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EARTHQUAKE DAMAGE EVALUATION AND REPAIR TECHNIQUES OF R/C COLUMNS WITH ROUND BARS

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SUMMARY

Reinforced column specimens are designed under the 1962 AIJ R/C Building Code. They are once loaded to various deflection angles. The two dimensional deforming modes are discussed on these specimens. The specimens are repaired or strengthened according to their damage states. Shear reinforcement of some specimens are newly increased. The repaired/strengthened specimens show equivalent or larger strengths and ductilities compared with the original ones.

INTRODUCTION

The notorious 1968 Tokachi-oki earthquake forced the Architectural Institute of Japan (AIJ) to revise its R/C Building Code in 1971. However, there are still many buildings designed before this revision. This paper deals with R/C columns designed under the 1962 AIJ R/C Building Code (Ref. 1). The characteristics of such columns are as follow:
(1) Shear reinforcement ratio can be as low as p_w = 0.15 % except in hinging regions.
(2) The flexible length of these columns are often shortened by monolithically cast spandrel walls, which are usually neglected in structural design.
(3) Round bars are usually used for both main and shear reinforcement.

Tested are eight R/C columns under constant axial force and anti-symmetric cyclic shear-bending up to various degrees of damage. Then, these columns (original specimens) are repaired or strengthened according to the degrees of damages. Firstly discussed will be the relationship between the deflection history and the transverse elongation due to shear cracks, which enables damage evaluation after earthquakes. Secondly discussed will be the validity of the repairing or strengthening techniques, which include the calculation of how much the shear reinforcement must be increased to provide sufficient ductility.

EXPERIMENTS OF ORIGINAL SPECIMENS

The tested specimens are listed in Table 1. Details of the original specimens are shown in Fig. 1. In the specimens' names, the number after S (2, 1 or 1/2) indicates shear span ratio. The letter of O or R indicates the original or repaired specimen. The specimens with shear span ratios 1 and 1/2 model the columns shortened by monolithically cast spandrel walls neglected in structural design. Accordingly, shear reinforcement ratio of these specimens is p_w = 0.15 %.

The compressive strength of concrete for the specimens RCC-S2-1-0, RCC-S2-2-0, RCC-S1-1-0 and RCC-S1-2-0 is 117 kgf/cm^2 (10 cm x 20 cm cylinder cured in air). The compressive strength of concrete for the specimens RCC-S1-3-0, RCC-S1-4-0, RCC-S1/2-1-0 and RCC-S1/2-2-0 is 157 kgf/cm^2. The yield strengths of the longitudinal and transverse reinforcement are 3.1 and 3.3 tf/cm^2, respectively. The loading apparatus is shown in Fig. 2. The axial forces are constantly kept at N = 12 tf ($N/bDF_c = 1/8$).

Table 1 List of tested specimens and repairing methods

Original Specimen	Name	RCC-S2-1-0	RCC-S2-2-0	RCC-S1-1-0	RCC-S1-2-0	RCC-S1-3-0	RCC-S1-4-0	RCC-S1/2-1-0	RCC-S1/2-2-0
	Maximum Deflection	0.08	0.02 (Rad.)	0.08 (Rough Values)	0.03	0.03	0.02	0.08	0.02
	Failure Mode	Flexural Failure		Shear Failure					
Repaired Specimen	Name	RCC-S2-1-R	RCC-S2-2-R	RCC-S1-1-R	RCC-S1-2-R	RCC-S1-3-R	RCC-S1-4-R	RCC-S1/2-1-R	RCC-S1/2-2-R
	Newly Arranged Hoops	-----	-----	6φ - @30 (mm) Pw=0.75%	6φ - @30 0.75%	-----	6φ - @30 0.75%	6φ - @15 1.5%	-----
	Repairing Method	①	①	③	①+②	①	②	③	①

① Injecting epoxy resin into the cracks. Removing the crushed concrete off, and replacing it with epoxy resin mortar.

② Removing the cover concrete off. Arranging new hoops, and replacing the cover concrete with expansive mortar by pressure process.

③ Removing the whole concrete off, and reforming the main bars deformed. Arranging new hoops, and inserting expansive mortar.

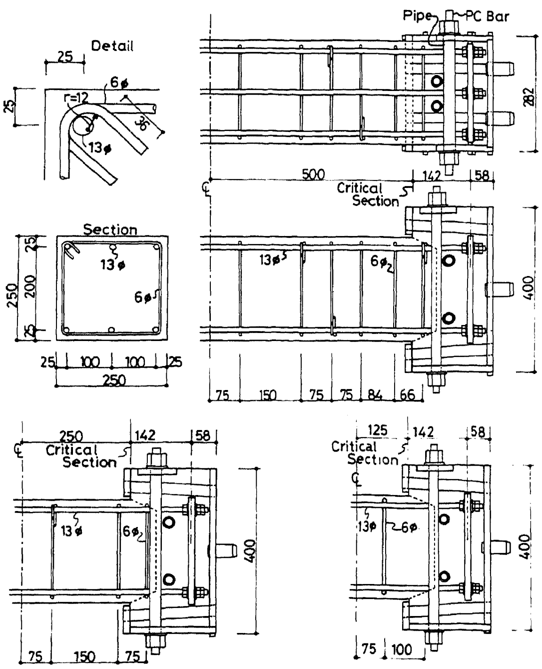


Fig. 1 Reinforcing details of original specimens

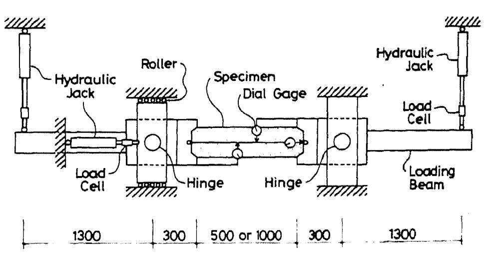


Fig. 2 Loading apparatus

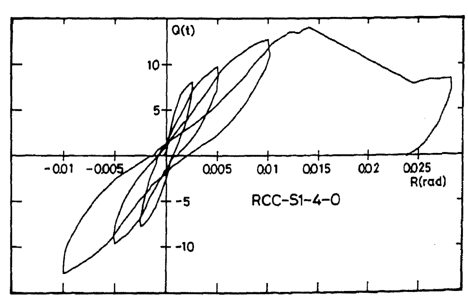
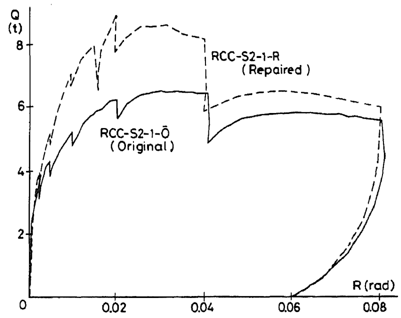
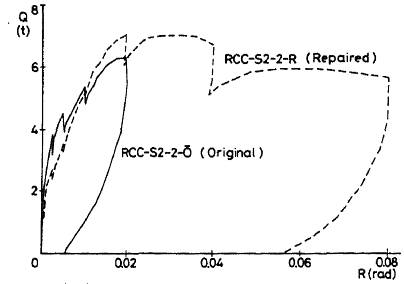


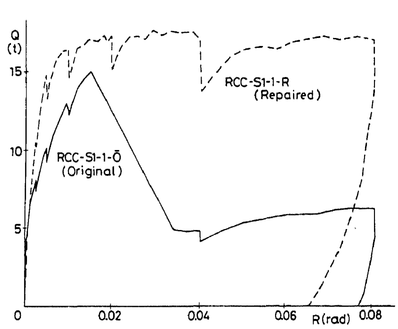
Fig. 3 Q-R (load-deflection) relation of RCC-S1-4-0



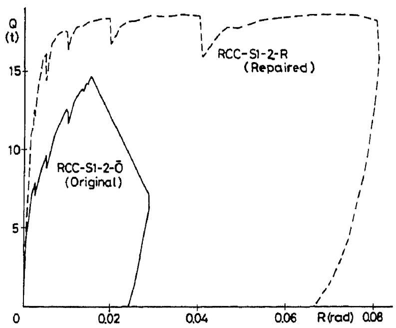
(a) Specimen RCC-S2-1-*



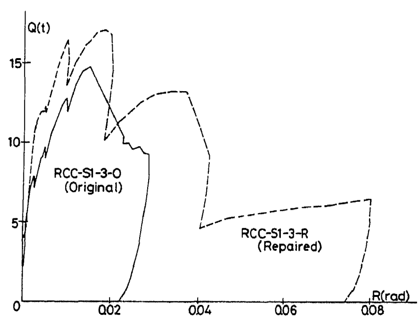
(b) Specimen RCC-S2-2-*



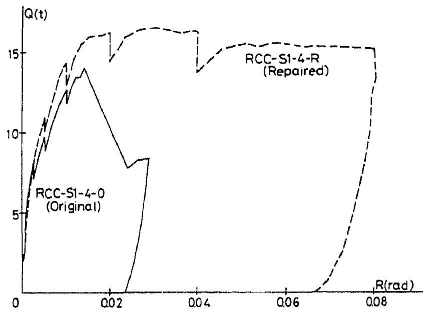
(c) Specimen RCC-S1-1-*



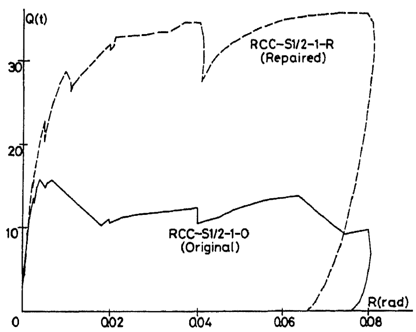
(d) Specimen RCC-S1-2-*



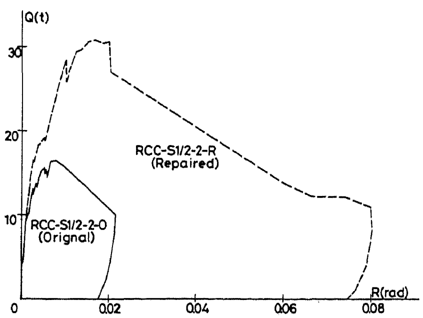
(e) Specimen RCC-S1-3-*



(f) Specimen RCC-S1-4-*



(g) Specimen RCC-S1/2-1-*



(h) Specimen RCC-S1/2-2-*

Fig. 4 Envelopes of Q-R relation of specimens

The shear force - deflection angle (Q-R) relation of one of the original specimen, RCC-S1-4-0, is shown in Fig. 3. The envelopes of Q-R relations of all the specimens are shown by the solid curves in Fig. 4. The typical failure patterns of the specimens are shown in Photos. 1-3. The bond stresses of the longitudinal bars calculated through the observed strain gage data were almost zero (less than $F_c/50$) when the strengths of the specimens are attained. The observed strengths of the specimens with shear span ratios 2 and 1 exceeded the flexural strengths calculated ignoring the bond of the longitudinal bars, though the specimens with shear span ratio 1 failed in shear after the strength.

The two dimensional deformation of the original specimens was measured with contact gage according to Ref. 2. The dark spots in Photos. 1-3 constituting square grids show the location of the contact points. The measured deformation is decomposed into five modes shown in Fig. 5(a). The contributions of these modes to the deflection angle R are shown in Fig. 5(b). Notable is that the mode SR diminishes when the deflection angle R is positive. As shown in Fig. 6, both the modes ST and SN induce transverse elongation:

$$e = L.R_s \tag{1}$$

where L is the clear span length of the column, and R_s is the deflection angle due to the modes ST and SN. Consequently, the transverse elongation represents the maximum shear deformation in a column with χ shaped shear cracks. This elongation can be roughly estimated after earthquake through investigation of cracks. Relation between the transverse elongation at the center of the clear span and the deflection angle (e-R) is shown in Fig. 7. The following two facts in this figure supports the statements above.

(1) The broken line (note L = 500 mm) is parallel to the measured data at the loading steps 224-225-228-321 (refer the numbers in the ellipses).

(2) The measured elongations at the loading steps 228 through 299 are almost constant.

The two dimensional deformation of the specimen RCC-S1/2-1-0 was also measured and decomposed into five modes shown in Fig. 8(a). The contributions of these modes to the deflection angle R are shown in Fig. 8(b). Notable is that the

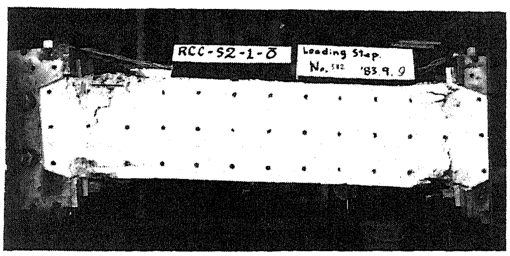


Photo. 1 RCC-S2-1-0 at R = -0.06 rad

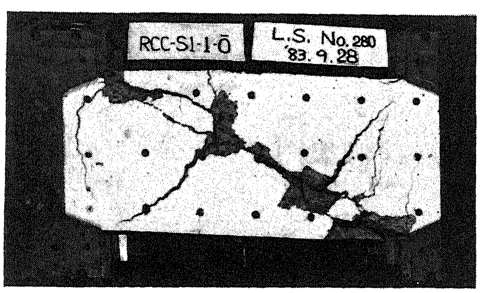


Photo. 2 RCC-S1-1-0 at R = -0.04 rad

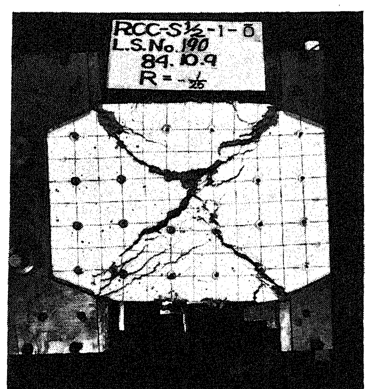


Photo. 3 RCC-S1-1-0 at R = -0.04 rad

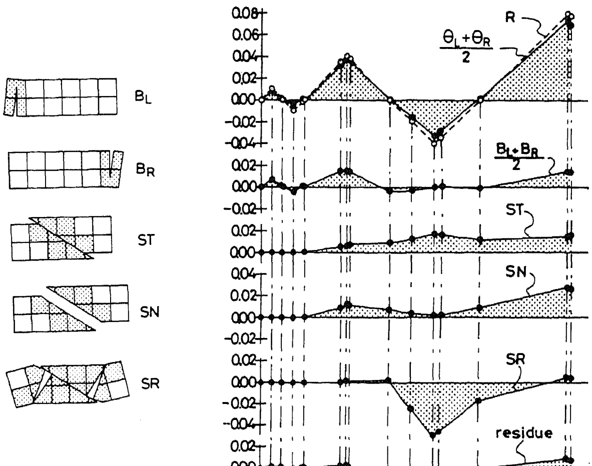
modes ST.R and SN.R never diminish when the deflection angle R is positive. The transverse elongation therefore represents the sum of the positive and negative maximum shear deformation (R_{ps} and R_{ns}) as follows:

$$e = L.(R_{ps} + R_{ns}) \tag{2}$$

Relation between the transverse elongation at the center of the clear span and the deflection angle is shown in Fig. 9, where (R_p + R_n) represents the sum of the positive and negative maximum deflection angle till that loading stage. This figure supports the statements above.

EXPERIMENTS OF REPAIRED/STRENGTHENED SPECIMENS

The original specimens were repaired or strengthened as shown in Table 1. The



(a) Deforming modes (b) Decomposition of deflection angle

Fig. 5 Two dimensional deformation of RCC-S1-1-0

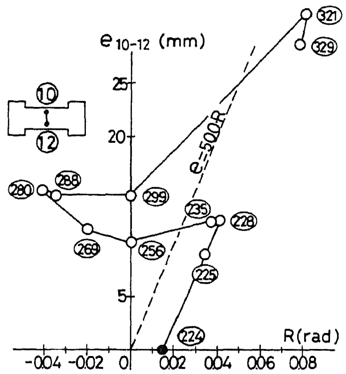
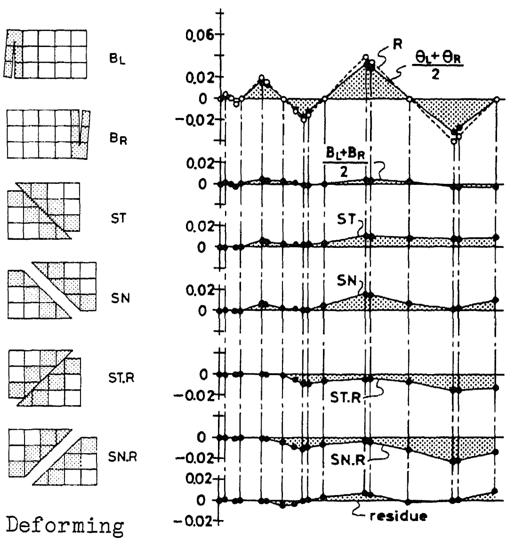


Fig. 6 Transverse elongation - deflection angle (e-R) relation of RCC-S1-1-0



(a) Deforming modes (b) Decomposition of deflection angle

Fig. 7 Two dimensional deformation of RCC-S1/2-1-0

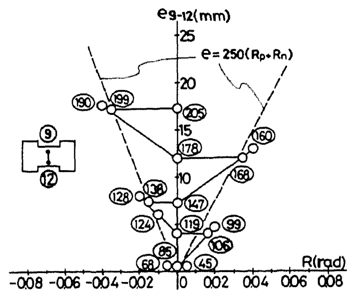


Fig. 8 Transverse elongation - deflection angle (e-R) relation of RCC-S1/2-1-0

repairing/strengthening method was selected according to the specimens' damage states. The strength of the injected epoxy resin was 721 to 826 kgf/cm^2 in compression and 397 to 428 kgf/cm^2 in tension. The strength of the epoxy resin mortar was 761 to 921 kgf/cm^2 in compression and 285 to 299 kgf/cm^2 in tension. The strength of the expansive mortar was 548 to 604 kgf/cm^2 in compression (5 cm x 10 cm cylinder cured in air). The newly arranged hoop shown in Fig. 12 was made of the same bar as that for the original specimens. The amount of newly arranged hoops of the specimens was decided so that the strengthened specimens failed in flexure. Ultimate shear strength of the specimens with shear span ratio 1 was calculated according to the modified Arakawa's empirical equation (Ref. 3). That of the specimen with shear span ratio 1/2 was calculated assuming that the total shear force be carried by the shear reinforcement (in this case, the modified Arakawa's equation requires more shear reinforcement than this assumption).

The repaired or strengthened specimens were tested under the same condition and the same amount of axial load. The envelopes of the load-deflection curves are shown with broken lines in Figs. 13-20. Because the crushed hinge-region of the specimen RCC-S2-1-0 (Fig. 13) was replaced by the stronger expansive mortar, the failure of the repaired specimen, RCC-S2-1-R, occurred mainly at the end of the unrepaired region. This increased the flexural strength of the specimen as shown in Fig. 13. The specimen RCC-S2-2-R in Fig. 14 showed smaller elastic stiffness than the original. This is attributable to the fact that the width of the cracks in the specimen was so narrow that the injection of the epoxy resin was difficult (and probably incomplete). The specimens with newly arranged hoops (Figs. 15, 16, 18 and 19) attained strengths larger than the calculated flexural ones as well as large ductilities. This indicate that the calculation on the amount of hoops in the preceding paragraph was adequate. The other specimens, RCC-S1-3-R and RCC-S1/2-2-R without increase of hoops attained at least equivalent seismic capacities after the repairing/strengthening.

CONCLUSIONS

(1) Transverse elongation of a column with X shaped cracks represents maximum shear deformation of the column during earthquake (see Eq. 1).
(2) Transverse elongation of a column with X shaped cracks represents the sum of positive and negative maximum shear deformation of the column during earthquake.
(3) A lightly damaged column can be repaired with epoxy resin and epoxy resin mortar. Elastic stiffness of the repaired column, however, may be smaller than that of the original.
(4) A column failed in shear can get larger strength and ductility providing additional hoops. A column with shear span ratio 1/2 can have enough strength and ductility if its shear reinforcement can carry the total flexural strength.

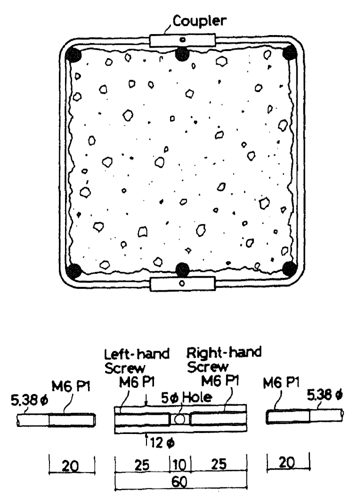


Fig. 9
Hoop for strengthening

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