RESIDUAL AXIAL CAPACITY AND DAMAGE RESTORABILITY OF REINFORCED CONCRETE COLUMNS AFTER EARTHQUAKE

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SUMMARY

Deterioration of axial strength of flexural column was analyzed by inelastic moment-curvature analysis of the section using fiber-model. In the analysis, after cyclic loading to the section, the axial strain uniformly increased to obtain the axial strength. The analysis demonstrated significant deterioration of axial strength before ultimate limit state defined as the state that axial load capacity decreased to the level of long-term axial load. Experimental program was executed not only to observe the phenomenon but also to study the effect of repair after the deterioration of axial strength. About a half scale column specimens were loaded in the axial direction after cyclic lateral loading. It was found that the deterioration of axial capacity was large under large long-term axial load or large compressive varying axial load. Simple repair methods were applied to specimens damaged due to lateral loading; i.e. replacing crushed cover concrete to rapid hardening type cement mortar with same strength as the original concrete or injecting epoxy into cracks. Both lateral stiffness and strength of repaired column whose axial strength deteriorated by the original lateral loading were lower than those of original one. Sequential moment-curvature analysis including original and post-repair loading indicated that softening of a part of core concrete during original loading significantly influenced on the performance after repair.

INTRODUCTION

Evaluation of residual capacity and restorability of structures or elements after specified earthquake in the site is important in performance based seismic design. Ultimate state of reinforced concrete columns has been often defined as a state just vanishing of axial capacity to sustain the live and dead loads (long-term load) in many researchers. However, the axial capacity of column subjected to seismic loading must gradually decrease as damage develops. The relation between the latent decrease of axial capacity of columns and restorability of them was investigated analytically and experimentally to contribute to the performance based seismic design.

PRELIMINARY ANALYSIS

2.1 Analytical Method

Deterioration of axial capacity in column after cyclic lateral loading was studied by elementary inelastic analytical method of the section; i.e. fiber model. As well known, by the method, after the section was divided into fiber-segments parallel to the neutral axis, assuming Bernoulli-Euler's hypothesis, inelastic moment vs. curvature relationship was analyzed based on the assumed uniaxial stress strain relationship of concrete and longitudinal reinforcement [Fujii, 1973]. Influence of shear and bond slip between steel and concrete was neglected. Assumed uniaxial stress strain relationship of concrete and steel are shown in Figure 1. In the concrete model, the difference of compressive strength and softening characteristic between core concrete and cover

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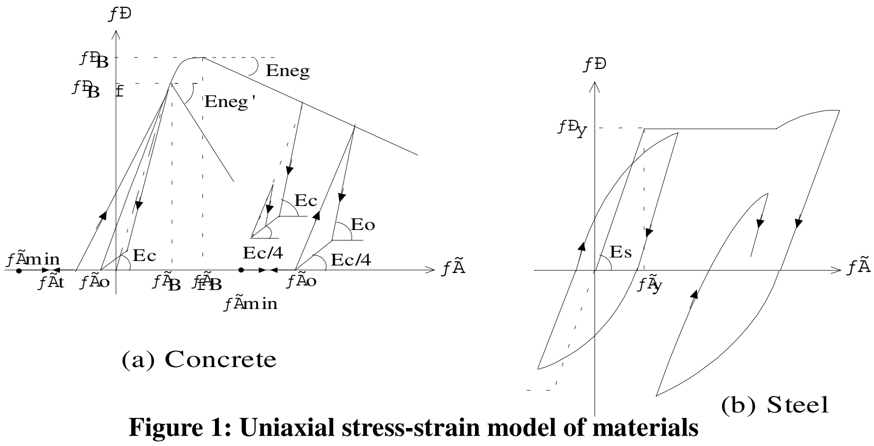

Figure 1: Uniaxial stress-strain model of materials

concrete was considered. In the steel model, strain hardening and Bauschinger effect were included. After optional cyclic loading, both moment and curvature were converged to the original point, and then the strain vertical to the section were increased uniformly to obtain the maximum axial strength.

2.2 Example of Analysis

A column at the first story in the twelve stories office building which was designed according to the design guidelines for earthquake resistant reinforced concrete buildings based on ultimate strength concept of AIJ, was chosen as an example of analysis. Deterioration of axial strength of the column after lateral cyclic loading of a constant amplitude is shown in Figure 2. The horizontal axis represents axial force ratio which was defined as the ratio of long-term load to the original axial strength of a column including the contribution of longitudinal reinforcement. The vertical axis ν represents ratio of residual axial strength which was defined as the following equation.

$$\nu = (N_{max}' - N_L) / (N_{max} - N_L) \qquad (1)$$

where, N_{max}: original axial strength of column,
N_{max}': axial strength of column after optional lateral loading, and
N_L: long-term axial load

When the column has lost the ability to sustain the long-term axial load, the value of ν just reaches zero, which means the ultimate limit state of the column. Figure 2 shows significant characteristics of residual axial strength. Under cyclic lateral loading, the axial strength deteriorated above a certain axial force ratio. The deterioration depended on the axial force ratio, the lateral deformation amplitude, and numbers of loading reversals. In the analysis, softening of a part of core concrete influenced on the deterioration strongly. Experimental program was executed not only to observe the phenomenon but also to study the effect of repair after the deterioration of axial strength.

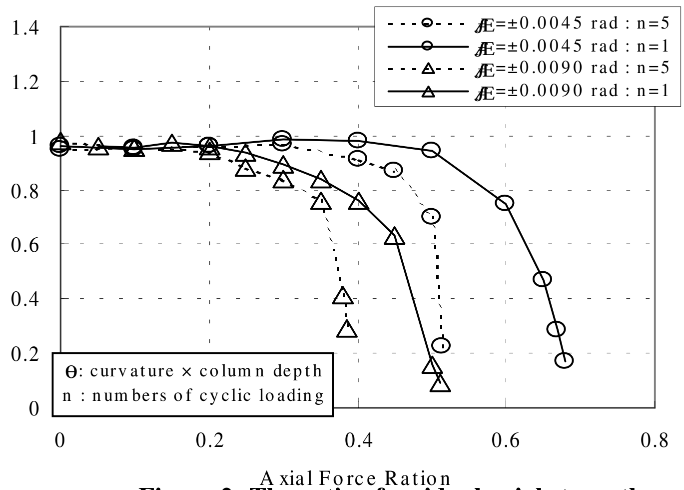

Figure 2: The ratio of residual axial strength

3. TEST OF COLUMNS

3.1 Testing Program

Total eight column specimens A1 – A8 were tested [Kitada, 1998][Watanabe, 1999]. All specimens were designed to fail in flexure and had a uniform section of 300 x 300 mm as shown in Figure 3. The shear span to depth ratio was 2.5 in specimens A1 – A4 and 2.0 in specimens A5 – A8. High confinement was given to specimens A5 – A8. Main parameters of test were damage level by controlling axial load and maximum lateral deformation, and repair methods as listed in Table 1. All specimens were subjected to antisymmetric bending reversals by loading apparatus shown in Figure 4. Constant axial load of two levels was applied to specimens A1 – A4, while varying axial load was applied to specimens A5 – A8 as the same rule shown in Figure 5. Specimens A1 and A2 with different axial load level were loaded in axial direction after corrected residual deformation by original lateral loading in order to observe the deteriorated axial strength. Specimens A3 and A4 which were subjected to the same loading condition as specimens A1 and A2 respectively, were repaired after original loading by simple repair method; i.e. replacement of damaged cover concrete to rapid hardening type cement mortar. Post-repaired specimens A3R and A4R were reloaded to investigate the restorability after deterioration of axial strength by the original lateral loading. The constant axial load was maintained during repair work and

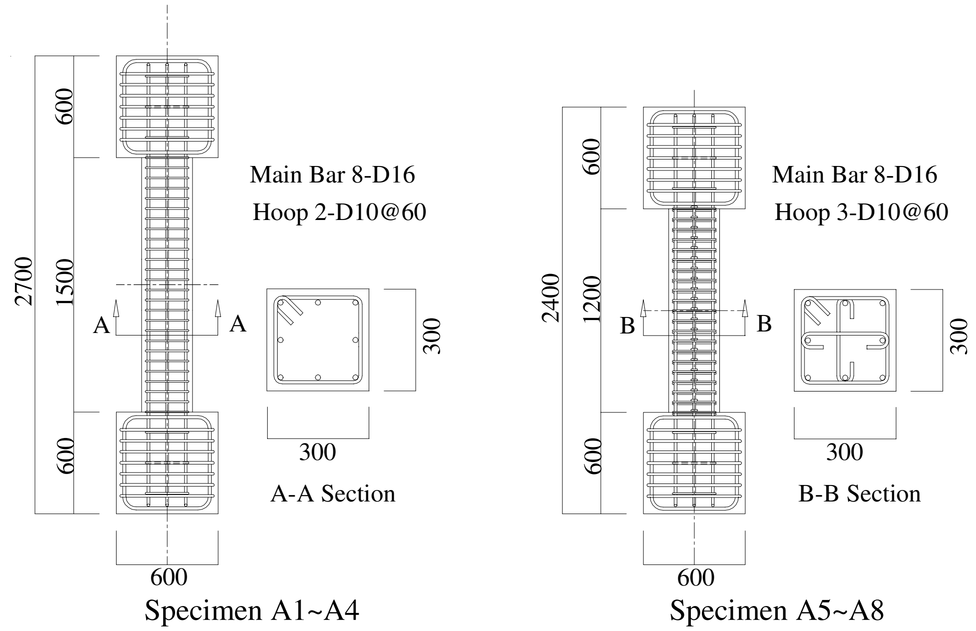

Figure 3: Outline of specimens

Table 1: Parameters of test

Specimen	Main Bar	Hoop	Pw (%)	Axial Load	Maximum Deformation Angle(rad.)		Repair Methods		Axial Loading
					Original	Post-Repair	Replacing Cover Concrete	Injecting Epoxy Resin	
A1	8-D16	2-D10 @60	0.79	$0.2\sigma_B$	1/33				Applied
A2				$0.35\sigma_B$					Applied
A3/A3R				$0.2\sigma_B$		1/33	Applied		Applied (A3R)
A4/A4R				$0.35\sigma_B$		1/33	Applied		
A5/A5R		3-D10 @60	1.19	$0.05\sigma_B$~$0.50\sigma_B$ ($0.25\sigma_B$)	1/33	1/100	Applied	Applied	Applied (A5R)
A6					1/100				Applied
A7/A7R					1/100	1/100	Applied		Applied (A7R)
A8/A8R					1/100	1/33	Applied	Applied	Applied (A8R)

Pw : Shear Reinforcement Ratio σ_B : Concrete Compressive Strength by Cylinder Test

Table 2: Material properties

A1~A4

	Concrete	Steel (yield)		Repair Mortar
	(comp.)	D16	D10	(comp.)
Stress (N/mm^2)	46.2	328	365	35.6

A5~A8

	Concrete	Steel (yield)		Repair Mortar	Epoxy Resin
	(comp.)	D16	D10	(comp.)	(comp.)
Stress (N/mm^2)	46.2	387	379	46.9	26.5

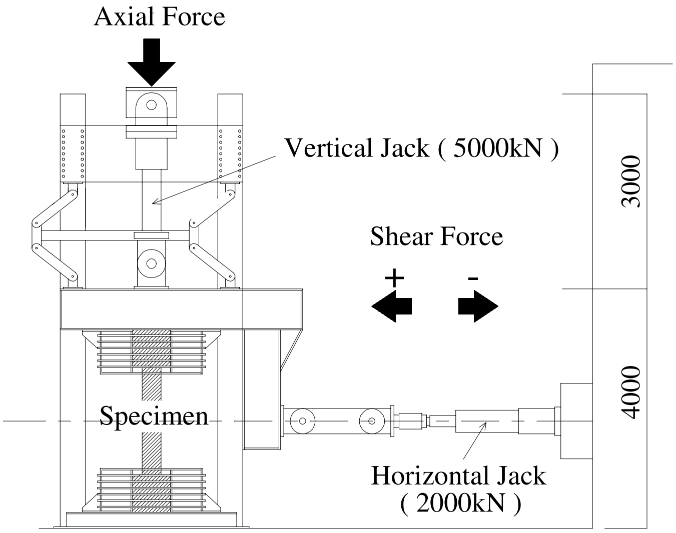

Figure 4: Loading apparatus

the curing to simulate actual repair condition. Specimens A5, A7, and A8 were also repaired after original lateral loading by replacing of damaged cover concrete to rapid hardening type cement mortar or injecting of epoxy resin into concrete cracks or both. Constant axial load was also maintained during repair work in these specimens. Specimen A6 and repaired specimens A5R, A7R, and A8R were loaded in axial direction after corrected residual deformation by the original or post-repaired lateral loading to investigate the axial strength. Material properties of concrete, reinforcement, and repair materials are listed in Table 2. In addition to the column test, prism specimens with same dimensions and materials as the column specimens were tested to obtain the uniaxial stress strain relationship of confined and unconfined concrete.

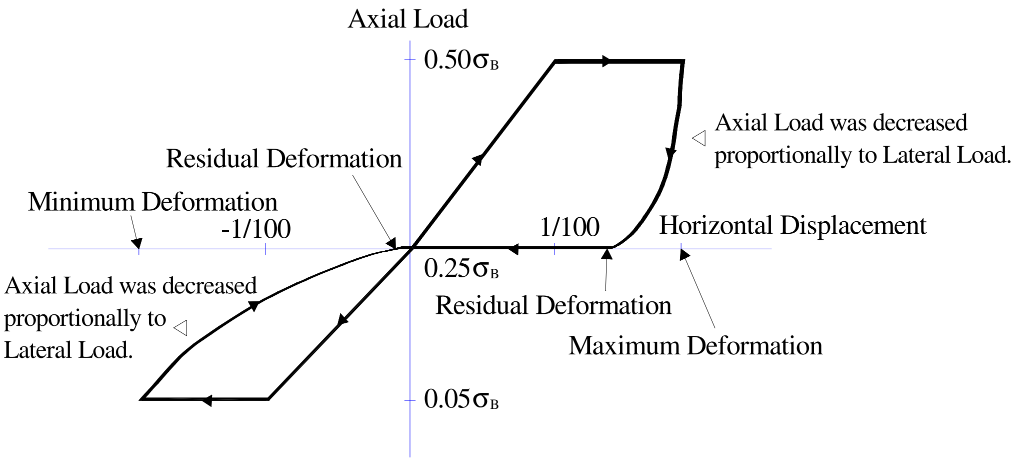

Figure 5: Rule of varying axial load

3.2 Outline of Test Results

In all specimens, cracks or crush of cover concrete concentrated in both ends of column within the length of the depth, demonstrating flexural damage by the original loading. Restoring force characteristics of specimens under constant axial load A3, A3R, A4, and A4R are shown in Figure 6. The P-Δ effect by the axial load was removed in the relationship. Stiffness and strength significantly deteriorated after repair in both specimens. Especially, specimen A4R which was subjected to higher axial load reached to the ultimate limit state and lost the ability to sustain the constant axial load at the final loading cycle. Restoring force characteristics of specimens under varying axial load are shown in Figure 7 after removing the P-Δ effect. In these specimens, stiffness after repair deteriorated in positive loading direction with increasing of axial load, especially, in specimen A5R in which the damage of concrete was significantly large during the original loading, the deterioration was remarkable. In negative loading direction with decreasing of axial load, the deterioration in stiffness and strength was observed to be small. The ratios of lateral strength after repair to the original one at the peak of each amplitude are shown in Figure 8. In the Figure, the ratios at the peak of +5 cycle and +8 cycle of specimen A5, which were equivalent

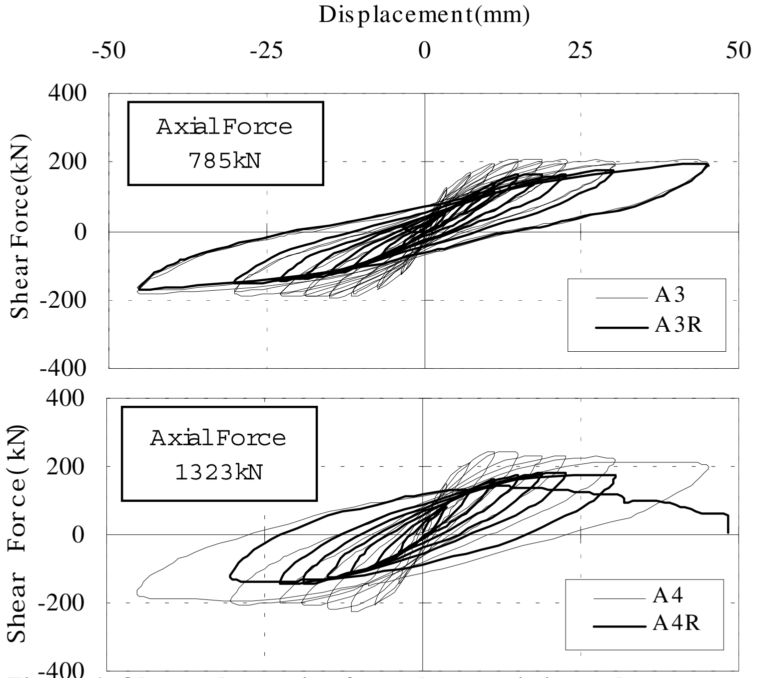

Figure 6: Observed restoring force characteristics under constant axial load

to the case with no repair, were also plotted. The strength in positive loading direction has not restored to the level of original loading in any repair case. However, the ratios of specimen A8R indicated that the deterioration was the smallest when the both repair methods were applied.

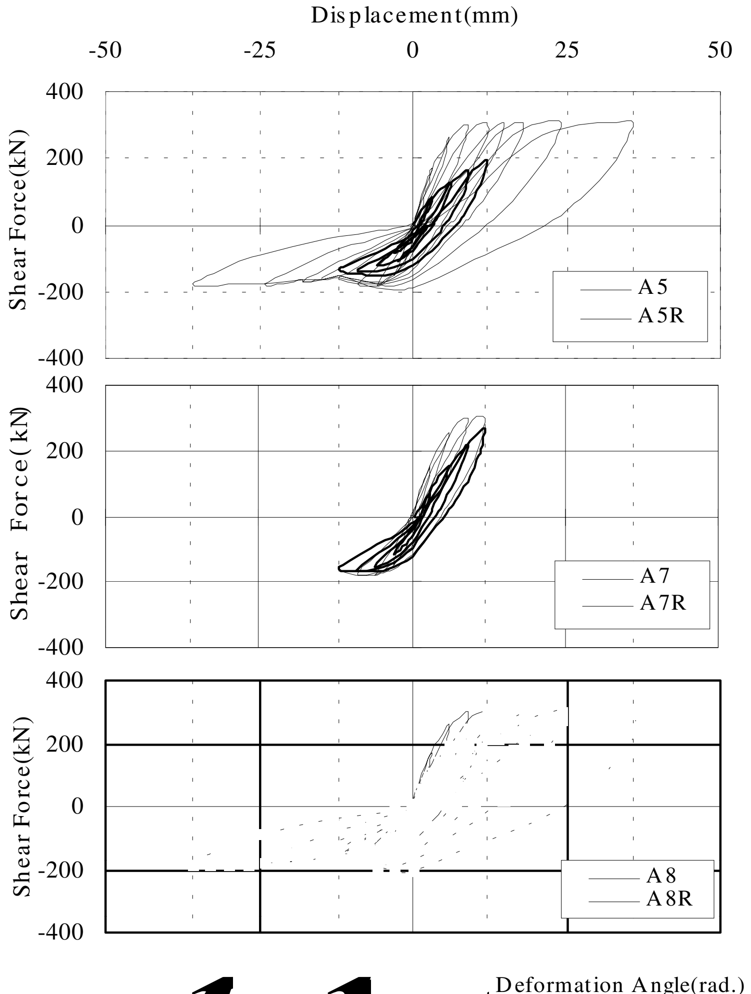

Figure 7: Observed restoring force characteristics under varying axial load

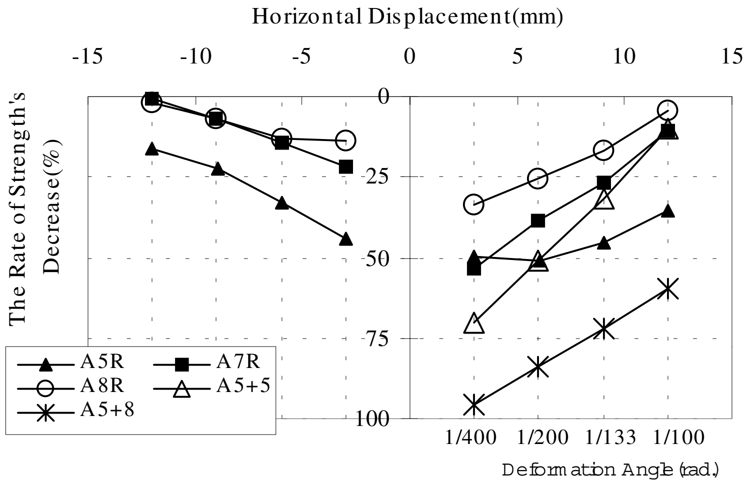

Figure 8: Decreasing ratio at peak strength

4. RESUDIAL AXIAL STRENGTH AND RESTORABILITY

4.1 Residual Axial Strength of Specimens

According to the procedure described in the chapter 2, residual axial strength of column specimens was analyzed based on the uniaxial stress strain relationship of confined core concrete and unconfined cover concrete obtained from the uniaxial compressive test of prism specimens. Example of the uniaxial models [Nakatsuka, 1989] used in the analysis is shown in Figure 9 comparing with test results of prism specimens. The curvature in the analysis was translated to the deformation of the specimen assuming that the curvature distributed uniformly along the height of column ends within the length equivalent to the column depth. Analyzed the relationship between axial force ratio and the ratio of residual axial strength ν for specimens A1 – A4 is shown in Figure 10. The test results obtained from axial loading after lateral cyclic loading of specimens A1 and A2 are also plotted in the Figure. The decrease in the ratio of residual axial strength was larger in the analysis than the test result. However, the remarkable decrease under the large axial force ratio was also observed in the test. It should be noted that the

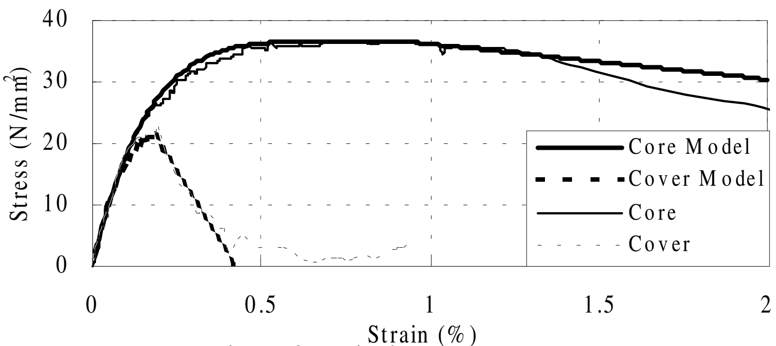

Figure 9: Uniaxial concrete model

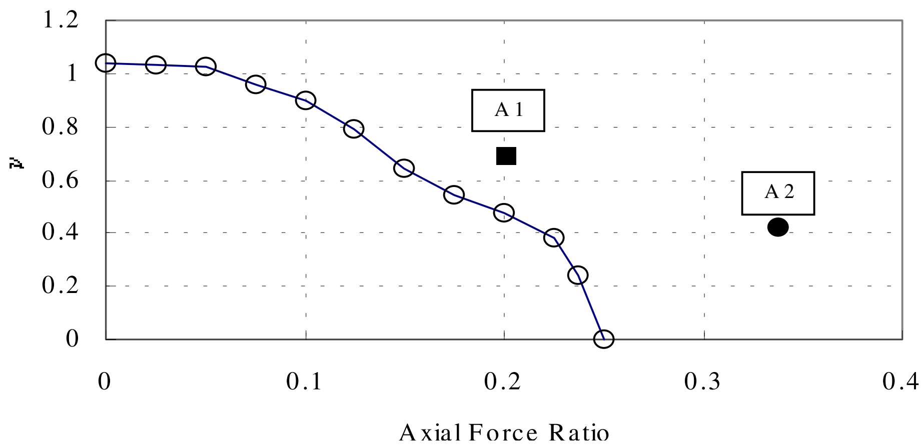

Figure 10: Residual axial strength under constant axial load

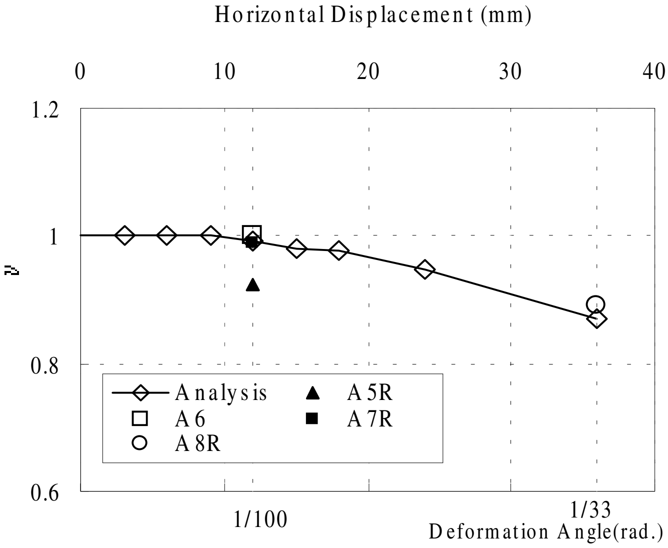

Figure 11: Residual axial strength under varying axial load

ratios of residual axial strength of specimens A3 and A4 were judged to have decreased to the same levels as specimens A1 and A2 respectively and the restorability of specimen A4R was lower than that of specimen A3R. The restorability related strongly to the residual axial strength. The ratios ν of specimens A6, A5R, A7R, and A8R are plotted together with analytical result in Figure 11. The ratio decreased even with high confinement. In specimen A5, the ratio was judged to have decreased about 0.9 and to have not restored to the original level by the repair because the ratio of specimen A5R was almost equal to that of specimen A8R. Deterioration in lateral stiffness and strength was remarkable in specimen A5R.

4.2 Analysis of Restorability

Restoring force characteristics of specimens under varying axial load was analyzed including post-repaired lateral loading by the procedure described in the chapter 2. The curvature in the analysis was translated to the deformation of the specimen assuming distribution of the curvature along the height. In the test, the repair work was conducted under constant axial load to the specimens. Assumption of linear distribution of strain in the section was impossible to be applied in the analysis of the post-repaired loading because of existing no axial strain in the new material formed instead of damaged cover concrete and existing axial strain corresponding to the constant axial load in the core concrete and longitudinal reinforcement at the beginning of post-repaired loading. Therefore, in the analysis of post-repaired loading, linear distribution of incremental strain was assumed after initializing the characteristics of cover concrete. Results of sequential analysis including original and post-repaired loading are shown in Figure 12. Deterioration of lateral capacity in increasing of axial load was well

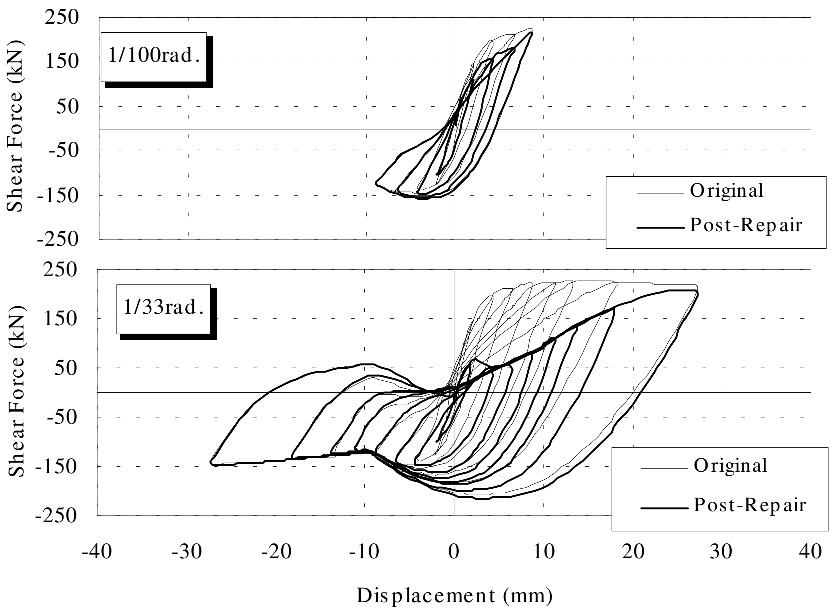

Figure 12: Analyzed restoring force characteristics

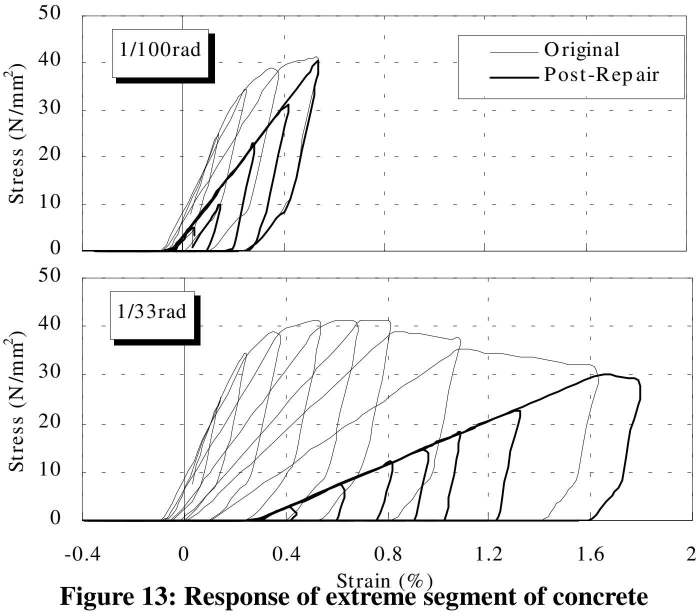

Figure 13: Response of extreme segment of concrete

demonstrated especially in case of large amplitude corresponding to specimen A5R. Responses of the extreme outer segment of core concrete subjected to compression during positive loading are shown in Figure 13. Deterioration of stiffness due to original loading was observed in post-repaired loading. It should be noted that the deterioration was remarkable when the response reached the softening range during original loading. Decreasing of residual axial strength and restorability of column member was judged to be caused by the deterioration of core concrete. In order to maintain the performance to resist vertical and lateral load after earthquake, it is necessary that the response of core concrete is controlled not to reach the inelastic range.

5. CONCLUSIONS

Residual axial strength and restorability of flexural reinforced concrete column after cyclic lateral loading were investigated analytically and experimentally. The following conclusions were obtained.

(1) Latent deterioration of axial capacity of reinforced concrete column subjected to seismic loading was observed experimentally even before the ultimate limit state. The ratio of residual axial strength was smaller in cases of the larger long-term axial load. The phenomenon was well predicted by the inelastic moment-curvature analysis using fiber model.
(2) The performance after simple repair replacing damaged cover concrete to new one or injecting epoxy into cracks deteriorated proportionally to the decrease of the ratio of residual axial capacity due to original loading. In case of being subjected to varying axial load, the deterioration of member stiffness was observed in compressive varying axial load even before the decrease of the ratio.
(3) The modified inelastic moment-curvature analysis clarified that the reason of the remarkable deterioration after repair was the softening of a part of the core concrete during the original loading. It is necessary that the response of core concrete is controlled not to reach the inelastic range.

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