Seismic Limit-State Evaluation of Reactor Building Structures through Seismic Response Analysis

Hiroyuki YAMANOUCHI
Building Research Institute, Ministry of Construction, Tsukuba, Japan
Kazuhide SATO, Akira HIGASHIURA
Sato Kogyo Co., Ltd., Atsugi, Japan

1 INTRODUCTION

The hysteretically absorbed energy of a structure consumed when the structure plasticizes during earthquake is a useful measure in the evaluation of the structure's earthquake resistance. This study was intended to acquire data needed to evaluate the seismic safety margins of reactor buildings through such energy-related considerations as energy inputs during earthquake and the hysteretically absorbed energy of structures.

In the preceding paper[1], the energy absorption capacity of reactor building structures (BWR Mark II type) was calculated from restoring force characteristics determined through horizontal load tests using a scale-model specimen of a reactor building. Seismic safety margins of the structure were then evaluated through the comparison of the calculated energy absorption capacities and energy inputs into the structure during earthquake.

This paper deals with a series of seismic response analyses using a restoring force characteristic model of a reactor building. The analysis was intended to determine whether the limit state of the building was such that the response deformation exceeded the limit deformation, or that the hysteretically absorbed energy accumulated under repeated loads exceeded the energy absorption capacity of the building. This approach was aimed at determining the relationship between the ultimate cumulative energy of the building and the input energy under seismic force, and at identifying dominant factors in defining the seismic limit state of the reactor building.

2 METHOD FOR SEISMIC LIMIT STATE EVALUATION

The seismic limit state of the building was evaluated by the following two methods:

(1) An earthquake response analysis of the building was conducted, and seismic limit ratio ζ_1 was determined by comparing results of this analysis and the ultimate strength of the building.

(a) A restoring force characteristic model of the building was defined, and an earthquake response analysis was conducted using this model.

(b) The acceleration of input seismic force was raised until the conditions in (c) below were satisfied.

(c) A judgment was made to determine whether it was that the maximum response shear deformation of the supper structure exceeded the limit deformation (hereafter called "seismic limit state D"), or that the hysteretically absorbed energy accumulated, until the shear deformation was maximized, reached the energy absorption capacity of the building (hereafter called "seismic limit state E"). The hysteretically absorbed energy was calculated from the relationship between the deformation of the supper structure and shear force.

(d) Seismic limit ratio z1 based on the amount of energy absorbed by the building was calculated from the acceleration ratio of the input seismic force in (b) above.

(2) In the preceding paper[1)], an evaluation method using Equation (2) was proposed. In the proposed method, the seismic limit state of a structure was evaluated on the basis of energy input (Ep) calculated, from Equation (1), and the energy absorption capacity (Ec) of the structure determined through experimentation or analysis. Also in this study, seismic limit ratio $\zeta 2$ of the building at its seismic limit state was determined by the proposed method:

$$Ep = 2Ve^2/m - Qy \cdot \delta y/2 \qquad \text{---------(1)}$$

$$\zeta_2 = Ec/Ep \qquad \text{---------(2)}$$

where,

Vc: Equivalent velocity

m : Mass at the mass-lumped point

Qy: Horizontal force at the elastic limit

dy: Deformation at the elastic limit

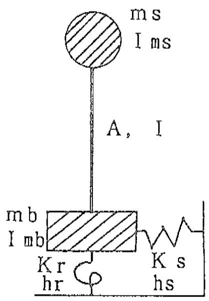
In this paper, through the above two methods (1),(2), the limit state of the structure based on shear deformation of members was assumed to be $4x10^{-3}$ rad, and the energy absorption capacity of the structure, $8.5x10^4$ tm.

3 METHOD OF EARTHQUAKE RESPONSE ANALYSIS

3.1 Modeling of Reactor Building

(1) Building Model

A BWR Mark II type reactor building was considered in the analysis. Although it was thought that the analytical model of the building should be replaced by a multi-mass system model, a two-mass system model reflecting sway and rocking was adopted so as to avoid too complicating factors. The base model used in the analysis was the one used in "Earthquake Response Analysis for BWR Reactor Buildings"2) and the weights of components and the elastic spring constant were determined on the basis of this model. Fig. 1 shows the analytical model used as a base model, and summarizes constants used in the analysis. The shear wave velocity (Vs) in the foundation ground was set at 1,000 m/sec.



$ms = 2.14 \times 10^{5}$ kg sec^{2} /cm

$I\,ms = 1.38 \times 10^{12}$ kg cm sec ^{2} /rad

$A = 3.63 \times 10^{6}$ cm^{2}

$I = 1.75 \times 10^{13}$ cm^{4}

$h = 0.05$

$mb = 1.27 \times 10^{6}$ kg sec^{2} /cm

$I\,mb = 6.80 \times 10^{11}$ kg cm sec ^{2} /rad

$K\,s = 5.35 \times 10^{8}$ kg/cm

$K\,r = 6.80 \times 10^{15}$ kg cm/rad

$hs = 0.20$ $h\,r = 0.075$

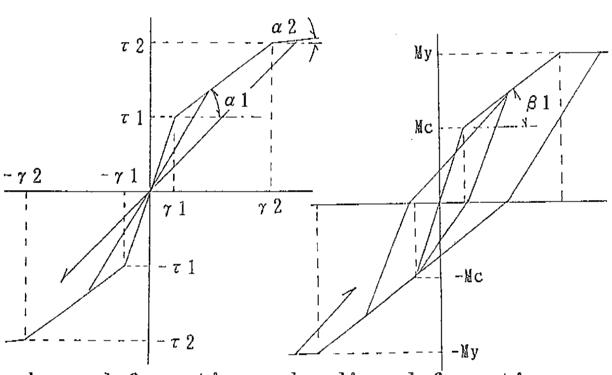
Fig.1 Analytical model

(2) Modeling of Restoring Force Characteristics

Nonlinearity of both bending deformation and shear deformation of the upper structure was considered. As restoring force characteristics of shear deformation components, a tri-linear type envelope and origin-oriented type hysteresis rules were adopted. As restoring force characteristics of bending deformation components, a tri-linear envelope and degrading type hysteresis rules were adopted. Restoring force characteristics of the shear deformation and bending deformation are shown in Fig 2.

(3) Variations in Restoring Force Characteristic Model

In the earthquake response analysis, the intrinsic accuracy of the most simplified two-mass system model used in the earthquake response analysis and variations in constants for structural members of the building were taken into consideration. In the analysis, therefore, the elastic spring constant in the analytical base model and the stresses expressing the skeleton curves for the restoring force characteristics were manipulated by $20% and +10%, respectively, in order to examine their effects. The analytical base model and the effects of the manipulation of the constants are shown in Fig. 3. The fundamental natural vibration period of the analytical base model was 0.31 sec. The natural period when the rigidity was change by +20% was 0.29 sec. while one when it was changed by -20% was 0.33 sec.



shear deformation   bending deformation

Fig.2 Restoring force characteristics

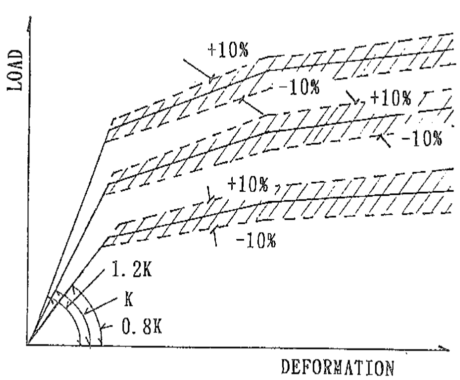
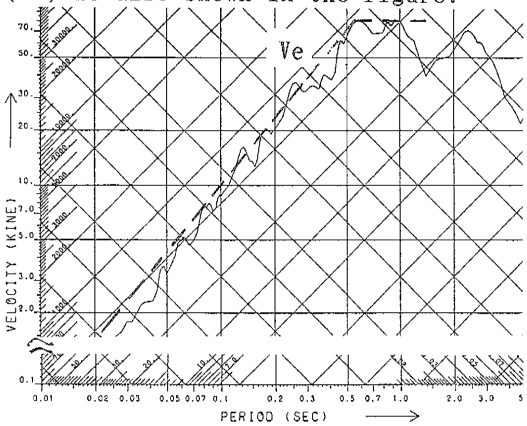


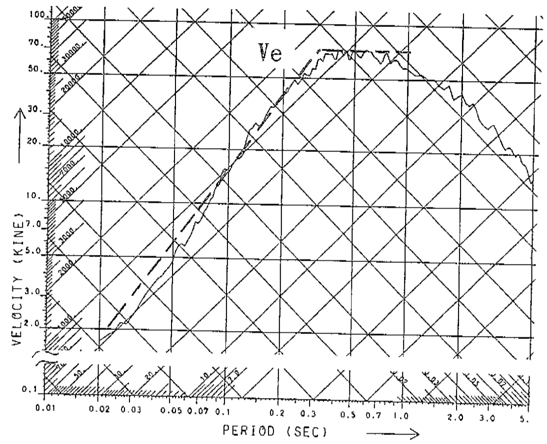
Fig.3 Manipulation of constant

3.2 Input Seismic Waves

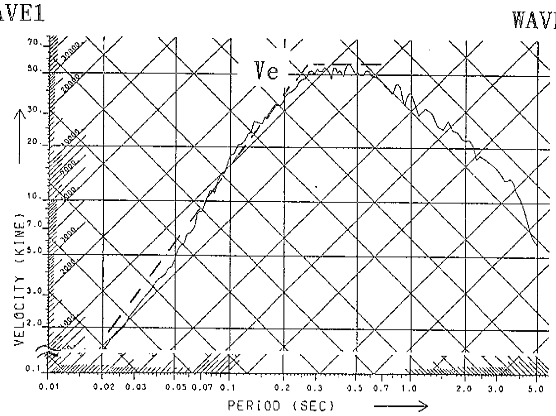
Three S2-scale simulated seismic waves were used as input seismic waves. Three types of phases of seismic waves were used: El-Centro, 1940 NS, Hachinohe, 1968 EW, and Taft, 1958 EW, WAVE1, WAVE2 and WAVE3, respectively. Fig. 4 shows response spectra of these seismic waves. Equivalent velocity (Ve) is also shown in the figure.



WAVE1



WAVE2



WAVE3

Fig.4 Response spectra of seismic waves

4 DETERMINATION OF LIMIT STATE

4.1 Evaluation by Earthquake Response Analysis

Fig. 5 illustrates the relationships between calculated values using the above simulated seismic waves and the seismic limit states. In this figure, Cumulative, hysteretically absorbed energy are measured on the axis of ordinates, the acceleration ratios of the input seismic waves on the axis of abscissas, and the shear deformation angles on the orthogonal axes. In all calculations for WAVE1 and WAVE3, seismic limit state D was reached by increasing the acceleration ratios of the input seismic waves. The acceleration ratios of the input seismic waves ranged from 3.09 to 4.05 for WAVE1 and from 5.38 to 6.25 for WAVE3. As for WAVE2, seismic limit state E was always reached before limit state D was reached. The acceleration ratios in this case ranged from 2.16 to 2.47. As seen from Fig. 5, different input

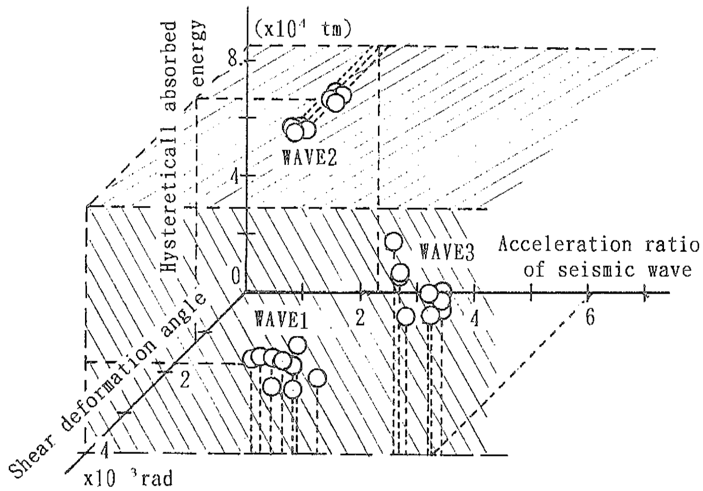


Fig.5 Relationship between calculated values and seismic limit state

seismic waves correspond to different groups of seismic limit state. It is thought that such differences in seismic limit state come more from differences in characteristics of input seismic waves rather than from variations in values concerning the restoring force characteristic model. In particular, the duration of earthquake before the seismic limit state is reached is considered to be a major influence.

4.2 Evaluation by Energy Input from Seismic Force

In Section 4.1, the acceleration ratios (limit input accelerations) of the input seismic waves when seismic limit state D or E was reached were obtained. Energy inputs from the limit input accelerations were compared with the energy absorption capacity of the building, and seismic limit ratio $\zeta 2$ was calculated accordingly. In this calculation, the equivalent velocity Ve of input seismic waves was determined by the method described in Reference 3). Table 2 listes the results of this calculation. The table also listes the results of calculation based on the accelerations of the original input seismic waves. Seismic limit ratio $\zeta 2$ of WAVE1 in the original state was between 76 to 128, while it ranged between 6.2 to 8.7 when WAVE1 was in the seismic limit state. The ratio of WAVE2 in the original state was between 39 to 54, and it was within the range between 5.6 and 11.8 when WAVE2 was in the seismic limit state. And the ratio of WAVE3 in the original state was between 60 to 103, and it was in the range between 1.76 to 2.33 when WAVE3 was in the seismic limit state.

Table 2 Seismic limit ratio $\zeta 2$

Restrong frce	WAVE1			WAVE2			WAVE3		
charactertic	K	0.8K	1.2K	K	0.8K	1.2K	K	0.8K	1.2K
Base model(Bm)	7.83	6.99	8.47	9.07	6.12	11.08	2.06	1.76	1.2K
Bm 90%	6.93	6.17	6.88	7.86	5.63	9.44	2.04	1.79	2.30
Bm110%	8.67	8.00	8.47	10.11	6.50	10.98	2.20	1.84	2.33
Orignal wave	109.4	129.8	76.2	54.2	65.6	38.6	83.6	103.0	60.4

4.3 Seismic Limit Ratio

Fig. 6 gives seismic limit ratios $\zeta 1$ and z2 representing the acceleration ratios of the input seismic waves expressed in the form of energy. The figure shows that seismic limit ratio $\zeta 1$ takes somewhat close values to seismic limit ratio $\zeta 2$ does. This indicates that seismic limit ratio $\zeta 2$ based on energy input from seismic force gives a useful side evaluation of the seismic limit ratio of the building.

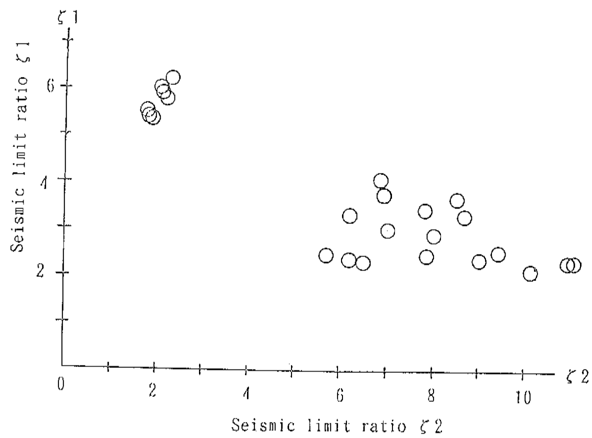


Fig.6 Seismic limit ratio $\zeta 1$ and $\zeta 2$

5 CONCLUSION

A seismic of earthquake response analyses was conducted using a restoring force characteristic model of a reactor building structure, and the limit states of the structure were evaluated by comparing results of this response analysis and the ultimate capacity of the structure. As a result, it was confirmed that the limit shear deformation and the energy absorption capacity of the structure were useful measures for defining the seismic limit state of the structure, and that characteristics of input seismic waves greatly affected the seismic limit state of the structure.

REFERENCES

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