Paper No. 333. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

STUDY ON THE FRAGILITY OF SYSTEM
PART 1 : STRUCTURE WITH BRITTLE ELEMENTS IN ITS STORIES

S. FUKUSHIMA[1], Y. KAI[2] and K. YASHIRO[3]

1. Tokyo Electric Power Services Co., Ltd.,
3-3, Higashi-Ueno 3-chome, Taito-ku, Tokyo 110, JAPAN

2. Shimizu Corporation,
2-3, Shibaura 1-chome, Minato-ku, Tokyo 105-07, JAPAN

3. Tokyo Electric Power Company,
1-3, Uchisaiwai-cho 1-chome, Chiyoda-ku, Tokyo 100, JAPAN

ABSTRACT

The relationship among the fragility of element, that of story and that of system, is examined using the Monte Carlo simulation (MCS). In this study, 2-story models whose stories consist of 2 brittle elements are employed. Through the simulation, the feature of the failure of brittle elements is derived. Using this feature, the method to evaluate the fragility of brittle element is presented. This method is an extension of the method previously proposed, and is also summarized here for convenience. The results by this method show a good agreement with those by MCS. Also presented is a method to estimate the fragility of the story and that of system.

KEYWORDS

Fragility of the system; System consisting of brittle elements; Approximate fragility analysis method; Monte Carlo simulation of the failure of the system

INTRODUCTION

Authors have been proposed the method which evaluates the fragility of system subjected to seismic loading (Mizutani *et al.*, 1994). This method can easily evaluate the failure probability (PF) of the series system where the PF of each story directly relates to that of the system. However, with the increasing complexity in the modeling, it comes necessary to employ the parallel system whose stories consist of several elements. In case of such a system, it is required to relate the PF of each element to that of story and that of system, since the failure of element does not directly relate to that of the system due to the redundancy.

After summarizing the method employed here, this paper investigates the relationship above using the MCS and verifies the applicability of the fragility analysis method to the parallel system. Part 1 of this study deals with the system consisting of brittle elements.

FRAGILITY ANALYSIS METHOD

Framework of Method

The fragility analysis method consists of evaluations of response and capacity, in which the median and the variability are evaluated. In this analysis, to save the computational effort, employed are some approximations as followings.

1. Random vibration theory in the frequency domain is employed to evaluate the response.
2. Effects of inelastic behavior are included in the evaluation of capacity.
3. Variability of response and that of capacity are assumed to be log-normally distributed.

Evaluation of Response

$R(a_s)$, which is the response subjected to seismic motion of intensity a_s, can be expressed with the following equation,

$$R(a_s) = r(a_s) \times F_1 \times F_2 \times F_3 \tag{1}$$

where $r(a_s)$ is the median response, F_1 and F_2 are the random factors due to the variability of input response spectrum and that of system property, and F_3 is also the random factor which corresponds to the modeling uncertainty.

The concept of the response analysis is illustrated in Fig. 1. The median and the log-normal standard deviations of F_1 and F_2 are obtained with the following equations,

$$med(F_1) = med(F_2) = 1.0 \tag{2}$$

$$sd(F_1) = \ln[r(R_{84}, T_{50}) \,/\, r(R_{50}, T_{50})] \tag{3}$$

$$sd(F_2) = \ln[r(R_{50}, T_{84}) \,/\, r(R_{50}, T_{50})] \tag{4}$$

where $r(R,T)$ is a response calculated for the combination of the response spectrum R and transfer function T, and subscript for R and T denotes the percentile value. The operator $med(\cdot)$ derives the median value, and the operator $sd(\cdot)$ does the log-normal standard deviation.

Evaluation of Capacity

Capacity of element C can be expressed with the following equation,

$$C = S \times F_4 \tag{5}$$

where S is the stochastic strength of element, and F_4 is the random factor expressing the effects of inelastic response such as an energy absorption and a damage concentration.

The feature of this method is that it requires only one nonlinear simulation to evaluate the effects mentioned above. Figure 2 shows the concept of the inelastic capacity.

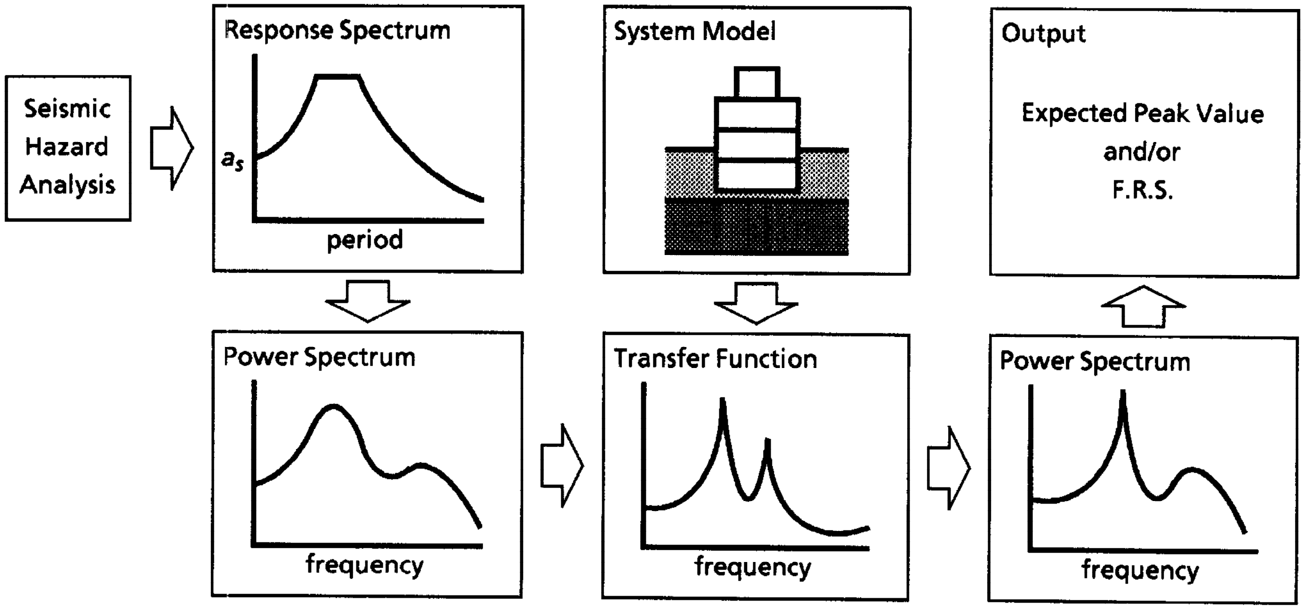

Fig. 1. Concept of response analysis

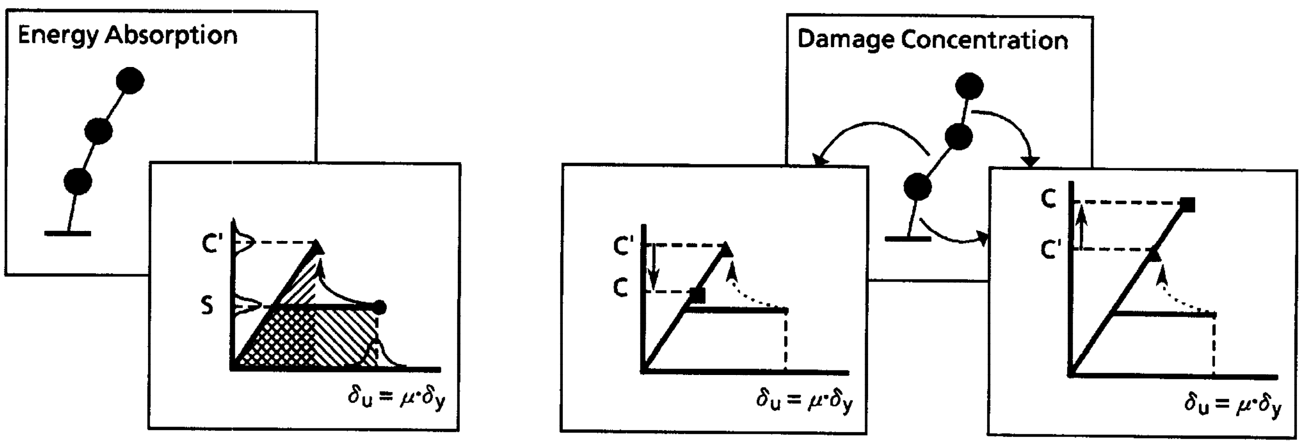

Fig. 2. Effects of inelastic behavior on capacity

Calculation of Fragility Curve

The median and the standard deviation of the ground acceleration capacity A are obtained with the following equations.

$$med(A) = med(C) \,/\, med(R(a_s)) \times a_s \tag{6}$$

$$sd(A) = [sd(F_1)^2 + sd(F_2)^2 + sd(F_3)^2 + sd(F_4)^2]^{1/2} \tag{7}$$

Therefore, the fragility curve can be calculated with the following equation,

$$P(a) = P(a > A) = \Phi[\ln(a/med(A)) \,/\, sd(A)] \tag{8}$$

where Φ denotes the standard normal distribution function.

Model and Input Motion

As shown in Fig. 3, this paper deals with 2-story models whose stories consist of 2 brittle elements. Random variables employed here are stiffness and strength of a element. Median of natural period is 0.3 sec. Damping factor is fixed at 0.03.

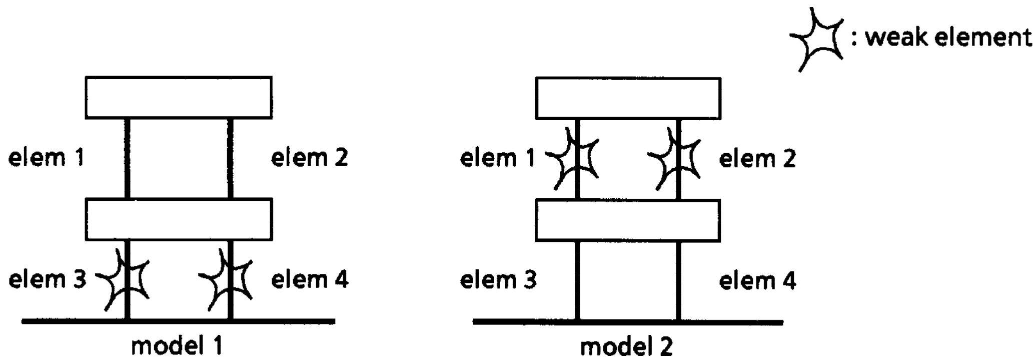

Fig. 3. Analysis model

In the MCS, the brittle element fails with the loss of its stiffness and member force when it exceeds its ultimate displacement. Failure of the story is defined as the intersection of those of the elements in the story, and the failure of the system is defined as the union of those of stories. In addition to the nonlinear analysis, linear analysis is carried out with the definition that the element fails when its response exceeds the strength, even though it does not lose its stiffness.

100 samples of each random variable are generated assuming the log-normal distribution. No correlation among the variables is considered. 100 artificial earthquakes are also generated according to the median, variability and auto-correlation matrix of the target response spectrum (Ishii *et al.*, 1989).

Table 1 shows the property of each element with the ground acceleration capacity.

Table 1. Properties and ground acceleration capacity of element

			stiffness (tf/m)		strength (tf)		capacity (Gal)	
model	story	element	median	s.d.	median	s.d.	median	s.d.
1	upper	1	54.667	0.412	2.265	0.102	1389.	0.444
		2	57.308	0.427	2.301	0.094	1346.	0.419
	lower	3	56.103	0.386	2.312	0.095	879.	0.455
		4	56.264	0.419	2.262	0.098	858.	0.419
2	upper	1	54.667	0.412	2.265	0.102	1389.	0.444
		2	57.308	0.427	2.301	0.094	1346.	0.419
	lower	3	56.103	0.386	4.624	0.095	1758.	0.455
		4	56.264	0.419	4.524	0.098	1715.	0.419

Result of Analysis

Figure 4 compares the fragility of the element in the weaker story with the fragility curve obtained using the capacity shown in Table 1. The fragility of the elastic element agrees with the fragility curve. On the other hand, the fragility of the brittle element does not.

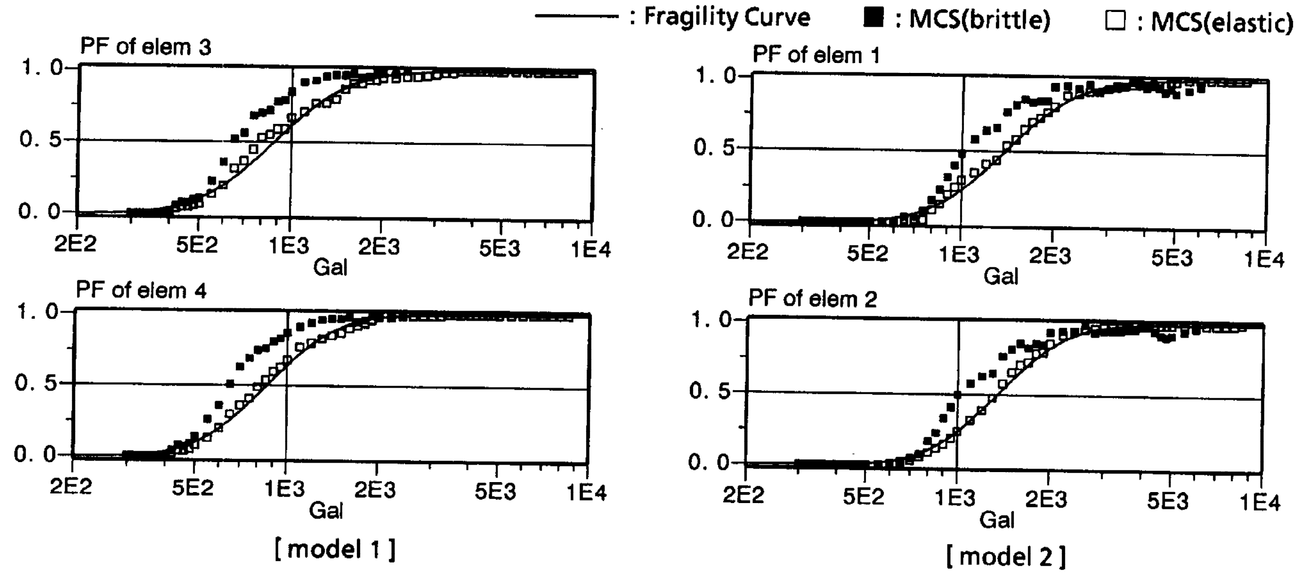

Fig. 4. Fragility curve of element in the weak story

MODIFICATION OF CAPACITY

Feature of Failure of Brittle Elements

In order to investigate the above difference, the failure of the brittle element is examined. Shown in Fig. 5 is the ratio of the PF of the story to that of element in the brittle system and the elastic system.

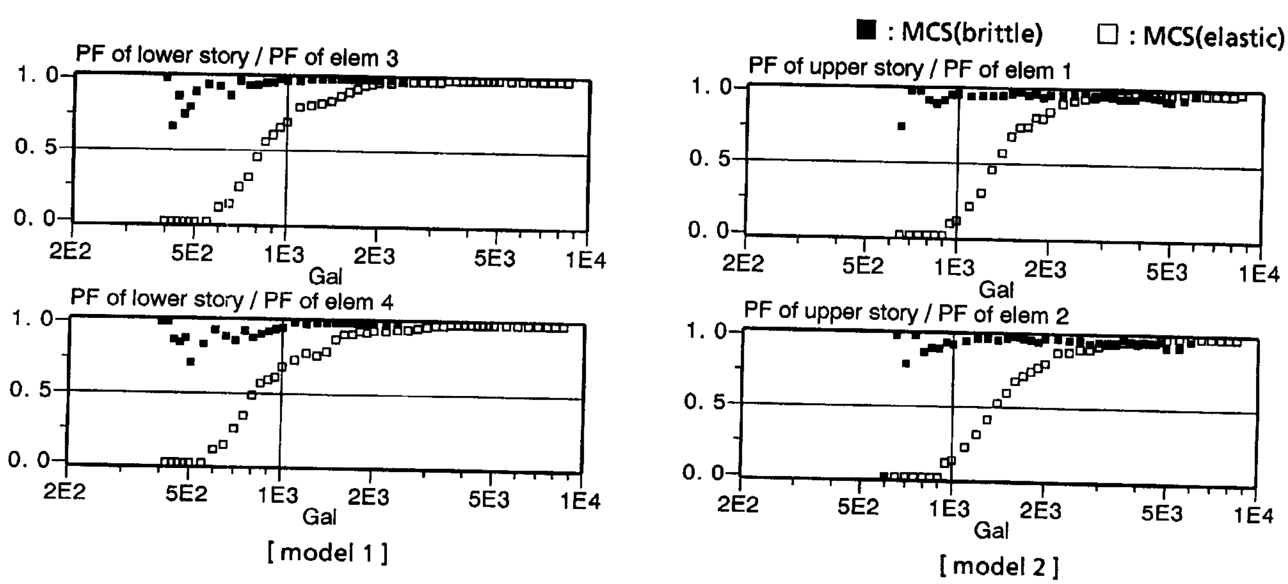

Fig.5. Conditional failure probability of story

The difference in the low acceleration range indicates the followings.

1. There is a strong correlation between the failure of the story and that of the brittle element. This means that the failure of the stronger element is caused by that of the weaker element.
2. On the other hand, the failure of the elastic element does not affect the failure of the another elastic element.

Sorting of Sample and Reevaluation of Capacity

Since the weaker element dominates the fragility of the story, it is important to examine the failure of the weaker element. For this purpose, Monte Carlo samples are sorted according to the ultimate displacement. Table 2 shows the results of sorting and the reevaluated ground acceleration capacity of each element.

Table 2. Properties and ground acceleration capacity of element after sorting

			stiffness (tf/m)		strength (tf)		capacity (Gal)	
model	story	element	median	s.d.	median	s.d.	median	s.d.
1	upper	weak	70.565	0.356	2.248	0.089	1067.	0.323
		strong	44.397	0.346	2.318	0.104	1749.	0.401
	lower	weak	71.550	0.305	2.257	0.102	673.	0.322
		strong	44.117	0.338	2.317	0.090	1120.	0.404
2	upper	weak	70.565	0.356	2.248	0.089	1067.	0.323
		strong	44.397	0.346	2.318	0.104	1749.	0.401
	lower	weak	71.550	0.305	4.514	0.102	1345.	0.322
		strong	44.117	0.338	4.634	0.090	2240.	0.404

Figure 6 compares the fragility of elements in a weaker story with the fragility curve obtained using the reevaluated capacity. It is found that the reevaluated fragility curve can express the fragility of the weaker element well.

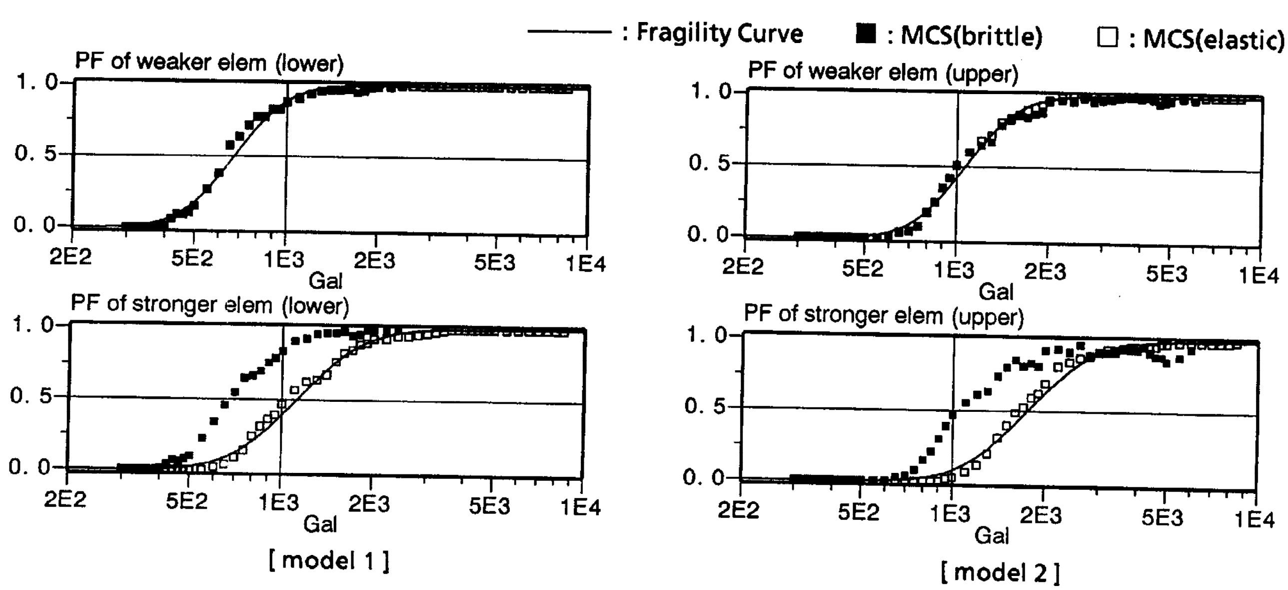

Fig.6. Reevaluated fragility curve of element in the weak story

Fragility of Story

Since the fragility of the story is defined by the intersection of those of the elements, the PF of the story is calculated with the following equation.

$$PF_{elem;strong} \cdot PF_{elem;weak} \leqq PF_{story} \leqq PF_{elem;strong} \tag{7}$$

Figure 7 shows the fragility of the weaker story, based on the assumption that the PF of the stronger element is same as that of the weaker element due to the strong correlation. For the evaluation of the PF of the story, the following equation is proposed.

$$PF_{story} = PF_{elem;strong} \approx PF_{elem;weak} \tag{8}$$

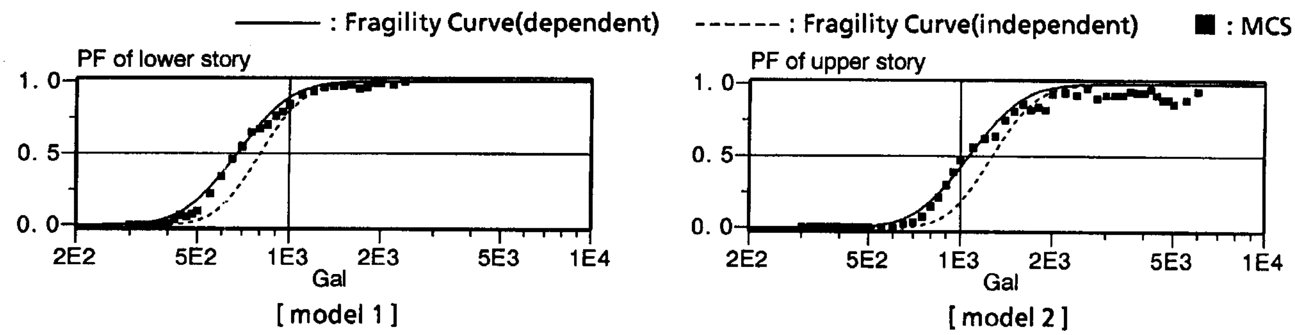

Fig.7. Fragility curve of story

In the estimation of reliability for actual structures, it is often difficult to sort the elements. The PF of the story can approximately be assumed to be the union of those of the unsorted samples, since the failure of the story is dominated by that of element which fails first.

$$max[PF_{elem1}, PF_{elem2}] \leqq PF_{story} \leqq 1-(1-PF_{elem1})(1-PF_{elem2}) \tag{9}$$

Figure 8 shows the fragility of the weaker story. The following equation is proposed, when the sorted samples are not available.

$$PF_{story} \approx 1-(1-PF_{elem1})(1-PF_{elem2}) \tag{10}$$

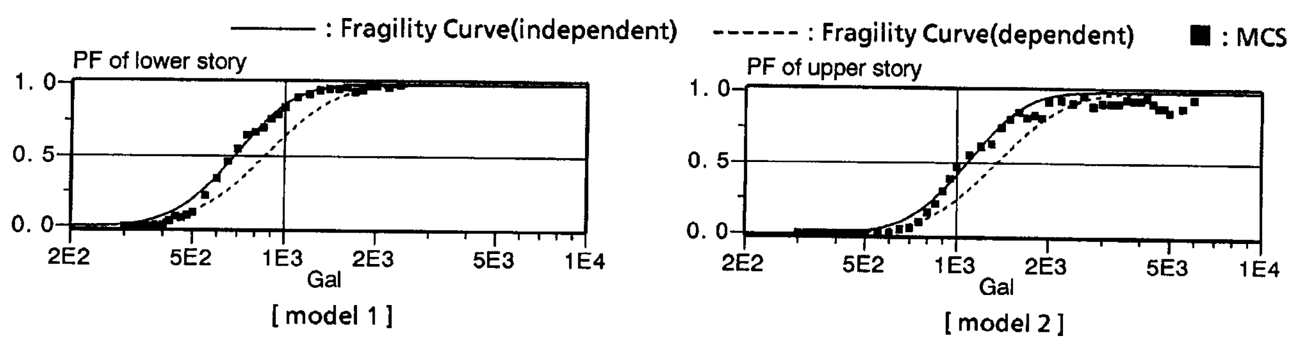

Fig.8. Approximated fragility curve of story

Fragility of System

Since the fragility of the system is defined by the union of those of the stories, the PF of the system is calculated with the following equation.

$$max[PF_{story1}, PF_{story2}] \leqq PF_{system} \leqq 1-(1-PF_{story1})(1-PF_{story2}) \tag{11}$$

Figure 9 shows the fragility of the system obtained from MCS with the fragility curve from equation (9). Proposed here is the following equation, which assumes that the failures of the stories are perfectly dependent.

$$PF_{system} = max[PF_{story1}, PF_{story2}] \tag{12}$$

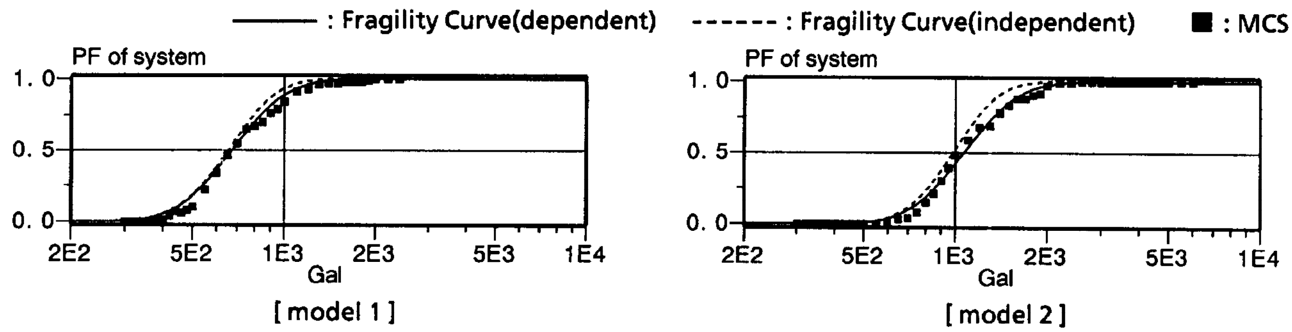

Fig.9. Fragility curve of system

CONCLUSIONS

The relationship among the fragility of the brittle element, that of the story and that of the system is examined. The followings are concluded.

1. The fragility of brittle element can be estimated with the approximate method proposed by the authors.

2. The fragility of the story can be estimated by that of the weaker element in the story, when using the sorted samples.

3. The fragility of the story can be estimated approximately as the union of those of elements in the story, when using the unsorted samples.

4. The fragility of the system can be obtained as the union of those of stories.

REFERENCES

Ishii, K., T. Okumura and M. Suzuki (1989). Earthquake Ground Motions Consistent with Probabilistic Seismic Hazard Analysis. *Structural Safety and Reliability*, 605-612.

Mizutani, M., M. Takeda, Y. Kai and M. Matsubara (1994). A study on the applicability of the response estimation of a PRA procedure. *Nuclear Engineering and Design*, 147, 211-230.