced mechanical properties similar to type M1 mortar according to EN 998-2 (2001) standard.

Masonry properties were chosen in such a way to obtain the desired "weak" masonry lateral strength. Cracking shear of solid infill without the confinement offered by the surrounding frame was

$$V_{w,u} = f_v \cdot t \cdot l = 27.3 \text{ kN} \tag{1}$$

where f_v is the masonry shear strength of the bed joints from diagonal tests on full size bare infills ($f_v/f_n = l/H = 1.5/1$ as presented in Section 2.2), l is the length of masonry infill, H is the height of masonry infill, t is the thickness of masonry infill.

Assuming that plastic hinges occurred at the bottom and the top of the columns, flexural resistance of the bare frame was

$$V_{f,u} = 4M_{pc} : h = 40.28 \text{ kN} \tag{2}$$

where M_{pc} is the plastic moment of the column considering the effect of the axial force, $h = H - l_p$, H is the height of masonry infill, l_p is the plastic hinge length equal to 0.5 times the column depth. $V_{w,u}$ was lower than $V_{f,u}$ and this relation represents actual construction in Greece.

2.2 Material properties

The experimental mean compressive strengths were: for the frame concrete 28.51 MPa, for the infill masonry parallel to hollows 5.11 MPa, for the infill masonry perpendicular to hollows 2.63 MPa, for the bricks 3.1 MPa and for the mortar 1.53 MPa respectively. The experimental elastic modulus of the masonry infill was 670.3 MPa for the case parallel to the hollows and 660.66 MPa for the case perpendicular to the hollows. The experimental shear modulus was 259.39 MPa. The masonry shear strength, (f_v) with normal stress, (f_n) were measured from diagonal compression tests of masonry panels for various values of the ratio l over H, where l and H are the length and the height of masonry panels respectively. The measured results for f_v and f_n were as following

l/H	f_v (MPa)	f_n (MPa)
1.50	0.33	0.23
1.00	0.39	0.30
0.58	0.21	0.37
0.27	0.20	0.73

For the case of full size masonry infills with l over H equal to 1.5 the results were $f_v = 0.38$ MPa and $f_n = 0.25$ MPa. Also the masonry shear strength, (f_v) without normal stress, ($f_n = 0$) was 0.08 MPa. The yield stress for the stirrups was 212.2 MPa and for the reinforcement bars in the longitudinal direction was 390.47 MPa.

2.3 Test setup and instrumentation

The test setup is shown in Fig. 3. The lateral load was applied by means of a double action hydraulic actuator. The vertical loads were constant and exerted by hydraulic jacks through four strands at the top of each column and continually adjusted during each test. The level of this axial compressive load per column was set equal to 50 kN (0.1 of the ultimate load). Location of all instrumentation used during tests is presented in Fig. 2(b). One LVDT measured the lateral drift of the frame and a load cell measured the lateral force of the hydraulic actuator. Strain gauges 1 to 8 were placed on the center steel bars of the members at their critical sections, to monitor directly the behavior of the reinforcement steel during tests. Dial gauges 9 to 12, digital gauges 13 and 14, LVDT's 16 and 17 were placed at critical sections of the frame to estimate the relative rotation of the members.

The loading program included full reversals of gradually increasing displacements as shown in Fig. 3. Two reversals were applied for each displacement level. The cycles started from a ductility level 0.8 corresponding to an amplitude of about ±2 mm (the displacement of yield initiation to the system is considered as ductility level $\mu = 1$). Then were followed gradually by ductility levels 2, 4, 6, 8, 10, 12 corresponding to the amplitudes 6, 12, 18, 24, 30, 36 mm. Fig. 4 shows specimens "WX2" and "DX2" under testing.

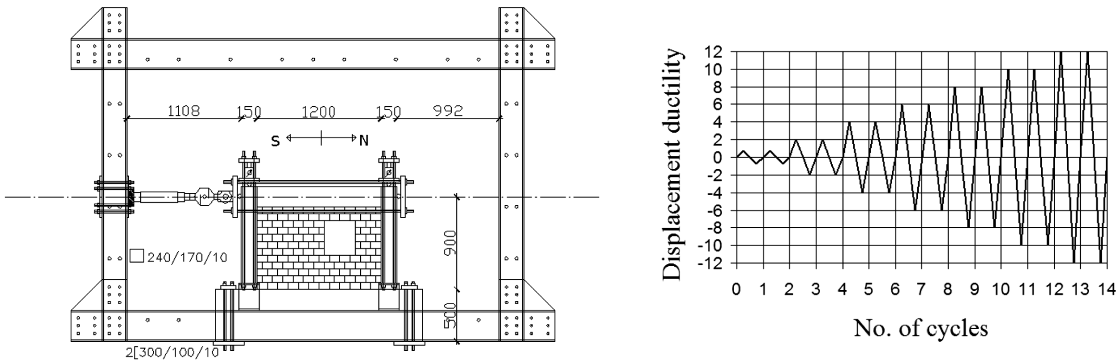
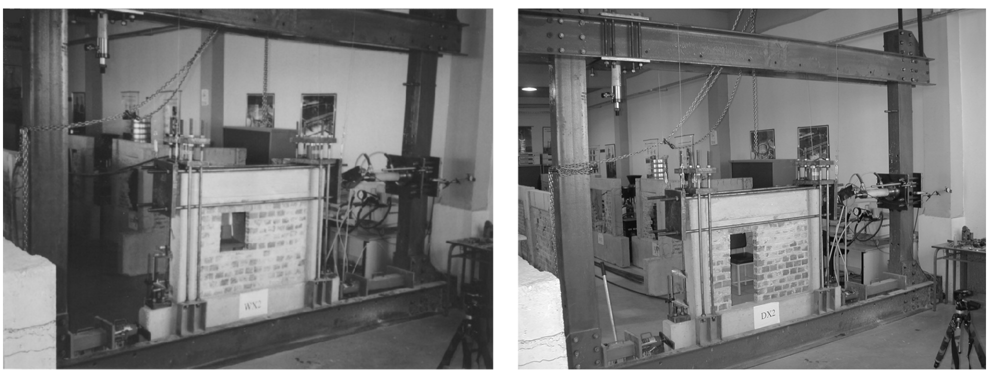
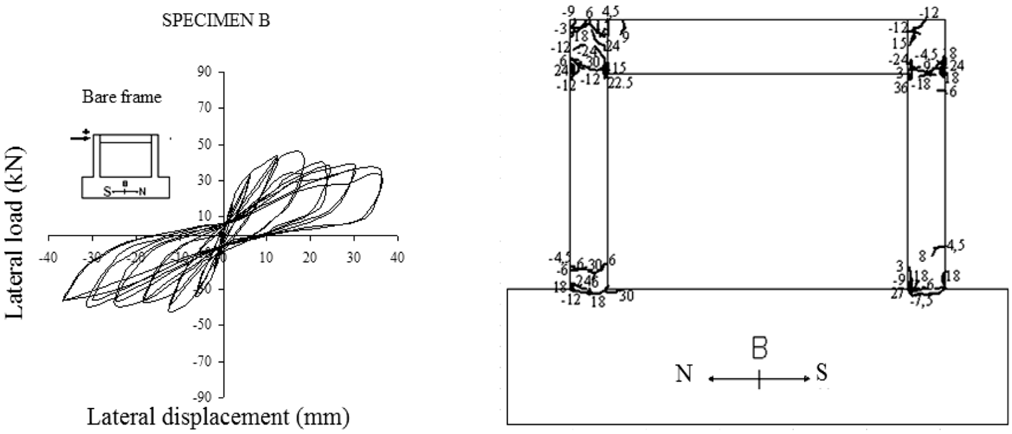


Fig. 3 Test setup (mm) and loading programme



(a) (b)

Fig. 4 Test setup of specimens: (a) WX2, (b) DX2



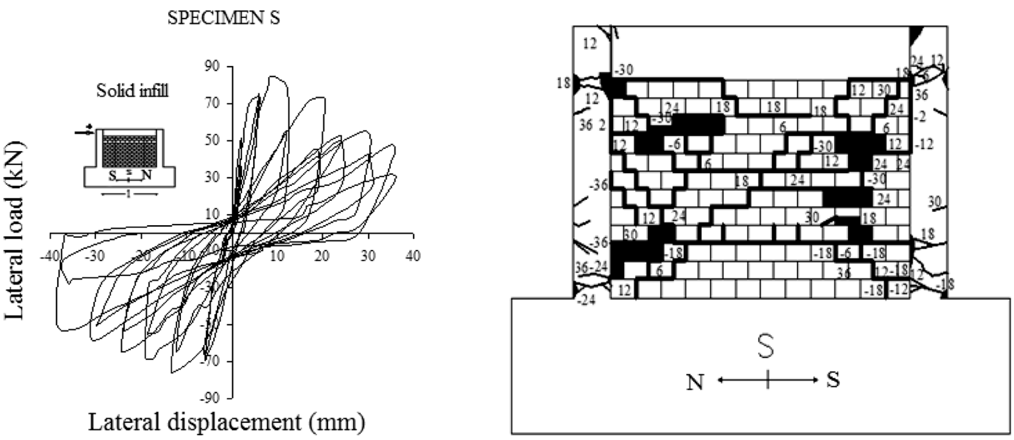
(a) (b)

Fig. 5 Lateral load against displacement hysteresis curves, (a) and failure mode, (b), of reference specimen of bare frame

3. Experimental results

The main output of the experimental investigation was a load against displacement curve for each frame shown in Figs. 5, 6, 7 and 8. The appearance and propagation of cracking was also recorded for both infill and frame throughout each test and presented in Figs. 5, 6, 7 and 8. The numbers on the damage patterns of specimens are cracking displacements in mm. The initial stiffnesses, critical loads, energy dissipation capacities and critical displacements of the eight specimens are summarized in Table 2.

Specimen “B” was the reference bare frame. Flexural cracks and corresponding plastic hinges



(a) (b)

Fig. 6 Lateral load against displacement hysteresis curves, (a) and failure mode, (b), of reference specimen with solid infill

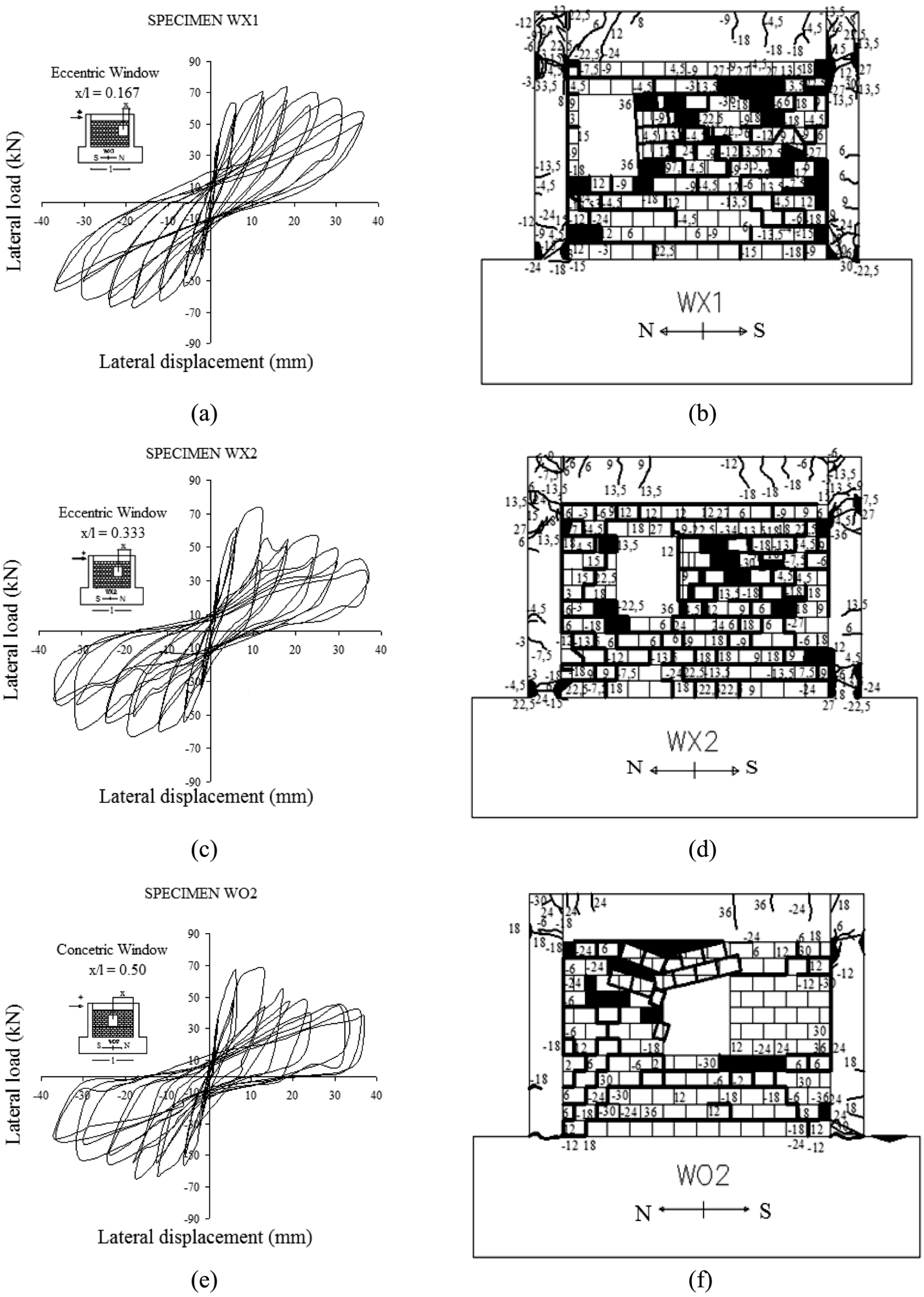


Fig. 7 Lateral load against displacement hysteresis curves and failure modes of infilled frame specimens with window openings and various opening locations, (a) and (b) x/l = 0.17, (c) and (d) x/l = 0.33, (e) and (f) x/l = 0.5

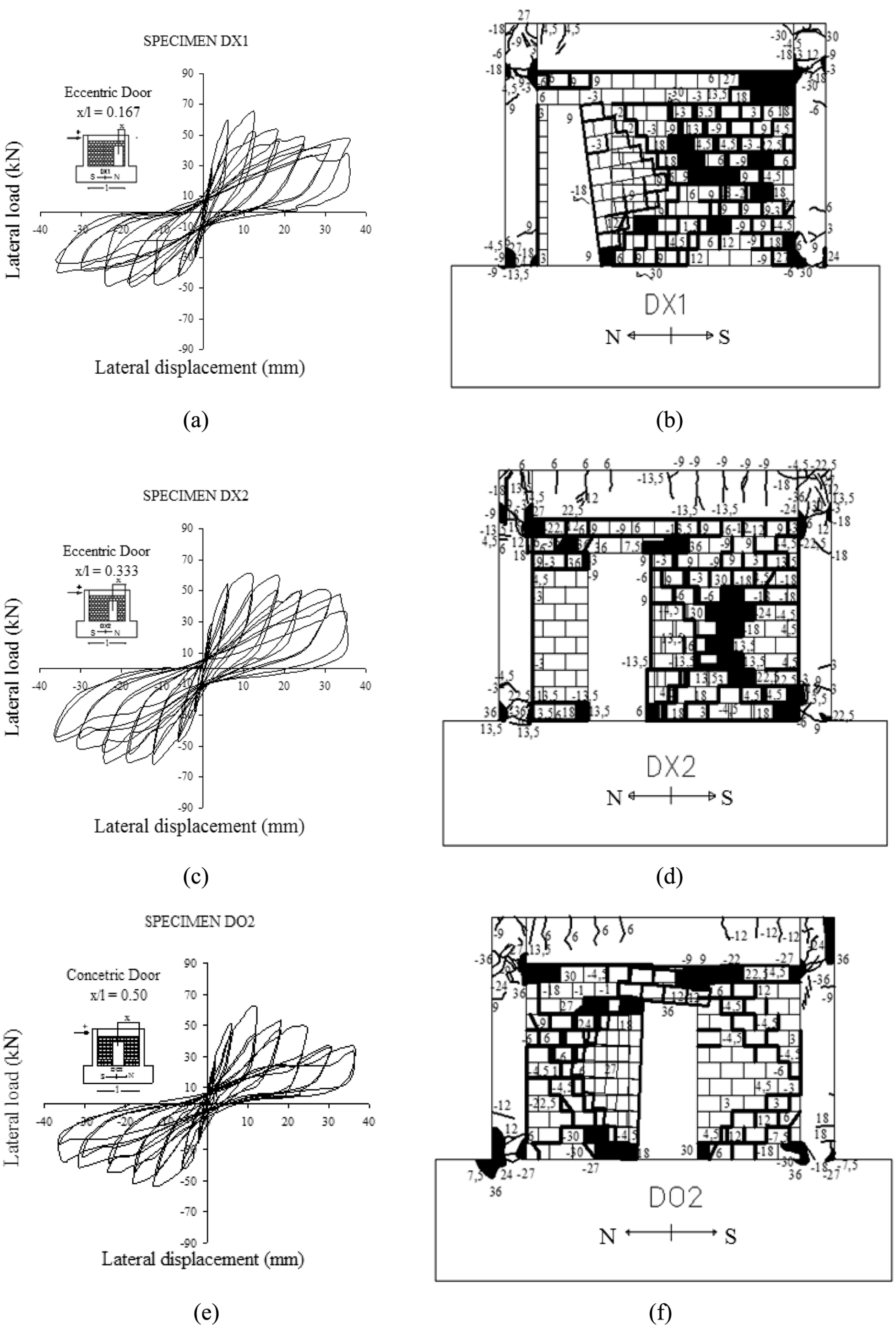


Fig. 8 Lateral load against displacement hysteresis curves and failure modes of infilled frame specimens with door openings and various opening locations, (a) and (b) x/l = 0.17, (c) and (d) x/l = 0.33, (e) and (f) x/l = 0.5

Table 2 Critical hysteretic characteristics of specimens

Specimen	Secant initial stiffness K_o (kN/mm)	Maximum lateral load V_u (kN)	Displacement at maximum load δ_u (mm)	Maximum normalized energy dissipation $W/2\delta$ (kN·mm/mm)	Displacement at maximum normalized energy dissipation δ_w (mm)	Cumulative energy dissipation ΣW (kN·m)
B	8.34	44.3	14.0	19.1	18	8.32
S	20.7	81.5	8.3	51.4	12	13.1
WO2	14.6	66.6	10.0	36.0	12	11.9
WX2	15.2	72.2	12.2	35.7	12	11.4
WX1	17.8	72.7	19.0	31.2	18	12.4
DO2	13.1	61.6	10.8	24.7	12	8.50
DX2	12.7	61.0	12.1	29.1	12	11.2
DX1	13.5	64.7	12.5	29.8	12	11.1

occurred at predicted critical locations at the bottom and the top of the columns and the ends of the beam as shown in Fig. 5(b). The sequence for the development of these cracks followed the distribution of the applied moments to the frame that is, first cracks formed in the bottom part of the tensile column, where moments were largest and axial compression was smallest – at a drift 0.4% – followed by cracking of the beam near the column face – at a drift 0.6%. The first bottom crack in the beam occurred before the first top crack. Spalling and crushing of concrete in columns developed at a drift 2.8%.

Specimen "S" had solid infill. The nonlinear behavior was initiated by the cracking of the infill. These cracks initiated in the form of inclined cracks in the top compression corners with approximately a 45 angle and were later joined by horizontal sliding cracks developed along the bed joints near the mid height of the panel at a drift 0.3%. Then developed plastic hinges at the top and the bottom of the columns at a drift 1.1%. The lower portion of the columns was braced by the bottom segment of the wall and flexural cracks formed at the columns higher than their bottom. As shown in Fig. 6(b) by the damage pattern of specimen, the failure was dominated by internal crushing in the infill – at a drift 1.9%.

Specimens "WO2", "WX2", "WX1" had infills with window openings as shown in Fig. 7. The first major diagonal – sliding crack in the infill was observed at a drift 0.3-0.4%. Plastic hinges developed at the top and the bottom of the columns at a drift 0.3-0.9%. Flexural cracks appeared in the external faces of the columns higher than their bottom, because the tensile columns were braced by the bottom segment of the wall up to a height level equal to 330 mm with the bottom of the opening. Also flexural cracks appeared in the external faces of the columns between the lower face of the beam and the top of the opening. The reason is because the upper segment of the wall formed a compressive bearing at the intersection of the compressive column with the top beam up to a height level with the top of the opening. The failure of these bottom and upper segments of the wall was dominated by sliding along their bed joints. Interior crushing of the wall segments between columns and window from shear failure was observed at a drift 1.7-2.1% and/or corner crushing of these segments from flexural failure of one or both of them was observed at a drift 2.0-3.5%.

Specimens "DO2", "DX2", "DX1" had infills with door openings as shown in Fig. 8. The first major diagonal – sliding crack in the infill was observed at a drift 0.3%. Plastic hinges developed at the top and the bottom of the columns at a drift 0.4%. Besides, flexural cracks appeared in the

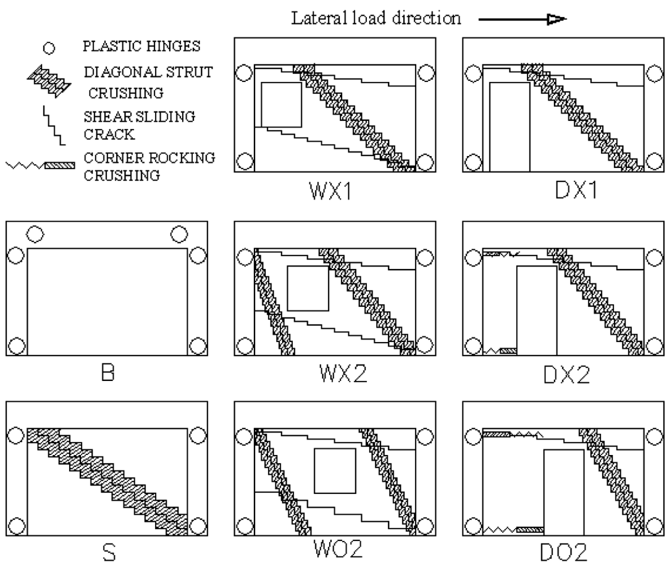


Fig. 9 Collapse mechanisms

external faces of the columns between the lower face of the beam and the top of the opening. The reason is because the upper segment of the wall formed a compressive bearing at the intersection of the compressive column with the top beam up to a height level with the top of the opening. This segment failed in sliding along the bed joints. The wall segment between the door and the tensile column was rocking and it failed by excess of the compressive and tensile strength both at the top and bottom edges at a drift 1.2-2.0%. The other wall segment between door and compressive column reached the interior crushing at a drift 2.0-2.7%.

In all infilled specimens with openings the cracking of the beam occurred far from the column face close to the mid-span vicinity of the beam. Plastic hinges in the beams were developed at drifts higher than 0.9% or they did not developed at all.

In the case of the present project shear failure of the columns was not observed.

The above identified failure mechanisms that can be possibly attributed to the frame – infill with eccentric openings interaction are summarized in Fig. 9. By comparing the crack patterns of the examined specimens, the following can be concluded: The mechanism of the frame with the weak solid infill is governed by plastic hinges at both ends of the columns and masonry diagonal crushing. The mechanism of the frame with window opening in weak infill is governed by plastic hinges at both ends of the columns, internal crushing of masonry segments among columns and window, shear sliding of masonry zones above and below the window. The mechanism of the frame with door opening in weak infill is governed by plastic hinges at both ends of the columns, corner – toe crushing from rocking of masonry segment among the tensile column and the door or the shorter one in the case of eccentric door, internal crushing of the other masonry segment among column and door, shear sliding of masonry zone above the door. Especially for the specimens "WO2" and "DO2" a none symmetrical behavior is observed. This may be occurred due to a premature downwards displacement of the spandrel as shown in Figs. 7(f) and 8(f). Consequently, it must be pointed out that the testing programme does not cover all cases of eccentric openings, since specimens with an x over l ratio equal to 0.67 and 0.83 have not been tested.

4. Interpretation of experimental results

4.1 Comparison of critical hysteretic characteristics

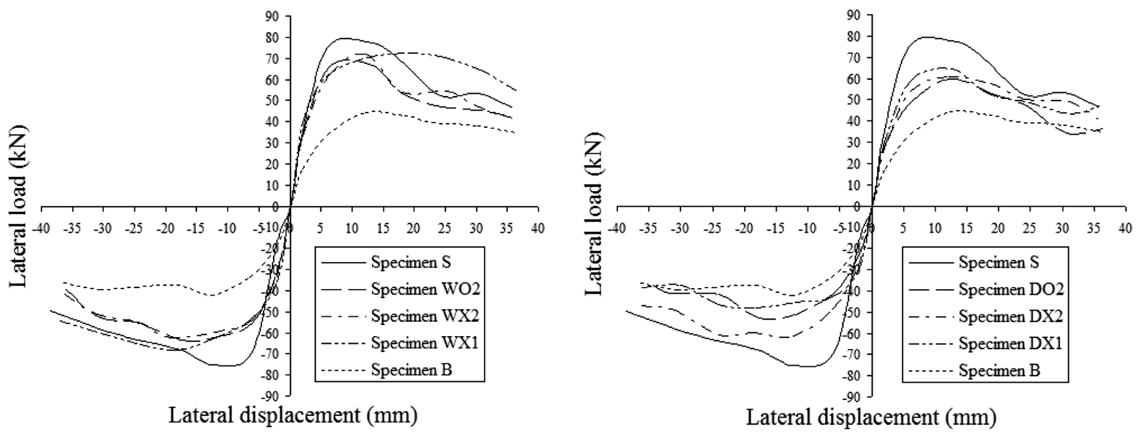
From the hysteresis loops envelops presented in Fig. 10 and from Table 3 it can be concluded that:

For all cases of infilled frames with openings lateral resistance (v) was from 1.38 up to 1.64 times that of the corresponding bare frame, while the resistance of solid infill specimen was 1.84 times that of the corresponding bare frame. The location of the opening towards the center of the span, on the diagonal, resulted to higher decrease of resistance.

For displacement four times larger than the one corresponding to the maximum shear resistance of the infilled frame with solid infill and at a stage of advanced damage, the residual lateral resistance (β_{res}) continued to be as high as 1.06 to 1.58 times the resistance of the bare frame. The residual resistance was larger in the case of windows than it was in the case of doors. The location of the opening towards the center of the span decreased the residual resistance especially in the case of doors.

The presence of the infill with openings increased considerably in all cases the initial stiffness (k) of the system about 1.52 up to 2.14 times that of the bare frame while the solid infill increased the stiffness 2.48 times that of the bare frame. The location of opening towards the center of the span, on the diagonal, resulted to higher decrease of stiffness.

In all the specimens tested the first major crack in an infill occurred at a drift (γ_y) between 0.25% and 0.39% which can be regarded as the serviceability limit for this type of structure. As a result of the increased stiffness, in most cases, this drift was smaller than that of 0.34% in the case of bare frame. The drift (γ_u) corresponding to the maximum lateral resistance of infilled frames ranges from 0.92% to 2.11% and it can be considered as the ultimate limit state. The location of the opening did not affect very much the serviceability limit of an infilled frame, while the location of the opening close to the center resulted to lower values of ultimate limit state.



(a) (b)

Fig. 10 Lateral load against displacement envelops; (a) Window openings of various locations, (b) Door openings of various locations

Table 3 Comparison of hysteretic characteristics for test specimens: (a) Reference specimens: Bare frame, solid infill, (b) Window openings of various locations, (c) Door openings of various locations

Spec.	Structural morphology	v	γ_y (%)	γ_u (%)	k	$v_{\lim}$	$\mu_{0,85}$	β_{res}	V_2/V_1 (m. v.)	W_2/W_1 (m. v.)	$\Sigma W/\Sigma W_B$
(a)											
S	Solid infill	1.84	0.28	0.92	2.48	0.65	4.24	1.34	0.87	0.85	1.57
B	Bare frame	1.00	0.34	1.55	1.00	0.54	3.97	1.00	0.90	0.70	1.00
(b)											
WX1	Window x/l=0.17	1.64	0.28	2.11	2.14	0.62	5.39	1.58	0.92	0.69	1.49
WX2	Window x/l=0.33	1.63	0.25	1.35	1.82	0.48	2.54	1.21	0.83	0.68	1.37
WO2	Window x/l = 0.50	1.50	0.38	1.11	1.74	0.76	3.89	1.19	0.85	0.72	1.43
(c)											
DX1	Door x/l = 0.17	1.46	0.28	1.39	1.62	0.53	3.33	1.36	0.84	0.71	1.33
DX2	Door x/l = 0.33	1.38	0.31	1.34	1.52	0.58	4.13	1.17	0.88	0.69	1.35
DO2	Door x/l = 0.50	1.39	0.28	1.20	1.57	0.53	3.20	1.06	0.87	0.69	1.02

where v is the lateral resistance of infilled frames normalized to the lateral resistance of the bare frame, γ_y is the serviceability limit, γ_u is the ultimate limit, k is the initial stiffness of infilled frames normalized to the initial stiffness of the bare frame, $v_{\lim}$ is the ratio between the shear force at the end of the linear stage and the maximum shear resistance, $\mu_{0,85}$ is the ductility factor, μ_{res} is the residual resistance of infilled frames normalized to the residual resistance of the bare frame, V_2/V_1 is the mean value for all cycle amplitudes of the ratios of the maximum recorded force during the second cycle to the maximum recorded force during the first cycle, W_2/W_1 is the mean value for all cycle amplitudes of the ratios of the energy dissipation during the second cycle to the energy dissipation during the first cycle, $\Sigma W/\Sigma W_B$ is the ratio of the cumulative energy dissipation by each infilled frame to the cumulative energy dissipation by the bare frame.

The presence, behavior and failure of the infills with openings did not reduce the ductility factor ($\mu_{0,85}$) of infilled frames, corresponding to a lateral force response equal to 85% of the maximum. The range of ductility was from 2.54 up to 5.39 while the ductility was 3.97 for the bare frame and 4.24 for the frame with solid infill. The location of the opening close to the center resulted to lower values of ductility factor.

The total energy dissipation capacity (ΣW) of the infilled frames with openings was 1.02 up to 1.49 times the capacity of the corresponding bare frame while the solid infill increased the capacity 1.57 times the capacity of the corresponding bare frame. It pointed out that higher values of the dissipation ratio appeared in the case of location of the opening towards the column.

It can be observed that a force-response degradation with a mean value equal to 8% up to 17% occurred during the second loading cycle in all examined specimens. Besides, it is apparent that a drastical reduction of energy dissipation capacity with a mean value equal to 15% up to 32% occurred during the second loading cycle in all examined specimens due to the pronounced pinching effect. The loss of energy dissipation capacity is greater than the corresponding loss of strength. Decreasing eccentricity of the openings resulted in larger amounts of loss of strength and energy due to cycling loading.

4.2 Comparison of hysteretic characteristics versus imposed displacements

Using the stiffness at the first major crack as a reference value from Fig. 11, it can be concluded that the loss of stiffness was greater after the maximum resistance. At very high drifts the loss of stiffness tends asymptotically to that of the bare frame because shear failure of the columns was not observed. When the opening was located towards the center the loss of stiffness was greater for doors at low drifts but the loss did not differ at all examined specimens at high drifts.

The ratios of the lateral strength, V, of the specimens to the flexural strength, V_B, of the corresponding bare frame were calculated. These ratios show the effectiveness of an infill with opening in increasing the lateral strength of a frame. From Fig. 12 it can be concluded that the increase of the system strength due to infills was more significant at low displacement ranges (from 2 mm to 12 mm) than at higher displacement ranges (from 18 mm to 36 mm) where this increase was lower. The average added strength due to a solid infill was 2.00 and 1.44 times at low and high displacement ranges respectively. Those specimens with eccentric of various locations window, as it

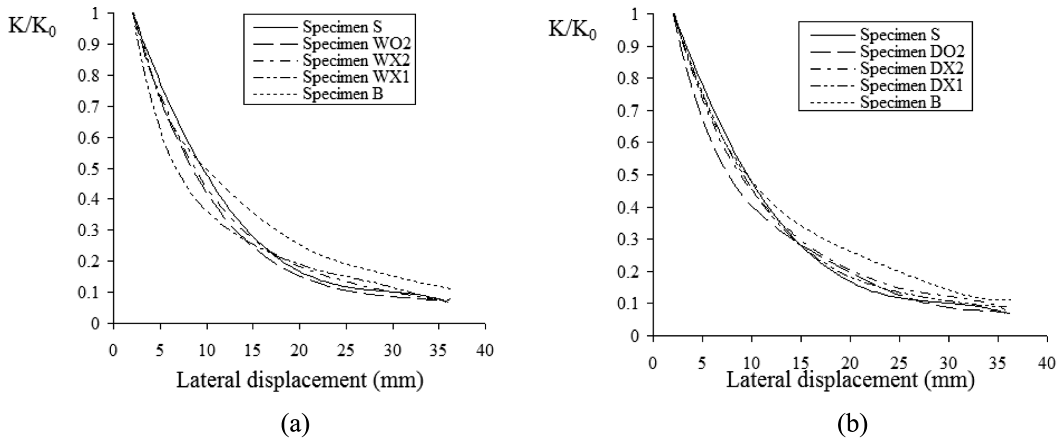


Fig. 11 Reduced stiffness of the infilled frames; (a) Window openings of various locations, (b) Door openings of various locations

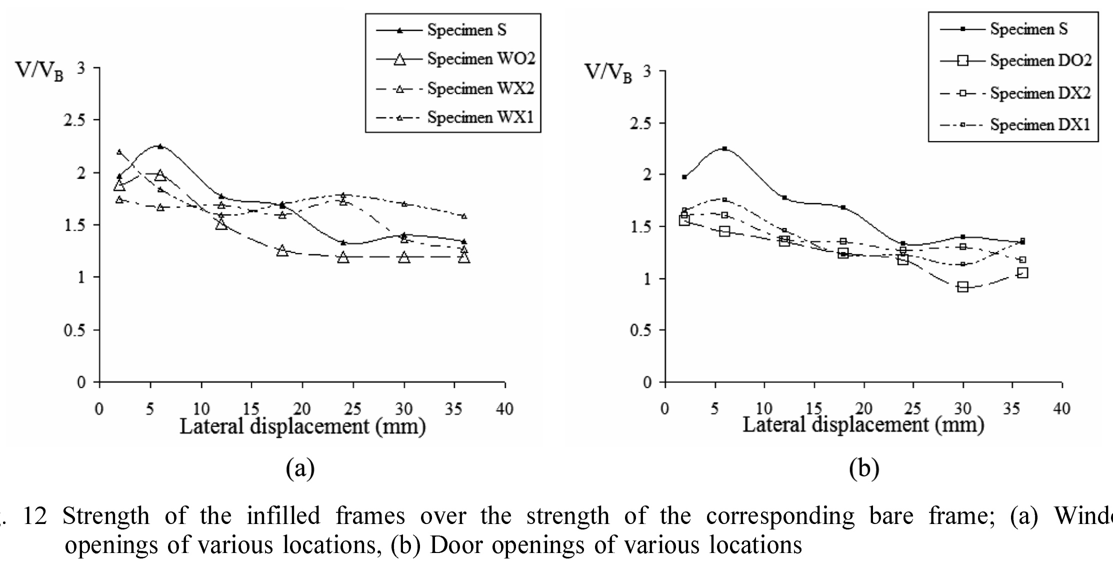
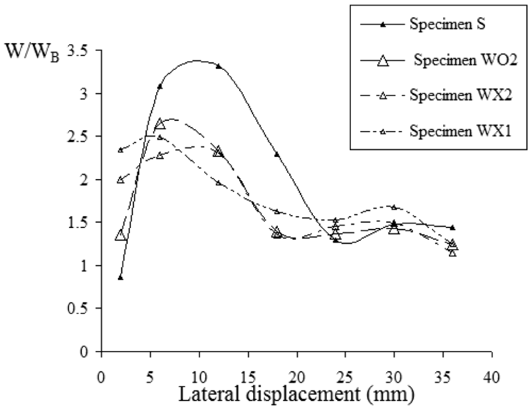


Fig. 12 Strength of the infilled frames over the strength of the corresponding bare frame; (a) Window openings of various locations, (b) Door openings of various locations



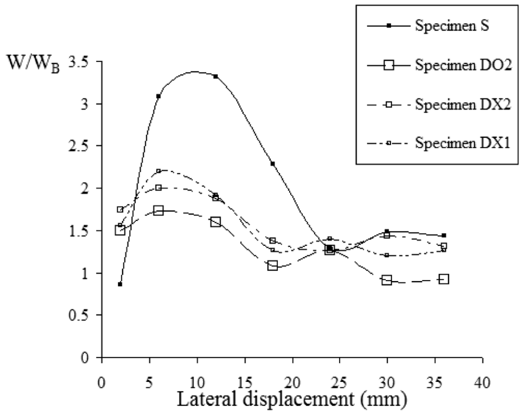
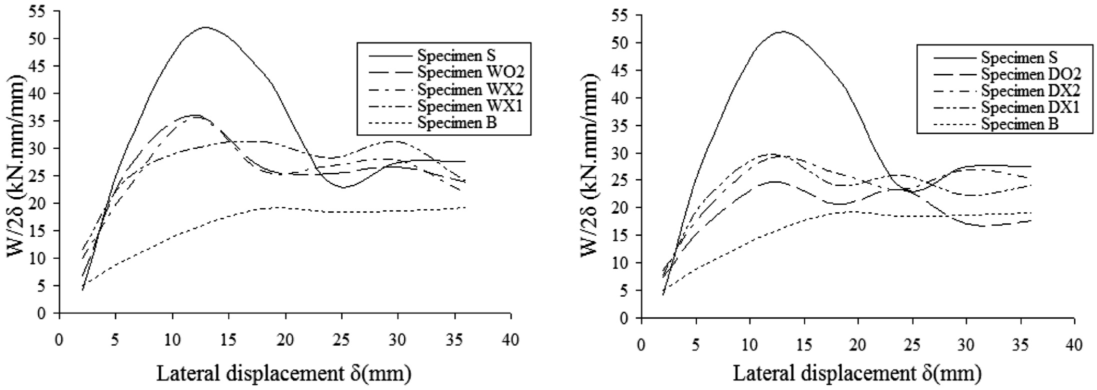


Fig. 13 Reduced energy dissipation capacity of the infilled frames over the reduced energy dissipation capacity of the corresponding bare frames; (a) Window openings of various locations, (b) Door openings of various locations

was moved away from the compressive column towards the center, added average strength from 1.88 and 1.69 times up to 1.79 and 1.21 times at low and high displacement ranges respectively. Those specimens with corresponding doors added average strength from 1.62 and 1.24 times up to 1.45 and 1.10 times at low and high displacement ranges respectively. It can be concluded that added average strength increased, increasing the opening eccentricity.

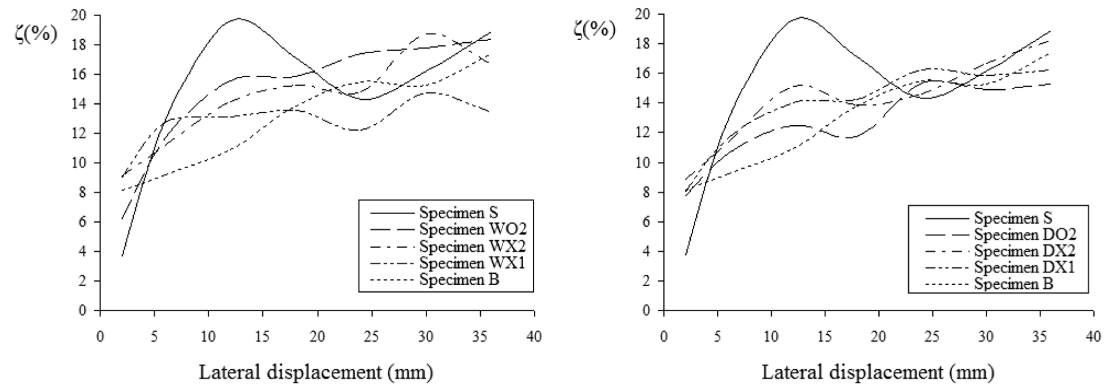
Comparing Fig. 12 and Fig. 13 it can be concluded that the contribution of the infill to the energy dissipation capacity of the system was greater than the contribution to the strength especially at low distortions. Indeed, from Fig. 13 it can be concluded that the energy dissipation added to the system due to infills was more significant at low displacement ranges (from 2 mm to 12 mm) than at higher displacement ranges (from 18 mm to 36 mm) where it was diminished but still considerable. The average added energy dissipation due to a solid infill was 2.42 and 1.63 times at low and high displacement ranges respectively. Those specimens with eccentric of various locations window, as it was moved away from the compressive column towards the center, added average energy dissipation from 2.26 and 1.52 times up to 2.11 and 1.36 times at low and high displacement ranges respectively. Specimens with corresponding doors added average energy dissipation from 1.89 and 1.28 times up to 1.61 and 1.04 times at low and high displacement ranges respectively. It can be concluded that added average energy dissipation increased, increasing the opening eccentricity.

The energy dissipated at a given cycle (in terms of the area bounded by the hysteretic curve for that cycle), W, normalized by the total peak-to-peak displacement variation for that cycle, 2δ, is presented in Fig. 14. Variable $W/2\delta$ has the physical meaning of the static force that produces the same work with the one produced by the hysteresis loop and expresses the average width of a hysteresis loop. Variable $W/2\delta$ is usually used to compare energy dissipation at any given level of displacement reversal for systems tested with different load patterns and histories. In the present study the same type of lateral displacement history was used for all specimens. Nevertheless, it is convenient to compare present results with the available experimental results from the literature. From Fig. 14 it can be seen that at all levels of displacement reversal infilled frames with location of the opening closed to the column dissipated more energy than infilled frames with location of the



(a) (b)

Fig. 14 Reduced energy dissipation per cycle divided by the corresponding displacement 2 of the cycle; (a) Window openings of various locations, (b) Door openings of various locations



(a) (b)

Fig. 15 Equivalent viscous damping ratio during the loading cycles; (a) Window openings of various locations, (b) Door openings of various locations

opening close to the center of the span.

On the basis of hysteresis loops obtained from the tests, the equivalent viscous damping ratio ζ was calculated as the ratio W over $(4\pi W_e)$ where W is the area of the hysteresis loop at the given amplitude of force and deformation (the amount of energy absorbed during one loading cycle), W_e is the area of the triangle defined by the given amplitude of force and deformation (the amount of elastic input energy at one loading cycle). It is evident from the results shown in Fig. 15 that there was an increasing hysteretic damping, ζ, with increasing imposed deformation. The energy absorption increased much more rapidly in relatively low distortion levels. After reaching a high value at a drift about 1.3%, it continued increasing with a smoother branch. The average damping values of a bare frame specimen were 9.42% and 15.5% at low and high displacement ranges respectively. The average damping values of a specimen with solid infill were 12.1% and 16.6% at low and high displacement ranges respectively. Decreasing eccentricity of window resulted in average damping values from 11.6% and 13.5% up to 11.2% and 20.1% at low and high displacement ranges respectively. Decreasing eccentricity of door resulted in average damping values from 11.3% and 15.7% up to 10.3% and 14.3% at low and high displacement ranges respectively.

Comparing the above findings with the results of similar work from other research, one observes the reasonable correlation between the records obtained in the present study and those from Mallick and Garg (1971) where the composite action between the frame and the infill is adversely affected as the opening position is moved towards the compression diagonal and from Dawe and Young (1985) where the negative effect of the doorway on the stiffness of the infilled frame is more pronounced for a symmetrically located opening. It should be noted that different parameters on which the characteristics related to the behavior of infilled frames are dependent, contribute to the discrepancy of the quantitative results.

5. Conclusions

The authors have carried out investigations on the seismic behavior of several types of infilled r/c frame specimens that are: reference frame specimens (bare frame and frame with solid infill), frame specimens with concentric window and door opening in infills and frame specimens with eccentric window and door opening in infills, with two eccentricities.

The experimental results indicate that the contribution of the infills with openings can significantly improve the performance of r/c frames in terms of load resistance, stiffness, ductility and energy dissipation capacity. Shear failure of the r/c columns was excluded and infills restrained the beams from bending and, consequently, the development of plastic hinges in the beams occurred near the end of the tests.

The location of the opening as close to the edge of the infill as possible provides an improvement to the performance of the infilled frame. The mechanism of energy dissipation by friction across the bounding frame and mainly across the cracks of the infill seems to be more active in the case of the larger vertical wall components, where a better distribution of cracks in the wall is developed. On the contrary when the opening is located in the center of the infill on the loaded diagonal, the infill loses its tension strength in the interior and a greater deterioration of the vertical wall components occurs at low drift levels. The above mechanism of energy dissipation is diminished in the case of smaller vertical wall components.

Infills with opening are cracking and separating from the surrounding frame at early stage before yielding occurs at the column reinforcement. For low lateral displacements, the energy dissipation is higher for the specimens with openings in comparison with the bare frame specimen. For high lateral displacements, the energy dissipation is reduced for the specimens with openings, and remains constant for the bare frame specimen. For high lateral displacements in the case of infilled frames with openings the energy continuous to be absorbed by the reinforced concrete elements, while the infills discontinue absorbing energy.

The experimental results have shown that masonry walls with window or door openings close to the columns can improve the effectiveness of the technique of repairing and strengthening buildings before and after an earthquake.

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