EVALUTION AND ASSESSMENT OF AXIAL FORCE FLUCTUATION IN CORNER COLUMNS OF MOMENT-RESISTING R/C DUCTILE FRAME DURING INTENSE SEISMIC ACTION

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ABSTRACT :

Significance of fluctuation of axial force produced within columns in a high-rise reinforced concrete building is examined and discussed, the seismic design of which is carried out based upon a moment-resisting ductile frame concept. A set of structural models are generated associated with variation of the strength of frame determined from the base shear coefficient in the structural design. A series of dynamic response analyses have been carried out. Through the analyses, the greater is the strength of frame specified, the greater fluctuation of axial force within columns is obtained, which is, however, not increased in a direct proportion to the prescribed strength of frame and remains constant when the strength of frame is taken moderately great. In conclusion, in the seismic design of high-rise reinforced concrete buildings with the concept of moment-resisting ductile frame, it is recommended that a sufficient level of strength of frame should be ensured not generating large deflection responses and not producing excessively large inelastic hinge rotations at the ends of beam. When the strength of frame is taken moderately great, the fluctuation of axial forces observed for columns within the building will not be yielded excessively great but will remain invariant with moderate fluctuation, not being increased extremely as speculated from the results of a static analysis.

KEYWORDS: reinforced concrete structure, high-rise building, seismic response, moment-resisting frame, ductile frame, axial force fluctuation

1. INTRODUCTION

For high-rise reinforced concrete buildings in seismic regions, the concept of moment-resisting ductile frames has been widely employed in the structural design. The well-designed moment-resisting ductile frame developed with the concept of weak-beam strong-column can reveal a considerable energy dissipation capacity generating flexural yielding hinges at the ends of beam, and it allows maximum floor space utilization. With a high capacity of energy dissipation expected for the moment-resisting ductile frame, the seismic responses of the building when subjected to an intense seismic action indicate good performance not producing excessively large responses.

It is well known that the following two issues are of significant for the moment-resisting ductile frame design when applied for high-rise reinforced concrete buildings. One is the fluctuation of axial forces within columns when subjected to lateral seismic force, in particular, within the corner columns. The other is the bi-axial bending effects for the columns when subjected to a bi-directional seismic action. Herein the study presented, major emphasis is placed on the fluctuation of axial forces when subjected to an intense seismic action. It is widely realized that the large fluctuation of the axial forces upon the columns can produce brittle failures caused by an excessively large compressive axial forces affecting the ductility of reinforced concrete columns.

Within the study herein, we examine the correlation of fluctuation of axial forces associated with the strength of frame specified in the seismic design for high-rise reinforced concrete buildings. On the one side, when the greater is taken the design frame strength, the greater axial force fluctuation is produced from the beam hinges, while the less number of hinges are expected to be generated within the frame during the seismic excitation. On the other side, when the less is taken the design frame strength, the less axial force fluctuation is produced from beam hinges, while the greater number of hinges are generated.

A structural model of twenty-four storied high-rise reinforced concrete building with its height of 83.3 in meter is employed for the numeral evaluation. Obviously increase of compressive axial force is critical, we generally examine the corner columns. Furthermore, since the columns at the lower stories will suffer greater fluctuation of axial forces than those at the higher stories, we examine and discuss the fluctuation of axial forces of columns at the first story exclusively.

2. ANALYTICAL MODELS OF MOMENT-RESISTING FRAME BUILDING

2.1 General Description of Analytical Model

Analytical models employed within the study are established in accordance with a structural design practice in Japan making some simplification upon a real structural design. The general dimension of the building for analysis is illustrated in Fig. 1, being six and four spans along the longitudinal and transverse directions, respectively, with span length of 6.6 m. The story height is 3.3 m invariant from the 4th to 24th stories, 4.5 m for the second and third stories, and 5.0 m for the first story with the total building height equal to 83.3 in meter.

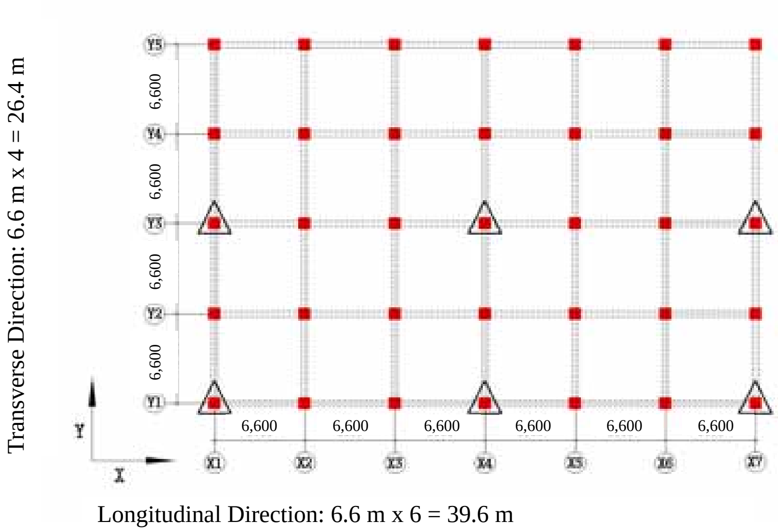


Figure 1. Structural plan layout for the twenty-four storied model building.

The cross-section dimensions of structural constituent members are tabulated in Table 1, within which the compressive strength of concrete is indicated. The contribution of slab to enlarge the beam stiffness is simply counted taking the contribution coefficient 1.25 for the beams with slab on one side, and 1.50 for the beams with slabs on both sides. The load of structure including both dead and live loads is taken as an average weight of 14 kN/m^2 for a simple estimation.

Table 1 Concrete Strength and Cross-Sectional Dimensions of Columns and Beams

Story Level	Compressive Strength of Concrete in N/mm^2
1-6	60
7-12	54
13-18	48
19-24	42

Story Level	Dimensions of Columns (BxD) in mm
1-3	950 x 950
4-12	900 x 900
13-18	850 x 850
19-24	800 x 800

Floor Level	Dimensions of Beams (bxD) in mm
2-3	500 x 850
4	550 x 800
5-19	400 x 750
20-RF	400 x 700

2.2 Analytical Models with The Specified Frame Strength

As previously described, we place our emphasis on the correlation of fluctuation of axial forces within the moment-resisting ductile frame with the frame strength specified within the seismic design. We produce a set of analytical models associated with variation of frame strength, strength of which is defined by a set of design base shear coefficients of 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18 and 0.20. In addition to a set of eight structural frames, for reference, we produce another analytical model within which load-deflection characteristics for beam elastic. Since yielding hinges shall not be produced within columns, we ensure a sufficient strength for columns (AIJ Guidelines 1994; Kubo et al. 2001), and we examine hinges not generated throughout dynamic response analyses.

The required strength for beam members is computed in accordance the elastic static analysis. Firstly, the load distribution along the height of building is specified. In the study presented hereby, simple manners of examination are accepted that a ratio of 0.05 to the base shear is concentrated at the top of the building, and the other, i.e., the ratio of 0.95 to the base shear, is distributed along the building with the inversed triangular shape. Other ratios of 0.10 and 0.20 have been studied, and we have reached the conclusion that the ratio of 0.05 will determine the rational strength for beams and columns giving rational responses for the specified seismic excitation.

3. NUMERICAL MODELING OF ANALYTICAL FRAME

3.1 Column Modeling

We use the Multi-spring modeling (Li et. al. 1993 and 1999) for the columns, with which we can take the interaction among the bi-axial bending moments and the varying axial load into consideration. In this study, since we examine exclusively flexural responses, the shear behavior is forced to be elastic. Further the beam-column connection is modeled by partial rigid zone for analytical simplicity.

3.2 Beam Modeling

We employ the uniaxial spring model for beams, using two nonlinear rotational springs at the both ends, and elastic shear and axial springs located in the mid-span. We specify the tri-linear moment-rotation relationship shown in Fig. 2 for the rotational springs placed at the ends of the beams. The prescribed moment-rotation primary curves are uniquely established by determining the yielding moment M_y of the spring. Herein, the cracking moment M_c is set one third of M_y invariant among beams. The initial stiffness is calculated from the geometrical dimensions of the beam. The stiffness after the cracking is taken as 1/4 of the initial stiffness, and that after the yielding is taken as 1/1000, respectively.

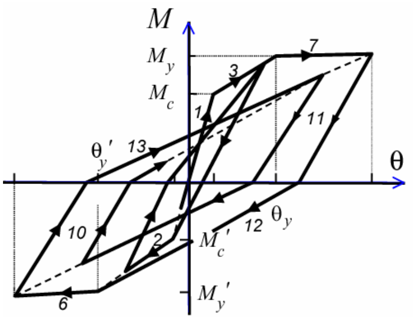


Figure 2. Moment-rotation hysteresis model established for the uniaxial spring of beams.

The moment M_y is determined from the pushover analysis. The moment M_y is obtained from the flexural moment response obtained for the corresponding ends of beam when the base shear falls in the specified values, i.e., the base shear coefficient Co equals 0.06, 0.08, 0.10 and others. We ensure the minimum flexural capacity of 180 kNm for every beam for the design against the vertical loads.

4. FLUCTUATION OF AXIAL FORCES OBTAINED FROM THE PUSHOVER ANALYSIS

4.1 Equivalent Lateral Deflection

Based on the specified lateral load distribution along the height of building, the acting point of the resultant lateral force is close to 2/3 of the total height of the building. The resultant lateral force point is closely located at the 17th floor level. Hereinafter the displacement at this acting point is defined as the equivalent frame displacement.

4.2 Analytical Results Obtained from The Static Pushover Analysis

The load-deflection primary curves obtained for the set of analytical models are illustrated in Fig. 3. Since within the study we keep the geometrical dimensions of columns and beams unchanged among the analytical models, the initial stiffness is common among the models. On observation upon the plots of the primary curves, we can estimate the equivalent frame displacement when the yielding mechanisms are produced about 1/260, 1/220, 1/170, 1/140, 1/120, 1/110, 1/90 and 1/70 in deflection angle for the set of analytical models, respectively.

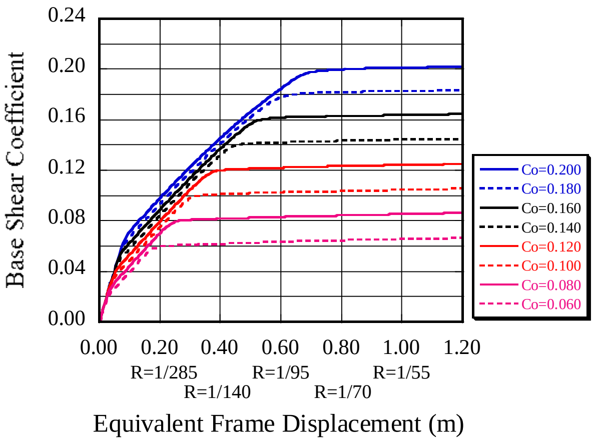


Figure 3. Load-deflection primary curves obtained from the pushover analysis
for a set of analytical models with variation of the design base shear coefficients.

We compute the overturning moment produced by the lateral loads. For an analytical model, within which the design base shear coefficient equals 0.10, the resultant overturning moment at the base of structure is 2,080 MNm. The fluctuation of axial forces in the longitudinal direction is consequently 52,600 kN yielded tensile and compressive by the group of columns within the X1 and X7 frames.

5. FLUCTUATION OF AXIAL FORCES OBTAINED FROM THE DYNAMIC RESPONSE ANALYSIS

5.1 Input Earthquake Ground Motions for Dynamic Response Analysis

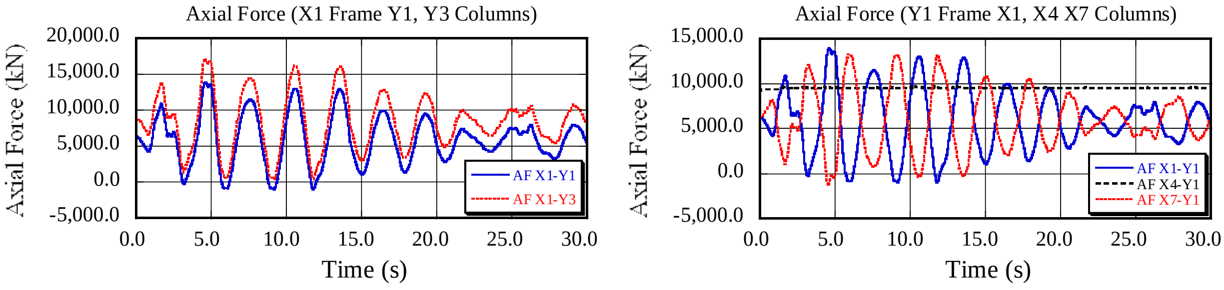
In practical seismic design of high-rise buildings in Japan, we examine the seismic performance against an extremely rare seismic action. When using real earthquake ground motions, we modulate the amplitudes of motion so as the peak ground velocity equal to 50cm/s. Herein the study, we use eight components of real earthquake ground motions for dynamic response analysis listed in Table 2.

Table 2 PGA and PGV of Input Earthquake Ground Motions for Response Analysis

	El Centro Imperial Valley Eq. (1940)		Taft Kern County Eq. (1952)		Hachinohe Tokachi-oki Eq. (1968)		Tohoku Univ. Miyagi-ken-oki Eq. (1978)	
	S00E	S90W	N21E	S69E	NS	EW	NS	EW
PGA (cm/s^2)	510.78	284.58	485.75	496.67	333.43	238.51	356.98	367.43
PGV (cm/s)	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Original PGA	341.70	210.14	152.70	175.95	229.65	180.23	258.23	202.57

5.2 Fluctuation of Axial Force Observed in The Columns during The Dynamic Responses

Fluctuation of axial force obtained during a dynamic response analysis is shown in Fig. 4. The analytical model employed herein is that of which design base shear coefficient Co is taken as 0.12, and the earthquake ground motion of El Centro S00E component is used. Figure 4.(a) shows the fluctuation of axial forces for the X1-Y1 and X1-Y3 columns within the X1 frame in the structural plan (Fig. 1). These two columns reveal an identical phase with each other and almost identical amount of fluctuation as well. Figure 4.(b) shows that for the X1-Y1, X4-Y1 and X7-Y1 columns within the Y1 frame. Two corner columns indicate an identical manger of fluctuation with each other except the phase, while the X4-Y1 column reveals less significant fluctuation as expected.



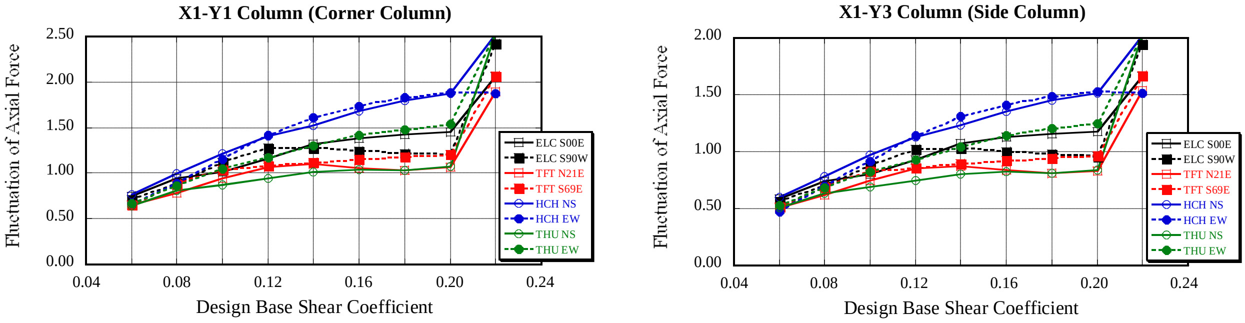
(a) Columns X1-Y1 and X1-Y3.

(b) Columns X1-Y1, X4-Y1 and X7-Y1.

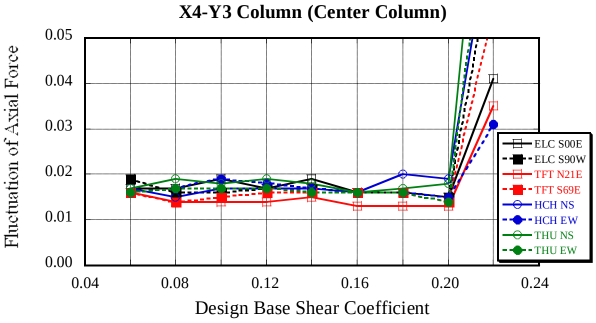
Figure 4. Fluctuation of axial forces obtained during a dynamic response analysis for the analytical case that the frame strength Co equals 0.12 and earthquake ground motion input is the El Centro S00E component: (a) for the columns X1-Y1 and X1-Y3; and (b) for the column X1-Y1, X4-Y1 and X7-Y1.

5.3 Fluctuation of Axial Force Associated with Variation of Frame Strength

Herein the study, we evaluate and examine the correlation of fluctuation of axial force produced in the columns within a moment-resisting frame associated with variation of the strength of frame. The strength of frame is expressed by the design base shear coefficient. The correlation of fluctuation of axial force associated with variation of frame strength is plotted in Figs. 5.(a) to 5.(c) for columns X1-Y1 (corner column), X1-Y3 (side-column) and X4-Y3 (inner column), respectively. We normalize the fluctuation of axial force by the load N_L, where N_L is obtained from the initial axial load produced by the vertical loads.



(a) Column X1-Y1. (b) Column X1-Y3.



(c) Column X4-Y3.

Figure 5. Fluctuation of axial force obtained from dynamic response analyses associated with the variation of frame strength of structure:
(a) for the column X1-Y1; (b) for the column X1-Y3; and (c) for the column X4-Y3.

Observation upon the plots of the correlation of fluctuation of axial forces in columns associated with the strength of frame leads the remarks as in the following:

(1) For the columns X1-Y1 (corner column) and X1-Y3 (side column), fluctuation of axial force is realized of much significance, while that for the column X4-Y3 (inner column) is less significant. The fluctuation of axial force in the column X4-Y3 is less than 0.02 compared to the initial axial force N_L, except the case when the strength of beam is taken infinite (elastic);

(2) The ratio of fluctuation of axial force compared to the initial axial force N_L for the column X1-Y1 is significant, since firstly for the corner columns N_L is less for other columns, and secondly it leads to the evidence that excessively large compressive axial forces are produced. Tensile axial forces will be created, when the ratio falls in the range greater than unity; and

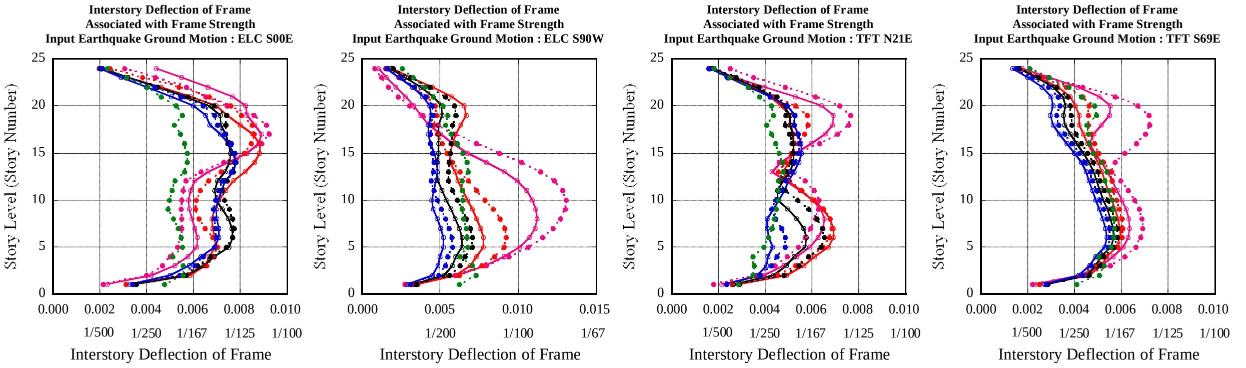
(3) The greater taken is the strength of frame, in general responses, the greater found is the fluctuation of axial forces for the columns X1-Y1 and X1-Y3. Based on the static pushover analysis, the fluctuation of axial force will be in proportion to the strength of frame. We can, however, realize the evidence that the fluctuation of axial force tends to keep constant not correlated with the strength of frame when the design base shear coefficient is taken greater than

0.14. We cannot recognize the evidence for responses when we employ the Hachinohe components for earthquake input in dynamic response analysis.

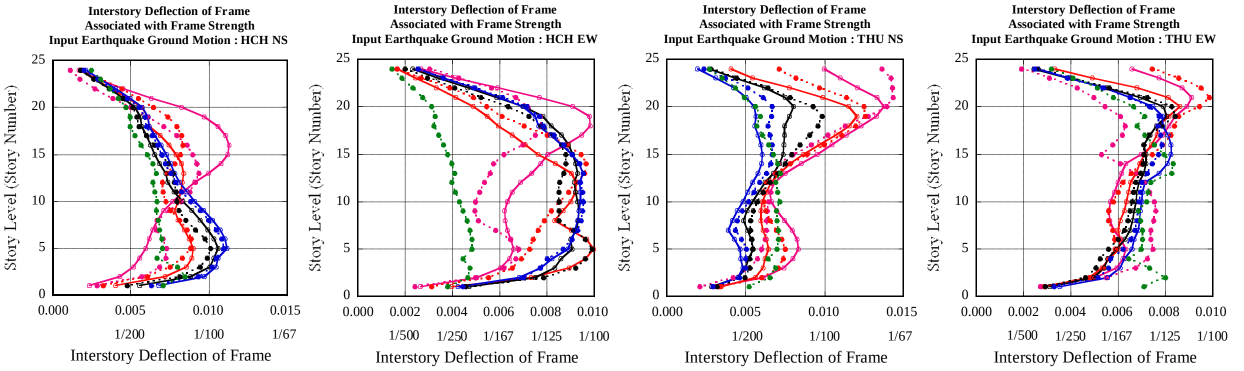
5.4 Frame Deflection Associated with Variation of Frame Strength

We evaluate the deflection of frames during intense earthquake ground motions. Herein the study, we examine the interstroy deflection angle obtained by the dynamic response analyses. In the design practice in Japan, we take the interstory deflection response as one of important design criteria. The response deflection should not be excessively large not revealing structural damages within the frame and unstable conditions caused by a large deflection and/or deformation as well. In the Japanese seismic design, commonly the maximum interstory deflection angle should not be greater than 1/100 for an extremely rare seismic event.

In Figs. 6, a set of frame deflection obtained during the dynamic response analysis associated with variation of strength of frame are summarized. Figures 6.(a) to 6.(h) show the interstory deflection angles for the earthquake ground motions listed in Table 2, respectively. Within the figures, responses associated with design frame strength of Co from 0.06 to 0.20 and an additional case with beam assumed elastic, respectively.



(a) El Centro S00E. (b) El Centro S90W. (c) Taft N21E. (d) Taft S69E.



(e) Hachinohe NS. (f) Hachinohe EW. (g) Tohoku Univ. NS. (h) Tohoku Univ. EW.

Figure 6. Interstory deflection responses obtained from dynamic response analyses associated with the variation of strength of frame with a set of input earthquake ground motions: (a) ELC S00E component; (b) ELC S90W component; (c) TFT N21E component; (d) TFT S69E component; (e) HCH NS component; (f) HCH EW component; (g) THU NS component; and (h) THU EW component.

- - ● - - Co = 0.06
—○— Co = 0.08
- - ● - - Co = 0.10
—○— Co = 0.12
- - ● - - Co = 0.14
—○— Co = 0.16
- - ● - - Co = 0.18
—○— Co = 0.20
- - ● - - Elastic

6. CONCLUDING REMARKS

Fluctuation of axial force produced on the columns within the moment-resisting ductile frame is examined and discussed. The fluctuation is evaluated associated with variation of the strength of frame determined from the design base shear coefficient. The conclusive remarks obtained within the study presented herein can be summarized as follows:

(1) For high-rise reinforced concrete buildings, the seismic design of which is based upon the weak-beam and strong-column concept yielding a moment-resisting ductile frame, the fluctuation of axial forces of columns in lower stories are significant. In particular, columns located at the corner of the building reveal a large fluctuation of axial force produced by the overturning moment induced by lateral forces during seismic action. Those columns are subjected to excessively large compressive forces when subjected to an intense seismic action;

(2) It is found in the static pushover analysis the greater is taken the strength of frame, the greater is the fluctuation of axial forces in the columns. The fluctuation of axial forces obtained from dynamic response analyses reveals to remain constant when the strength of frame is taken large, i.e., in the analytical models herein, when the design base shear coefficient is taken greater than or equal to 0.12, the fluctuation of axial force shows the evidence that it remains constant regardless the strength of frame; and

(3) When the strength of frame is taken less, it is expected that the fluctuation of axial forces will be less indicating a smaller amount of compressive forces for the columns of building. The responses of structure are, in general, yielded greater as the strength of frame is taken less. In particular, an excessively large inelastic deformation is produced at the ends of beams. In the evaluation herein, ends of beam reveal their inelastic responses with greater than 10 expressed by the ductility factor when the design base shear is taken small.

Evaluated and examined is the significance of axial force fluctuation produced within the columns in reinforced concrete high-rise buildings, the seismic design of which is carried out based upon a moment-resisting ductile frame concept. The less is the frame strength, the less fluctuation of axial forces in columns is found. The greater interstory deflection responses, however, can be yielded, and an excessively large inelastic deformation is forced to be produced at the ends of beam. The greater is the frame strength specified, the greater axial force fluctuation is obtained, which, however, remains constant when the frame strength is taken a sufficiently large. In conclusion, it will be recommended that a sufficient level of frame strength should be ensured not producing excessively large inelastic hinge rotation at the ends of beams. When the strength of frame is taken great, the fluctuation of axial forces on the columns within the building will not be expected excessively large but will remain at the specified amount of fluctuation, not being increased with the greater strength of frame as estimated based upon a static analysis.

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