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STUDY ON THE FRAGILITY OF SYSTEM

PART 2: SYSTEM WITH DUCTILE ELEMENTS IN ITS STORIES

Y. KAI[1] and S. FUKUSHIMA[2]

1. Power & Energy Project Division, Shimizu Corporation, No. 2-3, Shibaura 1-chome, Minato-ku, Tokyo 105-07, JAPAN

2. Seismic Engineering Department, Tokyo Electric Power Services Co., Ltd., No. 3-3, Higashi-Ueno 3-chome, Taito-ku, Tokyo 110, 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 model in which each story consists of 2 ductile elements, is employed. The method, which has been proposed by authors, to evaluate the fragility of ductile element is also demonstrated. The nonlinear response effect to the capacity of an element is considered in this approximate method. This method does not require the nonlinear MCS, saving a lot of computational efforts. The method shows good agreement with the result of MCS. Also examined is the correlation among the failure of elements in a system. According to the result, a method to estimate the fragility of the story and the system is proposed.

KEYWORDS

Fragility of the system; System consists of ductile elements; Approximate fragility analysis method; Monte Carlo simulation of the failure of the system; Correlation among the failure of elements in a system

INTRODUCTION

Authors have been proposed an approximate method which evaluates the fragility of a system subjected to seismic loading (Mizutani *et al.*, 1994). This method can easily evaluate the failure probability (PF) of the series system where the failure probability of each story directly relates to that of the system. However, in case of the parallel system in which each story consists of several elements and the failure of each element does not mean the failure of the story, it comes necessary to relate the failure probability of element to that of story and that of system.

This paper investigates the failure characteristics of element in a parallel system and the relationships among the failure of the elements, the stories and the system using the MCS, and verifies the applicability of the approximate fragility analysis method to the parallel system. Part 2 of this study deals with the system consisting of ductile elements.

Model and Input Motion

As shown in Fig. 1, this paper deals with 2-story model in which each story consists of 2 ductile elements. Model 1 is designed to fail at the lower story and model 2 is designed to fail at upper story. Random variables employed here are the stiffness, the strength and the ultimate ductility factor of element.

Other specifications for the analysis model and the samples of the input motion are as same as the ones described in Part 1 of this study (Fukushima *et al.*, 1996). The median and the log-normal standard deviation (β) of variables are summarized in Table 1. The failure of the story is defined as the intersection of the failure of the elements in the story. The failure of the system is defined as the union of the failure of the stories in the system. The elasto-plastic skeleton curve is employed with the peak oriented hysteresis rule for the restoring force characteristics of each element. When each element exceeds its ultimate displacement, it fails with the loss of its stiffness and restoring force.

In addition to the nonlinear analysis, linear analysis of the Monte Carlo sample is carried out with the definition that the elements fail when their response force exceed the strength, even though they do not loose their stiffness and the restoring force. The failure of the story is also defined as the intersection of the failure of elements in the story. The failure of the system is defined as the union of the failure of stories in the system.

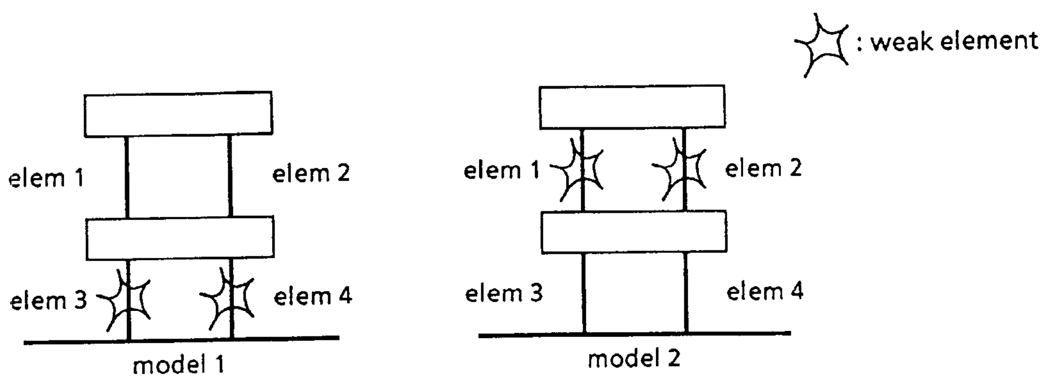

Figure 1. Analysis model

Table 1. Statistics of random variables

model	story	element	stiffness (tf/m) median	stiffness (tf/m) β	strength (tf) median	strength (tf) β	ductility factor median	ductility factor β
1	upper	1	54.667	0.412	2.265	0.102	4.030	0.199
		2	57.308	0.427	2.301	0.094	4.127	0.175
	lower	3	56.103	0.386	2.312	0.095	3.882	0.196
		4	56.264	0.419	2.262	0.098	4.021	0.212
2	upper	1	54.667	0.412	2.265	0.102	4.030	0.199
		2	57.308	0.427	2.301	0.094	4.127	0.175
	lower	3	56.103	0.386	4.624	0.095	3.882	0.196
		4	56.264	0.419	4.524	0.098	4.021	0.212

Table 2. Evaluation of capacity

model	story	element	elastic capacity (Gal) median	elastic capacity (Gal) β	capacity increment median	capacity increment β	inelastic capacity (Gal) median	inelastic capacity (Gal) β
1	upper	1	1389.	0.444	4.447	0.099	6174.	0.455
		2	1346.	0.419	4.508	0.088	6065.	0.428
	lower	3	879.	0.455	1.953	0.098	1717.	0.465
		4	858.	0.419	2.008	0.106	1722.	0.432
2	upper	1	1389.	0.444	1.555	0.099	2159.	0.455
		2	1346.	0.419	1.578	0.088	2123.	0.428
	lower	3	1758.	0.455	3.424	0.098	6020.	0.465
		4	1715.	0.419	3.493	0.106	5991.	0.432

$$\text{Capacity Increment (F)} = \frac{Q_e}{Q_{e'}}\sqrt{2\mu_u - 1}$$

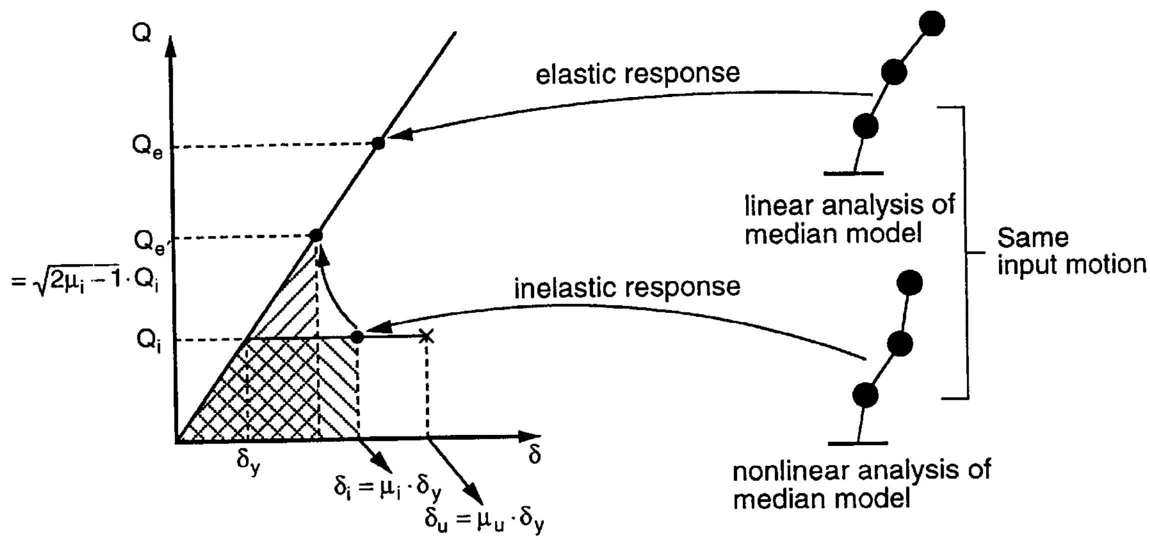

Figure 2. Concept of the capacity increment

Result of Analysis

Table 2 shows the elastic capacity (CE), the capacity increment (F) and the inelastic capacity (CI). The elastic capacity is obtained from the response and strength as stated in Part 1 of this study. The capacity increment includes the effect of the energy absorption due to the nonlinear response, and that of the damage concentration due to the irregularity of the stiffness and strength of each story in the multi-DOF system. The procedure to obtain the capacity increment is illustrated in the reference (Mizutani *et al.*, 1994).

The median and the variability of inelastic capacity are calculated by the following equations.

$$m_{CI} = m_F \, m_{CE} \tag{1}$$

$$\beta_{CI}^2 = \beta_F^2 + \beta_{CE}^2 \tag{2}$$

As shown in Fig. 2, it requires the nonlinear analysis of the median model to obtain the median of the capacity increment(m_F). The variance of the capacity increment(β_F^2) is a half of the variance of the ultimate ductility factor. The variance of the elastic capacity is the sam of the variance of the response and the strength.

Figure 3 compares the fragility of the ductile element in the weaker story with the fragility curve obtained from the inelastic capacity shown in Table 2. It is found that the median capacity agrees well, however, the inclination of the fragility curve tends to be estimated gentler than the result of the nonlinear MCS which means the variability of the inelastic capacity tends to be estimated larger.

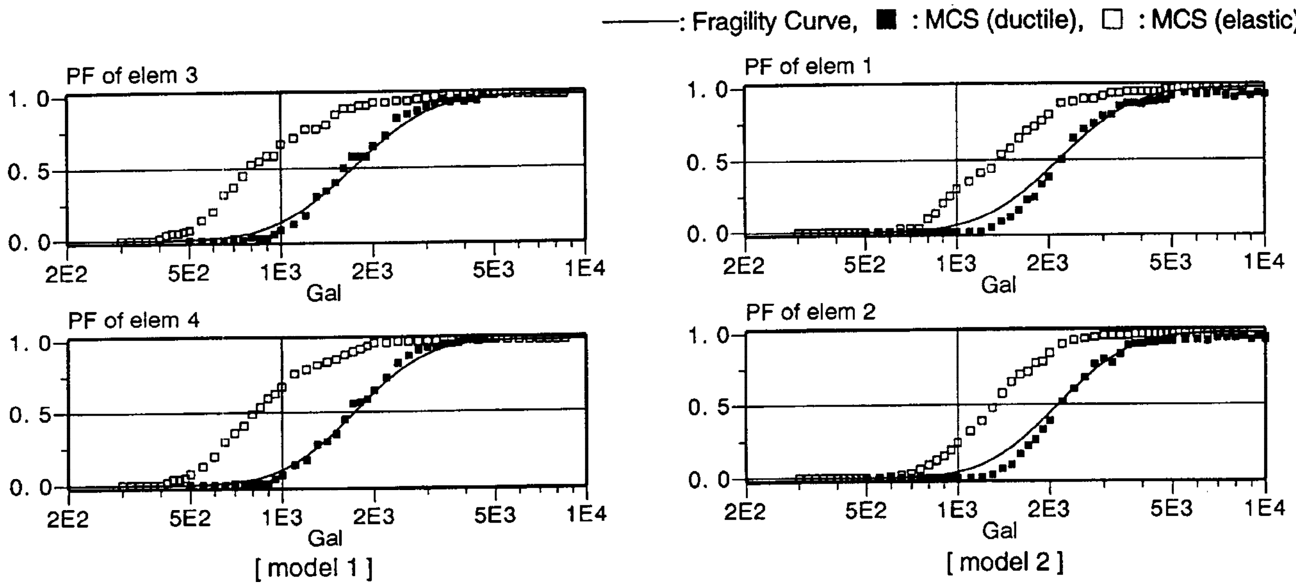

Figure 3. Fragility of ductile element

MODIFICATION OF CAPACITY OF ELEMENT

Correlation among the Failure of Ductile Elements

In order to investigate the above difference, the failure of the ductile element in the MCS is examined. Shown in Fig. 4 is the ratio of the PF of the story to that of element in the ductile system and linear system.

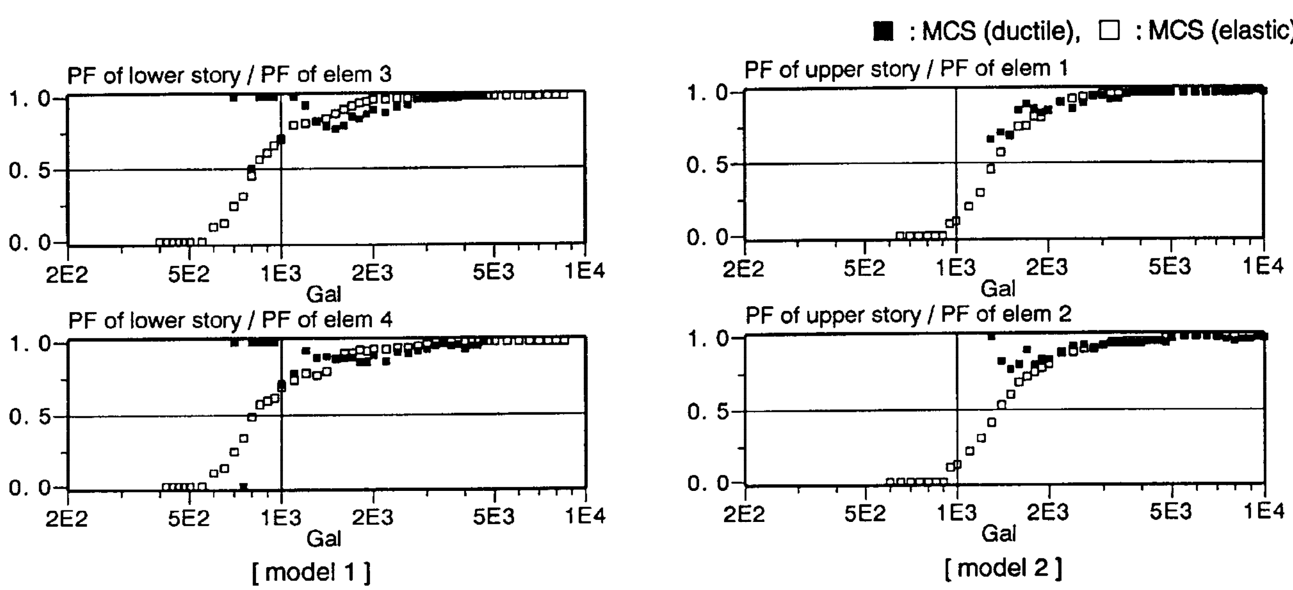

Figure 4. Conditional Fragility of story

Table 3. Reevaluation of capacity

model	story	element	elastic capacity (Gal) median	elastic capacity (Gal) β	capacity increment median	capacity increment β	inelastic capacity (Gal) median	inelastic capacity (Gal) β
1	upper	weaker	1090.	0.322	3.746	0.094	4082.	0.335
		stronger	1714.	0.326	3.956	0.088	6783.	0.338
	lower	weaker	691.	0.325	2.168	0.095	1499.	0.338
		stronger	1090.	0.319	1.750	0.102	1908.	0.335
2	upper	weaker	1090.	0.322	1.809	0.094	1972.	0.335
		stronger	1714.	0.326	1.232	0.088	2113.	0.338
	lower	weaker	1382.	0.325	3.479	0.095	4810.	0.338
		stronger	2180.	0.319	3.686	0.102	8037.	0.335

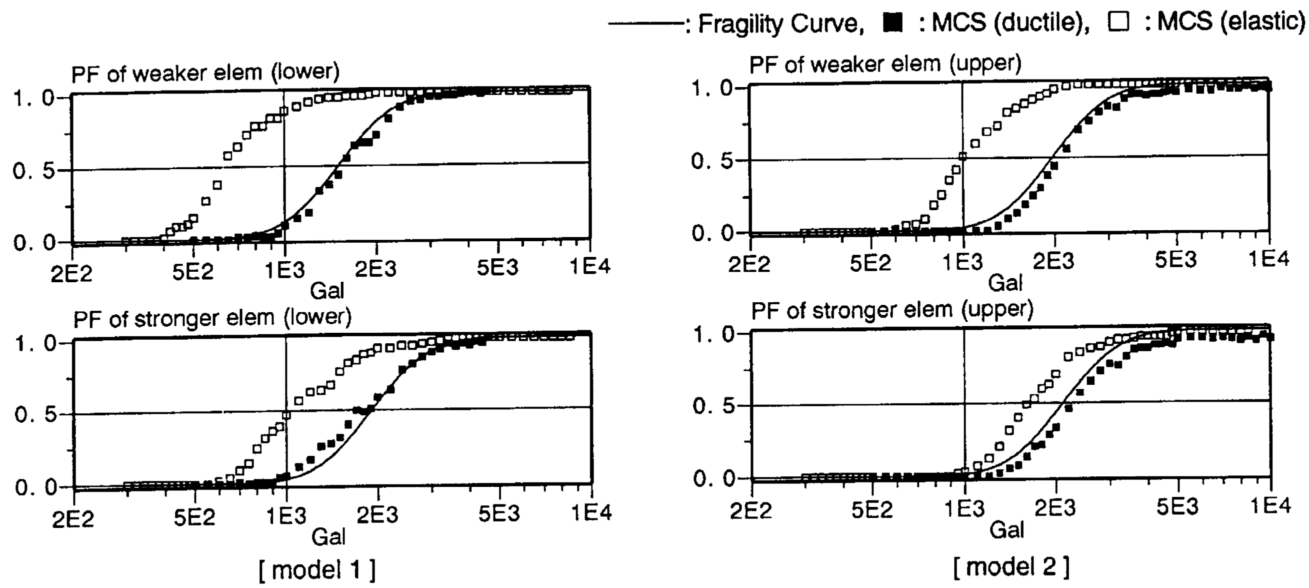

Figure 5. Fragility of ductile element using sorted samples

From the comparison in Fig. 4, the followings are derived.

1. The correlation between the failure of the story and the failure of the element for the ductile system, differs from that for the linear system in the low input acceleration range. Same tendency is shown in the study of the brittle system (Fukushima *et al.*, 1996). This causes the difference in the fragility.

2. Unlike brittle system, the correlation for the ductile system is close to that for the linear elements in the high input acceleration range. This means the ductile element does not affect the failure of the another ductile element as much as the brittle element does.

Sorting of Sample and Reevaluation of Capacity

Since the stronger element dominates the fragility of the story, it is important to examine the failure of the stronger element. The sorting of the Monte Carlo sample according to the ultimate displacement, as same as stated in Part 1, is employed for this purpose here again.

Table 3 shows the capacity reevaluated using the sorted Monte Carlo samples. To get the capacity increment, nonlinear response analysis of the median model of the sorted Monte Carlo sample is conducted. It is noted that the variability of the elastic capacity of the elements is reduced by the sorting process which leads to the decrease of the variability of the inelastic capacity.

Figure 5 compares the fragility of elements in a weaker story obtained from the MCS with the fragility curve obtained from the inelastic capacity of the sorted sample. It can be described that the fragility curves for the weaker element agree with the result of MCS well. Especially, the inclination of the fragility curve is duly corrected due to the reduction of variability of elastic capacity. This means that the estimation of the variability of fragility using sorting procedure is adequate even for the ductile system.

The median capacity shows slight difference from the result of MCS, although the inclination of the fragility curve is corrected. In order to solve this problem, it needs the further examination in the evaluation method of the capacity increment.

FRAGILITY OF STORY AND SYSTEM

Fragility of Story

Figure 6 shows the fragility of the weaker story obtained from the sorted samples. Since the failure of the story is intersection of that of its elements, the PF of the story is calculated with the following equation.

$$PF_{story,independent} = PF_{elem;weak}PF_{elem;strong} \leq PF_{story} \leq PF_{story,dependent} = PF_{elem;strong} \quad (3)$$

As shown in Fig. 6, the fragility of the lower story of model 1 obtained from the MCS is similar to the fragility curve assuming that elements fail perfectly dependently. On the other hand, the fragility of the upper story of model 2 obtained from the MCS is similar to the fragility curve assuming that elements fail independently. It is because in the case of model 2, the estimation of failure probability of each element is higher than MCS. In the result of MCS, the failure probability of the story is identical to that of strong element even for the model 2. Therefor fragility curve for the story can be estimated assuming the failure of the elements is perfectly dependent, that is,

$$PF_{story} \approx PF_{elem;strong} \quad (4)$$

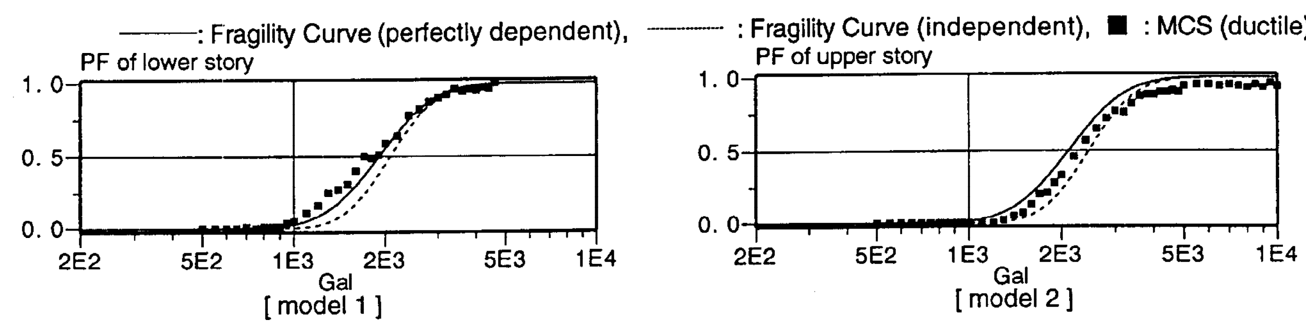

Figure 6. Fragility of story using sorted samples

In the fragility estimation of the actual structures, it is often complicated to sort the elements according to their ultimate displacement. Therefore, the following equation is tried to estimate the PF of the story using unsorted data.

$$PF_{story,independent} = PF_{elem1}PF_{elem2} \leq PF_{story} \leq PF_{story,dependent} = \min[PF_{elem1}, PF_{elem2}] \quad (5)$$

Figure 7 compares the fragility of the weaker story with the fragility curve obtained using the unsorted samples. In the low failure probability region, the result of MCS is similar to the fragility curve assuming that elements fail independently. On the other hand, the result of MCS is similar to the fragility curve assuming that elements fail perfect dependently in the high failure probability region. Although it can be seen that the failure of each element is independent in the ductile system from Fig. 4, most of part of the result of MCS fits with the fragility curve assuming that elements fail perfectly dependently. Therefor, fragility curve for the story can be estimated without sorting process assuming the failure of the elements is perfectly dependent, that is,

$$PF_{story} \approx \min[PF_{elem1}, PF_{elem2}] \tag{6}$$

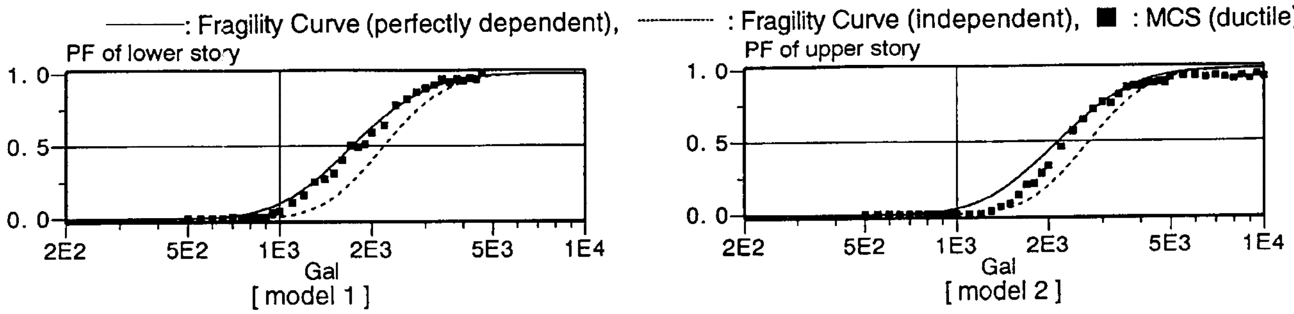

Figure 7. Fragility of story using unsorted samples

Fragility of System

Finally the fragility of the system is studied using the result of MCS. Since the failure of the system is defined as the union of that of its stories, the PF of the system is calculated with the following equation.

$$PF_{system,dependent} = \max[PF_{story1}, PF_{story2}] \leq PF_{system} \leq PF_{system,independent}$$

$$= 1-(1- PF_{story1})(1- PF_{story2}) \tag{7}$$

Figure 8 compares the fragility of the system obtained from the MCS and the fragility curves obtained from equation (7). Since the failure probability of each story differs very much, the fragility curves obtained with different correlation assumption are almost identical. According to the conclusion of Part 1 of this study, following eauation which assumes that the failure of the stories is perfectly dependent, is proposed here, that is ,

$$PF_{system} \approx \max[PF_{story1}, PF_{story2}] \tag{8}$$

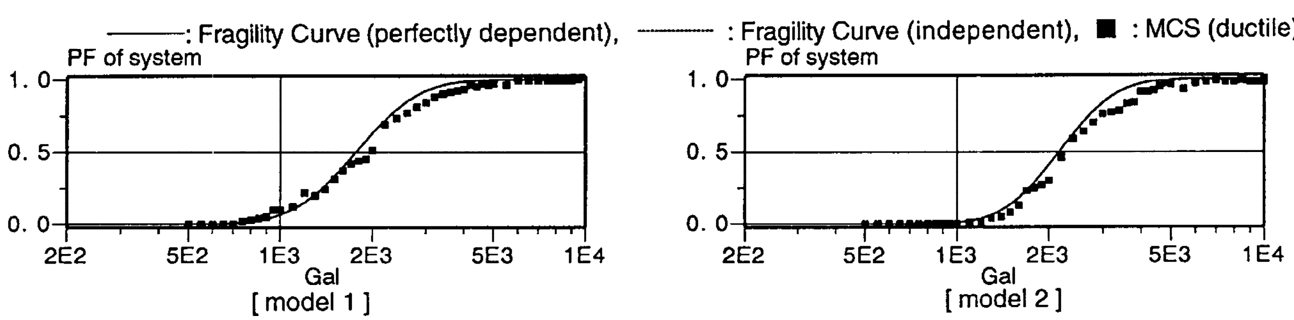

Figure 8. Fragility of system

CONCLUSIONS

The relationship among the fragility of the ductile element, that of the story and that of the system is examined, with the following conclusions,

1. Fragility of ductile element can be estimated with the approximate method proposed by the authors, in which an effect of nonlinear response is reflected in the capacity estimation.

2. Fragility of story can be obtained as the intersection of the fragility of the ductile elements assuming the failure of the elements is perfectly dependent.

3. Fragility of system can be obtained as the union of the fragility of the stories assuming the failure of the stories is perfectly dependent.

4. Accuracy of the estimation is improved when the elements are sorted according to their ultimate displacement.

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