The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

CUMULATIVE STRENGTH INDEX DISTRIBUTION ALONG BUILDING HEIGHT AND STORY COLLAPSE RATE IN REINFORCED CONCRETE BUILDINGS

Y. Hibino[1], M. Kikuchi[2] and M. Teshigawara[2]

[1] *Assistant Professor, Dept. of Environmental Engineering and Architecture, Nagoya University, Nagoya. Japan*
Email: hibino@dali.nuac.nagoya-u.ac.jp
[2] *Sumitomo Mitsui Construction Co. Ltd., Tokyo, Japan*
[3] *Professor, Dept. of Environmental Engineering and Architecture, Nagoya University, Nagoya, Japan*

ABSTRACT :

The seismic evaluation guideline of existing reinforced concrete (RC) buildings is provided by The Japan Building Disaster Prevention Association (JBDPA 2001). A study on effects of a cumulative strength index, C_T, distribution along the building height on story collapses in RC buildings was examined. The analytical results of models were mainly discussed by the story collapse rate and the strength ratio that is newly defined as the ratio of C_T index of weak story to average of C_T index of all the stories in a building. The strength ratio which leads to story collapse was presented by dynamic response analyses results. However, in case of the weak-beam-strong-column designed structure, even if the strength ratio is not ideal, the story collapse will not occur due to total beam yielding mechanism

KEYWORDS: Story collapse, Seismic evaluation, Seismic index of structure, Cumulative strength index

1. INTRODUCTION

The risk of a story collapse induced by the unbalance of strength distribution along building height such as pilotis type building is not negligible. Several types of RC buildings have collapsed or been caused severe damages at their soft-first-story during the earthquake in Kobe, Japan in 1995. Therefore, the seismic retrofitting of existing RC buildings is highlighted to prevent collapse from severe earthquakes. For seismic retrofitting, to ensure relevant strength distribution along building height after the retrofitting is important as well as the increasing strength.

Such as the publication of the ATC-40 Report (1996) and the FEMA 273 Report (2000) is provided for seismic evaluation guideline of existing structures. Both the documents present the method based on nonlinear static analysis to predict the structural capacity. The prediction of the inelastic force-deformation behavior of the structure is addressed using involve generation of a pushover curve.

On the other hand, in Japan, the seismic evaluation guideline of existing RC buildings provided by JBDPA (2001) presents the screening procedure based on the numerical estimation of force-deformation relationships representing the seismic capacity: the first; the second; and the third levels in accordance with its complexity.

In the screening procedure, an index, I_s, named "seismic index of structure" which is the basic concept to define the relevant seismic capacity is provided by following equation.

$$I_s = E_0 \cdot S_D \cdot T \geq I_{s0} \tag{1.1}$$

where E_0 is a basic structural seismic capacity index defined by a multiplication of a ductility index, F, and a cumulative strength index, C_T; S_D is a factor to modify E_0 index due to structural irregularity (e.g. with torsion, soft story mechanism); T is a factor to allow for the deterioration of original performance; and I_{s0} is seismic demand. Although seismic demand, I_{s0}, is provided as 0.6, the relevant C_T and F are provided only. The unbalances of the distribution of C_T and F index along building height may cause damage concentration to a story and it should be avoided.

The objective of this paper is to discuss about the effect of the distribution of C_T index along building height using an index newly defined to expect damage concentration to the story. Marubashi et al. (2006) concluded that even if the I_S is the same in all stories, damage concentration occurs in a story whose C_T index is the smallest and C_T index should be considered to prevent damage concentration. However, the papers did not address the effects of numbers of the weak stories and numerical discussion to expect damages. Then, this paper studied on the effect of distribution of C_T index along building height in case of the number and the positions of weak stories and those values.

2. STRUCTURAL SYSTEMS, ANALYTICAL MODELS AND GROUND MOTIONS

2.1. Configuration and Strength

The analytical model of multi-degrees-of-freedom (MDOF) system was used in this study. The numbers of story studied are 5- and 9-story models assuming RC buildings. The weight of each story is the same and the story heights are 3 m. The hysteresis models of shear springs at each story were assumed as Takeda model (Takeda et al. 1970), shown in Fig. 2.1. The flexural cracking strength, Q_c, of members was assumed as one-third of the corresponding yield strength, Q_y. The post-yield stiffness was assumed as 0.01 times the elastic stiffness, K, and the yield point stiffness was assumed as 0.3K. The yield deformation angle, R_y, defined by Eqn. 2.1 (JBDPA 2001) is assumed as 1/150.

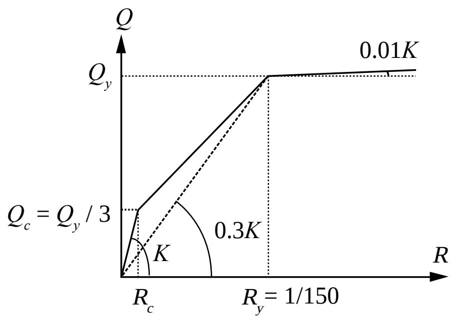


Figure 2.1. Hysteresis model

$$F = \begin{cases} 1.27\sqrt{150R_y} & R_y < 1/150 \\ \sqrt{300R_y - 1}\big/0.75\times\left(1+7.5R_y\right) & R_y \geq 1/150 \end{cases} \tag{2.1}$$

The yield strength, Q_y, of each story is defined by following equation with C_T:

$$Q_y = C_T \cdot \alpha_i \cdot A_i \tag{2.2}$$

where α_i is weight sustained by the story concerned and A_i is story shear coefficient factor along building height provided in Japanese Building Code (MLIT 1999).

The cumulative strength index, C_T, was assumed by the seismic index, I_s, previously defined by Eqn. 1.1. In this study, to neglect the effect of structural irregularity and deterioration due to aging, we assumed both S_D and T as 1. Then, the seismic index is expressed as below:

$$I_s = C_T \cdot F \tag{2.3}$$

The seismic index, I_s, was defined as 0.6 for simple examination; however, other indexes, C_T, and F are variable corresponding with strengths. We note that the cumulative strength index, C_T, used in this study is equal to C_{TU}, which is cumulative strength index at the ultimate deformation of structure. Hence, C_T denotes C_{TU}. The viscous damping of models was assumed as 2 %.

2.2. Analytical Models

We assumed one or two weak stories for each model. The weak story is defined as the story whose C_{TU} index is the smallest in the model. It is note that we call the story except for weak story as general story.

The index C_{TU} of general stories except for weak stories is set to from 0.3 to 0.6 with keeping the seismic index, I_s, equals to 0.6, and then the ductility index, F, decrease. The relationships between C_{TU} and F are depicted in Fig. 2.2. The x symbols shown in Fig. 2.2 mean the point of the story collapse. The points were obtained from Eqn. 2.1 by substituting 1/150 for R_y. Rigorously, the story collapse may not occur in that state; however, we defined the state as the limit of the safe in accordance with the guideline of seismic screening (JBDPA 2001).

The natural periods of 5-story and 9-story models are equal to from 0.5 s to 0.28 s and 0.6 s to 0.35 s, respectively.

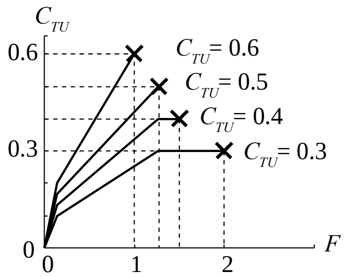
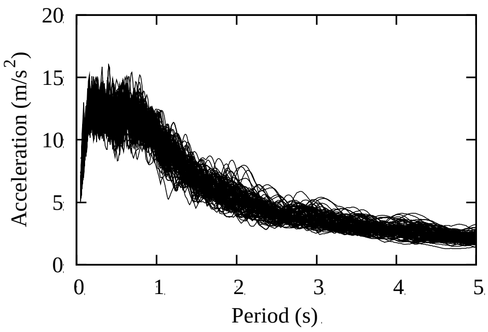


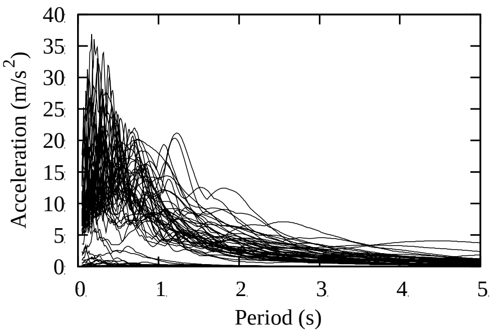
Figure 2.2. Relationship between C_{TU} and F

2.3. Input Ground Motions

The input ground motions used in this study were 100 generated ground motions and 59 recorded ground motions available at the website of the Pacific Earthquake Engineering Research Center (2006). The generated ground motion was made to be satisfied with a response acceleration spectral shape which is defined by Japan Building Code (MLIT 2000) as the safety-limit-design state of structures. The recorded ground motions selected are in accordance with two characteristics: the peak ground acceleration is greater than 5 m/s^2; and the peak velocity is greater than 0.5 m/s. The acceleration response spectra of both ground motions with 5 % damping are shown in Fig. 2.3. We assume that such a number of earthquakes and ground motion records sufficiently represent the variety of seismic characteristics and intensities that affects the inelastic responses of buildings.



(a) Generated ground motions



(b) Recorded ground motions

Figure 2.3. Acceleration response spectra (h = 5%)

2.4. Strength Ratio

The strength ratio R_q is defined by following equation.

$$R_q = C_{TU} / \overline{C}_{TU} \tag{2.4}$$

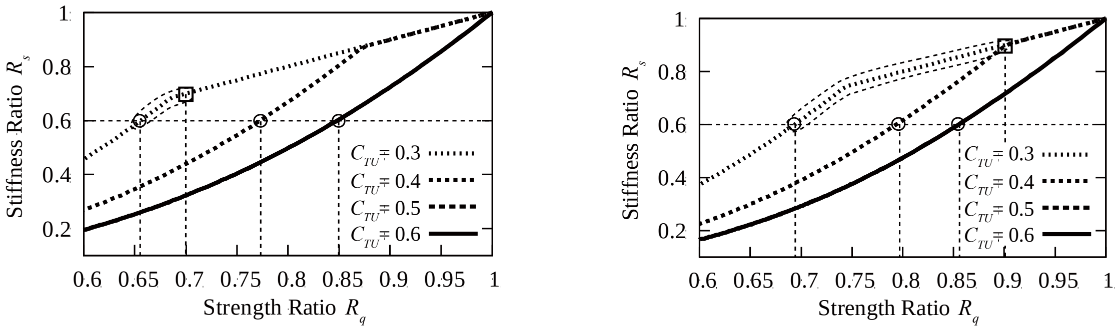
where $\bar{C}_{TU} = \sum C_{TU} / N$, N is the story of building.

If R_q index is enough larger than that of the other stories, the story will not collapse. Hence, it is ideal that the distribution of R_q along building height is uniform to prevent concentration of damage. On the other hand, a stiffness ratio is provided in allowable stress design method (AIJ 1999) as below:

$$R_s = r_s / \bar{r}_s \geq 0.6 \tag{2.5}$$

where $r_s = h_i / \delta_i$; h_i is story height; δ_i is story drift; $\bar{r}_s = \sum r_i / N$.

The relationship between R_s index and R_q index in case that C_{TU} index of weak story is between 0.3 and 0.6 is depicted in Fig. 2.4. Fig 2.4a shows the relationships of models with a weak story and Fig. 2.4b shows that of models with two weak stories: C_{TU} index of both weak stories are the same. The line of C_{TU}=0.6 is the same as that of C_{TU}=0.5 in both cases. The stiffness ratio of 0.6 is provided by Eqn. 2.5.



(a) Building with a weak story (b) Building with two weak stories

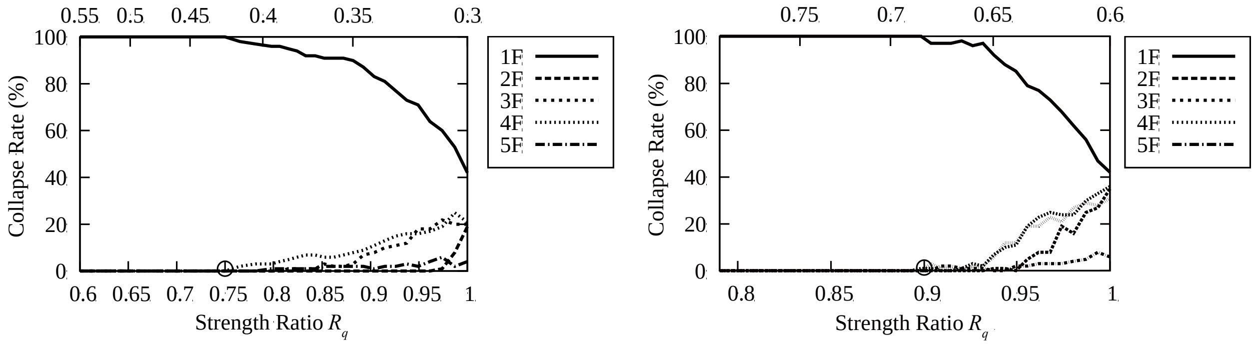
Figure 2.4. Relationships between stiffness ratio and strength ratio

3. DYNAMIC RESPONSE ANALYSIS RESULTS

The dynamic response analyses were carried out for buildings with a weak story and with two weak stories to consider the strength ratio for expecting the concentration of damage. The damage concentration was defined by the collapse rate which is defined as (numbers of collapsed model) / (total numbers of ground motion). We defined the strength ratio where a probability of damage concentrates of 100 % on weak story as collapsing strength ratio, R_{q0}, and discussed about the index to use for the structural design. The number of collapsed model is addition of models which is assumed as being collapsed. For generated and recorded ground motions, the collapse rate is obtained from 100 and 59 analyses, respectively. When the story collapse occurs in two stories at the same time, the rate can be more than 100 %.

3.1. 5- and 9-Story Building with One Weak Story

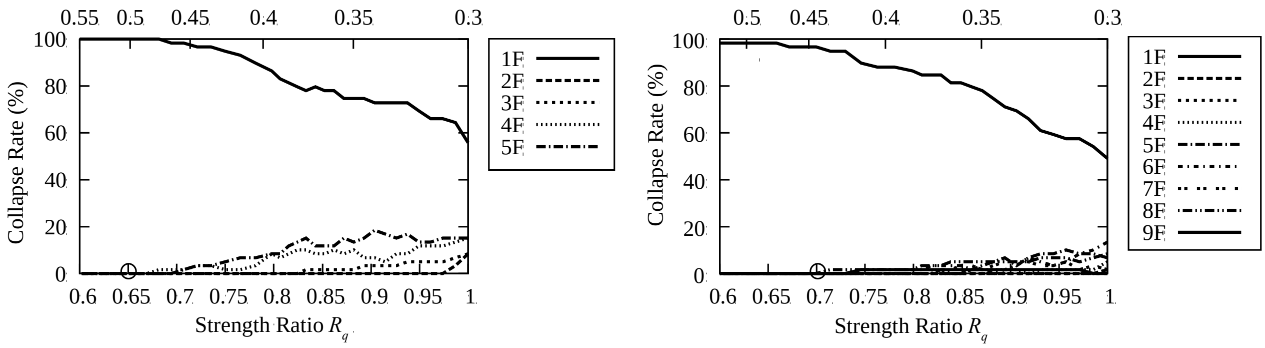
Fig. 3.1 shows the relationships between collapse rate and strength ratio of 5-story model with one weak story. The yield strength of weak story is fixed to C_{TU} and that of other stories increases. The Y-axis on top is the cumulative strength index, C_{TU}, of general story. The model of strength ratio of 1 has no weak story. The first story is likely collapse even if the strength distribution is uniform (in case that the strength ratio is 1). The collapse rate of the weak story increases with decreasing of strength ratio (see Fig. 3.1a and b). The collapsing strength ratio, R_{q0}, for C_{TU}=0.3 (see Fig. 3.1a) can be read off as 0.75 which means that C_{TU} index of weak story is about 1.4 times greater than that of general story. Similarly, R_{q0} can be read off as 0.9 for C_{TU}=0.6 (see Fig. 3.1b) which is a little larger than that of the models with C_{TU}=0.3. The strength ratio also was evaluated for 9-story models.



(a) C_{TU}=0.3 (b) C_{TU}=0.6

Figure 3.1. Relationships between collapse rate and strength ratio
(5-story model, Under generated ground motions)

Fig. 3.2 shows the results of under recorded ground motions. The collapse rate of weak story is increasing with decrease of strength ratio like as in Fig. 3.1. The collapsing strength ratio, R_{q0}, for 5-story and 9-story models under recorded ground motions can be read off as 0.65 and 0.7, respectively.



(a) 5-story (b) 9-story

Figure 3.2 Relationships between collapse rate and strength ratio
(C_{TU}=0.3, Under recorded ground motions)

Table 3.1 shows the collapsing strength ratio, R_{q0}, for each model obtained by dynamic response analyses results. In terms of the models with C_{TU}=0.3, minimum of collapsing strength ratio is 0.7, moreover, in terms of the models with C_{TU}=0.6, that is 0.9. The collapsing strength ratio of C_{TU}=0.6 is larger than that of C_{TU}=0.3 means that the strength distribution along building height affects the damage distribution for strength-resisting structure, yield deformation angle in all stories of which is small (see Fig. 2.2), higher than ductility-resisting structure. Then, the dispersion of the characteristics of ground motions greatly affects the responses and the stories of the model of C_{TU}=0.6 will collapse earlier than that of the model of C_{TU}=0.3.

Table 3.1 Collapsing strength ratio, R_{q0}

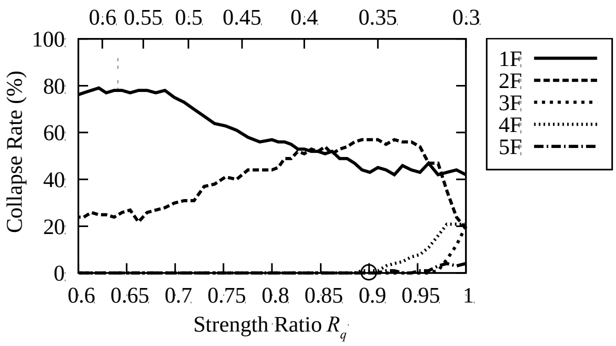
		C_{TU}=0.3	C_{TU}=0.4	C_{TU}=0.5	C_{TU}=0.6
Generated ground motions	5-story	0.75	0.8	0.9	0.9
	9-story	0.75	0.8	0.9	0.9
Recorded ground motions	5-story	0.7	0.8	0.85	0.9
	9-story	0.7	0.75	0.85	0.9

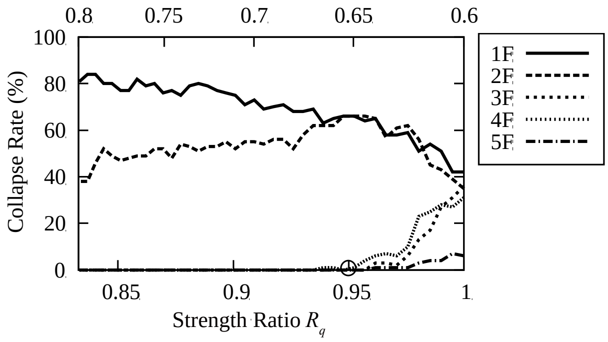
In this study, structures were modeled as MDOF system; however, in considering that the cumulative strength index of beams is assumed as 0.3 (JBDPA 2001), it is logical to consider models of C_{TU}=0.5 or 0.6 as the weak-beam-strong-column designed structure. The large-strength models (C_{TU}=0.5 and 0.6) may collapse at their beam hinges, even if the strength ratio is small. Then the collapsing strength ratio was discussed about for the models with C_{TU}=0.3 and 0.4 only.

The minimum of collapsing strength ratio on models of C_{TU} =0.3 and 0.4 is 0.7. Regarding the stiffness ratio and strength ratio, the stiffness ratio of about 0.7 which is corresponding with the strength ratio of 0.7 (see Fig. 2.5a) is larger than 0.6 (MLIT 1999). In the range of strength ratio between 0.6 and 0.7 (shown as the oval with broken line in Fig. 2.4a), even if the stiffness ratio is evaluated, the story collapse can be induced by the unbalances of strength distribution along building height. Hence, the strength ratio should be considered for structural design as well as the stiffness ratio.

3.2. 5- and 9-Story Building with Two Weak Stories

The results of dynamic response analyses for 5- and 9-story models with two weak stories the cumulative strength indexes, C_{TU}, whose are the same at both weak stories is shown in Fig. 3.3. The collapse rates of both weak stories are much larger than that of the other stories and the collapsing strength ratio can be read off as 0.9 in Fig. 3.3a. Similarly, Fig. 3.3b shows the collapsing strength ratio is 0.95 under recorded ground motions. Then, the collapsing strength ratio can be investigated as 0.9 for models with two-weak stories. The cumulative strength index of weak story when the strength ratio is 0.9 is about 1.1 times greater than that of general story. The stiffness ratio when the collapsing strength ratio is 0.9 in Fig. 2.4b is much larger than 0.6. Then, the collapsing strength ratio should be also considered as well as the stiffness ratio (the area drawn by the oval figure with broken line in Fig. 2.4b).





(a) Under generated ground motions (b) Under recorded ground motions

Figure 3.3 Relationships between collapse rate and strength ratio
(C_{TU}=0.3, Weak stories at the first and the third story)

4. STUDY ON BEAM YIELDING MECHANISM STRUCTURE

The collapsing strength ratio was evaluated for weak-column-strong-beam designed structure modeled by MDOF system. However, if the column-to-beam strength ratio, (yield strength of columns) / (yield strength of beams), is large, the damages can be converged on the hinges of beams. Additionally, the cumulative strength index of beams is assumed as 0.3 (JBDPA 2001) which is much smaller than that of columns. The column-to-beam strength ratio to prevent story collapse mechanism was provided as 1.2 (e.g. ACI 1999 and AIJ 1999). The models with the cumulative strength index of more than 0.4 can be collapsed with beam yielding mechanism. Therefore, to study the effect of strength distribution along building height in weak-beam-strong-column designed structure, the pushover analyses and dynamic response analyses were conducted in frame structure.

4.1 Analytical Model of Frame Structure

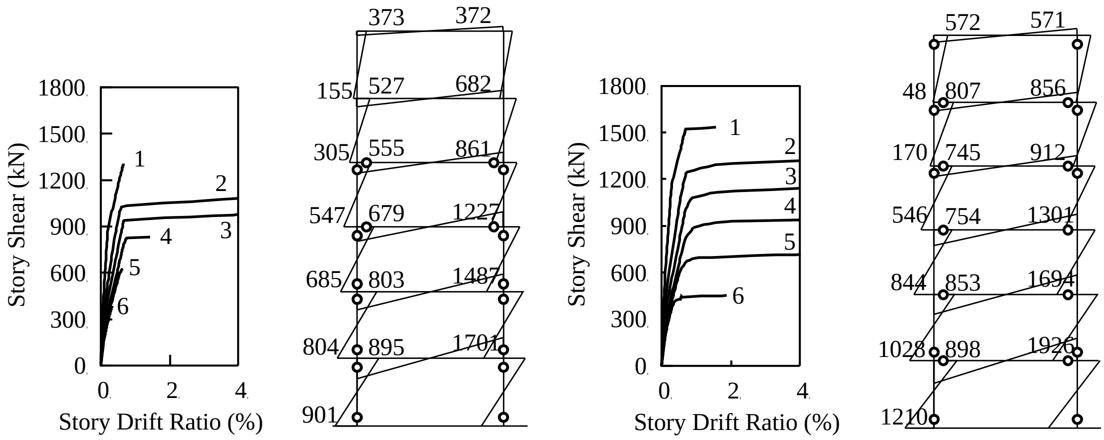
The analytical model is one-span frame structure which is assuming 6-story RC building built in before 1977. The hysteresis model of flexural springs at hinges was assumed as Takeda model (Takeda et al. 1970) the post-yielding stiffness of which is 0.001 times the elastic stiffness and the others are the same as Fig. 2.1. The yield strength of columns was assumed as the smaller one between ultimate flexural strength and ultimate shear strength. The cumulative strength index distribution along building height were obtained from the results of second screening in seismic evaluation and the distribution due to cumulative strength index of each story was assumed in accordance with the original distribution whose weak story is at the second floor as shown in Table 4.1. And the strength ratios are small at the second and third story which can be assumed as the weak story. To consider the variety of the strength distribution along building height, the cumulative strength indexes were changed with keeping the distribution of the cumulative strength index. We note that the name of model was defined by number of the cumulative strength index of the second story.

Table 4.1 Analytical frame model

Story	Original			C_{TU} =0.3	C_{TU} =0.4	C_{TU} =0.5	C_{TU} =0.6
	C_{TU}	Column-to-Beam Strength Ratio	R_q	C_{TU}			
6	1.13	1.8	1.4	0.55	0.73	0.91	1.1
5	0.95	1.5	1.2	0.46	0.61	0.77	0.9
4	0.67	1.1	0.9	0.32	0.44	0.54	0.65
3	0.64	1.0	0.8	0.31	0.41	0.52	0.62
2	0.62	1.0	0.8	0.30	0.40	0.50	0.60
1	0.70	1.1	0.9	0.34	0.45	0.56	0.66

4.2 Pushover Analysis

Fig. 4.1 shows the relationships between story shear and story drift ratio, the position of hinges and moment obtained from the pushover analysis in frames of C_{TU}=0.3 and 0.4. For the model of C_{TU}=0.3, the story collapse occurred in the first, second and third story (see Fig. 4.1a); however, the beam yielding mechanism were established in the model of C_{TU}=0.4 (see Fig. 4.1b), even if the strength distribution is the same. In case of the frame models, the strength distribution along building height should be considered particularly in buildings whose yield strength is low to expect damage concentration.



(a) C_{TU}=0.3 (b) C_{TU}=0.4

Figure 4.1 Story shear-drift ratio relationship, position of hinges and moment obtained from pushover analysis

4.3 Dynamic Response Analysis

Fig. 4.2 shows the relationships between story shear and ductility factor of columns and beams obtained from dynamic response analyses under 10 ground motions: 5 generated and 5 recorded ground motions. The left Y-axis is the number of story for columns and the right one is that for beams. The square and circle symbols mean the response of beams and columns, respectively. Fig. 4.2a shows the ductility factor of columns at the second, third and the fourth story are much larger than 1 which means the story collapse occurred, although the ductility factor of beams are large. On the other hand, the ductility factor of beams are larger than 1 in Fig. 4.2b and then the beam yielding mechanism were established.

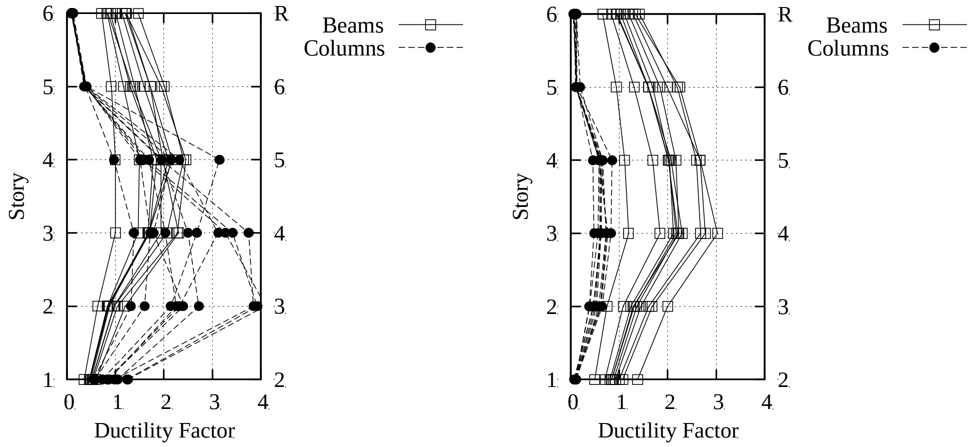


Figure 4.2 Story shear-ductility factor relationship obtained from dynamic response analysis

Fig. 4.3 shows that number of collapse mechanism: story collapse mechanism; and beam yielding mechanism, obtained from dynamic response analyses. The number of story collapse mechanism is small in the model of C_{TU}=0.5 and 0.6, nevertheless the strength distribution along building height was the same and not uniform: the strength ratio of the second and third story is smaller than 0.9 which is presented as not ideal in building with two weak stories for preventing damage concentration.

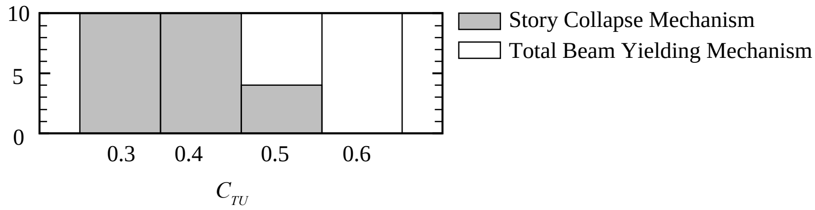


Figure 4.3 Number of collapse mechanism

5. CONCLUSIONS

This paper discussed about the effect of unbalance of strength distribution along building height and the strength ratio that is newly defined as the ratio of cumulative strength index, C_T, of weak story to average of C_T index of all the stories is investigated. From the trend of the results of present study, the following conclusions can be drawn:

1) In case of the building with the same cumulative strength index in all stories, the story collapse can occur in all stories, although the first story is likely to collapse.
2) In case of the building with a weak-first-story whose cumulative strength index is small: 0.3 and 0.4, if the strength ratio of the weak story is 0.7 (C_{TU} index of weak story is about 1.4 times greater than that of other stories), the story collapse will occur at the first story.
3) In case of the building with two weak stories whose cumulative strength index is the same and small: 0.3 and 0.4, if the strength ratio of the weak story is 0.9 (C_{TU} index of weak story is about 1.1 times greater than that of other stories), both weak stories will collapse.
4) To predict damage concentration, the strength ratio should be considered as well as the stiffness ratio.
5) In case of the building with a weak story whose cumulative strength index is large: 0.6, even if the strength ratio is not ideal, the story collapse will not occur due to total beam yielding mechanism.

REFERENCES

ACI Committee 318 (1999) Building Code Requirements for Structural Concrete (318-99) and Commentary (318R-99), Chapter 21 Special Provisions for Seismic Design, American Concrete Institute.

ATC (1996) Seismic evaluation and retrofit of concrete buildings, **1**, ATC-40, Applied Technology Council, Redwood City.

Architectural Institute of Japan. (1999) Standard for Structural Calculation of Reinforced Concrete Structures Based on Allowable Stress Concept. Architectural Institute of Japan, Japan (in Japanese).

Architectural Institute of Japan. (1999) Design Guidelines for Earthquake Resistant Reinforce Concrete Buildings Based on Inelastic Displacement Concept. Architectural Institute of Japan, Japan (in Japanese).

FEMA (2000) Prestandard and commentary for the seismic rehabilitation of buildings, **356**, The American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C.

Takeda T., Sozen M.A. and Nielsen N.N. (1970) Reinforced concrete response to simulated earthquakes. *Journal of Structural Engineering*. ASCE, **96:4**, 2557-2573.

The Japan Building Disaster Prevention Association. (2001) Seismic Evaluation and Retrofit, Japan.

Marubashi N., Ichinose T. (2006) Effects of strength distribution along building height on seismic capacity of each story in existing RC building. *Journal of Japan Concrete Institute*. Japan Concrete Institute, **28**, 1225-1230, (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism (2000) Notification No. 1457-2000, Technical Standard for Structural Calculation of Response and Limit Strength of Buildings, (in Japanese).

Pacific Earthquake Engineering Research Center (PEER) (2006) PEER strong motion database. http://peer.berkeley.edu/smcat/.

Paulay, T and Priestley, M.J.N. (1992) Seismic Design of Reinforced Concrete and Masonry Buildings, Wiley Interscience.