RESTORING FORCE MODEL OF RC COLUMN SUBJECTED TO DYNAMICALLY VARYING AXIAL FORCE

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SUMMARY

Dynamic loading test of reinforced concrete column (RC column) under varying axial force has been carried out. From the test results it is shown that the ratio of the restoring force to the ultimate strength of column which changes at each instance due to the axial force can be approximated by the modified Clough model. On the basis of this behavior the restoring force model of RC column subjected to dynamically varying axial force is proposed. The usefulness of the presented model to analyze RC frame is ascertained by the seismic response analysis of multi-story RC frame under strong ground motion calculated by the model. It is also shown that the varying axial force of column deteriorates the restoring force of RC frame and effects remarkably in some cases on the seismic response of it.

INTRODUCTION

When reinforced concrete frame (RC frame) is subjected to strong ground motion, the axial force of column extremely varies with time in some cases. The restoring force characteristics of column are effected by the dynamically varying axial force and the seismic response of frame is also related closely to this behavior.
To analyze the seismic response of RC frame strictly the restoring force model which can calculate the effects of dynamically varying axial force on the restoring force is required. From this reason the purpose of this study is to obtain the restoring force model of RC column which is subjected to dynamically varying axial force and easily applied to seismic response analysis. The restoring force model is derived from dynamic loading test of RC column. To examine the usefulness of the presented model some numerical analyses of RC frame under strong ground motion are carried out and the effects of the dynamically varying axial force of column on the seismic response deformation and the damage distribution of RC frame are investigated.

2. DYNAMIC AND STATIC LOADING TEST

2.1 RC column specimen

The specimens of dynamic and static loading test are the cantilever RC columns shown in Figure 1 and explained in Table 1 -Table 2. They are fully reinforced by hoop to prevent shear failure of column. The concrete strength, the axial force, the loading rate and the loading hysteresis of the specimens are different among them and the effects of them on the restoring force characteristics of RC column have been examined [Saisho and Suda, 1997], [Saisho et al, 1999].

2.2 Loading conditions

The specimens are subjected to axial load (N) and lateral load (F) as explained in Figure 1. The test setup is shown

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Table 1: Specimens

Specimen	Load	N_0/N_y	L_c	Axial steel	Hoop (%)	σ_c	ε_c	ε_u
SCSR-L-30	S R	0.33	30.0	4-D10	1.3	365	0.36	0.46
SCSI-L-20	S I	0.21	30.0	"	1.3	329	0.41	0.53
SCSR-S-15	S R	0.15	30.0	8-D13	3.2	1146	0.38	0.38
SCDR-L-30	D R	0.33	30.0	4-D10	1.3	365	0.36	0.46
SCDI-L-20	D I	0.20	30.0	"	1.3	303	0.38	0.49
SCDI-S-15	D I	0.15	30.1	8-D13	3.2	1146	0.38	0.38

L_c :column length (cm), σ_c :concrete strength (kgf/cm^2),
ε_c :strain at concrete strength (%)
ε_u :ultimate strain of concrete (%), N_0: initial axial force,
N_y :yield axial force
($N_y=\sigma_c A_c+\sigma_y A_s$, A_c:sectional area of concrete, A_s:sectional area of steel bar)

Description — SC S I-L-20 (1 2 3-4-5)
1:short column specimen
2:static loading (S), dynamic loading (D)
3:loading hysteresis (I-Wave, R-Wave)
4:concrete strength (S:high-strength concrete, L:ordinary concrete)
5:initial axial force ratio (N_0/N_y)

Table 2: Material properties

Properties	D10	D13
σ_y	3.58	3.59
σ_u	5.30	5.87
ε_y	0.19	0.19

σ_y :yield stress (tf/cm^2)
σ_u :tensile strength (tf/cm^2)
ε_y :yield strain(%)

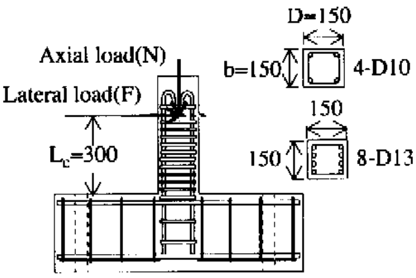


Figure 1: Specimen

in Figure 2. The specimen was set horizontally and fixed to rigid and strong steel frame. The lateral load was given by an actuator which was connected to the specimen by loading beam with universal joints. The axial force of column was loaded by pulling PC bars connected to the top of specimen. The principle of the lever was utilized to pull the PC bar as shown in Figure 2.

In dynamic loading test not only lateral load (F) but also varying axial load (N) were applied dynamically. The dynamically varying axial load was given by the inertia force of the weight attached to the loading beam which vibrated up and down caused by the dynamic axial deformation of column. Figure 3 and Figure 4 show the time histories of the applied lateral deformation (δ_c) and the dynamically varying axial force of column. As shown in these figure the axial force vibrated with the natural period of the loading beam and there was no relation between the lateral deformation and the varying axial force. In dynamic loading test the maximum velocity of lateral deformation was 10cm/second and the maximum strain rate of main reinforcement of the specimen was about 0.1/second -0.3/second.

Static loading test was also executed to examine the loading rate effect on the restoring force by comparing with the dynamic loading test. In static loading test small incremental deformation ($\Delta\delta_c$) was given and the deformation of column was kept stationary for one minute to exclude the loading rate effect on the restoring force. After the loading rate effect of column was fully excluded next incremental deformation was given to the column. Static loading test was carried out by repeating this loading process. In static loading test axial force of column was constant because the weight attached to the loading beam did not vibrate.

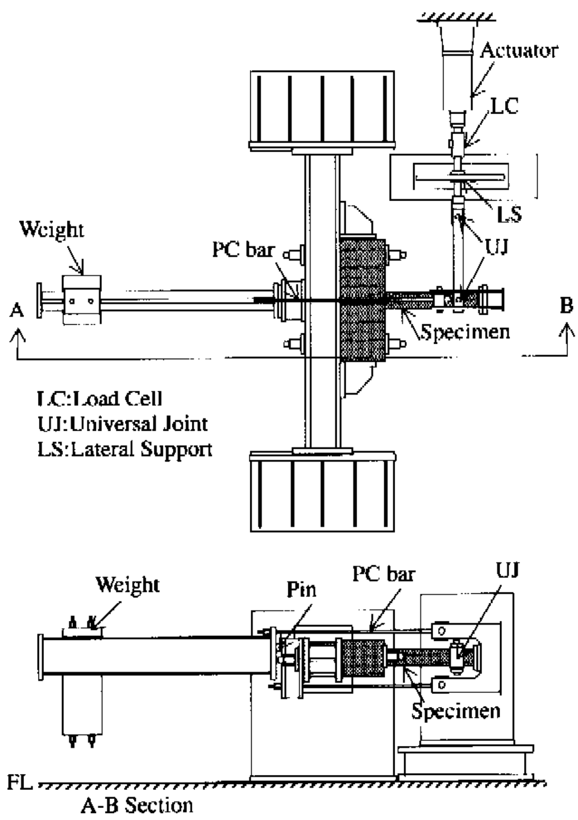


Figure 2: Test setup

2.3 Measurements and data acquisition

The lateral load (F) was measured by a load cell fixed to the actuator. The initial axial force (N_0) was decided by the weight and the lever length. The dynamically varying axial force was obtained from wire strain gages attached to PC bar. The inertia force of loading beam connected to the actuator and the direction of axial force of PC bar, which changes due to the defor-

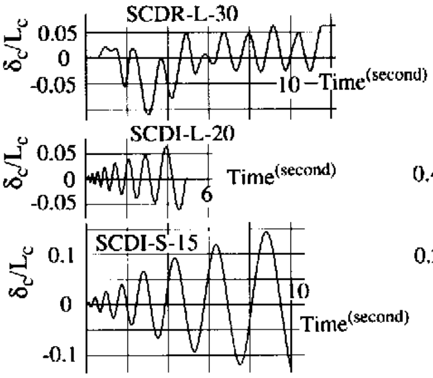


Figure 3:
Time history of lateral deformation

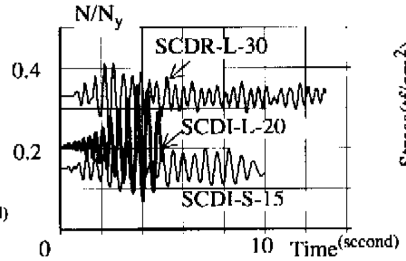


Figure 4:
Time history of varying axial force

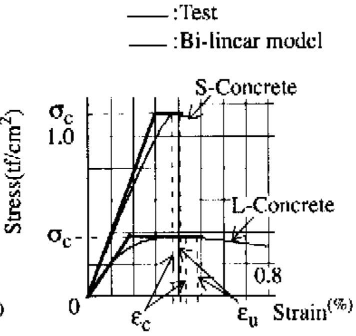


Figure 5:
Stress-strain relation of concrete

mation of column, were considered to determine the loads of column. Deformation of column (δ_c) was measured by linear variable displacement transducers (LVDT). The load and deformation of column were measured in every 1/100 second at the same time under dynamic load. In static loading test the test data were acquired after the deformation of column was kept stationary for one minute and the loading rate effect was fully excluded.

3. TEST RESULTS

3.1 Static loading test results

The load deformation relations of static test are shown with thick lines in Figure 6. M_c (=F L_c+N δ_c) is the bending moment at the fixed column-end which includes the P-Δ effect of axial force. M_{uo} is the ultimate bending strength under initial axial force (N_o). The ultimate bending strength is calculated under the following conditions.

i) The maximum compression strain in the column section is equal to the ultimate strain of concrete (ε_u).

ii) The stress-strain relation of concrete is expressed by the Bi-linear model as explained in Figure 5. The stress-strain relation of steel bar is also assumed to be expressed by the Bi-linear model whose plastic strength is equal to the yield stress (σ_y).

The restoring force expressed by the modified Clough model (Clough model) [Umemura, 1982] is also shown in Figure 6. As well known, the test results are well predicted by the Clough model. According to the result the dynamic restoring force under varying axial load is also derived by the use of the Clough model in the next section.

3.2 Dynamic loading test results

The load-deformation relations of dynamic loading test are shown in Figure 7 with thick lines. The restoring force characteristics of them are very complicated. The dynamically varying axial load of each column is in Figure 9. There is not clear relation between the restoring force in Figure 7 and the varying axial load in Figure 9.

Figure 8 shows the same load-deformation relation whose load (M_c) is divided by the ultimate bending strength (M_u) which changes at each instance due to the varying axial force. In this figure it is seen that the non-dimensional restoring force (M_c/M_u) becomes to be systematical and approximated by the Clough model shown with thin lines. This behavior is also ascertained in N-M relation of column as shown in Figure 10. The real lines and the dotted

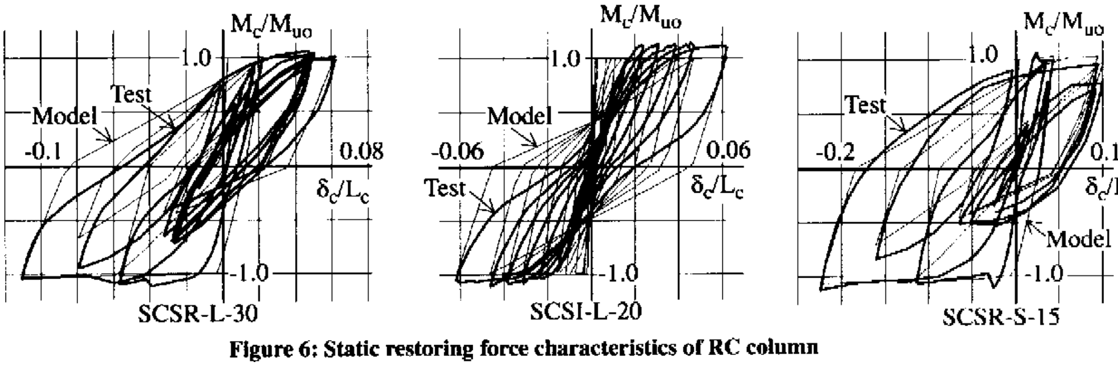


Figure 6: Static restoring force characteristics of RC column

lines show the calculated values and test results respectively. The loading rate effect is also examined in the figures. The authors have pointed out that the loading rate effect of RC column changes according to the hysteresis of plastic deformation and the restoring force increases by 0% -30% [Saisho and Suda, 1990]. To simplify the restoring force model, the loading rate effect of restoring force model is expressed here by 15% increase of restoring force. The N-M relation of dynamic restoring force is expressed by the thin lines in Figure 10. We can see that the test results are well approximated by the thin lines. The thin lines in Figure 7 show the dynamic restoring force whose non-dimensional value (M_c/M_u) is expressed by the Clough model. It is ascertained that the complicated restoring

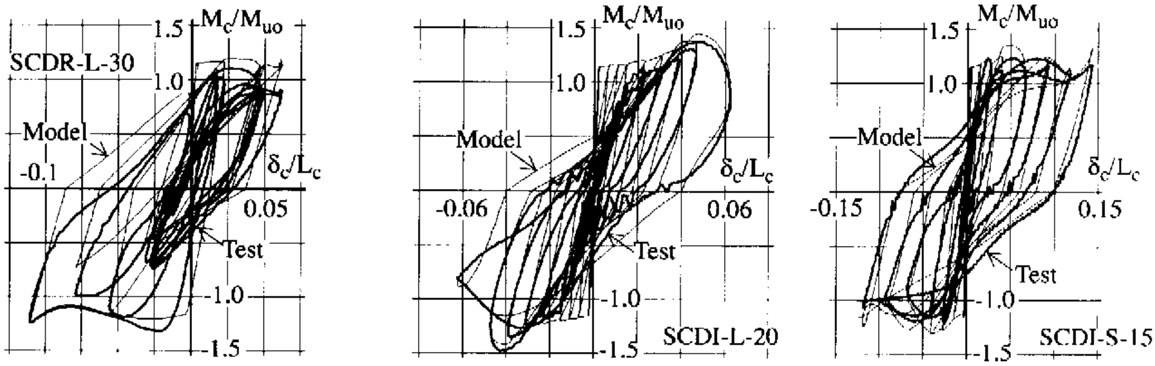


Figure 7: Dynamic restoring force characteristics by the test results and the presented model

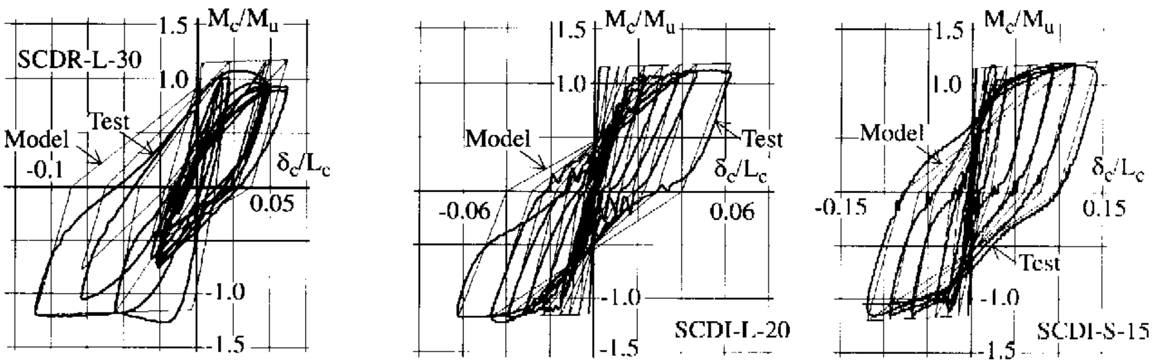


Figure 8: Non-dimensional dynamic restoring force characteristics by the test results and the presented model

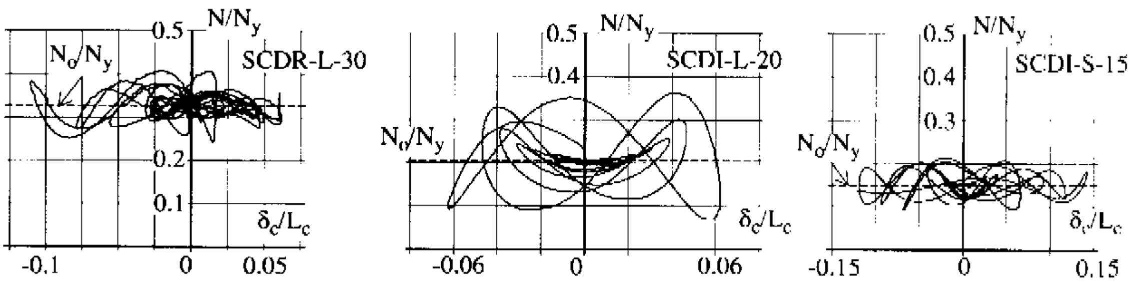


Figure 9: Hysteresis of dynamically varying axial force of RC column

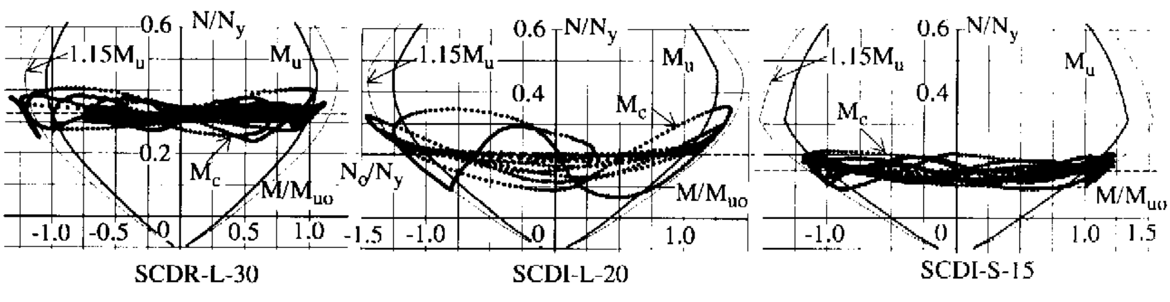


Figure 10: N-M relation by the test result and the presented model

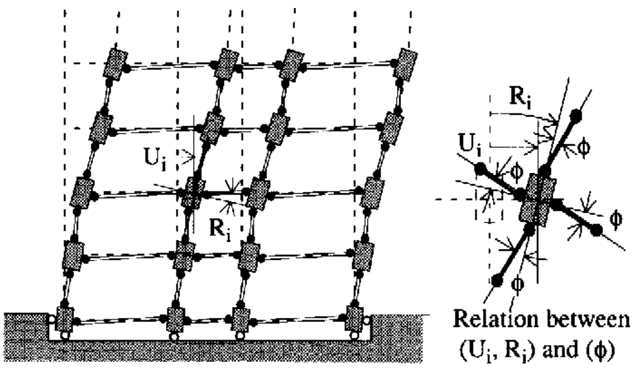


Figure 11: RC frame model for analysis

Table 3: Initial axial force ratio(N_0/N_y)

Story	F5-1	F5-3	F10-3
1	0.208	0.244	0.310
2	0.174	0.205	0.284
3	0.141	0.166	0.258
4	0.107	0.126	0.232
5	0.068	0.080	0.206
6	-	-	0.180
7	-	-	0.154
8	-	-	0.126
9	-	-	0.096
10	-	-	0.061

force characteristics are well predicted by the thin lines.
Accordingly the dynamic restoring force characteristics of RC column under varying axial force can be approximated by the non-dimensional restoring force expressed by the Clough model (the NRF model).

4. RC FRAME ANALYSIS BY PRESENTED RESTORING FORCE MODEL

4.1 Frame model for analysis

Multi-story plane RC frames are analyzed by using the presented NRF model. There are three frames to be analyzed. They are 5-story 1-bay frame (F5-1), 5-story 3-bay frame (F5-3) and 10-story 3-bay frame (F10-3) whose initial axial force ratios of column are in Table 3. The design conditions of these frames are as follows.

i) The frames are designed based on the Japanese seismic design code strictly.

ii) The column over design factor (COF) of every frame except the top floor is 1.2.

iii) The ultimate base shear strength of every frame is 0.25W (W: weight of frame).

iv) The tension reinforcement ratio of every member is 1.5%. The compression concrete strength and the yield stress of reinforcement are 250kgf/cm^2 and 3.0tf/cm^2 respectively.

In the analysis the frames are assumed to be composed of the rigid panel zones and the rigid members with elastic-plastic hinges at the both ends as explained in Figure 11. The mass of frame is concentrated in every panel zone and distributed uniformly in it. Accordingly the deformation of frame can be expressed only by the rotation (R_i, i: number of panel zone) and the horizontal displacement (U_i) of every rigid panel zone. The restoring force characteristics of the elastic-plastic hinge (M_j -ϕ_j, j: number of member) are assumed to be expressed by M_c-δ_c/L_c relation of the presented NRF model.

4.2 Frame analysis under monotonic horizontal load

Static analysis of RC frame under monotonic horizontal load is carried out. In this analysis it is assumed that vertical load and horizontal load are applied to the center of every rigid panel zone. The distribution of the horizontal load (H_i) is decided according to the Japanese seismic design code.
The calculated load-deformation relations are shown in Figure 12. The summation of the horizontal load (H_i) is expressed by the base shear ratio (α) and the deformation of frame is the horizontal displacement of the top floor (U_n). In the calculation shown by the thin lines the varying axial force is neglected and all axial forces of column are assumed to be constant. On the other hand the calculation shown by the thick lines includes the varying axial force of column. There is not clear difference among the calculated results except the load-deformation relation of F10-3 frame which is analyzed considering the varying axial force of column.
Figure 13 shows the distribution of plastic deformation in the frame at U_n/L=0.02. The thick lines near the member-end means the rotation of the elastic-plastic hinge. The numbers in the figure are the rotation of the column-end in the first story. We can see the

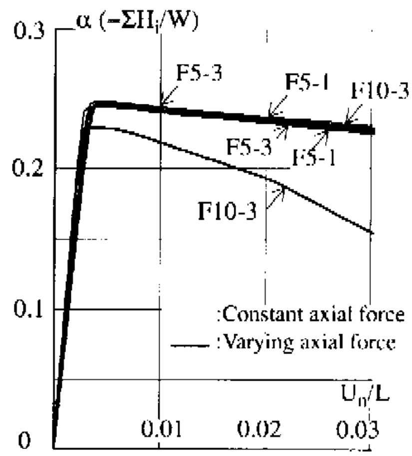


Figure 12:
Load -deformation relation of frames under monotonic horizontal load

plastic hinges appear at every beam-end as intended in the design of frame except F10-3 frame calculated under the condition of varying axial force. The plastic deformation of F10-3 frame analyzed by including the varying axial force is concentrated in the low stories and appears in the outer-column. This behavior is related to the deterioration of the ultimate horizontal strength of frame as explained in Figure 12. From this reason the varying axial force of column can not be neglected in the analysis of 10 story RC frame.

4.3 Frame analysis under strong ground motion

The seismic response of the three frames are analyzed by using the NRF model. The natural period of F5-1 frame, F5-3 frame and F10-3 frame are 0.78second, 0.82second and 0.95second respectively. The following conditions are assumed in the calculation.

i) The rotational inertia of the rigid panel zone in the frame model is decided by assuming the mass distributes uniformly in the panel zone.

ii) The damping of frame is expressed by the Rayleigh damping and the damping ratios of the first mode and the second mode are 3%.

iii) The vertical inertia force is neglected because the vertical deformation of frame is very small. Accordingly the varying axial force of column is given only by the shear force of beam.

iv) The input ground motion is horizontal motion and an artificial ground motion whose seismic response spectrum is shown in Figure 14. This ground motion, whose seismic intensity is equal to the double intensity of El Centro NS(1940) ground motion, is used to investigate the fully damaged response behavior of RC frame.

The numerical analysis is carried out by the step-by-step integration procedure assuming that the acceleration varies linearly during the increment. The time increment of this calculation is 10^{-3} second. In the analysis it has been ascertained that the error of the energy balance equation remains less than 0.01% compared with the input energy in every incremental step.

The calculated results are shown in Figure 15-Figure 19. Figure 15 shows the distribution of the plastic deformation of frame. The length of thick line in the figure means the maximum rotation of the elastic-plastic hinge in the

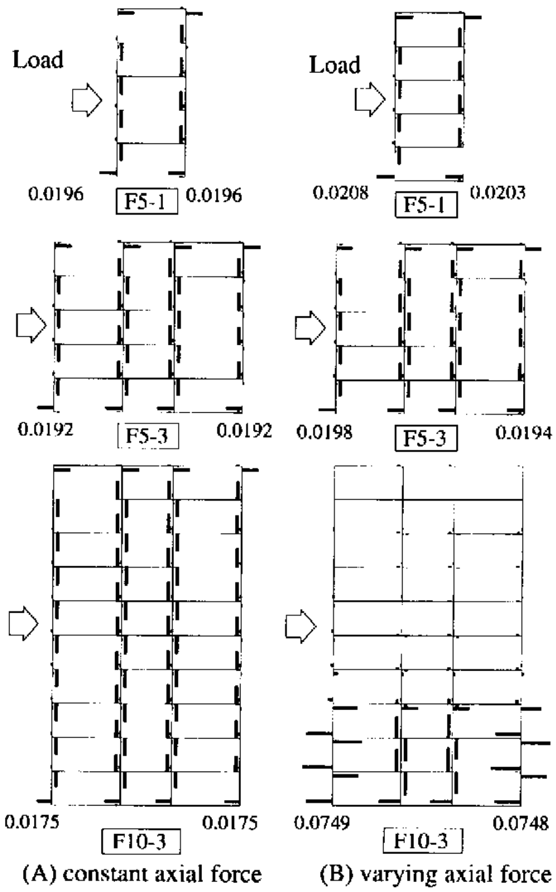


Figure 13: Distribution of plastic deformation under monotonic horizontal load

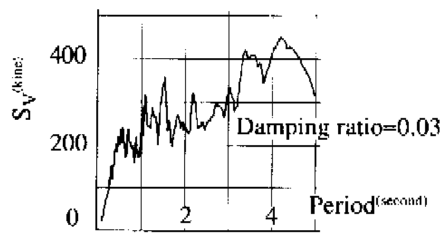
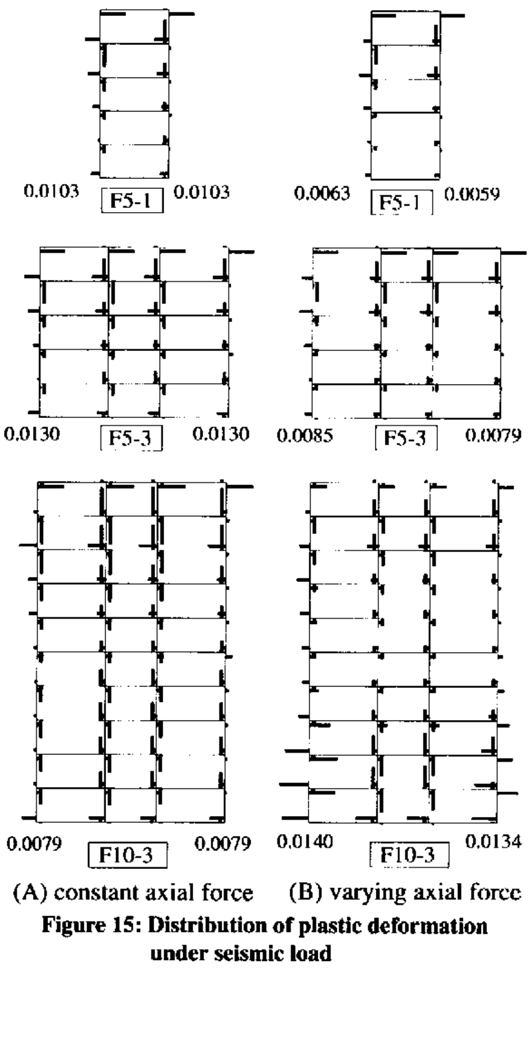


Figure 14: Seismic response spectrum of input ground motion

seismic response procedure. Figure 15(A) and Figure 15(B) are the plastic deformation calculated under the conditions of constant axial force and varying axial force respectively. Between the two responses of 5 story frames (F5-1, F5-3) there is no clear difference. But the responses of 10 story frame (F10-3) we can see the quite different distribution of plastic deformation. That is, the plastic deformation of 10 story frame is concentrated in the low stories because of the dynamically varying axial force of column. If the dynamically varying axial force of column is neglected in the response analysis of 10 story frame, the damage concentration in the low stories of frame does not appear.
This behavior is also explained in Figure 16 which shows the deformed shape of frame. The deformations in this figure are amplified by 20 times. Figure16(A) and Figure16(B) are the response deformations under the conditions of constant axial force and varying axial force of column respectively. From the difference between the two response deformations in Figure16(A) and Figure16(B) we can see the deformed shape of frame and the deformation in the low stories are clearly influenced by the dynamically varying axial force of column.
The restoring force characteristics of the first story column are shown in Figure 17-Figure 19. In these figures M and ϕ are the bending moment and the rotation of the elastic-plastic hinge. The thick lines in Figure 17 are the restoring force under dynamically varying axial force and the thin lines shows the restoring force under the condition of constant axial force. Figure 18 is the dynamically varying axial force and Figure 19 shows the N-M relation of the elastic-plastic hinge. The dotted lines and the real lines in Figure 19 indicate the seismic response of column and the N-M relations respectively. We can see the axial forces of the outside columns vary extremely. The restoring force characteristics of them are very complicated and deteriorate due to the varying axial force. These behaviors are the causes of the concentration of damage in the seismic response of frame as shown in Figure15-Figure 16 and related to the deterioration of earthquake resistant capacity of RC frame.

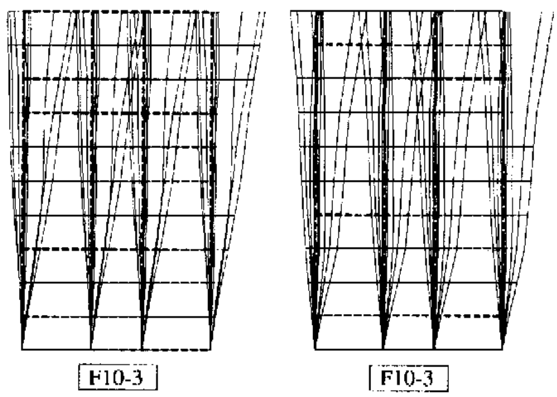
5. CONCLUSIONS

i) The presented NRF model is the restoring force model of RC column that the non-dimensional restoring



(A) constant axial force (B) varying axial force

Figure 15: Distribution of plastic deformation under seismic load



(A) constant axial force (B) varying axial force

Figure 16: Deformed shapes of RC frame under seismic load

force divided by the ultimate strength under the axial force at each instance is expressed by the Clough model. It is ascertained that the NRF model can predict well the restoring force characteristics of RC column under dynamically varying axial force by comparing with the dynamic loading test results.

ii) The usefulness of the NRF model has been shown by applying it to the multi-story frame analysis. From the calculations it is also pointed out that the response behaviors of RC frame under monotonic horizontal load and under strong seismic load are remarkably influenced by the varying axial force of column in some cases.

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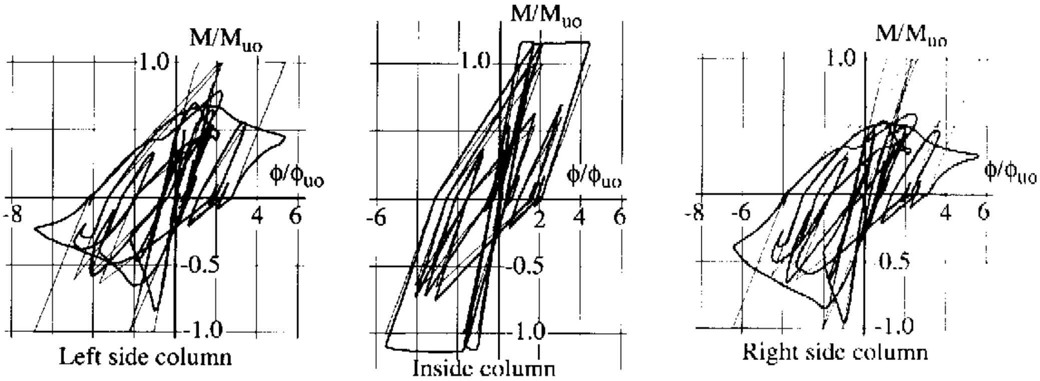

Figure 17: Restoring force characteristics of the first story columns (F10-3)

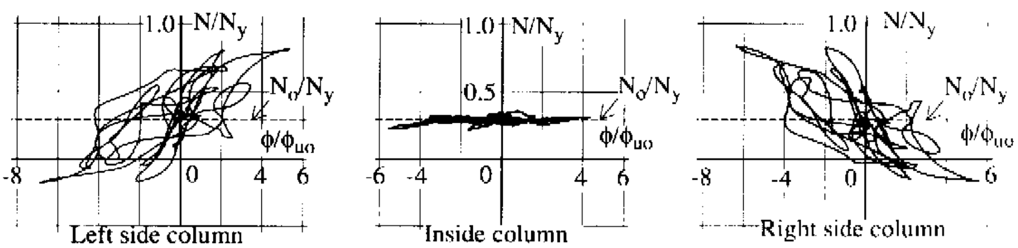

Figure 18: Varying axial force of the first story columns (F10-3)

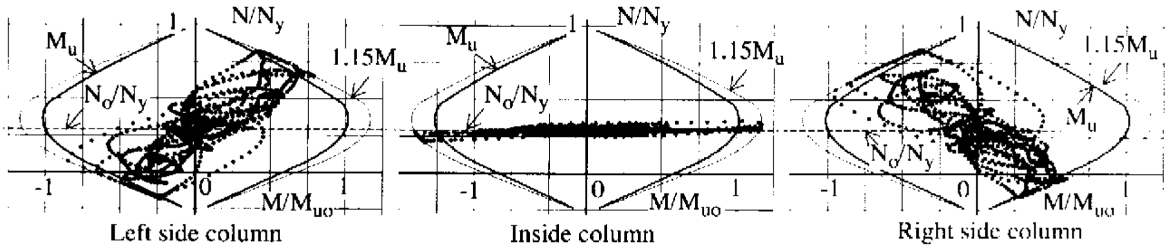

Figure 19: N-M relation of the first story columns (F10-3)