DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES - SEISMIC DESIGN AND ANALYSIS FOR CROSSOVER PIPING -

Akihito Otani[1], Teruyoshi Otoyo[2], Hirohide Iiizumi[3], Shunsuke Fukushima[4], Kotoyo Mizuno[5], Keisuke Sasajima[6], Takaaki Sakakida[7], Shigenobu Onishi[8]

[1] Manager, Design Group, Maintenance Engineering Dept., Nuclear Power Operation, IHI Corporation, Japan

[2] Engineer, Structural Dynamics Group, Structural Strength Dept., Research Laboratory, IHI Corporation, Japan

[3] Manager, Piping Design Group, Plant Design & Engineering Dept., Isogo Nuclear Engineering Center, Toshiba Corporation Power Systems Company, Japan

[4] Deputy Manager, Piping Design Group, Plant Design & Engineering Dept., Isogo Nuclear Engineering Center, Toshiba Corporation Power Systems Company, Japan

[5] Staff, Structure No.1 Lab., Strength Research Dept., Research & Innovation Center, Mitsubishi Heavy Industries, Ltd., Japan

[6] Manager, Vibration No.2 Lab., Vibration Research Dept., Research & Innovation Center, Mitsubishi Heavy Industries, Ltd., Japan

[7] Senior Engineer, Plant Design Section, Nuclear Plant Section, Nuclear Plant Dept., Hitachi-GE Nuclear Energy, Ltd., Japan

[8] Manager, Design & Engineering Group, Nuclear Power Dept., Nuclear Power Div., Chubu Electric Power Co. Inc., Japan

ABSTRACT

The crossover piping is installed between seismically isolated and non-isolated building; the reactor building is only isolated using seismic isolation systems whereas the turbine building is non-isolated. The crossover piping supported by both isolated and non-isolated building is deformed by large relative displacement between the two buildings. The flexible structure is required for crossover piping which allows the relative displacement. It also has to endure the seismic response of itself caused by different seismic excitations from both buildings. The seismic design for crossover piping needs evaluation considering both of the relative displacement and the seismic response.

In this study, the shaking table tests of 1/10 scaled piping model and the FEM analyses have been performed to investigate the seismic response and failure behaviour of crossover piping. The crossover piping model was excited and deformed by the two different seismic motions of isolated and non-isolated building. The failure mode of the crossover piping under extreme excitation has been confirmed as the low cycle fatigue at elbows. Moreover, the elastic-plastic response analysis which simulates the extreme level excitation test can appropriately predict the fatigue life until fatigue crack penetration bringing pressurized water leakage. Finally, based on the results of shaking table tests and the analyses, the seismic design method for crossover piping is proposed.

INTRODUCTION

A seismic isolation system could improve the seismic integrity of Nuclear Power Plant. The NPP design in Japan is currently developing Seismically Isolated Light Water Reactors (LWRs). The base isolation system for LWRs is not only to improve their seismic integrity but also to resolve an issue about site-unique seismic conditions and standardize plant design.

The seismically isolated LWR plant in this study has two types of conceptual design; one of which applies the seismic isolation system to the entire base of the plant, while the other applies it only to the Reactor Building (RB). In the latter, the Turbine Building (TB) retains a conventional earthquake-proof design. Accordingly, the vibrational characteristics of RB and TB, which are natural frequencies of isolated and non-isolated buildings, differ significantly and large relative displacement between both buildings emerges. Moreover, many kinds of piping must be arranged between both buildings. The crossover piping will be excited by both buildings, which have different vibrational responses. At the same time, the piping will be deformed by the relative displacement between two buildings. Seismic response analysis with multiple excitations or support motions may reveal the seismic response of crossover piping.

In this study, to verify seismic response analysis with multiple support motions, a shaking test on a 1/10 scale model for Main Steam (MS) crossover piping and time history analysis with multiple support motions were performed. The analytical result corresponded to that of the shaking test and the time-history analysis with multiple support motions was verified. Analysis method is closely connected with modelling, input condition, combination and evaluation method. Their relations were summarized and some issues were examined.

REPRESENTATIVE CROSSOVER PIPING

Many kinds of crossover piping must be arranged in the RB seismically Isolated Boiling Water Reactor (RBIBWR), which has a seismic isolation system for only RB as shown in Figure 1. The layout of MS crossover piping is shown in Figure 2. The authors thought applying flexible joints to MS crossover piping would be difficult and opted instead to apply a flexible piping layout. MS crossover piping has a 19 m vertical pipe part, as shown in Figure 2, which can deform horizontally and follow the relative displacement between RB and TB. The two elbows at the upper and lower ends of the vertical pipe are subject to high stress from the seismic response and relative displacement between RB and TB. It is also well known that elbow strength is dominated by in-plane bending. Accordingly, the relative displacement in the EW direction, as shown in Figure 2, could affect the elbows' strength. For the seismic design of this MS crossover piping, the responses of the buildings in an EW direction prevailed.
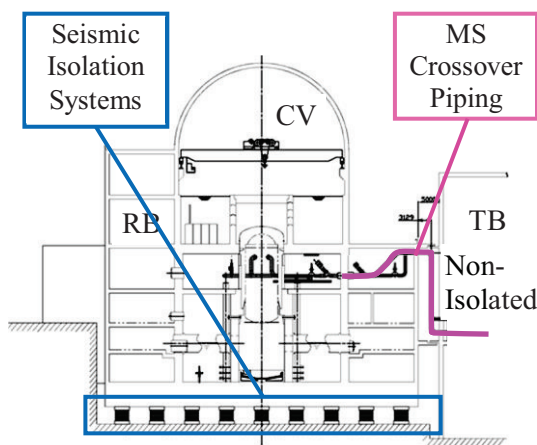

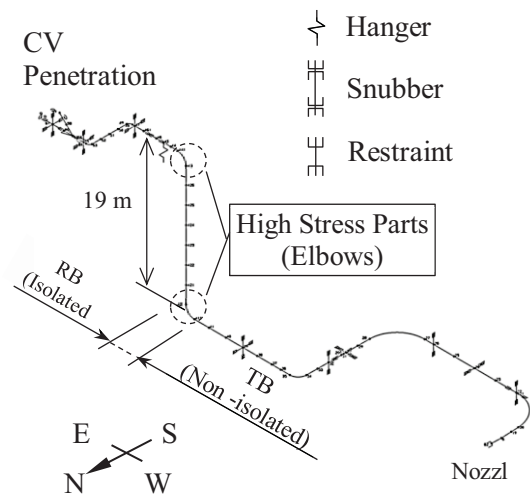Figure 1. Seismically isolated RB of a BWR plant

Figure 2. MS crossover piping

The 1st to 4th vibration modes of MS crossover piping are shown in Figure 3. The fundamental frequency is 2.88 Hz, which is considerably lower than that of conventional seismic designed piping, because the flexibility to follow the large relative displacement between RB and TB reduces the natural frequency.

The vertical pipe at the boundary between RB and TB vibrates horizontally and vertically in the vibration modes shown in Figure 3. The elbows at both ends of the vertical pipe undergo in-plane bending in the 2nd and 3rd modes and they are high-stress parts in MS crossover piping. These vibration modes are obtained from a model with unmovable supporting points but the supporting points of crossover piping move with seismically isolated RB.
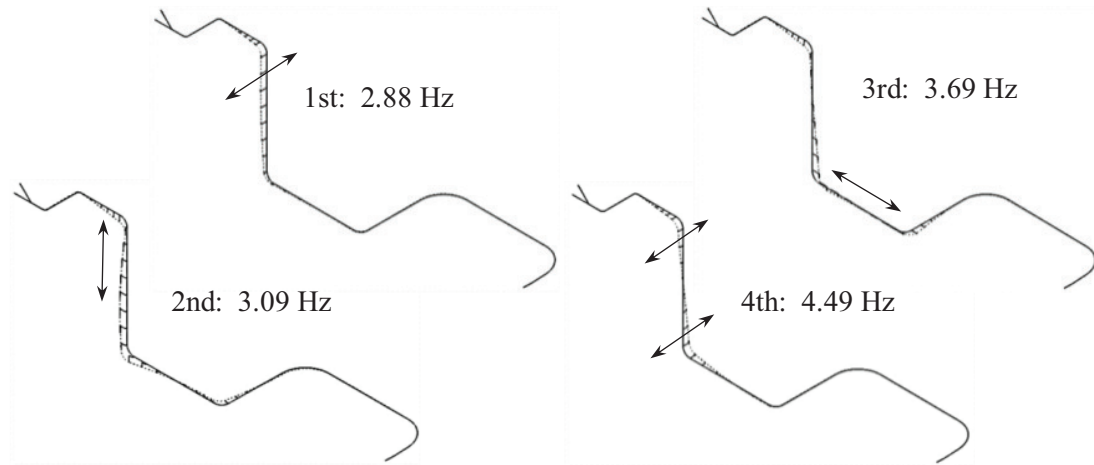

Figure 3. Vibration mode of MS crossover piping

EXCITATION TEST AND SIMULATION OF A 1/10 SCALE MODEL

Excitation test

Crossover piping of RBIBWR is shaken by both isolated RB and non-isolated TB seismic responses, while time-history analysis with multiple support motions has been verified by past studies. However, the crossover piping is deformed and excited by significant support motions. To verify the seismic response under such motions, a scale model shaking test of the MS crossover piping was performed. The details of the excitation test and the analysis have been presented by authors.

Scale models are usually designed using a similarity law, whereby with normal similarity, which simply scales length down, model acceleration increases beyond the performance of the shaking table. Meanwhile, a similarity law shown in Table 1, in which model acceleration can coincide with actual acceleration, has been adopted for the scaling model.

Table 1: Similarity law for scale model

Parameters	Ratio, Test / Actual
Length	$1/10$
Mass	$1/10^2$
Frequency	$10^{0.5}$
Time	$1/(10^{0.5})$
Displacement	$1/10$
Velocity	$1/(10^{0.5})$
Acceleration	1
Stress	1
Strain	1

Table 2: Sizes of crossover piping

Crossover Piping	Outer diameter [mm]	Thickness [mm]	Vertical length [m]
Actual	762.0	38.1	19.06
Scale model	76.3	4.2	1.906

To replicate isolated RB vibration, the seismic isolation model shown in Figure 4 was used, which comprises a 10-metric ton mass made of steel, 4 laminated rubber bearings made of natural rubber, 2 oil dampers and a steel structure. It is difficult to manufacture a model pipe using the same forming method as an actual pipe, so a standard Japan Industrial Standards (JIS) pipe was used. Table 2 shows the diameters and thicknesses of the actual and model pipes. A scale model of the crossover piping shown in Figure 4 is supported by two anchors and three restraints fixed to the seismic isolation model and shaking table. The piping model is restrained in transverse horizontal and vertical directions at the restraints, where frictional force is also exerted in the axial direction of the pipe. The piping model has 5 additional masses due to the tune mass of the scale model according to similarity. Typical time histories of TB seismic response were used as excitation waves for the shaking test, while the response of the seismic isolation model shows low frequency and high damping response from rubber bearings and oil dampers. The scale model of cross over piping could be shaken by isolated and non-isolated response waves.
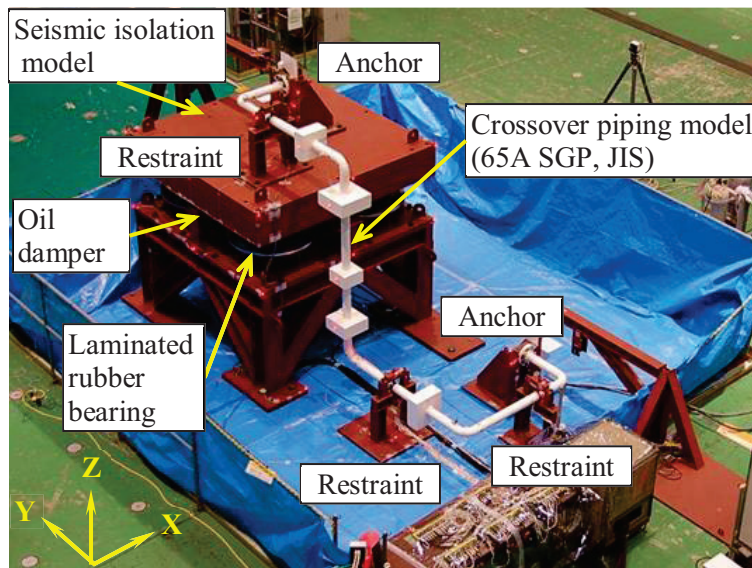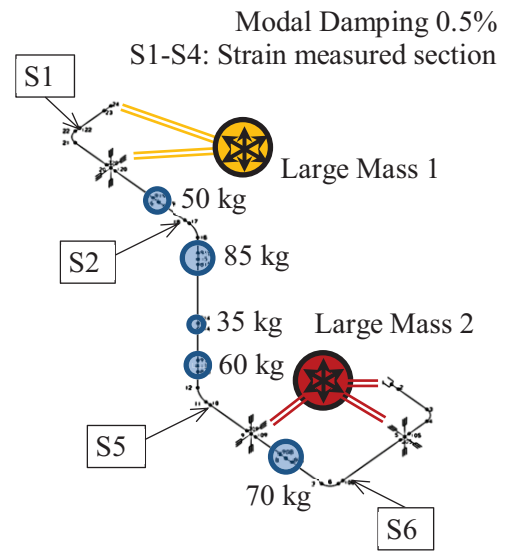

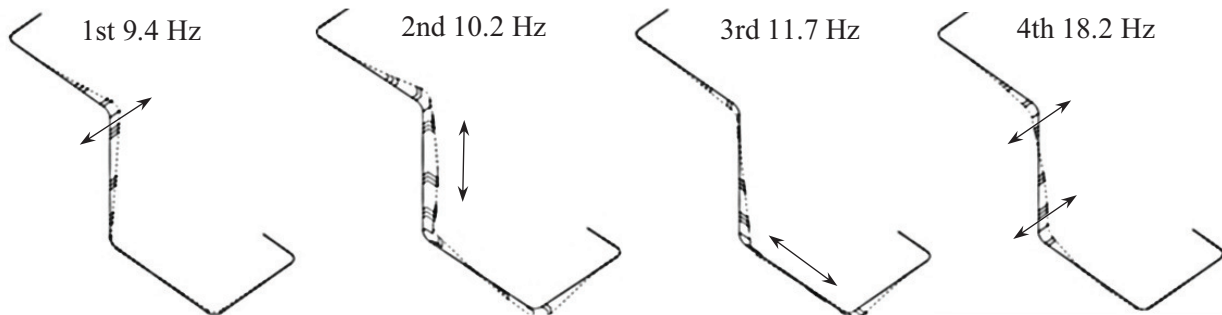Figure 4. Configuration of scale model

Figure 5. Analysis model

Figure 6. Vibration mode of scale model

FEM analysis

An analytical model for the crossover-piping scale model is shown in Figure 5. Two large masses were rigidly connected to the piping supports for inputs from the seismic isolation model and the shaking table. The vibration modes of the crossover piping model are shown in Figure 6 and are almost the same as those of the actual crossover piping shown in Figure 3. Moreover, the natural frequencies of scale model nearly correspond to those of the actual crossover piping calculated by similarity law.

Seismic response analysis of the crossover piping

By applying the displacements to two large masses, modal time-history analyses with multiple support motions were performed. MD NASTRAN was used for the analysis.

The stress time histories calculated from the strain measured at S2, which is the section near the upper elbow, are shown in Figure 7. The stress time histories by analysis are compared with the test results in this figure. The correlations between the maximum stresses at the four sections by the shaking tests and the analyses are shown in Figure 8. As shown in this figure, the analysis correlates well to the shaking test. The upper elbow becomes the part subject to highest stress because the in-plane bending dominates the elbow strength. As shown in Figure 7, stresses caused by Y, Y-Z and X-Y-Z excitation are similar, this means that the in-plane bending by Y excitation dominates.

The modal time-history analysis with multiple support motions was verified by comparing the stress by analysis with the stress by shaking tests in elastic level excitation. The non-linear analysis in elastic plastic level was also verified and fairly corresponded to shaking table tests. As a result, linear and non-linear time history analyses were verified by comparing with results of shaking table test.
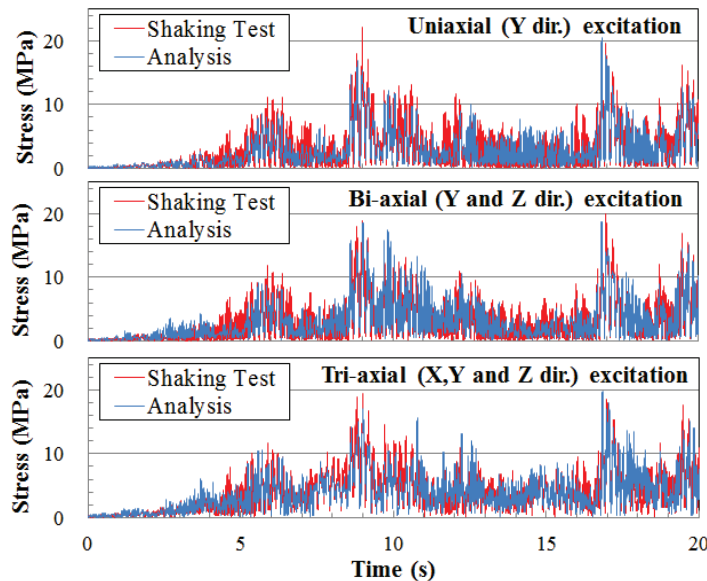
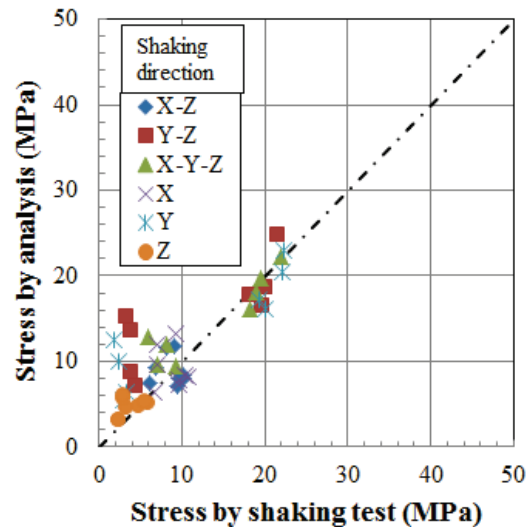Figure 7. Time history of stress intensity at S2 section

Figure 8. Comparison of max. stresses at S1 to S4 sections

SEISMIC RESPONSE ANALYSIS AND EVALUATION METHOD

Seismic evaluation is closely connected with analysis method. The relation between analysis and evaluation for crossover piping is not different from its connection. The relations of analysis model, input condition, combination method and evaluation method with analysis method are summarized in Table 3 to 6.

Time history analysis is the most detail analysis method and could simulate the seismic response of crossover piping. But uncertainties of seismic isolation system, soil and structure are not considered in time history analysis. Time history broadening described in *ASME B&PV Code Sec. III, Appendix N* is useful to consider the uncertainties.

Response spectrum analysis with multiple excitations requires combinations for responses by excitation directions and responses by multiple excitations. Moreover, a combination of response and deformation by anchor motion is also required. The appropriate combination methods were investigated by comparison with shaking table test. The result by applying SRSS for all combinations shown in Figure 8 is close to the result of shaking table test.

Fatigue evaluation from response spectrum analysis needs the required cycle which is an equivalent cycle of maximum stress level having the same fatigue damage as one by stress time history of seismic responses. The equivalent cycles for MS crossover piping was calculated as about 3 cycles. So it is considered that 10 cycles suffice to evaluate the fatigue of the crossover piping.

Table 3: Analysis model for MS crossover piping

Seismic response analysis method			Element	Damping	Remarks
Non-linear	Time history analysis	Multiple-input time history, Direct integral method, Nonlinear geometry, Elastic plastic	Shell, Pipe, Beam	Rayleigh damping 1.5 %** at control frequencies	Large mass method and SPCD method are available.
linear		Multiple-input time history, Direct integral method	Pipe, Beam		
		Multiple-input modal time history		Modal damping 1.5%** for all vibration modes	
		for removing rigid mode	Static analysis by relative disp. of supports (anchor motion)			
	Response spectrum analysis	CCFS method *			Information of building vibrational property is necessary.
		Multiple-input spectrum modal			With identifying support groups for each input condition, conventional analysis model is applicable.

*   An analysis method developed and proposed by Asfura and Kiureghian.

** 1.5% damping for MS crossover piping is provided by *JEAC4601-2008* which provides 0.5% damping for longer support span piping than 15m and 1.0% additional damping for with thermal insulation.

Table 4: Seismic input condition for MS crossover piping

Seismic response analysis method			RB's & TB's responses		Remarks
			Type	Broadening *	
Non-linear	Time history analysis	Multiple-input time history, Direct integral method, Nonlinear geometry, Elastic plastic	Acc. or disp. time history. (Tri-axial for fault model earthquake Bi-axial for spectrum earthquake)	Time history broadening or various time histories	Baseline correction of input time history is necessary for analysis by acceleration input. Multi-directional input is available.
linear		Multiple-input time history, Direct integral method			
		Multiple-input modal time history			
		for removing rigid mode — Static analysis by relative disp. of supports (anchor motion)	Anchor motion	Relative disp. variation	Relative disp. between RB and TB is expanded with softening of seismic isolation system.
	Response spectrum analysis	CCFS method	Acc. FRS (Tri-axial for fault model earthquake Bi-axial for spectrum earthquake)	Spectrum broadening	Single directional input is only available and combination of responses by each direction is necessary.
		Multiple-input spectrum modal			

* A method to account for the effect on structural frequency variation of the possible uncertainties in the material properties of seismic isolation system, the structure and soil.

Table 5: Combination method for MS crossover piping

Seismic response analysis method			Mode	Multiple inputs	anchor motion	Multiple direction
Non-linear	Time history analysis	Multiple-input time history, Direct integral method, Nonlinear geometry, Elastic plastic	Combined every moment.	Combined every moment.	Loads by responses and anchor motions are combined every moment at the same time.	Combined every moment at the same time.
linear		Multiple-input time history, Direct integral method				
		Multiple-input modal time history	Selected modes are counted every moment.			
		for removing rigid mode — Static analysis by relative disp. of supports (anchor motion)			Maximum loads by responses and anchor motions are combined by SRSS (or ABS).	Loads by multi-directional excitations or anchor motions are combined by SRSS (or ABS).
	Response spectrum analysis	CCFS method	Combined by considering correlation.			
		Multiple-input spectrum modal	Selected modes are combined by SRSS (or ABS).	Combined by SRSS (or ABS).		

Table 6: Evaluation method for MS crossover piping

Seismic response analysis method			Collapse (Primary stress)	Shake down (Primary + Secondary)	Fatigue (Peak stress)
Non-linear		Multiple-input time history, Direct integral method, Nonlinear geometry, Elastic plastic	At the present time, no evaluation criteria but collapse and ratchet deformation might be confirmed by analysis.		Strain time history and fatigue curve
linear	Time history analysis	Multiple-input time history, Direct integral method	Sprm < min[3Sh、2Sy] * Seismic response and dead load are considered. For no other mechanical load, above evaluation is exempted.	Sn < 2Sy * Elastic shakedown or not For satisfying above evaluation, fatigue evaluation is exempted.	Evaluation by peak stress time history and design fatigue curve.
		Multiple-input modal time history			$\Sigma(n_{eq}/N) < 1$ * Evaluation by required cycles n_{eq} and allowable cycles N calculated from peak stress Sl and design fatigue curve.
		for removing rigid mode	Static analysis by relative disp. of supports (anchor motion)		
	Response spectrum analysis	CCFS method			
		Multiple-input spectrum modal			

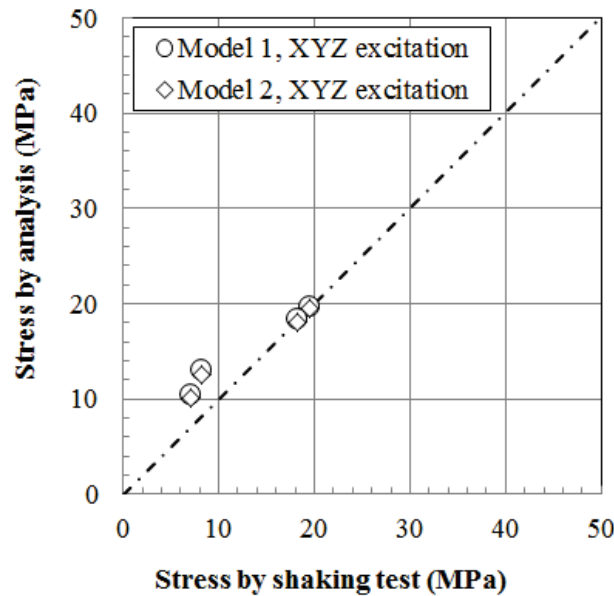* Evaluation by *JEAC4601-2008* and *JSME, S NC1-2012*

Figure 8. Comparison of max. stresses
by FRS analysis and SRSS combination

CONCLUSION

For the seismically isolated LWR, large relative displacement between RB and TB occurs when only RB is seismically isolated and many piping systems must be arranged at the boundary of the two buildings. The crossover piping will be excited by the two buildings with different vibration characteristics. At the same time, the crossover piping will be deformed by the large relative displacement between RB and TB. To establish seismic response analysis and evaluation method, a scale model excitation test and the simulation were performed and time history analysis method was verified. The seismic response analysis involving multiple support motions or multiple excitations should be utilized for crossover piping.
The relations of analysis model, input condition, combination method and evaluation method with analysis method are summarized. To considered uncertainties of seismic isolation system, soil and structure for time history analysis, time history broadening is useful and available. And response spectrum analyses with multiple excitations and combination methods were investigated by comparing with shaking table test. Consequently, SRSS for all combinations could correspond to the shaking table test.

ACKNOWLEDGMENTS

REFERENCES

Asfura, A. and Kiureghian, A. (1986). "Floor Response Spectrum Method for Seismic Analysis of Multiply Supported Secondary Systems", *Earthquake Engineering and Structural Dynamics*, Vol. 14, Page 245-265.

ASME B&PV CODE Sec. III, 2013, Appendix N, N-1222.3 Time History Broadening, N-1227: Multiple Input Response Spectra Analysis and N-1228: Multiple Time History Excitations.

Bezler, P., Subudhi, M. and Hartzman, M. (1987). "Dynamic Analysis Independent Support Motion Response Spectrum Method", *NUREG/CR-1677*, Vol. 2, Aug. 1987.

Chiba, T., Koyanagi, R., Ogawa, N. and Minowa, C. (1987). "An experimental study of the multiple support piping systems", *Proc. of 9th SMiRT*, Lausanne, Switzerland, Aug. 1987, pp. 975-980.

Chiu, H. C. (1997). "Stable Baseline Correction of Digital Strong-Motion Data", *Bulletin of the Seismological Society of America*, Vol. 87, No. 4, pp. 932-944.

JEAC4601-2008, Technical Code for Aseismic Design of Nuclear Power Plants, The Japan Electric Association, in Japanese.

JSME S NC1-2012, Code for Nuclear Power Generation Facilities Rule on Design and Construction for Nuclear Power Plants, in Japanese.

Kai, S., Kaneko, N. and Otani, A. (2012). "Analytical Study on Seismic Response of Piping under Multiple Support Excitations", *ASME 2012 Pressure Vessels & Piping Division Conference*, PVP2012-78203.

Kai, S., Watakabe, T., Kaneko, N., Tochiki, K., Moriizumi, M. and Tsukimori, K. (2013). "Study on Piping Response under Multiple Excitation, Part2: Validation for Multiple Analysis of Piping", *ASME 2013 Pressure Vessels & Piping Division Conference*, PVP2013-97841.

Kasawara, R. P. and Peck, D. A. (1973). "Dynamic Analysis of Structural Systems Excited at Multiple Support Locations", *ASCE 2nd Specialty Conference on Structural Design of Nuclear Plant Facilities*, Chicago, IL, Dec. 1973, pp. 73-88.

Otani, A., Otoyo, T., Hirai, H., Iiizumi, H., Shimizu, H., Saitoh, M. and Onishi, S. (2014). "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part 3), Seismic Response of Crossover Piping for Seismic Isolation System", *ASME 2014 Pressure Vessels & Piping Division Conference*, PVP2014-29012.

Otoyo, T., Otani, A., Fukushima, S., Jimbo, M., Yamamoto, T., Sakakida, T. and Onishi, S. "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part 4), Failure Behavior of Crossover Piping for Seismic Isolation System", *ASME 2014 Pressure Vessels & Piping Division Conference*, PVP2014-29011.

Shaw, D. E. (1975). "Seismic Structural Response Analysis for Multiple Support Excitation", *Proc. of 3rd SMiRT*, London, UK, 1975, K7/3 pp. 1-8.

Suzuki, Y., Sato, K., Iiizumi, H., Hisatsune, M. and Onishi, S. (2014). "Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities (Part 1), The Work Schedule of Project and a Seismic Design of Crossover Piping System", *ASME 2014 Pressure Vessels & Piping Division Conference*, PVP2014-29035.

Tai, K., Sasajima, K., Fukushima, S., Takamura, N. and Onishi, S. (2014). "DEVELOPMENT OF AN EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES (PART 2), APPLICATION OF CCFS METHOD TO THE MULTIPLY SUPPORTED SYSTEMS", *ASME 2014 Pressure Vessels & Piping Division Conference*, PVP2014-28999.

Thailer, H. J. (1976). "Spectral Analysis of Complex Systems Supported at Several Elevations", *Journal of Pressure Vessel Technology*, May 1976, pp. 162-165.

Vashi, K. M. (1975). "Seismic Spectral Analysis of Structural Systems Subject to Nonuniform Excitation at Supports", *2nd ASCE Specialty Conference on Structural Design of Nuclear Power Plant Facilities*, Vol. 1-A, New Orleans, LA, Dec. 1975, pp. 188-211.

Watakabe, T., Kaneko, N., Aida, S., Otani, A., Moriizumi, M., Tsukimori, K. and Kitamura, S. (2013). "Study ON Piping Response under Multiple Excitation, Part1: Triple Shaking Table Test of Piping Having Three-Supporting Points", *ASME 2013 Pressure Vessels & Piping Division Conference*, PVP2013-97832.

Watanabe, Y., Kuroha, M., Amada, K., Nishikawa, A., Iijima, T. and Shimizu, H. (1993). "Experimental and Analytical Study on Crossover Piping System in Seismic Isolation FBR Plant: (I) Main Steam Piping", *Proc. of 12th SMiRT*, 1993, pp. 181-186.