Experimental evaluation of seismic performance of low-shear strength masonry infills with openings in reinforced concrete frames with deficient seismic details

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SUMMARY

The influence of openings on lateral behaviour of low-shear strength masonry infilled reinforced concrete frames is investigated. The design of the reinforced concrete frames in this study are aimed to reflect common seismic design deficiencies, such as location of lap splices at bottom of columns, insufficient transverse reinforcements at column and beam ends and lack of stirrups at beam-column joints. Six half-scale single-storey, single-bay frame specimens were tested under in-plane lateral loading. The investigated parameters include shape (window and door), size (regular and large windows) and location of the openings (eccentric and central). The results indicate that presence of openings alters the failure mode, increases the damage level and reduces ductility, strength and stiffness of the infilled frame. The door opening led to reductions of 29% in strength, 34% in the effective stiffness and 23% in the energy dissipation capacity. The window openings led to average reductions of 23% in strength, 8% in effective stiffness and 11% in the energy dissipation capacity. Empirical equations are proposed for estimating overall reductions in stiffness and strength of infilled frames because of the presence of openings, which take into account the effects of size, shape and location of openings. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: reinforced concrete frame; masonry infill; opening; cyclic loading; seismic behaviour; macro-modelling

1. INTRODUCTION

Masonry infills are often used in steel and reinforced concrete (RC) frame structures. Infills interact with the surrounding frame under seismic action but do not necessarily improve performance of the structures and, in fact in some cases, may cause more severe damages.

Because of the significant influence of infills on the behaviour of the frames, extensive studies have been performed on this subject by several researchers. Stafford-Smith (1967) conducted a series of tests on small-scale mortar infilled steel frame specimens and found that the behaviour of the infill was completely independent of the beam section. Stafford-Smith (1967) and Stafford-Smith and Carter (1969) proposed a method for analysing infilled frames, in which the infill was replaced by a diagonal pin-jointed strut. Design graphs have been presented for effective width of equivalent strut. Mainstone (1971) conducted a series of experiments similar to those of Stafford-Smith and suggested empirical equations for estimating the stiffness on the basis of the equivalent strut model. Barua and Mallick (1977) carried out an experimental investigation on small-scale steel frame specimens infilled with mortar and proposed simple expressions for stiffness, strength and share of load between the frame and the infill. On the basis of the experimental results of Barua and Mallick (1977), Liauw and Kwan (1984) suggested an expression for the effective width of the equivalent strut as a function of the relative stiffness of the frame and the infill. The results of the studies conducted by Barghi and Azadbakht (2011) and Kose and Karslioglu (2009, 2011) showed that addition

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of infill walls to the buildings can change many of their structural characteristics such as natural period of vibration, maximum roof displacement and base reaction.

In recent years, seismic performance of infilled frames has been studied by performing tests on three-dimensional RC frame structures. The results of tests conducted by Chaker and Cherifi (1999), Hashemi and Mosalam (2006), Arulselvan and Subramanian (2008) and Pujol and Fick (2010) showed a relatively high increase in lateral stiffness and strength and a significant decrease in natural period of the framed structure. Negro and Verzeletti (1996) examined the formation of soft-storey mechanism by conducting a series of pseudo-dynamic tests on a full-scale four-storey reinforced concrete building. On the basis of test observations, irregularities in the panels result in unacceptably larger damage to the frame. Fardis et al. (1999) studied the bidirectional response of a two-storey RC frame structure with two adjacent sides infilled by shaking table tests and non-linear dynamic analyses. On the basis of test observations, despite relatively high slenderness, infill panels survived out-of-plane peak accelerations of 0.6 g at the base of the structure. Zarnic et al. (2001) tested two full-scale buildings of masonry infilled RC frames on a shaking table. Their experimental results show that buildings designed according to Eurocodes are able to sustain relatively high dynamic excitations.

The in-plane seismic behaviour of infilled frames has also been studied by performing tests on large-scale two-dimensional frame specimens. Mehrabi et al. (1994, 1996) tested 14 masonry infilled RC frame specimens. They concluded that in a frame with a weak panel, the resistance of the panel does not seem to be influenced by the frame-panel interaction. On the contrary, in the case of a strong infill and a strong frame, the ultimate resistance is governed by the corner crushing in the infill. Such a mechanism is very much influenced by the frame-panel interaction. Flanagan and Bennett’s (1999) experiments on the infilled steel frames show that the presence of the infill panel has increased the value of bending moment in the column at the loaded corner. Dukuze (2000) performed experiments on single-panel infilled RC frames as well as multi-storey, multi-bay frames and found that one-bay infills could be used with confidence to predict the shear capacity of multi-storey, multi-bay frames. Al-Chaar et al. (2002) carried out an experimental programme on single-storey laboratory models with different numbers of bays. The conclusion was that the peak strength and the initial stiffness of infilled structures increase with the number of bays but not linearly. Lee and Woo (2002) performed an experimental programme and concluded that the masonry infills can be beneficial to the seismic performance of the structure because the amount of the increase in strength appears to be greater than that in the induced earthquake inertia forces.

Considering the architectural requirements of buildings, providing window or door openings in infill walls is unavoidable in many cases. Presence of openings in an infill wall alters its behaviour and reduces load resistance and stiffness of the infilled frame. Although many experimental research studies have been reported on solid infilled frames, there are limited experimental data on infilled frames with openings. Mallick and Garg (1971) conducted a series of tests on small-scale mortar infilled steel frame specimens and found that the composite action between the frame and the infill is adversely affected as the opening position is moved towards the compression diagonal. They recommended that the door openings can best be located in the centre of the lower half of the panel and the window opening in the mid-height region of the left or right half of the panel as near to the vertical edge of the panel as possible. In Mosalam et al. (1997), experiments on the masonry infilled steel frames, openings in infill walls led to a more ductile behaviour. Buonopane and White (1999) tested a two-storey, two-bay RC frame infilled with masonry. The first-storey infills were solid, and the second-storey infills included window openings. These researchers reported different crack patterns and associated hysteretic behaviour in the two storeys. The final sequence of tests produced diagonal cracking in the upper storey but primarily bed-joint shear cracking in the lower storey. Naderi and Tasnimi (2007) investigated the effects of openings on the behaviour of masonry infilled RC frames by finite element (FE) analyses. They proposed two methods for modelling the effect of infill panels with opening on the global behaviour of RC frames.

Kakaletsis and Karayannis (2007) investigated the effect of opening shape and location by performing tests on masonry infilled RC frames. On the basis of the results, 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. Furthermore, Kakaletsis and Karayannis (2008) experimentally studied the effect of the opening shape and the masonry infill compressive strength on the behaviour of infilled RC frames. On the basis of the test results, specimens with strong infills exhibit a better performance than those with weak infills in terms of load resistance, stiffness, ductility and energy dissipation capacity. It should be noted that shear
failure of the RC columns was excluded in the experiments. The results of another experimental programme performed by Kakelaitis and Karayannis (2009) show that the size of openings of the same shape did not affect the behaviour of the specimens; however, larger openings seem to lead to a rather more ductile manner of behaviour. Kakelaitis (2009) used the collective results of experiments to propose a continuous force-deformation model based on an equivalent strut approach for masonry infill panels containing openings.

Blackard et al. (2009) reported the main experimental findings of a test programme on the masonry infilled non-ductile RC frames with eccentric openings. On the basis of the results, the solid wall was slightly more brittle than the walls with openings. Shear failure of columns was also observed in the tests. Stavridis (2009) performed a test on a three-storey, two-bay infilled RC frame on the shake table. At each storey, the specimen had a solid infill wall in one bay and an infill wall with a window opening in the other bay. Comparing the results of shake table test and those of the single-storey, single-bay frames (Blackard et al., 2009) reveals that in many aspects, the behaviour of these specimens was similar to each other, as indicated before, by similar cracking patterns and lateral strength. Tasnimi and Mohebkhah (2011) experimentally investigated the in-plane seismic behaviour of steel frames with infills having central openings. The results indicate that infilled frames with openings are not always more ductile than the ones with solid infill. Infilled frames with openings experienced pier diagonal tension or toe crushing failure and have smaller ductility factors than those frames with solid infill.

The seismic evaluation of masonry infilled structures requires appropriate macro-models for infill panels that have been calibrated by experimental results. Because of restriction of experimental data, most of the existing models have been developed by FE analyses and have not been verified by experimental results. Thus, more experimental investigation is required for predicting the stiffness and strength of infilled frames with openings.

This paper deals with an experimental programme to investigate the in-plane seismic behaviour of masonry infilled RC frames with openings. Six half-scale single-storey, single-bay frame specimens were tested under in-plane lateral loading. The frames were intentionally designed to include the most common deficiencies of typical older construction practice, i.e. wrong location of lap splices at the bottom of columns, insufficient lateral reinforcements at column and beam ends and lack of stirrups at beam-column joints. The influence of the shape, size and location of the opening on the hysteretic characteristics of the infilled frames was also examined. Furthermore, a simple macro-model is proposed to predict lateral stiffness and strength of infilled frames with openings.

2. EXPERIMENTAL PROGRAMME

2.1. Test specimens

Six half-scale, single-storey single-bay reinforced concrete frame specimens were constructed and tested under in-plane lateral loading. In order to select the prototype structure, a large number of existing RC structures were examined. The details of test specimens including the dimensions of RC members and infill panel and the amounts of reinforcements were chosen to represent the exterior bay at the mid-height of typical residential buildings (third storey of a five-storey reinforced concrete frame structure). Figure 1 illustrates geometry and reinforcing details of the specimens. The frames suffered from the following deficiencies: location of lap splice was at the bottom of the columns, and lap length was equal to 40 times of the longitudinal bars diameter; no transverse reinforcement was present in beam-column joints, and sufficient transverse reinforcement was not provided at column and beam ends; as it is the case in old construction practice.

Properties of the test specimens are presented in Table 1 and Figure 2. A bare frame and a solid infilled frame were also tested for comparison with frames with openings. Two specimens contained central window opening with different sizes: one specimen contained eccentric window opening, and one contained eccentric door opening. The height and length of infills were 1300 and 2100 mm, respectively, and the aspect ratio of infill wall was equal to h/l = 0.62.

The infill walls were constructed with solid clay bricks after finishing the construction of the frame. The brick dimensions were half-scale and were made in a manner identical to real solid bricks of the prototype...
The mean dimensions of brick units were 106 × 49 × 31 mm, and the number of wall courses was 33 similar to the prototype structure. The thickness of the double-wythe masonry walls was 106 mm, the mortar thickness in the bed joints was one-half of the prototype structure and the head joints were not filled with mortar in accordance with the common construction practice. No shear connectors.

Table 1. Test specimens (dimensions in millimetre).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Configuration</th>
<th>Opening length</th>
<th>Opening height</th>
<th>Opening location (x/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF</td>
<td>bare frame</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S</td>
<td>solid infilled frame</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>DO</td>
<td>infilled frame with door opening</td>
<td>450</td>
<td>1000</td>
<td>0.2</td>
</tr>
<tr>
<td>RWO</td>
<td>infilled frame with regular window opening</td>
<td>750</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>LWO</td>
<td>infilled frame with large window opening</td>
<td>1000</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>EWO</td>
<td>infilled frame with eccentric window opening</td>
<td>750</td>
<td>600</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: l is the length of infill panel, and x is the horizontal distance between infill and opening centres.

Figure 2. Dimensions (mm) and instrumentation of specimens with openings.
were used between the frame and the infill. For specimens with openings, two L30 × 30 × 3 mm steel angles were used to build lintel beams, which had a bearing length of 125 mm on both sides of the opening. Each specimen was cured for a week and tested at least 28 days after construction.

One of the important parameters in the behaviour of infilled frames is the ratio of infill strength to frame strength. This parameter was calculated using the available procedures in the literature. The solid infill strength could be estimated as

\[ V_{\text{inf}} = A_n f_v = 69 \text{ kN} \]

Where \( A_n \) is the area of net-mortared section across infill panel and \( f_v \) is the shear strength of masonry infill. Assuming that plastic hinges developed at the top and bottom of the columns, the strength of RC frame could be calculated as

\[ V_f = \frac{4 M_{pc}}{h} = 84.5 \text{ kN} \]

Where \( M_{pc} \) is the plastic moment strength of columns considering the effect of the axial load and \( h = h_{inf} - l_p \); \( h_{inf} \) is the height of infill panel, and \( l_p \) is the length of plastic hinge, which could be considered equal to half of the column depth. Therefore, the infill panel strength is less than that of the RC frame, and the ratio of infill to frame strengths is equal to 0.81.

2.2. Material properties

Tension tests were performed on samples of reinforcing bars. Concrete quality control samples were also obtained during the construction, and compression tests were conducted on them. Compressive strength tests of solid bricks, mortar and masonry prisms were carried out according to ASTM C67-02c (2002), ASTM C109/C109M-99 (1999) and ASTM C1314-00 (2000), respectively. The mortar mixture contained one part cement and six parts sand according to common construction practice. The sand used had a maximum aggregate size of 4 mm. It is worth mentioning that the elastic modulus of masonry was calculated as the slope of the initial linear part of the stress-strain curves. In situ tests were conducted for shear strength of masonry mortar according to ASTM C 1531-03 (2003). The results of tests are presented in Table 2.

2.3. Test set-up and instrumentation

The test set-up, reaction frame, specimen and loading system are shown in Figure 3(a, b). The lateral load was applied by means of a double action hydraulic actuator, which had a load capacity of 250 kN and a stroke of ±125 mm. The built-in load cell of the actuator was used to measure applied loads. Four stiff steel rods and two steel plates, placed at the ends of the overhang beams, were used to apply the

<table>
<thead>
<tr>
<th>Table 2. Test results of materials (MPa).</th>
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<tbody>
<tr>
<td><strong>Material</strong></td>
</tr>
<tr>
<td>Steel reinforcements</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Frame concrete</td>
</tr>
<tr>
<td>Brick units</td>
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<tr>
<td>Mortar</td>
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<td>Masonry</td>
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lateral load. The horizontal steel rods were tightened properly to ensure that they are not loose for the purpose. This system was used to avoid exertion of any tensile force to the RC beam while applying a pulling force to the specimen.

Vertical load was also applied to the RC columns by means of a vertical actuator via steel cross beam as shown in Figure 3. Test set-up of specimen with large window opening (LWO) is shown in Figure 4.

As shown in Figure 2, several linear variable displacement transducer (LVDT’s) were installed to monitor deformations of the specimen at different locations. Several strain gauges were also placed on the steel bars to measure the strain.

2.4. Load patterns

A constant vertical load equal to 0.1 of ultimate axial capacity (78 kN per column) was applied to the columns in force-controlled mode, which was continually adjusted during each test. Lateral load was
applied to specimens in displacement-controlled mode. For infilled frame specimens, a cyclic displacement history as per ACI T1.1-01 (2001) recommendations was imposed. The initial drift ratio was chosen to be within the essentially linear elastic response range, and it was estimated using the available data of other tests on infilled RC frames in the literature and by online control of the response. The sequence was intended to ensure that displacements were increased gradually in such steps that were neither too large nor too small. Considering the recommendations of ACI T1.1-01 (2001), subsequent drift ratios were set to be not less than one and one-quarter times, and not more than one and one-half times of the previous drift ratio. Three fully reversed displacement cycles were applied at each drift level, and then a half-domain cycle was adopted. The lateral loading protocol is presented in Figure 5. The bare frame specimen was also subjected to monotonically increasing lateral displacements up to a drift level of 3% in each direction.

3. EXPERIMENTAL RESULTS

3.1. bare frame specimen (BF)

Specimen BF was the bare RC frame, which was tested under monotonic lateral loading. The lateral load-drift curve is shown in Figure 6(a). Initial cracks were observed in both ends of the RC beam at a drift of 0.55% and at lateral load equal to approximately 0.35 of the maximum load resistance. Cracks at the bottom and top of the columns initiated at drifts of 0.75% and 1.6%, respectively. It is worth mentioning that initial cracks at bottom of columns were located at the end of lap-splice length of longitudinal bars. Considering the damage pattern of the bare frame, plastic hinge first developed in both ends of the beam and then at the bottom of the columns. The aforementioned hinges represent the flexural behaviour of the members. It should be noted that no brittle shear failure of frame members was observed. Hence the frame exhibited a fairly ductile behaviour. Severe cracking was not also occurred in the beam-column joints. Damage pattern of the frame at the end of east loading (a drift of 3%) is shown in Figure 7(a).

3.2. Specimen with solid infill (S)

Specimen S was the solid infilled frame that was tested under cyclic quasi-static lateral loading. The lateral load-drift hysteresis curve and its backbone are illustrated in Figure 6(b). The damage pattern is also shown in Figure 7(b). Considering the envelope curve and the slight strength degradation during the test, the behaviour of specimen was relatively ductile. The first observed damage in the specimen was the formation of cracks at the frame-panel interface at the corners of the wall at a drift of 0.05% and at a lateral load equal to approximately 0.15 of the maximum load. As the amplitude of the imposed displacement increased, horizontal cracks developed along the bed joints in all parts of the infill. As shown in Figure 7(b), the failure of the infill is dominated by sliding along its bed joints. This may be attributed to the relatively weak shear strength of the mortar. In such a case, total strength of the specimen may be assumed equal to the sum of flexural resistance of a bare frame plus the sliding-shear strength of the panel (Mehrabi et al., 1996). The initiation of cracks in both ends of the beam and

Figure 5. Lateral loading protocol of cyclic tests.
beam-column joint occurred at a drift of 0.75%, and first cracks in both ends of the columns were observed at a drift of 1.0%. Spalling and crushing of concrete in both ends of the beam and the bottom ends of the columns occurred beyond a drift of 3.5%. This represents the formation of plastic hinges in the aforementioned regions. Thus, the behaviour of frame and its damage pattern was almost identical to

Figure 6. Lateral load-drift curves: (a) specimen BF; (b) specimen S; (c) specimen DO; (d) specimen RWO; (e) specimen LWO; (f) specimen EWO.

Figure 7. Damage pattern of reference specimens: (a) bare frame specimen at the end of east loading; (b) specimen with solid infill.
that of the bare frame specimen. The maximum lateral resistance was reached at a drift of 3.5% in both directions, when crushing of the upper corners of infill occurred.

3.3. Specimen with door opening (DO)

Specimen DO was the infilled frame with eccentric door opening, which was tested under cyclic reversal lateral loading. The lateral load-drift ratio hysteresis curve and its backbone are shown in Figure 6(c). The damage pattern is also illustrated in Figure 8(a). Hairline cracks developed at the interface between the wall and the frame at a drift of 0.05%. A horizontal crack developed along the bed joint in the eastern masonry pier between the door and column at the top level of the door at a drift of 0.1%. As the amplitude of displacement cycles increased, sliding of the upper portion of the masonry wall along this crack was the major resistance mechanism in the east-ward loading. Several inclined cracks initiated in the eastern pier of masonry infill along a line joining the upper corner of the infill and the lower corner of the door at a drift of 0.5% and propagated in a stair-stepped manner through head and bed joints. These cracks indicate that a compression strut has developed in the eastern masonry pier. It is worth mentioning that compression strut was the major resistance mechanism in the west-ward loading. Figure 8(b) shows the major resistance mechanisms of the infill panel schematically. Cracking of frame members was first observed at a drift of 0.75%, and increasing the amplitude of displacement cycles finally led to the formation of plastic hinges in both ends of the beam and bottom of the columns. It should be noted that shear failure of frame members was not observed because of the weak infill panel compared with the RC frame. Joining horizontal and diagonal cracks of the pier led to separation of a triangular piece of the cracked wall on the eastern side of the door at a drift of 1.4%. Crushing of the upper end of the compression strut was observed at a drift of 1.75%. According to the load-drift relation and the damage pattern, the behaviour of the specimen in the east-ward was more ductile and with less strength degradation than the west-ward loading. On the contrary, the value of the dissipated energy in the west-ward loading was higher than that of the east-ward.

3.4. Specimen with regular window opening (RWO)

Specimen RWO was the infilled frame with regular central window opening that was subjected to cyclic quasi-static loading. The hysteresis response curve and its backbone are presented in Figure 6(d), and the damage pattern is shown in Figure 8(c). Separation cracks were initiated along the interface between the frame and the infill at a drift of 0.05%. Cracking of frame members also occurred at a drift of 0.75%. It should be noted that the failure mode of the RC frame was the formation of plastic hinges in both ends of the beam and the lower ends of the columns. Crushing of concrete in the aforementioned regions was observed at the end of the test. Cracking of the beam-column joint also occurred during the test. Sliding along two horizontal cracks that developed in the masonry piers on the two sides of the window at the top level of the opening was observed at a drift of 1.0%. This shows that one of the resistance mechanisms of the infill was bed-joint sliding. Several diagonal cracks initiated in the wall segments flanking the opening along two lines between the upper corners of the infill and the lower corners of the window at a drift of 1.0%. As the amplitude of the displacement increased, these cracks propagated toward the lower parts of the infill. These inclined cracks revealed the formation of compression struts in the masonry piers, which was another resistance mechanism of the infill. Two major resistance mechanisms of the infill panel of specimen RWO are shown in Figure 8(d). Crushing of the masonry material in the lower corners of the window that were located in the path of compression struts initiated at a drift of 1.75%, and the maximum lateral resistance of the specimen was reached at the next displacement cycle corresponded to a drift of 2.2%. The separation of a triangular piece of the wall near the opening led to the strength degradation at a drift of 2.75%. Considering the rate of strength degradation and the level of damage, specimen RWO exhibited are relatively brittle behaviour in both directions.

3.5. Specimen with large window opening (LWO)

Specimen LWO had a large central window opening. It was tested under cyclic quasi-static loading. Figure 6(e) illustrates the hysteresis curve and its backbone, and the damage pattern is also shown in Figure 8(e). Separation of the frame-panel interface occurred at the infill corners at a drift of 0.05%. Two horizontal cracks developed along the bed joints at the top level of the window in the western and
eastern masonry piers, at drifts of 0.35% and 0.5%, respectively. Sliding along these cracks shows that a load resistance mechanism was developed in the masonry zone above the window. Cracking of the frame members was observed at a drift of 0.5%. It should be noted that first cracks of the lower end of the columns were formed at the end of the lap length of longitudinal reinforcements, which was coincident with the bottom level of the opening. Considering the damage pattern of the frame, increasing the amplitude of displacement, finally led to formation of plastic hinges in both ends of the beam and the lower ends.

Figure 8. Damage pattern of specimens and resistance mechanisms of infills: (a) and (b) specimen DO; (c) and (d) specimen RWO; (e) and (f) specimen LWO; (g) and (h) specimen EWO.
of the columns. Cracking of beam-column joints was also observed in the specimen. Diagonal cracking of masonry piers similar to that of specimen RWO was observed at a drift of 1%. At some locations, these cracks propagated through the bricks, and at larger displacements, the cracks widened. The formation of these inclined cracks indicates that compression struts have developed in the masonry piers on two sides of the opening. Figure 8(f) illustrates the developed resistance mechanisms of the infill panel. Crushing of masonry material in the lower corners of the window was also initiated at a drift of 1.4%. Because of technical problems, the test was stopped at this stage.

3.6. Specimen with eccentric window opening (EWO)

Specimen EWO had a regular eccentric window opening and was tested under fully reversed displacement cycles. The load-drift hysteresis response and its backbone are presented in Figure 6(f), and the damage pattern is illustrated in Figure 8(g). The initial cracks of the infill panel were observed at a drift of 0.075%. The cracks at the frame-infill interface also formed at a drift of 0.15%. Sliding along the bed joint of a horizontal crack that was developed in the eastern masonry pier at the top level of the window was observed at a drift of 0.5%. Cracking of the frame was initiated at a drift of 0.75%. Failure mechanism of the frame was the formation of plastic hinges in both ends of the beam and the lower ends of the columns. Shear/bending cracks in the lower ends of the columns were generally formed at the level of the end of the lap length of longitudinal bars and the bottom level of the window. The formation of cracks in the columns at the bottom level of the opening was due to the relatively large stiffness of the masonry zone below the window and restricted lateral deformation of columns in this region. Cracking of beam-column joints was also observed during the test. There was a clear reduction in stiffness in the west-ward loading coincident with the onset of the formation of several inclined cracks in two perpendicular directions in the eastern masonry pier. These cracks show that two struts have developed in this pier. Thus, bed-joint sliding and the formation of the compression struts were two major load resistance mechanisms of the infill, as shown in Figure 8(h). The maximum load was reached in the west-ward loading at a drift of 1.4% when crushing of masonry in the eastern corners of the window that were located in the path of compression struts was observed. Separation of a triangular piece of the infill near the window and spalling and crushing of concrete in both ends of the beam and the lower ends of the columns were observed at drifts of 2.2% and 3.5%, respectively. According to the envelope in Figure 6(f), the behaviour of the specimen in the east-ward loading was more ductile with smaller strength degradation than that of the west-ward.

4. DISCUSSION OF TEST RESULTS

4.1. Strength and failure modes

The load-drift envelope curves of all specimens are plotted in Figure 9, and their hysteretic characteristics are also presented in Table 3. As can be observed from Table 3, maximum lateral strengths of the solid infilled frame and the specimen with door opening are 69% and 20% higher than that of the bare frame, respectively. Also, for the specimens with window opening, the strengths are averagely 30% higher than that of the bare frame. Hence, it could be concluded that presence of infill panel—even with weak material and containing opening—cannot be ignored if lateral resistance of the frame is considered.

The observed failure mode of the bare frame specimen was the formation of plastic hinges in both ends of the beam and bottom ends of the columns. Almost similar failure modes occurred for the RC frame in all specimens containing infill panels, and no brittle shear failure of the frame members is observed in any specimens. This may be explained by almost weak infill panels relative to the frames. Inclined cracks in the beam-column joints were observed in all specimens as expected because of lack of any stirrups in these regions. However, any types of failure or even widening of cracks was not observed in the joints, and their conditions did not show critical destruction during the tests.

In the bare frame specimen, cracking at the top of one end of the beam and at bottom of its other end occurred simultaneously. But in the infilled frame specimens, formation of cracks at the bottom of beams occurred in awhile after formation of cracks at the top. Considering smaller positive bending capacity relative to negative capacity of the beam, the delay may be attributed to expansion of the infill caused by opening of cracks and generation of negative curvature in the beam (Flanagan and Bennett, 1999).
The failure mechanism of the infill panel of the solid infilled frame was bed-joint sliding. Corner crushing was also observed at the maximum lateral load. The failure mechanism of specimens containing openings was a combination of bed-joint sliding—especially along a crack that was developed at the top level of the opening—and diagonal cracking of the masonry piers. In these specimens, crushing of the corners of the opening was also observed.

Separation and falling down of some pieces of wall near the opening was observed in specimens containing openings. Such event did not occur in the solid infilled frame. This indicates that the presence of openings can increase the level of damage in the infills. It is worth mentioning that such events could reduce the level of life safety for occupants in real earthquakes.

On the basis of Table 3, it can be observed that the door opening led to a reduction of 29% in lateral strength, and the window openings led to an average reduction of 23% in lateral strength. As shown in Table 3, the values of drift at maximum load for specimens with openings are smaller than that of the solid infilled frame because of more severe damage in these specimens.

4.2. Stiffness

Figure 10 illustrates the secant stiffness versus lateral drift curves and shows stiffness degradation of specimens with increasing drift. The secant stiffness at each point is calculated as the slope of the line joining the origin to that point. As shown in Figure 10, the bare frame and the solid infilled frame establish the lower and upper bounds, respectively. This figure also shows an obvious reduction in the rate of stiffness degradation at a drift of 0.25%, especially in specimens containing infills.

The values of initial tangent stiffness and effective stiffness are presented in Table 3. The initial tangent stiffness is defined as the slope of the load-displacement curve at the origin. The effective stiffness is also defined as the secant stiffness corresponding to half of the maximum load on the envelope. On the basis of Table 3, the initial tangent stiffness and effective stiffness of the solid infilled frame were 3.42 and 2.62 times larger than those of the bare frame, respectively. Comparison with lateral strength shows that the infill panel is more influential in stiffness than in lateral strength. Comparison of the results of specimens with perforated infills and the bare frame shows that infill panels even with openings of various sizes, shapes and locations can significantly increase lateral stiffness of the frame. As shown in Table 3, the initial tangent stiffness and effective stiffness of the specimen with door opening were 2.07 and 1.77 times higher than those of the bare frame. In specimens with window openings, the initial tangent stiffness was from 1.94 to 2.69 times larger than the bare frame, and the effective stiffness was 2.40 to 2.45 larger relative to the bare frame.

The tests indicate that door opening had more severe effect on stiffness than window openings. As it can be observed from Table 3, the initial tangent stiffness and effective stiffness of specimen with door opening were 40% and 34% less than those of solid infilled frame, respectively. For specimens with window openings, the initial tangent stiffness was reduced from 21% to 39%, and the effective stiffness had a reduction from 8% to 9% relative to the solid infilled frame.
Table 3. Hysteretic characteristics of test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial tangent stiffness (kN/mm)</th>
<th>Effective stiffness (kN/mm)</th>
<th>Maximum lateral load (kN)</th>
<th>Drift at maximum load (%)</th>
<th>Ductility factor</th>
<th>Average strength degradation from cycling (%)</th>
<th>Energy dissipation up to a drift of 1.4% (kN.mm)</th>
<th>Energy dissipation up to a drift of 4.5% (kN.mm)</th>
<th>Energy dissipation comparable with BF (kN.mm)</th>
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<tbody>
<tr>
<td>BF</td>
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<td>+3.0</td>
<td>+69.6</td>
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<td>2.02</td>
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<td>NA</td>
<td>NA</td>
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<td>+7.4</td>
<td>+117.3</td>
<td>+3.50</td>
<td>4.44</td>
<td>14</td>
<td>3770</td>
<td>39152</td>
<td>4724</td>
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<td>DO</td>
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<td>+77.2</td>
<td>+2.75</td>
<td>4.28</td>
<td>11</td>
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<td>30093</td>
<td>3655</td>
</tr>
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<td>+91.2</td>
<td>+2.20</td>
<td>4.92</td>
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<td>4218</td>
</tr>
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<td>NA</td>
</tr>
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<td>+6.3</td>
<td>+84.5</td>
<td>+4.50 *</td>
<td>6.60</td>
<td>11</td>
<td>3344</td>
<td>30421</td>
<td>4158</td>
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</tbody>
</table>

*The slope of the envelope curve in the positive direction is close to zero beyond a drift of 1.75%.

NA = not available or not applicable; BF = bare frame; S = solid infilled frame; DO = door opening; RWO = regular window opening; LWO = large window opening; EWO = eccentric window opening.
4.3. Strength degradation from cycling

In all cyclic tests, lateral strength in the second and third loading cycle was less than that of the first cycle. This is known as the strength degradation due to cycling and shows the increase of damage in successive cycles. The mean value of this parameter is presented in Table 3, which varies from 11% to 14% for different specimens.

4.4. Energy dissipation capacity

Amounts of energy dissipated by different specimens comparable with specimen BF that was subjected to monotonic lateral loading are presented in Table 3. It is calculated as the energy dissipated by the specimens in a loop similar to that of the bare frame specimen. It is seen that the energy dissipated by the solid infilled frame, the specimen with door opening and the specimens with window openings are 76%, 36% and 55 to 57% higher than that of the bare frame, respectively. Thus, the infill panels, even with openings, can improve energy dissipation capacity significantly.

The energy dissipated in each cycle normalized by the peak to peak displacement (2Δ) for that cycle is plotted against the lateral drift in Figure 11. The cumulative energy dissipated by infilled frame specimens up to a drift of 4.5% is also presented in Table 3. As shown in Figure 11, the solid infilled frame dissipated more energy than the specimens with perforated infills. On the basis of the results listed in Table 3, the cumulative energy dissipated by the specimen with door opening and the specimens with window openings were 23% and 11 to 12% less than that of the solid infilled frame, respectively.

Figure 10. Stiffness degradation curves.

Figure 11. Dissipated energy per cycle normalized by the peak to peak displacement of different specimens.
4.5. **Ductility**

In order to calculate the ductility factor, the actual load-displacement envelope curve was idealized with a bilinear curve (equivalent energy elastic–plastic curve). The bilinear curve circumscribes an area equal to the area enclosed by the envelope curve between the origin, the ultimate displacement and the displacement axis. The slope of the elastic portion of this curve is equal to the effective stiffness, which was defined in Section 4.2. The ultimate limit state is the point on the envelope curve corresponding to 0.85 $V_{\text{max}}$. The yield point can be also calculated using the bilinear curve. The values of the ductility factor for positive and negative directions are presented in Table 3. As it can be observed, the average value of the ductility factor for the solid infilled frame specimen is larger than other specimens except the specimen EWO. However, in this specimen and other specimens containing openings, the damage at the end of the test was more severe than that of the solid infilled frame; thus for safety aspects, smaller ductility factors than those calculated here might be considered in the design of perforated infilled frames.

4.6. **Effect of opening location**

Specimens RWO and EWO contained window openings with the same size located centrally and eccentrically, respectively. As shown in Figure 9 and Table 3, the specimen with central opening showed a symmetric load-drift response and almost similar hysteretic characteristics in two directions, but the behaviour of the specimen with eccentric opening was asymmetric in two directions.

The behaviour of the specimen with central opening was relatively brittle in both directions, but the eccentric specimen exhibited a relatively ductile behaviour in the east direction because of the dominance of the bed-joint sliding failure mode. Another observation was that the resistance of specimen EWO (the lesser strength between two directions) was 6% less than that of the specimen RWO. The average initial tangent stiffness of specimen with eccentric opening was 28% larger than that of the specimen with central opening. However, the average effective stiffness of two specimens was close to each other. The location of opening did not significantly affect the energy dissipation capacity of the specimens, as shown in Table 3.

4.7. **Effect of opening shape**

Specimens EWO and DO with window and door openings, respectively, had the same area and location ($x/l$) in the infill panel. Both specimens exhibited a fairly ductile behaviour in the east loading with dominant mechanism of bed-joint sliding, and both showed a relatively brittle behaviour in the west direction with formation of a compression strut in the infill. In both specimens, lateral strength and stiffness in the west direction were higher than those of the east direction. As shown in Table 3, the door opening led to higher reductions in lateral strength and stiffness compared with the window opening with the same area and location. On the basis of test observations, the specimen with door opening suffered more severe damages than the specimen with window opening at the same peak displacements. For instance, separation of a piece of wall near the opening occurred at drifts of 1.4% and 2.2% in specimens with door and window openings, respectively. As shown in Table 3, the values of cumulative dissipated energy up to a drift of 4.5% for these two specimens are very close to each other. However, as illustrated in Figure 11, the dissipated energy of the specimen with window opening is greater than that of the specimen with door opening up to a drift of 2.5%. Considering the severe damages suffered by infills after this drift, it might be advisable to peak lower drifts as a limit when evaluating structural performance of the specimens. As such, it could be concluded that the specimen with window opening dissipated greater energy than the specimen with door opening.

4.8. **Effect of opening size**

Specimens RWO and LWO contained central window openings with different dimensions. The area of their openings was about 16.5% and 27.5% of the whole area of the infill panel, respectively. The behaviour of both specimens was symmetric in two directions, and their major load resistance mechanism was formation of compression struts in the masonry piers on the sides of the opening. The tests show that increasing the size of opening does not affect the level of damage of the specimen. For instance, both specimens experienced diagonal cracking of masonry piers and crushing of masonry materials on the
corners of opening at drifts of 1.0% and 1.4%, respectively. Increasing in the size of opening led to accelerate initiation of cracks in the frame because of smaller stiffness of the infill, and thus, higher contribution of the frame in resisting lateral loads. On the basis of Table 3, the average initial tangent stiffness of the specimen with large opening was 7% less than that of the specimen with regular opening. Hence, the increasing of opening size led to a reduction in the stiffness. As illustrated in Figure 11, the specimen with large opening dissipated less energy relative to the specimen with regular opening, in all amplitudes of displacement. The values of cumulative dissipated energy of specimens up to a drift of 1.4% are also presented in Table 3, which is comparable with specimen LWO. These data also indicate that increasing the size of opening led to a reduction in energy dissipation capacity.

4.9. Comparison with other test results

The experimental programme conducted by Kakaletsis and Karayannis (2007, 2008, 2009) shows that infill panels even with openings can significantly improve the structural performance of RC frames. This has also been observed in our tests. On the basis of the present research work, the presence of openings in infilled frames leads to reductions in the stiffness and load resistance values. Similar results are obtained in the tests performed by Kakaletsis and Karayannis (2007, 2008, 2009). Blackard et al. (2009) also observed reduction in the strength in the specimens with openings, although they did not record significant stiffness degradation in perforated infilled frames compared with the solid infilled frame. Shear failure of the RC columns was excluded in our experiments; similar results were obtained in the research of Kakaletsis and Karayannis (2007, 2008, 2009). But, in the experimental programme performed by Blackard et al. (2009), the shear failure was observed in the columns, which could be a result of the non-ductile RC frames or the relatively strong infill panels. The size of the openings did not affect the failure mode and the behaviour of specimens in the present work; this was also one of the findings of the experiments of Kakaletsis and Karayannis (2009). The experimental programme of Kakaletsis and Karayannis (2007) shows that the location of the opening close to the centre resulted to higher decrease of strength and stiffness; it was also observed in our research programme in the lateral stiffness but not in the strength.

5. REDUCTION FACTORS FOR INFILLED FRAMES WITH OPENINGS

Although micro-model FE formulations are available for masonry walls (Farshchi et al. 2009), for global analysis of multi-storey, multi-bay infilled frame structures, relatively simple macro-models for infill panels are required. Several methods have been proposed by researchers for predicting lateral stiffness and strength of solid infilled frames. One of the simplest and more practical methods is the use of an equivalent diagonal strut. Different equations have been proposed for effective width of the equivalent strut. One of the most common expressions is suggested by Mainstone (1971) where the effective width is calculated on the basis of the relative stiffness of the infill to the frame. It should be noted that the aforementioned expression has been adopted by FEMA 306 (1998) and FEMA 356 (2000).

Regarding the effect of opening, an equivalent diagonal strut model with a reduced width can be used. In this method, the effective width of infill with opening \( w_o \) can be calculated by application of a reduction factor \( R_F \) to the effective width of infill without opening \( w \) as defined in Equation (1).

\[
w_o = R_F \times w
\]  

(1)

A number of equations have been proposed by several researchers for the reduction factors. The ratio of opening to infill area \( (A_O/A_F) \) is the basic parameter in the expressions suggested by Al-Chaar et al. (2003), Mondal and Jain (2008), Asteris et al. (2011), Tasnimi and Mohebkhah (2011) and Mohammadi and Nikfar (2012). Nevertheless, on the basis of the present research and other studies (Kakaletsis and Karayannis, 2007, 2008, 2009), other parameters such as location, shape and size of the openings are also effective in reduction of the strength and stiffness. Furthermore, in most research studies, only one reduction factor has been suggested for both stiffness and strength (Al-Chaar et al., 2003; Mondal and Jain, 2008; Asteris et al., 2011; Tasnimi and Mohebkhah, 2011), whereas the tests
show that reductions in stiffness and strength are not identical. An attempt is made here to propose reduction factors for strength and stiffness separately and to take into consideration different effective parameters.

The effect of the location, shape and size of the openings on in-plane behaviour of infilled frames has already been discussed in Sections 4.6–4.8. Considering the aforementioned explanations and on the basis of test results, Equation (2) is proposed as the stiffness reduction factor:

\[
R_{F1} = \left(1 - 0.31 \frac{A_o}{A_p}\right) \times \left(2.78 - 1.78 \frac{d_o}{\sqrt{2h_o l_o}}\right) \tag{2}
\]

Where \(A_o\) and \(A_p\) are areas of the opening and infill panel, respectively, and \(h_o, l_o\) and \(d_o\) are height, length and diagonal length of the opening, respectively. Considering the fact that earthquake loading is reversal, stiffness values are required for global structural analysis, and the distribution of loads between members, average values of the stiffness are used in determining Equation (2). The effect of the ratio of the opening to the infill area is considered in the first factor of Equation (2), which is obtained by comparing the results of solid infilled frame and the specimens with central openings and by carrying out a linear regression analysis over the results. The second factor considers the effect of the opening shape and its aspect ratio, which is obtained by comparing the results of specimens with window and door openings with the same area and location but with different aspect ratios. It is worth to remind that the effect of opening location is neglected in Equation (2) because it did not have a considerable influence on the average stiffness. The estimated values of the stiffness and the corresponding experimental results of the specimens with perforated infills are presented in Table 4. As shown in this table, the agreement between experimental and approximate results is satisfactory.

Similarly, Equation (3) is proposed for the estimation of ultimate strength of infilled frame with opening \((V_o)\) by means of that of the corresponding solid infilled frame \((V)\) and a strength reduction factor \((R_F)\).

\[
V_o = R_F \times V \tag{3}
\]

Equation (4) is proposed as the reduction factor for the ultimate strength based on the experimental results. For the determination of this expression, the lesser strength of the two directions of specimens was used.

\[
R_{F2} = \left(1 - 1.1 \frac{A_o}{A_p}\right) \times \left(1.6 - 0.6 \frac{d_o}{\sqrt{2h_o l_o}}\right) \times \left(1 - 0.3 \frac{x}{l}\right) \tag{4}
\]

The parameters of this equation are the same as those of Equation (2) except \(x\) and \(l\), which are the horizontal distance between the infill and opening centres and the length of the infill, respectively. Similar to Equation (2), the first and second factors of Equation (4) are related to the ratio of the opening to the infill area and the opening shape and aspect ratio, respectively. The third factor of Equation (4) also

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Opening shape</th>
<th>(A_o/A_p)</th>
<th>(\frac{d_o}{\sqrt{2h_o l_o}})</th>
<th>(K_{\text{solid}}) (kN/mm)</th>
<th>(R_{F1}) (stiffness)</th>
<th>(K_{\text{est}}) (kN/mm)</th>
<th>(K_{\text{exp}}) (kN/mm)</th>
<th>(K_{\text{est}}/K_{\text{exp}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO</td>
<td>Door</td>
<td>0.165</td>
<td>1.16</td>
<td>7.6</td>
<td>0.686</td>
<td>5.21</td>
<td>5.2</td>
<td>1.002</td>
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<tr>
<td>RWO</td>
<td>Window</td>
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<td>1.01</td>
<td>7.6</td>
<td>0.928</td>
<td>7.05</td>
<td>7.0</td>
<td>1.007</td>
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<td>LWO</td>
<td>Window</td>
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<td>1.02</td>
<td>7.6</td>
<td>0.881</td>
<td>6.70</td>
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<td>NA</td>
</tr>
<tr>
<td>EWO</td>
<td>Window</td>
<td>0.165</td>
<td>1.01</td>
<td>7.6</td>
<td>0.928</td>
<td>7.05</td>
<td>7.1</td>
<td>0.993</td>
</tr>
</tbody>
</table>

NA = not available; DO = door opening; RWO = regular window opening; LWO = large window opening; EWO = eccentric window opening.
considers the effect of opening location and is obtained using the results of specimens containing window openings with the same size and different locations. As presented in Table 5, the comparison of the approximate with the measured results of specimens with perforated infills shows a good correlation between them with a maximum error of 5%.

Because of limited number of tests conducted in this research, the reliability of the proposed equations was investigated by other experimental tests available in the literature. For this purpose, the values of the strength and stiffness of specimens tested by Kakaletsis and Karayannis (2007, 2008, 2009) and Tasnimi and Mohebkhah (2011) are compared with the proposed empirical relations. The general properties of specimens tested by these researchers and the results of their tests are presented in Table 6. It should be noted that the lesser strength of two directions is presented for specimens containing eccentric openings.

The comparison between the estimated values of stiffness and those obtained from tests is presented in Table 7. As it can be observed, the difference is less than 20% for most of the specimens. However, the deviation is higher in some cases, which may be attributed to the nature of the experimental work and also the complex behaviour of masonry materials.

Similarly, the values of the ultimate strength of specimens were obtained relative to that of the corresponding solid infilled frame and using Equation (4). The estimated values are compared with the experimental data in Table 8. As it can be seen, the difference in most of the specimens is less than 10%. The maximum deviation is 18% that belongs to specimen DO4.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Opening shape</th>
<th>$\frac{A_o}{A_p}$</th>
<th>$\frac{d_o}{\sqrt{2h_o}l_o}$</th>
<th>$\frac{x}{l}$</th>
<th>$V_{\text{solid}}$ (kN)</th>
<th>$R_{F_2}$ (strength)</th>
<th>$V_{\text{est}}$ (kN)</th>
<th>$V_{\text{exp}}$ (kN)</th>
<th>$\frac{V_{\text{est}}}{V_{\text{exp}}}$</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>RWO</td>
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<td>0.00</td>
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</tr>
</tbody>
</table>

BF = bare frame; S = solid infilled frame; DO = door opening; RWO = regular window opening; LWO = large window opening; EWO = eccentric window opening.

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Specimen</th>
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<th>$l_{\text{inf}}$ (mm)</th>
<th>$h_0$ (mm)</th>
<th>$l_o$ (mm)</th>
<th>$\frac{x}{l}$</th>
<th>V (kN)</th>
<th>$K_e$ (kN/mm)</th>
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</thead>
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<tr>
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</tr>
<tr>
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<td>Window</td>
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<td>1200</td>
<td>333</td>
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<td>14.6</td>
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<td>Door</td>
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<td>1200</td>
<td>640</td>
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<td>DO4</td>
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<td>1200</td>
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<td>—</td>
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<tr>
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<td>500</td>
<td>0</td>
<td>176.1</td>
<td>22.2</td>
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<tr>
<td>PW2</td>
<td>Window</td>
<td>1800</td>
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<td>700</td>
<td>0</td>
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<tr>
<td>PW3</td>
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<td>PW4</td>
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<td>2260</td>
<td>1450</td>
<td>700</td>
<td>0</td>
<td>116.5</td>
<td>17.4</td>
<td></td>
</tr>
</tbody>
</table>
6. CONCLUSIONS

In an experimental programme, the effects of openings on cyclic performance of masonry infilled RC frames have been investigated. In total, six frames have been tested, a bare frame, a solid infilled frame, three specimens with window openings of different sizes and locations and a specimen with door opening. According to the results, the following conclusions can be drawn:

1. Door opening led to a reduction of 29% in lateral strength, 40% in initial tangent stiffness, 34% in effective stiffness and 23% in energy dissipation capacity.
2. Window openings also led to an average reduction of 23% in lateral strength, 34% in initial tangent stiffness, 8% in effective stiffness and 11% in energy dissipation capacity.
3. Failure mode of all frames was the formation of plastic hinges in both ends of the beam and bottom of the columns, and no brittle shear failure of the frame members was observed because of the relatively weak infill panels of the specimens.
4. In the infilled frame specimens, formation of cracks at the frame-panel interface occurs at early stages at lateral loads equal to approximately 15% of the ultimate strength.

5. The failure mechanism of the infill panel in the solid infilled frame was bed-joint sliding, but in the specimens with openings it was a combination of bed-joint sliding and diagonal cracking of the masonry piers on the sides of the opening. This led to a more ductile behaviour in the solid infilled frame.
6. The presence of openings increased the level of damage in the infills. This reduced the deformation capacity of specimens with openings relative to solid infilled frame.
7. The door opening led to higher reductions in lateral stiffness, ultimate strength and energy dissipation capacity compared with the window opening with the same area and location. The specimen with door opening also suffered more severe damages than the specimen with window opening at the same peak displacements.
8. Increasing the size of the opening did not alter the load resistance mechanism and the level of damage of the specimen; however, a reduction in the stiffness and energy dissipation capacity was observed in the specimen with a larger opening.
9. For global analysis of structures, infill panels with openings can be modelled as equivalent diagonal struts with reduction factors to take into account the effects of size, shape and location of the openings.

It should be noted that the tests have been performed on single-storey, single-bay specimens, and the potentials for concentration of damage in the frames, because of torsional effects or to the formation of soft-storey mechanisms, are not explored. Furthermore, because of the limited number of tests conducted in this research, and limited reports available in the literature, more tests may be needed to generalize the aforementioned conclusions.

REFERENCES


AUTHORS’ BIOGRAPHIES

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