STRENGTH AND DUCTILITY OF DIAGONALLY REINFORCED CONCRETE COLUMNS

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SUMMARY

To improve the seismic performance of reinforced columns failing in shear, behavior of diagonally reinforced columns is investigated.Test of eight specimens is conducted, considering the diagonal reinforcement ratio and the shear reinforcement ratio. It is verified that the strength,ductility, and energy dissipation capacity increses with increse of diagonal reinforcement ratio without adding extra amount of shear reinforcements. Theoretical shear etrength of diagonally reinforced columns make use of the extended additive strength theory. An example of diagonally reinforced columns used in real building construction is introduced, and their successful used is demonstrated.

INTRODUCTION

To provide ductile behavior of reinforced concrete (RC) beames, particularly those functioning as boundary beams in reinforced concrete shearwalls, Paulay proposed a new reinforcing technique (called the diagonal reinforcement in this paper), in which longitudinal reinforcing bars are placed in diagonal directions (Refs.1, 2, 3). The writers speculated a possibility of using the diagonal reinforcement for the design of short RC columns subjected to high seismic loading, and subsequently conducted an experimental study on the seismic behavior of such diagonally reinforced columns (Refs.4, 5). This paper presents the test results of RC columns in which diagonal reinforcement is superposed to conventionally longitudinal(parallel) and shear reinforcement, and reports on the strength, ductility and energy dissipation characteristics of those columns. A theoretical study to estimate the shear strength of diagonally reinforced columns is also described. Finally, an example of the application of diagonally reinforced columns to real building construction is reported.

COMBINED LONGITUDINAL AND DIAGONAL REINFORCEMENT

The diagonal reinforcement is desirable, suited and easily applied in RC structures that have shear walls in one direction, and no walls in the perpendicular direction, and have many short columns, such as school buildings and housings. In general seismic load conditions, columns usually do not have their inflection point in the mid length, and the column top moment Mt is not identical in magnitude with the column base moment Mb. As shown in Fig.1, conventionally longitudinal reinforcement sufficient to sustain the uniform moment equal to (Mb - Mt)/2 should be provided in those columns. The remaining anti-symmentrical moment : (Mb + Mt)/2 can be resisted by placing

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diagonal reinforcement.The reinforcement arrangement designed in this procedure ensures the most ductile behavior for those columns. In real designs, it may be more practical to place less amount of diagonal reinforcement because of various restraints such as reinforcement limitation. It is conceived that combined longitudinal and diagonal reinforcement will improve seismic performance greatly.

EXPERIMENT

Planning of Test

To investigate the seismic behavior of diagonally reinforced columns, A total of eight specimens are prepared, considering two test parameters: the diagonal reinforcement ratio β (0, 0.2, 0.4 and 0.6) and the shear reinforcement ratio ρw (0.21 and 0.42 percent). The test program is shown in Fig. 2. Symbol β in the figure is the ratio of the diagonal to total reinforcement, and given as:

$$\beta = dTy / Ty = dTy / (dTy + pTy) \qquad (1)$$

in which:
dTy = Yield tensile force of diagonal reinforcement subjected to tension
pTy = Yield tensile force of longitudinal reinforcement subjected to tension
Ty = Yield tensile force of total reinforcement subjected to tension

The columns shown in Fig. 3 are 30 cm width and 30cm depth with a clear length of 90cm. The flexural tension reinforcement consists of 5-D16 deformed bar (tension reinforcement ratio: ρt =1.11 percent). 6 mm hoops at 4.5 cm and 9 cm spacing are provided in column with ρw =0.21 percent and 0.42 percent respectively. Columns are loaded by applied anti-symmetric moment of equal magnitude at both ends under constant axial load. Horizontal shear is applied under load reversals having gradually increasing amplitude,in which the amplitude is increased after every two cycles. The applied axial stress is 10 percent of the compressive strength of concrete for all of 8 columns. Mechanical properties of concrete and reinforcement is listed in Table 1.

Failure Mode

Photo 1 shows the final damage after the test. The failure mode change as the β varies from 0 (corresponding to longitudinal reinforcement only) to 0.6, and shifts from the shear-splitting failure with bond-splitting cracks along longitudinal reinforcement to flexural failure having some cracks along the diagonal reinforcing bars. To develop the desired large ductility, even in diagonally reinforced columns, the sufficient amount of shear reinforcement should be placed to avoid the brittle diagonal tension failure, and to prevent the instability failure of the diagonal compression bar at the intersection of the diagonal reinforcing bars.

Hysteresis Response

The hysteresis loops of columns are shown in Fig.4. In the figures, the ordinate represents applied shear Q and the abscissa gives the relative slope deflection of column R. Chain lines in those diagrams denote theoretically obtained ultimate strength. The hysteresis curves change from pinching to spindle shape as the β value increases. Furthermore, the theoretical strength

is found to be closed agreement with the experimental strength. Figure 5 shows the envelop curves obtained in the first cycle of loading for each amplitude level, verifying that both the ultimate shear strength and deflection capacity (the deflection at which the load carrying capacity starts deteriorating) increases with the increase of the ρw and β values. Note,however, that the strength reduction ratio in the post deflection capacity range is almost constant regardless of the ρw and β values. In Fig.6, the rotation angle corresponding to the deflection capacity Ru is plotted against the β value.Also, the ordinate in the figure gives a measure of the corresponding ductility ratio μ. The relation between Ru and μ is determined such that a rotation angle of 0.06 rad. equals a ductility ratio of 1.0.

Energy Dissipation Capacity

Figure 7 shows how the cumulative dissipated energy varies by the change of the ρw and β values.The ordinate denotes the cumulative dissipated energy divided by the cumulative dissipated energy corresponding to the second circle of R = 0.09 rad. of amplitude in the test of specimen L02 (β=0 , ρw= 0.21%). Black and white circles in the figure are respectively those measured in specimens having 0.42 and 0.21 percent of the ρw value. In a region of small displacement amplitude levels, the cumulative dissipated energy is constant regardless of the β value.In a region of large displacement amplitude, on the other hand, the dissipated energy increases as the β value increases; for instance, when the ρw value is 0.42 percent, the energy for β = 0.6 is three times as large as for β =0.

Shear Resisted by Diagonal Reinforcement

Shear resisting mechanism of RC beams or columns is characterized as a combination of beam and arch mechanism. When diagonal reinforcement is superposed to longitudinal reinforcement, the overall shear resisting mechanism can be treated as the sum of the two mechanisms stated above and the truss mechanism, which is likely to result in an increase of the total shear resistance. In Fig.8, shear resisted by diagonal reinforcement, dQ, and shear resisted by the remaining part, pQ (= Q - dQ), are plotted with respect to the rotation angle. White and black marks denote the shear resisted by positive and negative loading respectively, and round, square, and triangle marks are the total shear, shear resisted by diagonal reinforcement, and shear resisted by the remaining part. The figure indicates that the dQ value increases in proportion to the β value, and reveals that the total shear resisted by a diagonally reinforced column can be estimated as the sum of the shear to be computed if there is no diagonal reinforcement in the column, pQu , and the shear resisted by the diagonal reinforcement, dQu. Thus:

$$Qu = pQu + dQu \qquad (2)$$

ANALYSIS OF SHEAR STRENGTH

Figure 9 shows the shear resisting mechanism of a diagonally reinforced concrete column proposed by the writers (Refs.4, 6). Here, the member is supposed to be subjected to axial force, N, anti-symmetrical moment, M, and shear force, Q. It is postulated that the shear is resisted by a combination of the beam, arch, and truss mechanisms and that the total resisting shear is given as the sum of the three individual mechanisms. With the use of this shear

CONCLUSION

(1) For diagonally reinforced columns, the failure mode changes from shear to flexural failure, and the hysteresis curves from little energy dissipating pinched to energy effective spindle shape, as the amount of diagonal reinforcement increases.
(2) With the increase of diagonal reinforcement, the shear strength increases proportionally. The strength can be reasonably estimated as the sum of the strength of the column without diagonal reinforcement and the strength of the diagonal reinforcement.
(3) The seismic performance of a column whose diagonal reinforcement ratio relative to the total flexural reinforcement is 60 percent is as good as that of a column whose ratio is 100 percent (diagonal reinforcement only). It results that 60 percent of diagonal reinforcement is sufficient for design purpose.
(4) The deformation capacity depends largely upon that buckling of diagonal reinforcing bars. For better seismic performance, it is then needed to devise a new means to retard the buckling.
(5) Use of diagonal reinforcement is more effective in columns than in beams as far as the strength is concerned.

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Table 1 Mechanical Properties of Materials and Test Results

Specimens	Concrete Strength Fc(kgf/cm^2)	Applied Axial Load(tf)	Maximum Strength(tf) Measured Positive	Measured Negative	Theoretical
1.02	263	24.4	20.40	- 20.60	21.00
1.22	280	25.5	22.80	- 24.20	23.10
1.42	263	24.4	22.20	- 22.20	23.60
1.62	263	24.4	23.60	- 23.10	24.30
1.04	276	24.8	22.20	- 19.00	22.00
1.24	276	24.8	24.70	- 22.10	23.30
1.44	276	24.8	26.50	- 25.50	24.10
1.64	276	24.8	26.40	- 25.60	24.80

Notes: Yield strength of tension and shear reinforcement are 3782 kgf/cm^2 and 2526 kgf/cm^2 respectively.

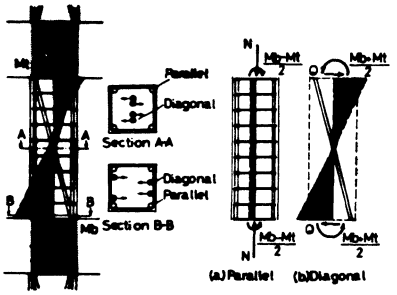
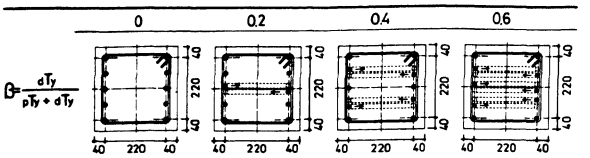


Fig.1 Design of Diagonally Reinforced Columns



Parallel	5-D16	4-D16	3-D16	2-D16
Diagonal		1-D16	2-D16	3-D16
ρ_w 0.21%	L02	L22	L42	L62
0.42%	L04	L24	L44	L64

Fig.2 Variables Chosen for Experiment

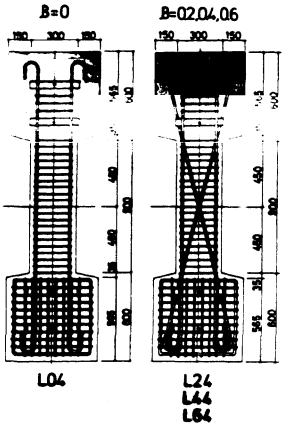
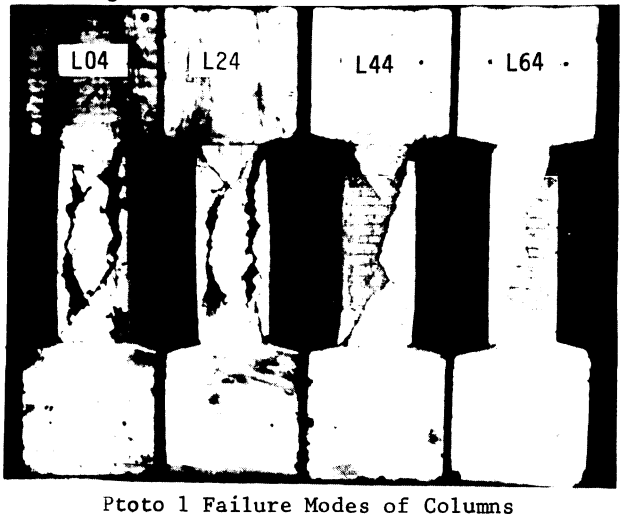


Fig.3 Overall Dimension of Columns with ρw=0.42% (units,mm)



Ptoto 1 Failure Modes of Columns with ρw=0.42%

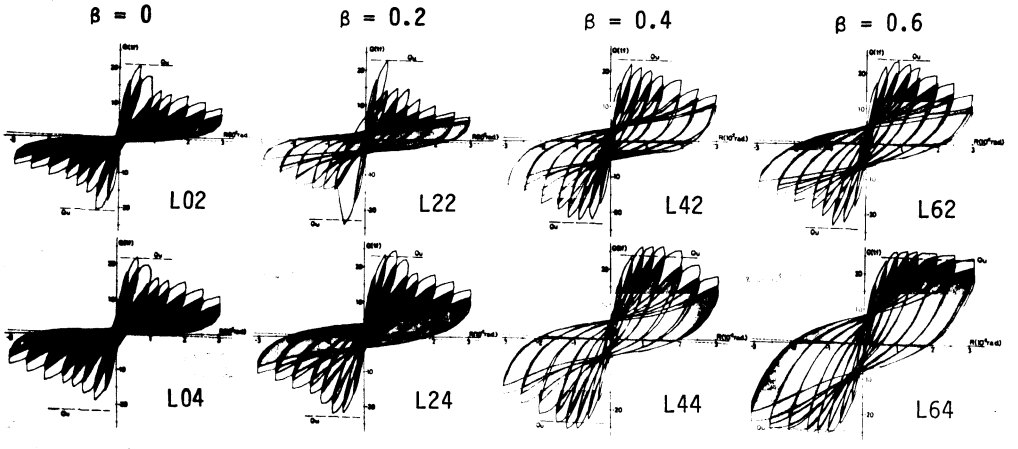


Fig.4 Load-Displacement Response to Cyclic Reversed Loading

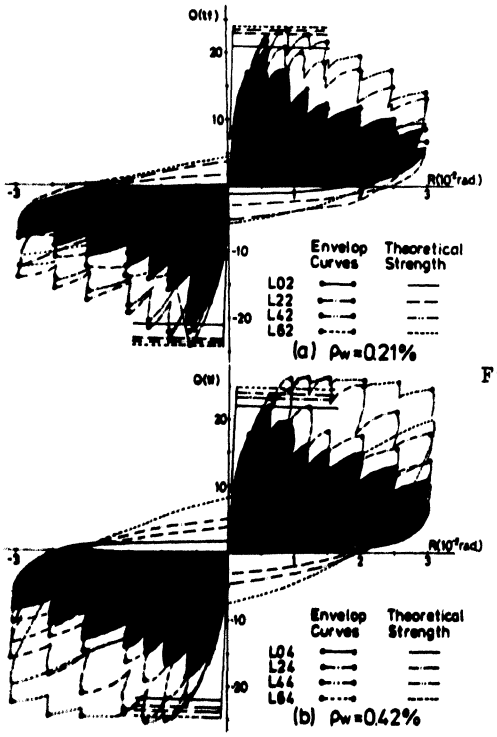


Fig.5 Variation of Envelope Curves with Diagonal Reinforcement Ratio

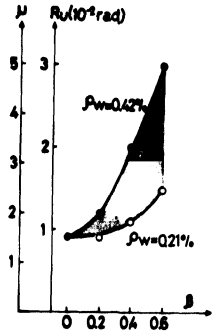


Fig.6 Deformation Capacity

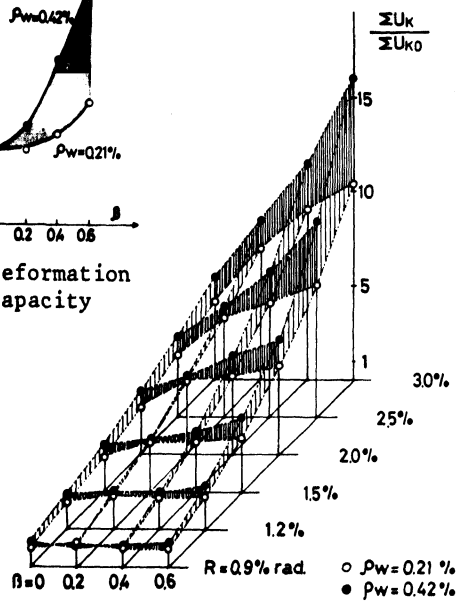


Fig.7 Contribution of Diagonal Reinforcement to Cummulative Energy Dissipation

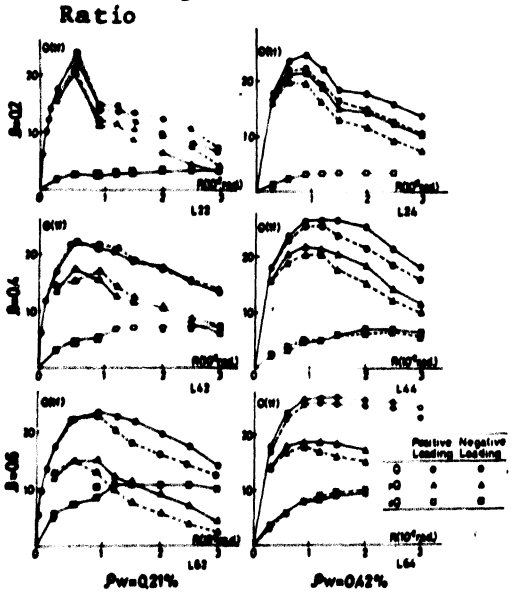


Fig.8 Contribution of Diagonal Reinforcement to shear Strength

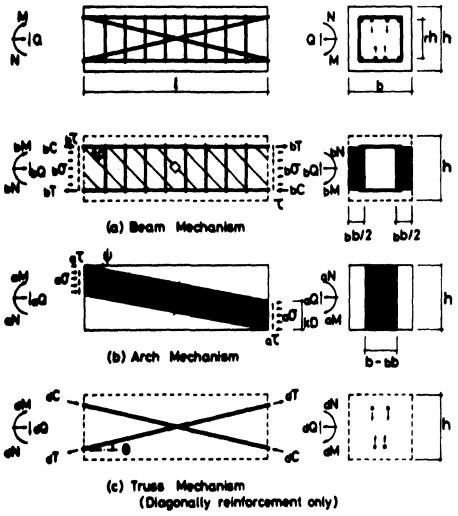


Fig.9 Shear Resistant Mechanism of Diagonally Reinforced Columns under Combined Compression, Bending and Shear

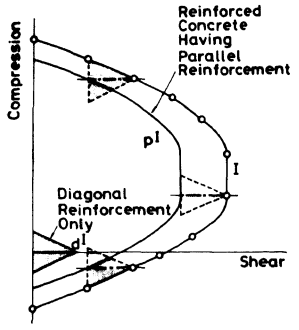


Fig.10 Axial Load-Shear Interaction Curves Based on Method of Superposition

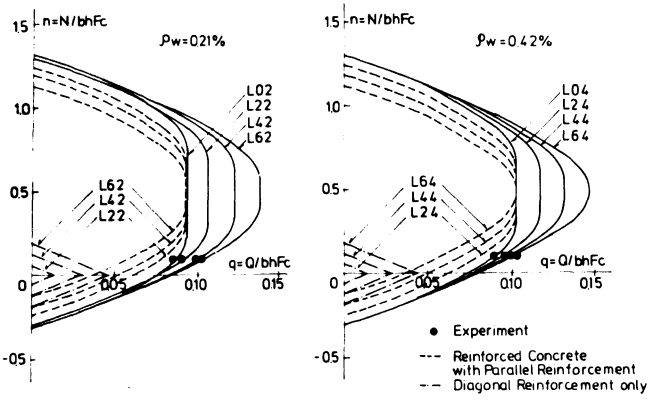


Fig.11 Comparison of Theoretical Prediction with Experimental Results

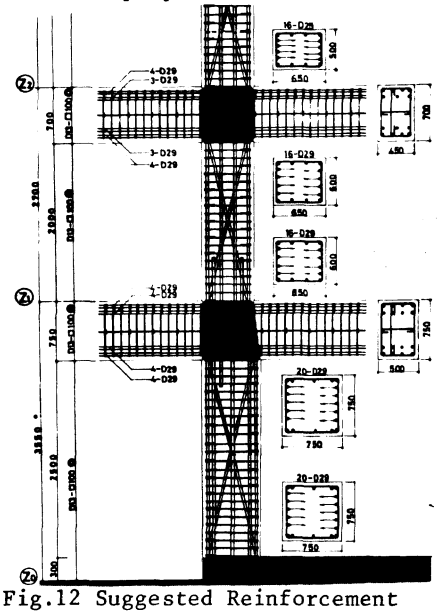


Fig.12 Suggested Reinforcement Arrangement in Diagonally Reinforced Columns(units,mm)

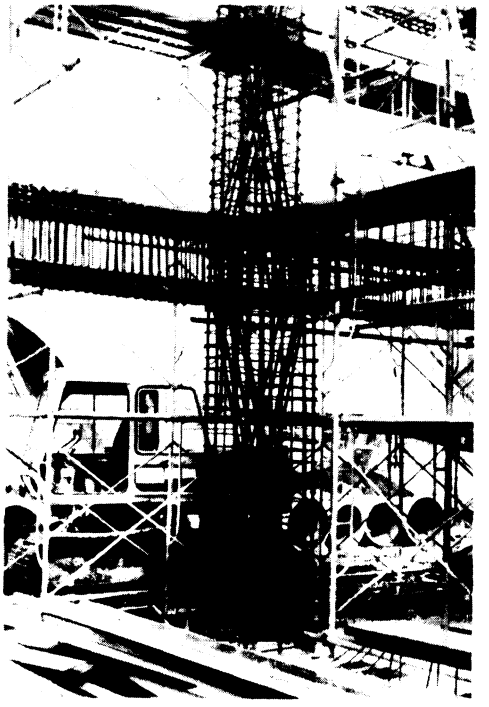


Photo.2 Construction of Reinforced Concrete Structure Containing Diagonally Columns

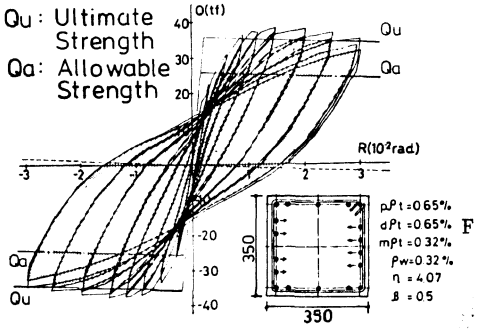


Fig.13 Hysteretic Response of Diagonally Reinforced Columns Based on Proposed Design Procedures (First Story Column)