Influence Of Masonry Panels With Openings On The Seismic Response Of Reinforced Concrete Infilled Frames

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Influence Of Masonry Panels With Openings On The Seismic Response Of
Reinforced Concrete Infilled Frames

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Abstract

Due to architectural considerations, openings are required in masonry infill panels. In this study, a pushover analysis is carried out to assess the behavior of RC infilled frames with emphasis on the effect of openings in the infills. The main parameters that will be considered concern the size, the location and the aspect ratio of the openings. Three reinforced concrete structures representative of rigid, semi-rigid and flexible structures are designed according to the Algerian seismic code. The numerical model of the structures consists of frame elements with concentrated plastic hinges at the ends and a nonlinear layered shell for the infills. The results obtained show that the presence of infills can drastically change the overall behavior of the structures by enhancing the strength capacities but with limited ductility and the presence of openings can modify the hinges locations and patterns according to their size, location and aspect ratio.

Key words: Infills, openings, plastic hinges, capacity curves, Nonlinear layered shell.
1. Introduction

Reinforced concrete (RC) frame buildings with masonry infill walls are widely constructed for commercial, industrial and multi-family residential uses in seismic-prone regions worldwide although the masonry infill panels are generally considered as non structural components and are thus neglected in assessing the seismic response of reinforced concrete frames. Numerous studies have shown both experimentally and numerically that the masonry infill panels can drastically affect the seismic response of reinforced concrete frames and should not be neglected anymore. The existence of the masonry infill panels in a frame can increase structural strength and stiffness (relative to a bare frame), but, at the same time, interaction should be considered. In general, the presence of the masonry infill panel and interaction with the RC frame changes the failure mechanism of the infilled frame in comparison to the bare frame. Masonry is a highly orthotropic material due to the existence of the mortar joint. In addition, the masonry or infill wall can experience different failure mechanisms, such as cracking, sliding, and compression failure. To simulate the behavior of the masonry wall, different types of models can be developed, depending on the level of accuracy needed, Micro-modeling and Macro-modeling. Solid infills have been extensively studied in the last six decades, analytically: Holmes (1961) [01], Mainstone and Weeks (1970) [02], Crisafulli (1997) [03], El-Dakhakhni et al. (2003) [04], Diana (2012) [05], Asteris (2013) [06], István and Zsolt (2015) [07], Ivan Radić et al. (2016) [08], numerically: Dhanasekhar and Page (1986) [09], Mehrabi and Shing (1997) [10], Oliveira and Lourenço (2004) [11], Stavridis and Shing (2010) [12], Koutromanos et al. (2011) [13], Manos et al. (2012) [14], Uva et al. (2012) [15], Baloevic’et al. (2013) [16], Ivo and Bartolomeo (2014) [17], Chen and Liu (2015) [18], Yuen and Kuang (2015) [19], Enzo Martinelli et al. (2015) [20], and experimentally: Mehrabi et al. (1996) [21], Mosalam et al. (1998) [22], Al-Chaar et al. (2002) [23], Alidad and Mosalam (2006) [24], Anil and Altin (2007) [25], Blackard et al. (2009) [26], Stavridis et al. (2012) [27],
Compared to RC frames with solid masonry panels, infills with windows or doors have received little attention. Abdel-Gawad et al. (2001) [34] tested ten half-scale models under fully reversed cyclic loading and studied the effect of openings size, openings location, the interface condition between the infill and the frame on strength, stiffness, ductility, energy dissipation and modes of failure. Their main conclusion consisted of the contribution of infilled frames containing openings, especially framed openings which should not be ignored because they improve the stiffness of masonry infill panel under cyclic lateral loads. Goutam et al (2008) [35] proposed a reduction factor for effective width of the diagonal strut to calculate its initial lateral stiffness when a central window opening is present. They concluded that the presence of central openings can be considered by reducing the effective width through a reduction factor, \( \rho_w = 1 - 2.6 \alpha C_0 \), where \( C_0 \) is the ratio of the area of opening to the area of the infill and, on the other hand, the effect of openings on the initial lateral stiffness of infilled frames should be neglected if the area of openings is less than 5% of the area of the infill panel. The effect of infill on the initial lateral stiffness of infilled frame may be ignored if the area of opening exceeds 40% of the area of the infill panel. Sachin and Kaushik (2012) [36] undertook a review of the behavior of masonry infill RC frames with openings under in-plane lateral load. They stated that precedent researchers tried to find out experimentally and analytically the influence of several parameters like openings size and location, aspect ratio of openings, connections between infill and frame. They revealed that the effect of openings was the subject of a large number of experimental analytically studies all over the world. The masonry infills with openings provide significant amount of stiffness to frames. The failure modes of masonry infilled frames change drastically due to the presence of openings in the wall. The location and size of openings in the infill walls influence deformability, ductility and energy dissipation capacity. Ephraim and Nwofor (2015) [37]
presented a comparative study concerning the composite behavior of multistory RC frames using the macro model of one strut configuration and the finite element micro model. The effect of openings in the infill was given particular attention. They concluded that introduction of the shear stress reduction factor enhanced the efficiency of the one-strut model to reproduce the shear strength, lateral stiffness and seismic demand of infilled frames with openings. Fatih Cetisli (2015) [38] analyzed the behavior of partly infilled RC frames, taking into account the dimensions and the location of openings. He undertook a numerical parametric study of infilled RC frames with emphasis of wall dimension and locations of openings. He presented an analytical expression for estimating the reduction stiffness of an equivalent diagonal compression strut. Khan and Saim (2015) [39] performed time history analyses on masonry infilled RC frames and studied the influence of variation of the number of bays, the number of stories, the percentage of opening in the infill wall, the location of the openings, the type of the openings, the number of openings, the infill strength and the outer frames strength and thickness on the performance of RC infilled frames. They concluded that the performance of the infilled frames is dependent on the geometric properties of the infill and the frame, and on the other hand, with the increase in the openings size, the time period, roof displacement, member forces and inter storey drift ratios increase due to the decrease in the lateral stiffness of the structure whereas infill stresses and base shear force decrease for infilled structures having openings. Maximum infill stresses were found at the corners of the openings unlike the fully infilled structures where the maximum infill stresses were found at the compression corners of the panel.

2. Description Of The Structures

Three structures representing low, medium and high rise reinforced concrete frame buildings with two, five and ten story have been used in this study. These structures are designed according to the Algerian seismic code (RPA 2003) [40], to assess the behavior of RC infilled
frames with emphasis on the effect of openings in the infill. The main parameters that will be considered concern the size, the location and the aspect ratio of the openings. Four structural configurations with different percentages of openings in the infill have been used: fully infilled, infilled frame with 10% openings, infilled frame with 25% openings and infilled frame with 50% openings, for the location and aspect ratio, six structural configurations with different locations of openings in the infill have been used: central window, left window, right window, central door, left door, right door, and six structural configurations with different values of aspect ratio.

The dimensions of the beams and columns for the three reinforced concrete frames are shown in Figures (1, 2 and 3). The thickness of the infills is equal 0.25m, the typical floor to floor height is 3.00m, the span between the axis of two following columns is 4.40m and the details for the beams and columns are shown in table 1, Material properties are assumed to be 25 MPa for the concrete compressive strength and 400 MPa for the yield strength of the longitudinal and transverse reinforcement steel. The material properties adopted in this study are shown in table 2.

3. Modeling Aspects

A Two dimensional model of each structure is created to undertake the non linear analysis. Beams and columns are modeled as nonlinear frame elements with lumped plasticity at the start and the end of each element. SAP 2000 [41] provides default-hinge properties and recommends PMM hinges for columns and M3 hinges for beams as described in FEMA-356 [42]. The infill masonry panels are modeled using a nonlinear layered shell element available in SAP 2000. The layered shell allows any number of layers to be defined in the thickness direction, each with an independent location, thickness, behavior, and material. Membrane deformation within each layer uses a strain-projection method Hughes (2000) [43]. In-plane displacements are quadratic. The “drilling” degrees of freedom are not used, and they should not
be loaded. These rotations normal to the plane of the element are only loosely tied to the rigid-body rotation of the element to prevent instability. For bending, a Mindlin-Reissner formulation is used which always includes transverse shear deformations. Out-of-plane displacements are quadratic and are consistent with the in-plane displacements. The layered Shell usually represents full-shell behavior. Unless the layering is fully symmetrical in the thickness direction, membrane and plate behavior will be coupled. The section is built-up in the thickness direction. Any number of layers is allowed, even a single layer. Layers are located with respect to a reference surface. According to the SAP 2000 manual, this model should only be used when the infill element is completely surrounded by frame or other supporting elements, and the elements should not be meshed.

The anisotropy of masonry will be modeled by 2 different stress strain curves, each of them will represent respectively vertical and horizontal stress $S_{22}$ and $S_{11}$, and shear stress $S_{12}$ (figure 4). The key to this approach is the prediction as good as possible of the stress strain curves for each direction. Here the $S_{11}$ and $S_{22}$ curves will have the same behavior. So far no tests are done in perpendicular direction due to the fact that bricks are mounted horizontally in a wall. Also it is very rare or not possible to apply a horizontal force to masonry and expect it to fail in compression, but in shear. Although no compression tests exist for this direction, it is expected that the compression resistance to be higher because the bricks have a greater percentage and they are stronger than mortar. A rigid full contact connection between frames and infills is adopted.

4. Pushover Analysis

The static pushover analysis (SPA) procedure has been presented and developed over the last three decades by numerous researchers [44], [45]. The static pushover analysis
method is mainly based on the assumption that the response of the structure is controlled by the first mode or by the first few modes of vibration, and that this shape remains constant throughout the elastic and inelastic response of the structure. To perform a pushover analysis, a pattern of increasing lateral forces needs to be applied to the mass points of the system. The purpose of this is to represent all forces which are produced when the system is subjected to earthquake excitation. By incrementally applying this pattern up to and into the inelastic stage, progressive yielding of the structural elements can be monitored. During the inelastic stage the system will experience a loss of stiffness and a change in its vibration period. In this study, uniform lateral forces proportional to storey masses are used and gravity loads remain constant. The pushover analysis provides a base shear vs. roof displacement relationship called capacity curve or pushover curve; (figure 5).

5. Results And Discussions

5.1. Effect of openings on the fundamental period

The fundamental period increases as the size of the infill openings increase due to the reduction of the lateral stiffness of the structures. For instance, the differences in the fundamental period between the bare frame (100% openings) and the fully infilled frame (0% openings) for the three structures are 27%, 31% and 37% respectively, for percentages of openings of 10%, 25% and 50%, the rates of increase in the fundamental period compared to the case of 0% openings are different for each structure, suggesting an influence of the dynamic characteristics of the models. However, the opening size of infill does not have an influence on the participation coefficient, (see table 3).

5.2. Capacity curves

The capacity curves for the three structures are shown in figures (6, 7 and 8). For
structure 1, the strength capacity of the fully infilled frame is increased by 86.74% compared to the bare frame. With the increase in the percentage of infill openings (from 10% to 50%) the strength capacity of the partially infilled frames is decreased by 7.17%, 45.71% and 68.52% respectively, the infill wall enhances the lateral stiffness of the frame, however the presence of infill openings tend to reduce the lateral stiffness. For structure 2, the percentage difference of strength capacity between the fully infilled and the infilled frame with 10%, 25%, 50% and 100% (bare frame) openings is 17.31%, 44.26%, 72.27% and 83.64% respectively. For structure 3, the percentage difference of strength capacity between the fully infilled and the infilled frame with 10%, 25%, 50% and 100% (bare frame) openings is 25.37%, 44.30%, 66.83% and 81.16% respectively. Globally, the bare frames exhibit better ductility than infilled frames which can be explained the brittle behavior of the masonry infill panels.

5.3. Effect Of Different Openings Locations

For this study six structural configurations with different locations of openings in the infill have been used: central window, left window, right window, central door, left door, right door, (Figures 9, 10 and 11).

The capacity curves for the three structures are shown in figures (12, 13 and 14). For structure 1, moving the opening window left or right results in an increase of the strength capacity compared to a central window, whereas for door opening the capacity curve is reduced when the opening is moved left or right. For structure 2: however, the percentages of increase are different for the left and right sides, the capacity of the left window opening is greater than that of the central and right opening which have approximately the same strength capacity. The strength capacity of the central and left door opening are equivalent while the capacity of the right door opening is reduced. In structure 3, the capacities associated with the left or right door and window opening are either reduced or increased suggesting an influence of the dynamic
characteristics of the models.

5.4. Effect of Aspect Ratio

To study the effect of the aspect ratio, six structural configurations with different values of aspect ratio $H_o/B_o$ (where $H_o$ and $B_o$ are the height and the width of the opening) ranging from 0.25 to 1.33 are considered, as shown in table 4. In all cases the area of the opening is kept constant.

The capacity curves for the three structures are shown in figures (15, 16 and 17). For structure 1, the strength capacity for an aspect ratio of 0.25 is equal to 600 KN. The strength capacity is increased by 20%, 34%, 39.71%, 45% and 53.48% for values of aspect ratio equal to 0.5, 0.75, 0.85, 1.0 and 1.33 respectively. The same trends are observed for structures 2 and 3. This can be explained by the fact that the masonry infill panels with opening behave like a coupled masonry wall and with the increasing of the aspect ratio the masonry wall piers will have a larger stiffness which enhances the bearing capacity of the structures and a coupling masonry thin beam which results in low shear stresses.

5.5. Plastic Hinges Mechanisms

Under incrementally increasing loads some elements may yield sequentially. Consequently, at each event, the structures experiences a stiffness change as shown in figure 18. Immediate Occupancy (IO), Life Safety (LS), Collapse prevention (CP), Ultimate capacity (C), C to D- between C and residual strength, D to E- between D and collapse >E collapse respectively are defined as per FEMA 356.

The hinging patterns are plotted in figures (19 and 20). The plastic hinges in the bare frames are spread over the height of the structures whereas in the infilled frames the plastic
hinges tend to concentrate in the lower levels, especially for solid infills and infills with low percentages of openings. The presence of openings changes the events at which the plastic hinges patterns occur. For instance, the hinge patterns of infills with 50% openings are different from those of bare frame. Furthermore, the location and aspect ratio of opening influence the failure modes of the infilled frames depending on the dynamic characteristics of the structures.

6. Conclusions

In this paper, the seismic performance of RC frames with and without infills with special emphasis of the effects of openings has been studied. The opening size of the infill has a significant influence on the fundamental period. Generally it increases as the opening size increases, indicating that the decrease in stiffness is more significant than the decrease in mass. Results of pushover analysis show an increase in initial stiffness, strength capacity for the infilled frame compared to the bare frame despite the masonry wall’s brittle failure modes. The presence of masonry walls has a significant effect on the collapse mechanism observed. Dynamic characteristics are seen to be an important factor to consider since they can influence notably the response parameters. Surprisingly, large size openings in the infills modified substantially the behavior of infilled frames compared to the bare frame, where it was expected that the two behaviors will be close. The location and the aspect ratio of openings are important parameters that should be given attention when designing this type of structures.
References


List of figures

Figure 1. Structure 1 with different percentages of openings in the infill.

Figure 2. Structure 2 with different percentage of openings in the infill.

Figure 3. Structure 3 with different percentage of openings in the infill.

Figure 4. A four node shell element and in plane stresses.

Figure 5. Pushover curve.

Figure 6. Capacity curve of structure 1 with different percentages of infill openings.

Figure 7. Capacity curve of structure 2 with different percentages of infill openings.

Figure 8. Capacity curve of structure 3 with different percentages of infill openings.

Figure 9. Structure 1 with different locations of 25% openings.

Figure 10. Structure 2 with different locations of 25% openings.

Figure 11. Structure 3 with different locations of 25% openings.

Figure 12. Capacity curve structure 1 with different locations of window and door in the infill.

Figure 13. Capacity curve structure 2 with different locations of window and door in the infill.

Figure 14. Capacity curve structure 3 with different locations of window and door in the infill.

Figure 15. Capacity curve of structure 1 with different values of aspect ratio Ho/Bo.

Figure 16. Capacity curve of structure 2 with different values of aspect ratio Ho/Bo.

Figure 17. Capacity curve of structures 3 with different values of aspect ratio Ho/Bo.

Figure 18. Generalized force-deformation relation for elements or components.

Figure 19. Hinges patterns for structures 1, 2 and 3 with different percentages of openings.

Figure 20. Hinges patterns for structures 1, 2 and 3 with different locations of openings.
List of tables

Table 1. Dimensions of the beams and columns

Table 2. Material properties

Table 3. Fundamental periods and mass contributions for various percentages of openings

Table 4. Values of aspect ratio $R=H_o/B_o$
Figure 1. Structure 1 with different percentages of openings in the infill

Figure 2. Structure 2 with different percentages of openings in the infill

Figure 3. Structure 3 with different percentages of openings in the infill
Figure 4. A four node shell element and in plane stresses

![Shell Element Diagram](image)

Figure 5. Pushover curve

![Pushover Curve](image)

Figure 6. Capacity curve of structure 1 with different percentages of infill openings

![Capacity Curve](image)
Figure 7. Capacity curve of structure 2 with different percentages of infill openings

Figure 8. Capacity curve of structure 3 with different percentages of infill openings

Figure 9. Structure 1 with different locations of 25% openings
Figure 10. Structure 2 with different locations of 25% openings

Figure 11. Structure 3 with different locations of 25% openings

Figure 12. Capacity curves of structure 1 with different locations of window and door in the infill
Figure 13. Capacity curves of structure 2 with different locations of window and door in the infill.

Figure 14. Capacity curves of structure 3 with different locations of window and door in the infill.

Figure 15. Capacity curve of structure 1 with different values of aspect ratio Ho/Bo.
Figure 16. Capacity curve of structure 2 with different values of aspect ratio Ho/Bo

Figure 17. Capacity curve of structure 3 with different values of aspect ratio Ho/Bo

Figure 18. Generalized force-deformation relation for elements or components
Figure 19. Hinges patterns for structures 1, 2 and 3 with different percentages of openings in the infill
Figure 20. Hinges patterns for structures 1, 2 and 3 with different locations of openings in the infill
<table>
<thead>
<tr>
<th>Building</th>
<th>Beams (cm x cm)</th>
<th>Columns(cm x cm)</th>
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</thead>
<tbody>
<tr>
<td>Two story</td>
<td>30x40</td>
<td>30x30</td>
</tr>
<tr>
<td>Five story</td>
<td>30x40</td>
<td>40x30</td>
</tr>
<tr>
<td>Ten story</td>
<td>30x40</td>
<td>50x40</td>
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Table 1. Dimensions of the beams and columns

<table>
<thead>
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<th>material</th>
<th>Compressive strength (KN/m²)</th>
<th>Modulus of elasticity (KN/m²)</th>
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Table 2. Material properties

<table>
<thead>
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<th>Structure</th>
<th>Period (sec)</th>
<th>Mass Contribution [%]</th>
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<tr>
<td>M1-A</td>
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</tr>
<tr>
<td>M1-B</td>
<td>0.08</td>
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<tr>
<td>M1-C1</td>
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<td>M1-C2</td>
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<td>M3-A</td>
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<td>M3-B</td>
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<td>M3-C2</td>
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<tr>
<td>M3-C3</td>
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<td>79.47</td>
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Table 3. Fundamental periods and mass contributions for various percentages of openings

<table>
<thead>
<tr>
<th>Cases</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>R=Ho/Bo</td>
<td>R1=0.25</td>
<td>R2=0.50</td>
<td>R3=0.75</td>
<td>R4=0.85</td>
<td>R5=1.00</td>
<td>R6=1.33</td>
</tr>
</tbody>
</table>

Table 4. Values of aspect ratio R=H_o/B_o
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