SEISMIC BEHAVIOR OF PRECAST REINFORCED CONCRETE WALLS

Yaw-Jeng Chiou ¹ Yuh-Wehn Liou² Chin-Chi Huang³ and Fu-Pei Hsiao⁴

ABSTRACT

This study experimentally investigates the seismic behavior of precast reinforced concrete walls by test of large-scale specimens. The parameters of connected steel cover plate, orientation of wall reinforcements, steel ratio of wall, and strength of concrete were studied. The results show that the precast reinforced concrete wall can effectively increase the earthquake resistance of structures and protect the structural frame. The performance of the precast reinforced concrete wall can be fully developed by using connected steel cover plates with two channel plates which were fixed by M16 chemical anchors. The modified conventional reinforcement with more steel at the corners produces better performance than the other orientations. The larger steel ratio and stronger concrete also definitely increase the earthquake resistance of structures.

Keywords: precast reinforced concrete wall, large-scale test, earthquake resistance

INTRODUCTION

Framed shear walls are extensively used as the components of earthquake resistant buildings. Previous researches (Zhang and Wang 2000; Palermo and Vecchio 2002; Hidalgo et al. 20002; Greifenhagen and Lestuzzi 2005) have demonstrated that framed shear walls behaved with higher strength and lower ductility. The hysteresis loops of mid-rise and low-rise walls were also characterized by obviously pinched shapes. The results presented by Sittipunt et al. (2001) showed that the high-rise framed-walls with diagonal reinforcement displayed rounded hysteresis curves, and more energy was dissipated by the walls with diagonal reinforcement. The authors (Chiou et al. 2006) also found that the mid-rise framed-walls with diagonal reinforcement displayed rounded hysteresis curves and failed due to crushing at the bottom of boundary columns.

Adding the concrete walls to frame structural system sounds an efficient retrofit method for reinforced concrete structures. However, the retrofit of reinforced concrete structures by using cast-in-place concrete walls takes a lot of site formwork and labor. Recent research has shown that precast concrete

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walls can be used as part of the lateral force resisting system (Kurama et al. 1999, Crisafulli et al. 2002). The incorporation of precast concrete components has the advantages of high quality control, reduction of site formwork and labor, increased speed of construction, and overall economy (Crisafulli et al. 2002).

The framed shear walls frequently induce failure of boundary columns (Chiou et al. 2006). The development of a retrofit method with most of the energy dissipated by the wall, and the structural frame system remains safe sounds like an innovative strategy. The precast concrete walls separate from the boundary columns, and the forces in the wall will not further transfer to columns. The retrofit of reinforced concrete structures by precast walls which are used as part of the lateral force resisting system seems to be an alternative attractive method. However, the performance of precast concrete walls will highly depend on the frame-wall connections which determine the loads transfer from frame to wall panel.

This study experimentally investigated the seismic behavior of precast reinforced concrete walls. A new vertical load experimental system was proposed to improve the conventional vertical load applied system. Nine large scale specimens subjected to both cyclic lateral force and vertical load were tested. The parameters of connected steel cover plate, orientation of wall reinforcements, steel ratio of wall, and strength of concrete were studied.

EXPERIMENTAL INVESTIGATION

1. Experimental Setup

Figure 1 shows the schematic configuration of the test setup. Each specimen was bolted at the steel foundation, which was then connected to the strong floor. Both vertical load and cyclic lateral force were applied to the specimen. A new vertical load experimental system was proposed to improve the conventional system. This new system was designed with lever and pulley block (Figures 1 and 2). A manually operated hydraulic jack with a loading capacity of \( \pm 1500 \text{kN} \) and a stroke of \( \pm 200 \text{mm} \) supplied the lateral force. The lateral displacements were measured by linear variable differential transformers (LVDT) and the force was measured by load cell. The experiment was displacement control, and its displacements were 1mm, 2.5mm, 5mm, 10mm, 20mm, 30mm, 40mm, 50mm, 60mm, and 70mm, respectively. Each displacement was repeated twice the amount of loading. The measured force and displacement were collected by TDS-302 data logger. The experiment was monitored by the load-displacement curve.

2. Design of Vertical Load Experimental System

The hydraulic actuator is frequently used in the conventional vertical load applied system. However, it is not an easy task to safely fix the actuator during test. Referring to Figures 1 and 2, a new vertical load experimental system was designed with lever and pulley block in this study. There are two pulley block systems applied to both left and right columns. Each column has 8 pulley blocks at one side of the specimen and each block connects to the steel cover for vertical load transfer (Figure 2a) via steel bar. The cable passes the pulley, and the load is transferred to steel bar and specimen eventually. The force in the steel bar is measured by strain gage. The friction force may exist between cable and the contacted surface of pulley.

Due to the effect of friction, the initial distribution of vertical force is trapezoid. However, the distribution of vertical force changes repeatedly from trapezoid to uniformly distribute and vice versa when the lateral force varies. It is found that the distribution of vertical force is nearly uniform in each loading cycle.

3. Design of Specimens
The walls were designed with conventional reinforcements (Figures 3a1 and 3a2), modified conventional reinforcements with more steel at four corners (Figures 3b1 and 3b2), and radial reinforcements (Figures 3c1 and 3c2). The reinforcements were welded to the drilling holes of steel cover plates. The connected steel cover plates were designed with two channel plates and one rectangular plate with an opening, and the M16 chemical anchors were used to transfer the force between the wall panel and the frame. Nine specimens including four walls with conventional reinforcements (PMLL1a, PMLL1b, PMHL1b, PMLH1b), two walls with modified conventional reinforcements (PMLL2b, PMHL2b), and three walls with radial reinforcements (PMLL3a, PMLL3b, PMHL3b) were tested. The first letter P represents precast; the second letter M represents the mid-rise wall; the third letter L and H represent lower and higher concrete strength; the fourth letter L and H represent lower and higher steel ratio; the fifth numbers 1, 2, and 3 represent conventional reinforcements, modified conventional reinforcements, and radial reinforcements, respectively; the last letter a and b represent one rectangular plate with an opening and two channel plates of connected steel cover plates. The dimensions and reinforcement layout of representative specimens are presented in Figure 3. Table 1 summarizes the properties of all specimens.

RESULTS AND DISCUSSION

1. Performance of precast walls

Figure 4 shows the crack patterns and load-displacement curves of tested specimens, respectively. The experimental results are summarized in Table 2. The crack patterns of Figure 4 demonstrate that the loads have transferred from frame to wall panel. The load-displacement curves in Figure 4 show that the behavior of precast specimens is similar to cast-in-place specimens (Chiou et al. 2006). There is also a pinching effect in the load-displacement curves. However, the crack patterns of precast specimens are obviously different from cast-in-place specimen. Due to the extra energy dissipation of chemical anchors, the ultimate displacement and energy dissipation of precast specimens are found to be larger than the comparable cast-in-place specimen. The proposed precast walls are demonstrated to be capable of increasing the earthquake resistance of reinforced concrete structures.

2. Effect of connected steel cover plate

The connected steel cover plates are found to significantly affect the crack patterns and behavior of precast specimens. Referring to Figure 4a1, it is found that there are some minor cracks at the top and bottom of columns of specimen PMLL1a. However, there is no observable diagonal crack in the wall. The shear forces sound don’t completely transfer to this precast wall and its performance is not fully developed. Due to the stress concentration around the open region of connected steel cover plate, the local cracks occurred in the left and right bottom corners of wall and the concrete in these regions eventually crushed. Also, during test, it was found that the steel of the wall in the crushed regions buckled and separated from the connected steel cover plate in the last loop of test. In contrast, referring to Figure 4b1, it is found that there are observable diagonal cracks in the wall of specimen PMLL1b. The shear force sound has transferred to this precast wall and its performance is well developed. The properties and steel ratio of specimen PMLL1b are the same as specimen PMLL1a, except the connected steel cover plate is different. Referring to Table 2, the ultimate load and displacement of specimen PMLL1b are higher than specimen PMLL1a. However, the energy dissipation and ductility of specimen PMLL1b are lower than specimen PMLL1a. Similar results are found for specimens PMLL3a and PMLL3b. Referring to Figures 5g1 and 5h1, it is found that there are much more observable diagonal cracks in the wall of specimen PMLL3b. Due to more steel around the open region of connected steel cover plate for specimen PMLL3a, the local cracks are not occurred in the bottom corners of the wall. Referring to Table 2, the ultimate load, ultimate displacement, energy dissipation, and ductility of specimen PMLL3b are higher than specimen PMLL3a. The connected steel cover plates with two channel plates is demonstrated to produce better performance than rectangular steel cover plate with an opening.

3. Effect of orientation of wall reinforcements
The behavior of precast specimens is significantly affected by orientation of wall reinforcements. Referring to Figures 5a1 and 5g1, the crack patterns of specimens PMLL1a and PMLL3a are obviously different. There is no observable diagonal crack in the wall and the concrete crushed at the bottom corners of wall for specimen PMLL1a. In contrast, there are observable diagonal cracks in the wall and there is no concrete crush in the bottom corners of wall for specimen PMLL3a. However, the experimental results in Table 2 show that there is no large deviation on ultimate load, ultimate displacement, energy dissipation and ductility for both specimens PMLL1a and PMLL3a.

Referring to Figures 5b1, 5e1, and 5h1, the behavior of specimens PMLL1b, PMLL2b, and PMLL3b are also different. The concrete of the left bottom corner of wall crushed for both specimens PMLL1b and PMLL2b. The steel of specimens PMLL1b buckled during test. In contrast, there is no concrete crush for specimen PMLL3b. Referring to Table 2, one can see that the energy dissipation, ultimate displacement, and ultimate load of specimens with modified conventional reinforcement are higher than the comparable specimen. Similar results are also found for specimens PMHL1b, PMHL2b, and PMHL3b. The modified conventional reinforcement with more steel at the corners is demonstrated to produce better performance than the other orientations.

4. Effect of steel ratio and strength of concrete

The crack pattern and crack growth of specimens with various concrete strength and steel ratio are similar, while their performance is obviously affected by the material properties. Referring to Table 2, the ultimate load, ultimate displacement and energy dissipation of specimens with higher concrete strength (specimens PMHL1b, PMHL2b, and PMHL3b) are larger than the comparable specimens with lower concrete strength (specimens PMLL1b, PMLL2b, and PMLL3b). Similar results are also found for the effect of steel ratio. Referring to Table 2, the ultimate load, ultimate displacement, energy dissipation, and ductility of specimen PMLH1b are higher than specimen PMLL1b. The larger steel ratio and stronger concrete are demonstrated to increase the earthquake resistance of structures.

CONCLUSIONS

The seismic behavior of precast reinforced concrete walls is studied by large scale test. The parameters of connected steel cover plate, orientation of wall reinforcements, steel ratio of wall, and strength of concrete were studied. The major findings are summarized as follows:

1. The precast reinforced concrete wall can effectively increase the earthquake resistance of structures. Although the ultimate load of specimens with precast reinforced concrete walls is lower than that of cast-in-place specimens. However, the ultimate displacement and energy dissipation of retrofitted specimens by using precast reinforced concrete walls are higher than those of cast-in-place specimen.
2. The performance of a precast reinforced concrete wall is affected by connected steel cover plate. The precast reinforced concrete wall can fully develop its performance by using connected steel cover plates with two channel plates which were fixed by M16 chemical anchors.
3. The modified conventional reinforcement with more steel at the corners produces better performance than the other orientations. The energy dissipation, ultimate displacement, and ultimate load of specimen with modified conventional reinforcement are higher than the comparable specimen.
4. The larger steel ratio and stronger concrete also definitely increase the earthquake resistance of structures. The energy dissipation, ultimate displacement, and ultimate load of these specimens become higher.
ACKNOWLEDGMENTS

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Table 1 Specimen cross-section and reinforcement properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Column Wall</th>
<th>Steel height (cm) × width (cm) × thickness (cm)</th>
<th>( f'_c ) (psi)</th>
<th>Steel ratio ( \rho )</th>
<th>Connected steel cover plate</th>
<th>Orientation of reinforcements</th>
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<tbody>
<tr>
<td>PMLL1a</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>3000</td>
<td>0.012</td>
<td>one rectangular plate with opening</td>
</tr>
<tr>
<td>PMLL1b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>3000</td>
<td>0.012</td>
<td>two channel plates</td>
</tr>
<tr>
<td>PMHL1b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>5000</td>
<td>0.012</td>
<td>two channel plates</td>
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<tr>
<td>PMLH1b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>3000</td>
<td>0.0166</td>
<td>two channel plates</td>
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<tr>
<td>PMLL2b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>3000</td>
<td>0.012</td>
<td>two channel plates</td>
</tr>
<tr>
<td>PMHL2b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>5000</td>
<td>0.012</td>
<td>two channel plates</td>
</tr>
<tr>
<td>PMLL3a</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>3000</td>
<td>0.012</td>
<td>one rectangular plate with opening</td>
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<tr>
<td>PMLL3b</td>
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<td>195×190×10</td>
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<td>PMHL3b</td>
<td>25×25</td>
<td>4-D19</td>
<td>195×190×10</td>
<td>5000</td>
<td>0.012</td>
<td>two channel plates</td>
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Table 2 Summary of experimental results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \rho ) (%)</th>
<th>( f'_c ) (MPa)</th>
<th>( P_y ) (kN)</th>
<th>( \Delta_y ) (mm)</th>
<th>( P_u ) (kN)</th>
<th>( \Delta_u ) (mm)</th>
<th>Energy dissipation (kN-mm)</th>
<th>( \frac{\Delta_u}{\Delta_y} )</th>
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<tbody>
<tr>
<td>CMLL1</td>
<td>1.20</td>
<td>21.52</td>
<td>532</td>
<td>9.9</td>
<td>616</td>
<td>12.69</td>
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<td>PMLL1a</td>
<td>1.20</td>
<td>21.31</td>
<td>300</td>
<td>24.2</td>
<td>361</td>
<td>47.81</td>
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<td>PMLL1b</td>
<td>1.20</td>
<td>21.01</td>
<td>349</td>
<td>43.1</td>
<td>387</td>
<td>49.03</td>
<td>11265</td>
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<tr>
<td>PMHL1b</td>
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<td>350</td>
<td>46.6</td>
<td>491</td>
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<td>21.66</td>
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<td>438</td>
<td>60.37</td>
<td>19118</td>
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<td>PMLL2b</td>
<td>1.20</td>
<td>22.12</td>
<td>411</td>
<td>46.5</td>
<td>442</td>
<td>60.57</td>
<td>17496</td>
<td>1.33</td>
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<tr>
<td>PMHL2b</td>
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<td>36.01</td>
<td>452</td>
<td>44.0</td>
<td>547</td>
<td>71.74</td>
<td>24562</td>
<td>1.63</td>
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<td>PMLL3a</td>
<td>1.20</td>
<td>22.15</td>
<td>320.73</td>
<td>26.2</td>
<td>383</td>
<td>49.73</td>
<td>12654</td>
<td>1.90</td>
</tr>
<tr>
<td>PMLL3b</td>
<td>1.20</td>
<td>21.87</td>
<td>348.26</td>
<td>25.1</td>
<td>423</td>
<td>55.29</td>
<td>15674</td>
<td>2.19</td>
</tr>
<tr>
<td>PMHL3b</td>
<td>1.20</td>
<td>35.67</td>
<td>432.8</td>
<td>27.1</td>
<td>529</td>
<td>45.32</td>
<td>16686</td>
<td>1.68</td>
</tr>
</tbody>
</table>
(1) steel foundation, (2) hinge support of hydraulic jack, (3) hydraulic jack, (4) load cell, (5) steel cover for lateral force transfer, (6) lateral support, (7) steel cover, (8) specimen, (9) support for LVDT, (10) LVDT, (11) steel cover for vertical load transfer, (12) steel bar, (13) lever, (14) pulley block

Figure 1 Schematic configuration of experimental setup

Figure 2 Schematic configuration of components of vertical load applied system

(a1) Specimen PMLL1b  (a2) Conventional reinforcement and steel cover plates with channel shape
Figure 3 Reinforcement layout of representative specimens

(b1) Specimen PMLL2b
(b2) Modified conventional reinforcement and steel cover plates with channel shape

(c1) Specimen PMLL3b
(c2) Radially orientated reinforcement and steel cover plates with channel shape

(a1) Specimen PMLL1a
(a2) Specimen PMLL1a
(b1) Specimen PMLL1b

(b2) Specimen PMLL1b

(c1) Specimen PMHL1b

(c2) Specimen PMHL1b

(d1) specimen PMLH1b

(d2) Specimen PMLH1b

(e1) Specimen PMLL2b

(e2) Specimen PMLL2b
Figure 4 Crack patterns and load-displacement curves of tested specimens

REFERENCES


