Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

M04/3

Application of fragility analysis method to realistic structure

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ABSTRACT: The proposed method to evaluate the fragility of system is applied to the realistic plant structure to validate its efficiency. The method considers the effect of the nonlinear response such as an energy absorption, a damage concentration and a failure chain. With the examination by the comparison with the Monte Carlo simulation, the method is found out to be a simple and applicable method for the estimation of structural reliability.

INTRODUCTION

Authors have been proposed the method to evaluate the fragility of system subject to seismic loading. This method can easily evaluate the failure probability of the series 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 failure probability of each element to that of story and that of system, since the failure of element does not relate to that of the system due to the redundancy.

At first, the method proposed by authors is summarized. Then, using the Monte Carlo simulation of the realistic system, this paper examines the proposed method as the fragility analysis method for the parallel system.

FRAGILITY ANALYSIS METHOD

framework of the method

The fragility analysis method consists of evaluation of probabilistic response and that of probabilistic capacity. To save a lot of computational effort, this method employs the following assumptions, that,
(1) random vibration theory in the frequency domain is employed to evaluate responses,
(2) effects of inelastic behavior are included in the evaluation of capacity, and
(3) variability of response and that of capacity are assumed to be distributed

log-normally.

Figure 1 illustrates the outline of the fragility analysis..

evaluation of probabilistic response

$R(a_s)$, which is the probabilistic response corresponding to the input motion of intensity a_s, is expressed by the following equation,

$$R(a_s)=r(a_s)\times F_1\times F_2\times F_3 \quad [1]$$

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 corresponding to the modeling uncertainty.

The concept of response analysis is illustrated in Fig. 2.

Median and log-normal standard deviation of F_1 and F_2 are obtained by the following equation,

$$F_1= F_2=1.0 \quad [2]$$

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

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

where $r(R_i,T_j)$ is a response calculated for the combination of the response spectrum R_i and transfer function T_j, and subscripts i and j denotes the i-th percentile and j-th percentile, respectively.

F_3 can be evaluated as the modeling error. Authors have studied on the evaluation of the modeling error and have proposed the following values as the statistics of F_3.

$$F_3=1.0 \quad [5]$$

$$\beta F_3=0.15 \quad [6]$$

It must be noted that βF_1 and βF_2 are categorized as random uncertainty βr, and βF_3 is categorized as modeling uncertainty βu.

evaluation of probabilistic capacity

Capacity of element C is expressed by the following equation,

$$C=S\times F_4 \quad [7]$$

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.

To get the capacity increment F_4, nonlinear response analysis of the median model is carried out.

When a story consists of several identical element, the effect of failure chain becomes important. Since the stronger element dominates the fragility of the story, it is important to examine which element would be the stronger element. To take account the effect a set of Monte Carlo sample is made. Then sorting of the sample is conducted to identify the stronger element and the weaker element. The median model for the evaluation of capacity increment is made according to the characteristics of the sorted sample.

The feature of this fragility analysis method is that it requires only one nonlinear simulation to evaluate the effects mentioned above. Figure 3 illustrates the concept of the inelastic capacity.

It is noted that both S and F_4 contain modeling uncertainty as well as random uncertainty.

:alculation of fragility curve

Median and log-normal standard deviation of the ground acceleration capacity A are obtained by the following equation.

$$A= C / R(a_s) \times a_s \qquad [8]$$

$$\beta A=\{\beta F_1^2+\beta F_2^2+\beta F_3^2+\beta F_4^2\}^{1/2} \qquad [9]$$

Therefore, the fragility curve can be obtained by the following equation,

$$P(a>A)=\Phi\, [\ln(a/A) / \beta A] \qquad [10]$$

where Φ denotes the standard normal distribution function.

In many case, βA is deconvolved into βr and βu by the following equation.

$$\beta A^2=\beta r^2+\beta u^2 \qquad [11]$$

In this case, fragility is expressed by the family of fragility curves by the following equation,

$$P(a>A)=\Phi\, [\ln(a/A)+ \beta u \Phi^{-1}(Q) / \beta A] \qquad [12]$$

where Q denotes the confidence level.

fragility of story

Since the failure of the story is the intersection of those of its elements, the failure probability of the story is calculated by the following equation.

$$PFelem;strongPFelem;weak \leqq PFstory \leqq PFelem;strong \qquad [13]$$

From the study using the Monte Carlo simulation the fragility curve of the story is similar to the fragility curve assuming that elements consists the story fail perfectly dependently. Therefore, the fragility curve for the story can be estimated assuming the failure of the elements is perfectly dependent, as shown below.

$$PFstory=PFelem;strong \qquad [14]$$

Failure of System

Since the failure of the system is defined as the union of that of its stories, the failure probability of the system is calculated by the following equation.

$$\max[PFstory_1,PFstory_2] \leqq PFsystem \leqq 1-(1-PFstory_1)(1-PFstory_2) \qquad [15]$$

From the study using the Monte Carlo simulation, following equation which assumes that the failure of the stories is perfectly dependent, is proposed as shown below.

$$PFsystem=\max[PFstory_1,PFstory_2] \qquad [16]$$

STUDY ON THE REAL STRUCTURE

The appropriateness of the proposed method is examined using a real structure. The analysis model using here is shown on Fig. 4. It is an 8 story model. Each stories are modeled by the beam elements which stand for the RC shear wall and the nodes which represent the mass at the floor. The 6 out of 8 stories are consist of 2 nodes which represent the in-plane deformation of the floor and are tied by elastic floor spring. The median resonant period of the structure is 0.2 sec. Damping factor is fixed at 0.03. The effect of the soil-structure interaction is considered with the springs and the dampers.

Random variables employed here are load-deformation relationship of the beam element and the input motion. The randomness of the load-deformation relationship is evaluated assuming the stochastic characteristics of the compressive strength of the concrete and the maximum ductility of the shear wall. The young's modulus and the shear modulus of rigidity of the concrete are calculated from its compressive strength.

The sample size of the Monte Carlo simulation is set to 100. Examples of the Monte Carlo samples of the load-deformation relationship of the beam element is shown in the Fig. 5. 100 artificial earthquake are also generated according to the target spectra, whose median and variability are shown in Fig. 6. The input acceleration level is set to 1800gal, 2000gal and 2500gal in Monte Carlo simulation. The result of the Monte Carlo simulation is shown on Table 1.

The fragility analysis using the proposed method is also conducted. Reference acceleration is set to 2300gal. Comparison between Monte Carlo simulation and the proposed fragility analysis method is shown on Fig. 7. It is obvious that the proposed method shows good agreement to the result of Monte Carlo simulation.

CONCLUSIONS

The fragility analysis method proposed by the authors is very practical and applicable to the real structure. Through the development of the method, the relationship among the fragility of element, that of the story and that of the system is examined, with the following conclusions,

(1) fragility of element can be estimated with the approximate method proposed by 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 element assuming the failure of the element is perfectly dependent,

(3) fragility of system can be obtained as the union of the fragility of the stories assuming that the failure of the stories is perfectly dependent, and

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

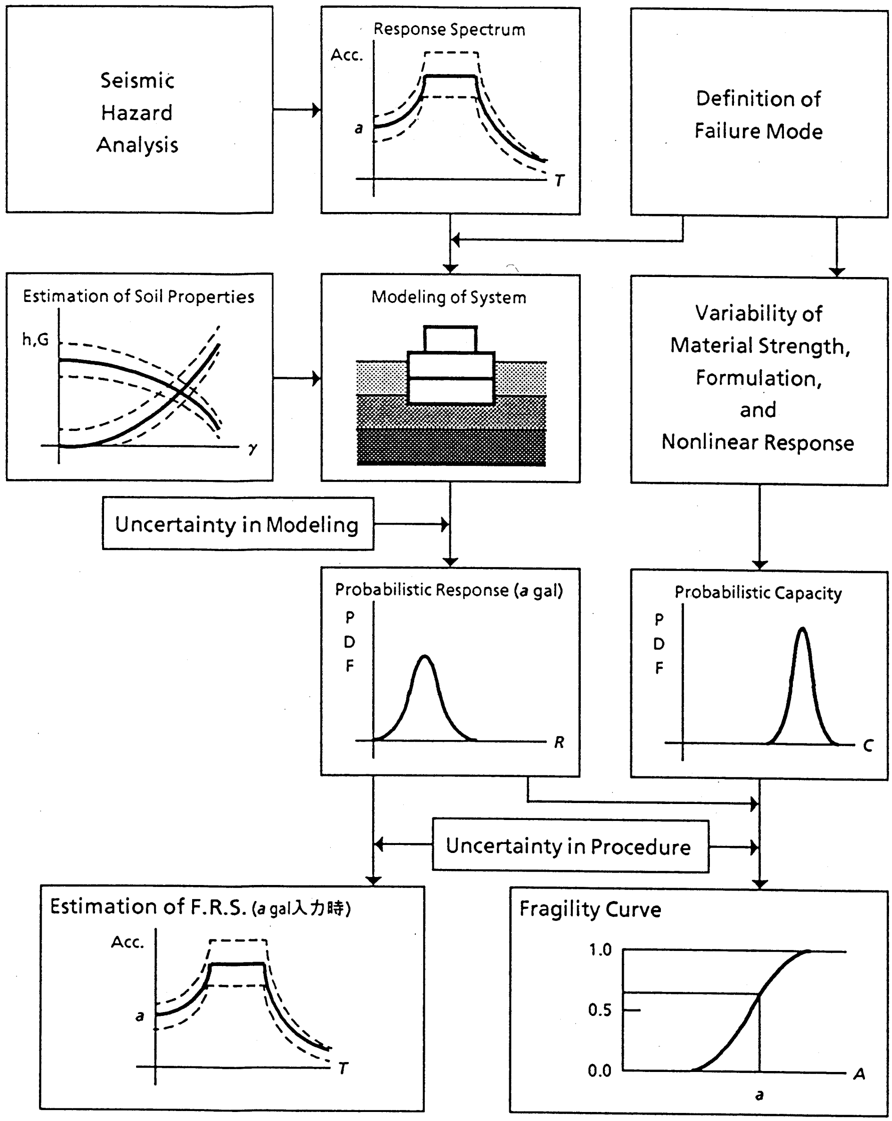


Fig. 1 Outline of Fragility Analysis

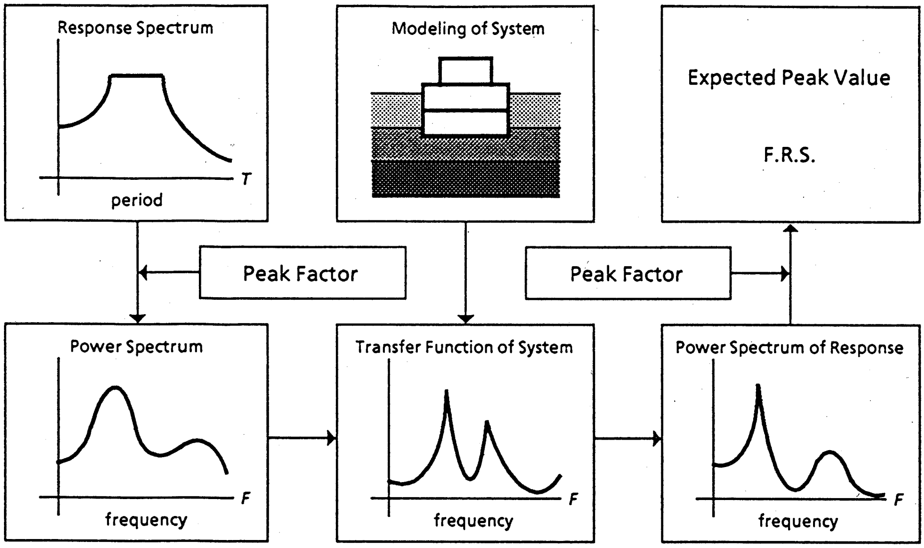


Fig. 2 Concept of Response Analysis

$$\text{capacity increment} = \frac{Q_e\sqrt{2\mu_u - 1}}{Q'_e} = \frac{Q_e\sqrt{2\mu_u - 1}}{Q_i\sqrt{2\mu_i - 1}}$$

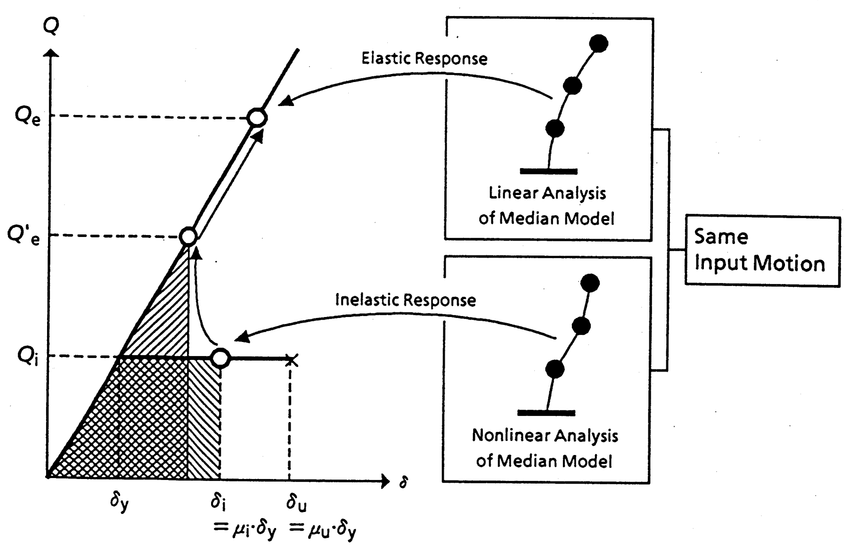


Fig. 3 Concept of Capacity Increment

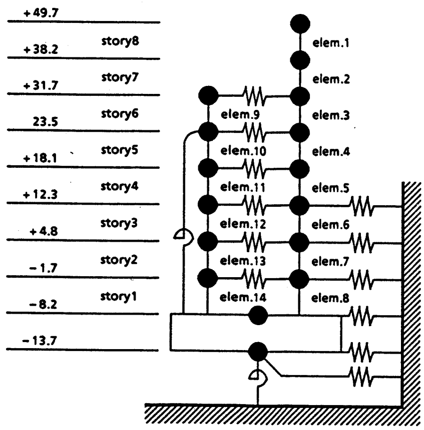
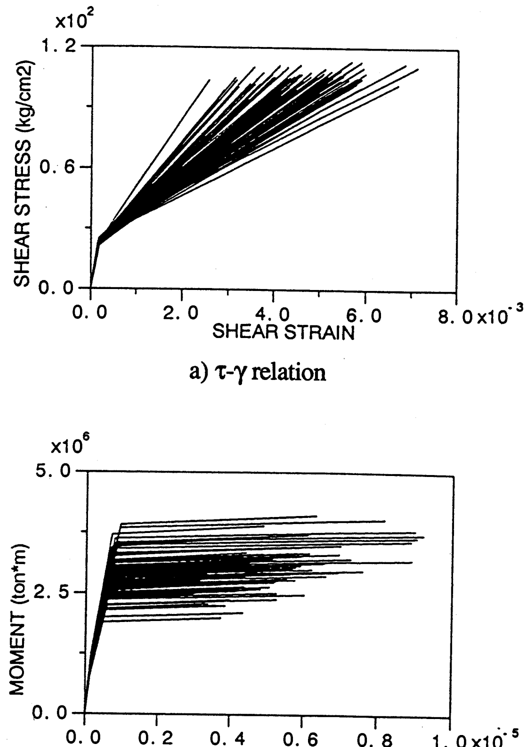


Fig. 4 Analysis Model



a) τ-γ relation

b) M-ϕ relation

Fig. 5 Samples of Skeleton Curve

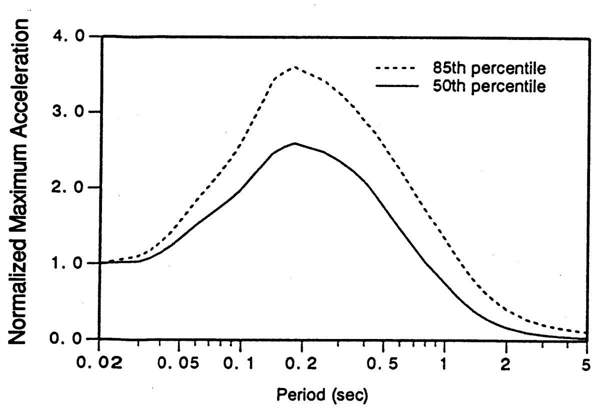


Fig. 6 Spectral Shape of Input Motion

Table 1 Result of Monte Carlo Simulation

Number of Failure at 1800 (gal)						
system	story		element			
28	story8	0		elem.1		0
	story7	0		elem.2		0
	story6	0	elem.9	elem.3	0	0
	story5	4	elem.10	elem.4	4	4
	story4	5	elem.11	elem.5	5	5
	story3	11	elem.12	elem.6	11	11
	story2	5	elem.13	elem.7	6	9
	story1	3	elem.14	elem.8	3	3

Nunber of Failure at 2000 (gal)						
system	story		element			
37	story8	0		elem.1		0
	story7	0		elem.2		0
	story6	0	elem.9	elem.3	0	0
	story5	5	elem.10	elem.4	8	5
	story4	5	elem.11	elem.5	7	5
	story3	15	elem.12	elem.6	15	15
	story2	8	elem.13	elem.7	9	8
	story1	4	elem.14	elem.8	5	4

Number of Failure at 2500 (gal)						
system	story		element			
59	story8	0		elem.1		0
	story7	0		elem.2		0
	story6	0	elem.9	elem.3	0	0
	story5	6	elem.10	elem.4	10	6
	story4	10	elem.11	elem.5	11	10
	story3	22	elem.12	elem.6	23	22
	story2	17	elem.13	elem.7	17	19
	story1	4	elem.14	elem.8	4	4

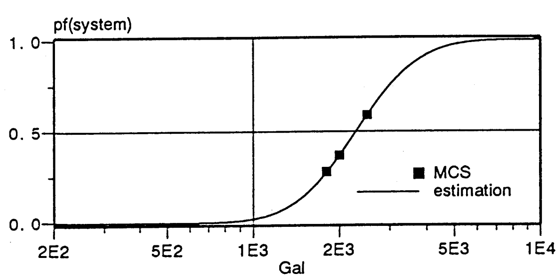


Fig. 7 Failure Probability of Real Structure