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Proving test on the seismic reliability of the main steam piping system (Part 2 : simulation for BWR feed water piping)

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ABSTRACT : Seismic proving tests have been conducted to verify the reliability of piping systems of carrying reactor coolant in nuclear power plant. The test was divided into two parts. The first was a conventional support piping test in which the model was supported by snubbers. The other was an energy absorbing support piping test in which the model was supported by EABs (: energy absorber), which will be applied to future plants. This paper reports a comparison between the test results and the calculation results obtained from the simulation analysis reflecting non-linear characteristics, and the validity of response-spectrum analysis used in piping design is shown for F-line (BWR feed water piping test model).

1. INTRODUCTION

Seismic design in nuclear plant has been considered in many ways including classfications of seismic importance, structural design, seismic load, load combination, evaluation of stress and function. This design technology has been developed by dynamic analysis and many simulation analyses by computer. However, it is necessary to prove seismic reliability in actual structures. Thus, under the sponsorship of the Ministry of International Trade and Industry (MITI), to prove the seismic reliability by comparison between test and analytical results, the Nuclear Power Engineering Corporation (NUPEC) conducted a seismic reliability proving test of a nearly full scale model of a main steam and feed water piping system, using the 1000-ton shaking table of NUPEC (from 1989 to 1996). In this paper, we report the results of this seismic reliability test and the validity of analysis methods in a conventional support piping test in which the model is supported by snubbers, and an energy absorbing support piping test in which the model is supported by energy absorbing supports, which will be applied to future plants.

2. PROVING TEST

2.1 *Test Model*

There were two kinds of test models. One was the feed water piping model of a Boiling Water Reactor(BWR), and the other was a main steam piping model of a Pressurized Water Reactor (PWR). In this paper, we only report on the test and the analysis results for the former. The test model is of piping and seismic supports, modeled from the isolation valve outside of the reactor containment vessel, through the reactor containment vessel, to the reactor pressure vessel. The test model was installed on the shaking table via a support structure. First, we conducted a conventional support piping test, and later we conducted an energy absorbing support piping test after some snubbers were replaced by EABs which are energy absorbing supports. Figures 1 and 2 show the schematic diagram of a conventional support piping test model and an energy absorbing piping test model. The scale of the piping model was 1/2.3 because of restrictions due to the shaking table size. To produce the same stresses in the test model as in the actual piping, the model was a scale model, to satisfy the law of similarity. However the natural frequency of the test model is too high. Therefore, we used a modified similarity law, in which added masses were attached to the test model and the ratio of natural frequencies between actual and testing piping was set to 0.7. Table 1 shows the modified similarity law for, the test model. In the testing, the fluid in the piping was pressurized to a pressure equivalent to the normal operating pressure of the actual piping, and the model was excited at room temperature.

Table 1 Modified Similarity Law of Test Model

Quantity	Symbol	Similarity Law (Similarity Ratio N)	Ratio
Length	l	$l_m / l_p = 1/N$	1/2.3
Sectional Area	A	$A_m / A_p = 1/N^2$	1/5.29
Strain	ε	$\varepsilon_m / \varepsilon_p = 1$	1
Stress	σ	$\sigma_m / \sigma_p = 1$	1
Displacement	x	$x_m / x_p = 1/N$	1/2.3
Force	P	$P_m / P_p = 1/N^2$	1/5.29
Frequency	f	$f_m / f_p = 1/\lambda$	1/0.7
Acceleration	a	$a_m / a_p = 1/N\lambda^2$	1/1.127
Weight	W	$W_m / W_p = \lambda^2 / N$	1/4.694
Stiffness	k	$k_m / k_p = 1/N$	1/2.3

Ratio of natural frequencies $f_m / f_p = 1/\lambda$
Subscript p : Actual piping
Subscript m : Model piping

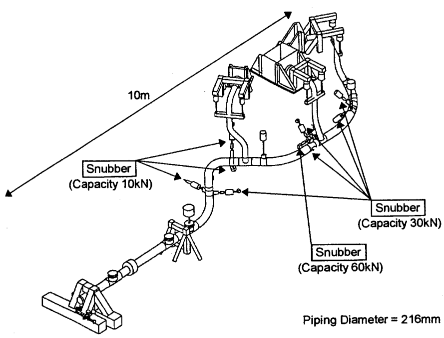


Fig.1 Schematic Diagram of Feed-water Piping Model with Conventional Supports

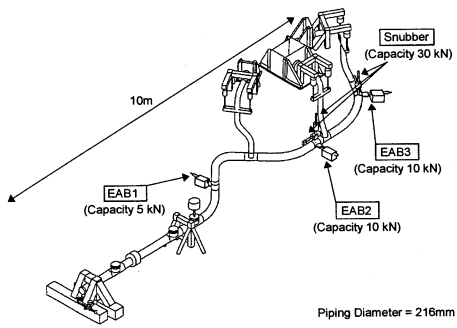


Fig.2 Schematic Diagram of Feed-water Piping Model with Energy Absorbing Supports

The energy absorbing support used was an elastoplastic damper (EAB : Energy Absorber) which utilizes vibration-energy absorption by the elastoplastic bending of a steel plate. The EAB uses X-shaped plates that provide a constant strain on the plate surface. Figure 3 shows a schematic diagram of an EAB.

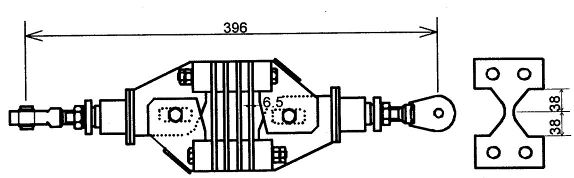


Fig. 3 Schematic Diagram of EAB

2.2 *Seismic Input Wave*

The seismic wave input used in our proving test was the strongest wave for the piping model, and was selected using the response waves of reactor-buildings as excited by the standard-earthquake ground motion for the high seismic area plant design of the MITI improved standard plant, other response waves for design earthquakes used to constructed actual PWR and BWR plants. Table 2 shows the specifications of the seismic input wave, and Figures 4 and 5 show the response-spectrum to the horizontal seismic wave.

Table 2 Specifications of Seismic Input Waves unit : m/s^2

Design earthquake wave	Input direction	Conventional support piping test model	Energy absorbing support piping test model
S_1	Horizontal	7.11	8.14
	Vertical	1.44	1.90
S_2	Horizontal	10.90	14.89
	Vertical	1.84	3.40

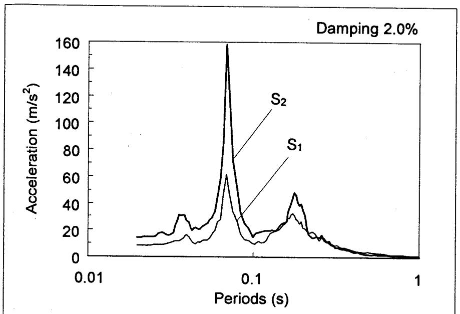


Fig. 4 Response Spectrum in Conventional Support Piping Test

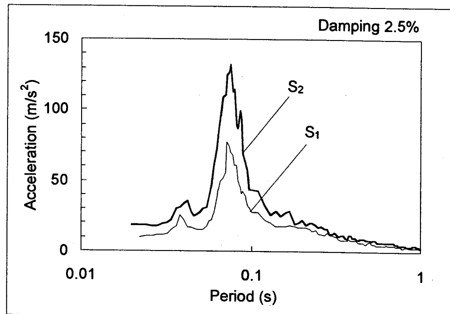


Fig. 5 Response Spectrum in Energy Absorbing Support Piping Test

2.3 *Testing Method*

The test was divided into two parts. The first was a preliminary test in which the vibration characteristics of the test model were examined. The other was a seismic proving test in which the model was excited by the design earthquake. In the former, we conducted a random wave excitation test and a sinusoidal wave sweep test. In the seismic proving test, we conducted S_1 and S_2 wave excitation tests, with the S_2 wave excitation conducted up to 1.3 times of the maximum acceleration.

2.4 *Test Results*

It is a known fact that snubber mechanical parts produce on infinitesimal gap. Figure 6 shows the transfer function in a conventional support piping test. We know that vibration response characteristics of the test models showed typical non-linear characteristics of a hard-spring type. It is assumed that this event is proper to the reduced test model with a larger mechanical gap, relatively. Thus, it seems necessary that modeling of snubbers produces infinitesimal gap in simulation analysis, which is described in the following section.

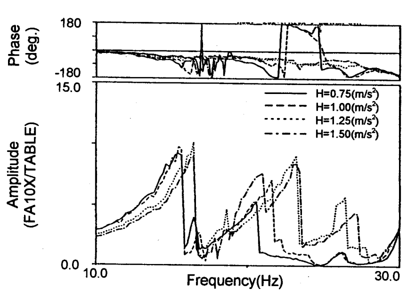


Fig.6 Transfer function in Conventional Support Piping Test

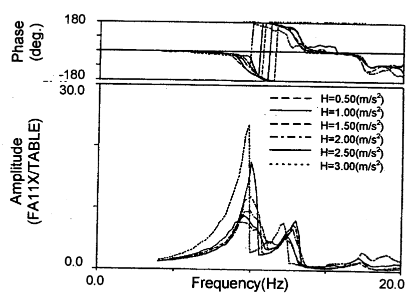


Fig.7 Transfer function in Energy Absorbing Support Piping Test

Figure 7 shows the transfer function in an energy absorbing support piping test. We know that the resonance frequency of the test models went down and the damping factor increased due to the elastoplastic behavior of EAB according to the increase in input acceleration. It is assumed that EABs dissipate vibration energy effectively.

3. ANALYSIS METHOD

The analysis methods used fall into two kinds. One was a simulation analysis that accurately calculates the response of the test model. The other was response-spectrum analysis which is a design analysis method. Design analysis of piping supported by EABs uses response-spectrum analysis, which is proposed in actual plant design, and requires iterative calculation of EAB displacement, and uses each mode's damping ratio.

3.1 *Simulation Analysis*

3.1.1 *Simulation Analysis Method*

The motion equation for multiple degrees of freedom (like our piping) including non-linear elements is as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K_l]\{x\}=-[M]\{1\}\ddot{y}-[K_n]\{x\} \quad (1)$$

where,

$[M]$	: Mass matrix
$[C]$	: Damping matrix
$[K_l]$	: Piping stiffness matrix (Subscript: linear)
$[K_n]$	: Stiffness matrix of non-linear supports (Subscript: non-linear)
$\ddot{y}$	: Seismic input acceleration
$\{\ddot{x}\},\{\dot{x}\},\{x\}$	: Acceleration, Velocity and Displacement vectors

The simulation analysis is a non-linear time-history analysis using a pseudo-force method that efficiently calculates the piping response. In this method the snubbers are modeled as gap elements and the EABs by Ramberg-Osgood (R-O) models, with each non-linear force transposed to the right side of the motion equation as in Eq. (1). The left side of the motion equation is solved using the modal superposition method. The time integration method used was the Wilson-θ method ($\theta = 1.4$) and the integral time increment was 0.001sec. All the modes were considered to be less than 50 Hz, to match the test-data acquisition condition (50 Hz low-pass filter). The measured waves in the X, Y, and Z directions at the support structure were inputted as the seismic input.

3.1.2 *Confirmation of Modeling*

We compared resonant frequency and the response amplitude of the linear-frequency response-analysis results with the measured transfer function of the piping (without Snubbers or EABs) under random wave excitation. The linear frequency response was obtained by the equation below:

$$f(i\omega)=\sum_{j=1}^{n}\{\phi\}_j\beta_j S_j(i\omega) \quad (2)$$

where,

$$S_j(i\omega) = \frac{1 + i2\zeta_j \dfrac{\omega}{\omega_j}}{1 - \left(\dfrac{\omega}{\omega_j}\right)^2 + i2\zeta_j \dfrac{\omega}{\omega_j}} \quad (3)$$

$\{\phi\}_j$: j th mode's vector of the piping model
β_j : j th mode's participation factor
ζ_j : j th mode's damping ratio
ω : circular natural frequency
ω_j : j th mode's circular natural frequency

Figure 8 shows a comparison between the transfer function of the piping without EABs or snubbers obtained under random wave excitation, and the transfer function of the FEM piping model obtained by the frequency-response analysis. The resonant frequency and response amplitude of the peaks of the transfer function are all almost the same in the test and the analysis. We were also able to confirm the validity of the mass matrix, damping matrix and stiffness matrix in Eq. (1).

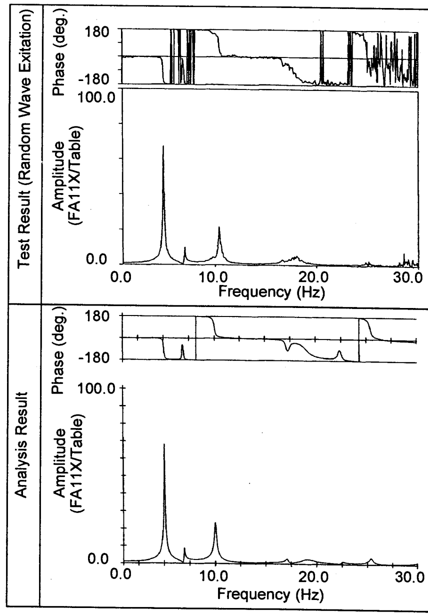


Fig.8 Transfer Function (Without EAB or Snubber)

The snubbers and EABs were modeled as gap elements and R-O models, respectively. Each model's constant was determined by fitting the force-displacement characteristics obtained from the model, to the ones obtained in snubber and EAB tests.

3.2 *Design Analysis*

3.2.1 *Design Analysis in Conventional Support Piping Systems*

As design parameter, absolute value of maximum response value is more important than time history response solved Eq.(1). And piping to confirm strength by analysis is huge in nuclear plant piping system. As design analysis, we use response-spectrum analysis which provides a reasonable solution with respect to tolerance and cost. A summation of modal response is obtained by the SRSS method. The natural frequencies considered were up to 50Hz. The damping ratio of the piping system is 2.0% in accordance with our design method which depends on the number of supports and thermal insulation. The response-spectrum is calculated using the wave measured at the support structure, and inputted in the X, Y, and Z directions. The response-spectrum was also broadened by $\pm 10\%$ in the period axis.

3.2.2 *Design Analysis in Energy Absorbing Support Piping Systems*

In energy absorbing support piping systems, the abovementioned method is not applicable because the eigenvalue and modal damping are changed by EAB's response displacement. Thus, design analysis is used in response-spectrum analysis, which requires iterative calculation of EAB displacement, and uses each mode's damping ratio. This method was developed for piping supported by EABs. Figure 9 shows the flowchart of our analysis method for response-spectrum analysis, which uses iterative calculation of EAB displacement and with each mode's damping ratio. We create separate files of equivalent stiffness and element-damping ratios for each EAB for each displacement value, and from these files we look up the equivalent stiffness and the element damping ratios at the assumed EAB displacement. Thus, natural frequency analysis is conducted, using the FEM piping model with the EAB stiffness changed to the equivalent stiffness, and we get the eigenvector and the participation factor. We also obtain i th mode's damping ratio ζ_i from the ratio of the EAB dissipating energy to the piping stain energy, using Eq. (4).

$$\zeta_i = \sum_{k=1}^{n} \frac{h_k E_{Sik}}{E_{Pi}} \tag{4}$$

d_k : k th EAB displacement

$E_k(d_k)$: k th EAB dissipating energy

k_k : k th EAB equivalent stiffness

h_k : k th EAB element damping ratio $\left(=\left\{\dfrac{E_k(d_k)}{4\pi(k_k d_k^2/2)}\right\}\right)$

ϕ_{dik} : Mode vector element equivalent to k th EAB displacement of i th mode vector

$\{\phi\}_i$: i th mode vector of the piping model

$[K]$: Stiffness matrix of the piping model

E_{Sik} : k th EAB strain energy of i th mode vector $\left(=\dfrac{1}{2}k_k\phi_{dik}^2\right)$

E_{Pi} : Strain energy of i th mode vector $\left(=\dfrac{1}{2}\{\phi\}_i^T[K]\{\phi\}_i\right)$

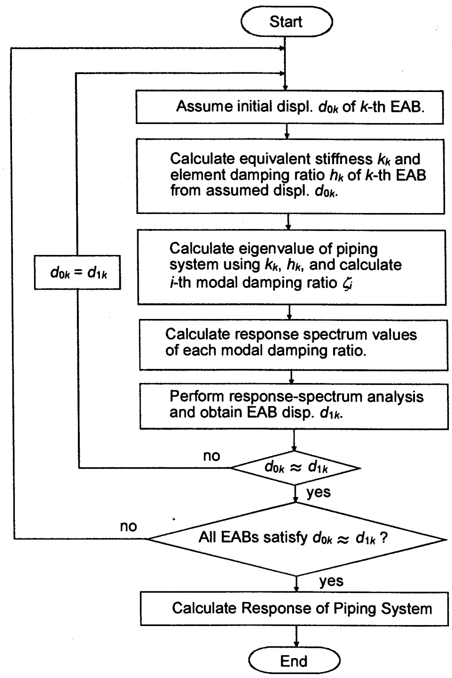


Fig. 9 Flow of Response-Spectrum Analysis

A response-spectrum is made for each obtained mode's damping, and response-spectrum analysis is conducted using them. Then, we obtain the EAB displacement from Eq. (5). We conduct the iterative calculation described above until the assumed EAB displacement is very close to the calculated EAB displacement, and we obtain the piping response.

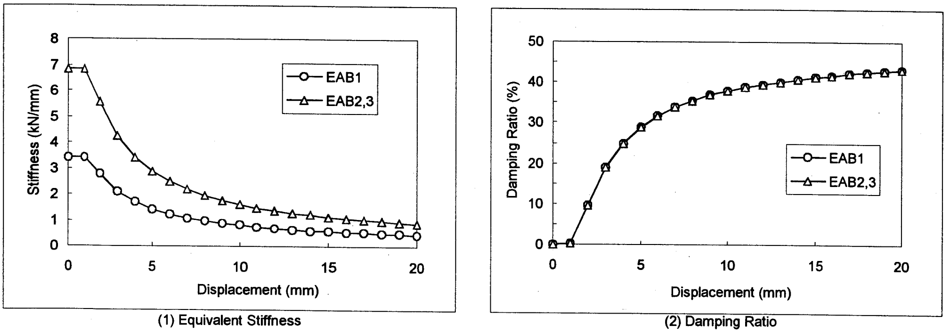
$$d_k = \sqrt{\sum_{i=1}^{n}\left\{\frac{\phi_{dik}\beta_i S_A(\omega_i,\zeta_i)}{\omega_i^2}\right\}^2} \tag{5}$$

β_i : i th mode's participation factor $\left(=\sum_{j=1}^{n} m_j\phi_{ij}\right)$

$S_A(\omega_i,\zeta_i)$: Acceleration response-spectrum

ω_i : i th circular natural frequency

The natural frequencies considered were up to 50Hz. The damping ratio of the piping alone is 0.5%. The response-spectrum is calculated using the wave measured at the support structure, and inputted in the X, Y, and Z directions. The response-spectrum was broadened by ±10% in the period axis. Response-spectrum analysis without broadening was also conducted to confirm the validity of analysis. Figure 10 shows the relationship among the displacement, the equivalent stiffness and the element damping ratio of the EABs as determined in the response-spectrum analysis.



(1) Equivalent Stiffness (2) Damping Ratio

Fig. 10 EAB Characteristics

4. COMPARISON BETWEEN TEST AND ANALYTICAL RESULTS

4.1 *Comparison in Conventional Support Piping Systems*

Figure 11 shows a comparison of maximum piping acceleration values from our test and from our simulation analysis for excitation by S_2 wave. Figures 12 and 13 compare the maximum values of the piping stress and the snubber force for the test results and the simulation-analysis results, and show the response-spectrum analysis results with and without spectrum broadening.

The simulation analysis results for piping acceleration and snubber force matched the test results with sufficient accuracy, confirming the validity of our simulation analysis and the modeling method.

In Figures 12 and 13, the results of response-spectrum analysis with spectrum broadening (the design analysis method) were greater than the simulation results, and the simulation analysis results tended to be greater than the response-spectrum analysis results without spectrum broadening. The response-spectrum analysis results with spectrum broadening and the simulation analysis results were confirmed to encompass the test results nearly completely. It was confirmed that the response-spectrum analysis, which is our design analysis method, is valid for the design of conventional support piping systems.

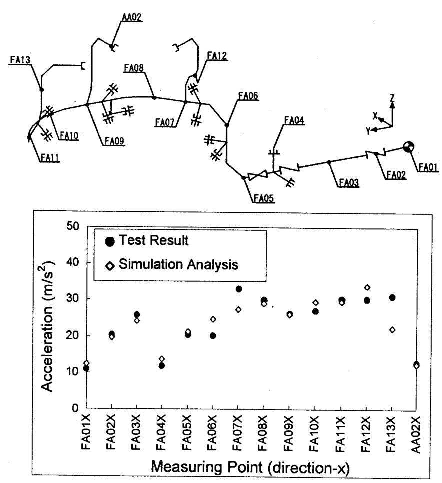


Fig. 11 Piping-acceleration Comparison

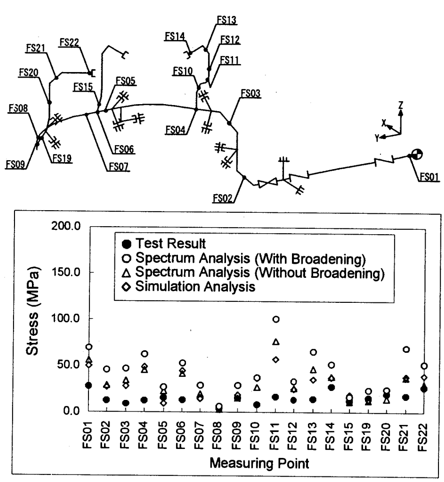


Fig. 12 Piping-stress Comparison

The maximum piping stresses cannot be compared directly between the test and the analysis results. This is because the test results are measured by the strain gauge placed axially and circumferentially on the piping surfaces, and the analysis results are obtained in a design-evaluation method in which the stresses are calculated from the 3 components of the moment obtained in the analysis and multiplied by stress-intensification factors. Measuring points at which the analysis results greatly exceed the test results are points that represent the elbow and tee joints considering the stress intensification factor. As the trends in the distribution of the analysis results are not much different in either simulation analysis or response-spectrum analysis with or without the spectrum broadening, the difference between the test results and analysis results is considered to depend on the effect of the stress intensification factor. That is, it does not depend on the difference in the analysis methods or on the broadening or lack of broadening of the spectrum.

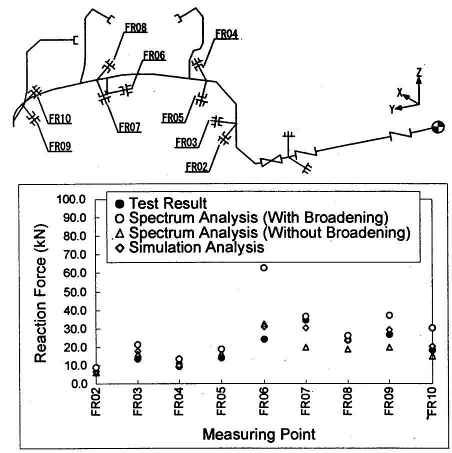


Fig. 13 Snubber Reaction Force Comparison

4.2 *Comparison in Energy Absorbing Support Piping Systems*

Figure 14 shows a comparison of maximum piping acceleration values from our test and from our simulation analysis for excitation by S_2 wave. Figures 15 and 16 compare the maximum values of the piping stress and the EAB displacement for the test results and the simulation-analysis results, and show the response-spectrum analysis results with and without spectrum broadening.

The simulation analysis results for piping acceleration, EAB displacement, EAB and snubber force matched the test results with sufficient accuracy, confirming the validity of our simulation analysis and the modeling method.

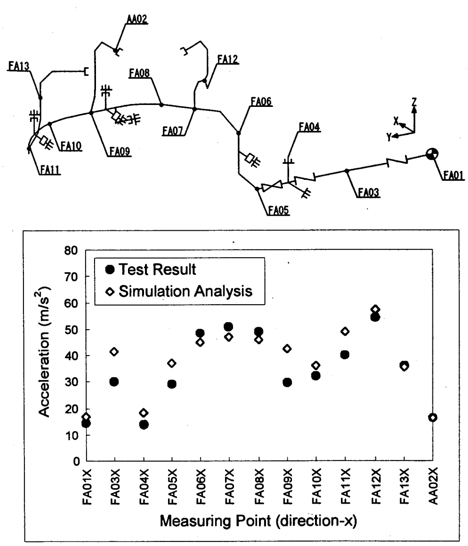


Fig. 14 Piping-acceleration Comparison

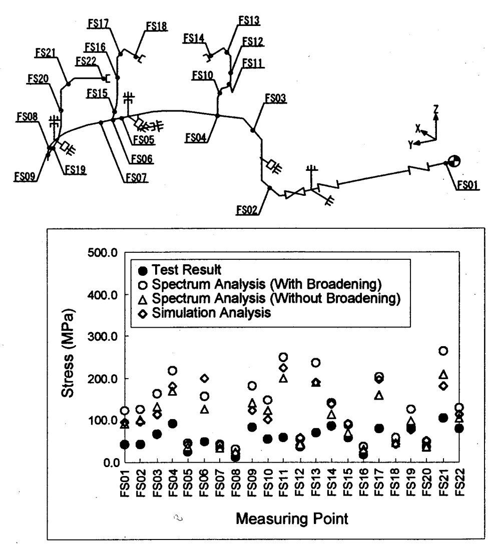


Fig. 15 Piping-stress Comparison

In Figures 15 and 16, the results of response-spectrum analysis with spectrum broadening (the design analysis method) were greater than the simulation results, and the simulation analysis results were greater than the response-spectrum analysis results without spectrum broadening. The response-spectrum analysis results with spectrum broadening and the simulation analysis results were confirmed to encompass the test results nearly completely. It was confirmed that the response-spectrum analysis, which requires iterative calculation of EAB displacement and uses the response-spectrum of each mode's damping, is valid for the design of piping supported by elastoplastic dampers.

The difference between the results of response-spectrum analysis, with the spectrum broadening and without, is smaller for piping models supported by EABs than for piping models supported by snubbers. The reason for this is that the margin in piping-damping values is small as the piping damping is obtained analytically, and the effect of the spectrum broadening becomes minimal as the piping damping becomes very large.

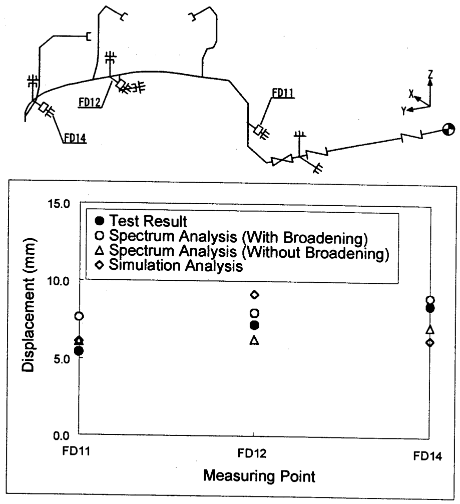


Fig. 16 EAB Displ. Comparison

The maximum piping stresses cannot be compared directly between the test and the analysis results as in a conventional support piping test. Measuring points at which the analysis results greatly exceed the test results are points that represent the elbow and tee joints, considering the stress intensification factor. The trends in the distribution of stresses is considered to depend on the effect of the stress intensification factor as a conventional support piping test.

4.3 *Detailed Evaluation of Piping Stress*

To confirm the validity of our simulation analysis using beam elements, the typical joints (piping elbow and tee) were modeled using 8 node solid elements, and the static analysis results using the axial force and moment values of the simulation were compared with actual stress measurements. To calculate the maximum stress value and the locations of stress occurrence using the solid model and to compare these values with the design stress values, we confirmed the validity of the standard stress-intensification factors. One end of the partial piping model which was cut out, was fixed in our analysis. The analysis was conducted on the test results under excitation by the S_2 wave in energy absorbing support piping test.

Compensation for the inertial force is needed, because static analysis is conducted at the time of maximum stress occurrence, instead of dynamic analysis. This compensation is conducted using Eq. (6).

$$[K]\{x\} = \{f\} - [M]\{\ddot{x} + \ddot{y}\} \tag{6}$$

$[M]$: Mass matrix of the partial model
$[K]$: Stiffness matrix of the partial model
$\{\ddot{x}\},\{x\}$: Acceleration and displacement vectors of the partial model
$\{f\}$: Load vector of the partial model
$\{\ddot{y}\}$: Seismic acceleration

The typical piping elements at which we conducted the detailed stress analysis were the tee joint (Fig. 15 : FS9,FS19) and an elbow (Fig. 15 : FS21,FS22). Sufficient distance was left between the loading point and the stress evaluation points, to avoid the negative effects due to loads that applied to the boundaries of the partial piping element.

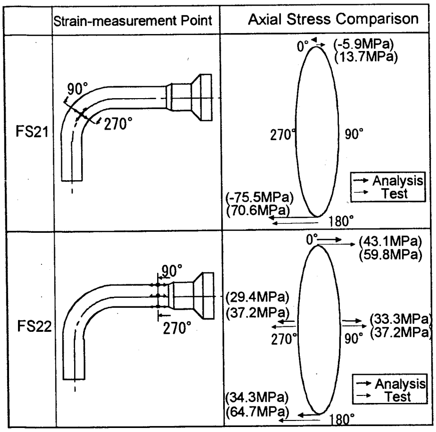


Fig. 17 Elbow Stress Comparison

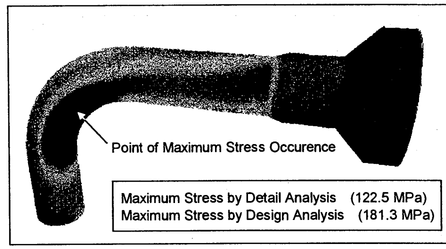


Fig. 18 Elbow Stress Distribution

Figure 17 shows a comparison between the test and the analysis for the axial and circumferetial maximum stress values of the elbow part. The test results of absolute stress value are in good agreement with the analysis results. The sign which shows whether the stress is tension or compression is also in good agreement between the test and analysis, so we can say that the analysis simulates the piping deformation sufficiently.

Figure 18 shows the stress distribution in the elbow part. The analyzed maximum stress was calculated to be at the inside of the bend. The stress from the design-evaluation method (which is calculated as the 3 components of the moment obtained in the simulation analysis multiplied by the stress intensification factor) was confirmed to overestimate the maximum stress obtained in the detailed analysis with an appropriate margin of safety. Similarly, the analysis results for the tee part showed the same level of accuracy.

Thus, we have confirmed the validity of our design stress evaluation method.

5. CONCLUSION

A seismic proving test of a BWR feed water piping model supported by snubbers (conventional support piping test) and supported by EABs which are energy absorbing supports (energy absorbing support piping test), was conducted and the test results were evaluated analytically. We confirmed the following :

(1) The BWR feed water piping model supported by snubbers or supported by EABs, had sufficient endurance against design-earthquake excitation, and seismic reliability was proved.

(2) Simulation analysis in which the snubbers are modeled as gap elements and the EABs are modeled as R-O models, match the test results with sufficient accuracy.

(3) Response-spectrum analysis which has been used as a design analysis method, is confirmed to be a valid design-analysis method for the piping supported by conventional supports. Rresponse-spectrum analysis which uses the iterative calculation of EAB displacement with each mode's damping ratio, is confirmed to be a valid design-analysis method for piping supported by EABs.

(4) The stress values obtained via the design evaluation method are confirmed to overestimate the maximum stress of a more detailed analysis by an appropriate margin, and the validity of the design stress evaluation method was thus confirmed.

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