BNL-NUREG-66409
Paper ID: K4-A6-US

NRC-BNL BENCHMARK PROGRAM ON EVALUATION OF METHODS FOR SEISMIC ANALYSIS OF COUPLED SYSTEMS

Xu, J. and DeGrassi, G.

Brookhaven National Laboratory, Upton, New York 11973-5000, USA

Chokshi, N.

The United States Nuclear Regulatory Commission, Rockville, Maryland, USA

ABSTRACT

A NRC-BNL benchmark program for evaluation of state-of-the-art analysis methods and computer programs for seismic analysis of coupled structures with non-classical damping is described. The program includes a series of benchmarking problems designed to investigate various aspects of complexities, applications and limitations associated with methods for analysis of non-classically damped structures. Discussions are provided on the benchmarking process, benchmark structural models, and the evaluation approach, as well as benchmarking ground rules. It is expected that the findings and insights, as well as recommendations from this program will be useful in developing new acceptance criteria and providing guidance for future regulatory activities involving licensing applications of these alternate methods to coupled systems.

INTRODUCTION

In analyzing the seismic response of equipment or piping systems contained within Nuclear Power Plant (NPP) building structures, the uncoupled analysis approach may provide acceptable results as long as interaction effects between the primary and secondary system are insignificant. This has generally been assumed to be the case for secondary systems of small mass compared to the primary system. However, in recent years, researchers have demonstrated that under certain conditions, interaction effects can be significant even for very light secondary systems. For these systems, a coupled analysis would be more appropriate and would provide more accurate results.

While a coupled analysis may be performed by developing a model of the combined primary/secondary (P-S) system and applying the same conventional finite element analysis techniques, a complication is encountered when the subsystems have different damping characteristics. In conventional analysis of NPP structures, it is generally assumed that damping may be defined in terms of modal damping ratios for different types of structures. These damping ratios are based on experimental data and prescribed in regulatory guidelines (e.g., 7% damping for reinforced concrete structures, 4% for welded steel structures, etc.). Systems in which damping can be defined in this manner are classically damped. The equations of motion of a classically damped system can be transformed into a set of independent modal equations by using their undamped mode shapes, and traditional modal superposition methods can be applied to obtain their solution. However, when two or more subsystems with different modal damping ratios are coupled, the combined system is no longer classically damped. For these non-classically damped systems the transformed modal equations are coupled by the system damping matrix. These equations cannot be solved by the traditional modal superposition methods.

In the nuclear industry, coupled seismic analysis of major subsystems with different damping (such as the Nuclear Steam Supply System and Reactor Building) has been performed by methods (Ref. 1, 2, 3, 4 and 5) that apply approximate schemes to estimate equivalent modal damping ratios of the coupled system as weighted sums of the component damping ratios based on mass or stiffness weighting functions. While these methods may provide reasonable approximations of the diagonal terms of the damping matrix, they ignore the effects of the off-diagonal terms. In more recent years, more rigorous approaches have been developed based on a method first proposed by Foss (Ref. 6). Unlike the traditional methods, the solution involves complex valued eigenvalues and eigenvectors. However, these methods are more complicated, require greater computational effort than the traditional methods, and to date have not been widely applied or accepted for general use in the nuclear industry. While current regulatory requirements do not prohibit the use of coupled analysis, there is no guidance on the implementation of these new methods. From the regulatory standpoint, it is important to understand the applicability and limitations of these methods to assure that they produce reasonable results with acceptable safety margins.

The US Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research is sponsoring a benchmarking program for evaluation of state-of-the-art analysis methods and computer programs for seismic analysis of coupled structures with non-classical damping. Under this program, Brookhaven National Laboratory (BNL) has developed a series of benchmark problems and generated "exact" solutions using the direct integration method. Practitioners were invited to analyze the set of problems and provide their solutions for comparison to the BNL solutions. This paper describes the scope, benchmark process, the benchmarking structural models, seismic inputs, and benchmarking ground rules. The analysis results submitted by participants are currently being evaluated. Comparisons of these results to BNL "exact" solutions and evaluation of the analysis methods applied by participants will be made available to the public upon completion.

PROGRAM SCOPE AND OBJECTIVES

The objective of this program is to evaluate state-of-the-art methods for performing seismic analysis of coupled NPP structures with non-classical damping. The program is focused on the analysis of a coupled primary-secondary system consisting of two subsystems with different modal damping ratios. A typical NPP application is the seismic analysis of a coupled model of a piping system with 2% damping supported by a reinforced concrete building with 7% damping. In order to evaluate the methods, BNL developed a series of benchmark problems designed to cover various aspects of application and complexity. BNL generated a series of "exact" solutions to these problems using the direct integration time history analysis method. Developers of alternate analysis methods were invited to apply their methods to analyze the benchmark problems and provide solutions for comparison to the BNL solutions. It is expected that the findings and insights, as well as recommendations from this program will be used to develop new acceptance criteria to provide NRC staff a guidance for evaluation of future licensing submittals involving the application of these alternate analysis methods to coupled systems.

BENCHMARKING PROCESS

BNL selected the direct integration time history analysis method to develop the "exact" benchmark problem solutions for this program. This methodology has been widely used and accepted in the nuclear industry for applications requiring dynamic analysis of linear and nonlinear systems. To apply this method to non-classically damped coupled systems, BNL developed a synthesis formulation (Ref. 7) for generating the fully populated damping matrix of the coupled system from the damping ratios of its subsystems. The formulation was programmed into a series of preprocessor codes, which interface with the BNL in-house modified version of the SAP program to perform direct integration time history analysis of the coupled models. The BNL programs for developing the "exact" benchmark problem solutions were tested and verified by comparison to other published solutions.

Four benchmark problem configurations were developed for this program. The problems were designed to investigate various aspects of problem complexity and application. They include three simple models and one complex model. For the simple models, a number of load cases were defined to test the applicability of various analysis methods to problems with different dynamic characteristics and input motions. The load cases cover variations in key parameters including secondary to primary system frequency ratio, mass ratio, different modal damping ratios and different earthquake input motions. The complex problem was designed to represent a typical NPP coupled building-piping system model with multiple support connections at different floor elevations. Complex model load cases involve mass variations to test the response of a flexible versus stiffer coupled system, and application of different earthquake input motions. Descriptions of the structural models for these benchmark problems are provided in the next section.

It was anticipated that participants would be primarily interested in benchmarking design analysis methods based on the response spectrum analysis method. Since the BNL "exact" solutions were generated by time history analysis, multiple load cases were generated to allow for averaging of comparisons. BNL recognizes that for any single earthquake input motion, a response spectrum analysis and a time history analysis would generally not give identical results. Therefore, in comparing participant solutions to the "exact" solutions, individual load cases are first compared to the corresponding BNL results and then the resulting comparisons are averaged to reduce bias due to random phasing. The ratios of participant response to the corresponding BNL response at each location for each problem are computed. The mean and standard deviation of each ratio are then determined for all the load cases for each benchmark problem, therefore allowing for both quantitative and qualitative evaluations of the analysis results and the methods applied. By averaging over a number of sets of solutions, an acceptable response spectrum method should give a mean response comparison ratio close to one with a small standard deviation.

DESCRIPTION OF BNL BENCHMARKING STRUCTURAL MODELS

This section describes the structural models of the benchmark problems, input ground motions and analysis load cases. Since the primary objective of this program is to evaluate state-of-the-art analysis methods for seismic evaluation of coupled structures with non-classical damping typically encountered in nuclear power plant facilities, the emphasis of the structural modeling for the benchmark problems is focused on coupled two-component primary-secondary (P-S) systems. Damping for components is defined in terms of modal damping ratios under fixed-constraint conditions (Ref.7). Because the scope of this program is limited to fixed-constraint coupled P-S systems such as piping supported by a reinforced concrete building, the component damping associated with rigid-body vibration modes is effectively ignored.

Four benchmark problem configurations have been developed for this program. They include three simple models and one complex model, each representing a coupled two-component P-S system. The dynamic properties of the models are representative of NPP structures, systems and components. For each simple model, a number of load cases covering variations in model properties were analyzed. In addition, for all configurations, multiple load cases were analyzed for different earthquake loads corresponding to both real and artificial earthquake records.

Benchmark Model No. 1

This model is representative of a simple P-S system of an NPP building and base-supported equipment as illustrated in Figure 1. The primary component (building) model consists of weightless shear beam elements and lumped masses and is fixed at the ground. The model has five degrees of freedom (DOF) with each node free to translate in one horizontal direction. The secondary component model consists of four weightless shear beam elements and four lumped masses. The model has four DOF with each node free to translate in one horizontal direction. The base of the secondary component is coupled to a mid-elevation primary component node. For simplicity, each model has equally spaced nodes with equal nodal masses and equal element stiffness properties. The shear beam elements are modeled using a standard 3-D beam element in SAP V by prescribing shear modulus G and shear area A_{shear} of the element so that the shear stiffness K_{shear} of the beam is determined by the relation: $K_{shear} = A_{shear}xG/L_e$, where L_e is the length of the beam. Other properties associated with flexural deformations of the beam element, such as bending and torsional moments of inertia, are preset to significantly large values so that those flexural deformations would be effectively removed. All DOF associated with rotation and translation in the other two directions were constrained. For the baseline model, properties were selected to provide fundamental frequencies of 5.0 Hz for both the uncoupled primary component and the uncoupled fixed-base secondary component. The ratio of secondary/primary (S/P) component mass was selected as .005 (on an individual mass basis) for the baseline model. Modal damping ratios of 7% for the uncoupled P-component and 2% for the uncoupled fixed-base S-component were assigned to the baseline model. The El Centro (1940) earthquake was selected as input to the baseline case.

In order to investigate the applicability of various analysis methods to problems with different dynamic characteristics and input motion, additional load cases were designed to cover a range of parameter variations including secondary to primary system frequency ratio, mass ratio, different modal damping ratios, and different earthquake input motions. A total of sixteen load cases were prepared to account for different parametric variations, and six real earthquake records plus one artificial time history compatible to the Reg. Guide 1.60 spectrum were used as ground motion inputs. Table 1 provides typical matrix of load cases covering the parametric variations that were analyzed for the benchmark problems. Note that load cases k through p, which are not listed, have the same structural properties as the load case a, but with different ground motion inputs which are described in Seismic Inputs.

Benchmark Model No. 2

The second model is representative of a simple multiple connected P-S system of an NPP building and multiply supported piping system as shown in Figure 2. This model is also composed of weightless shear beam elements and lumped masses. The primary component has five DOF and is identical to the primary component defined in Model No. 1. The secondary component consists of eight shear beam elements and six lumped masses. It has six degrees of freedom with each node free to translate in one horizontal direction. The secondary component model is connected to the primary system building model at three different nodal elevations. Therefore, two redundant constraints due to the P-component exist in this system. As in the first model, each model has equally spaced nodes with equal masses and equal element stiffness properties and the modeling considerations are the same as for the first model. The baseline model primary and multiply supported secondary uncoupled components have fundamental frequencies of 5.0 Hz.

Benchmark Model No. 3

The third benchmark model is shown in Figure 3. This model also represents a simple coupled P-S system similar to Model No. 2. However, in this case, the secondary component is attached to the building at two elevations and to the ground. Both the building and piping system are subjected to the same ground motion at their ground support points. As in the first two models, this model is composed of weightless shear beam elements and lumped masses. The primary component has five DOF and is identical to the primary component defined in the first two problems. The secondary component is identical to that of the second problem except for the support points. As in the previous problems, the baseline model primary and multiply supported secondary uncoupled components have fundamental frequencies of 5.0 Hz.

Benchmark Model No. 4a and 4b

The fourth benchmark model is shown in Figure 4. This model is representative of a realistic complex model of a coupled NPP building and piping system which utilizes the same type of elements that would be used in a design analysis. In this model, the primary system (building model) consists of seven weightless 3-D flexural beam elements and seven lumped masses. Each node has six DOF and the bottom node is fixed. The secondary component (the piping model) consists of twenty-three straight and curved SAP piping elements. Each node also has six DOF. The pipe is supported by anchors at its end points and by two-directional guides at intermediate points. Rigid weightless beam elements are used to support and couple the piping to the building as shown in Figure 4. To model the guide constraints, the SAP beam element end release option is used at the piping connection points to provide translational restraint in two directions perpendicular to the axis of the pipe. At the anchor points, the rigid beams provide full six DOF constraint. The model uses realistic piping and building material and cross-sectional properties. The properties and support configuration were selected to provide equal fundamental frequencies for the uncoupled building and the uncoupled piping system. Two configurations were selected, which provide uncoupled fundamental natural frequencies of 8.24 Hz (No. 4a) and 4.60 Hz (No. 4b), respectively. The pertinent material properties used for the benchmark problem No. 4a are given below:

For building: Young's modulus E = 3000 ksi, Poisson ratio = 0.2, Nodal mass =10.0 kips-sec^2/in;
For piping: 12-inch schedule 40S, D=12.75 inches, t = 0.375 inches, Piping elbow R=18.0 inches, Young's modulus E=30000 ksi, Poisson ratio=0.3, Weight density: w=0.00822 kips/in;

And for the benchmark problem No. 4b:
For building: Young's modulus E = 3000 ksi, Poisson ratio = 0.2, Nodal mass = 32.1 kips-sec^2/in;
For piping: 12-inch schedule 40S, D=12.75 inches, t=0.375 inches, Piping elbow R=18.0 inches, Young's modulus E=30000 ksi, Poisson ratio=0.3, Weight density: w=0.02644 kips/in.

Modal damping ratios of 7% for the uncoupled building and 2% for the uncoupled multiply supported piping system were assigned in both cases.

The input ground motion is applied at the base of the primary component (node 1 in Figure 5), in the global Y direction for the benchmark model #4a, and in the global X direction for the benchmark model #4b.

Seismic Inputs

Six recorded earthquake ground motion acceleration time histories plus one artificial acceleration time history compatible to Regulatory Guide 1.60 response spectrum were selected as ground inputs to the BNL benchmark models. The recorded earthquakes are numbered sequentially as follows: No. #1: El Centro, SOOE (1940), No. #2: Taft Comp. S69E (1952), No. #3: Olympia Comp. N86E (1949), #4: El Centro Comp. S40E (1979), No. #5: Loma Prieta, Foster City (1989), No. #6: Northridge Comp. N30W (1994).

PROGRAM GROUND RULES

A report containing the benchmarking problems was distributed to all individuals and organizations interested in benchmarking their methods and computer programs for performing seismic analysis of non-classically damped coupled systems against the NRC-BNL solutions. All of the necessary input information needed by participants to develop their own identical or equivalent benchmark problem models and perform the seismic analyses was provided. Participants were asked to apply their own methods and computer programs in their entirety to perform the analyses. This includes the formulation of the coupled system damping matrix from the given modal damping ratios of the subsystems. Participants were requested to report their results for both primary and secondary components (maximum nodal displacements, element forces and moments) to BNL.

It was anticipated that most participants would apply complex eigenvalue response spectrum analysis techniques based on the method originally proposed by Foss. However, this benchmark program was not limited to those methods. Participants could apply any exact or approximate method that is appropriate for solving this type of problem. If participants interested in benchmarking their complex eigenvalue response spectrum methods wanted to provide the corresponding modal superposition time history results in support of their methodology, BNL would accept and compare both sets of results.

The seismic inputs were provided as both acceleration time histories and unbroadened response spectra. These inputs could be used directly to perform time history or response spectrum analysis. Participants may generate their own ground response spectra. However, if a response spectrum method is applied, participants should base the analysis on the ground response spectrum input and should not use the specific earthquake time history in the analysis. For example, participants who apply complex eigenvalue response spectrum methods may need two sets of spectra based on relative velocity and relative displacement. The relative velocity spectra should be estimated from the input ground spectra in accordance with their analysis method rather than calculated from the time history input motion.

In addition to providing the solutions, participants were requested to provide a description of their analysis methods and computer programs. The description should explain the analytical formulation, identify and explain the basis for assumptions and approximations in the methodology. It should describe the method for developing the coupled system damping matrix from the modal damping ratios of the subsystems. For complex eigenvalue response spectrum analysis, participants should describe the method for estimating the relative velocity-based response spectrum from the relative displacement-based ground spectrum, the modal combination method, and the method for treating high frequency modes (missing mass effects).

Upon receipt of the participant results, BNL performs comparisons of all results by calculating the response ratios (participant response/BNL response) for all load cases. The mean and standard deviation of each ratio are determined for each benchmark problem. An acceptable method is expected to provide a mean ratio close to one and a small standard deviation. The results of the comparisons will be provided to the participants for their review and comment. If needed, BNL will organize a meeting or workshop with participants to discuss the results. BNL will publish the results of this program including the comparisons, finding, recommendations and conclusions in a final NUREG/CR report. A preliminary copy of the report will be provided to all participants for their review and comment prior to publication.

CONCLUSIONS

This paper described a NRC-BNL benchmark program for evaluation of state-of-the-art analysis methods and computer programs for seismic analysis of coupled structures with non-classical damping. The program includes a series of benchmarking problems designed to investigate various aspects of complexities, applications and limitations associated with methods for analysis of non-classically damped structures. For the purpose of benchmarking, BNL developed the structural models typical of NPP P-S systems and generated "exact" solutions using direct integration with the BNL synthesis formulation for damping. Participants were invited to analyze the set of benchmarking problems with their alternate methods and provide results to BNL for comparison to the BNL solutions. It is expected that the findings and insights, as well as recommendations from this program will be useful in developing new acceptance criteria and providing guidance for future regulatory activities involving licensing applications of these alternate methods to coupled systems.

REFERENCES

1. Johnson, T. E. and McCaffery, R. J. "Current Techniques for Analyzing Structures and Equipment for Seismic Effects", ASCE, Meeting on Water Resource, New Orleans, 1969.
2. Tsai, N. C. "Modal Damping for Soil- Structure Interaction", Journal of Engineering Mechanics, Div., EM2, pp.323-341, 1974.
3. Biggs, *Introduction to Structural Dynamics*, McGraw-Hill Book Company, 1964.
4. Whitman, R. V. "Soil-Structure Interaction", Seismic Design for Nuclear Power Plants, MIT Press, 1970.
5. Rosset, J. M., et al., "Modal Analysis for Structures with Foundation Interaction", ASCE, J. Struct. Div., Mar. 1973.
6. Foss, K. A., "Coordinated Which Uncouple the Equations of Damped Linear Dynamic Systems", Transactions of the American Society of Mechanical Engineers, Vol. 82, 361-364, 1960.
7. Xu, J. "Overview on Methods for formulating Explicit Damping Matrices for Non-Classically Damped Structures", ASME-PVP Conf., San Diego, US, July 1998.

DISCLAIMER NOTICE

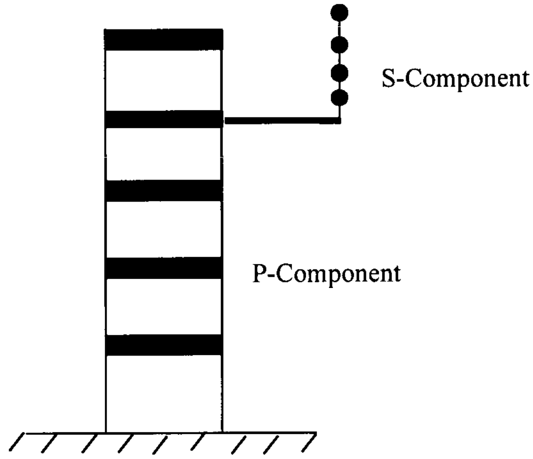

Figure 1. BNL benchmark model no.1

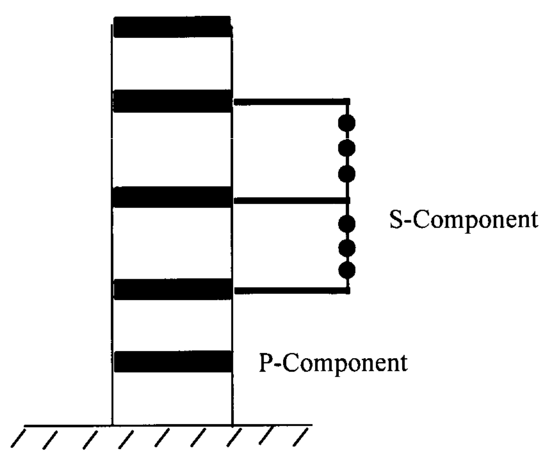

Figure 2. BNL benchmark model no. 2

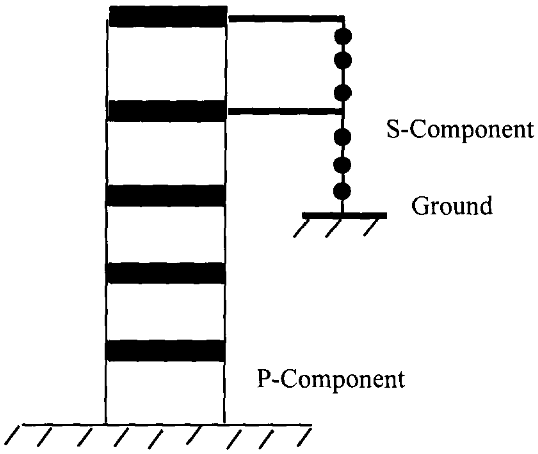

Figure 3. BNL benchmark model no. 3

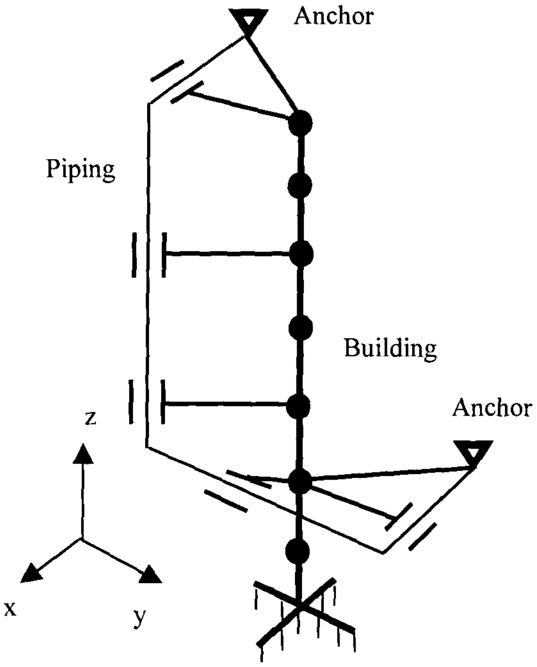

Figure 4. BNL benchmark model no.4a & 4b

Table 1. Typical Matrix for BNL Benchmark Problem Load Cases

Parameter/Load Variations		Load Case									
		a	b	c	d	e	f	g	h	i	j
Frequency Ratio (S/P)	0.5		X								
	0.9			X							
	1.0	X					X	X	X	X	X
	1.1				X						
	2.0					X					
Mass Ratio (S/P)	.0001						X				
	.005	X	X	X	X	X				X	X
	.1							X			
	.5								X		
Modal Damping (P,S)	7%, 2%	X	X	X	X	X	X	X	X		
	7%, 5%									X	
	7%,20%										X