September 26, 2000

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulations

FROM: Ashok C. Thadani, Director /R/ Margaret V. Federline for
Office of Nuclear Regulatory Research

SUBJECT: TRANSMITTAL OF RESEARCH INFORMATION LETTER RIL-0006, "METHODS TO ANALYZE COUPLED MODES WITH NON-CLASSICALLY DAMPED MODES"

This memorandum is in response to partial fulfilment of the user need request (NRR-98-033), dated December 16, 1994. Item number 2 in the user need request was a revision of R.G. 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis." Attached is the subject Research Information Letter (RIL), which describes the results of the research performed by RES, and regulatory implications suggesting that the existing regulatory guidance should be revised to include insights gained from this research. Efforts are ongoing to revise the R.G. 1.92, and as discussed in the attachment, we are further proposing that NRR should consider a revision to the Draft SRP 3.7.2, Rev. 3 - April 1996.

The preparation of this RIL has been coordinated with your staff through a memo from Sher Bahadur to Eugene Imbro, dated September 5, 2000, with the draft RIL, and an advanced copy of the final RIL delivered to Kamal Manoly on September 13, 2000.

Attachment: As stated

cc: W. Travers
C. Paperiello
F. Miraglia

September 26, 2000

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulations

FROM: Ashok C. Thadani, Director /R/ Margaret V. Federline for
Office of Nuclear Regulatory Research

SUBJECT: TRANSMITTAL OF RESEARCH INFORMATION LETTER RIL-0006, “METHODS TO ANALYZE COUPLED MODES WITH NON-CLASSICALLY DAMPED MODES”

This memorandum is in response to partial fulfilment of the user need request (NRR-98-033), dated December 16, 1994. Item number 2 in the user need request was a revision of R.G. 1.92, “Combining Modal Responses and Spatial Components in Seismic Response Analysis.” Attached is the subject Research Information Letter (RIL), which describes the results of the research performed by RES, and regulatory implications suggesting that the existing regulatory guidance should be revised to include insights gained from this research. Efforts are ongoing to revise the R.G. 1.92, and as discussed in the attachment, we are further proposing that NRR should consider a revision to the Draft SRP 3.7.2, Rev. 3 - April 1996.

The preparation of this RIL has been coordinated with your staff through a memo from Sher Bahadur to Eugene Imbro, dated September 5, 2000, with the draft RIL, and an advanced copy of the final RIL delivered to Kamal Manoly on September 13, 2000.

Attachment: As stated

cc: W. Travers
C. Paperiello
F. Miraglia

Distribution:
NChokshi
KManoly, NRR
CGrimes
ERAB r/f
Memo - ML003751283
RIL- ML003753890

DOCUMENT NAME: g:\shaukat\MemoRIL-0006
To receive a copy of this document, indicate in the box: "C" = Copy without enclosures "E" = Copy with enclosures "N" = No copy

OFFICE	ERAB/RES		ERAB/RES		D/DET		D/RES	
NAME	SShaukat		SBahadur		MMayfield		AThadani	
DATE	09/20/00		09/20/00		09/22/00		09/26/00	

OFFICIAL RECORD COPY

RESEARCH INFORMATION LETTER RIL-0006

Methods to Analyze Coupled Models with Non-Classically Damped Modes

Background

The equipment or piping systems contained within a nuclear power plant (NPP) that are important to safety must be designed to meet the requirements of General Design Criterion (GDC) 2 in Appendix A to 10 CFR Part 50 and Appendix A to 10 CFR Part 100 concerning natural phenomena such as earthquakes.

Conventional methods for analyzing and evaluating the seismic response of equipment or piping systems in a NPP generally involve a two-step process. In the first step, a mathematical model of the building structure (or primary system) is developed and analyzed using the seismic ground motion to obtain the floor level responses. In the second step, a separate mathematical model of the secondary system (equipment or piping) is developed and analyzed using the floor level support point responses from the building analysis as seismic input motion. This uncoupled analysis approach provides 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 in which the mass is small compared to that of 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 desirable and may provide more accurate results.

While a coupled analysis may be performed by developing a mathematical model of the combined primary and secondary systems and applying the same conventional analysis techniques, a complication is encountered when the subsystems have different damping[1] 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 called 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 frequencies and 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. This system cannot be solved by the traditional modal superposition methods.

The current SRP Section 3.7.2 (Ref. 1) describes several approximate seismic analysis methods for a complex system that has components with different damping characteristics. These approximate methods basically provide means to make classical modal superposition methods applicable to the complex system. In doing so, they generally introduced significant conservatism. In some limited situations, they can also underestimate the responses.

---

[1] Damping refers to a parameter that accounts for the energy loss mechanism in a system. For example, friction between moving parts of a structural joint is one source of the energy loss. The damping values are important as underestimation of energy losses will lead to the prediction of higher responses and loads and vice versa.

In the last two decades, several approaches have been developed that attempt to deal with the non-classically damped systems without resorting to converting them into the classical systems.

These methods are expected to improve the realism of the analysis. Evaluation of these methods was needed as they had been proposed for use in an operating plant and it is expected that licensees would use them in future.

In order to evaluate these methods, RES conducted a research program at Brookhaven National Laboratory (BNL) to develop benchmark problems, that can be used to judge the suitability of currently available and proposed methods. These benchmark problems, along with the evaluation of four different methods, are presented in NUREG/CR-6661, “Benchmark Program for the Evaluation of Methods To Analyze Non-Classically Damped Coupled Systems” (Ref. 2). The purpose of this Research Information Letter (RIL) is to document guidelines for applying these methods that would help the applicants as well as the reviewers.

Research Summary

These newly developed methods for non-classically damped coupled systems claim to bring benefits to the design process by improving the realism in the analysis and in some cases by reducing the conservatism embedded in classical approaches, thereby reducing design, construction, and replacement costs. However, from the regulatory standpoint, it is imperative that these state-of-the-art methods and their applicability, as well as their limitations, be understood to assure that they produce reasonable results with acceptable safety margins. RES, in the research program, evaluated state-of-the-art methods for performing seismic analysis of coupled NPP structures with non-classical damping (Ref. 2). The research focused on the analysis of a coupled primary-secondary system consisting of two subsystems with different modal damping ratios. The benchmark program developed in this research was carried out in two phases. Under Phase I, a series of benchmark problems that cover various aspects of application and complexity of typical coupled NPP structures with non-classical damping were first developed. These benchmark problems were subsequently analyzed by BNL using the exact methods[1] of direct integration time history analysis with a rigorous formulation for the explicit damping matrices. During the development of the research program, it was decided that researchers from academia and industry would be solicited to voluntarily participate in the program by analyzing the benchmark problems using their own methods and submitting results to BNL for evaluation. Four participants, two from industry and two from universities, participated in this program. A preliminary report, with detailed descriptions of the benchmark problems and the BNL analysis method with necessary input was distributed to the program participants. The participants were free to use their own alternative state-of-the-art analysis methods. In Phase II of the program, the analysis results were submitted to BNL by the participants. These results were then compared to and evaluated against the BNL “exact” solutions. The research report (Ref. 2) provides the participants’ analysis results of the benchmark problems and their comparisons to the BNL solutions. The report also provides the evaluation of the analysis methods applied by the participants, and the findings with respect to the applicability and limitations of various alternative state-of-the-art analysis methods for coupled NPP structures with non-classical damping.

[1] The exact methods require considerable computer time and a high level of skill in modeling. This approach is generally not practiced for designing systems with a larger number of components.

Details of the Research Approach

In BNL's program, four benchmark problem configurations were developed. 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 considered 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.

In order to capture the true dynamic characterization for the earthquake response of structures, the seismic ground inputs to the benchmark models were defined in terms of a series of recorded earthquake ground motion time histories. In this context, the BNL direct integration time history analysis method is, therefore, considered an appropriate approach for generating the "exact" solution to the benchmark problems. The BNL method to produce the "exact" solutions for the benchmark problems is described in Section 2 of Reference 2. It also provides the benchmark models, including both structural and material data, the load cases defined to account for various parametric effects (e.g., frequencies, masses, damping), and different ground motion effects for benchmark problems. In addition to providing the earthquake ground motion time history inputs (in terms of acceleration, velocity, and displacement), the corresponding acceleration response spectra were also generated and provided to the program participants. Finally, the ground rules defined for the benchmark process are provided.

Brief descriptions of methods utilized by participants to obtain their independent solutions to the benchmark problems are described in Section 3 of Reference 2. The aspects of formulation in each method that affect the dynamic response of non-classically damped systems such as complex modes, non-classical damping, approximation of velocity spectrum input, and modal combinations are discussed. Four methods were submitted by the participants with the results for benchmark problems. All four methods provided solutions for a suite of seven input motions, using the same response spectrum analysis methods. Three of the four methods used complex mode solutions and dealt with the complexity by using the approximation in the response spectrum analysis or modal superposition time history analysis. Each one used different approximations in this step. The fourth method presented another approach converting the complex problem into the classical problem and provided solutions based on classical normal mode response spectrum analysis.

BNL compared the participants' responses to the corresponding BNL responses for all problems. 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 parametric studies of effects such as frequency ratios, mass ratios, and damping. The comparisons were made in terms of the ratios of participant response to the corresponding BNL response at each location for each problem. In addition, 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, additional sets of load cases were defined using a suite of ground motions as inputs to the same baseline structural model, and for each load case, the participants' solutions were compared to the "exact" solutions. The mean and standard deviation of the response comparisons over the suite of ground motions were then calculated for each benchmark problem, as well as maximum ratios and minimum ratios of the response comparisons.

Research Results

Comparisons and discussions of results, which include nodal displacements and element forces, are discussed in Section 4 of Reference 2. In addition to comparisons for single ground motion, statistical estimates such as mean and coefficient of variation are provided for a suite of ground motions inputs, as well as maximum ratios and minimum ratios of the responses.

As a result of the comparisons and evaluations of the finalized benchmark analysis, the following significant observations were made:

1. For the smaller benchmark Problems 1, 2, and 3, the complex-mode time history analysis results of three of the four methods were in excellent agreement with the BNL direct integration time history results. Based on these results, it is concluded that, for these problems, the participants' complex-mode time history analysis methods provide results comparable to those generated by the benchmark direct integration time history analysis methods.

2. For the larger benchmark Problems 4a and 4b, which represent realistic coupled NPP building-piping systems, the complex-mode time history analysis results of three of the four methods were in good agreement with the BNL direct integration time history results. Based on the overall results for both the small and large benchmark problems, it is concluded that the participants' complex-mode time history analysis methods provide results comparable to those generated by the benchmark direct integration time history analysis methods and are acceptable.

3. For the smaller benchmark Problems 1, 2, and 3, the complex-mode response spectrum analysis results of three of the four methods showed larger deviations when individual load case results were compared against the corresponding BNL direct integration time history analysis results. However, because of inherent differences between response spectrum and time history analysis methods, exact one-to-one correspondence of solutions is not expected for a specific load case. In comparing response spectrum to time history analysis results, one should expect that the average responses using a suite of input ground motions should be close to the responses from the corresponding response spectrum analysis. For this benchmark program, using a suite of seven earthquake input motions, it was shown that the mean ratios of participants' responses to BNL responses were in reasonably good agreement with the BNL results. Based on these results, it is concluded that, for these problems, the participants' complex-mode response spectrum analysis methods provide reasonably accurate and generally conservative results.

4. For the larger benchmark Problems 4a and 4b, the comparisons of complex-mode response spectrum analysis results of three of the four methods, when compared to BNL time history

results, were generally consistent with the smaller benchmark problem. Based on the overall results for both the small and large benchmark problems, it is concluded that the participants' complex-mode response spectrum analysis methods provide reasonably accurate and generally conservative results.

5. For the smaller benchmark problems, parametric studies were performed by varying model properties to investigate potential limitations of alternative analysis methods in predicting the response of coupled systems with (a) tuned, near-tuned, and untuned subsystems, (b) low to high subsystem mass ratios, and (c) low to high secondary system damping. The complex-mode time history analysis methods provided very good agreement with the benchmark results over the entire range of parameter variations. The response spectrum analysis methods showed larger deviations, but since the comparisons were based on single earthquake input motions, it is not possible to determine whether the deviations are due to the parametric variations or to the normal differences in results caused by the different analysis methods. It is reasonable, however, to assume that the findings and conclusions from the modal time history analysis parametric studies can be extended to response spectrum analysis. On that basis, no significant limitations were identified within the range of frequency and mass ratios investigated. Based on limited trends in the data and currently accepted practice, it would be prudent to limit the damping ratio to 20%.

6. The solutions of the fourth method using the classical response spectrum method with composite modal damping provided interesting comparisons with the non-classical complex mode method solutions. For the small benchmark Problems 1, 2, and 3, results of the fourth method, which attempts to use the classical approach, were comparable and in several cases slightly better than the responses generated using the complex-mode based response spectrum methods. However, for the larger, more complicated coupled models of benchmark Problems 4a and 4b, the results showed much larger deviations with significant over-prediction of responses in many locations.

Regulatory Implications and Closure

The current SRP Section 3.7.2 (Ref. 1) describes seismic analysis methods to solve problems where structural responses have different damping characteristics. When these methods are used with decoupled models, they tend to introduce artificial conservatism. The current regulatory requirements do not prohibit the use of coupled analyses, however, no detailed implementation guidance is available.

In recent years, new methods for performing seismic analyses of coupled structures were developed that attempted to deal with the non-classically damped systems without resorting to diagonalizing the damping matrix. These methods tend to reduce conservatism embedded in classical approaches.

The research results suggest that existing regulatory guidance should be revised to include reference to the benchmark problems and insights gained from this research. The solution of benchmark problems provides an important tool to judge the adequacy of the proposed methods. Such solutions are being used as review tools for the piping design. As a part of an ongoing effort for a proposed revision to Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," it is likely that, in the future, the SRP

Section 3.7.2 may have to be revised with the inclusion of guidance on reviewing and accepting newly developed methods for more complex coupled models with non-classically damped modes.

REFERENCES

1. NUREG-0800, SRP Section 3.7.2, Seismic System Analysis, Draft Rev. 3, U.S. Nuclear Regulatory Commission, April 1996.

2. NUREG/CR-6661, "Benchmark Program for the Evaluation of Methods To Analyze Non-Classically Damped Coupled Systems," U.S. Nuclear Regulatory Commission, January 2000.