A Study on Application of Energy Absorber to Piping System in Nuclear Power Plant

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1 INTRODUCTION

Machines and piping systems of nuclear and chemical plants are generally designed to be held rigid by supports for safety and for protection from earthquakes. The piping design must balance seismic and other stresses, such as thermal stress. But making a piping system rigid by using many support devices may cause the thermal stress to increase. And the seismic design of machines and piping systems should be more rational.

Contrary to a rigid design, it is possible to design a flexible piping system and to decrease seismic response by increasing the damping through the use of energy absorbing elements which dissipate vibration energy. Recently the damping effect of these elements, including elastoplastic and friction types and so on, has been analytically and experimentally analyzed by domestic and foreign laboratories. However, there has been little actual application of this technology to plants(1)(2).

This paper investigates elastoplastic piping support (Energy Absorber(EAB)) for application to an actual piping system. Element characteristics tests investigating dynamic characteristics, durability, etc have already been reported(3). This paper reports on the response characteristics of one- and three-dimensional piping models to a sinusoidal and a random wave. As the seismic response analysis method to design a piping system supported by EAB, some analysis method were developed.

2 ENERGY ABSORBER (EAB) CHARACTERISTICS

2.1 Basic Construction

Figure 1 shows the basic EAB construction. The EAB is made by deforming the plate spring to the plastic region. The force-displacement curve shows nonlinear hysteretic characteristics. The seismic response of the piping system is reduced by the energy dissipation of the hysteresis loop. Because steel is used in the plastic region, this region must be generated to prevent plastic hinges from developing. A uniformly strong X-shaped plate is used as a plate spring. When the X-shaped plate has large deformation, the plastic domain progresses in the thickness direction of the plate.

2.2 Dynamic Characteristics

It has been reported that EAB dynamic characteristics were evaluated by modeling X-shaped plates by the beam theory in consideration of elastoplastic characteristics(3). EAB dynamic characteristics can be shown by the equivalent stiffness K and the element damping ratio h. The former is obtained by the tangential stiffness at the reversal point of the skeleton curve. The latter is obtained by the ratio between the element strain energy and the dissipating energy per a cycle ΔE. The displacement's relationship to equivalent stiffness and element damping ratio is shown in Fig.2. The displacement was non-dimensionized by the yield displacement dy, and the equivalent stiffness was non-dimensionized by the stiffness Ke of the elastic region. The equivalent stiffness and the element damping ratios from the analysis value of the EAB hysteresis loop are represented by the solid line and the dotted line respectively.

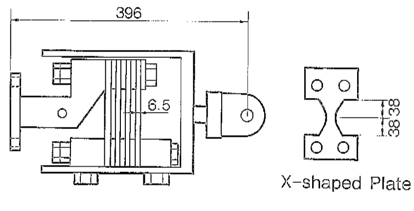


Fig.1 Energy Absorber

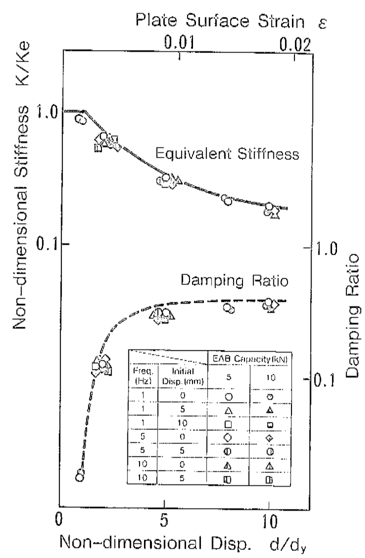


Fig. 2 Relation during Disp. and Stiffness and Damping

3 PIPING MODEL TEST

3.1 Testing Method

(1) Testing model
The one-dimensional piping model is shown in Fig.3. It is a cantilever with a 3B diameter, Sch40, a 4m length and a 200kg concentrated mass at the top. It was horizontally supported by an EAB near the top, and the added mass was vertically supported by a wire cable.

The three-dimensional piping is shown in Fig.4. It has 4B diameter, Sch40 and 2B diameter, Sch80 piping, 120kg and 60kg added masses, and is supported by four EABs and three restraints.

(2) Input seismic wave
The input seismic wave is the response wave of the sway-rocking analysis model of the BWR reactor building excited by the standard design seismic wave. Seismic wave A is the severest wave that is resonant to the piping model. The seismic wave B or C's remarkable frequency component is moved to the long or short period, respectively. Figure 5 shows the response spectrum of seismic waves A, B, and C.

(3) Testing item
Testing items are the sinusoidal wave sweep test and the seismic wave shaking test. In the former, the changes of resonant frequency and the damping ratio of the piping model were investigated when

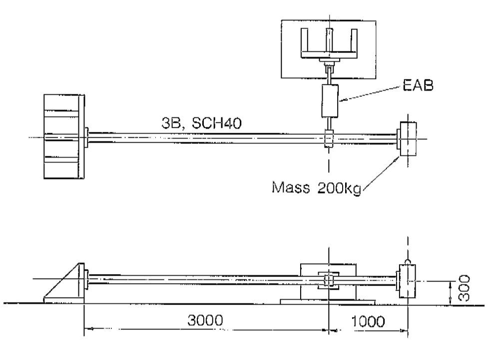


Fig.3 One-Dimensional Piping Model

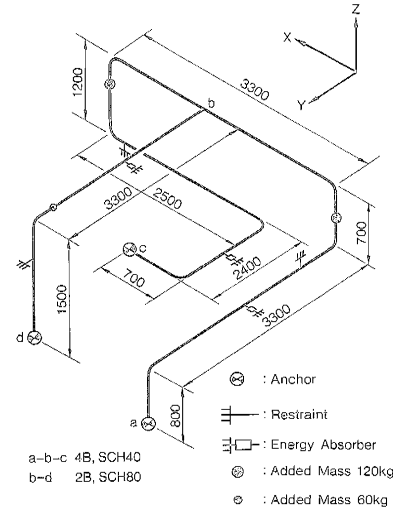


Fig.4 Three-Dimensional Piping Model

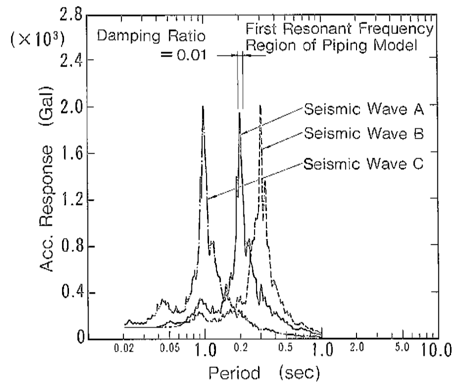


Fig.5 Response Spectrum of Input Seismic Wave

the input acceleration level increased. The stability of the piping response and damping effect were investigated in the later.

3.2 Test Results

(1) Sinusoidal wave sweep test
The transmissibility function of the top mass acceleration of the one-dimensional piping model to the table acceleration obtained by the sinusoidal wave sweep test is shown in Fig.6. The resonant frequency of the model was defined by the peak frequency of the transmissibility function, and the damping ratio was defined using the response amplitude and half power methods. The table acceleration's relationship to resonant frequency and damping ratio is shown in Fig.7. The transmissibility function had a soft-spring type nonlinearity. However, the nonlinearity isn't so serious. And at higher order vibration modes in which the support points became nodes, the damping effect by EAB didn't work sufficiently. Thus, piping system supported by EAB must be designed because the previously mentioned vibration modes are absent in the low order vibration modes which largely contribute to the seismic response.
(2) Seismic wave shaking test
The maximum response value of stress of the three-dimensional piping model, displacement of the EAB, and input acceleration during seismic wave A shaking are shown in Figs.8 and 9. The stress of the model saturates at a large shaking level. Thus, the damping is significantly effected by the shaking level. The EAB displacement increases almost linearly with the shaking level. Thus, the response

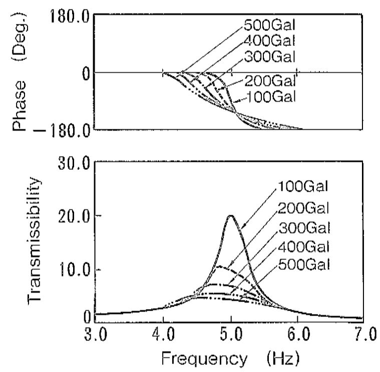


Fig.6 Transmissibility Function

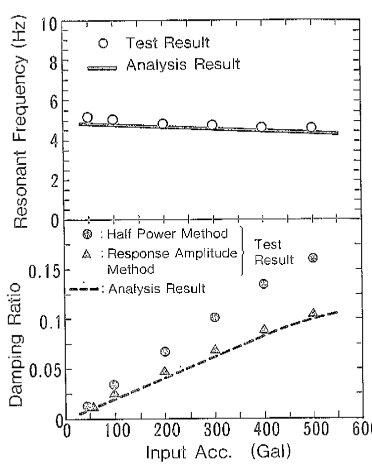


Fig.7 Relation during Input Acc. and Resonant Frequency and Damping Ratio

reduction caused by the EAB damping effect prevents response increasing by EAB stiffness decreasing. The response characteristics by wave B and C shaking are almost the same as those by wave A.

3.3 Test and Analysis Comparison

(1) Sinusoidal wave sweep test
The dynamic characteristics of the one-dimensional model were evaluated using the equivalent stiffness and the element damping ratio as a factor of the EAB displacement shown in Fig.2. The equivalent stiffness is obtained by EAB displacement at each shaking level. The resonant frequency from its equivalent stiffness is the solid line in Fig.7. The damping ratio ξi of the i-th mode is the ratio between the strain energy Ei of the piping at i-th mode and the dissipating energy ΔEi at EAB(4). The analytical damping ratio at each shaking level is represented by the dotted line in Fig.7. Analysis results agree with test results of the response amplitude method. Thus, the transmissibility function of the piping system supported by the EAB has a spreading foot.

(2) Seismic wave shaking test
To investigate the seismic response analysis method in order to design an EAB supported piping system, the seismic wave shaking test results were compared to the results of the time history analysis using the force-displacement characteristic of the EAB modeled by the Ramberg-Osgood model (R-O model), and the iterative response spectrum analysis method which uses different modal damping ratios as a rationalized analysis method. The analysis flow of the rationalized response analysis method is shown in Fig.10. Figures 8 and 9 compare test and analysis results of the maximum response value of the stress of the three-dimensional model and the displacement of EAB. Figures 11 and 12 compare the time history and the hysteresis loop of the test and analysis results of the one-dimensional model. The time history analysis using the R-O model sufficiently simulates the test results, and the response analysis results using different modal damping slightly underestimate the EAB displacement, but sufficiently estimate the other response. These two analysis methods sufficiently estimate the test results for seismic wave B and C shaking tests.

4 STUDY OF APPLICABLE LIMIT OF RATIONALIZED ANALYSIS METHOD

4.1 Study method

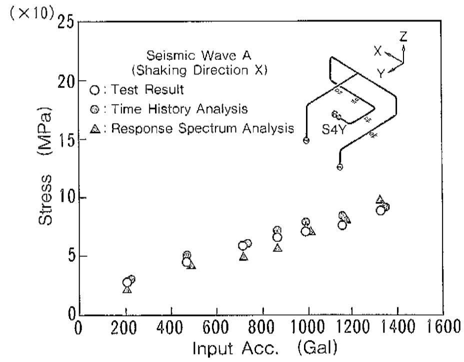


Fig. 8 Relation between Input Acc. and Stress (Measuring Point S4Y)

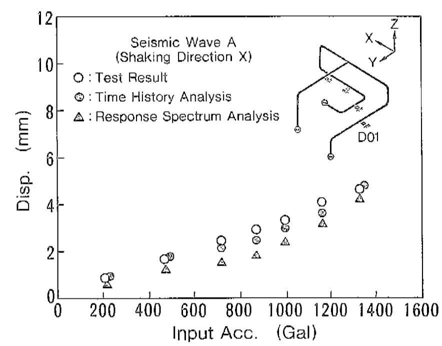


Fig. 9 Relation between Input Acc. and EAB Disp. (Measuring Point D01)

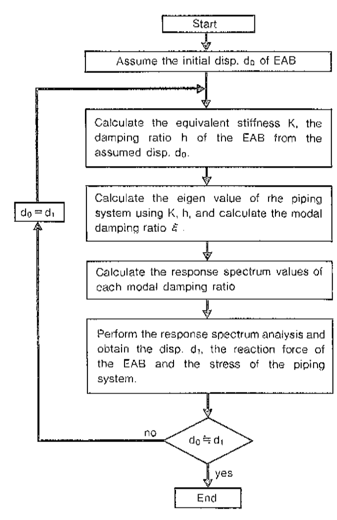


Fig. 10 Response Spectrum Analysis using each Modal Damping Ratio

The nonlinear time history analysis results and the rationalized analysis results by the response spectrum analysis were compared with the test results in the piping model test, and the latter had some error. Applicable limits of this analysis revealed that this error was caused mainly by the bad ratio of the piping and the EAB stiffness. To study the effect of these factors, two analyses were performed : nonlinear time history analysis of the single degree of freedom(SDOF) system, and the equivalent linear time history analysis using maximum EAB displacement from the nonlinear time history analysis. Then both response values were compared. The EAB force-displacement characteristics used in the nonlinear analysis is the perfect elastoplastic model. This model is shown in Fig.13. The input wave is the one resonant to the model and is used in the piping model test. The ratio of the piping and the EAB stiffness was changed and the response ratio of the nonlinear and the equivalent linear analysis was calculated. The ratio d/dy of the response displacement d and the yield displacement dy is the ductility factor μ and the effect of μ was also studied.

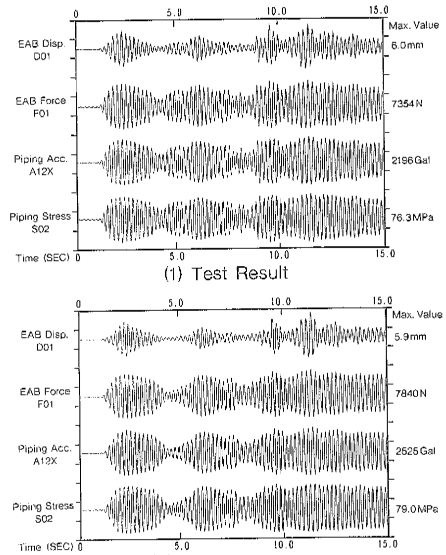


Fig.11 Comparison of Time History
(Seismic Wave A, Input Acc. 600Gal)

4.2 Study results

The displacement response ratio of the nonlinear and the equivalent linear analysis to the ratio of the piping and the EAB stiffness is shown in Fig.14. The response ratio of the displacement changes significantly with the stiffness ratio. When the EAB stiffness is much harder than the piping stiffness, the equivalent linear and nonlinear analysis results are very different. This is the reason why the EAB nonlinearity significantly affects the response when the EAB stiffness is much harder than the piping stiffness. When the ductility factor increases, the equivalent linear and nonlinear analysis results are similar. This is the reason why the relationship between the equivalent damping ratio and the EAB displacement has the maximum value, and if the response displacement is less than the displacement at which the maximum damping ratio occurs, the equivalent damping ratio from the response displacement is too large for the equivalent linear system. The above study was performed on the SDOF system. The nonlinear time history analysis results were compared to rationalized analysis results on the one-dimensional piping model in which the EAB stiffness was decreased. It was confirmed to make errors of the rationalized analysis result few as same as the study of SDOF system. From above results, the following items were confirmed to need to

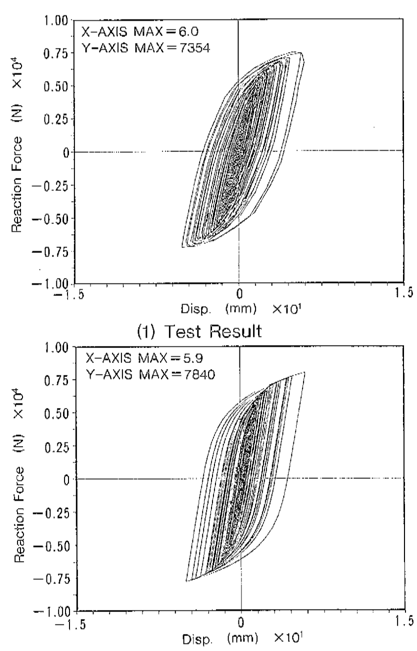
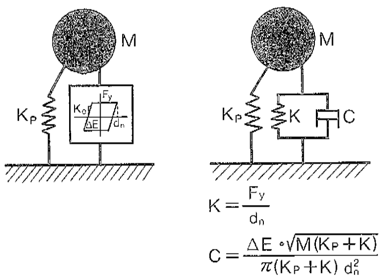


Fig.12 Comparison of Histeresis Loop
(Seismic Wave A, Input Acc. 600Gal)



(1) Nonlinear Model (2) Equivalent Linear Model

Fig. 13 Analysis Model

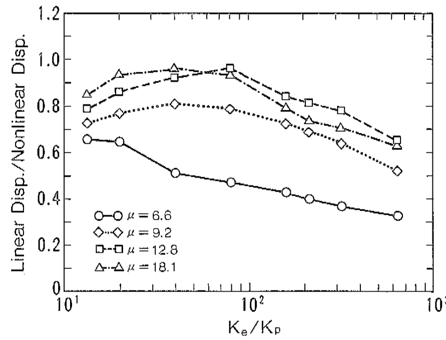


Fig. 14 Relation between Response and Stiffness Ratio

keep the accuracy of the rationalized analysis result.

1) The ratio Ke/Kp of the piping stiffness Kp and the EAB stiffness Ke should be less than 10^2.
2) The response displacement should be larger than the one at which the equivalent damping ratio is maximum.

5 CONCLUSION

To study the application of the energy absorber (EAB) to nuclear power plants, the piping model supported by EAB was tested and its seismic response analysis was performed and the following results were obtained.

1) It was confirmed that EAB was applicable to the nuclear power plant.
2) Iterative response spectrum analysis using each mode damping ratio was developed as a rationalized seismic response analysis method for the piping supported by EABs.
3) The application limit of the rationalized response analysis method was clarified regarding EAB stiffness.

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