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July 12, 1996

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555

Subject: Catawba Nuclear Station, Units 1 & 2,
Docket Nos. 50-413 and -414
McGuire Nuclear Station, Units 1 and 2,
Docket Nos. 50-369 and 370
Response to RAI - Seismic Analysis Methodology

By letters dated March 16 and June 30, 1995, Duke Power Company requested approval for use of alternative seismic methodologies. By letter dated May 7, 1996, the NRC provided a Request for Additional Information. A response to this request is provided in Attachment 1.

Please note that the previous Duke Power submittals on this subject (March 16, 1995, June 30, 1995, September 20, 1995, November 20, 1995, and February 16, 1996 were all submitted on Docket Nos. 50-369, -370, -413 and -414. The May 7, 1996 RIA did not reference Catawba Unit 2. The request for approval of the CREST methodology is for all four McGuire and Catawba units.

Please contact R. O. Sharpe at (704) 382-0956 if you have any questions.

Very truly yours,

M. S. Tuckman

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A001/1

Attachments

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Attachment 1

Duke Power Company
Steam Generator Replacement Project

Response to Request for Additional Information

The staff has reviewed the licensee's responses, dated November 20, 1995, and February 16, 1996, to the staff's request for additional information (RAI) dated July 6, 1995, regarding the proposed use of the CREST Computer Code for performing seismic analysis of coupled structural systems. The staff's review indicated that the current version of the CREST program may underpredict the structural responses when compared to the time history method. The staff noted the following observations on the basis of its review of the CREST verification Problem No. 1 results:

a. In Tables 3 to 6 of Problem No. 1 report, the percent difference should be calculated on an individual response basis as (C-A)*100/A instead of (C-A)*100/A_{max}. Dividing the difference by the largest response value, A_{max}, is not meaningful and gives a misleading representation of the differences between the CREST and the time history analysis responses.

b. Recalculating the percent difference in significant member responses based on the correct formula stated in (a), the staff found a mean underprediction of 10% for El Centro input motion and 6% for Taft input motion. Six out of 23 El Centro responses were underpredicted by more than 20%. The largest percent underprediction was 33%.

c. Problem No. 1 report states that the differences between the CREST results and the time history results are due to the inherent differences between the time history method and the response spectrum method of analysis. While the staff agrees that a response spectrum analysis may underpredict responses at a few points, studies have demonstrated that on the average, a response spectrum analysis will overestimate response when compared to a time history analysis.

d. Based on the results presented for Problem No. 1, which show average overall response underprediction for two different earthquakes, the staff noted that a piping analysis using the CREST methodology may not provide adequate design margins for such complex piping systems as Problem No. 1.

In consideration of the above observations, provide additional justification and/or additional limitations on the CREST Code to support its use in seismic analysis applications.

It is further determined, in light of the verification problem results and the recent program revisions, that additional verification of the CREST program is necessary for non-classically damped as well as classically damped coupled systems. The three piping verification problems only considered classically damped systems. Since the non-classically damped solution method is a very significant aspect of the CREST program, provide additional non-classically damped piping system verification problems.

RESPONSE

1. Introduction

Staff's statement "the current version of *CREST* program may *under predict* (our emphasis) the structural responses when compared with the time- history method" is correct but incomplete. The *CREST* program performs a response spectrum analysis. Any one response spectrum analysis may *under* or *overpredict* responses in comparison to those predicted by a corresponding time-history analysis. Average of differences in responses due to several motion time histories and the corresponding response spectra should converge to zero as the number of motions is increased. Standard deviation of the differences, which is a measure of spread in the differences, will be relatively small in a well formulated method and large when a formulation is less rigorous.

In the meeting on July 27, 1995 at North Carolina State University, Professor Gupta clearly stated the above position, and that the *CREST* program was already validated in accordance with scholarly standards and NRC requirements. Most computer programs currently in use in the industry have been validated using very simple problems consisting of only a few elements. **By the very definition of the response spectrum method, it is impossible for any one to prove what we were and are being asked to prove.** Further evidence in support of our position is given in the following paragraphs.

2. Reed and Kennedy

Frequencies and mode shapes of the coupled piping-building model given by *CREST* are in excellent agreement with those obtained from *ANSYS*. Differences in response spectrum and time-history analyses occur due to the modal combination procedure used in the response spectrum method. Discussing a paper by Wilson et al, (*Earthquake Spectra*, Vol. 22, No. 4, 1995) in the context of high frequency modes, Reed and Kennedy (Vol. 12, No. 2, 1996) endorse Gupta's modal combination method:

"The CQC method (read double sum or Rosenblueth method without absolute sign) is an appropriate approach for combining responses from modes that are closely spaced. However, this method does not properly combine high-frequency response modes that are in phase with the ground motion....

"Unfortunately, we do not know of any commercially available computer programs that address the problem of high frequency modes in phase with the ground motion in a response spectrum analysis....

"Important high-frequency modal responses that are in phase with the ground input can be easily combined in a response spectrum analysis using approaches that have been developed by Gupta [Gupta and Cordero, SMiRT 6, Paris, 1981; Gupta and Chen, SMiRT 7, Chicago,, 1983] and Lindley and Yow [ASCE, Knoxville, 1980]....

"We recommend when high-frequency modes are in phase with the ground input and are important contributors to the combined response that a proper modal combination procedure be used. We strongly encourage incorporation of either or both the Gupta and Lindley and Yow methods into commercially available computer programs for performing structural analysis as one way of adopting this recommendation."

3. *CREST* Program and the Current Practice

CREST is a major technological advancement. Various assumptions that are necessary in the currently accepted methods of analysis need not be made (when using the *CREST* analysis). Some of these features are listed below.

(a) Building and piping systems are treated as coupled (connected) in *CREST* without physically developing a finite element model of the complete coupled systems. Coupling is accomplished through an elegant and rigorous mathematical formulation. Most conventional analyses are performed by treating the two systems as uncoupled.

(b) Uncoupling of building and piping ignores interaction between the two systems.

(c) Response spectrum at the base of the building is directly used as input in the *CREST* analysis. It need not be converted either into a compatible time-history, as done in most conventional methods, or into an equivalent PSDF (power spectral density function) which is done occasionally. Both conversion processes are non-unique and introduce inaccuracy in the calculated responses.

(d) Floor response spectra used in conventional analyses are not (don't need to be evaluated in the *CREST* analysis. Support motions are directly transmitted from building into the piping system. Therefore, the *CREST* analysis avoids several arbitrary steps associated with different versions of conventional analysis methods such as: enveloping of floor response spectra, combining responses (SRSS, absolute sum, grouping, etc.) due to spectral input at various floors when using the independent support motion or ISM approach instead of the envelope spectrum, calculating effect of relative anchor movements, and combining effects of floor response input and relative anchor movements.

(e) In lieu of the conventional uncoupled analysis, a time-history analysis is infrequently performed using a combined building-piping finite element model to reduce the calculated piping response. Such an analysis is permitted by the NRC. Size of a coupled problem and dissimilar masses and stiffnesses in different parts of the model may unsuspectedly cause numerical problems. *CREST* elegantly avoids potential problems associated with such brute-force methods.

(f) The *CREST* analysis accounts for different damping values of building and piping systems. These different values cause the coupled system to become *nonclassically* damped. Using the Foss method, a complex eigen-value problem is solved to evaluate coupled frequencies, damping values and mode shapes (each complex modal vector results in two real mode shapes). No finite element computer program capable of accurately accounting for different damping values exists. Various heuristic procedures are used intend. Type and magnitude of errors caused by such heuristic procedures are unknown.

4. NUREG/CR-5627

A comprehensive comparison of the response spectrum and time-history methods was performed by Bezler et al in *Alternate Modal Combination Methods in Response Spectrum Analysis*, Prepared for U.S. Nuclear Regulatory Commission, Brookhaven National Laboratory, NUREG/CR-5627, 1990. The report contains results from response spectrum and time-history analyses of six piping systems. Two of these systems were analyzed for 33 motion histories and corresponding response spectra, the remaining four for one motion and spectrum each. In the response spectrum analyses, modal responses were combined by a grouping method specified in RG (Regulatory Guide) 1.92, and by Gupta, Hadjian and Lindley-Yao methods. Percent differences between responses from each set of response spectrum (RS) and time-history (TH) analyses are tabulated in the report. The percent difference is defined as, PD = 100X(RS-TH)/TH.

Response spectrum results when using the RG 1.92 method were up to 99 percent too low and 1525 percent too high as compared to the time-history results. The corresponding percentages for the other three methods are (99,103), (99,118), and (99,260), respectively. These numbers are not very meaningful because the extreme differences come from relatively unimportant responses with small values. A more useful definition of the percent difference is PD = 100X(RS-TH)/THmax, in which THmax is the maximum absolute value of similar responses from same response time-history.

The report also has statistics for the two piping systems analyzed for 33 input motions each. Since very few responses are so low as to give meaningless percent differences like the ones cited above, the statistics of differences still offer a good insight into the merits of various methods. These statistics show that each response spectrum modal combination method used in the study, including the RG 1.92 method, on the average, can *under*-estimate responses relative to the time-history responses up to 25 percent. The mean over-estimation in the RG 1.92 method is around 150 percent, and that in the rest 25 percent. The overall mean percent difference for the RG 1.92 method is 20 percent (too high) and for the other candidate methods 3 percent (closer to zero). Standard deviation of the percent difference in the RG 1.92 results is also much higher (too much scatter) than that in other results (much less scatter).

In the conclusion of the report it is pointed out that "--the response spectrum method is a design method and is not expected to give results that are in total agreement with the time-history results. On the average, the *error* (read difference) between the response spectrum and the time-history results are likely to be quite small, tending to zero as the number of ground motions considered in the analysis is increased. This will be true only when the response spectrum methods are rational and applied correctly. Understanding of this concept is important when reviewing the results from the present study (NUREG/CR5627). There are many response spectrum results that are less than (and others that are more than) those from the corresponding time-history results. That does not make the response spectrum method unconservative (or conservative). For design purpose, a rationally formulated response spectrum analysis is superior to a single time-history analysis."

5. Chopra

Results from time-history and response spectrum analyses of a building are illustrated by Chopra in *Dynamics of Structures* Prentice Hall, 1995, pp 523-529 (Article 13.8.2 Example: Five Story Shear Frame). El Centro (SOOE, 1940) motion history and corresponding response spectrum are used as input. The maximum difference between the two sets of results is in the fifth story shear for which the response spectrum value is about 15 percent lower than the time-history value. Chopra comments that the difference between the response spectrum values using mean spectrum derived from many ground motions and the mean of the peak values from time-history analysis using the same motions will be generally much smaller than that for a single excitation--perhaps no more than several percent.

6. Gupta and Jaw

Gupta and Jaw in "Response Spectrum Method for Nonclassically Damped Systems," *Nuclear Engineering and Design*, Volume 91, January 1986, pp 161-169, analyzed nine nonclassically damped coupled primary-secondary systems subjected to 12 real earthquake motions using the response spectrum (*CREST*) and time-history methods, a total of 108 analysis pairs. Results from this reference are also summarized by Gupta in *Response Spectrum Method*, Blackwell, 1990 (CRC Press, 1992). For one of the nine cases, Case 2, it is shown that the difference between the displacements calculated using the two methods varied from -0.05 to 3.4 percent and those in element forces between -0.2 and -21.4 percent. Among all the 108 pairs, the maximum absolute difference in displacements and element forces from the two types of analyses were 41 and 45 percent, respectively, which are reasonable and well within the norm of such comparisons. Mean and standard deviation for difference in all the displacements were 1.33 and 9.65 percent, and that in element forces 0.48 and 10.31 percent, respectively.

The above set of results validate accuracy of the CREST program.

7. A and Amax

Both (CA)*100/A and (CA)*100/Amax are acceptable ways of calculating percent difference. As explained in Item 4 above, the first expression may give absurd results for relatively small and unimportant response values. It is incorrect to say that use of Amax is not meaningful. The use of Amax may be misleading only if one does not know that it is being used.

8. Under-Prediction

We consider staff findings, mean *under*-prediction of 10 percent for El Centro and 6 percent for Taft responses, more than 20 percent *under*-prediction of six out of 23 El Centro responses, and the largest *under*-prediction of 33 percent, consistent with the theory.

9. Average Results

No theoretical basis exists for stating "on the average, a response spectrum analysis will *over*-estimate response when compared to the time-history."

10. Nonclassically Damped Systems

As stated in Item 6, Gupta and Jaw have already analyzed 9 nonclassically damped systems using the response spectrum and time-history methods for 12 actual earthquakes. They have shown that, on the average, difference between results from the two methods is 1.33 percent for displacements and 0.48 percent for element forces. No computer program exists which is capable of performing time-history analysis of large nonclassically damped systems. Further, such an analysis is unnecessary.

11. Recent Changes in *CREST*

The original *CREST* used an approximate method of complex eigen-value solution that has given accurate results for a large range of parameters. One of the validation problems which was concocted for the ongoing review had some unusual characteristics that are not encountered in real life. The program did not work for the particular problem. Therefore, we replaced the approximate eigen-routine with a theoretically exact, validated routine taken from public domain archives of Oak Ridge National Laboratory. A large number of problems that were previously analyzed using the approximate routine were re-analyzed using the exact routine. The two sets of results were almost identical. The exact eigen-routine also worked for the unusual validation problem for which the original approximate routine did not.