

AXIAL LOAD OF COLUMNS WITHIN A MOMENT-RESISTING DUCTILE R/C BUILDING SUBJECTED TO INTENSE BI-DIRECTIONAL EARTHQUAKE GROUND MOTIONS

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SUMMARY

The objective of the study herein is to assess the fluctuation of axial load of columns within a momentresisting medium-rise reinforced concrete building during strong earthquake ground motion through a nonlinear dynamic analysis employing a three-dimensional analytical building model. In this study, excitation of the ground motion is considered in the two different schemes: first expressed by a single component of motion, and second by two components of motion representing two horizontal components of strong ground motion. It is concluded that the fluctuation of axial load of columns under intense earthquake excitation is of significance in the seismic design on reinforced concrete buildings based on an ultimate strength concept. The fluctuation of axial load is verified critical in the corner columns. It is revealed that the loading scheme that one component of motion is applied to the building along its diagonal direction can generate a critical situation evaluated when applying two components of motion under realistic earthquake excitation.

INTRODUCTION

Design procedure for earthquake resistance of reinforced concrete (RC) buildings based on ultimate strength concept is widely employed for medium- and high-rise RC buildings in Japan. The concept of the design is, in general, based on the two points as follows: (1) first to ensure a certain level of frame resisting strength as minimum as required for constituent structural components; and (2) secondly to ensure a ductile total yield mechanism within a building with which a significant amount of vibration energy can be dissipated yielding the seismic responses less during strong seismic actions [1].

Within the study, major attention is focused on RC buildings that have been designed in accordance with the practice commonly and widely utilized in Japan. Fluctuation of axial load of columns within a moment-resisting medium-rise RC building with the weak-beam and strong-column concept is examined. Since the building is designed so as the frame strength as small as required in both longitudinal and transverse directions of building, the consideration of bi-directional excitation is essential in analysis. The

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yield mechanism will be developed simultaneously in both longitudinal and transverse directions of the building, and the columns will undergo both bi-axial bending moments and significant axial load fluctuation, when the building is subjected to a bi-directional ground motion excitation.

A number of researchers have studied the behavior of RC columns subjected to biaxial bending. There are several findings in both experimental and analytical researches, and design steps are available for the strength design of columns for biaxial bending moments for RC columns. For an example, Kang-Ning Li reviewed the so-named Multi-Spring model (MS model) [2-5] in comparison with the fiber model [6], with both of which one can perform a three-dimensional nonlinear analysis considering the interaction between bi-directional bending moments with varying axial loads.

In this study presented herein, a three-dimensional RC building model is established. Using the analytical model, fluctuation of axial loads produced during a strong earthquake ground motion is examined and discussed obtained when subjected to both uni-directional excitation and bi-directional excitation. Variation of fluctuation for columns positioned at the corner of building, those on the side and those at the center of building is examined and discussed.

BUILDING MODEL UTILIZED IN THE ANALYSIS

Dimensions of the Model Building

In this study, a medium-rise building model is established for analysis, which is designed as a momentresisting ductile frame structure consisting of 12 stories in height. The architectural plan of building is square in plane and is symmetric in both longitudinal (hereinafter abbreviated as x) and transverse (hereinafter as y) directions. A set of three regular symmetric frames are placed in both x and y directions, respectively.

The dimensions such as those of spans of frame, height of building are determined from examination on medium- and high-rise RC buildings in Japan. The length of span is 8m in both x and y directions, and the height of story is 3.2m in general. Figure 1 illustrates the schematic plan of the building employed for analyses herein. The total height of the building is 39.40 in meter with 12 stories.



Figure 1. Plan of the analytical building and location of columns within the frame.

Materials Utilized in the Model Building

The materials used in the model building are summarized as follows: (1) design strength of concrete falls in the range of 36 N/mm² and 48 N/mm²; and (2) yield strength of reinforcing steel bars fy is 490 in N/mm². Mechanical properties of materials are tabulated in Table 1.

Concrete					Reinforcin	g Steel Bar
Design Concrete Strength in (N/mm ²)	Tensile Strength in (N/mm ²)	Compressive Strain in (%)	Young's Modulus in (N/mm ²)	Shear Modulus in (N/mm ²)	Tensile Strength in (N/mm ²)	Young' s Modulus in (N/mm ²)
36	1.8	0.2	2.85 x 10 ⁴	1.22 x 10 ⁴		
42	2.1	0.2	3.00 x 10 ⁴	1.28 x 10 ⁴	490	2.00 x 10 ⁵
48	2.4	0.2	3.13 x 10 ⁴	1.34 x 10 ⁴		

Table 1. Material mechanical properties used in the analysis

Dimensions of Columns and Beams

Referring to design procedures of RC buildings common in Japan [7], dimensions of the constituent components within the analytical building model are established according to the following steps: (1) dimensions of columns are determined so as average compressive stress to be about one-third of design stress of concrete used for the columns; and (2) depth "D" of beams (in this study, "beam" will cover "girder") is determined as about one-tenth of the span length, and width "B" of beams is determined from a design practice. The dimensions of constituent columns and beams within the analytical model building are presented in Table 2.

Table 2.	Dimensions of	f columns	and beam	members	and design	concrete strength
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Height of Story in (Meter)	Dimension of Columns B and D in (Meter)	Dimension of Beams B and D in (Meter)	Design Concrete Strength in (N/mm ²)
6F ~ 12F 3.20	9F ~ 12F 0.85 x 0.85	6F ~ 12F 0.45 x 0.90	11F and 12F 36 6F ~ 10F
			42
2F ~ 5F 3.25	1F ~ 8F 0.90 x 0.90	2F ~ 5F 0.50 x 0.95	1F ~ 5F 48
1F 4.00		1F 0.50 x 1.00	

Strength of Columns and Beams

The strength properties of constituent structural components; i.e., the yielding and cracking strengths of columns and beams within the frames, are determined from a stress analysis carried on the analytical building model. A stress analysis is carried out, specifying the distribution of story shear force along the height of building by the so-called Ai distribution commonly employed in Japanese practices and assuming a certain figure for the design base shear coefficient C_B.

Establishment of the Analytical Building Model

The stress analysis has been repeated varying the base shear coefficient, C_B as well as the dimensions of columns. As a final result within the study, the analytical building model was established. The resultant design base shear coefficient C_B within the model is yielded as 0.19.

In this study, the analysis is carried out based on both the force equilibrium and the displacement compatible conditions. Therefore, initial stresses resulting from the gravity loads are taken into account.

Note that the floor mass is assumed to be uniformly distributed with assumed unit weight is to be 12kN/m² for an approximate estimation.

Degree of Freedoms Considered within the Analysis

The computer program named "CANNY" is utilized in this study, which has been developed for a threedimensional analysis of frame and frame-wall structure using the so-called MS model [4].

The building within this study is modeled as a beam-column frame system, and the floor slabs are considered well integrated to connect all the columns. Therefore, rigid movements of floor slabs (rigid diaphragm) are assumed to represent the lateral displacements (translation in both x and y directions) and the torsional motion (the rotation in the horizontal x-y plane). The structural nodes (beam-column joints), however, have independent displacements along the vertical axis (z-direction), and rotations in the vertical planes (the both x-z and y-z planes). Lateral displacements of the structural nodes are determined from the rigid diaphragm movement. The torsional motions at the beam-column joints are neglected, resulting from that the torsional stiffness properties of column elements are ignored.

EARTHQUAKE MOTION USED IN THE ANALYSIS

Earthquake Motion

Four sets of strong ground motions recorded during real earthquakes are employed, each of which has ground acceleration data along the two orthogonal horizontal directions. The vertical component of motion is not included in the analysis, since discussions of the study are focused on the axial load fluctuation of columns varied with the higher-mode responses caused by a lateral excitation under the condition of bi-directional excitation, with which yield hinge mechanisms can be generated simultaneously in both directions of building.

Station Name	Earthquake Name	Date	Component	Peak Ground Acceleration: PGA (cm/s ²)	Peak Ground Velocity: PGV (cm/s)
El Centro	Imperial Valley,	May 18, 1940	SOOE	341.7	34.2
(ELC)	(ELC) Calif., USA		S90W	210.1	37.1
TaftKern County,(TFT)Calif., USA	July 21, 1952	N21E	152.7	15.5	
		S69E	175.9	17.7	
Hachinohe	Tokachi-oki,	May 16, 1968	NS	229.6	34.9
(HCH) Japan	Japan		EW	180.2	38.9
Tohoku Univ. Miyagi-ken-oki, (THU) Japan	Miyagi-ken-oki,	June 12, 1078	NS	258.1	36.5
	Japan	Julie 12, 1978	EW	203.4	27.8

 Table 3. Earthquake ground motions employed within the analysis

The earthquake motions utilized within the analysis are tabulated in Table 3. For the reference in the following, of the two horizontal components of motion, the component characteristics of the selected earthquakes are presented in Table 3. Of the two components of an earthquake, the component that has the greater peak ground velocity than the other is referred to the major component, and the other to the minor component. According to the definition herein, for the El Centro motion, not the S00E component but the S90W component is treated as the major component of motion for analysis.

Direction of Earthquake Excitation

The following three ways of thinking on the direction of excitation are taken into consideration to study the axial load fluctuation.

(1) Bi-directional excitation using two components of motion

In a real phenomenon, a building is essentially subjected to the ground motion in the horizontal plane, excited simultaneously by the two components of motion. Herein the study, the major and minor components are subjected to the building along the North-South and East-West directions, respectively. The way of excitation defined herein would be considered to correspond to a real phenomenon, within which a ground motion will be well represented by the three translational components in a three-dimensional physical world.

(2) Bi-directional excitation using a single component of motion

In a general design procedure, the seismic design load is specified along the one specific direction of building; i.e., along either the longitudinal or transverse direction of building. The second definition for the direction of earthquake excitation herein is to apply a component of motion along the diagonal direction of building; i.e., to apply a single component of motion inclined by angle of 45 degree from the principal axes of building. Herein the study, the major component of motion is utilized for the component along the diagonal axis of building, generating a bi-directional excitation in a simply manner. The fundamental thinking on the way of excitation is to take a direct correlation with the seismic design procedure as described previously.

(3) Uni-directional excitation using a single component of motion

In a simple way of treatment in a dynamic response analysis, a single component of ground motion is applied to the building. The so-defined major component is used for analysis, and the translational single component of motion is simply applied along the North-South direction of building; i.e., along the transverse direction of building.

Figure 2 shows the three ways of thinking of directions of earthquake excitation that are considered within this study.

Intensity of Earthquake Excitation

Four different intensity levels of the ground motion are considered in this study. The amplitudes of acceleration of motion are scaled so as the peak ground velocity of the major component of motion to be equal to 1.0, 25, 50, and 75 in cm/s, respectively. The amplitudes of the minor component are modified by the identical scale factor to that employed for the major component.



Figure 2. Direction of earthquake excitation: (1) Bi-directional excitation using two components of motion; (2) Bi-directional excitation using a single component of motion; and (3) Uni-directional excitation using a single component of motion.

Analytical results obtained from the case when the peak ground velocity is taken equal to 1.0cm/s will represent the axial load fluctuation of columns when the building remains fully linear elastic. The results obtained from the other cases of the peak ground velocity to be 50cm/s represent the general situation in the Japanese practice during the maximum credible earthquake excitation. Those obtained from the case of 25cm/s represent during the maximum possible earthquake excitation, and those obtained from the case of 75cm/s represent the stage to discuss the behaviors of columns for an assuring design concept for fluctuation of column axial loads.

The three levels of ground motion of which peak ground velocity is taken equal to 25, 50, and 75cm/s, respectively, correspond directly to the condition that how many yielding hinges are generated at the ends of beams/girders within the model building. Implicitly these levels are regarded to be a structural parameter for the strength of frame obtained for the model building considered within this study.

RESULT OF RESPONSE ANALYSES

Dynamic Response Analysis

Dynamic response analyses are carried out based on a three-dimensional structural model. The step-bystep numerical integration is carried out at the time interval of 0.01 second, and the equations of motion are solved by the Newmark's β method, where the parameter β is taken as 1/4, i.e., for a stable response. Damping properties of the building is assumed as internal viscous type proportional to the instantaneous stiffness during the responses, in which the fraction of critical damping is taken as 0.03.

The fundamental period of oscillation is found to be 0.67 seconds for the model building, the height of which is 39.40 in meter.

Definition of Axial Load Fluctuation

In this study, only increment in the axial load is considered to represent the fluctuation of axial loads on the responses of column, since it is considered most significant for the columns to be collapsed. The increment of axial loads is calculated from as follows:

$$\Delta P_1 = P_{\max,1} - P_L \tag{1}$$

$$\Delta P_2 = P_{\max,2} - P_L \tag{2}$$

where the parameters $P_{\max,1}$ and $P_{\max,2}$: the maximum response in compression occurred in the column when the analytical building subjected to the uni-directional and bi-directional excitation, respectively; and P_L : the gravity axial load of the column.

Note that ΔP_1 will denote the axial load fluctuation for the responses obtained during the uni-directional excitation using a single component of motion: i.e., the major component of motion along the North-South direction of the model building, and ΔP_2 will denote for the axial load fluctuation obtained during the bidirectional excitation using either a single component of motion along the diagonal direction of the model building or two components of motion along the North-South and East-West directions, respectively.

Columns Examined within the Study

Since the analytical model building is symmetric with respect to both the North-South and East-West axes. For discussion of axial load fluctuation of columns obtained when subjected to the horizontal component of motion, the five distinctive columns are selected for examination and discussion as indicated in Figure 2, columns C1 and C2 positioned at the corner of building, columns C5 and C6 at the side of building, and C9 at the center of building, respectively, for the 12 story levels within the building.

Herein the study, major discussion is placed on the responses of two specific columns; i.e., the corner column C1 and side column C5 at the three selected floor levels; i.e., at the ninth, fifth and first floor levels representing the upper, intermediate and lowest floor level columns with low, moderate and high axial forces, respectively.

Axial Load Fluctuation under Uni-directional Condition Using a Single Component of Motion: ΔP_1

Results of axial load fluctuation ΔP_1 of the selected columns obtained from a dynamic response analysis for the uni-directional excitation are shown in Figure 3 for the corner columns C1 and C2, and in Figure 4 for the side column C5, respectively. In Figures 3 and 4, the axes x and y represent the intensity level of seismic excitation in the peak ground velocity (PGV hereinafter) and the axial load fluctuation of the columns ΔP_1 in kN, respectively. Note that the excitation of motion is applied along the North-South direction of building employing the so-defined major components of motion recorded at the El Centro, Taft, Hachinohe and Tohoku University stations. As is expected, the axial load fluctuations for the columns C6 and C9 are found of less significance, since these columns are positioned near the neutral axis for the overturning moment of the building produced when it is subjected to the uni-directional excitation. The plots of the results are not shown within this paper. The gravity axial loads for the columns C5 and C6 (the side columns) at the intermediate and lowest story levels are 2.98×10^3 kN and 4.47×10^3 kN, respectively. The gravity axial loads for the columns C1 and C2 (the corner columns) are evaluated as half as large as, and those for the column C9 (the center column) are twice as large as those for the side column, respectively.

It is observed from the results shown in Figures 3 and 4 that: (1) the model building that is examined within this study develops hinges at the beam-end with the level of seismic action in PGV 25cm/s and higher for the motions of the Hachinohe and Tohoku University records; (2) it develops beam hinges with the PGV of 50 cm/s and higher for the motions of the El Centro and Taft records; and (3) when the hinges are generated at the beam-ends, the axial load fluctuations at the specific intermediate and lowest floor levels are increased 0.8 and 0.95 times as large as the gravity axial load for the side column, and 1.5 and 1.8 times as large as the gravity axial load for the corner column.

Axial Load Fluctuation under Bi-directional Condition Using Either a Single Component of Motion or Two Components of Motion: ΔP_2

Results of axial load fluctuation of column ΔP_2 obtained from a dynamic response analysis for the bidirectional excitation are shown in Figures 5 through 8 for the corner column C1, the other corner column C2, the side column C5 and the center column C9, respectively.

The following two ways of thinking for the bi-directional excitation of motion are considered; i.e., the one to employ two horizontal components of motion applied along the North-South and East-West directions of building, and the other to employ a single component of motion applied along the diagonal direction of building. The legends of Figures 5 through 8 are identical to those of Figures 3 and 4, while the solid lines represent the results obtained when subjected to two components of motion applied along the principal axes of the building, and the dotted lines when subjected to a single component of motion directed along the diagonal axis of the building, respectively.

As is verified with ease from Figures 3 to 8 when the results obtained during the bi-directional excitation are compared to those obtained during the uni-directional excitation, it has been found that: (1) axial load fluctuation observed at the corner column is of significance when the bi-directional excitation is considered, since the yielding hinges at the beam-ends are generated simultaneously in both the North-South and East-West directions of building; (2) axial load fluctuation at the side column with the bi-directional conditions is almost identical to that with the uni-directional condition, since the side column is positioned around the neutral axis for the total overturning moment of building for the minor component excitation; and (3) when the bi-directional excitation is considered with a single component applied along the diagonal direction of building, the building does not develop hinges at the beam-end with the level of seismic action in PGV 25cm/s for the Hachinohe and Tohoku University motions, since the resultant PGV in the principal axes of the building falls in the value of 0.7 times of 25 in cm/s.

Axial Load Fluctuation under Bi-directional Condition for the Center Column

As is expected, the fluctuation is of less significance with respect to either the amount of load fluctuation or moreover the ratios of fluctuation compared to the gravity axial force. Roughly speaking, the ratios lie in the range of 0.045 to 0.02, indicating the fact that the axial load fluctuation for the center columns will be negligibly small.





(a) Responses of the 9th story level column



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.



Figure 3. Axial load fluctuation ΔP_1 for the corner columns C1 and C2.

(a) Responses of the 9th story level column.



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

− ⊖− ELC Major	<u>−</u> △− HCH Major
−⊟− TFT Major	→ THU Major

Figure 4. Axial load fluctuation ΔP_1 for the side column C5.







(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

ELC Major Diagonal	
ELC Major-Minor	
- 🗗 - TFT Major Diagonal	∆THU Major Diagonal
- TFT Major-Minor	─▲ THU Major-Minor

Figure 5. Axial load fluctuation ΔP_2 for the corner column C1.



(a) Responses of the 9th story level column.



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

ELC Major Diagonal	
	→ HCH Major-Minor
- 🗗 - TFT Major Diagonal	∆THU Major Diagonal
	THU Major-Minor

Figure 6. Axial load fluctuation ΔP_2 for the corner column C2.



(a) Responses of the 9th story level column.



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

- 🗢 ELC Major Diagonal	HCH Major Diagonal
ELC Major-Minor	
- 🕀 - TFT Major Diagonal	∆THU Major Diagonal
TFT Major-Minor	THU Major-Minor

Figure 7. Axial load fluctuation ΔP_2 for the side column C5.



(a) Responses of the 9th story level column.



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

 ELC Major Diagonal 	HCH Major Diagonal
ELC Major-Minor	
- 🖽 - TFT Major Diagonal	∆THU Major Diagonal
TFT Major-Minor	THU Major-Minor

Figure 8. Axial load fluctuation ΔP_2 for the center column C9.

RATIOS OF THE AXIAL LOAD FLUCTUATION ΔP_2 COMPARED TO ΔP_1

Definition of Ratios of Axial Load Fluctuation

Ratios of the axial load fluctuation obtained during the bi-directional excitation ΔP_2 to that obtained during the uni-directional excitation ΔP_1 are examined. The axial load fluctuation ΔP_2 obtained when employing two components of motion will be considered to represent a realistic world that the ground motions essentially consist of two horizontal component of motion, and the axial load fluctuation ΔP_1 will be generally examined in common structural analytical procedures for simplicity. The axial load fluctuation ΔP_2 obtained when employing a single component of motion along the diagonal axis of building will be regarded as a simple process, not representing a real world but producing realistic responses for the axial load fluctuation of columns. Therefore, that simplified process has been widely utilized for a verification analysis on axial loads of high-rise reinforced concrete building.

Ratios for the Corner Columns

Figure 9 represents the ratios of the axial load fluctuation obtained during the bi-directional excitation compared to that obtained during the uni-directional excitation for the corner column C1; i.e., the ratios of $\Delta P_2/\Delta P_1$ for the column C1. The axis y in Figure 9 designates the ratio of the axial load fluctuation $\Delta P_2/\Delta P_1$. The solid lines within the plot illustrate the results for the case when the axial load fluctuation with bi-directional excitation has been evaluated by the two components applied along the North-South and East-West directions of building representing a realistic world, and the dotted the results for the case when evaluated by a single component along the diagonal direction of building representing a fake world within which realistic phenomenon can be simply produced that the earthquake ground motions has two horizontal components of motion.

Ratios for the Side Column

Figure 10 illustrates the ratios of the axial load fluctuation obtained during the bi-directional excitation compared to that obtained during the uni-directional excitation for the side column C5. The legends of the figure are identical to those in Figure 9.

Since the axial load fluctuation ΔP_1 for the side column C6 and the center column C9 is found almost null for a single component excitation along the North-South direction of building, the ratios of $\Delta P_2/\Delta P_1$ for these columns show high fluctuation yielding no further interests in assessment of the axial load fluctuation.

DISCUSSIONS AND CONCLUDING REMARKS

It would be worth your attention to note the axial load fluctuation for the bi-directional condition has been evaluated the following two ways of thinking for the bi-directional excitation of motion within this study. The one is to employ two horizontal components of motion; i.e., the major and minor components, along the North-South and East-West principal directions of the model building, respectively, and the other to use a single component of motion; i.e., the major component, in the diagonal direction of the model building. Let define ΔP_{22} and ΔP_{21} designate the axial load fluctuation for the former and latter cases, respectively hereinafter.







(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.



Figure 9. Ratios of axial load fluctuation $(\Delta P_2 / \Delta P_1)$ for the corner column C1.



(a) Responses of the 9th story level column.



(b) Responses of the 5th story level column.



(c) Responses of the 1st story level column.

ELC Major Diagonal	HCH Major Diagonal
ELC Major-Minor	
- 🗄 - TFT Major Diagonal	∆THU Major Diagonal
-TFT Major-Minor	

Figure 10. Ratios of axial load fluctuation $(\Delta P_2 / \Delta P_1)$ for the corner column C5.

Based on the observation upon Figures 9 and 10 illustrating the ratios of axial load fluctuation obtained for the bi-directional condition compared to that obtained for the uni-directional condition, the discussions are itemized as in the following:

- (1) For the corner column C1, the ratios $\Delta P_{21}/\Delta P_1$ denoted by the dotted lines in Figure 9 lie on 1.4 as expected when the building responds linearly elastic. The ratios $\Delta P_{22}/\Delta P_1$ represented by the solid lines fall in the range of 0.9 to 1.8 depending on the excitation of motion. The ratios $\Delta P_{22}/\Delta P_1$ falls in general greater than unity, while it is found less than unity at both the fifth and first story levels when the Hachinohe motion is applied to the building. In the case when the ratios are less than unity, the minor component of motion would produce the tensile axial load when the major component produces the compressive axial load, and vice versa.
- (2) For the column C1, with an increased peak ground velocity of excitation of motion, the ratios $\Delta P_{21}/\Delta P_1$ reach 2.0, indicating the evidence that the yield hinge mechanisms are simultaneously generated in both the North-South and East-West directions of building. The ratios $\Delta P_{22}/\Delta P_1$ are revealed generally smaller than those $\Delta P_{21}/\Delta P_1$. It leads to a conclusive remark that the effect of bi-directional excitation of motion on the axial load fluctuation on columns can be well evaluated by an analysis using a single component excitation applied along the diagonal direction of the building in a simple manner.
- (3) For the column C1, with the PGV of 25cm/s, the ratios $P_{22}/\Delta P_1$ become greater than two when subjected to the El Centro motion. It can be possibly observed that the responses of the unidirectional excitation of the PGV 25cm/s do not produce yield hinge mechanisms, and those of the bi-directional excitation generate a large amount of axial load fluctuation in the East-West direction of building. Note that the minor component of the El Centro motion is yielded by the S00E component of motion, which is one of the typical strong ground motion records.
- (4) For the side column C5, the ratios $\Delta P_{22}/\Delta P_1$ are found to be unity, since the minor component of motion applied along the East-West direction of building does not essentially produce a fluctuation of axial loads. The ratio $\Delta P_{21}/\Delta P_1$ at the linear elastic stage should be 0.71, and is increased to unity as the peak ground velocity is increased.

From an analysis on a regular symmetric moment-resisting ductile frame building subjected to both unidirectional and bi-directional excitation of motion, the axial load fluctuation produced on columns for an ultimate strength design is examined and discussed. Interpretation on analytical results obtained herein can lead to the concluding remarks as follows:

- (1) The axial load fluctuation is of importance in the structural design. The fluctuation is 1.8 times as large as the gravity load for the corner column at the fist story level, indicating that the tensile force will be generated during an intense seismic action.
- (2) For the moment-resisting ductile frame building examined within this study, the axial load fluctuation when obtained subjected to bi-directional excitation will be twice as large as that obtained subjected to uni-directional excitation during an intense seismic action. A large amount of axial load fluctuation will be expected.
- (3) The effect of bi-directional excitation of motion on the axial load fluctuation can be well represented by a single component of excitation applied along the diagonal direction of building, instead of applying two components of motion along the two principal axes of building. The way of thinking for the bi-directional excitation is simple and corresponds directly to that employed in a static seismic design procedure within which seismic design force is defined in uni-directional treatment.

- (4) The way of thinking for the bi-directional excitation with a single component applied along the diagonal direction of building, however, yields less amount of axial load fluctuation than that for the bi-directional excitation with two components, for a case when the level of excitation is moderate or small.
- (5) A large amount of axial load fluctuation is observed for the side column as well as for the corner column. The responses, however, do not produce tensile force on the side column with an intense seismic excitation, since firstly it takes a larger gravity load, and secondly the bi-directional excitation produces less significant fluctuation for the side column compared with that for the corner column.
- (6) It is observed that axial load fluctuation is produced for the column positioned at the center of building due to the elongation of columns caused by the total overturning on the building. The evaluated amount of fluctuation is negligibly small with 1.5 to 2.0 percentage of the gravity load.

Further studies are necessary for the assessment of significance of axial load fluctuation of columns for establishment of an ultimate strength design procedure. An exemplary study herein has revealed general evidences for a model building that is designed based upon the procedure proposed for common Japanese practices.

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