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EARTHQUAKE RESISTANCE MECHANISM OF LOWEST PORTIONS OF HIGH-RISE RC BUILDINGS

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ABSTRACT

This paper presents the analytical and experimental investigations of the resistance mechanism of reinforced concrete frames subjected to both varying lateral and axial forces. These frames are considered to represent mechanically the lowest portions of thirty- to fifty-story RC building when subjected to high shear and high overturning moment during a major earthquake. Based on the experiments and analyses, the following conclusions can be made. Lateral restoring force characteristics of overall frames and re-distributions of shear force among columns in the multi-span frames were obtained in detail. Envelope curves of lateral restoring force characteristics of overall frames and vertical restoring force characteristics of the exterior columns and hinge mechanism could be evaluated by analytical method. The possibility of constructing higher than thirty-story RC buildings using members of the same size was confirmed.

KEYWORDS

RC high-rise building; earthquake resistance mechanism; high varying axial force; exterior column; P-delta effect; concrete strength; re-distribution of shear force; analytical simulation.

INTRODUCTION

Resisting capability of exterior columns subjected to high varying axial forces during a major earthquake is one of the most important structural factors in design of high-rise RC buildings. To prevent the brittle failure of single-story exterior columns many experimental and analytical researches have been carried out, (Park *et al.*, 1984) to determine the required transverse and longitudinal reinforcement. On the other hand, in the research of three-story continuous columns (Teraoka *et al.*, 1993) it was proved that even if the brittle failure of columns can be avoided, the lateral strength decreases rapidly at large lateral displacement due to the P-delta effect. It is very important to investigate the interaction of plural continuous columns in the frame.

To understand the structural mechanism of RC frames, experimental and analytical works were performed on scaled RC two-span and one-span test structures with three storys. Each of the test structures represented the mechanical model of the lower portion of RC thirty-story building (Araki *et al.*, 1995, 1996). The external columns were subjected to varying axial force while the interior column being subjected to a constant axial force throughout the test. Possibility of constructing taller high-rise RC buildings using members of the same size was also investigated.

METHODS OF EXPERIMENTS

Details of Test Structure

Test structures were one-seventh scaled down RC frames as shown in Fig. 1. The test structures were three-story two-span frames [FRA-2, FRA-5, FRA-6] or three-story one-span frames [FRA-7, FRA-8], mechanically designed from the prototype of a thirty-story six-span RC frame building. All of test structures had the same column section (bxD=120mmx120mm) and the same beam section (bxD=90mmx120mm). The exterior columns were heavily reinforced with both transverse and longitudinal bars for high axial compression and tension forces. As shown in Table 1 a total of five test structures was tested . The objective of using both types is to obtain shear force re-distributions up to ultimate among compression exterior column, interior column and tension exterior column. Designed concrete strength F_c was 400kgf/cm^2 for three test structures while it was 600kgf/cm^2 for the other two. The two test structures with the high concrete strength were tested to examine the potentiality of constructing taller high-rise RC buildings (40~50 storeys) using members of the same size.

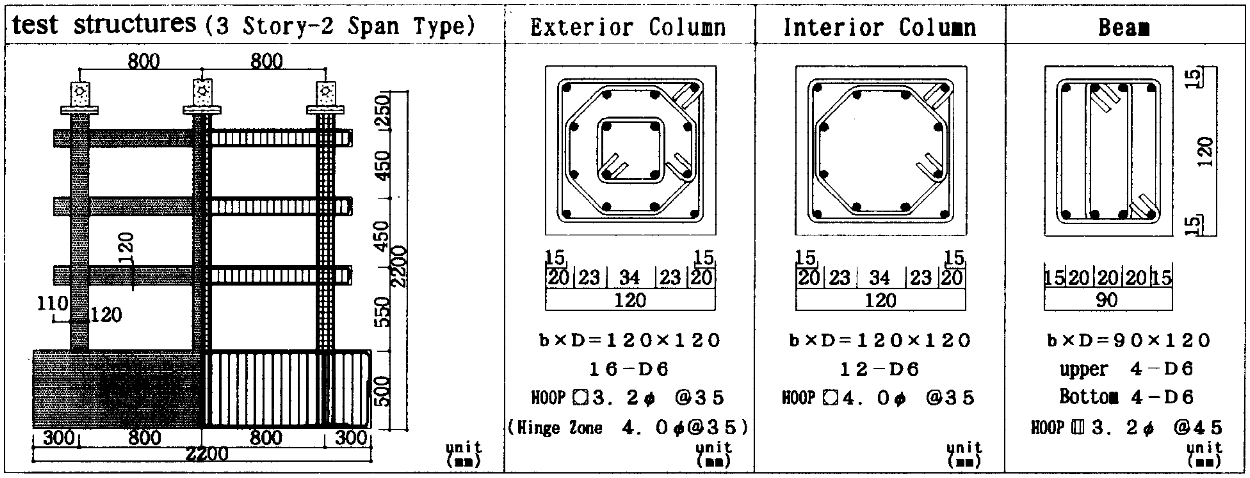
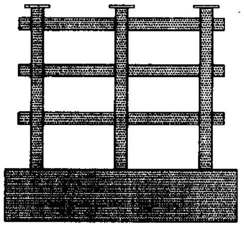
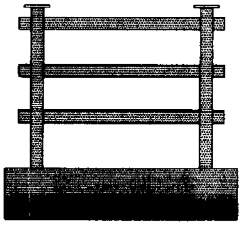


Fig.1. Details of test structure and section for each member

Table 1. Descriptions of test structures

Test Structure	test structures	Design Concrete Strength Fc(kg/cm2)	Exp.day Concrete Strength Fc(kg/cm2)	Main Reinforcement (ton/cm2)	Hoop Reinforcement (ton/cm2)	Axial Loading Program Type
FRA-2		400	415	D6 σy=3. 89 E =1960 σu=5. 49	4. 0φ σy=5. 38 E =2131 σu=5. 57	I
FRA-5		400	459			II
FRA-6		600	622			I
FRA-7		400	399		3. 2φ σy=5. 66 E =2045 σu=5. 98	I
FRA-8		600	613			I

Test Apparatus and Loading Program

Test Apparatus. The experimental work was conducted by controlling the cyclic lateral displacement after a constant axial force equal to the gravity load was applied. Test apparatus is shown in Fig. 2. The lateral shear force were concentrated manually on the top of the interior (center) column with the assumption that story shear force is constant along the lower 1/10th portion of high-rise buildings. For the one span test structures, the lateral force were applied to the same location using the rigid steel beam between both side of the exterior columns.

Loading Program. The amplitude of lateral displacement was increased in steps as shown in Fig. 3. The applied varying axial forces for external columns were considered to be proportional to the applied cyclic lateral force as shown in Fig 4. The axial forces N were $N_0 - 0.45F_cbD \leq N \leq N_0 + 0.45F_cbD$ [type I] for four test structures ($F_c = 400$ kgf/cm^2 : FRA-2, FRA-6, $F_c = 600$ kgf/cm^2 : FRA-7, FRA-8), where N_0 is the constant axial force ($0.20F_cbD$) and (F_cbD) is the maximum compression values for the exterior columns. The exterior columns of the other test structures ($F_c = 400$ kgf/cm^2 : FRA-5) were subjected to a varying axial force of $N_0 - 0.45F_cbD \leq N \leq N_0 + 0.6F_cbD$ [type II].

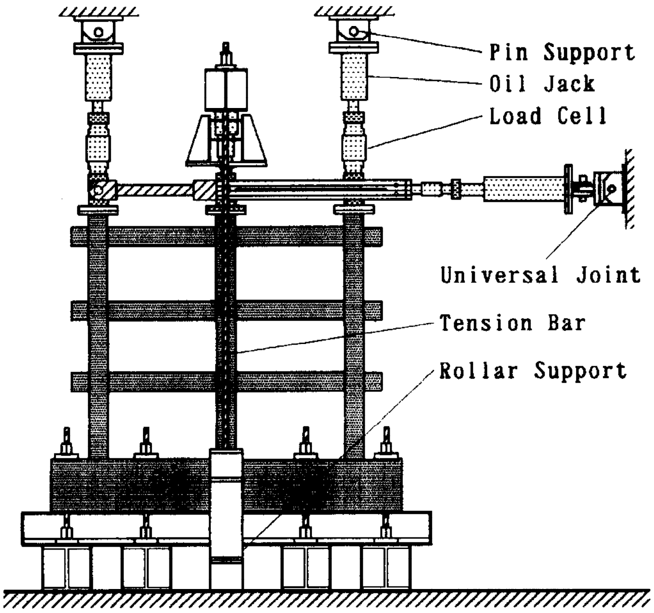


Fig.2. Loading apparatus

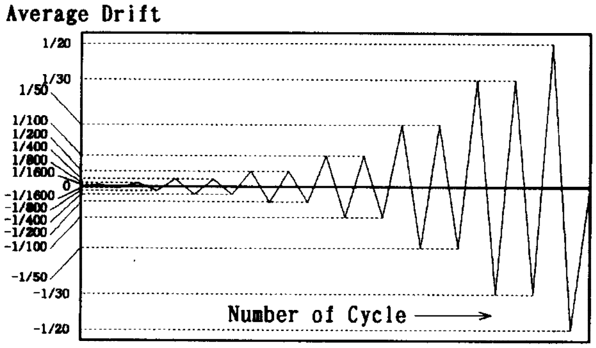


Fig.3. Lateral loading program

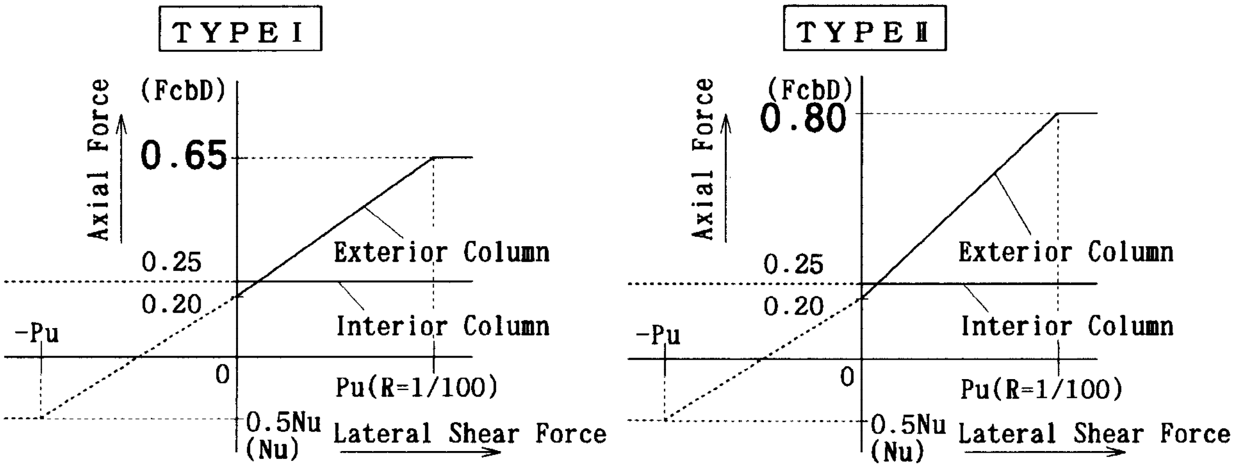


Fig.4. Axial loading program

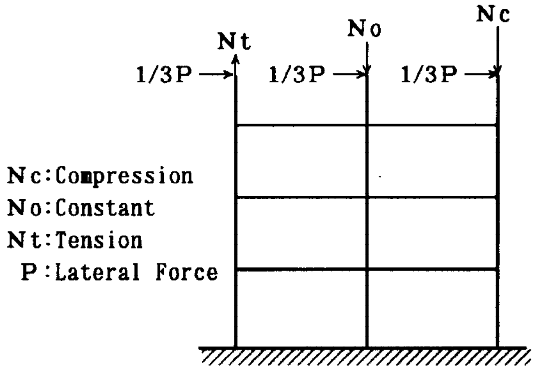


Fig.5. Analytical model

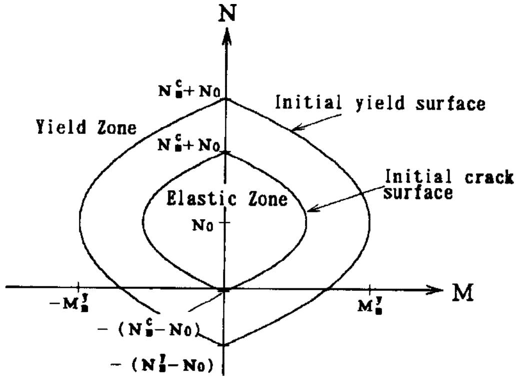


Fig.6. Initial crack and yield surface

Analysis. The non-linear analysis was also carried out using plastic hinge method which is based on the plastic flow theory (Inoue *et al.*, 1974). The analytical model of test structures is shown in Fig. 5. Monotonic lateral loading was applied equally on three points at the top of the three columns. The gradual application of axial force simulated the load application as in the experiments. The assumed initial cracking and yielding surfaces (axial force and moment interaction curves) for columns are shown in Fig. 6.

Measurement. During the experimental work, the data of more than 200 points were recorded from load cells, displacement transducers and strain gages and were stored into computer.

TESTS RESULTS AND DISCUSSIONS

Cracking Patterns

Flexure yield crack patterns were observed at both ends of the beams and at the bottom ends of the lowest story columns for all test structures as illustrated in Fig.7 [FRA-2, FRA-7]. Neither compressive failure of columns nor shear failure of each member was observed until the final stage (1/30rad.~1/20rad.), however, spalling of the cover concrete of the bottom part of each column could be noticed. Core concrete of all columns remained in transverse reinforcing area due to the additional confinement that was provided at assumed hinging zones and beam-column connections. Nevertheless, buckling of longitudinal main bar were observed in some columns. Also diagonal cracks occurred slightly at the panels of beam-column connections. Tension cracks perpendicular to the axial direction of column member were observed in the exterior columns when axial force became tension. Hinging length of beams for one-span test structures were longer than those of two-span test structures because moment gradient of beam were small for one-span test structure.

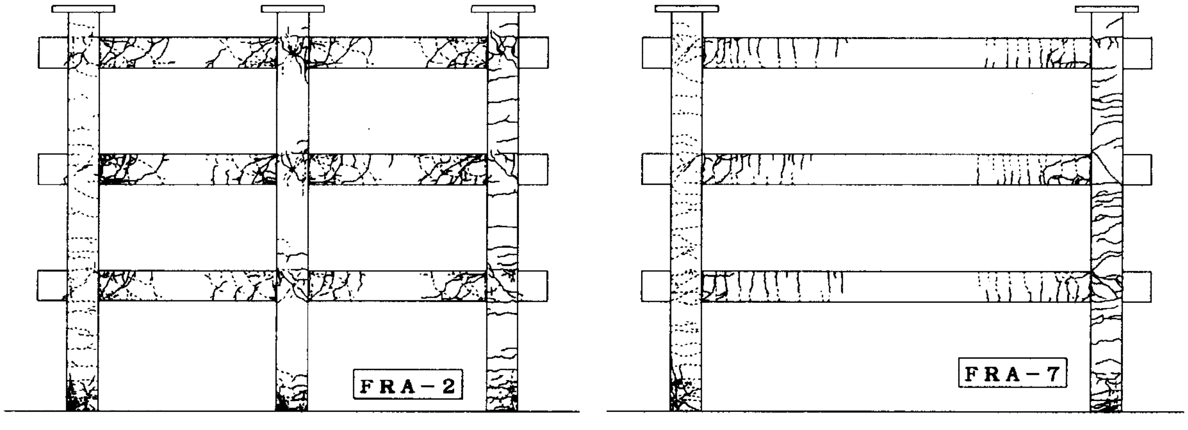


Fig.7. Crack pattern [FRA-2, FRA-7]

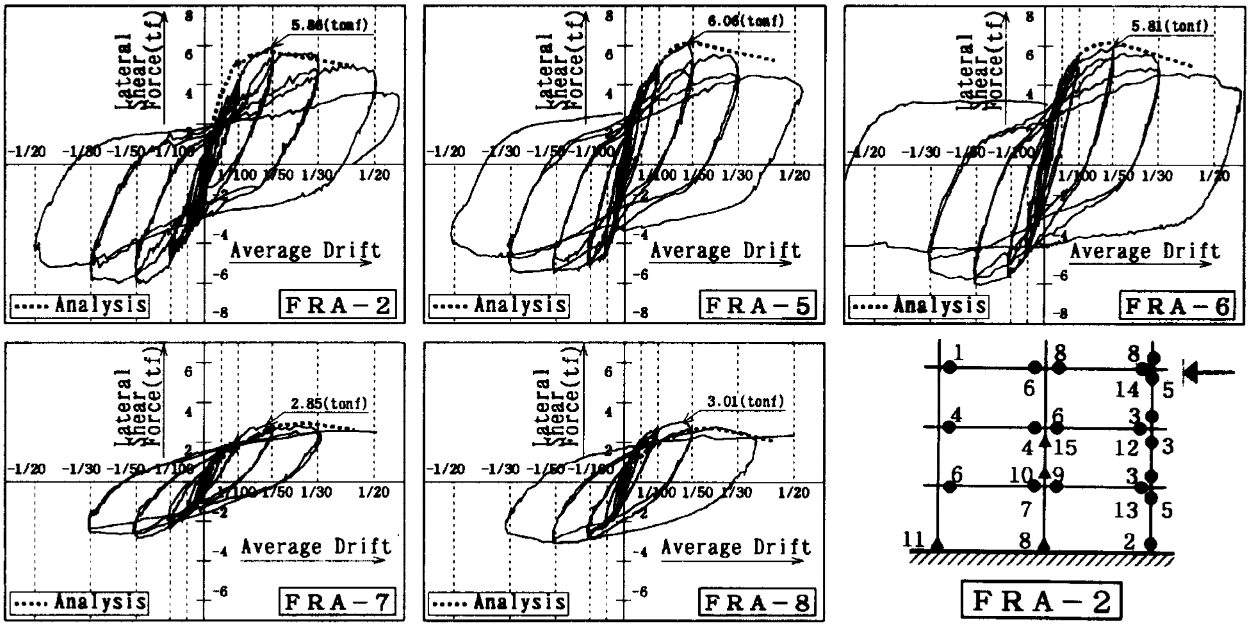


Fig.8. Lateral shear force versus average drift of overall frames
and analytical hinge forming mechanism

Lateral Shear Force versus Average Drift

Envelopes. Obtained cyclic lateral shear force versus average drift curves of all test structures indicated that maximum strengths were recorded at about 1/50 rad. average drift and that strengths gradually decreased due to P-delta effect after the maximum strength without rapid strength degradation (Fig.8). However, negative gradients of strength degradation after maximum strength for the one-span test structures were a little larger due to the lack of interior clumns than those for two span test structures. There was good agreement between the experimental and analytical results of the hysteresis loop envelopes throughout the test for all test structures .

Loops. The hysteresis loops under cyclic lateral loading were of flexure dominant types. These loop shapes for two-span test structures were of spindle type with a slight pinching action. On the other hand, loop shapes for one-span test structures were of spindle type due to large span ratios of beams. There was a tendency that the higher axial force was, the larger quantity of energy dissipation was; [FRA-2 FRA-5 FRA-6] or [FRA-7 FRA-8].

Hinge mechanism. Hinge mechanism obtained from the analytical work is also illustrated in Fig.6 for FRA-2. The first plastic hinge formed at the end of intermediate story beam at 1/100rad. When the bottom end of the lowest story column subjected to compression force yielded at 1/50rad., the lateral strength of overall frame reached the maximum. The total sequence of hinge formation was beam collapse mechanism, however formation of plastic hinges at the lowest end of columns could be observed for tension columns at each story.

Re-distribution of Shear Force for Lowest Story Columns

Relations between shared shear force and story drift of the bottom columns of all test structures were investigated from experimental and analytical results and illustrated in Fig.9. Experimental shear force was obtained from the data of strain gages attached to both sides of longitudinal reinforcement of bottom columns. Shear force of the compression exterior columns increased till a story drift of 1/50 rad. and after the maximum value, shear force decreased gradually to zero at 1/30 rad. due to the P-delta effect. On the other hand, shear forces of the tension exterior columns increased continuously to the final stage while

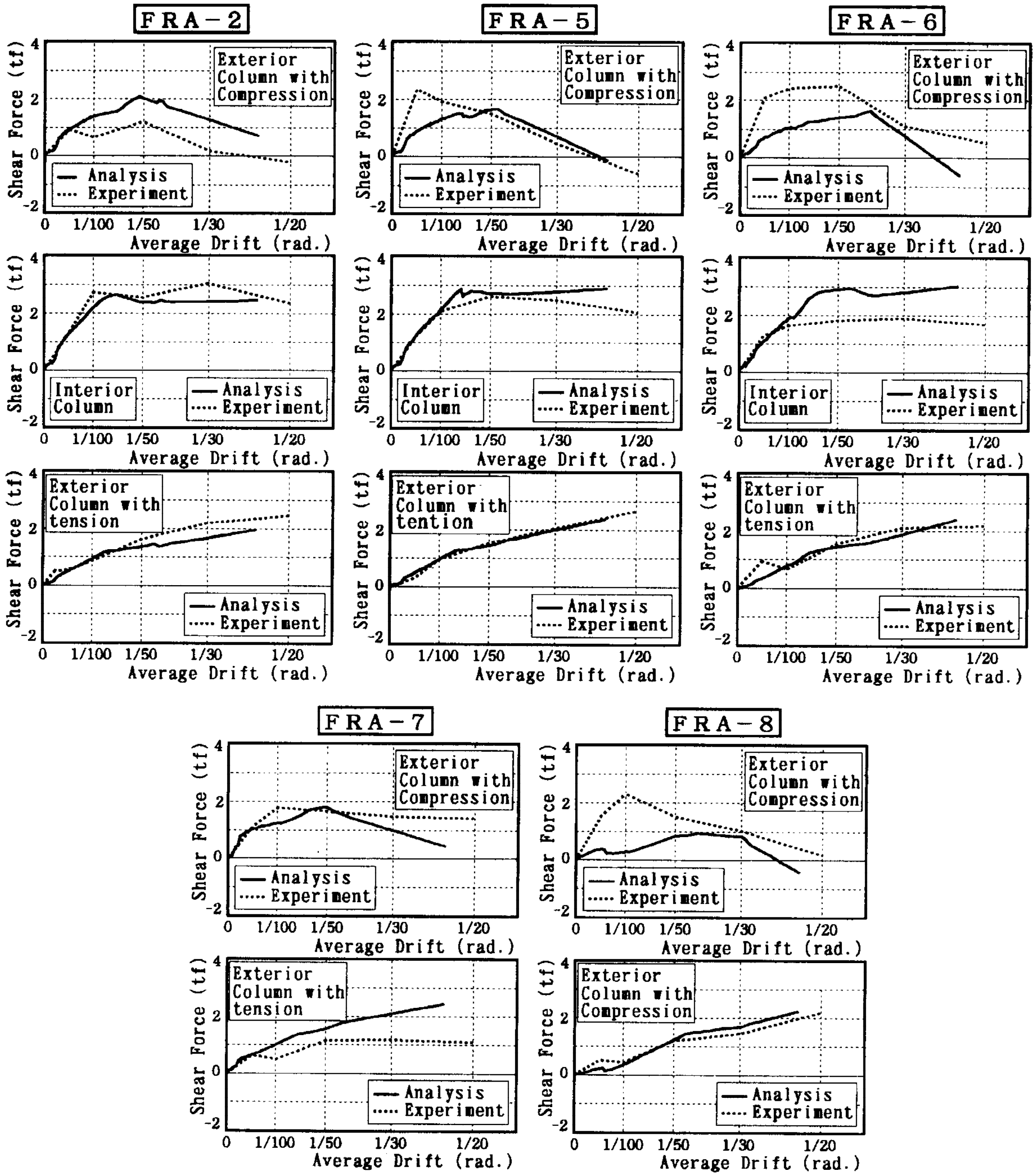


Fig.9. Re-distribution of lateral shear force of external columns

those for interior columns were constant after story drift 1/100~1/50 rad. The effect of concrete strength or number of span was not observed clearly. Both compression and tension exterior columns of test structures without interior column showed the same behavior of two-span test structures. The re-distribution of the lateral shear force from the compression exterior column to the tension external column was the main reason for the three overall frames to have envelope curves without a rapid strength degradation. The analytical results also supported this conclusion and a good agreement between the experimental and analytical results from the initial to the final stage could be obtained.

Axial Force versus Axial Displacement of Exterior Columns

Axial force versus axial displacements of the exterior columns up to lateral story drift of 1/50rad. are shown in Fig.10. Both axial forces and displacements were measured at the top of the exterior column (3rd floor or at 1450mm height of test structure). Spalling of cover concrete caused a degradation of the axial

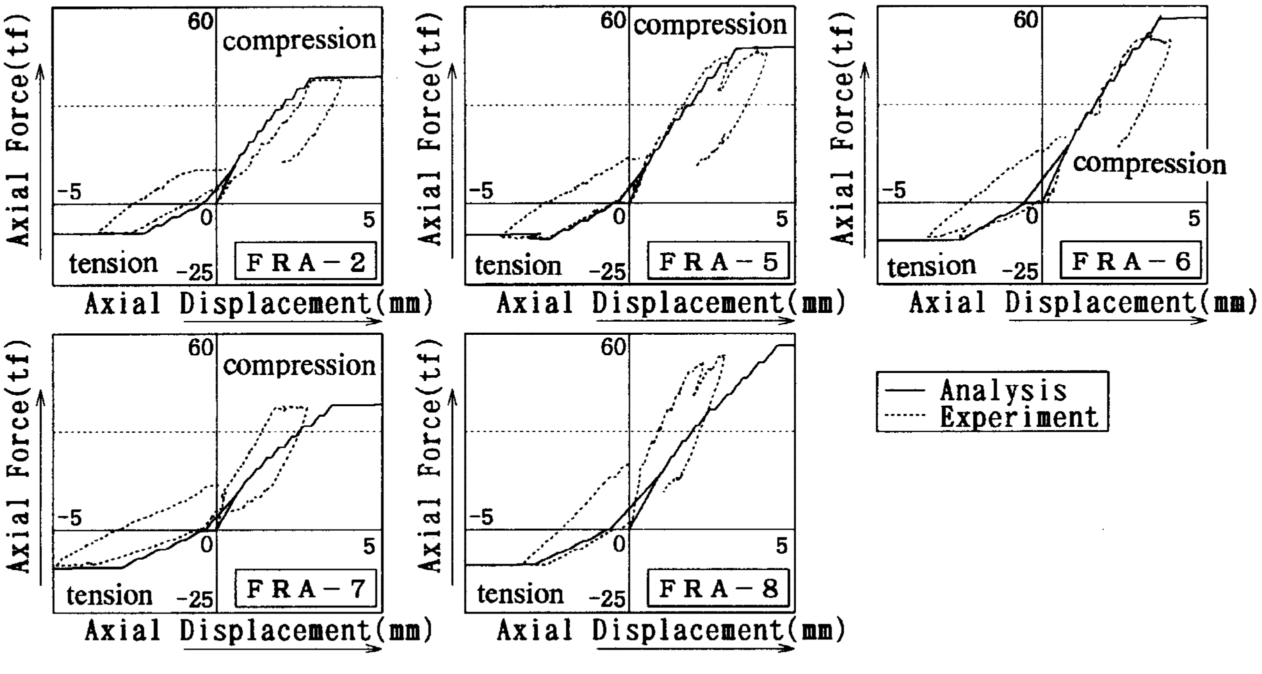


Fig.10. Axial force versus axial displacement of external columns

force carrying capacity, consequently axial displacement increased gradually in compression after axial force reached constant maximum value, indicating that all beams yielded. The maximum axial displacements in tension and in compression were of the same values of less than about 5mm quantitatively.

There was good agreement between the experimental and analytical envelopes of those relations for two-span test structure. But a slight difference between experimental and analytical results in compression zone for one-span test structures was observed due to geometric reasons. Based on the above results vertical restoring force characteristic for test structures subjected to high varying axial force had advantageous results for constructing taller high-rise RC buildings provided that transverse confinement and longitudinal main bar at the center of the exterior column were strengthened adequately.

CONCLUSIONS

Based on the experiments and analyses reported in this paper, the following conclusions can be drawn.

(1) Lateral restoring force characteristics of overall frames were of overall yielding types to the final stage. This dominant type was caused by the beam collapse mechanism.

(2) Lateral envelope curves of restoring force characteristics and hinge mechanism could be evaluated efficiently by the analytical method.

(3) Re-distributions of shear force among columns in the multi-span frames were obtained in details.

(4) The exterior columns continued to support the high axial force without showing brittle behavior at large lateral displacements. The axial load-displacement relationship could be also simulated by analytical method.

(5) The possibility of constructing taller high-rise RC building using members of the same size was confirmed.

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REFERENCES

Inoue K and K.Ogawa (1974).Nonlinear analysis of strain hardening frames subjected to variable repeated loading, *Technical Report of Osaka Univ.*, **1222**, 763-781. *(in Japanese).*

Park.R., F.A.Zahn and T.J.Falcorne (1984).Strength and ductility of reinforced and prestressed concrete columns and piles under seismic loading. *Proc. of 8th WCEE,* **Vol.6**, 513-520.

Teraoka M., Y.Kanoh, K.Hayashi and A.A.Mollic (1993).Experimental study on lower part of External frames in RC high-rise building. *Proc. of Japan Conc. Ins.*, **Vol.15-2**, 1137-1142. *(in Japanese).*

Araki, H., T.Shimazu, H.Yamatoko,, S.Oohara and M.Teraoka (1995).Seismic resistance of multi-span, multi-story frames subjected to varying axial loads. *J. Strc. Eng. AIJ*, **Vol.41B**, 485-492. *(in Japanese).*

Araki, H., T.Shimazu, H.Yamatoko,, S.Oohara and M.Teraoka (1996).Seismic resistance of the lower part of frames for high-rise RC buildings. *J. Strc. Eng. AIJ*, **Vol.42** (in print). *(in Japanese).*