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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 sever 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 PU08 series and XU06 series are shown in Fig. 1 as examples. The test plan is represented in Table 1.

Table 1 Test Plan

Concrete Strength Fc(kgf/cm²)	Axial Compression N(tf)	n(=N/bDFc)	Specimen				
285	11.2	0.10	PU081	XU061	XR111	XR081	XR061
310	36.0	0.29	PU083	XU063	XR113	XR083	XR063
285	48.0	0.42	PU085	XU065	XR115	XR085	XR065
Material of Transverse Reinf.			High Strength Bar		Normal Strength Bar		
Transverse Reinf. Ratio Pw (%)			0.76	0.55	1.10	0.76	0.55
Confining Reinf. Ratio Pws(%)			0.34	0.34	0.68	0.34	0.13
Tensile Reinf. Ratio : Pt=0.72%							
Column Height-Depth Ratio : L/D=2							

Table 2 Mechanical Properties of Reinforcing Bars

Longitudinal Reinforcement	: D10	fy = 4032 kgf/cm²
Transverse Reinforcement	: 4.5ϕ	fwy = 3460 kgf/cm²
	: 3.56ϕ	fwy = 20500 kgf/cm²

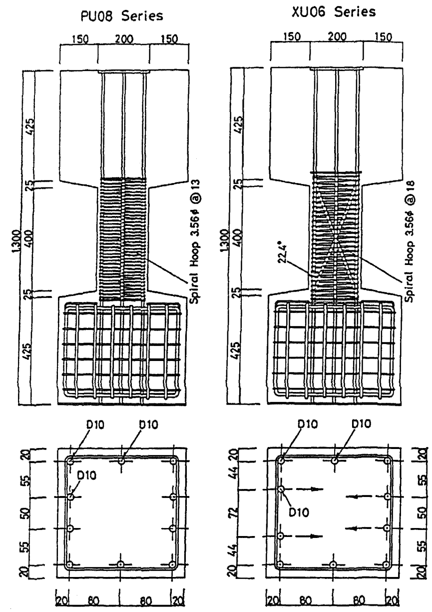

Fig. 1 Dimension of Columns

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, Pt, 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, β, 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, 3.56ϕ high strength reinforcing bars and 4.5ϕ 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/cm^2, 90 kgf/cm^2 and 120 kgf/cm^2). 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:

$$Pw = Pws + Pwc \qquad (1)$$

where Pw is the transverse reinforcement ratio, Pws is the shear reinforcement ratio and Pwc is the confining reinforcement ratio. Furthermore, Pws 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

$$Pws = 2 \cdot \beta Pt \cdot fy / (fwy \cdot \eta) \qquad (2)$$

where pPt is the tensile reinforcement ratio of the parallel reinforcements, fy and fwy are the yield stresses of the parallel and transverse reinforcements respectively, and η 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, Pw, as 0.76% (Pwc=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 Pw of 0.55% (Pwc=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 Pw of 1.10% (Pwc=0.68%) and the same Pw fwy as the specimens in the XU06 series. The specimens in the XR08 series had a Pw of 0.76% (Pwc=0.34%) and the same Pwc as the specimens in the XU06 series. The specimens in XR06 series had a Pw of 0.55% (Pwc=0.13%) and the same Pw 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/cm^2 for the high strength reinforcing bars, and 3000 kgf/cm^2 for the normal reinforcing bars, and value of the yield stress of the longitudinal reinforcing bars was used 3500 kgf/cm^2.

TEST RESULTS

The hysteresis 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, R. Also, the dotted lines represent the P-Δ 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 hysteresis 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 hysteresis 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

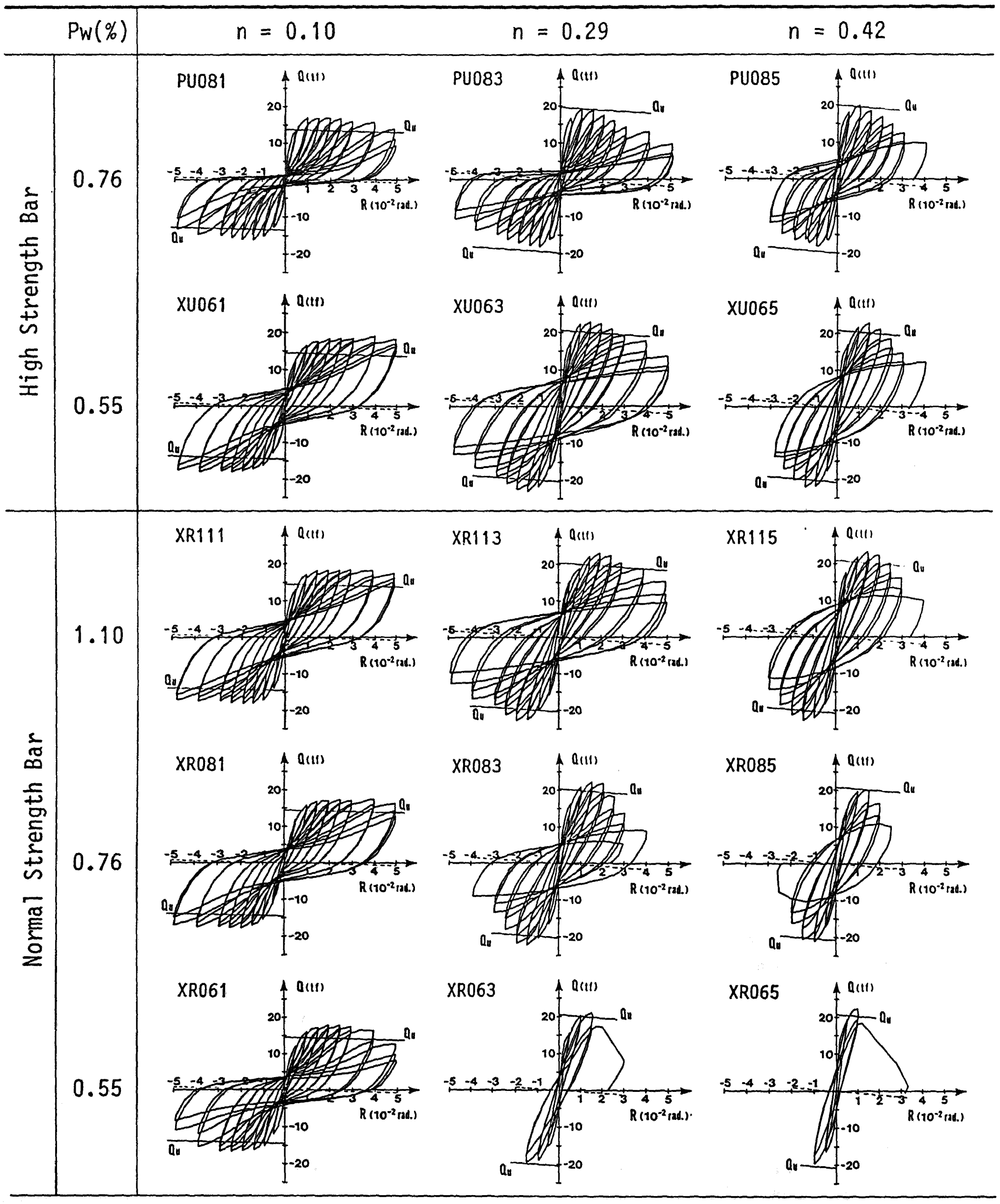

Fig. 2 Load-Displacement Response

Table 3 Maximum Strength

n = 0.10				n = 0.29				n = 0.42			
Specimen	Maximum Strength(tf) Pos.	Maximum Strength(tf) Neg.	Theoretical Strength Qu(tf)	Specimen	Maximum Strength(tf) Pos.	Maximum Strength(tf) Neg.	Theoretical Strength Qu(tf)	Specimen	Maximum Strength(tf) Pos.	Maximum Strength(tf) Neg.	Theoretical Strength Qu(tf)
PU081	17.0	16.2	13.5	PU083	19.3	18.1	19.7	PU085	20.2	17.9	20.0
XU061	19.0	18.1	14.5	XU063	23.1	22.8	20.5	XU065	22.6	22.2	20.7
XR111	18.5	17.9	14.5	XR113	22.9	22.9	20.5	XR115	23.4	22.7	20.7
XR081	17.7	18.0	14.5	XR083	22.4	22.3	20.5	XR085	20.1	21.1	20.7
XR061	17.9	16.7	14.5	XR063	21.0	19.6	20.5	XR065	22.7	19.5	20.7

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, σc, and the relative displacement angle, R, 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, σco, respectively. The values of σc ($\sigma cmax$ and σco) were calculated from the strain of the transverse reinforcement located 75mm 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:

$$\text{in the case of } \varepsilon < \varepsilon y \qquad \sigma c = Pw \cdot Es \cdot \varepsilon$$
$$\text{in the case of } \varepsilon \geqq \varepsilon y \qquad \sigma c = Pw \cdot fwy \qquad (3)$$

where Es is Young's modules of transverse reinforcement and εy 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, σcs (= $\sigma cmax - \sigma co$), is similar to the variation of the applied shear forces, before the attainment of the maximum capacity of the column, Rmax = 0.015 rad. Furthermore, using the above-mentioned Pws, σcs and R are approximately related as follows:

$$\sigma cs = Pws \cdot Es \cdot \varepsilon \cdot R/Rmax \qquad (4)$$

where R $\leqq$ Rmax. 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, σcy (= $Pw \cdot fwy$).

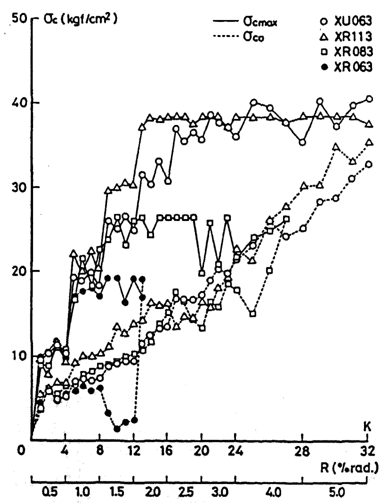

Fig. 3 σc-R, K Relationship

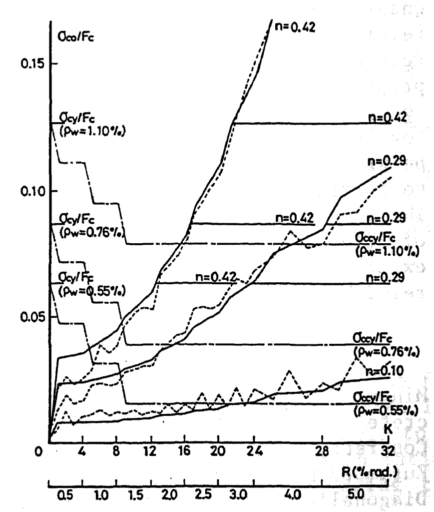

Fig. 4 $\sigma co/Fc$-R, K Relationship

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 σco, and R and K is given by:

$$\sigma co/Fc = 0.075 \cdot n^3\sqrt{R(K-1)^3} + 0.01 \cdot K \cdot R + 0.08 \cdot n \qquad (\sigma co < \sigma cy)$$
$$\sigma co/Fc = \sigma cy/Fc \qquad (\sigma co \geqq \sigma cy) \qquad (5)$$

The relation between the non-dimensional confining stress, $\sigma co/Fc$, 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 $(\sigma cy - \sigma cs)/Fc$ when $R \leqq Rmax$ (= 0.015rad.), and $\sigma ccy/Fc$ (= $Pwc \cdot fwy/Fc$) when $R > Rmax$, where, $\sigma ccy/Fc$ 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, σco, in each cycle didn't exceed $\sigma cy - \sigma cs$ or σccy, the columns had superior seismic behavior with extremely small deterioration of load carrying capacity. However, if σco in each cycle exceeded $\sigma cy - \sigma cs$ or σccy, 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 $R \leqq Rmax$, and σccy when $R > Rmax$). From the experimental results, we found that the quantity of transverse reinforcements required to ensure the deformation capacity at the relative displacement angle Ru with Ku cycles in diagonally reinforced columns is given by

$$Pw = Pws + Pwc$$
$$= Pws + \{0.075 \cdot n^3\sqrt{Ru(Ku-1)^3} + 0.01 \cdot Ku \cdot Ru + 0.08 \cdot n\} Fc/fwy \qquad (6)$$

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.

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