第３回構造物の破壊過程解明に基づく
地震防災性向上に関するシンポジウム論文集　2002年2月

# SEISMIC TESTS ON REINFORCED CONCRETE COLUMNS TO COLLAPSE UNDER CONSTANT AND VARYING AXIAL LOADS

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The experimental results for the behavior of six reinforced concrete columns subjected to unidirectional cyclic lateral loading with constant and variable axial loads are presented. Four specimens were tested under constant axial loads and two specimens under variable ones. Two types of concrete strength and two types of lateral reinforcement ratio were used. Failure modes and cracking patterns are discussed. The results indicated the influence of the variation of axial forces and their magnitudes on lateral strength, stiffness and deformation characteristics of the columns.

*Key Words: reinforced concrete columns, varying axial loads, shear failure, ultimate compression load*

## 1. INTRODUCTION

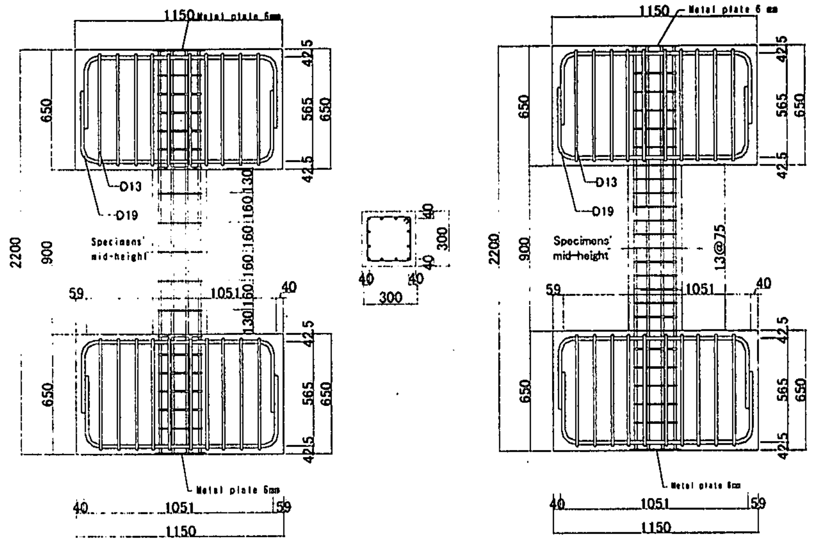
The dynamic behavior of medium to high-rise reinforced concrete building structures under seismic loads is controlled by many factors, for example the seismic performance of individual structural elements. Collapse and damage undergone by structural elements in existing constructions during catastrophic earthquakes pointed to the importance of columns, especially at the first story.

Failure types of columns depend, basically, on three parameters, material strength, reinforcement content and, to a great extend, on axial load type and intensity[1, 2, 3]. Under realistic seismic loading, column axial forces may change from high compression to net tension, therefore column behavior is more complex than considering constant axial loads. As a matter of fact, Japanese guidelines[4] introduced a procedure to find an appropriate equivalent axial load to a varying one. The assessed value reflects the limit axial load and the procedure is based on flexural assumptions, ignoring the effect of shear deformations. To that effect, experimental investigation was necessary. The obtained results from the presented experiment showed that the actual value, given in term of axial load ratio, is lower than the value given by the guidelines.

From a comprehensive testing program that included fourteen specimens, six of them were tested bared while eight others were wrapped by polyester belts. Two objectives were planned for the whole testing program. The first objective was a study on strengthening while the second one was the study as to equivalent axial load, mentioned herein above and treated through this paper.

## 2. TEST SPECIMENS, TEST SETUP AND PROCEDURE

Six one-third-scale reinforced concrete columns, considered representative of those occurring in the first story of moderately tall R/C structural systems located in seismic regions, were tested using



Specimen 1

Specimens 4, 6, 8, 10 and 12

**Fig.1** Geometric details of test specimens (Unit: mm)

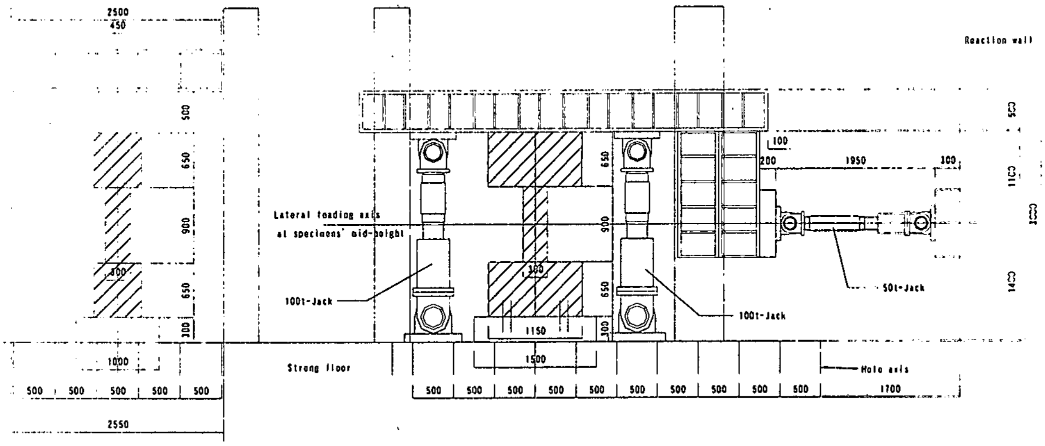


**Fig.2** Test setup and loading apparatus

constant and varying axial loading histories. All columns had, as depicted in **Fig.1**, a square cross section of 300x300 mm$^2$ and a height of 900 mm, which results in a shear span ratio of 1.5. Amount of reinforcements and mechanical characteristics of concrete and steel bars are listed in **Table 1**. The specimens were designated according to the global testing program.

The columns were tested in a vertical position as shown on the loading setup in **Fig.2**. Independent forces were applied simultaneously to specimens through a steel beam by using two 100-ton-jacks for axial loads and one 50-ton-jack for lateral loads. Laterally, columns were subjected to an anti-symmetric double curvature bending where the loading path was controlled by lateral deformations as shown in **Fig.3**. Axial load $N$, when varied, was proportional to the lateral shear forces $Q$ according to equation (1)

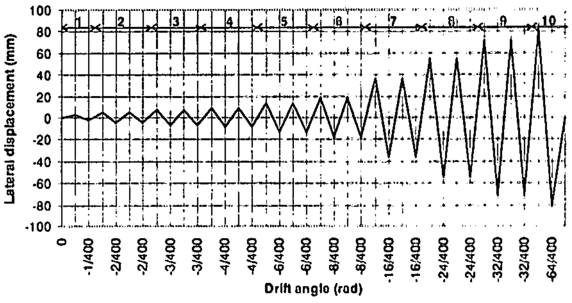


**Fig.3** Lateral displacement loading history

$$N = N_0 + \alpha Q \qquad (1)$$

where $N_0$ is the initial compressive force and $\alpha$, the axial load factor, taken as 4.5 simulating the varying axial load in a medium-rise building. The applied axial loads are given in Table 1. LVDTs and clip gages were used to measure lateral deflection, vertical deformation, rotation and distortion while

**Table 1** Summary of specimens

| Specimen | Longitudinal Reinforcement (Mpa) | Transversal Reinforcement (Mpa) | Concrete Strength $F_c$ (Mpa) | Axial load type | Initial axial load (kN) | Range of Axial load (kN) |
|---|---|---|---|---|---|---|
| 1 | 12-D13<br>$\rho_g$ =1.693%<br>$\sigma_y$ =340 | 2-5$\phi$ @ 160<br>$\rho_w$ =0.083%<br>$\sigma_{wy}$ =587 | 13.5 | Constant | 364.5<br>($0.3F_c$) | 364.5<br>($0.3F_c$) |
| 4 | | 2-D6 @ 75<br>$\rho_w$ =0.284%<br>$\sigma_{wy}$ =384 | | Constant | 364.5<br>($0.3F_c$) | 364.5<br>($0.3F_c$) |
| 6 | | | | Varying | 243.0<br>($0.2\ F_c$) | $-185.0 \leftrightarrow 1035.0$<br>($-0.15F_c \leftrightarrow 0.85F_c$) |
| 8 | | | 18.0 | Constant | 486.0<br>($0.3\ F_c$) | 486.0<br>($0.3F_c$) |
| 10 | | | | Varying | 243.0<br>($0.15\ F_c$) | $-245.0 \leftrightarrow 1375.0$<br>($-0.15F_c \leftrightarrow 0.85F_c$) |
| 12 | | | | Constant | 324.0<br>($0.2\ F_c$) | 324.0<br>($0.2F_c$) |

electrical resistance gages were used to measure steel strains. An automatic data acquisition system and a microcomputer were used to record the data.

## 3. TEST RESULTS, OBSERVED BEHAVIOR AND DISCUSSION

All the specimens did not develop their full flexural yield strength prior to shear failure. Bond failure was observed on all models while rupture occurred under diagonal tension cracks with different inclination angles. Collapse was reached when the column was unable to resist any more the applied axial load.

### (1) Crack patterns and visible damages

As a general behavior, flexural cracks formed at both ends of column from the first lateral loading cycle followed later by inclined ones with each cycle. When the deflection increased the inclined cracks propagated, their number increased and their widths widened, showing a truss form on column faces and resulting in a bond degradation. During unloading stages, the formed cracks, depending on the level of lateral loading cycle, closed completely or partially, or narrowed to their minimum width. The behavior of specimen 1 was an exception where only steep shear failure occurred while no bond deterioration was noticed, obviously, because of its very low transversal reinforcement ratio.

Therefore, as it can be seen from **Fig.4**, a splitting crack line formed along the height of columns subjected to varying axial loads, at the level of one of the inner longitudinal bars. This line was not observed on specimens subjected to constant axial loads. Furthermore, specimens 1, 4 and 8 had steep critical diagonal cracks (22-degree-angle) while specimens 6, 10 and 12 had moderate critical diagonal cracks (45-degree-angle).

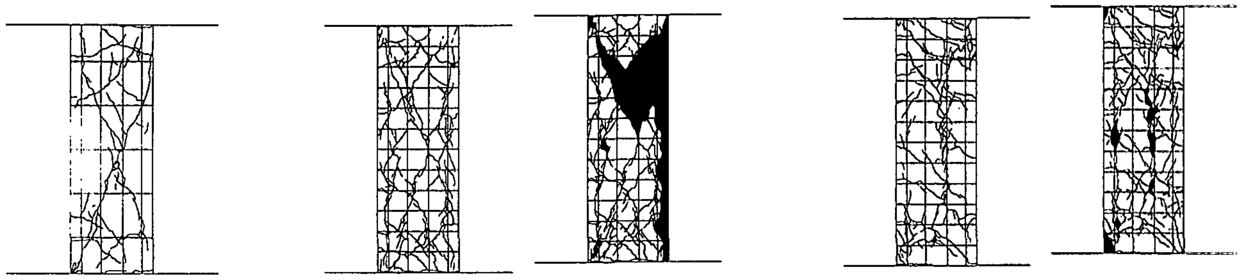
As for spalling of concrete cover, all specimens experienced it, except specimen 1. Large blocks spalled off from column faces, mainly from lateral ones. It was noticed that the spalling of concrete cover was not due to high compressive strains in concrete but because of bond deterioration.

### (2) Lateral load-lateral displacement responses

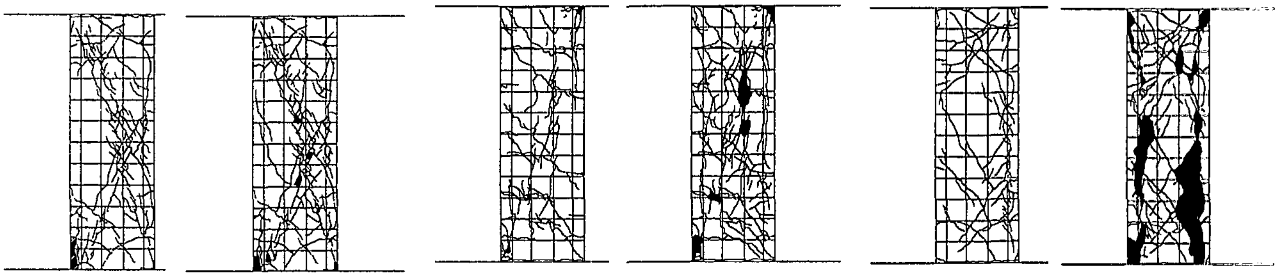
Column shear force-lateral displacement responses for all models are shown through **Fig.5**.

As observed on specimens, obviously, higher transverse reinforcement ratio provided higher shear resistance and allowed larger deformations. Higher axial load ratios induced higher shear ratios, thus higher shear resistant forces but reduced lateral deformations.

Also, it was noticed that the application of higher axial loads increased the shear resistant force till a certain level of lateral displacement, while the application of lower axial loads allowed larger deformations. Also, varying of axial loading increased shear resistance, allowed larger deformation and lowered shear degradation. Higher concrete strength enhanced the previous observations. All specimens exhibited an increase in shear resistance during the first and second loading cycles (1/400 and 2/400) before a loss occurred in the following cycles, which was attributed to shear cracks, splitting cracks, bond deterioration and spalling of concrete cover. Also, it was noticed that repeating the same cycle increased shear resistance loss. Discrepancies in the loss rate were observed



Specimen 1 (-4/400) Specimen 4 (-4/400, -16/400) Specimen 6 (-4/400, -16/400)



Specimen 8 (-4/400, -6/400) Specimen 10 (-4/400, -16/400) Specimen 12 (-4/400, -16/400)

**Fig. 4** Crack patterns

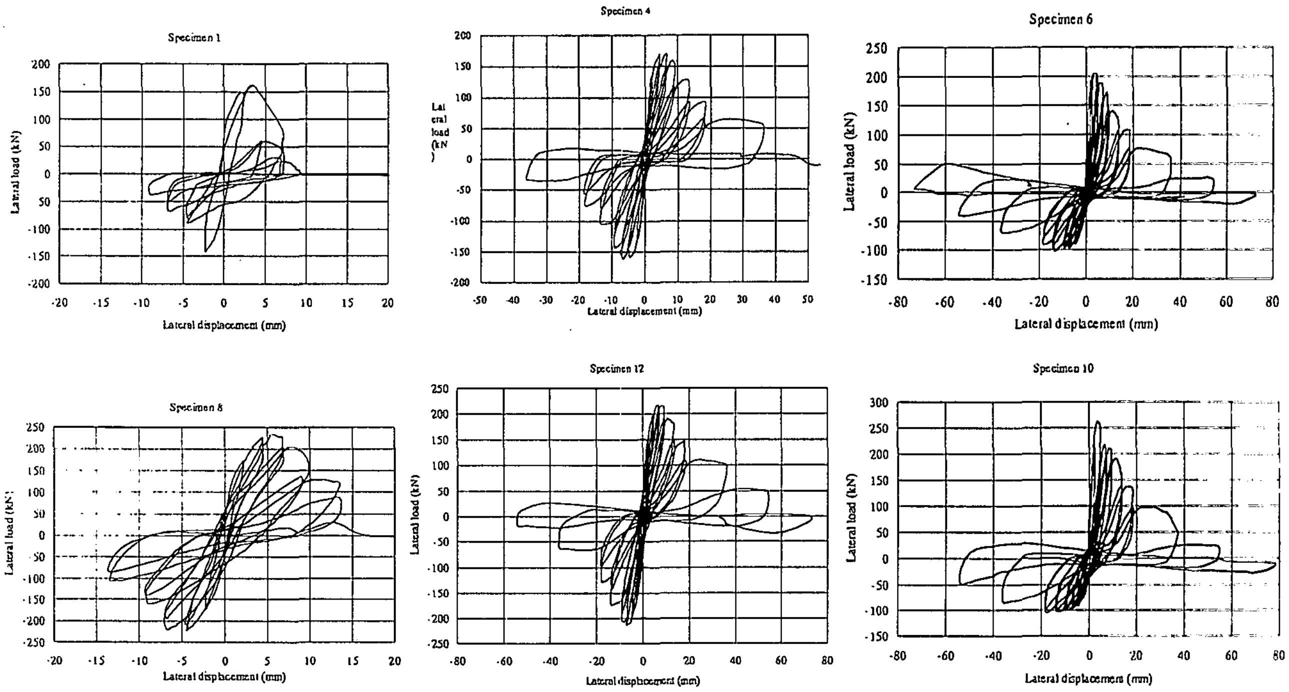


**Fig.5** Column lateral load-lateral deflection relationship

among specimens and they were attributed to the magnitude and type of applied axial loading. Under constant axial loads, higher loads induced higher loss rates. However, under variable axial loads, loss rates were almost the same, with a slight difference probably due to the difference in concrete strength.

Furthermore, the pinching in the hysteretic loops influenced the loss in shear resistance and the degradation of stiffness in all specimens. Besides the fact that cracks, which had formed in the

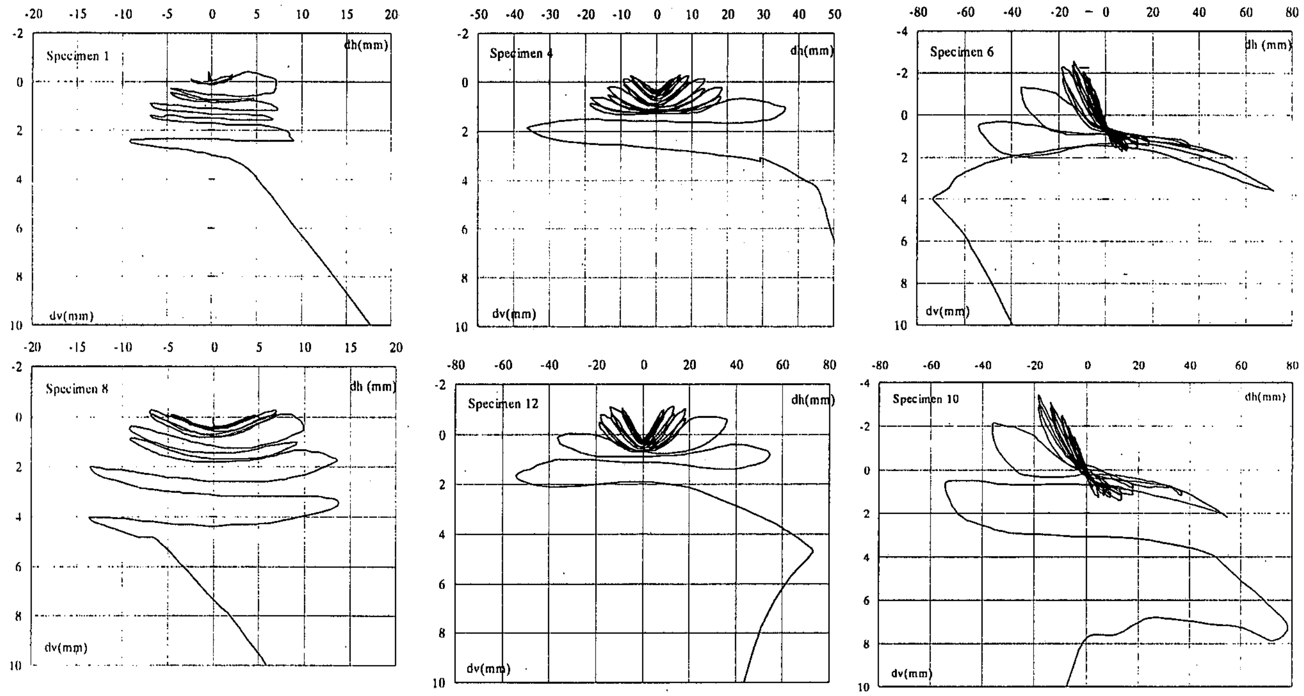


**Fig. 6** Column axial deformation-lateral deflection relationship

previous load direction, did not close completely at zero load, pinching reflected slip between longitudinal steel bars and concrete. Effect of pinching in loops appeared at different cycles from one specimen to another. This phenomenon became more pronounced with each lateral deflection cycle, especially for larger ones, indicating an increase in the bond deterioration, which resulted in the observed stiffness and shear degradation.

### (3) Column shortening and axial stiffness degradation

Axial deformations were measured using LVDTs. As shown on **Fig.6**, a distinct behavior was noticed, as to axial deformation, between columns.

As a first result, it was noticed that the amount of transverse reinforcement affected considerably the axial deformation and stiffness. This fact was illustrated by the behavior of specimen 1.

For specimens subjected to constant axial loads, with each cycle, the axial deformation-lateral deformation curve shifted gradually on the axial deformation axis to the compressive side. This shift was caused by the degradation of the column axial stiffness. It was noticed that the shape of the curve and the shift variation depended on the applied axial load magnitude and the concrete strength. Higher axial load ratios induced less concave curves and higher axial loads induced higher axial deformations.

For specimens subjected to varying axial loads, slight shifts to the compressive side on the axial deformation axis were noticed on the axial deformation-lateral deformation curves, where the shift variation was negligible. However the variation increased and was noticeable after the opening of the longitudinal splitting cracks.

Furthermore, for specimens subjected to varying axial loads the curve shift was moderate than for specimens under constant axial loads, thus the degradation in the column axial stiffness is more gentle for specimens under varying axial load.

**Table 2** Deformability level

| Spec. | Duct. | Corresponding axial load ratio | Corresponding lateral deflection (%) |
|---|---|---|---|
| 1 | 3.93 | 0.3 (const.) | 1 |
| 4 | 15.72 | 0.3 (const.) | 4 |
| 6 | 31.44 | 0.22 (var.) | 8 |
|  | 23.58 | 0.32 (var.) | 6 |
| 8 | 6.52 | 0.3 (const.) | 1.5 |
| 10 | 26.09 | 0.24 (var.) | 6 |
|  | 17.39 | 0.36 (var.) | 4 |
| 12 | 17.39 | 0.2 (const.) | 4 |

### (4) Ultimate axial loading and deformability

All specimens experienced collapse at different lateral deflections, which were lower than the maximum reached during previous lateral loading cycles. All specimens could sustain higher axial loads at peak cycles. For specimens under varying axial loads, maximum axial load ratios at the last lateral peak cycle before collapse were 0.185 for specimen 6 and 0.14 for specimen 10.

The level of column deformability attained under different axial loadings was assessed by means of displacement ductility. Specimens under varying axial loads had showed higher lateral deformability than specimens under constant axial loads. When the applied axial load for specimens subjected to varying axial loads reached the same level of axial load ratios of specimens subjected to constant axial loads, the ductility level was higher in the first specimens than in the second ones, as given in **Table 2**. Furthermore, specimens under higher axial loads had lower ductility. This fact was explained by the variation in the axial stresses and strains, mainly in the central zone of the cross section, thus the variation in the column axial deformation. This part of the cross section was always under compression when constant axial loads were applied, then the axial degradation continually increased, however, when varying axial loads were applied the compression level varied considerably and the central part experienced very low compression levels, as a consequence the axial stiffness degradation was not so severe as in the case of constant axial loading.

As for the equivalent axial load ratio, the ratio values obtained from test for specimens 6 and 10, and shown in Table 2 were found below the value proposed by the Japanese guidelines, which is approximately around 0.5. As a consequence, the guidelines overestimated the actual values.

## 3. CONCLUSIONS

From the experimental results, the following conclusions can be drawn:

1. Higher axial loads induce steeper diagonal collapse and lower axial loads induce moderate diagonal collapse. Higher axial load ratios induce higher shear ratios and lower lateral deformations.
2. Varying axial loadings increase shear resistance, allow larger deformations and lower shear degradation. Higher concrete strength enhances them.
3. Column axial stiffness degradation is lower for columns under varying axial loads.
4. Ductility level reached under constant axial load is lower than under varying axial load.
5. The equivalent axial load ratio assessed using flexural assumptions gives an overestimated value.

## ACKNOWLEDGEMENTS:

The experiments was sponsored by Structure Quality Assurance Inc. and conducted at Yokohama National University. Graduate and undergraduate students from Yokohama National University and Shibaura Institute of Technology prepared and tested the specimens.

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