Experimental Research on Seismic Performance of High-Strength Concrete Short Column Reinforced with High-Strength Rebar

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Abstract: The purpose of this paper is focusing on increasing the seismic capacity of high-strength concrete short column confined with high-strength steel. By the experimental method, eight short model columns, in which ultra-strength rebar with the yield strength of 1420 MPa are used as the longitudinal reinforcements and stirrups and the strength degree of concrete are C60 and C90, are tested under low cycle reciprocating load. The factors of shear span ratio, axial compression ratio, stirrup and strength of concrete which influence the seismic performance of the short column are researched. The failure mechanism of high-strength concrete short columns with high-strength steel has been clearly analyzed. The test results show that the shear span ratio, axial compression ratio and others factors have important influence on the seismic behavior of the concrete short columns. The suitable amount of high-strength steel can effectively improve the bearing capacity of short column, guaranteed the good energy dissipation during earthquakes, and develop the seismic performance of reinforced concrete short columns.

Keywords: high-strength steel; high-strength concrete; short column; seismic performance; low cycle load.

1. Introduction

With the appearance of high and ultra-high-rise building, due to the requirements of the large space at the bottom of building, and the regulations [1] on the upper limit value of axial compression ratio, the cross section of the column becomes large, and short column, even ultra-short column will be formed at the bottom of the building. Short column has poor ductility and the ductility of ultra short column is worse. During an earthquake, short columns prone to shear failure, resulting in structural collapse and causing casualties and economic losses heavily, which is unable to achieve the building design guidelines [2] of “repairing for moderate earthquake and not collapsing for a severe earthquake” in China. High-strength concrete with better durability, high strength and stiffness characteristics has been widely used in the actual project. In recent years, many scholars and researchers proposed some methods to increase and improve the seismic performance of concrete short columns [3-7]. Beijing University of Technology, Harbin Institute of Technology, and other institutes in China have carried out some related research on the concrete columns and made some results, such as steel reinforced concrete structures, FRP bar reinforced short column with, GFRP reinforced casing-steel concrete, etc. [8-13]. But the scope of its use is also limited. The author of this paper carried out eight quasi-static model tests which high-strength concrete short columns are reinforced with PC bars as longitudinal reinforcement and stirrups to study the failure mechanism and related factors. The results show that high-strength concrete short columns with high-strength reinforcement can have a good seismic performance.

2. Overview of the experiment

2.1 Design and material properties of the specimens

According to the literature [9], specimens are designed by half scale. The test is composed of eight specimens reinforced with PC steel bars and the strength grades of concrete are C60 and C90, respectively. The views of reinforcement and dimensions of the specimen in detail are shown in Fig.1, and the designed specimen parameters are shown in Table 1.

2.2 Test setup and loading scheme

During the test, a hydraulic jack of 5000kN is placed on the top of the column to apply vertically axial load which keeps unchanged. An electro-hydraulic servo actuator of 1500kN manufactured by MTS System Corporation is used to apply a horizontal load on the top of columns. The UCAM-70A data acquisition
instrument is applied for data acquisition, and $P$-$\Delta$ hysteresis curve is simultaneously drawn during the test. The test loading setup is shown in Fig.2.

Loading history of specimens in the tests is divided into load and displacement control, shown in Fig.3. At the beginning of the test, the horizontal load control is used, and then the load values gradually increase to 30%, 50% and 70% of the maximum horizontal load, respectively. When the specimen enters into the yield stage, the displacement control strategy is used, and each displacement control loop goes twice until the horizontal load reduces to about 85% of maximum horizontal load. Meanwhile, stop loading and unload axial load, and the test is finished.

3. Test procedure and result analysis

3.1 Specimen failure characteristics

Table 1 Parameters of specimens

<table>
<thead>
<tr>
<th>Number</th>
<th>Concrete</th>
<th>Axial compression ratio</th>
<th>Shear span ratio</th>
<th>$f_y$/MPa</th>
<th>$d$/mm</th>
<th>Spacing/mm</th>
<th>Stirrups</th>
<th>Volume stirrup ratio/%</th>
<th>Longitudinal reinforcement d/mm</th>
<th>Reinforcement ratio/%</th>
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</thead>
<tbody>
<tr>
<td>HHH91-2</td>
<td>C90</td>
<td>0.7</td>
<td>1.75</td>
<td>1286.00</td>
<td>7.10</td>
<td>50.0</td>
<td>2.199</td>
<td>12.6/16</td>
<td>5.243</td>
<td></td>
</tr>
<tr>
<td>LHH92-2</td>
<td>C90</td>
<td>0.5</td>
<td>1.75</td>
<td>1286.00</td>
<td>7.10</td>
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<td>7.10</td>
<td>50.0</td>
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<td>12.6/16</td>
<td>5.243</td>
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<td>LLH91-2</td>
<td>C90</td>
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<td>1.75</td>
<td>300.00</td>
<td>8.00</td>
<td>50.0</td>
<td>2.904</td>
<td>12.6/16</td>
<td>5.243</td>
<td></td>
</tr>
<tr>
<td>DH91-2</td>
<td>C90</td>
<td>0.3</td>
<td>1.75</td>
<td>1286.00</td>
<td>7.10</td>
<td>50.0</td>
<td>2.199</td>
<td>12.6/16</td>
<td>5.243</td>
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</tr>
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<td>50.0</td>
<td>2.199</td>
<td>12.6/16</td>
<td>5.243</td>
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</tr>
<tr>
<td>LHH61-2</td>
<td>C60</td>
<td>0.5</td>
<td>1.75</td>
<td>1286.00</td>
<td>7.10</td>
<td>50.0</td>
<td>2.199</td>
<td>12.6/16</td>
<td>5.243</td>
<td></td>
</tr>
<tr>
<td>LH91-2</td>
<td>C90</td>
<td>0.5</td>
<td>1.75</td>
<td>1286.00</td>
<td>7.10</td>
<td>50.0</td>
<td>2.199</td>
<td>12.6/12.6/12</td>
<td>4.010</td>
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</tr>
</tbody>
</table>

Fig.1 Cross sectional dimensions and reinforcement in details

At the first stage of the test, the load control is used. In the first three cycles during the test, no noticeable diagonal cracks appear on the surface of the specimen, but some tiny transverse and longitudinal cracks come out on the lateral root of individual specimens. As increasing close to the ultimate load of specimen, at the specimen position of 30cm below the specimen, obvious oblique fractures come out on the abdominal part and the angle between diagonal cracks and horizontal ling is about 30° to 45°, slowly extending along both sides of the diagonal. At the second stage of the test, the displacement control is applied. For each displacement level,
the test goes twice loops and the displacement increases 0.5\(\Delta\) each time. As the lateral displacement increasing, new diagonal cracks in the bottom of the specimen are constantly generated. As the displacement increasing to 1.5\(\Delta\)~3.0\(\Delta\), obvious diagonal cracks in the bottom of the specimen come out and extend to the ends of the diagonals, shown in Fig.4.

![Fig.2 The schematic of test setup](image)

![Fig.3 Loading history of specimens](image)

(a) 1.0\(N_y\)  
(b) 3.0\(\Delta\)  
(c) 3.5\(\Delta\)  
(d) Specimen damaged

![Fig.4 Failure patterns of specimens](image)
Since high-strength steels are installed inside the specimens, serving as longitudinal bars and stirrups, the bearing capacity of the specimens has no obvious downward trend, and the specimens still have a good ability to resist loads. As the load increasing, the displacement develops to \(3.5 \Delta\), and no new cracks are generated at the bottom of the specimen and only the crack width increases. Four corners of the bottom of the specimens begin to slightly appear drop of the concrete debris, and the same phenomenon also appears at the intersection of the main diagonal cracks. At this point, the bearing capacity of the specimen has a significant downward trend. Keep loading back and forth on specimens, the main diagonal crack width also keeps increasing, and concrete stalling phenomenon becomes more and more serious, meanwhile, the specimen internal longitudinal exposed reinforcement and stirrups can be found, but the longitudinal reinforcement and stirrups have no serious damage occurred. When the applied load drops to 85% of maximum limit load, both axial and horizontal loads are unloaded, and the test is finished.

3.2 Hysteretic behavior analysis

According to quasi-static test of eight high-strength concrete short columns under cyclic loads, their relationships between the horizontal load and displacement are recorded. The eight hysteretic curves are shown in Fig.5, specifically.
The above-mentioned eight hysteresis curves can obtain the following conclusions:

(1) As opposed to the specimen LHH91-2 reinforced with ordinary steel stirrups, specimen LHH91-2 with high-strength steel has better ductility, and hysteresis curve is quite full and has good energy-dissipation effects, but the bearing capacity of the short column with high-strength stirrups is not significantly improved.

(2) Under the same condition, compared with specimen LHH61-2 that concrete grade is C60, specimen LHH91-2 that concrete strength class is C90 has a relatively full hysteresis curve, and the carrying capacity of specimen LHH91-2 is significantly improved.

(3) By observing the specimens DHH91-2, LHH91-2 and HHH91-2, which all have the compression ratio of 0.3, the hysteresis curve of specimen DHH91-2 is the fullest with much more hysteretic cycles. For the axial compression ratio of 0.5, the hysteresis curve cycles of the test piece LHH91-2 increases, showing that the capacity of specimen LHH91-2 is improved. For the axial compression ratio of 0.7, the hysteresis curve cycles of the specimen HHH91-2 reduce and the full degree of the hysteresis curves decline, but the carrying capacity has increased.

(4) Compared with the specimen LHG91-2 which is reinforced with high-strength longitudinal steel, the carrying capacity of the specimens LHH91-2 which is reinforced with the hybrid of high-strength steel and ordinary steel as longitudinal reinforcement is not significantly increased, and the hysteresis curve of the specimen is not full with the reduced energy-dissipation effect.

3.3 Ductility analysis

Displacement ductility coefficient defined in Equation (1) is often used to represent the ductility of structure or member:

\[ \mu_\Delta = \frac{\Delta_\text{u}}{\Delta_y} \]

\( \mu_\Delta \) is the displacement ductility coefficient, \( \Delta_\text{u} \) is the ultimate displacement related to 85\% ultimate load, and \( \Delta_y \) is yield displacement. The specific ductility coefficients are shown in Table 2.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>( n_t )</th>
<th>( \Delta_\text{u}/\text{mm} )</th>
<th>( \Delta_y/\text{mm} )</th>
<th>( \mu_\Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHH91-3</td>
<td>0.5</td>
<td>12.01</td>
<td>1.40</td>
<td>6.67</td>
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<tr>
<td>LLH91-2</td>
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<td>6.14</td>
<td>1.75</td>
<td>3.51</td>
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<td>LHH92-2</td>
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<td>4.84</td>
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<td>LHG91-2</td>
<td>0.5</td>
<td>9.51</td>
<td>1.50</td>
<td>6.34</td>
</tr>
<tr>
<td>LH61-2</td>
<td>0.5</td>
<td>6.53</td>
<td>1.42</td>
<td>4.59</td>
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<td>0.7</td>
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<td>1.90</td>
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<td>DHH91-2</td>
<td>0.3</td>
<td>8.97</td>
<td>1.62</td>
<td>5.54</td>
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</tbody>
</table>
In Table 2, taking the specimens LHH91-2 and LLH91-2 as an example, as using high-strength steel, the ductility of specimen LHH91-2 has greatly improved, compared with specimen LLH91-2 with ordinary steel, showing that the proper configuration of high-strength stirrups will improve the seismic performance of short column. Specimen LHH91-3 with high shear span ratio has better ductility than LHH91-2. By comparing LHH92-2 and LHH91-2, the closely reinforced stirrups can greatly confined the core concrete in three compression statuses to improve the ductility of short columns.

4. Summary and conclusions

Through low cycle reciprocating load experiment, 8 high-strength concrete short columns reinforced with high strength steels, considering shear span ratio, axial compression ratio, reinforcement ratio, concrete strength and other factors, have been tested to research the effect on the seismic performance, and results can be conclude:

(1) Under the same conditions, the use of high-strength steel as stirrups can effectively improve the bearing capacity and the ability of absorbing as well as seismic energy dissipating of concrete short column, so that for short column to meet seismic design requirements.

(2) The closely reinforced stirrups in the short concrete columns can effectively constrain the core concrete in order to effectively improve the ductility of short columns and enhance energy dissipation capacity of short column.

(3) Axial compression ratio is one of the main factors affecting the seismic performance of short column. The increase of axial compression ratio can obviously decrease the ductility of short column, but the bearing capacity of short column increases.

Acknowledgments

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