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DYNAMIC PROGRESSIVE FAILURE OF MULTISTORY FRAMES HAVING BRITTLE COLUMNS

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ABSTRACT

The purpose of this study is to clarify the dynamic progressive failure behavior of multistory frames having elastic-plastic-brittle columns and to establish the strength or ductility against a severe earthquake, by means of numerical analysis. The energy introduced in a structure by an earthquake is assumed to be absorbed only in columns. The capacity of columns' plastic ductility is limited by random occurrence of brittle fracture, and thus, the ductility capacity of the frame is various. Such variation causes the concentration of damage in a particular story, resulting in a weaker frame. Therefore, in order to make the brittle frames survive a severe earthquake, over-strength or over-ductility is required, and its calculation method is proposed according to the energy balance of input and absorption.

KEYWORDS

seismic response, brittle fracture, dynamic progressive failure, ultimate strength, ductility capacity variation

INTRODUCTION

Recently high strength and extremely thick steel members are used in building structures. They have the harmful character of collapse not by buckling but by brittle fracture as demonstrated by large-scale test of box columns (Kuwamura and Akiyama,1994). But the ductility capacity against this fracture is not yet well-investigated and is very variable. Reinforced concrete structures are also susceptible to brittle fracture in case that shear reinforcing bars are not spaced close. These brittle fracture modes were actually witnessed in the Hyogoken-Nanbu Earthquake of January 17, 1995 as shown in Fig.1. The objective of this research is to make it clear numerically how the frames having elastic-plastic-brittle columns behave and how much extra strength or ductility is necessary for the frame to survive a severe earthquake.

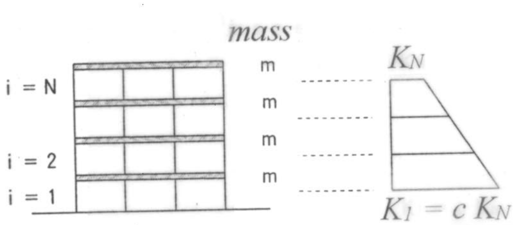
OUTLINE OF NUMERICAL ANALYSIS

Analysis Model

The structure model of this analysis is shown in Fig.2(a),which is an undamped multi-mass system. Only its columns can deform because beams and panels are assumed to be sufficiently rigid and strong. The number of stories is represented by N, and the number of the columns by n_c. The mass m is distributed equally in every story. The story stiffness is linearly proportioned so that the ratio of the bottom story stiffness to the top story is c to have a designated natural period T, as shown in Fig.2(b). The ratio c is c = 2, 3 and 4 corresponding to N=2, 4 and 8. T's are selected from 0.5, 1.0, 2.0 and 4.0 seconds. Six cases of (N,T) = (2, 0.5), (2, 1.0), (4, 1.0), (4, 2.0), (8, 2.0), (8, 4.0) are examined for the combinations of N and T.

(a) Failure of a steel structure (b) Failure of a reinforced concrete structure

Fig. 1. Dynamic progressive fialures in the Hyogo-ken Nanbu Earthquake of January 17,1995



(a) Shearing multistory frame (b) Story horizontal stiffness distribution

Fig. 2. Vibrational model (N= 4, n_c= 4)

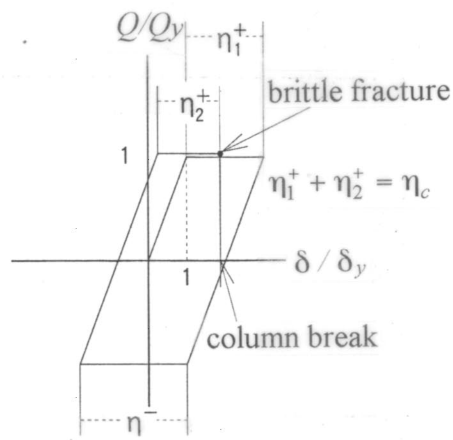


Fig. 3. Hysteretic system of brittle column

Characteristics of Column Hysteresis

Column hysteresis is shown in Fig.3, in which the column has an elastic-perfectly plastic type of restoring force characteristics and collapses with brittle fracture after some plastic excursions. Strain hardening , effect of an alternating axial force and Bauschinger's effect are ignored because of their secondary effects on dynamic behavior. Since the relation between brittle fracture and plastic hysteresis has not been established yet, the columns are assumed to lose their restoring force and horizontal stiffness thoroughly when the cumulative plastic ductility either in plus or minus loading reaches a critical ductility η_c. But the axial load can be still sustained after brittle fracture. The column end subjected to brittle fracture becomes a pin-roller which cannot convey shearing force and bending moment.

Story Hysteresis Characterized by Ductility Capacity Variation

The columns which constitute a story have the same horizontal stiffness k and the same shear yield strength

q_y. Therefore, story stiffness K and story yield shear strength Q_y are represented by $n_c k$ and $n_c q_y$, respectively.

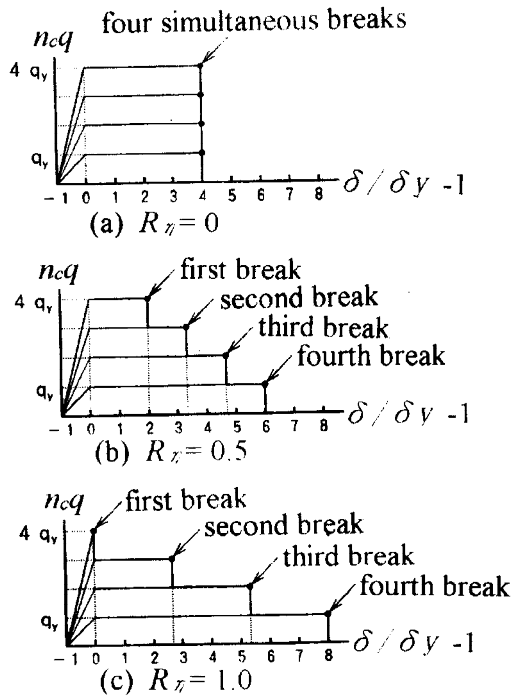


Fig. 4. Relation between story load-deformation characteristics and R_η ($n_c = 4$)

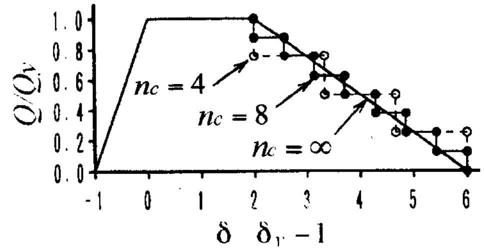


Fig. 5. Influence of column number on the load-deformation of brittle story

It is verified by latest research that the cumulative plastic ductility limited by brittle fracture is accompanied with a large uncertainty. In order to consider this influence, the cumulative plastic ductility capacity preceding brittle fracture is assumed to be variable with an equal interval in a certain range. This variation is represented by the index R_η defined by following Eq.(1):

$$R_\eta = \frac{\eta_{c \cdot max} - \eta_{c \cdot min}}{\eta_{c \cdot max} + \eta_{c \cdot min}} \qquad \cdots\cdots\cdots(1)$$

where

$$\eta_{c \cdot max} + \eta_{c \cdot min} = 2\bar{\eta}_c \qquad \cdots\cdots\cdots(2)$$

$$\eta_{c \cdot min} \geq 0 \qquad \cdots\cdots\cdots(3)$$

$$0 \leq R_\eta \leq 1 \qquad \cdots\cdots\cdots(4)$$

R_η : variation index of column ductility η_c

$\eta_{c \cdot \max}$: maximum η_c in all columns, $\bar{\eta}_c(1 + R_\eta)$

$\eta_{c \cdot \min}$: minimum η_c in all columns, $\bar{\eta}_c(1 - R_\eta)$

$\bar{\eta}_c$: average of column ductility η_c ($\bar{\eta}_c = 2,4,8$ in this research)

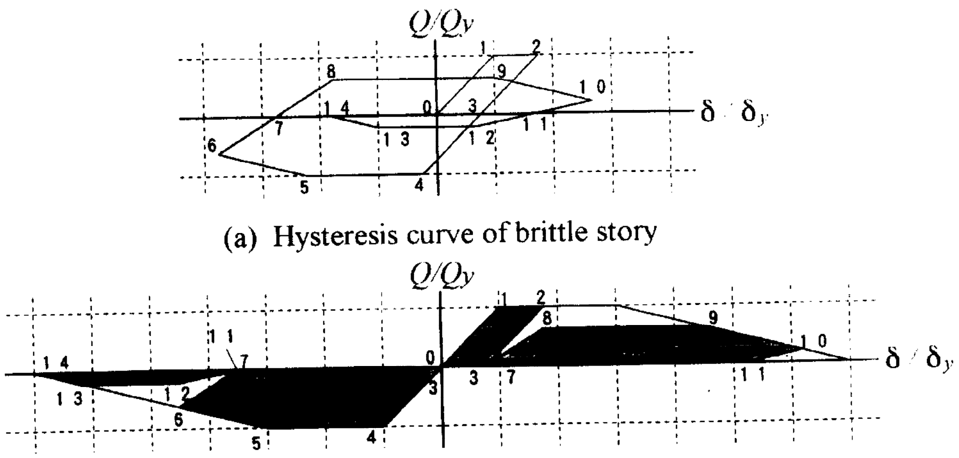
R_η changes between 0 and 1. $R_\eta=0$ means that there is no variation in the column ductility capacity, i.e., all columns' η_c's are equal. $R_\eta=1$ means that η_c's are spread between 0 and $2\bar{\eta}_c$. The load-deformation curves in case of uni-directional loading are shown in Fig.4, in which three cases of R_η = 0 , 0.5, and 1.0 are shown. Thick lines are the relations for a story and thin lines are the relations for each column. As the areas underneath the load-deformation curves are equal irrespective of R_η, the energy absorption capacity of a story is kept constant.

The examples of load-deformation curves for different column number n_c = 4 and 8 are shown in Fig.5 in the case of R_η=0.5. As n_c is larger, the step size in the curve is smaller. And the step for $n_c=\infty$ disappears and the curve becomes a straight line.

An example of the hysteresis curve of a story with infinite number of brittle columns ($n_c=\infty$) is shown in Fig.6(a). In order to make the hysteresis rule clear, the hysteresis curve is re-arranged into a monotonous curve in Fig.6(b).The numbers in Fig.6(a) are corresponding to those in Fig.6(b). The characteristics of this hysteresis curve composed of elastic, perfectly-plastic, and weakened parts are as follows:

(1) After story strength is weakened in either plus loading side or minus, the strength in the opposite side becomes the left strength in the weakened side.
(2) After the strength is weakened, the elastic stiffness decreases in proportion to the weakened strength.
(3) When either plus cumulative plastic ductility or minus reaches the skelton curve under monotonic, loading, weakening occurs.

These characters result from the column behavior in which columns broken by brittle fracture cannot contribute to the restoring force of the story.



(a) Hysteresis curve of brittle story

(b) Skeleton curve of brittle story

Fig. 6. Load-deformation of brittle story

Numerical Analysis Method and Input Earthquake

Linear acceleration method is used in numerical integration. In case of finite columns, brittle fracture causes an abrupt change in story restoring force like stairs. In this case, Eq.(5) is applied so that the strength difference between before and column's brittle fracture (i step and i+1 step) doesnot violate the force balance by replacing the loss of restoring force ΔQ_i with the acceleration.

$$\ddot{x}_{i+1} = \ddot{x}_i - \frac{\Delta Q_i}{m}, \dot{x}_{i+1} = \dot{x}_i, x_{i+1} = x_i \qquad \cdots\cdots\cdots(5)$$

The input earthquake is El Centro, NS, 1940, in which time length is 30 seconds and time step is 0.002 second.

Standard Frame

The frame of $R_\eta=0$ in that the plastic ductility capacity limited by brittle fracture of each column is equal, is called a standard frame, when it has the minimum base shear coefficient to survive the given earthquake motion. The cumulative plastic ductility in this frame is called a standard cumulative plastic ductility. The distribution of story yield strength is established in this frame so that the bigger response in story cumulative plastic ductility of plus or minus direction is equal to $\bar{\eta}_c$ in all stories.

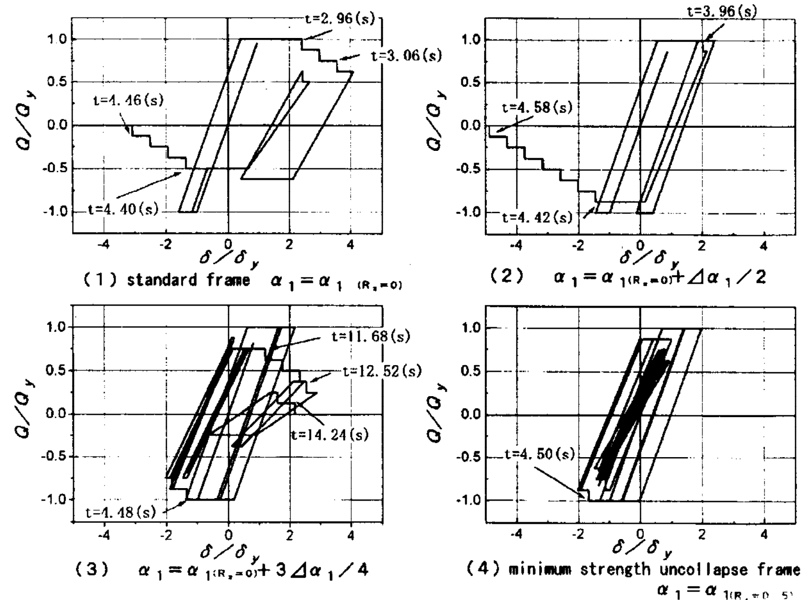


Fig. 7. Hysteresis curves with dynamic progressive failure
($N=4$, $T=1.0$, $n_c=8$, $R_\eta=0.5$, $\Delta\alpha_1=\alpha_{1(R_\eta=0.5)}-\alpha_{1(R_\eta=0)}$)

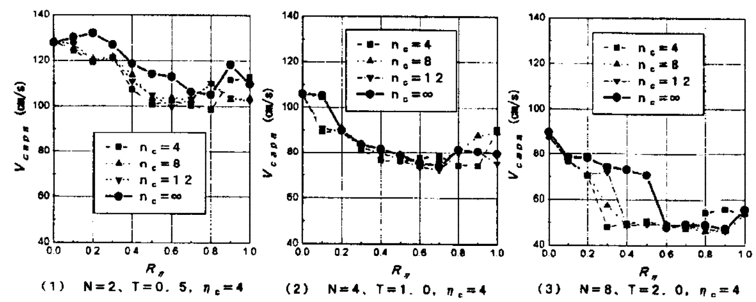


Fig. 8. Energy absorbing capacity of standard frame when R_η is increased

RESULTS OF RESPONSE ANALYSIS

Dynamic Progressive Failure

The standard frame, if its R_η-value is bigger than 0, collapses during the earthquake motion because the stories are weakened by the fracture of the weakest column. In this analysis, collapse is defined as story collapse. The hysteresis curves are shown in Figs.7 in that responses of four frames having increased base shear coefficients are shown. Fig.7(4) is the story hysteresis having the minimum base shear coefficient to survive. The dynamic progressive failure happens in the frames of Figs.7(1),(2) and (3), in which the columns failure successively in a very short second.

Capacity to Absorb Energy in Dynamic Progressive Failure

The changes of energy absorbed to the frame collapse are shown in Figs.8 when R_η is increased with the base shear coefficient unchanged. The vertical axis of this figure is the velocity defined by the following Eq.(6):

$$V_{capa}=\sqrt{\frac{2W_{capa}}{M_1}} \qquad \cdots\cdots\cdots\cdots(6)$$

where

W_{capa} : all energy absorbed up to frame collapse

M_1 : total mass

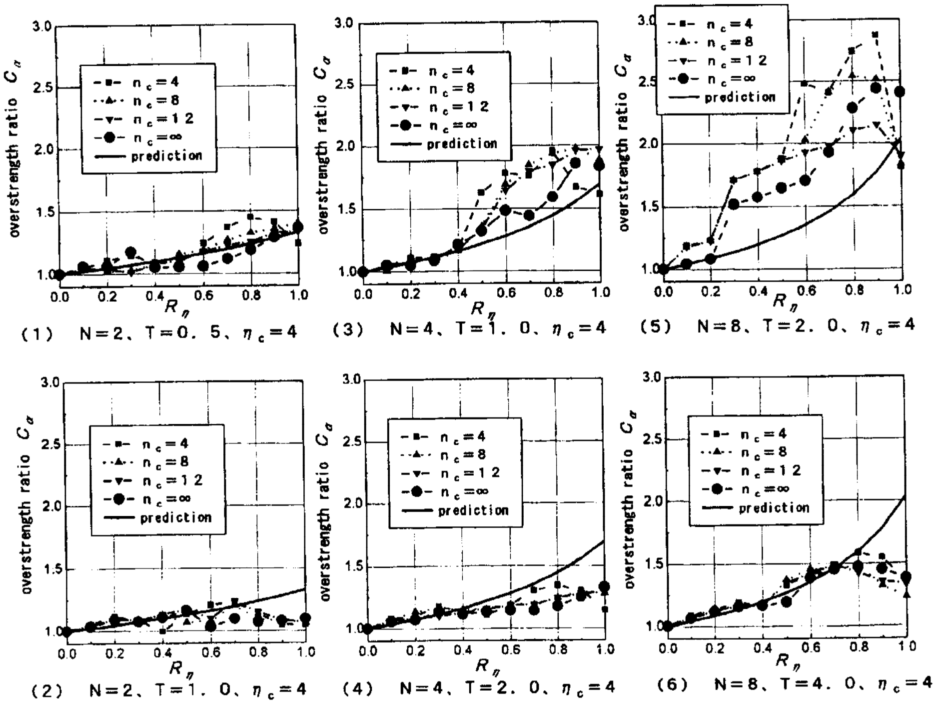


Fig. 9. Required overstrength to survive, C_α

According to Figs.8, the frame capacity to absorb energy is smaller as R_η is bigger, the reason of which is that a frame of larger R_η has a very brittle column, which breaks at the beginning of input earthquake resulting in the energy concentration in the weakened story. It is noted that the number of columns has little influence on the frame capacity.

Required Overstrength To Survive

Since the frame capacity in terms of absorbing energy to resist a severe earthquake is apt to decrease with R_η. Overstrength or over-ductility-capacity is necessary to survive. First, the results of response analysis on the overstrength are shown in Figs.9. The vertical axis is C_α which is the overstrength ratio of minimum base shear coefficient for survival to the standard strength above-mentioned. The overstrength ratio is bigger as the variation index R_η is bigger, and the number of columns has little influence. The thick line is the prediction curve by Eq.(10) mentioned later.

Required Over-Ductility-Capacity to Survive

The results of response analysis on over-ductility-capacity are shown in Figs.10. The figure shows the ratio C_η defined as cumulative plastic ductility to the standard. C_η is bigger, as R_η is bigger, and there is little influence of column number. The thick line is the prediction curve by Eq.(11) mentioned later.

PREDICTIONS OF OVERSTRENGTH AND OVER-DUCTILITY-CAPACITY

In this research the predictions of overstrength and over-ductility-capacity of the frames with brittle columns are obtained on the basis of energy balance of input and absorption (Kato and Akiyama, 1976). First, the dynamic response of energy absorbing is divided into stable and unstable states. The stable state is that there are no broken columns in the story which will collapse finally. The unstable state is the remaining after the stable state up to the frame collapse. In the stable state, no particular story is likely to be damaged concentratedly. Therefore, the response of cumulative plastic ductility is assumed to be equal in the all

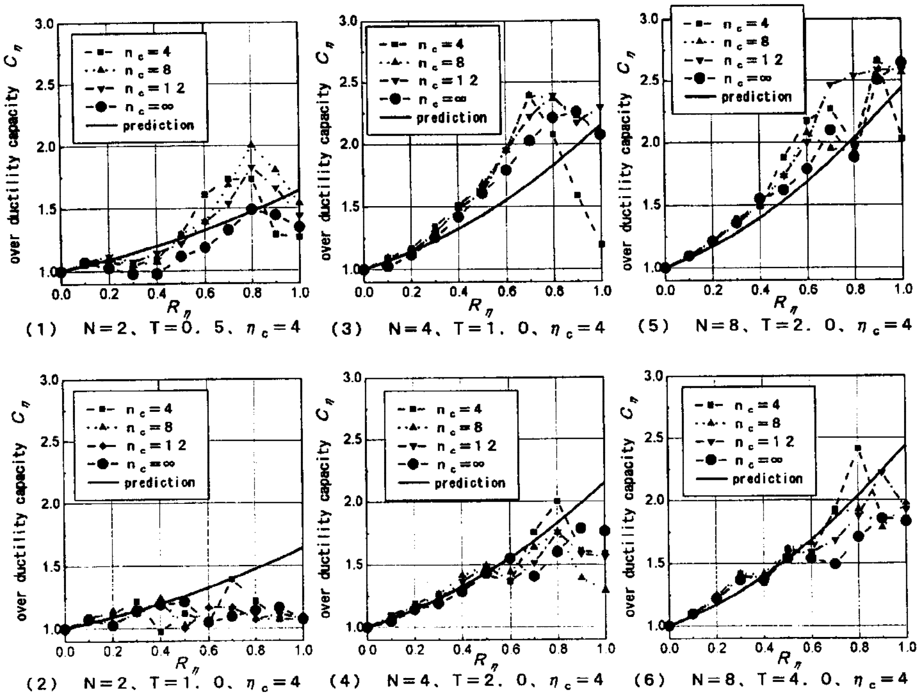


Fig. 10. Required over-ductility-capacity to survive, C_η

stories and the stable energy is obtained from the sum of all stories' energy absorption because the frame is designed on the basis of the optimum strength distribution. In the unstable state, the story having fractured columns is subject to damage concentration as the story is weaker. The energy absorbed in the unstable state is divided into those in the failure story and other stories. The former unstable energy is obtained from the capacity of collapsed story energy absorption and the latter energy is obtained from the average in response. Finally, these obtained energy are added up and this total input energy is given by Eq.(7):

$$W_p = \left(\frac{M_1^2 g^2}{K_1}\right)\alpha_1^2 \cdot \eta_c \cdot A_N \left[\rho_s \cdot (1-R_\eta) + \rho_{d1} R_\eta \frac{1}{N} + \rho_{d2}\eta_c R_\eta \cdot \frac{N-1}{N}\right] \qquad \cdots\cdots\cdots\cdots(7)$$

where

$$A_N = \sum_{i=1}^{N} \frac{(\alpha_i/\alpha_1 \cdot M_i/M_1)^2}{K_i/K_1} \qquad \cdots\cdots\cdots\cdots(8)$$

g : acceleration of gravity

α_i : yield shear coefficient of i-th story

K_i : horizontal stiffness of i-th story

M_i : total mass supported by i-th story

ρ_s : efficiency of energy absorption in stable state $(\rho_s = 1.0)$

ρ_{d1} : collapsed story's efficiency of energy absorption in unstable state $(\rho_{d1} = 1.5)$

ρ_{d2} : uncollapsed story's efficiency of energy absorption in unstable state $(\rho_{d2} = 0.05)$

Next, Eq.(9) of survival requirement is derived from the assumption that the energy input E of earthquake to the frame is invariable.

$$W_p = E \qquad \cdots\cdots\cdots\cdots(9)$$

When Eq.(7) is substituted into the Eq.(9) and is solved about α_1 or η_c, the required base shear coefficient or ductility capacity is obtained. But in this process elastic and kinetic energy is ignored because it is much smaller than plastic strain energy. The required overstrength ratio and over-ductility-capacity ratio are calculated by the following equations:

overstrength ratio :

$$C_\alpha = \sqrt{\frac{\rho_s}{\rho_s \cdot (1-R_\eta) + \rho_{d1} R_\eta \cdot \frac{1}{N} + \rho_{d2}\eta_c R_\eta \cdot \frac{N-1}{N}}} \qquad \cdots\cdots\cdots\cdots(10)$$

over - ductility - capacity ratio :

$$C_\eta = \frac{-s + \sqrt{s^2 + 4r \cdot \rho_s \cdot \eta_{c(R_\eta = 0)}}}{2r} \qquad \cdots\cdots\cdots\cdots(11)$$

$$r = \rho_{d2} R_\eta \cdot \frac{N-1}{N} \qquad \cdots\cdots\cdots\cdots(12)$$

$$s = \rho_s(1 - R_\eta) + \rho_{d1} R_\eta \cdot \frac{1}{N} \qquad \cdots\cdots\cdots\cdots(13)$$

The predictions by Eqs.(10)and(11) are shown in Figs.9 and 10. The accuracy of these predictions is not always very good but they follow the general tendency. The details of this method is shown in the reference.

However, it should be noted that the input earthquake is only El Centro motion in this research. Since above-derived ratios may be influenced by the wave character of input earthquake, it seems to be necessary to study the cases of other earthquakes, although in the case of Hachinohe motion almost the same tendency is acquired (Sato and Kuwamura, 1994). In addition, the cases that beams and panels have elastic-plastic hysteresis and that columns' ductility responses of a story are not equal because of torsional vibration are necessary to study. And the collapse modes of over turning resulting from no tensile resistance in broken columns is also important for slender buildings.

CONCLUSIONS

Fracture of the brittlest column causes the damage concentration in its story, and then the remaining columns in the same story fracture progressively. The tendency of this dynamic progressive failure is more accelerated, as the variation of ductility capacity of columns preceding brittle fracture is bigger. The following methods to prevent such dynamic progressive failure are available: the method to make the ductility capacity larger and the method to make the yield strength larger. The ratio of overstrength and over-ductility-capacity to survive an earthquake under the risk of dynamic progressive failure is proposed on the basis of energy balance of input and absorption. The accuracy of the proposed formulae isn't always very good but the general tendency is acquired.

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