

EXPERIMENTAL AND ANALYTICAL STUDY ON CROSSOVER PIPING SYSTEM IN SEISMIC ISOLATION FBR PLANT: (II) CCWS-SEA WATER PIPING

Y. Watanabe¹, M. Kuroha¹, K. Amada¹, M. Kohda², K. Arai² and S. Kajii³

¹The Japan Atomic Power Company, Tokyo, Japan

²Mitsubishi Atomic Power Industries, Tokyo, Japan

³Mitsubishi Heavy Industries, Ltd., Takasago, Japan

1. Introduction

In a seismic isolation FBR plant, crossover piping, which is the piping that crosses the open space around the seismically isolated building, is subjected to large relative displacements and inertia forces during earthquakes. Sea water piping of the Component Cooling Water System (CCWS), which is a safety-related system of an FBR plant, is one of such systems.

In order to accommodate extremely the large displacements caused by seismic loads, hinged bellows expansion joints are an important feature of this piping system. There is no experience of such piping system in nuclear power plants in Japan, now. This system aims at achieving a rational (short length) piping route design, by considering its low pressure and low temperature conditions. First a design study was made which showed this piping system would maintain its structural integrity during the extreme design basis earthquake (S_2 earthquake). Then two kinds of vibration tests were carried out to examine the analysis methods, and to demonstrate the feasibility of this piping system. Based on the test results, some analysis models were examined and conventional seismic piping stress evaluation analyses were performed.

The objectives of this study are to examine and demonstrate the following items based on analyses and tests, and then, to demonstrate the feasibility of the new piping system in the seismic isolation plant.

- (1) The feasibility of a piping system which employ bellows to accommodate large displacements during earthquakes.
- (2) The acceptability of the conventional analytical method by using some general piping analysis models and modal analysis with response spectra, for such type of piping system.

2. Design of CCWS

The design conditions of the sea water piping are ① Seismic class: As (the highest class), ② Component classification: ASME Code Class 3 piping, ③ Line size: 16 inches, ④ Material: ASME Code SA 106 Gr. B, ⑤ Design pressure/temperature: $7.0\text{kg/cm}^2 / 50^\circ\text{C}$, and ⑥ Displacement due to earthquakes: 129mm for the maximum design basis earthquake (S_1 earthquake) / 387mm for the S_2 earthquake.

An "L" shaped pipe routing configuration was adopted, which employs three hinged bellows expansion joints (with three, four and five convolutions, respectively) to adequately accommodate the large relative displacement caused by the S_2 earthquake. The layout of the sea water piping of an actual plant is shown in Fig.1. By adopting this new piping design, a great deal of space can be saved.

3. Experiments

3.1 Individual test of a bellows unit

(1) Test scope

This test was to obtain the rotational stiffness of the bellows which was essential for the analytical models.

The schematic drawing of the test is shown in Fig.2. The test apparatus used 1/1.9 scale models. Vibration tests for three kinds of bellows were carried out. The specifications of the bellows are shown in Table 1. The bellows unit (with three convolutions) which was used for the test is shown in Fig. 3.

(2) Test results

The relation between the rotational stiffness and the angles of rotation under two pressure conditions (7.0 kg/cm^2 or 0 kg/cm^2) are shown in Fig.4. In the case of 7.0 kg/cm^2 , it is noticeable that the rotational stiffness becomes greater as the angle of rotation is decreased. This is because, internal pressure has an effect on the pin joint of the bellows, so that the rotational friction factor around the pin increases. Fig.5 is an example of the dissipated energy.

3.2 Vibration test of the piping system

(1) Test scope

The schematic drawing of the piping system vibration test is shown in Fig.6. Fig.7 shows the piping analysis model. The tests were carried out using a 1/1.9 scale model using a large mass to simulate the dynamic behavior of the isolated building on the shaking table. Inertia type shaking equipment was installed on the large mass to simulate vibration behavior (damping factor etc.) of the seismic isolated building.

Sinusoidal wave sweep vibration tests and several kinds of earthquake wave vibration tests were carried out. In addition static load tests were also carried out in which loads on the test apparatus were caused by static displacements.

(2) Test results

Acceleration, displacement, strain, and pressure were measured at several points of the test piping. Because of the alignment of the bellows relative to the direction of the seismic input, the rotational angle of bellows "A" (with three convolutions) was very small. The vibration behavior of the piping was measured by the rotational angles of bellows "B" (with five convolutions) and bellows "C" (with four convolutions). The rotational angles were obtained from the bellows's strain data and the calibration curves, obtained from the individual bellows test. The time history stress of a typical point (point "a") is shown in Fig.8. In Fig.8, the stress is divided into two components, one being the primary stress caused by inertia forces and the other being the separated stress caused by relative displacements. For the bellows "B", both the rotations measured during the time history, and the rotations caused by relative displacements which were obtained from the static load test results, are shown in Fig.9.

The test results demonstrated that the structural integrity of this piping system would be maintained during earthquakes.

4. Analysis to simulate the test

The results of the simulation study identified the following points which should be taken into consideration.

- ① The rotational stiffness of the bellows depends on the angle of rotation. It is necessary to change the rotational stiffness of the bellows for each test and/or each analysis. Thus, the rotational stiffness of the piping is non-linear with respect to the responses (forces and displacements).
- ② The friction factor of the vertical support structure should be considered.
- ③ The damping ratio of this piping system is very large.

The simulation, therefore, was carried out by employing linear models that were equivalent to the non-linear test piping. We constructed two kinds of linear models. One model yields the inertia forces that agree with the test results and the other yields the same large relative displacements as the test piping. Static analysis, eigenvalue computation, and dynamic analysis were conducted iteratively until the responses converged.

The analytical models used to simulate the tests are shown in Table 2. These were called "model (a)" models. The vibrational behavior of the piping system could be simulated, using these models. The natural frequency and damping ratio were estimated to be 20.4 Hz and 15.0 % for the S_1 earthquake model, and 17.25 Hz and 8.8 % for the S_2 earthquake model.

5. Seismic analysis method

5.1 Scope of analysis

(1) Analysis model

The above "model(a)" models were complex and had no generality. Therefore two kinds of simplified analysis models were made which were generally applicable. One was "model(b)" in which the values of EJMA (STANDARDS OF EXPANSION JOINT MANUFACTURERS ASSOCIATION, INC.) stiffness were used for the rotational stiffness, because they represent stiffness very well as shown in Fig.4. The other was "model (c)" in which bellows could rotate freely to calculate the largest bellows rotations. The specifications of "model (b)" and "model(c)" are shown in Table 2.

(2) Seismic input conditions

The response spectra were made from time history response accelerations and damping factors were obtained, by the Newmark- β method. The response spectra were broadened by ± 10 %. The response spectra of the S_2 earthquake are shown in Fig.10.

(3) Seismic analysis method

For the purpose of analyzing inertia forces, the "Enveloped response spectrum analysis method" and the "Independent input response spectrum analysis method" were used. On the other hand, for the purpose of analyzing displacements, a static forced displacement analysis was performed. The total piping stress and the total rotational angle of the bellows were evaluated by means of an absolute summation method.

5.2 Results

Table 3 shows a comparison of piping stresses as calculated in the analysis and as measured in the tests. Table 4 shows similar information for angle of bellows rotation. The following points can be seen. First, the "Enveloped response spectrum analysis method" has a tendency to give larger piping stresses and rotational angles than the "Independent input response spectrum analysis method", as was expected. Second, the analytical results are almost in agreement with the test results or are conservative, except for one stress evaluation point, when calculated by the "Independent input response spectrum analysis method". The total piping stress and the total rotational angle of analytical results from the three models are in close agreement.

6. Conclusions

The new piping system which employs hinged bellows expansion joints, is useful for a seismic isolation plant. The piping vibration tests demonstrated that the structural integrity of this piping system could be maintained under the large relative displacements and inertia forces caused by earthquakes. The conventional analytical method using some general piping analysis models and the modal analysis with response spectrum, was applied to this study. By comparing these analysis results with the test results, it was confirmed that the conventional analytical method was acceptable.

7. Acknowledgement

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Table 1 Specifications of the test bellows

bellows	A	B	C
design pressure (kgf/cm ²)		7.0	
design temperature (°C)		50	
material	SUS316(SA182 F316 as ASME Code)		
outside diameter (mm)		265	
convolution depth (mm)		30	
bellows pitch (mm)		25	
thickness (mm)		1.0	
total number of convolutions	3	5	4
length (mm)	375	430	400

Table 2 Specifications of simulation models and simplified models

analysis model	earthquake	objective of analysis	rotational stiffness of bellows (kgf-mm/deg.)			spring const. of rigid support (kgf/mm)
			A	B	C	
simulation model(a)	S ₁	inertia force relative displ.	5.05×10 ⁴	3.40×10 ⁴	2.79×10 ⁴	173
	S ₂	inertia force relative displ.	5.05×10 ⁴	1.54×10 ⁴	2.22×10 ⁴	58.3
simplified model(b)	S ₁ , S ₂	inertia force and relative displ.	1.58×10 ⁴	9.46×10 ⁴	1.18×10 ⁴	—
simplified model(c)	S ₁ , S ₂	inertia force and relative displ.	0	0	0	—

Table 3 Comparison of piping stress from test results and analytical results (kgf/mm²)

point		a		b			
earthquake		S ₁	S ₂	S ₁	S ₂		
test results	inertia forces	0.1	0.0	0.5	0.5		
	relative displ.	0.1	0.4	0.1	0.3		
	total stress	0.2	0.4	0.6	0.8		
analytical results of Enveloped response spectrum analysis method	model(a)	inertia forces	1.0	2.4	0.5	1.0	
		relative displ.	0.4	0.7	0.0	0.0	
		total stress	1.4	3.1	0.5	1.0	
	model(b)	inertia forces	1.8	2.9	0.6	1.0	
		relative displ.	0.2	0.6	0.0	0.1	
		total stress	2.0	3.5	0.6	1.1	
	model(c)	inertia forces	1.8	3.0	0.6	1.0	
		relative displ.	0.0	0.0	0.0	0.0	
		total stress	1.8	3.0	0.6	1.0	
	analytical results of Independent input response spectrum analysis method	model(a)	inertia forces	0.6	1.1	0.3	0.4
			relative displ.	0.4	0.7	0.0	0.0
			total stress	1.0	1.8	0.3	0.4
model(b)		inertia forces	0.7	1.3	0.2	0.5	
		relative displ.	0.2	0.6	0.0	0.1	
		total stress	0.9	1.9	0.2	0.6	
model(c)		inertia forces	0.7	1.3	0.2	0.4	
		relative displ.	0.0	0.0	0.0	0.0	
		total stress	0.7	1.3	0.2	0.4	

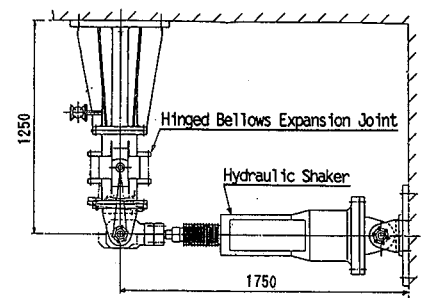


Fig.2 Test apparatus for individual bellows unit test

Table 4 Comparison of bellows rotations from test results and analytical results (deg.)

bellows		B		C		
earthquake		S ₁	S ₂	S ₁	S ₂	
test results	inertia forces	0.2	0.3	0.1	0.1	
	relative displ.	3.2	8.8	3.2	8.0	
	total angle	3.4	9.1	3.3	8.1	
analytical results of Enveloped response spectrum analysis method	model(a)	inertia forces	0.3	0.6	0.1	0.2
		relative displ.	3.2	8.9	3.2	8.9
		total angle	3.5	9.5	3.3	9.1
	model(b)	inertia forces	0.5	0.8	0.1	0.2
		relative displ.	3.2	8.8	3.2	8.9
		total angle	3.7	9.6	3.3	9.1
	model(c)	inertia forces	0.5	0.8	0.1	0.2
		relative displ.	3.2	8.9	3.2	8.9
		total angle	3.7	9.7	3.3	9.1
analytical results of Independent input response spectrum analysis method	model(a)	inertia forces	0.2	0.3	0.1	0.1
		relative displ.	3.2	8.9	3.2	8.9
		total angle	3.4	9.2	3.3	9.0
	model(a)	inertia forces	0.2	0.3	0.1	0.1
		relative displ.	3.2	8.8	3.2	8.9
		total angle	3.4	9.1	3.3	9.0
	model(b)	inertia forces	0.2	0.3	0.1	0.1
		relative displ.	3.2	8.9	3.2	8.9
		total angle	3.4	9.2	3.3	9.0

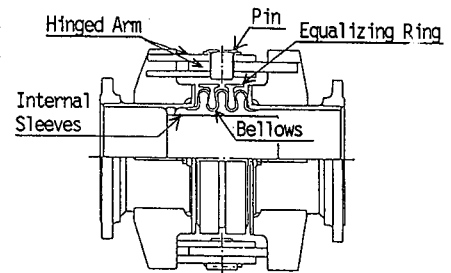


Fig.3 Bellows unit used for tests (three convolutions)

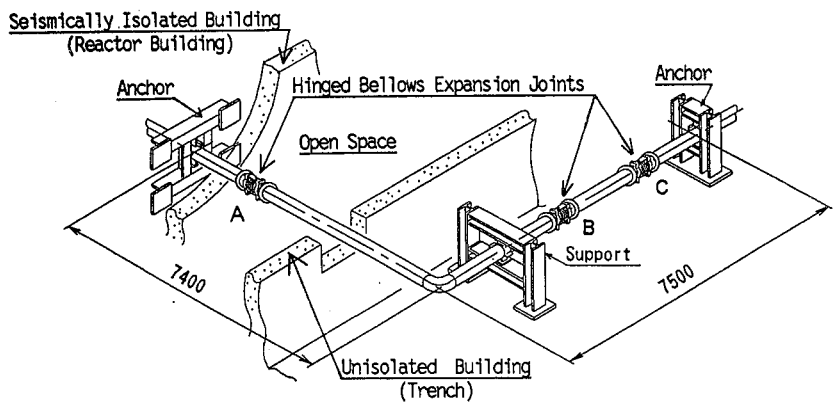


Fig.1 Layout of sea water piping of an actual plant

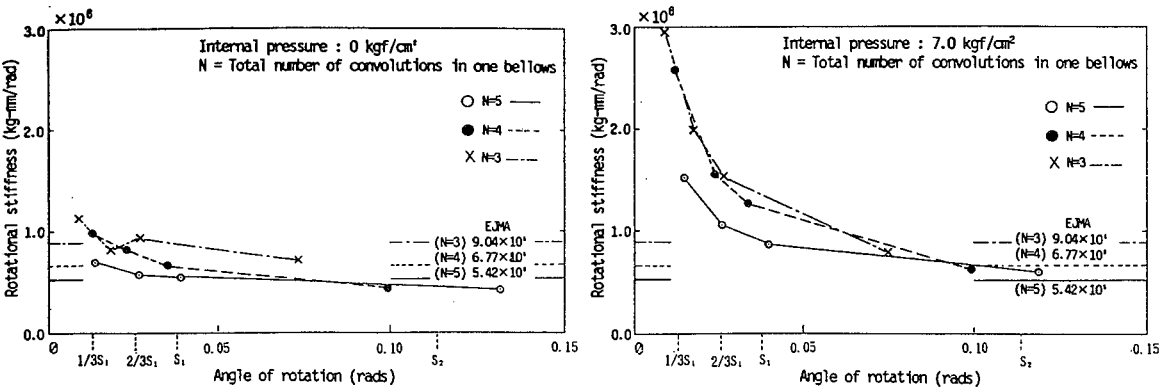


Fig.4 Relation between rotational stiffness and angle of rotation (left: internal pressure is 0 kgf/cm², right: 7.0 kgf/cm²)

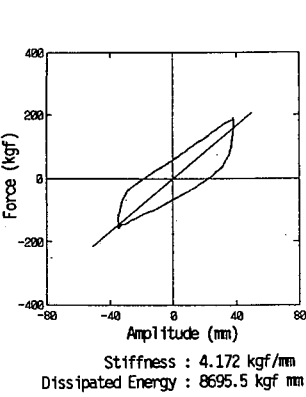


Fig.5 Hysteresis loop for dissipated energy of a bellows (four convolutions, S₂ earthquake)

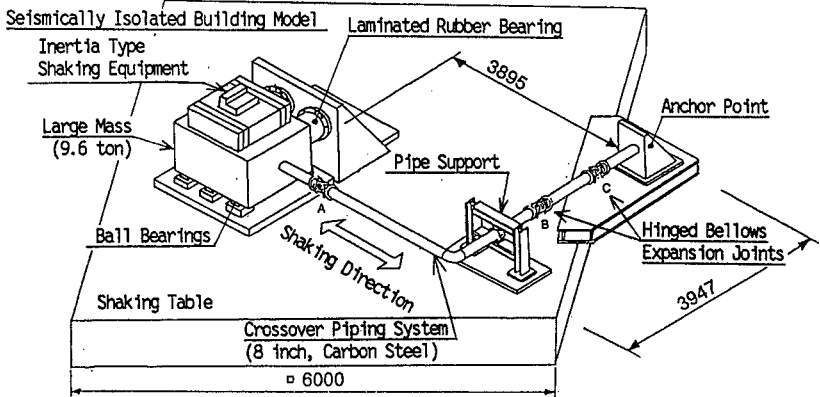


Fig.6 Test apparatus for piping system vibration test

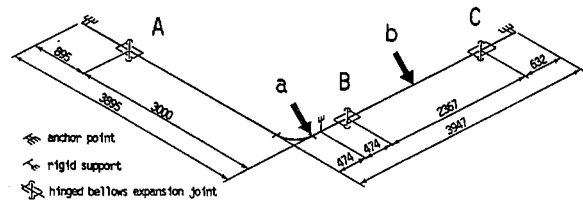


Fig.7 Piping analysis model

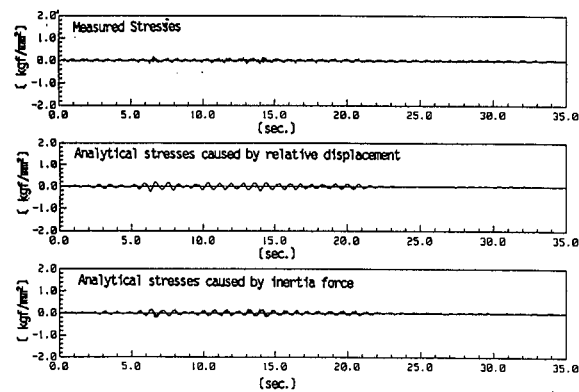


Fig.8 Time history piping stress at point "a" (S₂ earthquake)

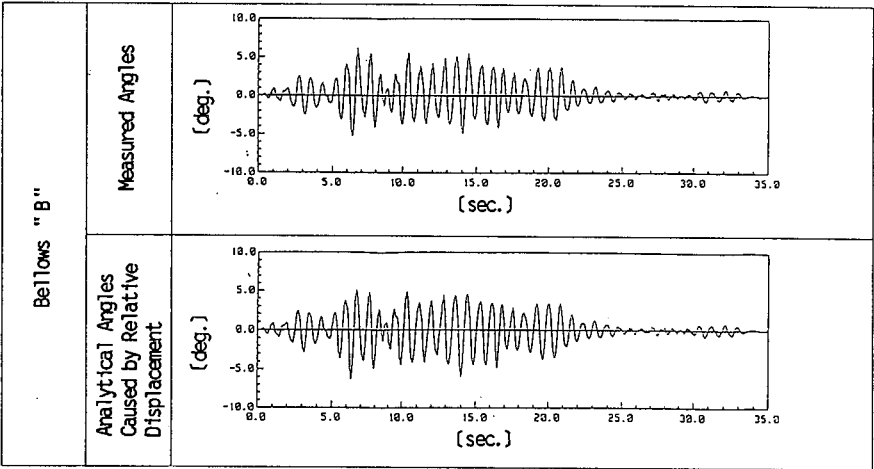


Fig.9 Time history bellows rotations of "B" (S₂ earthquake)

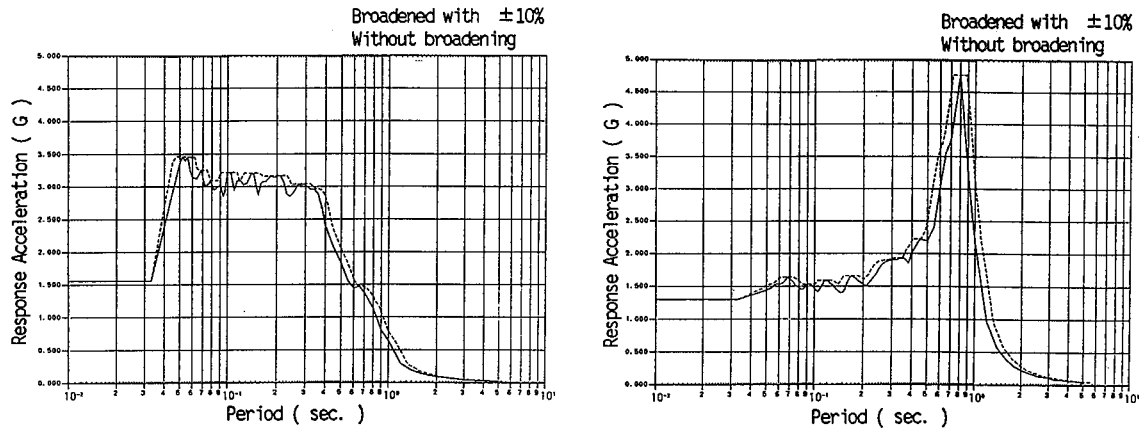


Fig.10 Response spectra of S₂ earthquake (damping ratio: 8.8%) (left: unisolated building, right: isolated building)