DEFORMATION CAPACITY OF DIAGONALLY REINFORCED CONCRETE SHORT COLUMNS SUBJECT TO HIGH AXIAL COMpressIVE STRESS

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SUMMARY

Fifteen reinforced concrete short columns subject to axial compression loading and cyclic lateral loading were tested. Included were twelve diagonally reinforced columns. The main variable investigated was the quantity of transverse reinforcements. In this paper, it is assumed that the transverse reinforcements consist of the shear reinforcements and the confining reinforcements. The quantity of shear reinforcements is theoretically given by the cumulative strength theory (Ref. 1), and the quantity of confining reinforcements is estimated from the results of the above-mentioned experiment. The relationship between the quantity of transverse reinforcements and the deformation capacity of diagonally reinforced short columns is examined.

INTRODUCTION

In high-rise or super-high-rise reinforced concrete building structures, the columns at low stories are short and subject to high axial compressive stress. Though such columns are apt to fail in shear during a severe earthquake, they must exhibit ductile behavior such as flexural failure, at the first story in particular. To prevent brittle failure in shear and to improve the seismic performance of such columns, the behavior of diagonally reinforced short columns subject to high axial compressive stress was investigated.

In this paper, the effects of different quantities of transverse reinforcements and the levels of the axial compression load for the strength and deformation capacity of the diagonally reinforced short columns are described. Furthermore, the quantity of transverse reinforcements required to secure ductile behavior of the diagonally reinforced short columns is estimated from the experimental results.

TEST SPECIMEN

Fifteen quarter-scale column specimens including twelve diagonally reinforced column specimens were tested, representing a part of a first-story column in a reinforced concrete frame structure. The variables investigated were the quantity and the yield stress of transverse reinforcements, the types of arrangement of main reinforcements which were conventional parallel reinforcement and diagonal reinforcement, and the levels of axial compression loading. The configurations and dimensions of the specimens of the PU06 series and XU06 series are shown in Fig. 1 as examples. The test plan is represented in Table 1.
Table 1 Test Plan

<table>
<thead>
<tr>
<th>Concrete Strength P_{c}(kgf/cm²)</th>
<th>Axial Compression M(t) n(N/mm²)</th>
<th>Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>285</td>
<td>11.2 0.10</td>
<td>P9005 X0051 X1111 X0051 X0051</td>
</tr>
<tr>
<td>310</td>
<td>11.2 0.10</td>
<td>P9008 X0063 X1113 X0063 X0053</td>
</tr>
<tr>
<td>285</td>
<td>11.2 0.10</td>
<td>P9008 X0065 X115 X0065 X0055</td>
</tr>
</tbody>
</table>

Material of Transverse Reinforcement:
- Transverse Reinforced Ratio Pw (2) = 0.76 0.55 1.10 0.76 0.55
- Confining Reinforced Ratio Pws (2) = 0.34 0.34 0.68 0.34 0.13

Tensile Reinforced Ratio = P_t = 0.72%
Column Height-Depth Ratio = L/D = 2

Table 2 Mechanical Properties of Reinforcing Bars

<table>
<thead>
<tr>
<th>Longitudinal Reinforcement : D10</th>
<th>fy = 4032 kgf/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Reinforcement : 4.56 3.565</td>
<td>f_y = 3460 kgf/cm² 2052 kgf/cm²</td>
</tr>
</tbody>
</table>

Fig. 1 Dimension of Columns

The specimens had a 200mm x 200mm square cross section, with a column height-depth ratio of 2.0. The flexural tension reinforcement consisted of 4-D10 deformed bars (tensile reinforcement ratio, P_t, of 0.72%), and all specimens had middle reinforcements, 2-D10 deformed bars. In the diagonally reinforced column specimens, the ratio of the tension diagonal to total tension reinforcement, B, was 0.5, and the diagonal reinforcements were bent inside at 15mm from the ends of the columns. Two kinds of transverse reinforcements were used, 3.56% high-strength reinforcing bars and 4.5% normal reinforcing bars. The mechanical properties of the reinforcing bars are shown in Table 2.

The axial compressive stress levels selected were 10%, 29%, and 42% of concrete compressive cylinder strength (28 kgf/cm², 90 kgf/cm², and 120 kgf/cm²). The test specimens were loaded by axial compression on the centrally loaded column and by repeatedly applying anti-symmetric bending moments of equal magnitude at both ends with controlled displacement (Ref. 2). The fundamental controlled displacement is relative to the displacement angle, R. The displacement angle, R, is the angle formed by horizontal displacement between both ends of the column, 400mm.

CONFINING REINFORCEMENT

In this paper, it is assumed that the transverse reinforcements consist of shear reinforcements which contribute to shear forces, and confining reinforcement which confine core concrete expanded with plastic deformation. Namely, the relation between these is given as follows:

\[ P_w = P_{ws} + P_{wc} \]  \hspace{1cm} (1)

where \( P_w \) is the transverse reinforcement ratio, \( P_{ws} \) is the shear reinforcement ratio and \( P_{wc} \) is the confining reinforcement ratio. Furthermore, \( P_{ws} \) is the minimum transverse reinforcement ratio required to determine the yielding of both tensile and compressive reinforcements in the beam mechanism. This mechanism is one of the shear-resistant mechanisms in the cumulative strength theory proposed by the authors (Ref. 1), and is given by

\[ P_{ws} = 2 \cdot p_t \cdot f_y / (f_{wy} \cdot \eta) \]  \hspace{1cm} (2)
where $p_{Pt}$ is the tensile reinforcement ratio of the parallel reinforcements, $f_y$ and $f_w$ are the yield stresses of the parallel and transverse reinforcements respectively, and $\eta$ is the column height-depth ratio.

From the design example of a thirteen-story reinforced concrete frame structure, the specimens in the PU08 series (the conventional parallel reinforced columns) determined the transverse reinforcement ratio, $P_w$, as 0.76\% ($P_{wc}=0.34\%$) by using high strength reinforcing bars. In the diagonally reinforced columns, the specimens in the XU06 series, which used the high strength reinforcing bars, had a $P_w$ of 0.55\% ($P_{wc}=0.34\%$), the same confining reinforcement ratio as the specimens in the PU08 series. The specimens in the XR11 series, XR08 series and XR06 series, which used the normal reinforcing bars, determined the quantity of transverse reinforcements by basing it on of the specimens in the XU06 series. The specimens in the XR11 series had a $P_w$ of 1.10\% ($P_{wc}=0.68\%$) and the same $P_w$ as the specimens in the XU06 series. The specimens in the XR08 series had a $P_w$ of 0.76\% ($P_{wc}=0.34\%$) and the same $P_w$ as the specimens in the XU06 series. The specimens in the XR06 series had a $P_w$ of 0.55\% ($P_{wc}=0.13\%$) and the same $P_w$ as the specimens in the XU06 series. In the calculations of the transverse reinforcement ratio for each specimen, values of the yield stresses of the transverse reinforcements were used 6000 kgf/cm² for the high strength reinforcing bars, and 3000 kgf/cm² for the normal reinforcing bars, and value of the yield stress of the longitudinal reinforcing bars was used 3500 kgf/cm².

TEST RESULTS

The hysteretic loops of each specimen are shown in Fig. 2. In the figure, the ordinate represents applied shear, $Q$, and the abscissa gives the relative displacement angle, $\Delta$. Also, the dotted lines represent the $P-A$ effect, and solid lines presented by Qu give the theoretical strength obtained from the cumulative strength theory (Ref. 1). The measured and theoretical strengths of each specimen are shown in Table 3.

The specimens in the PU08 series, the conventional parallel reinforced columns, showed slip-shaped hysteretic loops with a extremely small capacity for energy dissipation. Also, as the level of axial compression loading applied to the columns increases, the deterioration in the load carrying capacity of the columns after attainment of the maximum capacity with the increase of deflection amplitude also increases proportionately. However, even specimen PU085, subjected to a high level of axial compression loading, $n=0.42$, could reach relative displacement angles $R$ of at least 0.03 rad., because the specimens in the PU08 series had many high strength transverse reinforcements.

On the other hand, the all diagonally reinforced columns showed spindle-shaped hysteretic loops with a large capacity of energy consumption. In spite of the quantity and strength of transverse reinforcement, the different test specimens, the specimens at the same level of axial compression loading had the about same maximum shear capacity, which was greater than the PU08 series specimens. However, the rate of deterioration in load carrying capacity, after the maximum capacity of the diagonally reinforced columns was exceeded, was remarkably affected by the levels of axial compression loading, and the various quantities and strengths of transverse reinforcements.

The specimens in the XU06 series with high strength transverse reinforcements had approximately the same deformation capacity as the specimens in the PU08 series, in spite of a lower number of transverse reinforcements, because the diagonal reinforcements effectively contributed to shear forces. In the diagonally reinforced columns which had normal transverse reinforcements, as the quantity of transverse reinforcements decreased and/or the level of axial compression loading increased, the deformation capacity of the columns decreased proportionately. In particular, the specimens XR063, XR085 and XR065 had brittle
Table 3 Maximum Strength

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum Strength (cf)</th>
<th>Theoretical Strength (cf)</th>
<th>Maximum Strength (tf)</th>
<th>Theoretical Strength (tf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU081</td>
<td>17.0</td>
<td>16.2</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>XU061</td>
<td>19.0</td>
<td>18.1</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>XR111</td>
<td>18.5</td>
<td>17.9</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>XR061</td>
<td>17.7</td>
<td>18.0</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>XR063</td>
<td>17.9</td>
<td>16.7</td>
<td>14.5</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Load-Displacement Response
failure in shear with hoop fracture at extremely small displacement. Namely, at a high level of axial compression loading, to prevent such brittle failure, even the diagonally reinforced columns should be arranged with transverse reinforcements sufficient in quantity and strength to confine core concrete expanded with plastic deformation.

EVALUATION OF CONFINING REINFORCEMENT

The relation between the equivalent confining stress of core concrete, \( \sigma_c \), and the relative displacement angle, \( \alpha \), or the load cycle frequency, \( K \) (\( K \) supposes a half cycle of 1), of the diagonally reinforced columns in the series with a non-dimensional axial compression of 0.29 is shown in Fig. 3. In the figure, the solid lines and dotted lines represent the confining stress at maximum capacity in each cycle, \( \sigma_{cmax} \), and at unloading (applied shear force is zero) in the end of each cycle, \( \sigma_{co} \), respectively. The values of \( \sigma_c \) (\( \sigma_{cmax} \) and \( \sigma_{co} \)) were calculated from the strain of the transverse reinforcement located 75 mm above and below the center of the column. The strain of these bars was the largest of the transverse reinforcing bars arranged in the column, and by using the following relations:

\[
\begin{align*}
\text{in the case of } \varepsilon < \varepsilon_y & \quad \sigma_c = Pw \cdot E_s \cdot \varepsilon_c \\
\text{in the case of } \varepsilon \geq \varepsilon_y & \quad \sigma_c = Pw \cdot f_{wy}
\end{align*}
\]

where \( E_s \) is Young's modulus of transverse reinforcement and \( \varepsilon_y \) is the yield strain of transverse reinforcement.

At both the maximum capacity in each cycle and the unloading, the confining stress of each column increases equally in spite of the quantity and strength of transverse reinforcements, until they yield. The variation of the remainder obtained when subtracting the confining stress at unloading from the confining stress at the maximum capacity in each cycle, \( \sigma_{cs} \) (= \( \sigma_{cmax} - \sigma_{co} \)), is similar to the variation of the applied shear forces, before the attainment of the maximum capacity of the column, \( R_{max} = 0.015 \) rad. Furthermore, using the above-mentioned \( Pws \), \( \sigma_{cs} \) and \( R \) are approximately related as follows:

\[
\sigma_{cs} = \frac{Pws \cdot E \cdot \varepsilon \cdot \varepsilon'R}{R_{max}}
\]

where \( R \leq R_{max} \). Also, in specimens XR083 and XR063, hoop fracture was observed during the next cycle when the confining stress at unloading reached the yield confining stress, \( \sigma_{cy} \) (= \( Pw \cdot f_{wy} \)).
For the diagonally reinforced columns in the series with non-dimensional axial compressions of 0.10 and 0.42, similar results to the columns in the 0.29 series were obtained. Namely, the deformation capacity of diagonally reinforced columns is extremely affected by the variation of confining stress at unloading. Then, the relation between $\sigma_{co}$ and $R$ and $K$ is given by:

\[
\begin{align*}
\sigma_{co}/F_c &= 0.075 \cdot n^1 \cdot \sqrt{R(K-1)^3} + 0.01 \cdot K \cdot R + 0.08 \cdot n \quad (\sigma_{co} < \sigma_{cy}) \\
\sigma_{co}/F_c &= \sigma_{cy}/F_c \quad (\sigma_{co} \geq \sigma_{cy})
\end{align*}
\]

(5)

The relation between the non-dimensional confining stress, $\sigma_{co}/F_c$, and the relative displacement angle, $R$, or the load cycle frequency, $K$, is shown in Fig. 4. In the figure, the dotted lines represent the non-dimensional confining stresses obtained from the tests of the XU06 series' columns. Also, the chain lines express $(\sigma_{cy} - \sigma_{cs})/F_c$ when $R \leq R_{max} (= 0.015 \text{rad.})$, and $\sigma_{cy}/F_c (= P_{uw}/f_{wy})$ when $R > R_{max}$, where, $\sigma_{cy}/F_c$ is the non-dimensional yield confining stress contributed by the confining reinforcement only.

In comparison with the experimental results, in spite of the levels of axial compression loading, if the confining stress at unloading, $\sigma_{co}$, in each cycle didn't exceed $\sigma_{cy} - \sigma_{cs}$ or $\sigma_{ccy}$, the columns had superior seismic behavior with extremely small deterioration of load carrying capacity. However, if $\sigma_{co}$ in each cycle exceeded $\sigma_{cy} - \sigma_{cs}$ or $\sigma_{ccy}$, the column brittle failure occurred in shear with hoop fracture after three or four cycles. Namely, to further improve the seismic performance of diagonally reinforced columns subject to high axial compressive stress in particular, the transverse reinforcements should be arranged in the columns so that the confining stress at unloading at the end of each cycle doesn't exceed the yield confining stress $(\sigma_{cy} - \sigma_{cs}$ when $R \leq R_{max}$, and $\sigma_{ccy}$ when $R > R_{max}$). From the experimental results, we found that the quantity of transverse reinforcements required to ensure the deformation capacity at the relative displacement angle $R_u$ with $K_u$ cycles in diagonally reinforced columns is given by

\[
P_w = P_{ws} + P_{wc} = P_{ws} + [0.075 \cdot n^1 \sqrt{R_u(K_u-1)^3} + 0.01 \cdot K_u \cdot R_u + 0.08 \cdot n]F_c/f_{wy}
\]

(6)

CONCLUSIONS

From the experimental results obtained in this study, the following conclusions were reached:

1. Under low levels of axial compression loading, strength and ductility of reinforced concrete columns can be increased by utilizing the diagonally reinforced arrangement, even though the quantity of transverse reinforcements proportionate to the shear contributed by diagonal reinforcements decreases.

2. To prevent brittle failure and to increase deformation capacity under high levels of axial compression loading, diagonally reinforced columns should also be arranged with transverse reinforcements of sufficient quantity and strength to confine the core concrete expanded with plastic deformation.

3. The quantity of transverse reinforcements required to ensure ductile behavior of the diagonally reinforced short columns is given by Eq.(6), which is expressed by the sum of the quantities of shear reinforcements and confining reinforcements from this experimental study.

REFERENCES
