EXPERIMENTAL STUDY ON RC FRAME-INFILL INTERACTION

Yaw-Shen TÜ¹, Tsung-Chih CHIOU²*, Yi-An LI³

ABSTRACT

The seismic design provision of reinforced concrete (RC) buildings requires that the walls need to be included in the structural analysis; however, engineers usually ignore RC infill in the structural calculation, except for RC shear walls. However, reconnaissance experience of past major earthquakes has indicated that RC infill might affect the lateral behavior of the adjacent RC frame. Therefore, this experiment studied the interactive effect between a RC frame and RC infill. Two 50% scaled down specimens of a RC frame with a thin infilled wall were used to conduct lateral cyclic loading tests in the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The test results indicate that shear crack propagation in the partition wall extended into the adjacent small columns, while sliding shear cracks occurred between the interface of the partition wall and the adjacent large columns. The lateral strength and stiffness of the both frames were significantly increased by RC infill. However, the toughness of frames with small columns was obviously reduced. The failure mode of this frame was shear failure instead of flexural. This means that low-rise RC buildings with RC infill may experience severe shear failure in their columns due to the interaction of the RC infill. In addition, for mid- to high-rise RC buildings, RC infill may not significantly induce shear cracks on the adjacent columns but the enlargement of the initial stiffness of that frame due to RC infill was essential. Consequently, determination of seismic demand for mid- to high-rise RC buildings should consider a reasonable stiffness in the RC frames.

Keywords: reinforced concrete frame; RC infill; frame-infill interaction; low-rise building; high-rise building

1. INTRODUCTION

The majority of buildings in Taiwan are reinforced concrete structures. However, due to the demand for private space, partition and external walls are installed in these buildings. These walls are usual reinforced concrete (RC) infill with a thickness of 12 cm to 15 cm. The rebar of the RC infill is usually designed with only minimum reinforcement requirements for cracking control. High-rise buildings in Taiwan are designed with columns that have a larger cross-section. However, the thickness of the infilled walls remains at 12 cm to 15 cm. Therefore, large sized frames with thin walls are normal in high-rise buildings (Figure 1a). However, engineers may neglect to consider the effects of RC infill. They tend to design these buildings with moment resisting frames (MRF), even though RC infill is installed in the frames. The question of whether or not the effect of RC infill can be neglected still needs clarification by experiment. Previous experimental studies have indicated that RC infill and RC frames significantly interact with each other (Hwang and Lee 1999; Hwang et al. 2001; Ono and Tokuhiro 1992). However, most of these experiments were conducted in low-rise RC frames with RC infill, which used small sized frames with RC infill (Figure 1b). Due to the lack of tests for high-rise building MRF with RC infill, a large sized column RC frame with RC infilled wall test was conducted to clarify the interaction between the RC frame and the RC infill. In this study, two specimens of different sized column frames

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with infilled wall were designed for a seismic behavior simulation of high-rise buildings and low-rise buildings. The major purpose of this test is to clarify the difference in the seismic behavior of infilled frames with different sized columns.

![Image](image1.png)

(a) Sliding shear failure at the interface between infill and adjacent columns in a high-rise building  
(b) Shear failure of the infill and adjacent columns in a low-rise building

Figure 1. Failure patterns of RC infill in MRF buildings after earthquakes.

2. TESTING PROGRAM

The buildings in Taiwan have an M-type trend. Most of the old buildings are low-rise buildings with under five stories, while most of the new buildings are high-rise condominiums with over 12 stories. According to the survey data, buildings with more than 12 floors were configured with a column section of about 100 cm × 100 cm and the column section of low-rise buildings was proportional to their height (Huang et al. 2014). For example, buildings with four or five stories were configured with a column section of 40 cm × 40 cm. The RC infilled wall is normally about 12 cm thick and about 300 cm high. The span between the columns center to center is about 600 cm.

In this study, two 50% scaled down specimens of RC frames with thin infilled walls were used to conduct lateral cyclic loading tests in the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The first specimen (C50W6) consisted of 50 cm × 50 cm RC columns with an infilled wall of 6 cm thickness for seismic behavior simulation of mid- to high-rise RC buildings with partition walls. The other specimen (C20W6) consisted of small columns (20 cm × 20 cm) with infilled walls of the same thickness for simulation of low-rise RC buildings with partition walls. The infilled walls were configured with single-layer, bi-directional (horizontal and vertical) rebar. The steel rebar only conforms to the temperature reinforcement requirements of the design code (Construction and Planning Agency 2011). The detail of the column section and the RC infill are illustrated in Figure 2. The testing parameters, ratio of column depth \((h_c)\) to wall thickness \((t_w)\), are listed in Table 1, in addition to the material properties, including the compressive strength of concrete \((f_c')\) and the tensile strength of rebar \((f_y)\).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(h_c/t_w)</th>
<th>(f_c'\ (MPa))</th>
<th>(f_y\ (MPa))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D25(#8)</td>
<td>D22(#7)</td>
</tr>
<tr>
<td>C50W6</td>
<td>8.3</td>
<td>27.2</td>
<td>467.5</td>
</tr>
<tr>
<td>C20W6</td>
<td>3.3</td>
<td>33.3</td>
<td>370.7</td>
</tr>
</tbody>
</table>
The specimens were tested by cyclic lateral loading with a constant axial loading of $0.1A_gf'_c$. In which $A_g$ is the cross-section area of the columns and wall. An axial loading of 1768kN was applied on specimen C50W6, while axial loading of 826kN was applied on specimen C20W6. Lateral supporting frames were installed on both sides of the specimens to prevent out-of-plan deformation of the infill frames. The testing setup is shown in Figure 3.
3. TEST RESULTS

3.1 Specimen C50W6

The hysteresis loop of the cyclic lateral loading is shown in Figure 4. The envelope of the load-deformation curve is shown in Figure 5. The maximum strength of the test was 2345 kN at the drift ratio (D.R.) of 0.375%: the drift ratio was defined as a horizontal displacement of the beam center divided by the height from column bottom to beam center. The crack pattern at this drift ratio is shown in Figure 6. Diagonal incline shear cracks could be found in the wall, while slight shear cracks were found in both ends of the columns. However, the shear cracks did not continuously propagate from the infilled wall into the columns. Sliding cracks on the interface between wall and column edge were found, as illustrated in right-hand side of Figure 6.

According to the mechanics of the materials, the distribution of shear stress on an uncracking dumbbell section is shown in Figure 10. Shear stress on wall panel will be instantaneously reduced to column shear stress because the wall thickness rapidly changes in relation to the column width. In accordance with the elastic shear stress formula of the mechanics of the materials,

$$\tau = \frac{\nu Q}{1b}$$

(1)

shear stress at the column edge ($\tau_1$) of the specimen C50W6 (Figure 10a), as an example, will proportionally reduce from shear stress ($\tau_0$) at the edge of wall panel, as calculated in Equation 2,

$$\tau_1 = \left(\frac{6}{50}\right) \tau_0 = 0.12 \tau_0$$

(2)

If the shear stress at the column edge ($\tau_1$) is much less than the shear cracking strength of the 50 cm × 50 cm column, then the diagonal incline shear cracks on the wall panel do not propagate into the boundary columns. Therefore, the wall panel and the RC frame may be independently considered without the interacting effect on seismic behavior.

For the behavior of post ultimate strength, a plateau was found from D.R. of 0.75% to 3% as shown in Figure 5. The lateral strength at D.R. of 0.75% was 1683kN. Meanwhile, significant horizontal cracks were found on the wall panel below the beam. Slight vertical cracks were also found along the vertical interfaces between the boundary columns and the wall panels, as shown in Figure 7.

The lateral strength at D.R. of 3% was 1607kN; the crack patterns are illustrated in Figure 8. A severe fracture was found on the interfaces between the wall panel and RC frame. The lateral strength started to drop due to the severe shear failure on the column.

Finally, the test was terminated at D.R. 5% when the lateral strength only remained 447kN (less than 20% of ultimate strength). Figure 9 shows that the wall panels and columns were severely fracture, such as: longitudinal bar buckling and transverse hoop opening of the columns, and rebar rupture of the wall panels.
Figure 4. Hysteresis loop of C50W6.

Figure 5. Envelope of C50W6.

Figure 6. Crack pattern of C50W6 at D.R. of 0.375%.

Figure 7. Crack pattern of C50W6 at D.R. of 0.75%.

Figure 8. Crack pattern of C50W6 at D.R. of 3%.

Figure 9. Crack pattern of C50W6 at D.R. of 5%.
3.2 Specimen C20W6

The hysteresis loop of cyclic lateral loading is shown in Figure 11. The envelope of load-deformation curve is shown in Figure 12. The maximum strength of the test was 1184 kN at the drift ratio (D.R.) of 0.5%. The crack pattern at this drift ratio is shown in Figure 13. Diagonal incline shear cracks were found on the wall panel. Moreover, the shear cracks continuously propagated from the infilled wall into the boundary columns. This means that the boundary columns sustained a shear force larger than the shear cracking strength.

The shear stress at the column edge ($\tau_2$) of the specimen C20W6 (Figure 10c) will proportionally reduce from shear stress ($\tau_0$) at the edge of wall panel, as calculated in Equation 3,

$$\tau_2 = \left(\frac{6}{20}\right) \tau_0 = 0.3 \tau_0$$  (3)

The column section of 20 cm × 20 cm sustained 2.5 times the shear stress ($\tau_1$) of the column section of 50 cm × 50 cm. If the shear stress at the column edge ($\tau_2$) is much larger than the shear cracking strength of the 20 cm × 20 cm column, then the diagonal incline shear cracks on the wall panel propagate into the boundary columns. Therefore, the wall panel and the RC frame should be dependently considered with the interacting effect on seismic behavior.

For the behavior of the post ultimate strength, the lateral strength remained with 1033 kN at D.R. of 0.75% while shear failure was found on the columns (Figure 14). Finally, the test was terminated with lateral strength of 233 kN at D.R. of -0.75% in the opposite direction because the boundary columns lost the axial loading resistance capacity when bar buckling was found in the bottom of the columns (Figure 14).
3.3 Discussion of the testing results

The testing results indicate that flexural behavior of a RC frame might be affected by an infill panel. If the shear strength capacity of the RC frame was insufficient, then the shear cracks on the infilled wall would propagate into the columns of the RC frame. Eventually, the RC infill frame would experience shear failure. In contrast, the RC frame would retain its flexural behavior after the infilled wall experienced shear fracture.

Shear strength is proportional to the gross section area of the structural elements. For a square column, the shear strength ratio of the column to the infilled wall may be presented as a ratio of column depth to wall thickness. For the C20W6 specimen, for example, the ratio of column depth to wall thickness was 3.33 (20/6). The crack patterns of the specimen indicated that the boundary columns experienced shear failure while the wall panel experienced shear fracture. Therefore, the infill frame of C20W6 did not present the flexural behavior of a moment resisting frame.

In contrast, the ratio of the column depth to wall thickness was 8.33 (50/6) for the C50W6 specimen. The infill frame could retain the flexural behavior of a moment resisting frame after wall panel experienced shear fracture.

A mid-rise building, for instance, is designed as a MRF with 70 cm depth of column and 20 cm thickness of RC infill. The ratio of column depth to wall thickness is 3.5. In accordance with the observation from the experiment, this MRF may experience shear failure due to the effect of the RC infill. Consequently, the thickness of RC infill for mid- to high-rise buildings should be limited to prevent the MRF from reducing the deformation capacity.
4. CONCLUSIONS

Two RC frames with RC infill were tested in the seismic behavior simulation of multiple story buildings. Based on the observation of this experimental study, the following conclusions can be drawn,

(1) For mid- to high- rise buildings with RC infill, the lateral strength and stiffness of the RC frame were significantly increased by RC infill. After the RC infill passed its shear strength, sliding shear cracks occurred between the interface of the partition wall and the adjacent large columns. The toughness of the adjacent RC frame remained. For mid- to high- rise RC buildings, the RC infill may not significantly induce shear cracks in the adjacent columns but enlargement of the initial stiffness of that frame due to RC infill was essential. Consequently, determination of seismic demand for mid- to high- rise RC buildings should consider RC frames of reasonable stiffness.

(2) The RC infill of low-rise buildings will dominate their seismic behavior. When the RC infill developed its shear strength, shear crack propagation on the partition wall extended into the adjacent small adjacent columns. Consequently, the toughness of frames with small size columns was obviously reduced. The failure mode of that frame was shear failure instead of flexural. This means that low-rise RC buildings with RC infill may experience severe shear failure in the columns due to the interaction of the RC infill. Therefore, the RC infill of low-rise buildings should be simulated by an equivalent column when modeling the shear failure effect of the adjacent columns.

(3) When the ratio of column depth to wall thickness is larger than 8.33, the structure system would be classified as a high-rise building with RC infill. Meanwhile, when the ratio is less than 3.33, the structure might be classified as a low-rise building with RC infill.

5. ACKNOWLEDGMENTS

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6. REFERENCES


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