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# A proposal of new R/C short columns as an aseismic element with high strength and energy absorption capacity

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ABSTRACT: Reinforced concrete shear walls and/or steel bracing are widely accepted as aseismic elements for moment-resisting space frames in earthquake countries. By means of these aseismic elements, however, it would be difficult to satisfy all of the effective conditions simultaneously which are required for earthquake resistant design such as high stiffness and strength, deformability and large energy absorption capacity. Although a number of new design methods have been developed to control the earthquake behavior of building structures, those methods including base-isolation system and computer-controlled aseismic design approach are not practical because of being expensive and high technique being required. Herein, more practical aseismic element with high strength, large ductility and excellent energy absorption capacity is proposed by using a concrete filled steel tubular short column with special reinforcing bar arrangement.

## 1 INTRODUCTION

A large number of brittle shear failures in reinforced concrete (R/C) short columns have been reported during recent destructive earthquakes. While, it is also widely accepted that the ultimate shear strength carried by a R/C short column with conventional hoops and/or spirals does not increase remarkably even if considerable amount of transverse reinforcement is provided for the R/C short column. On the contrary, other experimental studies by authors have demonstrated that, if the R/C short column is confined by a steel square tube, then brittle shear failure can be prevented and the short column can develop its ultimate flexural capacity. Although strength and deformability of the R/C short column can be improved by using a steel square tube, remarkable high strength (or lateral load-carrying capacity) and large energy absorption capacity cannot be expected by using the ordinary method for longitudinal reinforcement based on parallel main reinforcing bar (Rebar) arrangement.

Main objective of the present study is to develop more effective reinforcing method for R/C short columns against strong earthquakes. Herein, ten different specimens with a R/C short column are tested under alternately repeated lateral forces and the effective reinforcement details for R/C short columns are investigated. Test results indicate that the earthquake resistant element composed of a concrete filled steel tubular short column with diagonal (or X-shape) bar arrangement has higher strength, larger ductility and more excellent energy absorption capacity than ordinary practical aseismic elements. Since proposed earthquake resistant element can be designed and manufactured easily and inexpensively under plant-controlled conditions, this element with lateral-load resistance is suitable for precast concrete frame structures.

## 2 SPECIMENS

Each of the specimens tested is composed of a R/C short column and top- and bottom-girders as shown in Fig.1. Although twenty-eight test specimens with various reinforcement details, material properties and loading conditions were tested using four different test setups, test results for ten specimens are presented in this paper. Cross-sectional details in and around the short column of all the specimens are illustrated in Table 1 together with

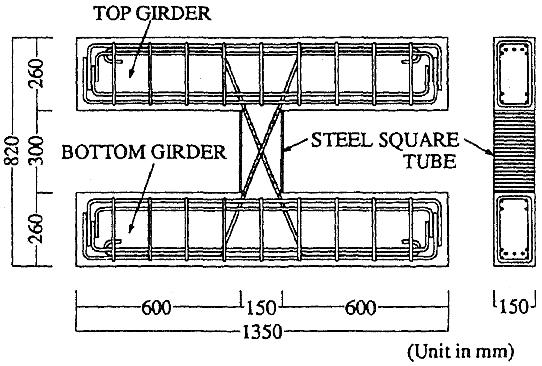
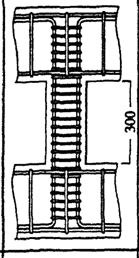
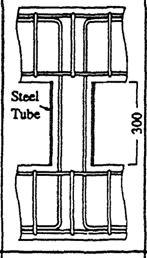
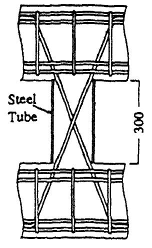
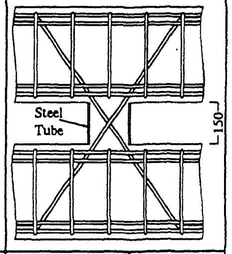
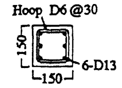
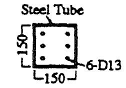
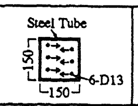
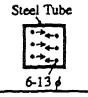
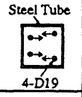
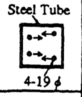
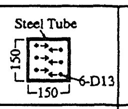
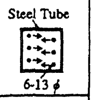


Figure 1. Size and shape of test specimen.
(Specimen SN-3.5-2 and SH-3.5-2)

Table 1. List of specimens and material properties.

(Uuit in mm)

| Specimen | | RC-3.4-2 | CF-3.4-2 | DN-3.4-2 | DH-3.4-2 | SN-3.5-2 | SH-3.5-2 | DN-5.1-2 | SN-5.0-2 | DN-3.4-1 | SN-3.5-1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reinforcement of Short Column | |  |  |  | | | | | |  | |
| Cross-Section of Short Column | |  |  |  | |  | |  |  |  |  |
| Longitudinal or Diagonal Reinforcing Bar in Short Column | $\sigma_y$ | 332 | 369 | 369 | | 316 | | 354 | 308 | 369 | 316 |
| | $\sigma_u$ | 494 | 569 | 569 | | 454 | | 562 | 444 | 569 | 454 |
| | $\varepsilon_u$ | 29 | 20 | 20 | | 32 | | 19 | 32 | 20 | 32 |
| | $\varepsilon_{st}$ | —— | 1.8 | 1.8 | | 3.0 | | 1.6 | 2.7 | 1.8 | 3.0 |
| Concrete | ${}_c\sigma_B$ | 35.5 | 26.4 | 28.9 | 40.9 | 27.5 | 41.5 | 25.8 | 24.7 | 26.7 | 26.7 |

[Remarks] (1). Smooth Bars (13 ϕ and 19 ϕ) within the short column are coated by paraffin wax more than 1 mm in thickness.
(2). Thickness of steel tube is 4.5 mm.
(3). $\sigma_y$ = Yield strength (MPa)
(4). $\sigma_u$ = Tensile strength (MPa)
(5). $\varepsilon_u$ = Elongation (%)
(6). $\varepsilon_{st}$ = Strain at initiation of strain hardening (%)
(7). ${}_c\sigma_B$ = Compressive Strength (MPa)

the material properties used for those specimens.

Specimen, RC-3.4-2, in Table 1 has a R/C short column with conventional longitudinal (or parallel) and transverse reinforcement, while all of the short columns in other nine specimens are confined by a steel square tube with 4.5 mm thickness. Except that the short column in CF-3.4-2 has a parallel longitudinal Rebar arrangement, other eight short columns confined by a steel tube have special reinforcement by diagonal (or X-shape) bar arrangement as shown in Table 1. These eight specimens with diagonal bar arrangement are designated by a four symbol code such as DN-3.4-2 and SH-3.5-2. The first letter "D" or "S" denotes the deformed or smooth bar used for X-shape Rebars, and the second letter "N" or "H" represents that the normal or high strength of concrete is used for the specimens, respectively. The third and fourth numerals such as 3.4 and 2 show the total cross-sectional area of X-shape Rebars divided by gross area of the short column in percent, and height-to-depth ratio of the short column, respectively. On the surface of all the smooth bars located within the short column, paraffin wax more than 1 mm in thickness is coated in order to cut the bond between smooth bars and surrounded concrete perfectly. This is to minimize the bond deterioration caused by cracking of core-concrete within the steel tube and to prevent the local excessive elongation of the smooth bars when those are subjected to high tensile forces.

## 3 TEST SETUP AND INSTRUMENTATION

Test setup adopted in the present study is shown in Fig.2, where top- and bottom-girders of the specimen are fixed to the loading beam and reaction frame. Between loading beam and reaction frame, a pantograph is installed to prevent the out-of-plane deformation of the test specimen and to keep the top girder horizontally.

Alternately repeated lateral loads are applied by a double-acting hydraulic jack, whose longitudinal axis is always kept to be located at mid-height of the short column as shown in Fig.2. Since main objective of the present study is to develop a lateral-load resistant element composed of a R/C short column which is intended to place within the plane enclosed by precast beam and column members, any axial (or vertical) loads

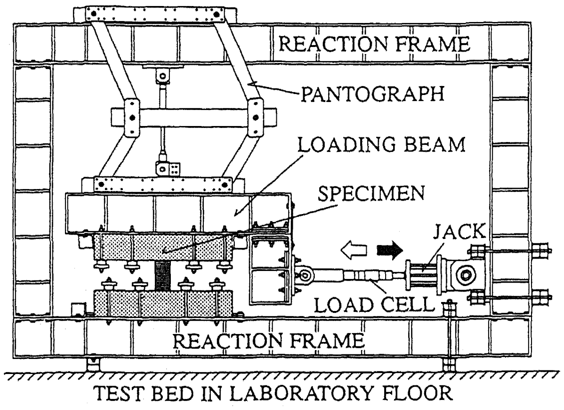


Figure 2. Test setup.

were not applied to all the specimens.

All the displacements including interstory drifts and elongation of the short column caused by cracking were measured by displacement transducers, and strains occurred in the reinforcing bars and steel tube were also measured by using electrical strain gages.

For all the test specimens, displacement-controlled procedure was adopted for loading program, where interstory displacement was gradually increased, and all informations measured during the loading reversals were sent to a personal computer and were processed simultaneously.

## 4 EXPERIMENTAL RESULTS AND DISCUSSIONS

All the Q-R relations obtained from the experiment are shown in Figs.3 through 7, where Q represents the lateral loads applied to the specimen and R is the deflection angle defined as the relative lateral displacement between top and bottom of the short column. By using the Q-R hysteresis loops shown in these figures, energy absorption capacity of each specimen was calculated. Results are compared in Fig.8, in which the area surrounded by each hysteresis loop is plotted against the corresponding displacement.

Summarizing the test results obtained;

(1). The R/C short column in RC-3.4-2 failed in brittle shear failure mode with poor deformability, and could not develop its ultimate flexural strength given by dashed lines in Fig.3(a).

(2). Shear failure did not occur in the short column in CF-3.4-2 and the column reached its ultimate flexural moment capacity given by dashed lines in Fig.3(b). This specimen showed excellent ductility, but had poor energy absorption capacity due to pinching caused by bond deterioration of the longitudinal Rebars (see Fig.8).

(3). In comparison with the RC- and CF-3.4-2 specimens, all other short columns with diagonal bar arrangement showed extremely excellent energy absorption capacities as is observed in Fig.8, because significant pinching phenomena did not occurred in their Q-R hysteresis loops.

(4). Hysteresis loops in Figs.4, 5 and 7 are more excellent than Fig.6, and especially in case of using deformed bars, any pinching does not occur (see Figs.4(a), 5(a) and 7(a)). This fact suggests that, by selecting appropriate bar size for diagonal Rebars, it is possible to disappear the pinching phenomena completely.

(5). In case of using larger bars, however, pinching phenomena again took place as can be seen in Fig.6, although ultimate lateral strengths increased apparently.

(6). Further research is needed to determine the most appropriate bar size for the diagonal reinforcement provided inside the steel tube.

(7). If smaller clearance than the present specimens is provided between smooth bar surface and concrete, then unstable region of the hysteresis loops in Figs.4(b), 5(b) and 7(b) would disappear.

(8). Difference in concrete strength did not have a large

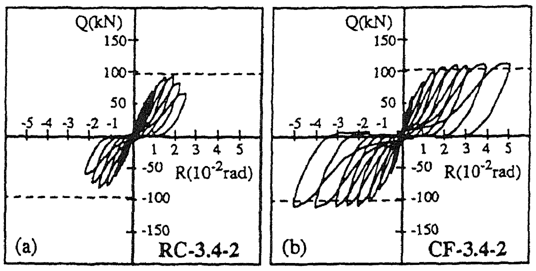


Figure 3. Q-R relations.

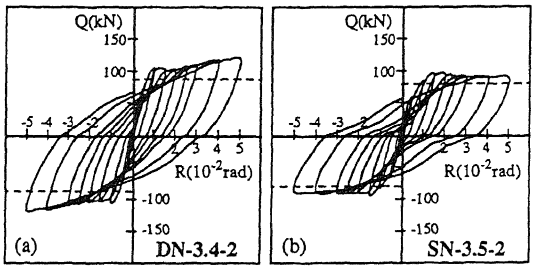


Figure 4. Q-R relations.

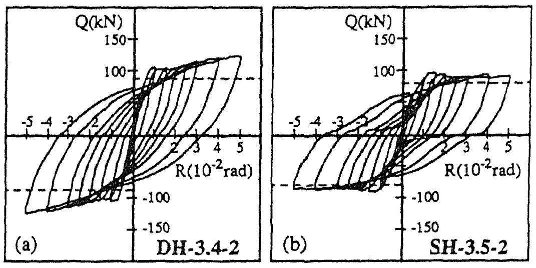


Figure 5. Q-R relations.

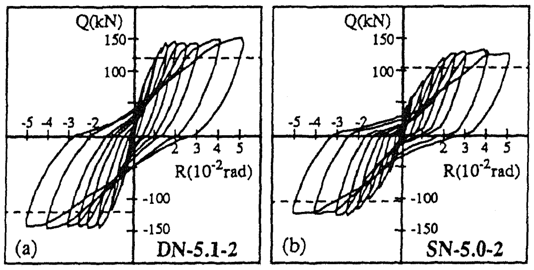


Figure 6. Q-R relations.

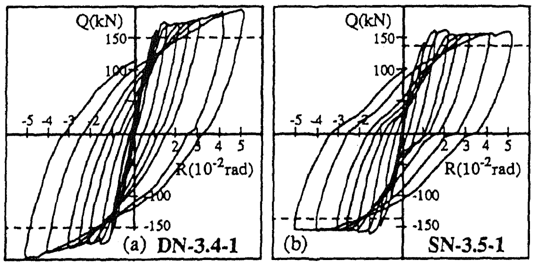


Figure 7. Q-R relations.

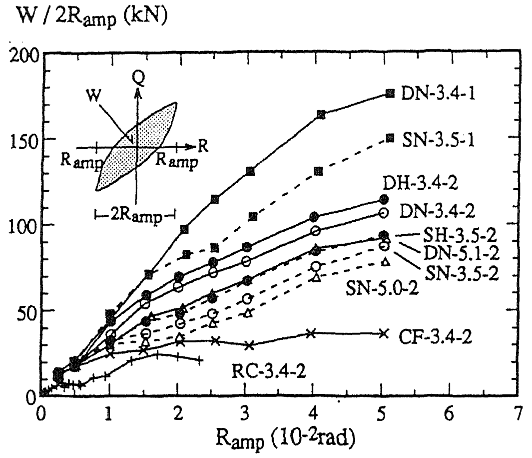


Figure 8. Energy absorption capacity.

effect on structural behavior of short column with diagonal bar arrangement (see Figs.4 and 5).

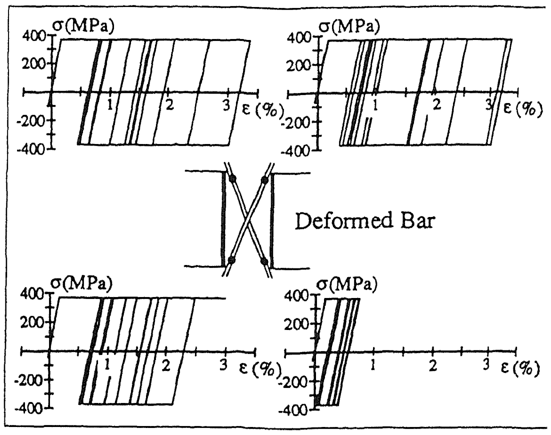
(9). Considerable difference in size and shape can be observed between hysteresis loops in Fig.4 and 7. This means that, by changing the shear-span ratio of the diagonally reinforced short column, ultimate strength and energy absorption capacity as well as stiffness can be easily controlled.

(10). Since mechanical properties such as yield strength and strain hardening were considerably different in deformed bars and smooth bars, difference in the structural behavior caused by these bars could not be discussed.

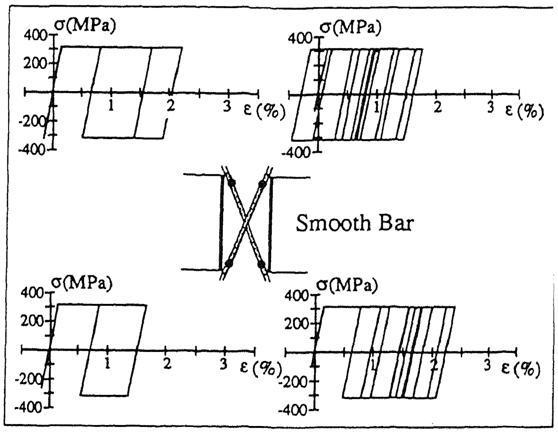
(11). Fig.9 shows typical results on stress($\sigma$)-strain($\varepsilon$) relations of diagonal bars calculated from measured strains. It can be understood from these figures that, during inelastic loading reversals, top and bottom of all the diagonal bars located within the steel tube are yielded alternatively in tension or compression. In addition, it can be noted that the deformed bars are subjected to more inelastic strain reversals than the smooth bars. Theoretical ultimate strengths shown by dashed lines in Figs.4 through 7 were calculated based on this test result, assuming that all lateral forces are carried only by diagonal bars and role of the concrete within the steel tube is only to prevent the buckling of diagonal bars. Good agreement between calculation and test results are observed from these figures, although theoretical values are slightly smaller than the experiments.

## 5 CONCLUSIONS

By placing main reinforcing bars diagonally, various types of reinforcing methods have been proposed for improving seismic behavior of R/C members. While it has been also demonstrated by authors that R/C short columns confined by a steel tube does not fail in brittle shear failure mode and can develop its ultimate flexural moment capacity. Herein, by combining a concrete filled steel tubular short column with diagonal bar arrangement method, a new aseismic element with high strength, excellent deformability and large energy absorption capacity was proposed.



(a) DH-3.4-2



(b) SH-3.5-2

Figure 9. Examples of stress-strain relations in diagonal bars. (Elastic-perfectly-plastic $\sigma$-$\varepsilon$ relation is assumed.)

## ACKNOWLEDGMENT

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