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## Study on the fragility of structure with several elements in its story. Part 1: Structure with brittle elements

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**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. From this results, 2 methods to evaluate the fragility of brittle element are presented. Also presented is a method to estimate the fragilities of the story and the system.

### 1. INTRODUCTION

Authors have been proposed the method which investigates the reliability of structure subjected to seismic loading. This method evaluates the failure probability (*PF*) of element in the system. However, if a system consists of several stories with several elements, it comes necessary to relate the *PF* of each element to those of stories and that of system.

This paper investigates the relationship using the *MCS*. Part 1 of this study deals with the system consisting of brittle elements.

### 2. MONTE CARLO SIMULATION

#### 2.1 Model and input motion

As shown in Fig. 1, 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.

100 samples of each random variable are generated assuming the log-normal distribution, whose median and variability are shown in Table 1. No correlation is considered among the variables.

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.

Table 1 Statistics of random variables

model	elem	stiffness (tf/m)		strength (tf)		ductility factor	
		median	beta	median	beta	median	beta
1	1	54.667	0.412	2.265	0.102	1.000	0.000
	2	57.308	0.427	2.301	0.094	1.000	0.000
	3	56.103	0.386	2.312	0.095	1.000	0.000
	4	56.264	0.419	2.262	0.098	1.000	0.000
2	1	54.667	0.412	2.265	0.102	1.000	0.000
	2	57.308	0.427	2.301	0.094	1.000	0.000
	3	56.103	0.386	4.624	0.095	1.000	0.000
	4	56.264	0.419	4.524	0.098	1.000	0.000

In addition to the nonlinear analysis, linear analysis is carried out with the definition that the elements fail when their response exceed the strength, even though they do not loose their stiffness.

100 artificial earthquakes are generated according to the median, variability and auto-correlation matrix of the target response spectrum.

## 2.2 Result of analysis

Table 2 shows the response of each element and its capacity.

Figure 2 compares the fragility of the element in the weaker story with the fragility curve obtained using the capacity shown in Table 2. The fragility of the linear element agrees with the fragility curve. On the other hand, the fragility of the linear element does not.

## 3. MODIFICATION OF CAPACITY OF ELEMENT

### 3.1 Feature of failure of brittle elements

In order to investigate the above difference, the failure of the brittle element is examined. Shown in Fig. 3 is the ratio of the *PF* of the story to that of

Table 2 Evaluation of capacity

model	elem	response at 800 gal (tf)		capacity (Gal)	
		median	beta	median	beta
1	1	1.305	0.432	1389.	0.444
	2	1.368	0.408	1346.	0.419
	3	2.104	0.445	879.	0.455
	4	2.110	0.407	858.	0.419
2	1	1.305	0.432	1389.	0.444
	2	1.368	0.408	1346.	0.419
	3	2.104	0.445	1758.	0.455
	4	2.110	0.407	1715.	0.419

element in the brittle system and the linear system.

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 linear element does not affect the failure of the another linear element.

### 3.2 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. The results of sorting are shown in Table 3.

Table 3 Statistics of sorted random variables

<i>model</i>	<i>elem</i>	<i>stiffness (tf/m)</i>		<i>strength (tf)</i>		<i>ductility factor</i>	
		<i>median</i>	<i>beta</i>	<i>median</i>	<i>beta</i>	<i>median</i>	<i>beta</i>
1	<i>weak</i>	70.565	0.356	2.248	0.089	1.000	0.000
	<i>strong</i>	44.397	0.346	2.318	0.104	1.000	0.000
	<i>weak</i>	71.550	0.305	2.257	0.102	1.000	0.000
	<i>strong</i>	44.117	0.338	2.317	0.090	1.000	0.000
2	<i>weak</i>	70.565	0.356	2.248	0.089	1.000	0.000
	<i>strong</i>	44.397	0.346	2.318	0.104	1.000	0.000
	<i>weak</i>	71.550	0.305	4.514	0.102	1.000	0.000
	<i>strong</i>	44.117	0.338	4.634	0.090	1.000	0.000

Table 4 shows the reevaluated capacities using the sorted samples. Figure 4 compares the fragility of elements in a weaker story with the fragility curve obtained using the reevaluated capacity. For the weaker element, the good agreement is observed.

Table 4 Reevaluation of capacity

<i>model</i>	<i>elem</i>	<i>response at 800 gal (tf)</i>		<i>capacity (Gal)</i>	
		<i>median</i>	<i>beta</i>	<i>median</i>	<i>beta</i>
1	<i>weak</i>	1.685	0.311	1067.	0.323
	<i>strong</i>	1.060	0.387	1749.	0.401
	<i>weak</i>	2.684	0.305	673.	0.322
	<i>strong</i>	1.655	0.394	1120.	0.404
2	<i>weak</i>	1.685	0.311	1067.	0.323
	<i>strong</i>	1.060	0.387	1749.	0.401
	<i>weak</i>	2.684	0.305	1345.	0.322
	<i>strong</i>	1.655	0.394	2240.	0.404

## 4. FRAGILITIES OF STORY AND SYSTEM

### 4.1 Fragility of story

Figure 5 shows the fragility of the weaker story. Since the failure of the story is caused by that of the weaker element, the  $PF$  of the story is calculated by the following equation.

$$(1) \quad PF_{story} = PF_{elem;strong} \approx PF_{elem;weak}$$

In the estimation of reliability for actual structures, it is often difficult to sort the elements according to the ultimate displacement. The fragility curves obtained using the unsorted samples agree well with the fragilities of linear elements. It is, therefore, possible to estimate the fragility of the story approximately, assuming that it is the union of the independent fragility of the brittle elements. Figure 6 shows the results of the approximation using the following equation.

$$(2) \quad PF_{story} \approx 1 - (1 - PF_{elem1})(1 - PF_{elem2})$$

### 4.2 Fragility of system

Figure 7 shows the fragility of the system. Since the fragility of the system is defined by the union of those of the stories, a  $PF$  of the system is calculated by the following equation.

$$(3) \quad PF_{system} = \max[PF_{story1}, PF_{story2}]$$

## 5. 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 the story and those of the elements in it are close to one another.
2. The fragility of the story is estimated by that of the weaker element, whose fragility is evaluated using the sorted samples.
3. The fragility of the story is estimated approximately as the union of those of elements, which are evaluated using the unsorted samples.

## REFERENCES

- Ishii, K., et al. 1989. Earthquake Ground Motions Consistent with Probabilistic Seismic Hazard Analysis, Structural Safety and Reliability: 605-612.
- Mizutani, M., et al. 1994. A study on the applicability of the response estimation of a PRA procedure, *Nuclear Engineering and Design* 147: 211-230.

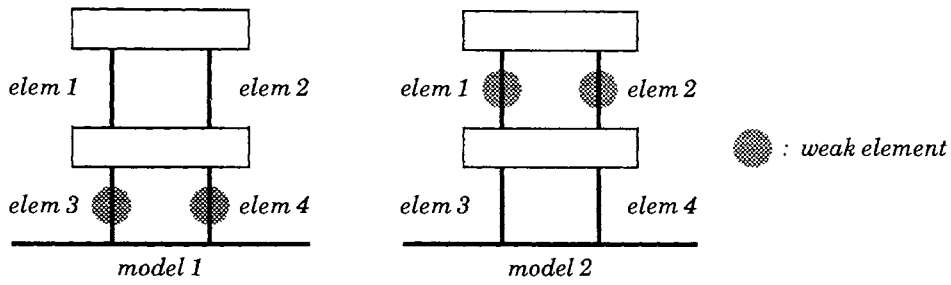


Fig. 1 Analysis model

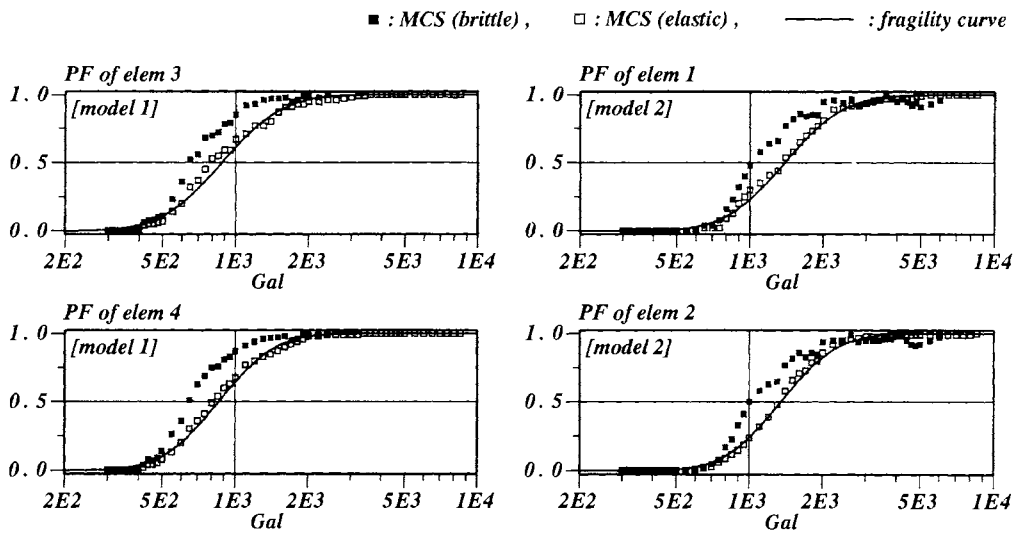


Fig. 2 Fragility of brittle element

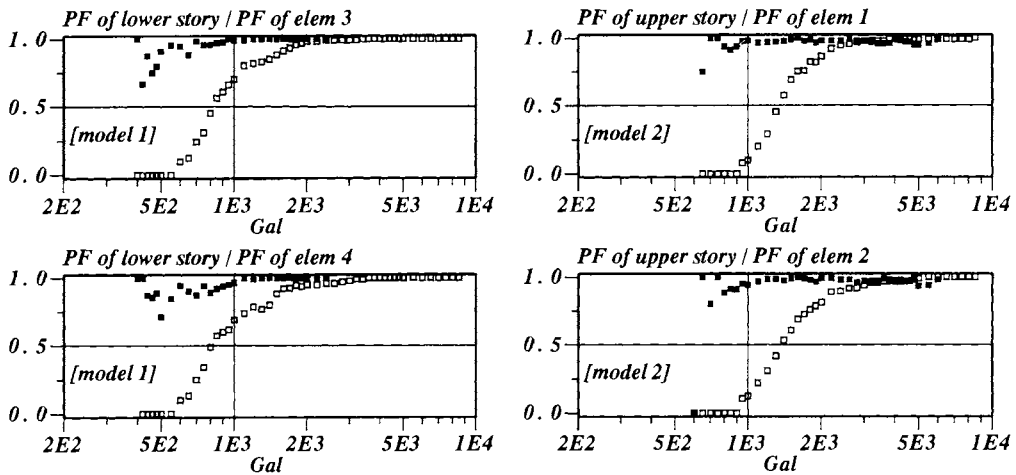


Fig. 3 Conditional fragility of story

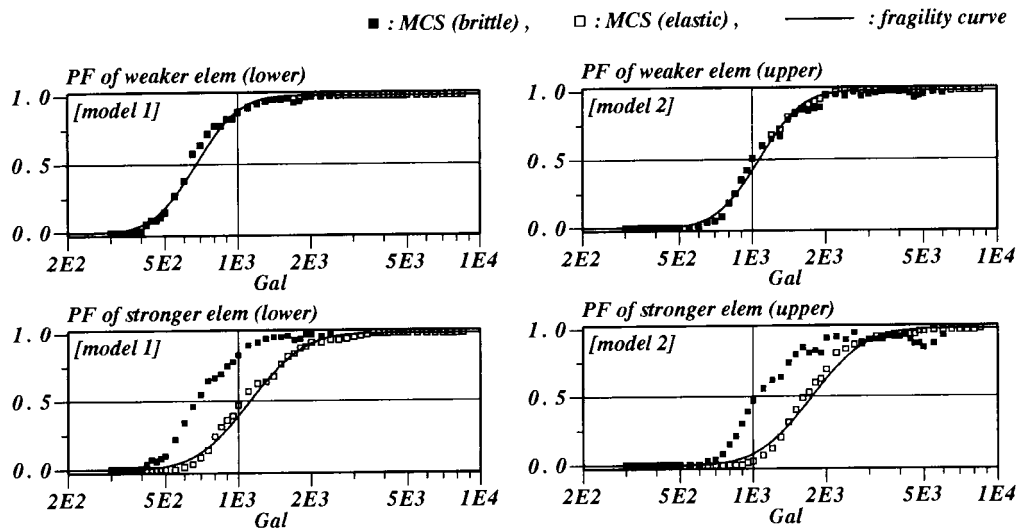


Fig. 4 Fragility of brittle element using sorted samples

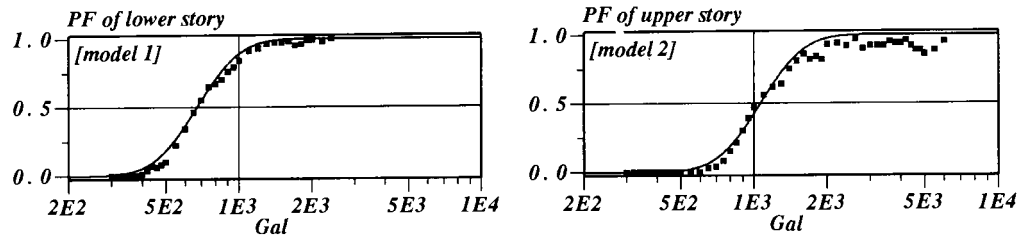


Fig. 5 Fragility of story

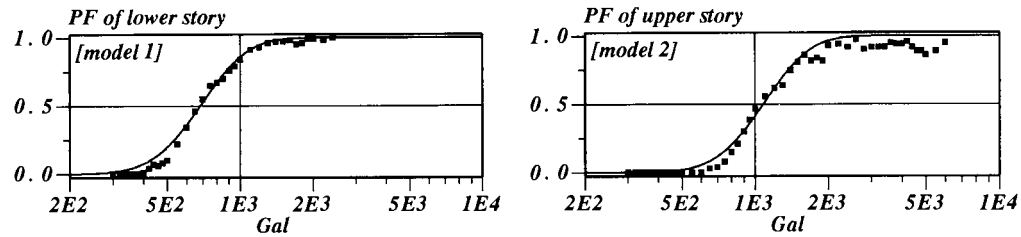


Fig. 6 Fragility of story approximated using unsorted samples

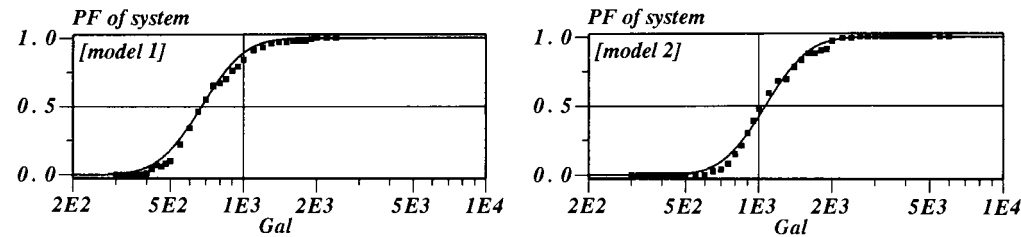


Fig. 7 Fragility of system