INFLUENCES OF LOADING EXCURSIONS ON RESTORING FORCE CHARACTERISTICS AND FAILURE MODES OF REINFORCED CONCRETE COLUMNS

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SYNOPSIS

Presented is a brief summary of experimental study on restoring force characteristics and failure modes of reinforced concrete columns subjected to constant axial load and cyclic lateral load. In this study, the four kinds of loading excursions, controlled by lateral displacement, were adopted for eight series of test specimens to obtain the characteristics of restoring force and failure. The following problems are discussed emphasizing the behaviors after yielding. 1) The relation between the failure mode and loading excursion. 2) The relation between the envelope curve and loading excursion. 3) The relation between the equivalent viscous damping factor and loading excursion.

INTRODUCTION

Many experimental researches have been performed to investigate strengths, deformations and failure modes, etc., of reinforced concrete members under cyclic forces for modeling the restoring force characteristics and proportioning of them. However, in almost test data, the number of load reversals was not so many and various arrangements of loading excursions have been planed by every researcher's experiences. Therefore, these test data are not so available to discuss on the inefluences of loading excursions. Moreover, on dynamic response analysis using Bi-linear or Degreeding-Tri-linear, etc., the restoring force characteristics not influenced by the loading excursions such as displacement amplitude and the number of load reversals in previous stage were used.

In view of these points, a series of loading tests of reinforced concrete columns were conducted to investigate the influences of loading excursions on restoring force characteristics and failure modes.

These experimental tests were carried out, as a part of the national projects on Earthquake Resistant Characteristics of Reinforced Concrete Columns.[1)]

TEST SPECIMENS

An example of test specimens used in this series tests is shown in Fig. 1. The test specimens with 25x25 cm cross-section are classified in eight series by the combination of shear-span ratio, longitudinal reinforcement ratio, web reinforcement ratio, and axial force ratio. These parameters of test specimens are shown in Table 1. The combinations of these parameters are expected to result the following failure modes; flexural compression, shear-compression, shear-tension, diagonal tension and bond-splitting failure.

The mechanical characteristics of materials are shown in Table 2.

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TEST PROCEDURE

To decide the loading excursions, the relation between the displacements and the number of reversals on dynamic response analysis of single-degree of freedom were statistically investigated changing the parameters of restoring force characteristics and seismic waves.[2] From its response analysis, the following results were obtained. 1) The response displacements which exceed the yielding displacement δ_y were very frequent after experienced maximum displacement. 2) The response number of reversals in the displacement levels which exceed $2\delta_y$ was not so many as that of reversals under $2\delta_y$. 3) The response displacements had a tendency to incline towards positive or netative direction in some cases.

Taking account of these points, the following four kinds of loading excursions, controlled by lateral displacement, were adopted to test the specimens with same sectional properties and same materials.

A) SL-Loading: One way loading as increased simply.
B) AL-Loading: Alternate cyclic loading with asymmetric loops in which only the displacements of positive direction were increased gradually from δ_y to $8\delta_y$, and remained at δ_y in negative direction. The number of load reversals was three in every displacement level, and 26 in total.
C) CL-Loading: Alternate cyclic loading with symmetric loops. The displacement levels and the number of load reversals were same as above.
D) CL10-Loading: Alternate cyclic loading as same as CL-Loading. But the number of load reversals in every displacement level were 10, and 47 in total. The above loading excursions are shown in Fig. 2.

The testing apparatus is shown in Fig. 3.

The horizontal relative displacements between the top and the bottom of column were measured.

TEST RESULTS AND DISCUSSIONS

Figs. 4 and 5 show the examples of the relationships between the lateral force and the relative displacement.
Fig. 6 shows the envelope curves of the above relationships.
Fig. 7 shows the examples of the crack pattern of CL-Loading after cycles with $3\delta_y$.
Fig. 8 shows the failure progress comparing with the displacement ratio (δ/δ_y) and the final failure mode of each test specimen.

The relations between maximum load, displacement at maximum load and negative gradient after maximum load in the envelope curve respectively with loading excursions are shown in Fig. 9. Table 3 shows the comparisons of the above relations under CL-Loading with those under CL10-Loading. The negative gradient was obtained by the method of least squares because the envelope curve after yielding was nearly linear.

Fig. 10 shows the relation between the equivalent viscous damping factor h_e and the relative rotation angle R. h_e was obtained from the 2nd hysteresis loops in each displacement level, and R was a mean value of the positive and negative rotation angles. h_e is related to the ratio of the dissipated energy obtained from area of the hysteresis loop to potential energy.
1) The yielding of the tensile reinforcements were observed in all specimens as shown by mark F in Fig. 8. However, the failing behaviors after yieldings depended the loading excursions as follows. The displacements at the crushing of concrete (C), shear-compression failure (SC), shear-tension failure (ST), diagonal tension failure (DT) and bond-splitting crack

(BO) decreased as the number of load reversals increased, and they also decreased with severity of loading condition in the order of one way, asymmetric and symmetric loading.

However, the final failure modes, except 2B specimens, were not affected by the loading excursions, i.e., 3A and 3B specimens were DT, 6A specimens were SC, 6B specimens were ST and 7B, 8A and 8B specimens were BO failure modes. In case of 2B specimens in which the axial force was comparatively large, the final failure modes under SL and AL-loading were flexural compression (FC), but those under CL and CL10-loading were shear-compression (SC).

2) As shown in Fig. 6, the yielding load and yielding displacement were mutually equal in each series of test specimens, because the loading excursions were not so different until this stage. But the envelope curves after yielding were different depending on the loading excursions.

As shown in Fig. 9 a), b) and Table 3, the influences of loading excursions on the maximum load don't appear, but the displacements at the maximum load are clearly different depending on the loading excursions. In case of DT and BO failure mode, the displacements at the maximum load are reduced in the order of one way, asymmetric and symmetric loading. The ratio of its reduction in BO failure mode increases as the number of load reversals increases.

Comparing the symmetric loading with the other loadings, the negative gradients after the maximum load in the envelope curves of 2B, 3B and 8B specimens increase remarkably as shown in Fig. 9 c). It is observed that as the number of load reversals increases, the negative gradients have also a tendency to increase in every failure mode, except for DT mode, as shown in Table 3.

3) As shown in Fig. 10, the equivalent viscous damping factor he's in 2B, 6A and 6B specimens of flexural failure increased almost proportionally to the rotation angle R. However, he's in 7B, 8A and 8B specimens of bond-splitting failure were approximately constant. Though, in case of AL and CL-Loading, he's in 3A and 3B specimens increased almost proportionally to R after diagonal tension crack, this phenomenon was not observed in case of CL10-Loading. This depends on the difference of the number of load reversals.

CONCLUSIONS

The results, which were obtained varying the combination of the number of load reversals and displacement levels, indicate that the failing behavior after yielding, the displacement at maximum load, the negative gradient after maximum load in envelope curve and the equivalent viscous damping factor are influenced by the loading excursions.

Therefore, in the decision of restoring force characteristics on dynamic response analysis, the considerations of the influences by loading excursions will be necessary.

REFERENCES

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2) Y. Kano, K. Yamamoto and K. Katayama, "Synthetic Research on Earthquake Resistant Characteristics of Reinforced Concrete Columns, Part 28", Report of AIJ, 1975.

3) Y. Higashi, M. Ohkubo and M. Ohtsuka, "Synthetic Research on Earthquake Resistant Characteristics of Reinforced Concrete Columns, Part 23, 24, 38 and 39", Report of AIJ, 1975 and 1976.

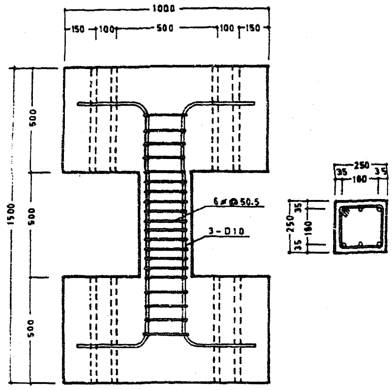

Fig. 1 An Example of Test Specimens

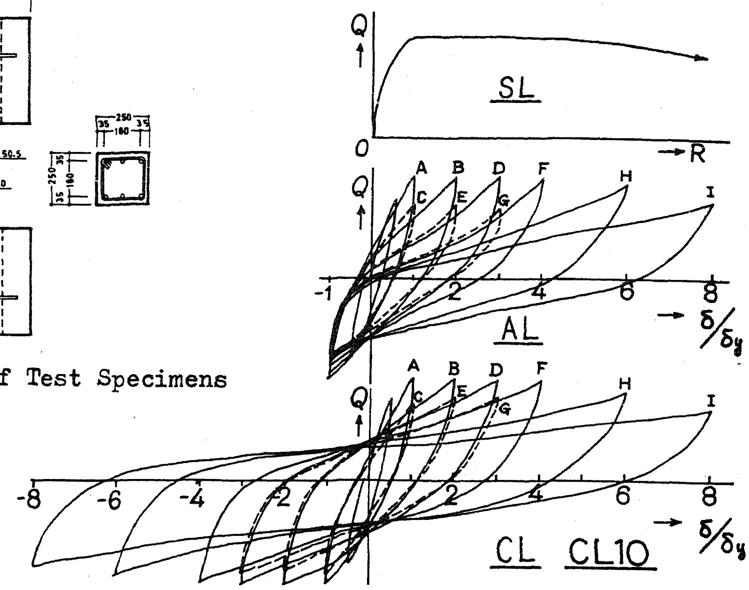

Fig. 2 Adopted Loading Excursions

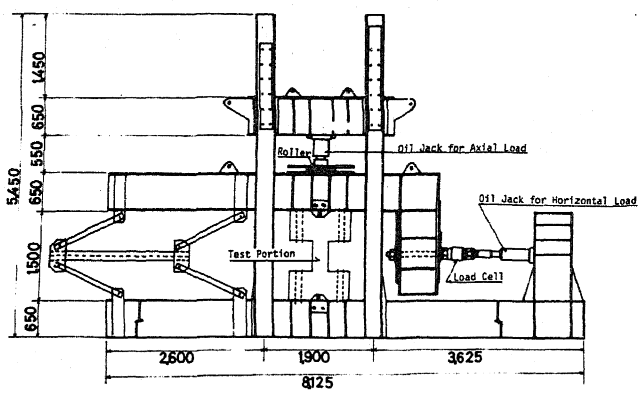

Fig. 3 Testing Aparatus

Table 1 List of Test Specimens

Test Specimen	Tensil Reinforcement	Tensil Reinforcemnt Ratio	Shear Span Ratio	Web Reinforcement	Web Reinforcement Ratio	Axial Unit Stress	Loading Excursion
	Number - Size	p_t (%)	M/QD	Number-Size-Spacing(mm)	p_w (%)	N/bD (kg/cm^2)	
2 B	3 - D10	0.34	2	17- 6- 62.5	0.36	210/4	SL.AL.CL.CL10
3 A	3 - D10	0.34	1	10 - 9 - 55.5	0.92	210/8	CL.CL10
3 B	3 - D10	0.34	1	11 - 6 - 50.5	0.45	210/8	SL.AL.CL.CL10
6 A	3 - D13	0.61	2	24- 6- 43.5	0.51	210/8	CL.CL10
6 B	3 - D13	0.61	2	28- 4 - 37.0	0.27	210/8	CL.CL10
7 B	3 - D16	0.95	2	25- 9 - 41.7	1.22	210/4	CL.CL10
8 A	3 - D16	0.95	2	26- 9 - 40.0	1.27	210/8	CL.CL10
8 B	3 - D16	0.95	2	28- 6- 37.0	0.61	210/8	SL.AL.CL.CL10

Table 2 Mechanical Characteristics of Materials

Test Specimen	Concete Compressive Strength (kg/cm²)	Reinforcemnt					
		Main	Yield Stress (kg/cm²)	Max. Stress (kg/cm²)	Web	Yield Stress (kg/cm²)	Max. Stress (kg/cm²)
2B 6A	240	D 10	4131	6219	4φ	3789	5013
6B 7B		D 13	4266	6471	6φ	4546	5028
8A 8B		D 16	3950	6049	9φ	3431	4912
3A 3B	146	D 10	3873	5709	6φ	3988	4405
					9φ	3417	4859

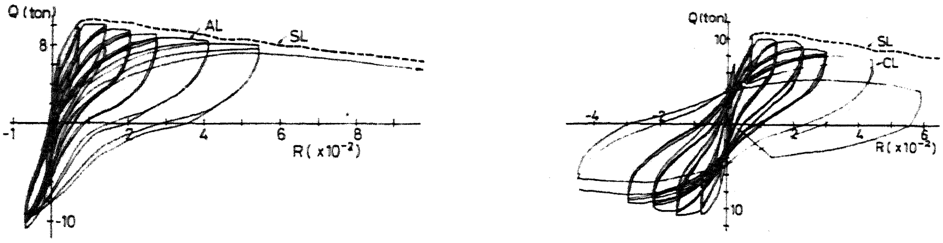

Fig. 4 Load-Displacement Diagrams for 2B Specimens

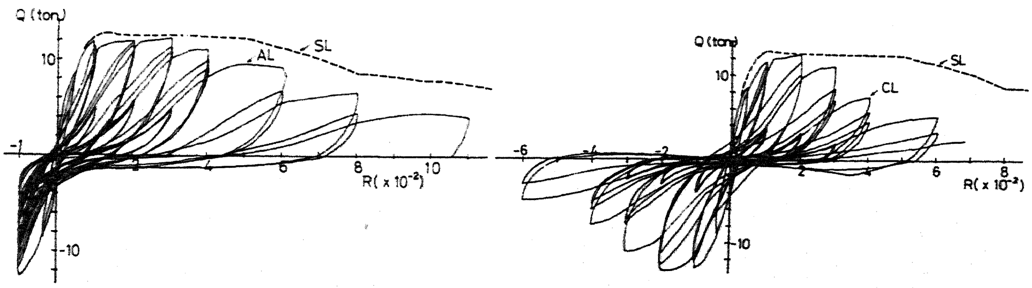

Fig. 5 Load-Displacement Diagrams for 8B Specimens

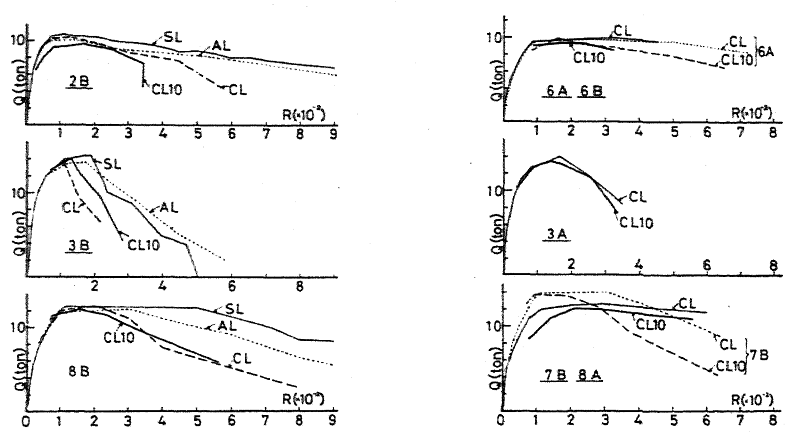

Fig. 6 Envelope Curves of Load-Displacement Diagrams

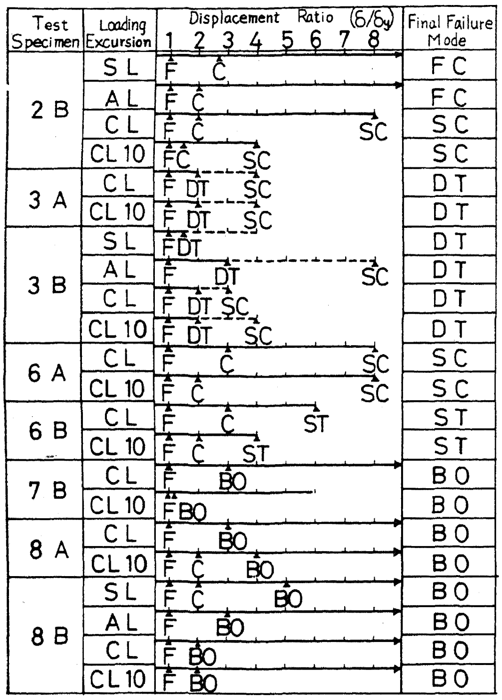

Fig. 8 Failure Progress and Final Failure Mode

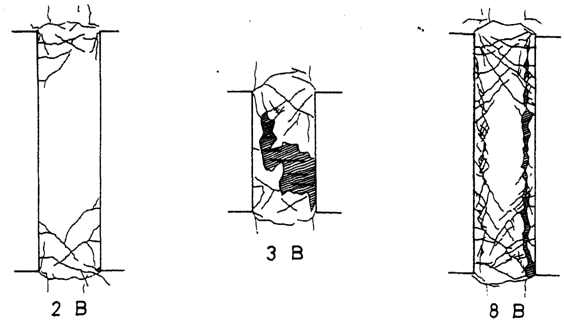

Fig. 7 Crack Pattern of CL-Loading after Cycles with $3\delta_y$

Table 3 Comparison of CL10-Loading with CL-Loading

Test Specimen	CL-10 Pmax / CL Pmax	CL-10 δPmax / CL δPmax	CL-10 ks / CL ks
2 B	0.9 4	1.3 2	1.6 8
3 A	0.9 6	0.8 0	1.1 1
3 B	1.0 4	1.1 5	0.9 4
6 A	1.0 1	0.5 9	1.7 6
6 B	0.9 4	0.7 1	3.8 7
7 B	0.9 9	0.5 9	1.4 4
8 A	0.9 5	0.7 0	0.9 3
8 B	0.9 8	0.7 9	1.1 2

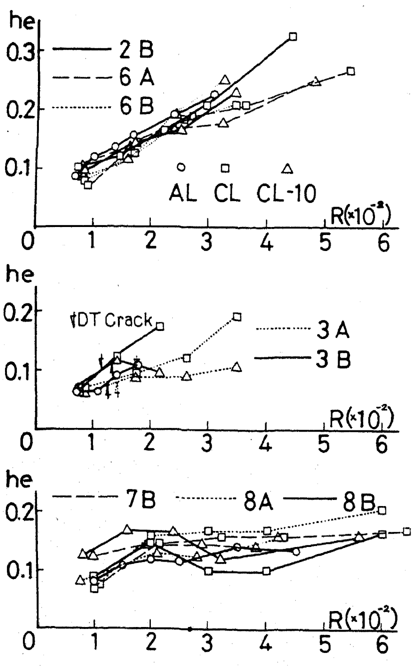

Fig. 10 Equivalent Viscous Damping Factor vs Relative Rotation Angle

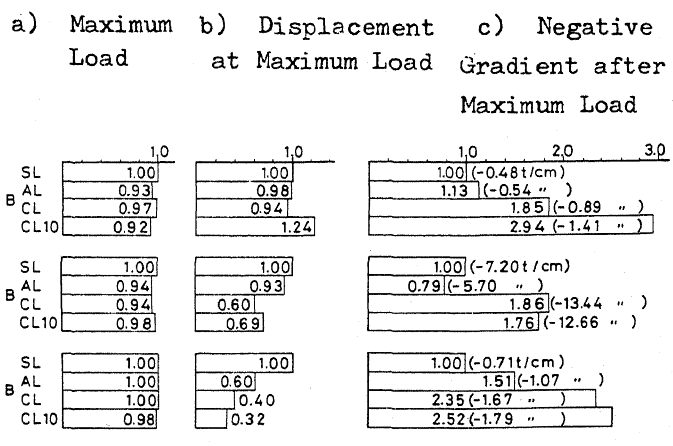

Fig. 9 Comparison of Each Loading Condition with SL-Loading