

EXPERIMENTAL STUDY ON SEISMIC BEHAVIOR OF REINFORCED CONCRETE COLUMNS UNDER CONSTANT AND VARIABLE AXIAL LOADINGS

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ABSTRACT: The behavior of six reinforced concrete columns subjected to unidirectional cyclic lateral loading with constant and variable axial loads, and their experimental results 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, cracking patterns and ductility levels 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.

KEYWORDS: reinforced concrete columns, variable axial loads, equivalent axial load ratio, ductility

1. INTRODUCTION

The dynamic behavior of medium to high-rise reinforced concrete building structures under seismic loads is controlled by many factors, mainly the seismic performance of each individual structural element. Collapse of old structures and damage undergone by structural elements in modern construction 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 extent, on axial load type and intensity[1,2,3]. Under realistic seismic loading, column axial forces that arise from a combination of the framing action of multiple column system and vertical ground motion, 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 forces and deformations. To that effect, experimental investigation was necessary. The obtained results from the presented experiment showed that, due to early shear failure, the actual limit axial load, given in term of axial load ratio, is lower than the value given by the guidelines for elements failing in flexure after yielding.

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 considered 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 constant and

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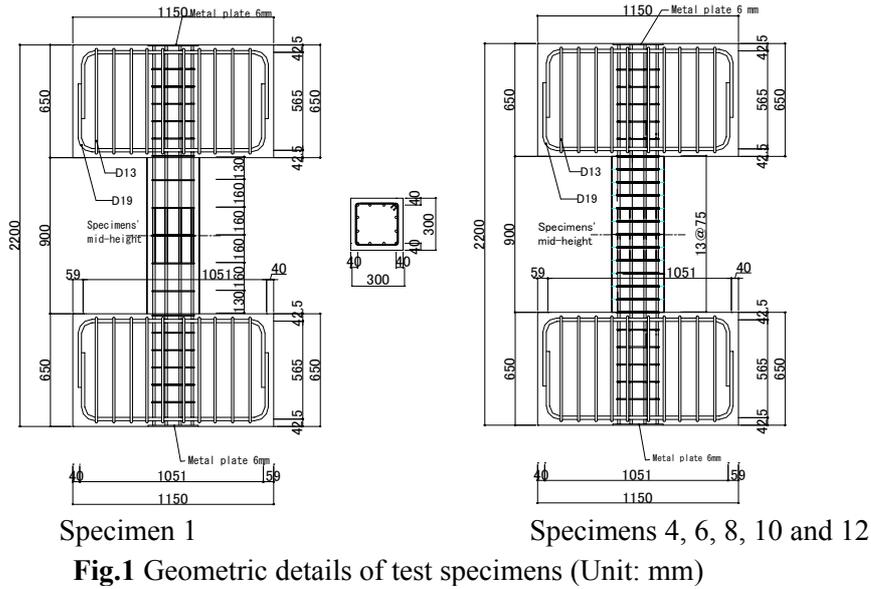


Fig.2 Test setup and loading apparatus

varying axial loading histories. All columns had, as depicted in Fig.1, a square cross section of 300x300 mm² 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 chronology of the 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 Eq. (1)

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

where N_0 is the initial compressive force and α the axial load factor, taken as 4.5 simulating the varying axial load in a medium-rise building. LVDTs and clip gages were used to measure lateral deflection, vertical deformation, rotation and distortion while electrical resistance gages were used to measure steel strains. A microcomputer and an automatic acquisition system were used to record data.

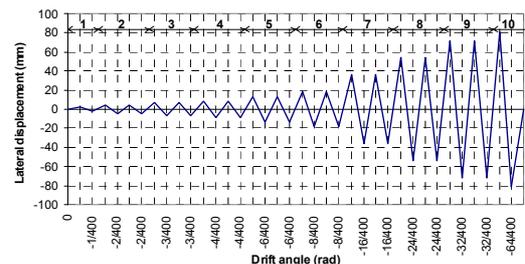


Fig.3 Lateral displacement loading history

Table 1 Summary of specimens

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

3. TEST RESULTS, OBSERVED BEHAVIOR AND DISCUSSION

All the specimens did not develop their full flexural yield strength prior to shear failure and collapsed along their critical diagonal cracks. 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.

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

As for spalling of concrete cover, all specimens experienced it, except the 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.

3.2 LATERAL LOAD-LATERAL DISPLACEMENT RESPONSES

Column shear force-lateral displacement responses for all models are shown through **Fig.4**. 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 for both nominal and concrete core sections, thus higher shear resistant forces and reduced capacity for 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 before a loss occurred in the following

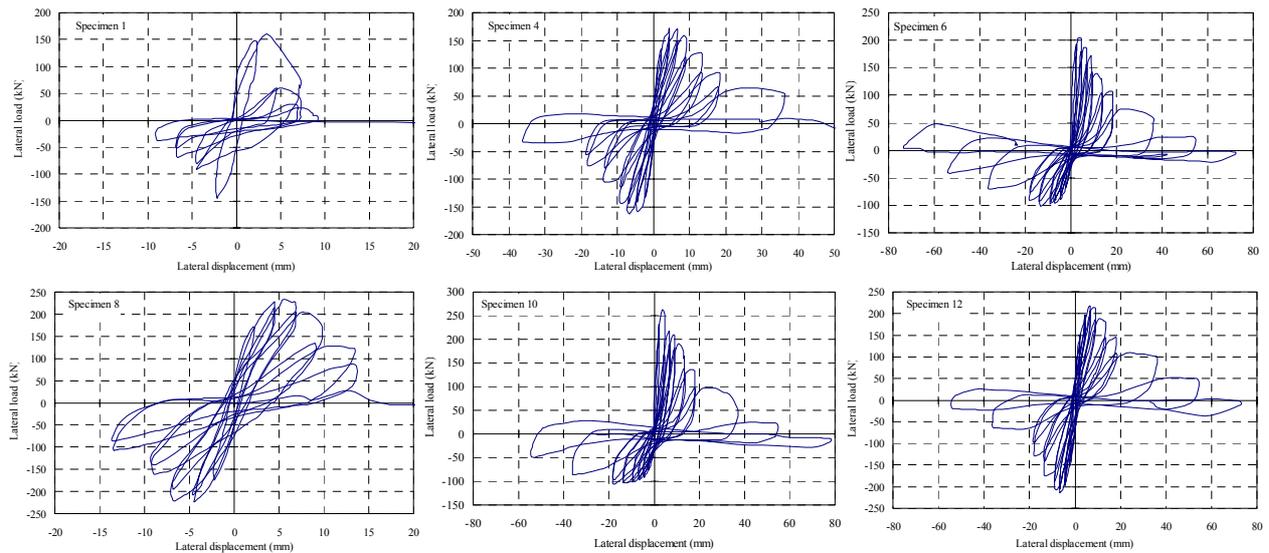


Fig.4 Column lateral load-lateral deflection relationship

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 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. 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.

3.3 COLUMN SHORTENING AND AXIAL STIFFNESS DEGRADATION

As shown on **Fig.5**, 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 the 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.

3.4 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

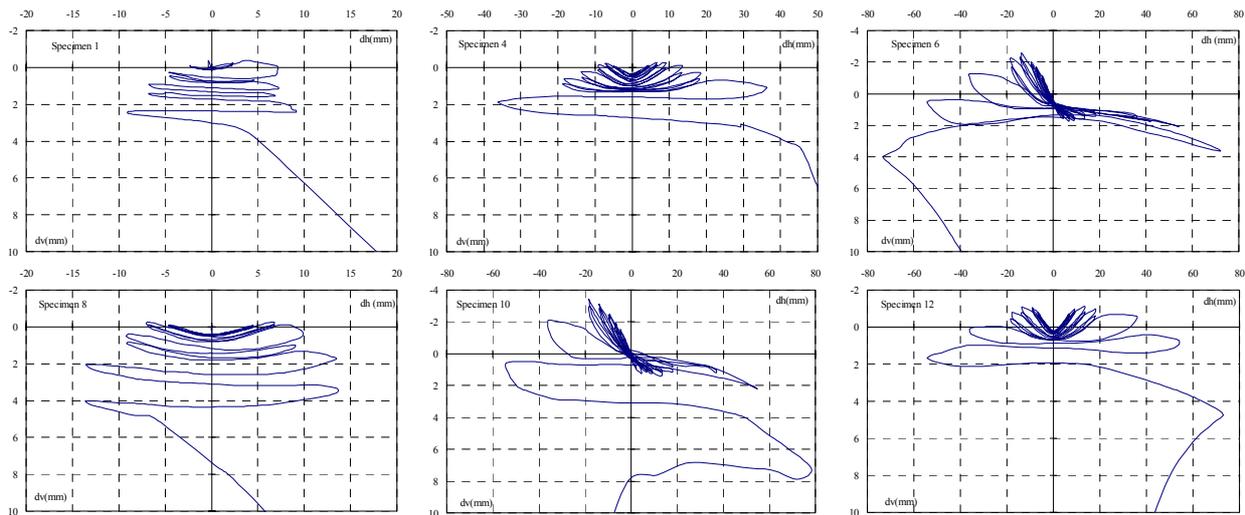


Fig.5 Column axial deformation-lateral deflection relationship

collapse were 0.185 for the specimen 6 and 0.14 for the specimen 10.

The maximum level of deformability attained by specimens 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 shown in **Fig.6**. 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, fact that allowed larger lateral deformability.

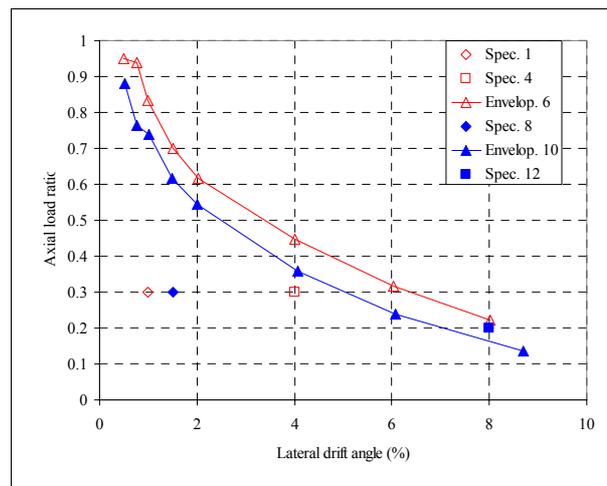


Fig.6 Columns performance

As for the equivalent axial load ratio, the ratio values obtained from test for the specimen 6 and 10, and shown in **Fig.6** were found below the value proposed by the Japanese guidelines, which is approximately around 0.5. As a matter of fact, the specimen 12 was the reference at which the results and behavior of the specimen 6, 8 and 10 were compared. The magnitude of applied axial load on the specimen 12 was selected after careful observations on behavior of the specimens previously tested. The behavior of the specimen 6 and 10 showed the same cracking pattern, shear failure modes, critical diagonal cracks and collapse mode as those of the specimen 12. Therefore, as to shear resistance, the specimen 12 reached slightly a higher level than the specimen 6 and was 15% below the level reached by the specimen 10. Also, the slope of shear force-lateral deflection envelope curves had almost the same tendency and inclination for the specimen 6, 10 and 12. As to column's axial deformation, the level of the three specimens at the last cycles was comparable. Therefore, as to lateral deformability, the specimen 6, which was under a constant axial load ratio of 0.2,

performed better than the specimen 8 that was under a constant axial load ratio of 0.3. Also, the specimen 12 had slightly lower deformability than the specimen 6 and 10, which were under varying axial load. Larger deformability could be obtained from specimen 12 in case of more precise conditions, particularly in the assessment of the applied axial load.

The results and behavior obtained from testing the specimen 6 and 10 under varying axial load, with an applied maximum axial load ratio over than 0.85, were comparable to those obtained from the specimen 12 that was under a constant axial load ratio of 0.2. The limit axial loads obtained for the tested specimens, which failed in shear, were found lower than those given by the guidelines for elements failing in flexure after yielding. However, it should be emphasized that this conclusion is not meant to be general but applies to the columns tested.

4. 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. Also, lower axial load ratios result in higher ductility.
- (5) The equivalent axial load ratio assessed for elements failing in flexure is higher than the one for specimens failing in shear.

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