13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2253

# EFFECT OF STRENGTH VARIATION ON SEISMIC RESPONSE OF STRUCTURES

Nanako Marubashi[1], Hisashi Umemura[2] and Toshikatsu Ichinose[3]

## SUMMARY

Story strengths in real structures are uncertain due to the dispersion of material strength and non-structural members. Even if the pushover analysis predicts that the building has a weak story, the other stories may deform more than the predicted weak story due to the strength uncertainty. In this paper, we estimated the effect of strength uncertainty on seismic response of structures. We selected structures idealized 6story reinforced concrete buildings with weak 1st story. The Monte Carlo simulation is performed assuming that the strength of each story is distributed in accordance with normal distribution of 10% COV. As a result, the damage distribution of each story is different from the normal distribution although the strength variation was assumed as the normal distribution. It is noted that the damage of the 2nd to 6th story in the case of the relative ratio = 0 to 20% can be larger than the damage of the 1st story.

## INTRODUCTION

Pushover analysis has been successfully applied to building structures [1]. It is powerful in predicting story drifts of structures which have clear collapse mechanism such as total mechanism.

However, story strengths in real structures are uncertain due to the dispersion of material strength and non-structural members. Recent researches evaluated the effect of various uncertainties such as the variation of member strength on seismic response. Kuwamura [2] examined the uncertainty factors which impaired overall collapse mechanism by the statistical method. Moriguchi [3] confirmed that the coefficient of variation of the flexural strength of columns is about 10% in the general structure design.

It is possible that the damage distribution is different from that given by the pushover analysis due to strength uncertainty. Even if the pushover analysis predicts that the building has a weak story, the other stories may deform more than the predicted weak story due to the strength uncertainty.

The main goal of this paper is to estimate the effect of strength uncertainty on seismic response of structures. The selected structures are idealized reinforced concrete buildings with weak story, where beams are stronger than the columns. The Monte Carlo simulation is performed assuming that the strength of each story is distributed in accordance with normal distribution.

1 Graduate Student, Faculty of Engineering, Nagoya Inst. of Tech., Nagoya, Japan.
2 Assist. Prof., Dr. Eng, Faculty of Engineering, Nagoya Inst. of Tech., Nagoya, Japan
3 Prof., Dr. Eng, Faculty of Engineering, Nagoya Inst. of Tech., Nagoya, Japan

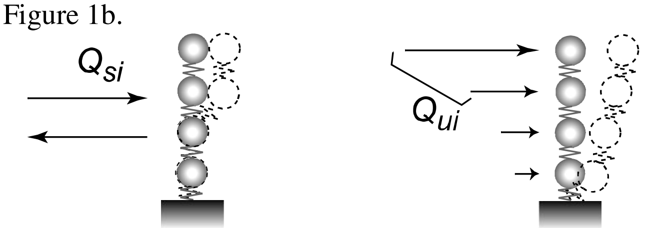
## ANALYSIS METHOD, STRUCTURE SYSTEMS AND GROUND MOTIONS

### Analysis method and Story -safety-factor Subheading

In this paper, the Monte Carlo simulation was used to consider the strength variation. We analyzed 2000 mass shear system models of 6stories. Each of the story strengths was fluctuating according to the normal distribution. Each story of model is independent. We decided the COV of the yielding strength is 10%. We used the story-safety factor as an index to the relative ratio of strength of each story. The story -safety factor, which represents the reserve capacity of the *i*th story, is defined by the following equation:

$$f_i = \frac{Q_{si}}{Q_{ui}} - 1$$

where $Q_{si}$ = the strength of the *i*th story under the forces shown in Figure 1a and $Q_{ui}$= the shear force of the *i*th story when the structure reaches the strength under the external forces specified by the Japanese Building Code shown in Figure 1b.




(a) Forces causing story collapse

(b) Forces specified by design code

**Figure 1.** Two kinds of fources

### Structure systems and ground motions

The structural systems are lumped mass shear system models of 6 stories with a weak story. The height of each story is 3m and the weight is 100t. The hysteresis characteristics of the models are Takeda model [4]. The yielding strength of the *i*th story $Q_{yi}$ is designed by the following equation:

$$Q_{yi} = C_b \times A_i \times W_i \times (1 + f_i)$$

where $C_b$ = the base shear coefficient (0.5), $A_i$ = the height-wise distribution of story shear coefficients specified by the Japanese Building Code and $W_i$ = the weight of the stories from the *i*th story to the $6^{th}$ story. The yielding strength of the *i*th story is 3cm.

Assuming the RC building with soft first story, the value of $f_i$ for the 1st story is 0 while the $f_i$ for the other stories are set as the parameter with values of: 0, 0.1, 0.2, 0.3, 0.4 and 0.5 shown in Table 1. Figure 2 shows the assumed probability density distribution of the strength of each story. The horizontal axis represents ($1+f_i$) as the relative ratio of strength of each story. Table 2 shows input ground motions and the scale factor of the ground motions decided so that the maximum velocity becomes 100cm/s.

**Table 1.** Structure systems

| $f_i$ | | natural period (s) |
|---|---|---|
| 1F | 2F-6F | |
| 0 | 0 | 0.515 |
| | 0.1 | 0.496 |
| | 0.2 | 0.48 |
| | 0.3 | 0.466 |
| | 0.4 | 0.454 |
| | 0.5 | 0.443 |

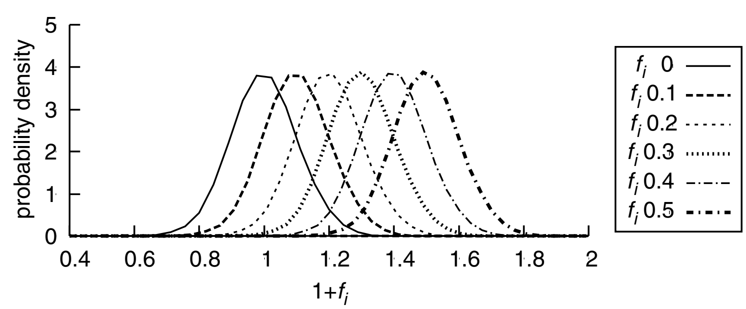


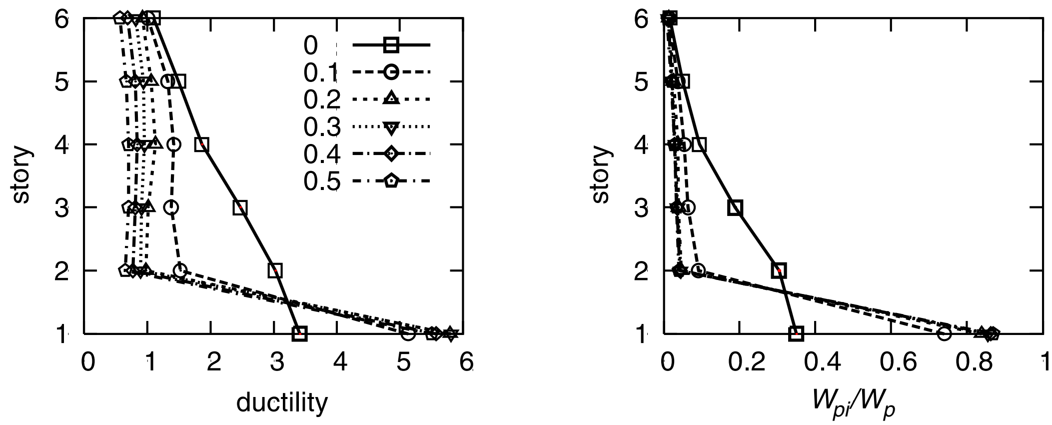

**Figure 2.** The assumed probability density distribution of the strength of each story

**Table 2.** The detail about input ground motions

| Year/Earthquake/Station/Channel | scale factor | appellation |
|---|---|---|
| 1968/Tokachi-oki/Hachinohe Harbor/EW | 2.6 | hach |
| 1995/Kobe/JMA/NS | 1 | JMA |

## THE CASE OF THE BUILDINGS WITHOUT STRENGTH VARIATION

Figure 3 shows the result of the dynamic analysis using the buildings without strength variation, where the input ground motion is hach. Figure 3a shows the ductility distribution and Figure 3b shows the distribution of $W_{pi}/W_p$, where $W_{pi}$ =cumulative plastic energy of the $i$th story and $W_p = \Sigma\, W_{pi}$. The values in the legend represent $f_i$ value from the 2nd to 6th story. When $f_i$ value from the 2nd to 6th story is 0.1, the ductility of the 1st story and $W_{p1}/W_p$ become quite large. The results of the models of $f_i$ = 0.2 to 0.5 are similar to that of 0.1. In case of buildings without strength variation, plastic deformation concentrates in the 1st story if $f_i$ is larger than 0.1 in the other stories.




(a) Ductility distribution (b) Distribution of $W_{pi}/W$

**Figure 3.** The damage distribution of the buildings without strength variation

## THE EFFECT OF STRENGTH UNCERTAINTY

### Distribution of the cumulative plastic energy ratio

We evaluated concentration ratio of the cumulative plastic energy given by the dynamic analyses using the buildings with strength variation. Figure 4 shows $W_{p1}/W_p$, where **a-f** represent respectively the result of models with $f_i$ = 0, 0.1, 0.2, 0.3, 0.4 and 0.5. The solid straight line represents the result of the model without strength variation. The solid and grey histograms represent the result of the models with strength variation of COV of 5% and 10%, respectively. The broken line represents the mean of the grey histogram and σ represents the standard deviation. The peak of histogram increases with an increase in the $f_i$ value. Although the strength variation was assumed as the normal distribution, every histogram is very different from the normal distribution. The value of $W_{p1}/W_p$ of the model without strength variation (the solid straight line) is larger than mean (the broken line) in every case. The distribution of COV of 5% has similar shape to that of 10%. The peak of the histogram becomes shaper when $f_i$ increases till 0.3, but becomes similar shape when $f_i$ >0.3.

Figure 5 shows $W_{p2}/W_p$ and $W_{p3}/W_p$, where the solid straight line and the broken line represent, respectively, the result of $W_{p2}/W_p$ and $W_{p3}/W_p$. The 2nd and 3rd story are selected because extensive damage of the stories is confirmed next to the 1st story. The values with strength variation frequently exceed that without strength variation. It is noted that t $W_{p2}/W_p$ and $W_{p3}/W_p$ in the case of $f_i$ = 0 to 0.2 can be larger than 0.7 or 0.8. ($W_{p1}/W_p$ when $f_i$ > 0.1)

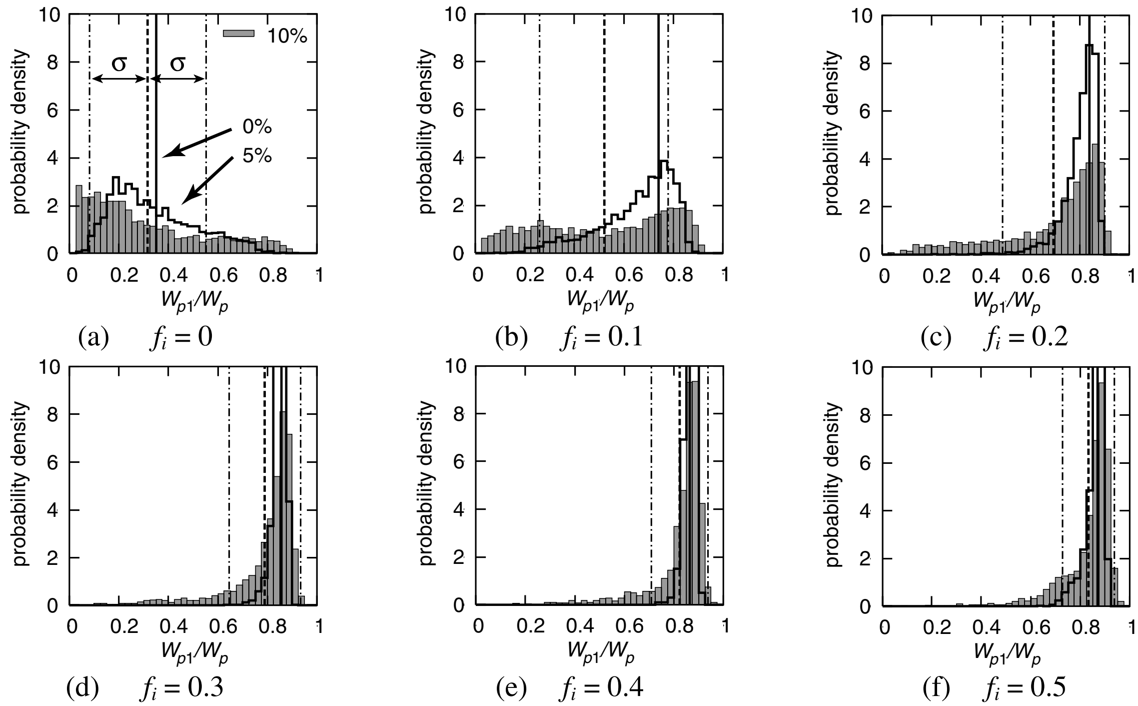



**Figure 4.** Disdribution of $W_{p1}/W_p$

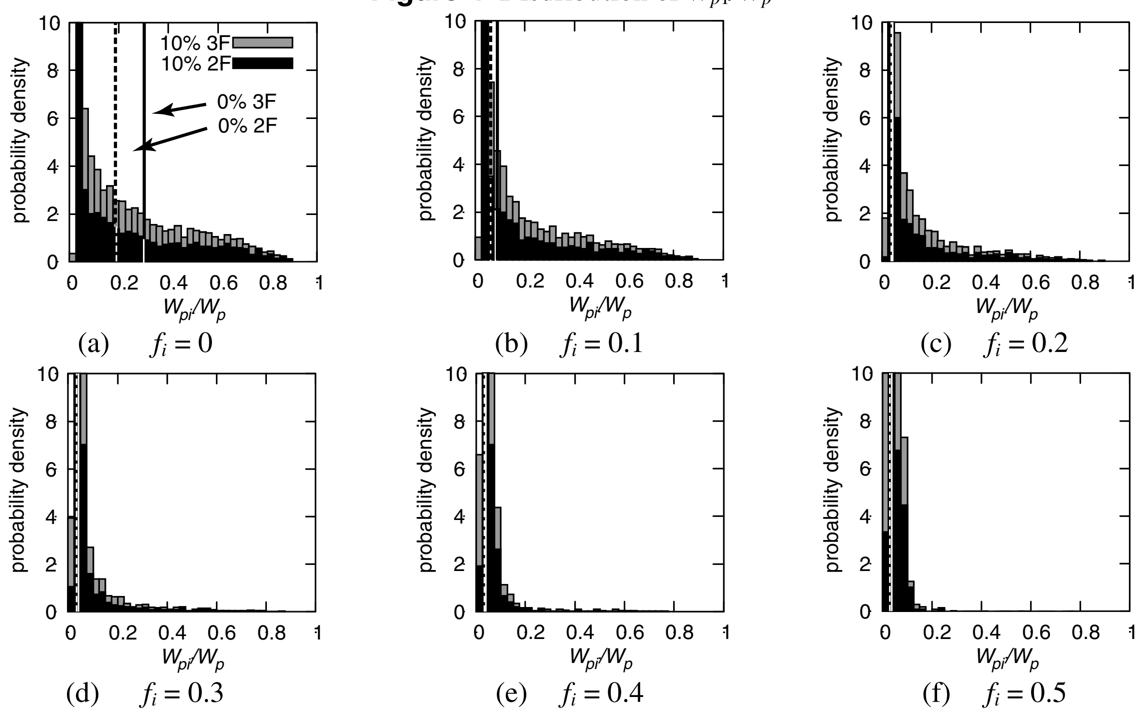
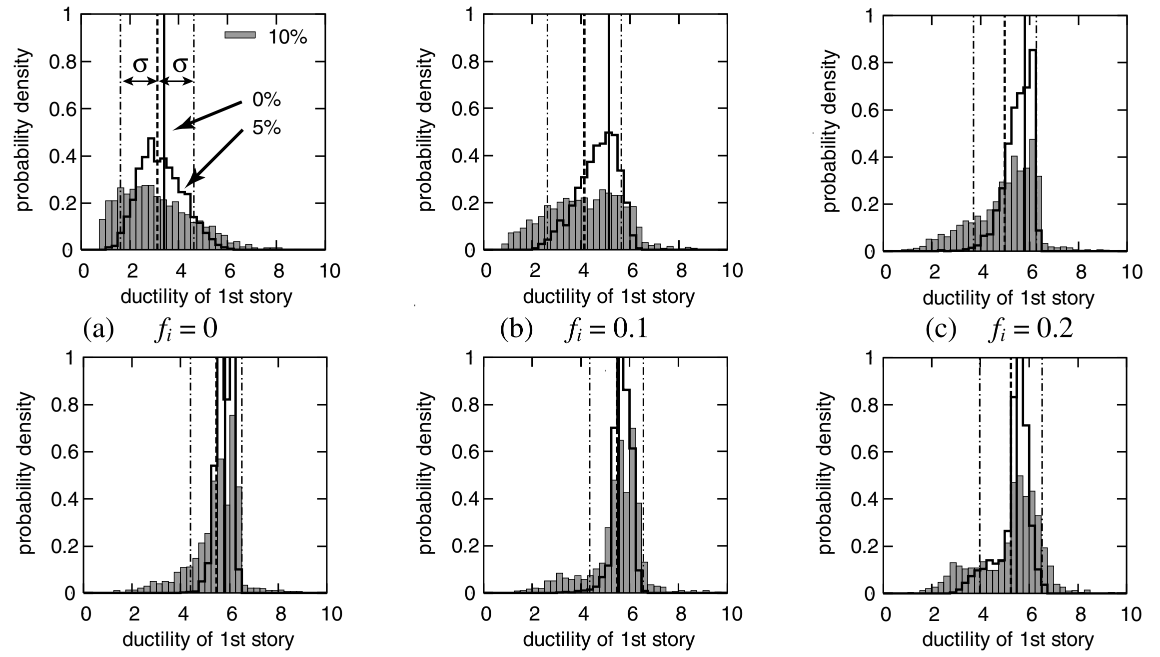



**Figure 5.** Disdribution of $W_{p2}/W_p$ and $W_{p3}/W$

**Ductility distribution**

Figure 6 show the ductility of the 1st story given by the dynamic analysis using the buildings with strength variation. The peak of the histogram increases with an increase in the values of $f_i$ corresponding to the change of $W_{p1}/W_p$ distribution as shown in Figure 4. Every histogram is very different from the normal distribution. The peak of the histogram becomes shaper when $f_i$ increases till 0.3, but becomes less shaper when $f_i$ >0.3. The reason is that the total displacement of the model becomes great change as the natural period of model increase from 0.515s to 0.443s as shown in Table 1.

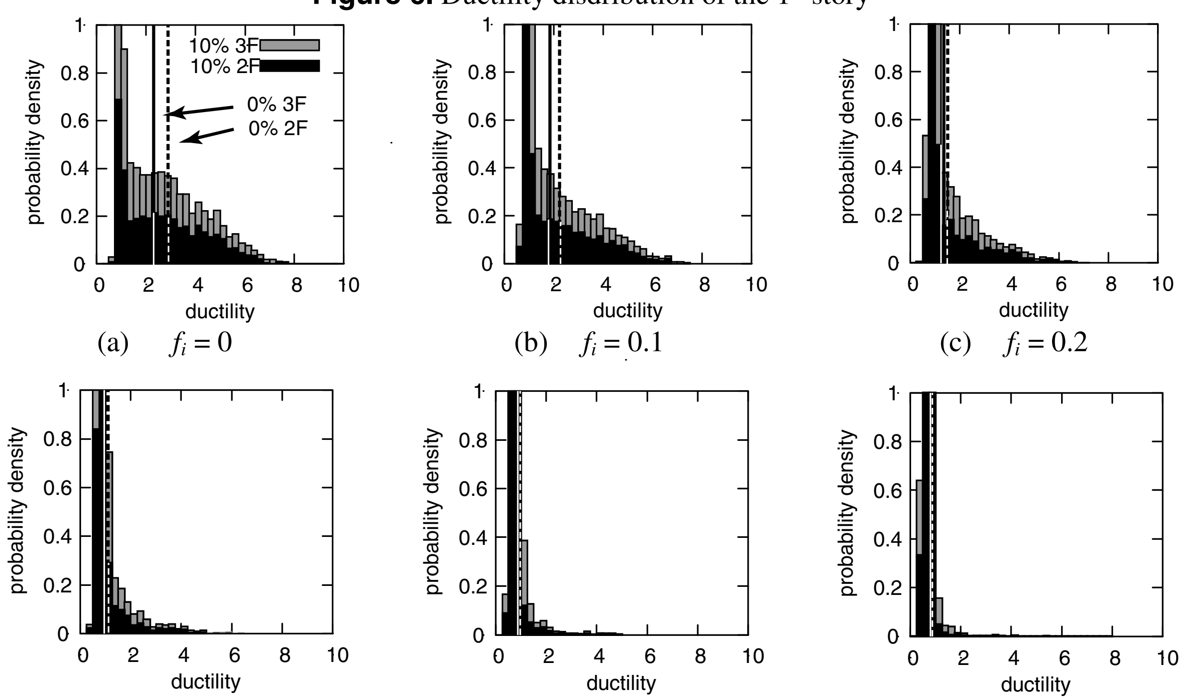
Figure 7 show the ductility of the 2nd and 3rd stories. The results show much the same pattern as Figure 5. It is noted that the ductility of the 2nd and 3rd stories in the case of $f_i = 0$ to 0.2 can be larger than 5 or 6. (the ductility at the 1st story when $f_i > 0.1$)




(a) $f_i = 0$ (b) $f_i = 0.1$ (c) $f_i = 0.2$

(d) $f_i = 0.3$ (e) $f_i = 0.4$ (f) $f_i = 0.5$

**Figure 6.** Ductility disdribution of the 1st story




(a) $f_i = 0$ (b) $f_i = 0.1$ (c) $f_i = 0.2$

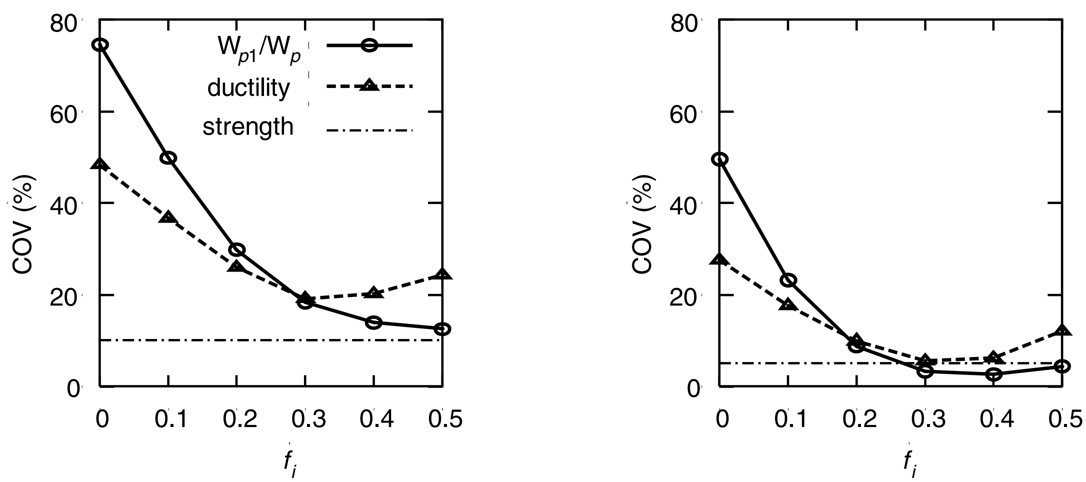
(d) $f_i = 0.3$ (e) $f_i = 0.4$ (f) $f_i = 0.5$

**Figure 7.** Ductility disdribution of the 2nd and 3rd story

**The comparison of variation**

Figure 8 shows the COV of the ductility and $W_{p1}/W_p$ as a function of $f_i$. Figure 8a shows the results when the COV of strength is 10% and Figure 8b shows the results when the COV of strength is 5%, where the solid line represents the COV of $W_{p1}/W_p$, the broken line represents that of the ductility of the 1st story and the dashed line represents that of the strength.

In Figure 8a the COV of $W_{p1}/W_p$ decreases gradually with the value of $f_i$. It can be seen that the cumulative plastic energy tends to concentrate on 1st story because the strength of the 1st story can be rarely larger than that of the other stories. The COV of the ductility decreases with an increase when $f_i < 0.3$. But that increase slightly when $f_i > 0.3$, which correspond to the change of distribution as shown in Figure 4d-f. In Figure 8b the COV of $W_{p1}/W_p$ and the ductility of 1st story increase for the value of $f_i > 0.3$.



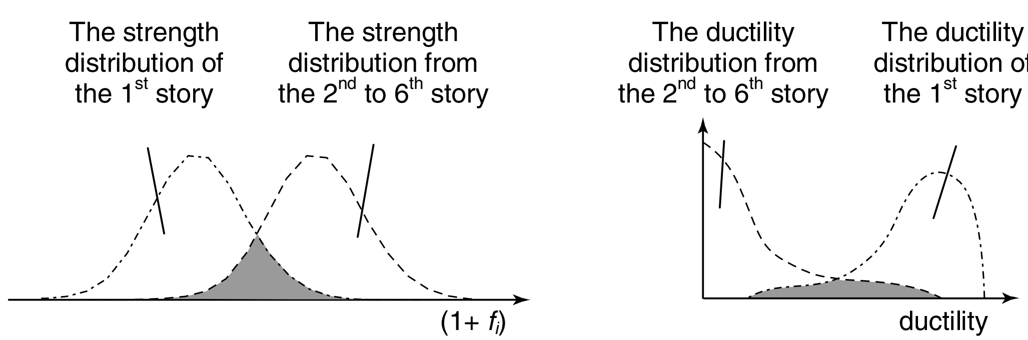

(a) 10% (b) 5%

**Figure 8.** COV

## THE INVERSION RATE

In this paper RC buildings with weak 1st story under pushover analysis were object of research. However, it is possible that the 1st story is stronger than the other stories if the strength is uncertain. This can be the reason why the ductility of the 2nd to 6th story can be larger than that of the 1st story as shown in Figure 7.

The inversion rate of the strength and ductility are defined as the probability of the shaded area in Figure 9a and Figure 9b, respectively.




(a) Strength (b) Ductility

**Figure 9.** The inversion rate

Figure 10 shows the inversion rate of the strength and the ductility as a function of $f_i$, where the notation of the plots is shown in Table 3. There is a decrease in the every plot with the value of $f_i$. The inversion rate of the ductility is larger than that of the strength irrespective of the seismic characteristics. When $f_i = 0.3$ in the case that the strength variation is 10%, the inversion rate of the strength is nearly 0 but that of the ductility is between 5 and 20%. When the value of $f_i = 0.2$ in the case that the strength variation is 5%, the inversion rate both the strength and the response ductility remains nearly 0.
Figure 11 shows the relation between the inversion rate of the strength and that of the ductility. The inversion rate of ductility increases as that of strength increases, but not linearly.

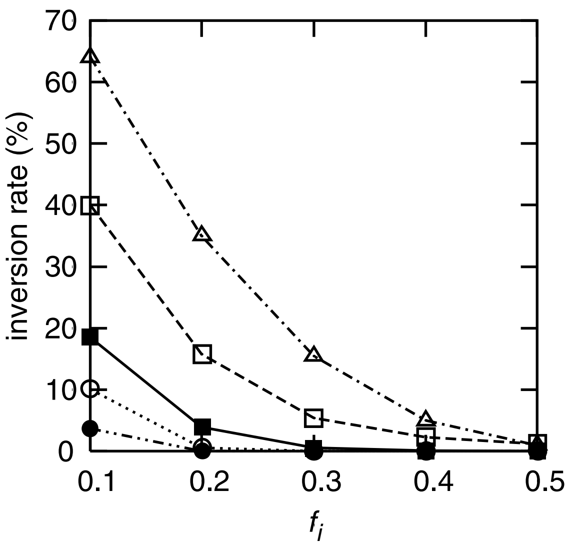



**Figure 10.** The inversion rate of the strength and the ductioity

**Table 3.** The notation of the plots

| plot | COV of strength | ground motion | inversion rate |
|---|---|---|---|
| ■ | 10% | - | strength |
| □ | | hach | ductility |
| △ | | JMA | |
| ● | 5% | - | strength |
| ○ | | hach | ductility |

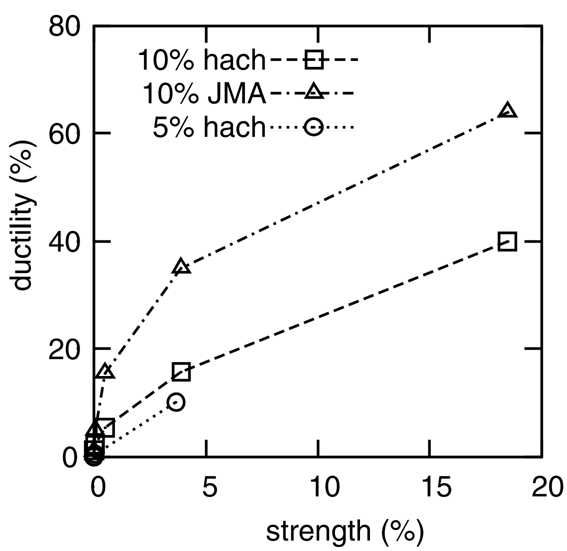



**Figure 11.** The relation between the inversion rate of the strength and that of the ductility

## CONCLUSION

This paper estimated the effect of strength uncertainty on seismic response of structures. The selected structures are idealized 6story reinforced concrete buildings with weak 1st story. The Monte Carlo simulation is performed assuming that the strength of each story is distributed in accordance with normal distribution of 10% COV. As a result, the following can be concluded.

1. In case of buildings without strength variation, plastic deformation concentrates in the 1st story if the relative ratio of strength is larger than 10% in the other stories.

2. Although the strength variation was assumed as the normal distribution, the damage distribution is different from the normal distribution. It is noted that the damage of the 2nd to 6th story in the case of the relative ratio of strength = 0 to 20% can be larger than the damage of the 1st story.

3. The inversion rate of the ductility is larger than that of the strength irrespective of the seismic characteristics. The inversion rate of ductility increases as that of strength increases, but not linearly.

## REFERENCES

1. Chatpan Chintanapakdee and Anli K. Chopra: Evaluation of modal pushover analysis using generic frame, *Earthquake Engineering and Structural Dynamics*, 2003; **32**: pp.417-442.
2. Hitoshi Kuwamura, Michio Sasaki and Ben Kato: Mechanism-based seismic design considering random yield strength, *J. Struct. Constr. Eng.,* AIJ*,* No. 401, pp. 151-162.
3. Hideki Moriguchi, Yosiaki Nakano and Kaoru Fujiwara: Column-overdesign-factor and probability of yielding in columns considering the uncertainties of strength of members, *J. Struct. Constr. Eng.,* AIJ*,* No. 509, pp. 119-126.
4. Takeda, T., Sozen, M.A., and Nielson, N.N. (1970): Reinforced concrete response to simulated earthquakes, *Journal of Structural Engineering*, ASCE, Vol. 96, No. 4, pp. 2557-2573.