Experimental study on deformation capacity of reinforced concrete shear walls after flexural yielding

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ABSTRACT: This paper describes the deformation capacity of multistory reinforced concrete shear walls after flexural yielding. Lateral loading tests on five shear walls were conducted. The primary variables were (a) the boundary column concrete confinement i.e. the amount of reinforcing hoop in the boundary columns, (b) the type of concrete confinement in the panels, and, (c) the percentage of steel used in the panels. Compression tests were conducted on square and rectangular sections of columns (which simulated the boundary columns and panels) to investigate the effect of the confining reinforcing. The relationship between the compressive ductility of the boundary columns and panels and the deformation capacity of shear walls was then analyzed.

1 INTRODUCTION

Multistory shear walls installed in high-rise reinforced concrete buildings effectively reduce seismic vibration. In order to improve the seismic performance of such shear walls, it is best that the failure modes of the shear walls are flexural as a flexural mode is the most ductile kind of failure mode. Flexural-type shear walls have a hinging region at the base. The deformation capacity of this region greatly affects the overall deformation capacity of the shear wall. When multistory shear walls are laterally loaded during an earthquake, the boundary columns and panels in the hinging region are subjected to high compressive and shear stress. Reinforcing the boundary columns or panels is therefore effective in improving the deformation capacity of shear walls. This paper examines the relationship between the degree of confinement or reinforcing in the boundary columns and panels and the deformation capacity of the shear wall. Evaluation was based on the results of multistory shear wall lateral loading and compression tests. The column compression tests simulated the boundary columns and panels.

2 LATERAL LOADING TEST OF SHEAR WALLS

2.1 Test specimen

Five one-fifth scale shear wall specimens were tested. Each of the specimens represented the shear walls of the lower three stories in a building of approximately thirty stories. The variables included the amount of hoop reinforcing in the boundary columns, the type of confining steel used in the panels, and the percentage of horizontal steel used in the panels. The configurations and dimensions of the specimens are shown in Fig.1. The specimens were 1380mm in height, the panels were 60mm in thickness, and the percentage of vertical steel used in panels was 0.7% of panel. The boundary
columns had a (180mm measuring x 180mm) square cross section.

D13 and D5 deformation bars were the main kind of reinforcing bars used in the boundary columns and the panels respectively. The high-strength reinforcing bars 5.1φ and 4φ were used for the boundary column hoop reinforcing and the panel confining bars respectively.

The boundary column main reinforcing ratio was 3.14% for all the specimens.

The maximum aggregate size was 13mm. The physical properties of the concrete and reinforcing are listed in Table 1 and 2.

Specimen NO.1 was designed to have a low transverse reinforcing ratio of 0.2% while the high transverse reinforcing ratio of NO.2 stood at 0.7%.

Specimen NO.3 was designed to have a high wall horizontal reinforcement ratio of 1.2%. This contrasts with Specimen NO.2's horizontal reinforcement ratio which stood at 0.7%.

Specimens NO.4 and NO.5 were confined at the first story of the panel using tie bar and closed reinforcing.

2.2 Test procedures

The loading tests were conducted as shown in Fig.2 and Fig.3. In the lateral loading tests, the specimens were subject to forces from an actuator connected to the reaction wall. A constant axial loading force of 9.8MPa was applied to each boundary column. The added moment was loaded in proportion to the lateral loading in order to keep the shear span ratio (2) at the bottom of the shear wall. Two actuators were vertically connected to the reaction frame to achieve this.

The loading was controlled by the horizontal drift angle at the first story (h:700mm). The loading program is listed in Table 3.

2.3 Test results

Fracture process  The test results are listed in Table 4. In every test, flexural cracks first appeared at the bottom of the boundary column on the side being stretched. Next, shear cracks appeared at the panel bottom on the side being stretched. Shortly after that, the panel vertical reinforcing and the boundary column main reinforcing

<table>
<thead>
<tr>
<th>specimen</th>
<th>σ_y (MPa)</th>
<th>σ_u (MPa)</th>
<th>E_s (GPa)</th>
<th>ε_u (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO.1</td>
<td>37.4</td>
<td>2.95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NO.2</td>
<td>38.1</td>
<td>2.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NO.3</td>
<td>39.2</td>
<td>2.95</td>
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<td>2.3</td>
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<td>NO.4</td>
<td>40.5</td>
<td>2.99</td>
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<td>2.4</td>
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<td>NO.5</td>
<td>41.0</td>
<td>2.95</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td>SCT</td>
<td>42.4</td>
<td>3.00</td>
<td>-</td>
<td>2.8</td>
</tr>
<tr>
<td>ECT</td>
<td>46.7</td>
<td>2.89</td>
<td>-</td>
<td>2.8</td>
</tr>
</tbody>
</table>

σ_y: compressive strength

E_s: Secant Modulus at σ/3

σ_u: splitting tensile strength

SCT: compressive test specimen(at start)

ECT: compressive test specimen(at end)

<table>
<thead>
<tr>
<th>type of reinforcing</th>
<th>σ_y (MPa)</th>
<th>σ_u (MPa)</th>
<th>E_s (GPa)</th>
<th>ε_u (%)</th>
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</thead>
<tbody>
<tr>
<td>4φ (NO.3,4,5)</td>
<td>887.9</td>
<td>1450.5</td>
<td>5.9</td>
<td>5.5</td>
</tr>
<tr>
<td>5.1φ (NO.1,2)</td>
<td>1388.4</td>
<td>1483.7</td>
<td>2.13</td>
<td>11.4</td>
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<tr>
<td>5.1φ (NO.3,4,5)</td>
<td>1334.8</td>
<td>1413.9</td>
<td>2.01</td>
<td>8.7</td>
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<tr>
<td>D6 (NO.1,2)</td>
<td>367.5</td>
<td>508.3</td>
<td>1.79</td>
<td>14.1</td>
</tr>
<tr>
<td>D6 (NO.3,4,5)</td>
<td>402.5</td>
<td>521.3</td>
<td>1.83</td>
<td>25.2</td>
</tr>
<tr>
<td>D13 (NO.1,2)</td>
<td>378.1</td>
<td>550.0</td>
<td>1.89</td>
<td>18.8</td>
</tr>
<tr>
<td>D13 (NO.3,4,5)</td>
<td>382.7</td>
<td>526.3</td>
<td>2.02</td>
<td>19.2</td>
</tr>
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σ_y: Yield strength

σ_u: Tensile strength

E_s: Young's Modulus

ε_u: Elongation

Table 3 Loading Program

<table>
<thead>
<tr>
<th>Cycle</th>
<th>1</th>
<th>2.3</th>
<th>4.5</th>
<th>6.7</th>
<th>8.9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (x10 red.)</td>
<td>2</td>
<td>5</td>
<td>7.5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>last</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R: Drift angle

Fig.2 Test Setup

Fig.3 Loading System
yielded. The bottom of the boundary column on the side being compressed also appeared to crumble a little during this time. Eventually, the panel horizontal reinforcing and the beam main reinforcing yielded.

The flexural strength of the shear walls was calculated through fiber model analysis. The equations previously mentioned, matched the experimental results fairly closely.

*Load deflection curves* Fig.4 shows the load deflection curves. The load of Specimen NO.1 decreased rapidly during the second cycle (15/1000 rad.) due to the concrete at the bottom of the boundary column and the panel being crushed. The load of Specimen NO.2 decreased after it had exceeded 15/1000 rad. This was due to the bottom panel slipping and no crumbling occurred. Specimens NO. 3,4 and 5 kept withstood most of the maximum loads until 40/1000 rad.. There was little difference between NO.3, 4 or 5. At the final stage, NO.3 crumbled in the compressive region at the bottom of the panel. NO.5 slipped at the bottom of the panel.

Fig.6 shows the load deflection envelope curves. The deformation capacity of Specimen NO.3 (which was designed to have a high wall horizontal reinforcement ratio of 1.2%) increased. The deformation capacity of Specimens NO.4,5 (which were confined at the first story of the panel using tie bar and closed reinforcing) increased.

*Crack patterns* Fig.5 shows the crack pattern of Specimen NO.3 during the final stages. The test specimens all had similar crack patterns. Shear cracks with a constant angle appeared before 2/1000 rad., and after 5/1000 rad., cracks appeared in a radial manner with the bottom of the boundary column on the side being compressed being at the center. The number of shorter cracks that appeared at the first story of Specimen NO.5 was greater than that of other specimens.

### Table 4 Test Results

<table>
<thead>
<tr>
<th></th>
<th>NO. 1</th>
<th>NO. 2</th>
<th>NO. 3</th>
<th>NO. 4</th>
<th>NO. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_o ) (KN/cm)</td>
<td>2303.0</td>
<td>3518.2</td>
<td>4684.2</td>
<td>3000.4</td>
<td>3800.4</td>
</tr>
<tr>
<td>( Q_{fc} ) (KN)</td>
<td>91.1</td>
<td>206.8</td>
<td>187.2</td>
<td>127.4</td>
<td>147.0</td>
</tr>
<tr>
<td>( Q_{m} ) (KN)</td>
<td>184.6</td>
<td>177.4</td>
<td>226.4</td>
<td>257.4</td>
<td>225.4</td>
</tr>
<tr>
<td>( Q_{y} ) (KN)</td>
<td>351.8</td>
<td>391.0</td>
<td>381.2</td>
<td>348.9</td>
<td>358.7</td>
</tr>
<tr>
<td>( Q_{y} ) (KN)</td>
<td>397.9</td>
<td>335.2</td>
<td>416.6</td>
<td>406.8</td>
<td>386.1</td>
</tr>
<tr>
<td>( Q_{v} ) (KN)</td>
<td>324.4</td>
<td>364.6</td>
<td>381.2</td>
<td>378.3</td>
<td>384.2</td>
</tr>
<tr>
<td>( Q_{y} ) (KN)</td>
<td>324.4</td>
<td>402.8</td>
<td>407.7</td>
<td>402.8</td>
<td>392.0</td>
</tr>
<tr>
<td>( Q_{max} ) (KN)</td>
<td>401.8</td>
<td>413.6</td>
<td>415.5</td>
<td>403.8</td>
<td>396.9</td>
</tr>
<tr>
<td>( Q_{cal} ) (KN)</td>
<td>406.7</td>
<td>406.7</td>
<td>402.8</td>
<td>402.8</td>
<td>403.8</td>
</tr>
<tr>
<td>( Q_{cal} ) (KN)</td>
<td>392.0</td>
<td>392.0</td>
<td>388.1</td>
<td>388.1</td>
<td>388.1</td>
</tr>
<tr>
<td>( Q_{cal} ) (KN)</td>
<td>418.5</td>
<td>418.5</td>
<td>401.8</td>
<td>401.8</td>
<td>401.8</td>
</tr>
</tbody>
</table>

**Eo:** Initial stiffness

- **Qfc:** Flexural cracking load
- **Qsc:** Shear cracking load
- **Qym:** Load at yielding of main reinforc.
- **Qyb:** Load at yielding of beam main reinforc.
- **Qvy:** Load at yielding of vertical reinforc.

**maxQexp:** Maximum strength (experimental results)

**maxQcal1:** Maximum strength (calculation 1)

**maxQcal2:** Maximum strength (calculation 2)

**maxQcal3:** Maximum strength (calculation 3)

**calculations:** (A. I. J. 1990)

\[ Q_{max} = \frac{Q_{u}}{N} + \frac{Q_{u}}{N_s} \cdot \frac{\sigma_{y} - D + 0.4w - cw - D}{0.5N(1-N/BeDf_c)} \]

**calculation2:** (A. I. J. 1990)

\[ Q_{max} = \frac{Q_{u}}{N} + \frac{Q_{u}}{N_s} \cdot \frac{\sigma_{y} - \omega_{w} - \omega_{w - 1} + 0.5N \cdot Lw}{0.5N \cdot Lw} \]

**calculation3:** (S. Fuji 1970)

fiber model analysis

### 3 COMPRESSION TESTS

#### 3.1 Test specimens

Twenty one specimens (see Fig.7, Table 5) were tested. The variable of the boundary column specimens (C0001 – C0703) was the amount of the transverse reinforcing. The variable of the panel specimens (W0001 – W0303) was the type of concrete confinement. The specimens were made from the same materials as the specimens used in the shear wall lateral loading tests.

#### 3.2 Test procedures

The specimens were subject to monotonic uni-axial compression. Axial strain was measured with transducer (see Fig.8 for measuring length). Strain gauges were attached to both longitudinal and transverse reinforcing.

#### 3.3 Test results

Fig.9 shows the relationship between specimens axial
compression stress and axial strain. The maximum and post-failure stresses of Specimen C0701 (Pw=0.7%) which simulated the boundary columns of shear wall specimens NO.2,3,4 and 5, were much higher than the stresses of Specimen C0203 (Pw=0.2%) which simulated the boundary columns of Specimen NO.1.

Specimen W0502 which was confined with closed reinforcing and which simulated the panel of Specimen NO.5, showed the highest maximum and post-failure stresses. The second highest was Specimen W0402 which was confined with tie bars and simulated the panel of Specimen NO.4.

Fig.10 shows the relationship between the strain of the transverse reinforcing or confining reinforcing and the axial strain of the specimens. The strain of Specimen C0701's transverse reinforcing increased as the axial strain increased, indicating an increase in confining stress. Although the transverse reinforcing strain rate decreased after the point maximum axial stress was ruled, strain continued to increase within measurable range.

On the panel specimens, Specimen W0501, which simulated the panel of Specimen NO.5, behaved in a similar manner to boundary column specimen C0701. Specimen W0402, which simulated the panel of Specimen NO.4, showed decrease in confining reinforcing strain for axial strain exceeding a certain level.

4 ANALYSIS TEST RESULTS

4.1 Strain distribution in boundary columns

Fig.11 shows the strain distribution in the boundary column of the shear wall specimen NO.1. The strain was measured using the transducer located 60mm from the edge of the shear wall. The tensile hinging region expanded in a vertical direction as the drift angle increased.

The compressive hinging region was concentrated around the bottom of the boundary columns. Judging from this, it is possible to conclude that confining concrete with lateral reinforcing in the region helps deformation capacity in multistory shear walls.

4.2 Boundary column base compressive strain

Fig.12 shows the relationship between the drift angle and compressive strain at the bottom of boundary

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Table 5 Test Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. Load (KN)</th>
<th>Strain at Max. Load (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0001</td>
<td>1228.9</td>
<td>0.31</td>
</tr>
<tr>
<td>C0002</td>
<td>1181.9</td>
<td>0.40</td>
</tr>
<tr>
<td>C0003</td>
<td>1316.1</td>
<td>0.26</td>
</tr>
<tr>
<td>C0201</td>
<td>1384.7</td>
<td>0.24</td>
</tr>
<tr>
<td>C0202</td>
<td>1458.2</td>
<td>0.31</td>
</tr>
<tr>
<td>C0203</td>
<td>1457.3</td>
<td>0.37</td>
</tr>
<tr>
<td>C0701</td>
<td>1650.3</td>
<td>0.71</td>
</tr>
<tr>
<td>C0702</td>
<td>1636.6</td>
<td>0.43</td>
</tr>
<tr>
<td>C0703</td>
<td>1679.7</td>
<td>0.68</td>
</tr>
<tr>
<td>W0001</td>
<td>338.1</td>
<td>0.99</td>
</tr>
<tr>
<td>W0002</td>
<td>408.7</td>
<td>0.74</td>
</tr>
<tr>
<td>W0003</td>
<td>374.4</td>
<td>0.70</td>
</tr>
<tr>
<td>W0301</td>
<td>383.2</td>
<td>0.68</td>
</tr>
<tr>
<td>W0302</td>
<td>383.2</td>
<td>0.66</td>
</tr>
<tr>
<td>W0303</td>
<td>427.3</td>
<td>0.95</td>
</tr>
<tr>
<td>W0401</td>
<td>396.9</td>
<td>0.59</td>
</tr>
<tr>
<td>W0402</td>
<td>454.7</td>
<td>0.98</td>
</tr>
<tr>
<td>W0403</td>
<td>505.7</td>
<td>1.04</td>
</tr>
<tr>
<td>W0501</td>
<td>532.1</td>
<td>1.38</td>
</tr>
<tr>
<td>W0502</td>
<td>545.9</td>
<td>1.41</td>
</tr>
<tr>
<td>W0503</td>
<td>660.5</td>
<td>2.38</td>
</tr>
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</table>

boundary column specimen

C0201, Pw=0.2%

panel specimen W0301 simulating specimen NO.3

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Fig.7 Test Specimens

Fig.8 Measuring System
columns. The strain was measured with a transducer located 60mm from the edge of the shear wall. The measuring length was 180mm. Compressive strain increased in proportion to the drift angle. The compressive strain for each of the five shear wall specimens was approximately the same for angles up to 10/1000 rad. One exceeded, the strain of Specimen NO.1 increased rapidly.

The average axial strain at the point of maximum axial compressive stress for the boundary column specimens C0201, C0202 and C0203 (Pw=0.2%) (which simulated the boundary column of Specimen NO.1), was 0.307% (see Table 5). The compressive strain at the bottom of Specimen NO.1's boundary columns, however, was approximately 0.5% and 1.0% for the drift angles of 10/1000 rad. and 15/1000 rad. respectively (see Fig. 12). The axial compressive stress of Specimen C0203 also decreased a great deal at an axial strain of 0.5% and 1.0% (see Fig. 9(a)). From these results one may conclude that the compression tests results reflect the rapid decrease in Specimen NO.1's load what is caused by the boundary column reaching crumbling point at 15/1000 rad.

Until reaching an axial strain of 6.0%, Specimen C0701 (Pw=0.7%) maintained its axial stress for a longer period than Specimen C0203's (Pw=0.2%) maximum stress. These results correspond to the non-crumbling of the boundary columns of the shear wall specimens NO.2, 3, 4, and 5.

4.3 Strain distribution of confining reinforcing at panel along span

The load of shear wall specimen NO.2 decreased after 15/1000 rad. due to destruction of the panel, even though no crumbling occurred at the base of the boundary columns. Destruction of the panel was thought to be due to crumbling through compressive stress or through the failure of the shear-resisting mechanism.

The confining reinforcing in the panels of Specimens NO.4 and NO.5 was arranged to improve the panel's compressive ductility. The effects of confinement are shown in Fig. 9(b), 10(b) and 10(c). An increase in confining reinforcing strain reflects an increase in confining stress (see Fig. 10(a) and 10(b)). It can therefore be concluded that the compressive ductility of the panel specimens was improved (see Fig. 9(b)).

Fig. 13 shows the confining reinforcing strain distribution of the span at the bottom of the panel of shear wall specimens NO.4 and NO.5 respectively.

Distribution is shown at a height of 125mm.

Strain increased near the compressive boundary column with the increase in drift angle in both NO.4 and NO.5 specimens. Strain in Specimen NO.5 was larger than that in Specimen NO.4 for the entire length of the span. As the amount of confining reinforcing in Specimen NO.4 and NO.5 was approximately the same, the confining stress of Specimen NO.5 was considered to be higher than that of NO.4. Specimen NO.5's range of strain increase was greater than that of NO.4. Specimen NO.4's concentrated strain increase range was also near the compressive boundary column. Judging from the strain distribution patterns, confining reinforcing is regarded to be more effective when used to confine concrete near the boundary columns. It is therefore desirable that confining reinforcing be

Fig. 10 Strain of Confining Reinforcing versus Axial Strain

Fig. 11 Strain Distribution in Boundary Column

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employed as a means of improving the deformation capacity of the mulltistory shear walls.

Fig. 15 shows Specimen NO.5's confining reinforcing strain and lateral load hysteresis loops for the panel base (height 125mm) near the boundary column (inside of column by 60mm).

In this figure, the measuring point was located in the compressive region as lateral loading was positive. The concrete in the panel was therefore considered to be confined by confining reinforcing during concrete compression.

As a result, concrete confinement through confining reinforcing in the panel helped to improve the compressive ductility of the panel, and improve the deformation capacity of the multistory shear wall.

4.4 The effect of the horizontal reinforcing in panels

Fig. 16 shows the relationship between the drift angle and the horizontal reinforcing strain for the first story of the shear wall specimens NO.2 and NO.3 panels at medium height. Strain in Specimen NO.2 was larger than that in Specimen NO.3 for the measuring points in the mid span and near the boundary column. In spite of the yielding of Specimen NO.2's reinforcing at approximately 15/1000 rad., the reinforcing of Specimen NO.3 did not yield until 30/1000 rad. These drift angles correspond to the drift angles at which the specimen load decreased markedly.

From these results one may conclude that the deformation capacity of a shear wall may be increased by increasing the amount of horizontal reinforcing in the panel. More horizontal reinforcing reduces the amount of stress on the reinforcing which results in a shear wall with a greater ability to resist shear forces.

5 CONCLUSIONS

1. The concrete confinement of the boundary columns were observed to illustrate by the compressive crumpling of the boundary columns or panels.
2. The compressive hinging region was concentrated at the base of the boundary columns. The compressive strain of concrete at the end was observed to be nearly in proportion to the drift angle.
3. The deformation capacity of the shear wall increased as the ratio of the horizontal reinforcing in the panels increased.
4. The confinement of the concrete using the confining reinforcing in the panels had a significant effect on the deformation capacity.
5. The flexural strength of the shear walls calculated through fiber model analysis and the equations previously mentioned, matched the experimental results fairly closely.

REFERENCE


Fig. 12 Drift angle versus Compressive Strain at Base of Boundary Columns

Fig. 13 Confining Reinforcing Strain Distribution

Fig. 14 Confining Reinforcing Strain Distribution

Fig. 15 Confining Reinforcing Strain and Lateral Load Hysteresis Loop

Fig. 16 Drift Angle versus Horizontal Reinforcing Strain