A Review of Seismic Analysis of the Steam Supply Piping Connected to the High Pressure Turbine of OPR1000

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ABSTRACT

The steam supply piping connected to the high pressure turbine of OPR1000 (standard pressurized water reactor type of nuclear power plant in Korea) is a typical example of a multiply supported piping system routed from the Containment building to the Turbine building via the Main Steam Isolation Valve room in the Auxiliary building, and is seismically analyzed on the basis of the independent support motion (ISM) method. Although many study results show that the ISM is the most efficient method for seismic response analysis of structural systems subjected to multiple support excitations, acceptable guideline in nuclear piping industry has not yet been proposed to allow the use of ISM method on a consistent and regular basis. In this study, several topic studies were performed to review the adequacy of technical bases applied to the seismic analysis of the steam supply piping connected to the HP turbine of OPR1000. Topics studied include support grouping effects, square root sum of squares (SRSS) and absolute sum (ABS) response combination effects of groups, PVRC and Regulatory Guide 1.61 damping effects, and closely spaced and residual mode effects. The study results show that support grouping by each floor of buildings, SRSS combination of groups, PVRC damping and ±15% spectrum peak broadening, and absolute double sum (ADS) of modal combination are considerably preferable than any other combinations.

INTRODUCTION

Many nuclear power plant components are supported at multiple locations of the building structures with non-uniform seismic excitation applied at each of these locations and anchor points. For example, a piping system may span different buildings and be anchored at several different elevations. With respect to the seismic analysis method for this category of piping system, there are three methods conventionally used by the nuclear piping industry, i.e., enveloped response spectra (ERS) method, independent support motion (ISM) method and time history method. Among these three, ERS method is found often too conservative while time history method is not economical for large practical applications. ISM method is a mathematically rigorous technique that uses the principles of spectral analysis, superposition of normal modes and response spectra input to calculate the magnitude of seismic response excitation at each support point. Many study results have shown that the ISM method is more realistic and reasonably economic than other methods [1], [2], [3], [4].

The steam supply piping connected to the high pressure (HP) turbine of OPR1000 (standard type nuclear power plant in Korea) is a typical example of a multiply supported piping system routed from the Containment building to the Turbine building via the Main Steam Isolation Valve room in the Auxiliary building [5]. This piping subsystem is seismically analyzed on the basis of the independent support motion (ISM) method with the simultaneous use of following methods: Grouping supports by each floor of buildings, square root sum of squares (SRSS) combination of groups, PVRC damping with ±15% spectrum peak broadening, and absolute double sum (ADS) of modal combination.

However, in spite of the realistic and less-conservative approach, the application of ISM has been limited in nuclear power plant piping design because there are no acceptable industry's guidelines to allow the use of the ISM method on a consistent and regular basis. Major issues associated with the limited use of this method are support grouping, group combination, modal combination and piping system damping. Some studies were conducted in this regard. As an example, the USNRC piping review committee has recommended the ISM method with absolute sum (ABS) combination between groups and Regulatory Guide 1.61 damping. However, Electric Power Research Institute (EPRI) has reported that ISM method with SRSS combination between groups and PVRC damping with ±15% spectrum peak broadening is more realistic and should be acceptable for the design of piping systems. The USNRC position is that the simultaneous use of ISM method and PVRC damping remains as an item requiring further justification. There are several piping system designs in typical nuclear power plants that could be significantly enhanced simply by the application of ISM with SRSS combination between groups and PVRC damping to eliminate unnecessary conservatism.

Therefore, in this paper, several topic studies were performed and the effects of each different combination were reviewed for the steam supply piping connected to HP turbine of OPR1000. Topics studied include support grouping effects, SRSS and ABS response combination effects of groups, PVRC and Regulatory Guide 1.61 damping effects, and closely spaced and residual mode effects.

PIPING SUBSYSTEM DESCRIPTION

The steam supply piping connected to the HP turbine of OPR1000 is devided into three piping subsystems considering analytical purpose and limitation of capacity of piping stress analysis program. The subsystem boundaries are depicted in Figure 1. The first piping subsystem is inside the Containment building from Steam Generator nozzles to the flued-head penetration anchors of Containment building. The second piping subsystem is inside the Main Steam Isolation Valve (MSIV) room from the penetration anchors of Containment building to the flued-head penetration anchors of MSIV room. The last piping subsystem is from the flued-head penetration anchors of MSIV room to the nozzles of HP turbine in Turbine building via the main steam enclosure attached to Auxiliary building and turbine pedestal structures as enveloped within the dotted line in Figure 1. Specifically, the last piping subsystem is to be mainly reviewed in this paper because it is a typical example of multiply supported piping system. This piping subsystem is classified as non-safety-related piping and seismic category II. However, the routing through Auxiliary building necessitates this piping subsystem to be designed to eliminate postulation of intermediate breaks to protect Auxiliary building from the pipe whip loads. To eliminate the postulation of intermediate breaks on this piping, the pipe stresses due to deadweight, thermal expansion, and operating basis earthquake (OBE) must meet 80% of the Code specified allowable. Also, the main piping from the stop and control valves to the HP turbine nozzles must remain functional during an OBE event as stipulated in the turbine-generator contract of OPR1000.

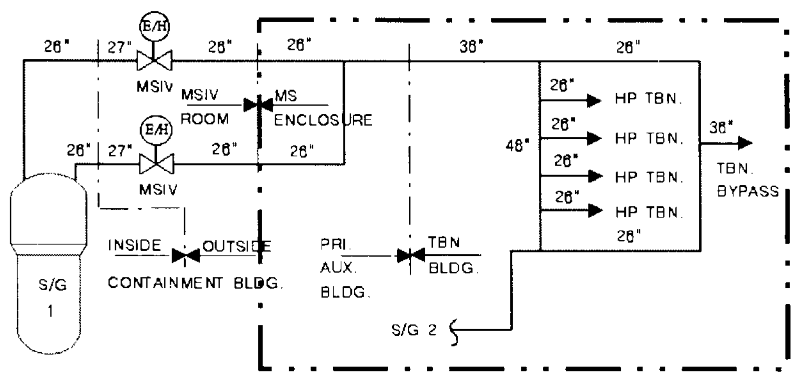
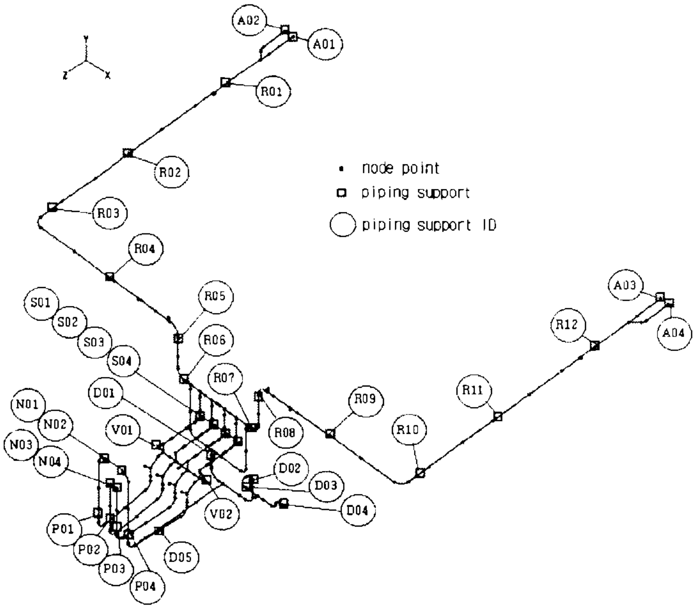


Figure 1. Subsystem Boundary of Steam Supply Piping

ANALYTICAL PIPING/SUPPORT MODEL DESCRIPTION

The finite-element model of the piping subsystem (in the dotted line in Figure 1) has 1461 static degrees-of-freedom and it is depicted in Figure 2. The Cartesian coordinate system X, Y, Z represents the reference global coordinate system. The nodal points of piping support where the excitations are applied are also depicted in Figure 2.

Supports A01 thru A04 (penetration sleeves attached to the exterior wall of the MSIV room in the Primary Auxiliary building) and N01 thru N04 (HP turbine nozzles) are modeled as anchors (six degrees-of-freedom restrained). Supports S01 thru S04 (snubbers), V01 and V02 (turbine stop valves supports), R01 thru R12 (struts), P01 thru P04 installed on the turbine pedestals are modeled as guides which are laterally and/or longitudinally restrained. Supports D01 thru D05 are non-seismic guides to decouple turbine bypass from this subsystem by the using of 3-restraint rule. Details of restraining direction and installed location for each support are also depicted in Figure 2.



Support ID	Restraint Direction	Location	
		Building	Elevation
A01, A02, A03,A04	X, Y, Z (Anchor)	Aux.	170′
R01, R02, R11, R12	X, Y	Aux.	170′
R03, R04, R09, R10	Y	Aux.	170′
R05, R08	X, Z	Aux.	162′
R06, R07	Y	Aux.	144′
S01, S02, S03, S04	Z	Aux.	122′
V01, V02	Y	Turbine	118′
P01, P02, P03, P04	X, Z	Pedestal	108′
N01, N02, N03, N04	X, Y, Z (Anchor)	Pedestal	147′
D01	X, Z	Turbine	102′
D02	Z	Turbine	108′
D03	Y	Turbine	114′
D04	Z	Turbine	120′
D05	X, Y	Turbine	93′

Figure 2. Analytical Isometric Drawing for the Steam Supply Piping Subsystem

PIPING RESPONSE SPECTRA ANALYSIS WITH TOPIC STUDIES

Consideration of Different Groupings

A certain set of supports may have spectra with different phasing characteristics such as in-phase, out-of-phase or randomly. Since the appropriate procedure for summation between support groups is dependent upon the phasing characteristics of the input spectra, the definition of a support group must consider the phasing aspect as well as the spectral amplitude. To study the appropriate support grouping, seven spectral groups are defined along with the buildings and locations as shown in Table 1, and five different combinations of spectral groups are considered as shown in table 2.

Table 1. Spectral Group

Support ID	Location		Spectral Group
	Building	El.	
A01, A02, A03,A04	Aux.	170′	A-1
R01, R02, R11, R12	Aux.	170′	A-1
R03, R04, R05, R08, R09, R10	Aux.	170′ 162′	A-1
R06, R07	Aux.	144′	A-2
S01, S02, S03, S04	Aux.	122′	A-3
V01, V02	Turbine	118′	T-1
P01, P02, P03, P04	Pedestal	108′	P-1
N01, N02, N03, N04	Pedestal	147′	P-2
D01	Turbine	102′	T-2
D02	Turbine	108′	T-1
D03	Turbine	114′	T-1
D04	Turbine	120′	T-1
D05	Turbine	93′	T-2

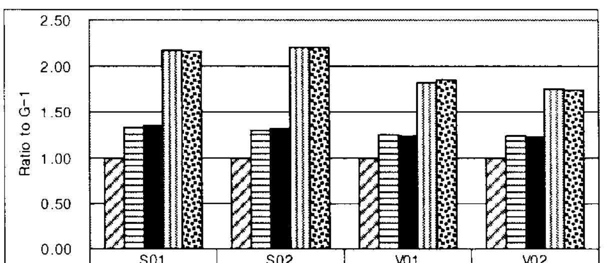
Table 2. Groups Considered for Multiple Support RS Analyses

Group Name	Spectral Group	Response Spectra Analysis
G-1 (7 groups)	<A-1>, <A-2>, <A-3>, <T-1>, <T-2>, <P-1>, <P-2>	ISM with each floor spectrum in each building
G-2 (3 groups)	<A-1>, <T-1>, <P-2>	ISM with the highest floor spectrum in each building
G-3 (3 groups)	<A-1, A-2, A-3>, <T-1, T-2>, <P-1, P-2>	ISM with the enveloped spectrum in each building
G-4 (1 group)	<A-1, A-2, A-3, T-1, T-2, P-1, P-2>	ISM with the enveloped spectrum for all building
G-5 (1 group)	<A-1, A-2, A-3, T-1, T-2, P-1, P-2>	ERS with the enveloped spectrum for all building

Piping response spectrum analyses for the five different groups are performed using the PIPSYS program [6]. To review the analyses results conveniently, three places of structural responses such as snubber support (S01, S02), valve body support (V01, V02) and HP turbine nozzle (N01) are selected, and all the responses of each grouping are compared with the responses of support grouping G-1.

Figure 3 presents comparison ratios of responses on node of S01, S02, V01 and V02 for five support groupings to those of support grouping G-1. Figure 4 presents comparison ratios of responses on HP turbine nozzle N01 to those of support grouping G-1. Also, piping stresses on piping support nodes S01 thru S04 for all support groupings are compared with those for support grouping G-1 as shown in Figure 5.

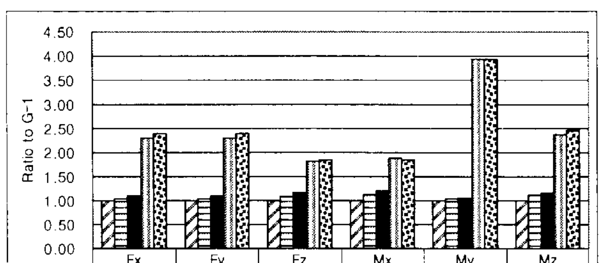
Through the comparison of the magnitudes of responses for five support groupings, G-1 case using the ISM with each floor spectrum in each building shows the lowest responses. G-2 using ISM with the highest floor spectrum in each building shows less conservative results than those of G-3 using ISM with the enveloped spectrum for all floors in each building. However, the differences are not significant. G-4 using ISM with the enveloped spectrum for all floors and buildings shows almost same to those of G-5 using ERS with the enveloped spectrum for all floors and buildings. This confirms the fact that ERS is a special case of ISM with only one enveloped support group. Also, responses for G-4 and G-5 show too much conservative than those of G-1. Therefore, it is confirmed that ISM with G-1 is the best combination to reduce the conservatism in the seismic analysis of HP turbine steam supply piping of OPR1000.



	S01	S02	V01	V02
G-1	1.00	1.00	1.00	1.00
G-2	1.33	1.30	1.25	1.24
G-3	1.35	1.32	1.24	1.24
G-4	2.18	2.21	1.82	1.76
G-5	2.17	2.20	1.85	1.74

Support

Figure 3. Support Loads for 5 Support Groupings



	Fx	Fy	Fz	Mx	My	Mz
G-1	1.00	1.00	1.00	1.00	1.00	1.00
G-2	1.05	1.05	1.09	1.13	1.04	1.12
G-3	1.10	1.10	1.17	1.21	1.06	1.16
G-4	2.31	2.31	1.83	1.89	3.94	2.36
G-5	2.40	2.40	1.84	1.83	3.96	2.45

Nozzle(N01) Load

Figure 4. HP Turbine Nozzle (N01) Loads for 5 Support Groupings

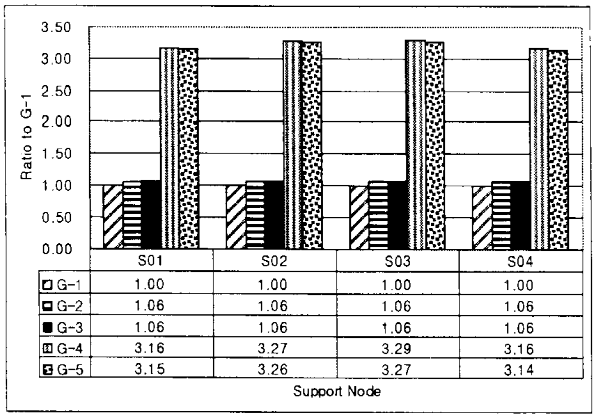


Figure 5. Piping Stresses for 5 Support Groupings

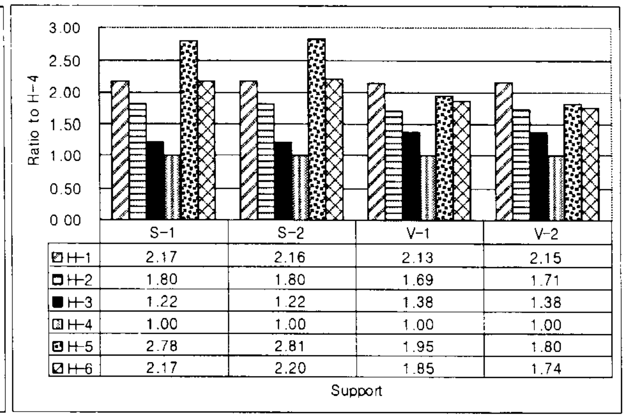


Figure 6. Support Loads for 6 Comination Cases

Group Combination and Piping System Damping

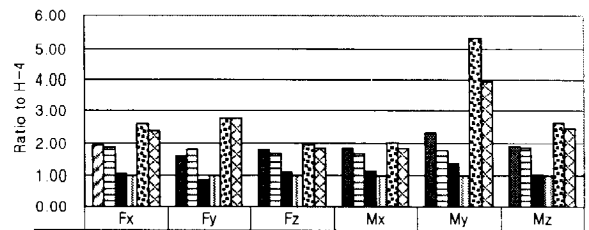
Method of combination and grouping support groups and piping system damping are the major factors effecting directly on the analysis results of the seismic analysis of piping using ISM. Although the USNRC piping review committee has recommended the ISM method with ABS combination between groups and Regulatory Guide 1.61 damping, exceptions have been made based upon plant specific cases. Also, many study results report that that ISM method with SRSS combination between groups and PVRC damping with ±15% spectrum peak broadening is more realistic and should be acceptable for the design of piping systems. Therefore, it is necessary to review the effects of each different combination for the steam supply piping subsystem of OPR1000 to eliminate unnecessary conservatism.

Six combination cases are studied as shown in Table 3 to evaluate the effects of combination between groups, damping values and ISM or ERS response spectrum (RS) analysis method. Analyses of six combination cases are performed by using OBE spectra with ±15% speak broadening and G-1 case of support grouping except H-5 and H-6. Also, for the convenient review, three response locations such as snubber support (S01, S02), valve body support (V01, V02) and HP turbine nozzle (N01) are selected, and all the responses of each analysis case are compared with the responses of analysis case H-4.

Figure 6 presents comparison ratios of responses on support S01, S02, V01 and V02 for all six combination cases to those of H-4. Figure 7 compares responses on HP turbine nozzle N01 for all six combination cases with those of analysis case H-4. Also, piping stresses on piping support nodes S01 thru S04 for H-1 thru H-6 were compared with those for H-4 as shown in Figure 8. Per Figure 6 thru Figure 8, H-4 using ISM with SRSS combination between groups and PVRC damping shows the lowest responses. Case H-1 using ABS combination between groups and Regulatory Guide 1.61 damping shows more conservative results by almost two times than those of H-4. However, specifically, responses on support V01 and V02 for case H-1 show more conservative results than those for case H-6 using ERS with PVRC damping as shown in Figure 6. This is contradictary to the fact that ISM has been developed to reduce the unnecessary conservatism of ERS for seismic response analysis of structural systems subjected to multiple support excitations. Therefore, it is confirmed that ISM with SRSS combination between groups and PVRC damping is the best combination to reduce the conservatism in the seismic analysis of HP turbine steam supply piping of OPR1000.

Table 3. Combination between Groups and Damping

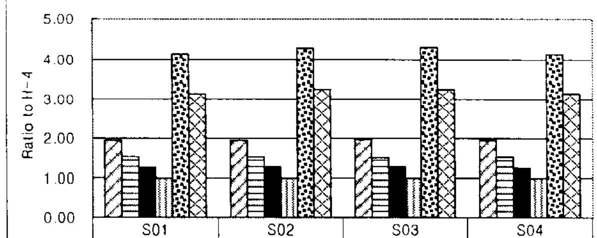
Analysis Case	Damping	Combination Between Groups	RS Analysis
H-1	Reg. Guide 1.61 (2%)	ABS	ISM
H-2	PVRC	ABS	ISM
H-3	Reg. Guide 1.61 (2%)	SRSS	ISM
H-4	PVRC	SRSS	ISM
H-5	Reg. Guide 1.61 (2%)	-	ERS
H-6	PVRC	-	ERS



	Fx	Fy	Fz	Mx	My	Mz
H-1	1.93	1.58	1.80	1.83	2.33	1.89
H-2	1.87	1.82	1.69	1.68	1.77	1.88
H-3	1.06	0.84	1.09	1.11	1.34	1.03
H-4	1.00	1.00	1.00	1.00	1.00	1.00
H-5	2.60	2.76	1.96	2.02	5.30	2.62
H-6	2.40	2.74	1.84	1.83	3.96	2.45

Nozzle(N01) Load

Figure 7. HP Turbine Nozzle (N01) Loads for 6 Comination Cases



	S01	S02	S03	S04
H-1	1.95	1.97	1.97	1.95
H-2	1.53	1.52	1.52	1.53
H-3	1.27	1.28	1.28	1.27
H-4	1.00	1.00	1.00	1.00
H-5	4.15	4.31	4.33	4.15
H-6	3.15	3.26	3.27	3.14

Support Node

Figure 8. Piping Stresses for 6 Comination Cases

Effect of Closely Spaced Modes

In response spectrum modal dynamic analysis, two consecutive flexible modes are defined as closely spaced if their frequencies differ each other by 10 percent or less of the lower frequency. If there are some closely spaced modes in flexible modes, modal combination by algebraic summation may give too conservative results. Several specific mathematical combination methods of modal responses are defined in Reglatory Guide 1.92. Throughout the modal analysis of the subsystem, several closely spaced modes were found. As a further comparison of various combination studies, four combination cases are considered as shown in Table 4 based on with and without contribution of closely spaced modes. Analyses are performed respectively using SRSS method for without contribution of closely spaced modes and ADS method for with contribution of closely spaced modes.

Table 4. Consideration of Closely Spaced Modes

Analysis Case	Damping	Combination Between Groups	Combination Flexible Modes
M-1	Reg. Guide 1.61(2%)	ABS	SRSS
M-2	Reg. Guide 1.61(2%)	ABS	ADS
M-3	PVRC	SRSS	SRSS
M-4	PVRC	SRSS	ADS

Figure 9 presents comparison ratios of responses of supporting loads on nodes of S01, S02, V01 and V02 for four analysis cases to those for case M-3. In Figure 9, M-2 analysis case that uses 2% damping, ABS combination between support groups and ADS of flexible modes shows the highest responses. In other hand, M-3 analysis case that uses PVRC damping, SRSS combination between groups and SRSS of flexible modes shows the lowest responses. Specifically, ADS combination (M-2, M-4) shows more conservative results by 1.11~1.33 times than SRSS combination modes (M-1, M-3) if other combinations such as support grouping method and damping are assumed as being equal in ISM analyses. This means that the effect of closely spaced modes is somewhat significant for the seismic analysis of steam supply subsystem of OPR1000.

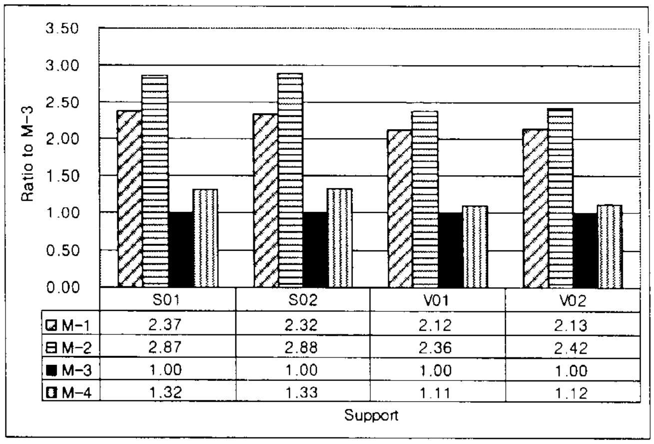


Figure 9. Support Loads for 4 Comination Cases

CONCLUSIONS

From the evaluation results of several case studies, the following conclusions are made:

1) The application of ISM method to the seismic analysis of the HP turbine steam supply piping of OPR1000 instead of ERS method is a very reasonable approach for reducing unnecesary conservatism.
2) Its application with support grouping by each floor in each building and ADS method with closely spaced modes for combination of flexible modes is adequate for the steam supply piping of OPR1000.
3) Its application with SRSS between support groups and PVRC damping is more desirable for the seismic analysis of the HP turbine steam supply piping of OPR1000 than with ABS between support groups and Regulatory Guide 1.61 damping recommended by NRC because the latter shows so conservative responses that overly excessive design could be anticipated.

REFERENCES

1. R.W. Wu, F.A. Hussain and L.K. Liu, "Seismic Response Analysis of Structural System Subjected to Multiple Support Excitation," Nuclear Engineering and Design, Vol. 47, 1978.
2. K.M. Vashi, "Seismic Spectral Analysis of Structural Systems Subject to Non-Uniform Excitation at Supports," Proceedings of ASCE Specialty Conference, New Orleans, 1975.
3. Subudhi, M. Bezler, P., "Seismic Analysis of Piping Systems Subjected to Independent Support Excitation," ASME-PVP Conference, Vol. 73, Portland, 1983.
4. J.M. Kelly and A.D. Cowell, "Experimental Studies of Multiple Support Seismic Response of Piping Systems and Components," EPRI RPT 964-8.
5. KOPEC, "Main Steam System P&ID," 9-521-M105-001, Rev. 5.
6. Integrated Piping Analysis System, KOPEC Registration No. E-P-PD-1157-1.0.
7. Westinghouse Electric Corporation, "Seismic Analysis of Multiply Supported Piping Systems," EPRI Report NP-6153, March 1989.
8. U.S. NRC Piping Review Committee, "Evaluation of Other Dynamic Loads and Load Combinations", NUREG-1061, Vol. 4, December 1984.
9. Welding Research Council, "Independent Support Motion(ISM) Method of Modal Spectra Seismic Analysis," Bulletin 352, April 1990.
10. Brookhaven National Lab., "Alternative Procedures for the Seismic Analysis of Multiply Supported Piping Systems," NUREG/CR-3811, October 1984.
11. Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants," October 1973.
12. Regulatory Guide 1.92, "Combining Modal Responses & Spatial Components in Seismic Response Analysis," February 1976.
13. Regulatory Guide 1.84, "Design and Fabrication Code Case Acceptability, ASME Section III Division 1," August 2005.