SEISMIC RESISTANCE OF DIAGONALLY REINFORCED CONCRETE COLUMNS

by

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SUMMARY

One of the problems related to the structural safety of reinforced concrete buildings under earthquake loading is the brittleness of short columns subjected to large shear. A simple technique of preventing short columns from failing in shear and providing them with appropriate earthquake resistance is to arrange their main reinforcements diagonally as diagonal bracings in a steel frame. Described in this paper is a few of basic properties of diagonally reinforced concrete columns under large shear, and the points to ponder in the application of such columns in the practice are discussed.

INTRODUCTION

In order to suffice low-to mid-rise concrete buildings with seismic resistance, it is necessary to prevent short columns from brittle shear failure and to improve seismic reisitance of columns. Learned from the recent earthquake damages in Japan and other countries, extensive experimental studies, some including full-scale tests, were carried out by several Japanese research institutes to establish effective techniques of improving reinforced concrete column's seismic reisistance,and valuable knowledge have been resulted. However, all of these researches were based on conventional way of arranging main (longitudinal) reinforcements, that is, the main reinforcements were placed parallel to the column axis, and mainly proposed such arrangement and set-up of hoops (transverse shear reinforcements) as welding hoops to have closed configuration, use of single or double spiral hoops and others. All of these referred only to the amount, configuration or arrangement of hoops, and practically none treated the arrangement of main reinforcements to improve seismic resistance of concrete of columns.

APPLICATION OF DIAGONAL REINFORCEMENTS

In 1971, Paulay et al.[1)–4)] first introduced the idea of using diagonal arrangement of main reinforcements (hereafter referred as diagonal reinforcements) to prevent concrete beams from brittle failure under shear. Their proposal was to place diagonal main reinforcements in the boundary beams located between the adjacent raws of multi-storied shear walls in a center-corridor type of building where sufficient ductility was required as well as strength. The idea of providing required structural properties by this method was then tried in a practical design.

Implied by the proposal of Paulay et al., Bertero et al.[5),6)] applied the idea in shear resistant beams. Authors, on the other hand, considered the application of the same idea to improve the seismic resistance of short

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concrete columns, which have repeatedly been pointed out to be greatly affected by shear under earthquake loading, and carried out some basic experiments[7),8)]. The results showed that the columns with diagonal reinforcements had considerably superior resistance against seismic loading to those with conventional paralled reinforcements. This report describes a few of basic properties of concrete columns under large shear and discusses problems that are to arise in applying the diagonal reinforcement in practice.

SHEAR TEST METHOD

Diagonal reinforcement arrangement in concrete structure has been adopted in such parts as concrete supports, where, in design, basically no moment transmission is assumed at the intersecting section of main reinforcements. However, for a member which has its inflection point at the mid-point of the member and is subjected to antisymmetric bending, the diagonal arrangement of main reinforcements is very rational since the main reinforcements are placed in accordance with the moment distribution. This holds especially for columns that are aften determined by horizontal earthquake loads.

In the experiments, all the main reinforcements were diagonally placed to intersect at the mid-height of columns in order to clearly observe the basic properties of such columns. Test specimens were loaded, making use of the loading apparatus shown in Fig.1, by repeatedly applied antisymmetric bending moments of equal magnitude at both ends (Fig.2).

COMPARISON OF PARALLEL AND DIAGONAL ARRANGEMENT OF MAIN REINFORCEMENTS

Test Plan   Shown in Figs.3(a) and 3(b) are the typical test specimens and their reinforcement arrangement adopted for the experiments to know the difference in column properties and failure modes under repeatedly applied bending and shear and to compare the diagonal reinforcement with the conventional parallel reinforcement. All the column specimens had the same height (h=45cm), depth (D=15cm ; h/D=3), main reinforcement ratio ($_rP_t$=1.18 %) and hoop ratio ($_rP_w$=0.42%). The specimen XA (with diagonal reinforcements) had another set of logitudinal reinforcements 6mm in diameter to keep the hoops in place and they were not anchored at the ends. Both types of specimens were also loaded by axial compression equal to 15% of the compressive yield load of centrally loaded column.

Failure Modes and Hysteresis Loops   Failure modes of the specimens are sketched in Figs.4(a) and 4(b). Specimen PA (with conventional parallel reinforcements)showed so-called bond-splitting cracks, while the specimen XA showed the cracking pattern that indicated flexural failure at member ends with some cracks along the diagonal reinforcements. Shown in Figs.5 (a) and 5(b) are the hysteresis loops of both specimens. In the figures, the ordinate represents applied shear, Q, and the abscissa gives the relative slope deflection of columns, R. The specimen PA showed comparatively large deterioration in load carrying capacity after attainment of the maximum capacity with the increase of deflection amplitude, and also showed appreciable deterioration under cyclic loading at constant deflection amplitude. The specimen XA, on the other hand, showed the larger maximum strength than PA, no appreciable deterioration after the attainment of the maximum capacity, spindle-shaped hysteresis loops with large capacity of energy consumption, and the smaller deterioration under cyclic loading at constant deflection amplitude. All of these indicate that the major weak points in the properties of concrete columns under large shear are considerably compensated.

Capability of Energy Consumption Compared in Fig.6 are the envelops of the first cycle of the hysteresis loops for both specimens XA and PA(Fig. 5). The figure clearly indicates the difference, between the two types of the reinforcement arrangement, in the magnitude of the maximum load carrying capacity and the degree of deterioration after attainment of the maximum capacity. Capability of energy consumption of the two columns is given in Fig.7. The ordinate gives the cumulative energy absorbed by the column calculated from the hysteresis loops, and the abscissa represents the number of loading. There is no appreciable discrepancy between the two in the range of small amplitude of deflection. In the larger range of deflection amplitude, on the other hand, there exists a great difference between them, and at the final stage of experiments, the cumulative energy concumption of the specimen XA turned out to be approximately twice as much as that of the specimen PA.

DEFORMATION PROPERTIES OF STUB COLUMNS WITH DIAGONAL REINFORCEMENTS

Test Plan Shown in Figs.8(a) and 8(b) are the shape, dimensions and reinforcement arrangement of column specimens which had smaller shear span ratio and were tested for deformation properties under larger compression, a severer loading condition than that in the previous shapter. The same value of main and hoop reinforcement ratios as the specimen XA were adopted for the test. Experimental variables were the shear span ratio (h/D=1 and 2) and the ratio of the applied axial compression, N, to the yield load of the centrally loaded column, No (N/No=0, 0.2 and 0.4 ; or N/bDFc=0, 0.27 and 0.52 in which b and D are the column width and depth, respectively and Fc is the compressive strength of concrete).

Deformability Hysteresis loops obtained on these six specimens are given in Figs.9(a) through 9(f). The ordinate in the figures represents the applied shear, Q, and the abscissa gives the relative slope deflection of column, R. Even for the columns with diagonal reinforcements it is noted that load carrying capacity and deformation properties were largely affected by the values of the shear span and the applied axial compression. Except the columns subjected to large compression of N/No=0.4, all the column specimens with both shear spans of h/D=1 and 2 showed the deformability up to R=0.02 rad. and it was proved that the diagonal reinforcement helped improve the column's with small shear span, their seismic resistance is greatly dependent on the load transmission efficiency at the member ends where mein reinforcements are bent. Therefore, the arrangement of reinforcements and other structural detailing need to be carefully made. Further, for the betterment of diagonal rienforcement application, a certain limit value of the working compression on columns must be determined to assure the column's deformation capacity.

ULTIMATE SHEAR STRENGTH OF COLUMNS WITH DIAGONAL REINFORCEMENTS

Failure Machanism Illustrated in Fig.10 is the ultimate state of columns with diagonal reinforcements resisting compression, bending and shear. The strength of a reinforced concrete column can be given by the sum of concrete strength and the strength of the system of diagonal reinforcements. Concrete, without reinforcement, only works against diagonally inrtoduced compression and prevents compressed reinforcements from buckling. Therefore, no shear failure takes place in concrete although eccentric compressive failure may occur. One set of main reinforcements is subjected to uniform compression, and the other set to uniform tension. When they reach their yield stress, plastic deformation progresses. At this state, bondage between concrete and main reinforcements is not recessary to resist the external load, and no bond failure should take place.

Equilibrium Analysis and Results Using a simple model of statical equilibrium of concrete and system of reinforcements as shown in Figs.10(a) and 10(b), their strengths are obtained. The strength of a reinforced concrete member is then calculated by the extended concept of adding component strength of concrete and reinforcements. Ultimate shear strengths computed for the column specimens with diagonal reinforcement are given in Table 1 with test results. Computed strengths are generally in good agreement with the test results except for the specimens X_{14} and X_{24} which were tested under large compression. This implies that the strength computation described here using the simple model enables a reasonable prediction of the shear resistance of reinforced concrete members with diagonal reinforcements. In the above analysis, hoops contributed none in estimating the member's shear capacity. However, hoops are desirable in reality since concrete under direct compression shows brittleness and they help improve the concrete property.

APPLICATION OF DIAGONAL REINFORCEMENT IN PRACTICE AND POINTS OF PONDER

The diagonal arrangement of main reinforcements described above is desirable, suited and easily applied in concrete structures that have seismic walls in span derection, have frames without load bearing walls in ridge direction, and have many short columns, such as school buildings and low to mid-rise housings. Fig.11 is an example of diagonal reinforcement arrangement in such structures, which is a mixed use of parpllel and diagonal reinforcements. Since, under various loading conditions, column inflection point does not necessarily fall on the mid-height of the column, conventional parallel reinforcements are always required. Usually its amout that is required to resist the bending moment at mid-point is not very large. Thus required parallel reinforcements shall be placed with minimum hoops so that flexural failure dominates, and the rest of the required main reinforcements had better be placed diagonally, which do not introduce unnecessary shear failure to the column. In practical designs, mixed use of parallel and diagonal reinforcements is generally advisable. However, practically no experimental study[9] has been made on the shear resistant properties of reinforced concrete members for such mixed use. Authors are currently in preparation of conducting such experiments, and hope to have experimental data accumulated on the application of reinforced concrete columns with diagonal reinforcements.

CONCLUDING REMARKS

Reinforced concrete structure, as a type of earthquake resistant structures, has its most critical problem in the brittleness of short columns under large shear. If this brittle failure is to be avoided, safety and reliability of reinforced concrete structures under large earthquake load can be considerably improved. To provide short columns with ductility, considerable amount of hoops are required in the conventional parallel arrangement of main reinforcements. By adopting diagonal reinforcements, however, shear failure of short columns can be minimized and the desired seismic resistance of columns can be sufficed without adding extra amount of hoops. Authors consider that the diagonal arrangement of main reinforcements is one of the effective measures to take in order to improve the seismic resistance of reinforced concrete buildings and hope that fundamental studies and application researches should be extensively done on the matter in the future.

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APPENDIX

Based on the extended concept of adding component strength of concrete and reinforcement, computed shear strength of reinforced concrete columns with diagonal reinforcements in a non-dimensional expression are given below, depending on the non-dimensional magnitude of working compression, n.

(a) $n_1 \leqq n < n_2$ $$q = \frac{1}{2}\cdot\{\sqrt{\eta^2 + 4\cdot(n - n_1) - 4\cdot(n - n_1)^2} - \eta\} \quad (1)$$

(b) $n_2 \leqq n < n_3$ $$q = (n - n_3)\cdot\tan\phi + 2\cdot\mu_t\cdot\sin\phi + q_3 \quad (2)$$

(c) $n_3 \leqq n < n_4$ $$q = 2\cdot\mu_t\cdot\cos\phi + \frac{1}{2}\cdot\{\sqrt{\eta^2 + 4\cdot n - 4\cdot n^2} - \eta\} \quad (3)$$

(d) $n_4 \leqq n < n_5$ $$q = -(n - n_4)\cdot\tan\phi + 2\cdot\mu_t\cdot\sin\phi + q_3 \quad (4)$$

(e) $n_5 \leqq n \leqq n_6$ $$q = \frac{1}{2}\cdot\{\sqrt{\eta^2 + 4\cdot(n + n_1) - 4\cdot(n + n_1)^2} - \eta\} \quad (5)$$

in which $n_1 = -2\cdot\mu_t\cdot\cos\phi$, $n_2 = -2\cdot\mu_t\cdot\cos\phi + (1 - \lambda)/2$,
$n_3 = (1 - \lambda)/2$ and ≥ 0, $n_4 = (1 + \lambda)/2$ and ≤ 1,
$n_5 = 2\cdot\mu_t + \cos\phi + (1 + \lambda)/2$, $n_6 = 1 + 2\cdot\mu_t\cdot\cos\phi = 1 - n_1$,
and $q_3 = \frac{1}{2}\cdot\{\sqrt{\eta^2 + 4\cdot n_3 - 4\cdot n_3^2} - \eta\}$

where $n = N/bDF_c$ (positive for compression), $q = Q/bDF_c$,
$\mu_t = T_o/bDF_c$, $\lambda = \sqrt{\tan^2\phi\cdot(1 + \eta^2)/(1 + \tan^2\phi)}$, $\eta = h/D$
b : column width, D : column depth, h : column length,
F_c : compressive strength of concrete,
T_o : tensile yield strength of diagonal reinforcement,
ϕ : angle between column axis and diagonal reinforcement,
N : applied axial compression, Q : shear strength of column.

Table 1. Summary of Maximum Strength of Tests and Analysis

Testing Parameter				Maximum Strength (ton)		
Specimens	Applied Axial Compression Ratio		Shear Span Ratio	Measured Strength		Culculated Strength
	N/No	N/bDFc	h/D	Positive Loading	Negative Loading	
XA	0.15	0.20	3	7.70	7.18	6.26
X10	0	0	1	10.92	10.79	9.83
X12	0.20	0.27	1	16.92	15.51	16.81
X14	0.40	0.52	1	14.12	13.30	18.79
X20	0	0	2	6.68	6.85	5.66
X22	0.20	0.27	2	9.37	9.03	8.93
X24	0.40	0.52	2	9.74	7.45	10.97

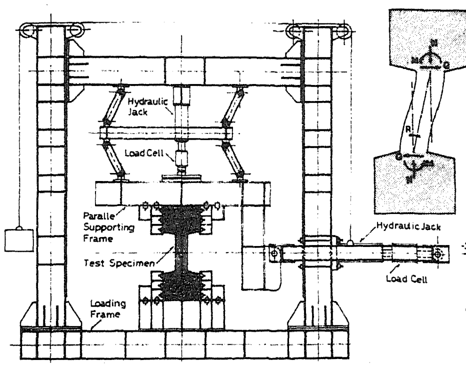


Fig. 1 Loading Apparatus.

Fig.2 Data Detection System

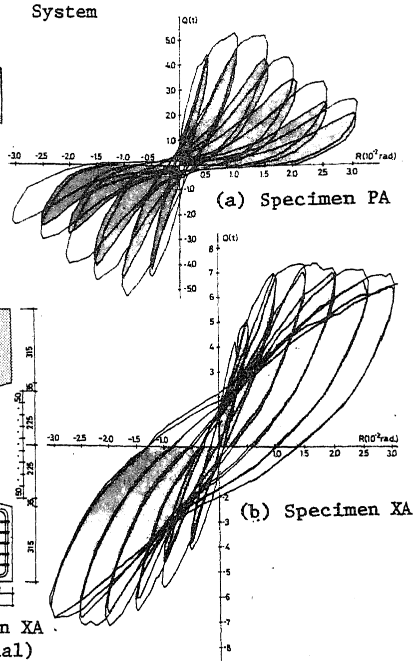
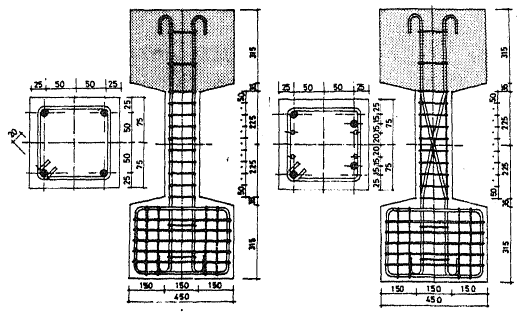


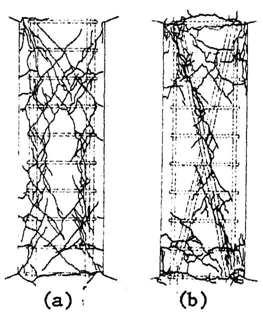
Fig. 5 Hysteresis Loops.



(a) Specimen PA (Parallel)

(b) Specimen XA (Diagonal)

Fig. 3 Dimensions and Reinforcements for Test Specimens. (Uuits;mm)



(a) Specimen PA (b) Specimen XA

Fig. 4 Failure Modes.

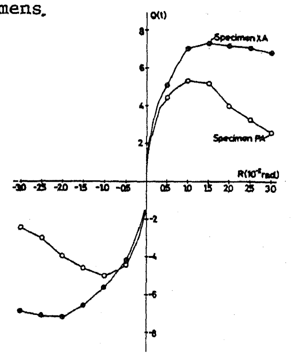


Fig. 6 Envelope Curves Obtained by Connecting Unloading Point at the First Cycle.

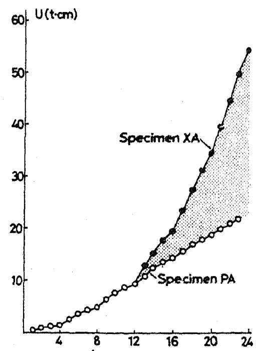
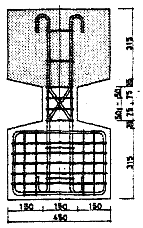
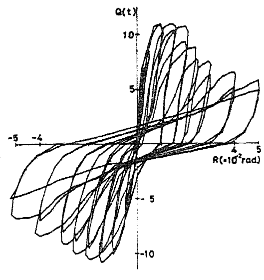


Fig. 7 Relationships between Cummulative Energy Absorption and Number of Cycles.

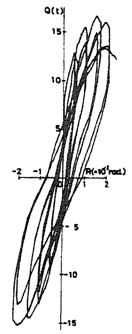
N/No = 0 N/No = 0.20 N/No = 0.40

(a) h/D = 1

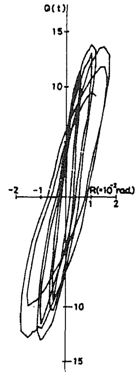




(a) Specimen X10

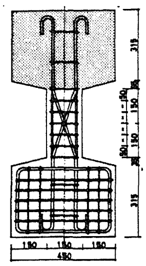


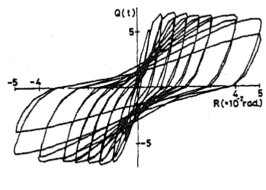
(b) Specimen X12



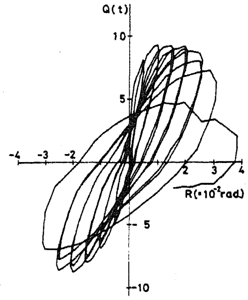
(c) Specimen X14

(b) h/D = 2

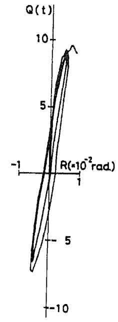




(d) Specimen X20



(e) Specimen X22



(f) Specimen X24

Fig. 8 Test Specimens. (Units; mm)

Fig. 9 Hysteresis Loops of Stub Columns.

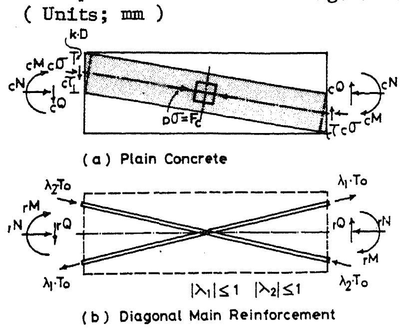


Fig.10 Equilibrium Analysis.

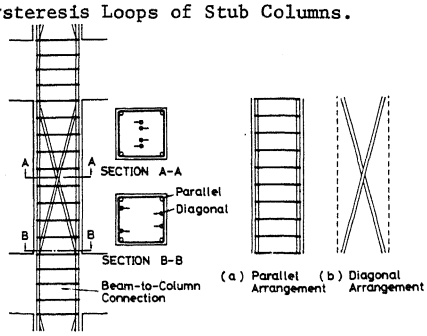


Fig.11 Application of Diagonal Reinforcement.