Practical Application of CQC Modal Combination Technique for a Fuel Reprocessing Plant

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ABSTRACT

The complete quadratic combination mode combination technique is used to calculate seismic responses for the Chemical Separation Plant structure of the THORP complex. The CQC technique is compared to other mode combination techniques, such as absolute summation, SRSS and the 10 percent (grouping method) rules in R.G. 1.92, as well as the time history technique.

The CQC technique compares very closely with the time history technique. The R.G. 1.92 technique results in over 100 percent excess conservatism. The CQC technique is recommended as an acceptable alternative to R.G. 1.92 techniques.

1.0 INTRODUCTION

The NRC R.G. 1.92 (1) methodology for combining modal responses has come under close scrutiny by the engineering profession in recent years. Consequently, several improved combination techniques have been proposed in recent years. Because closely spaced modes can have opposite influence on each other, these techniques suggest that closely spaced modes should be summed algebraically rather than absolutely. One such technique which accounts for sign is the Complete Quadratic Combination (CQC) rule (2). Most previously published work describes CQC application in very simple 2D or 3D problems. Herein, we describe the CQC application for a large complex 3D structure. The conclusions we draw highlight the practical importance of CQC versus R.G. 1.92 rules. We strongly suggest that CQC be adopted as an acceptable procedure for nuclear plant qualification.

2.0 MODEL DESCRIPTION

The results presented herein are based upon a preliminary seismic analysis of the Chemical Separation Plant (CSP) (see Figures 1 and 2). The CSP is a part of the THORP (Thermal Oxide Reprocessing Plant) complex being built by British Nuclear Fuels.

The CSP is 137m x 77m in plan, and 37m tall. The CSP is composed of a series of large concrete cells, each about 20m x 20m in plan, and 25m tall. The typical wall thickness of these cells is 1m. Each cell is separated from neighboring cells by 5m to 10m. All cells are founded on one continuous basemat. Surrounding all the concrete cells is a light steel framed structure, which forms the exterior and roof of the CSP. The cells are interconnected by concrete floor diaphragms at three levels.

A computer model is developed to analyze the CSP. All descriptions herein pertain to the fixed-based analysis of the CSP, excluding soil-structure interaction effects. Each cell is represented with a lumped-mass and beam element model. Floor diaphragms are modelled as horizontal links, with suitable stiffness. The steel exterior and roof system is modelled with a series of beams, each representing individual cross-braced bays. The model has 685 nodes, 264 dynamic degrees-of-freedom, and 161 beam elements. The seismic input motion is characterized by a response spectra having spectral shape similar to R.G. 1.60, with maximum amplified frequency content from 5 Hz to 12 Hz, and peak ground acceleration of 0.25g. The same motion is used for all three directions of earthquake.

The first 78 modes of the structure are calculated, through 33 Hz. The major modes are as follows:

1.27 to 2.55 Hz:	East-West:	Steel Roof and Appendages
3.51 Hz:	North-South:	Steel Roof
4.18 Hz:	East-West:	Steel Roof (second mode shape)
7.34 to 8.42 Hz:	East-West:	Concrete Cells (several coupled modes)
9.33 to 10.45 Hz:	North-South:	Concrete Cells (two coupled modes)
13.39 to 26.79 Hz:	Vertical:	Concrete Cells (several modes)

A detailed summary of modal masses percentages in each mode is given in Table 1. From this table, we see the following:

- East-West cell response is dominated by four closely spaced modes, from 7.34 Hz to 8.42 Hz.
- North-South cell response is dominated by one mode at 9.33 Hz.
- Vertical cell response is spread through ten modes, ranging from 13.39 Hz. to 26.58 Hz.
- East-West steel roof response ranges from 1.27 to 4.18 Hz.
- North-South steel roof response is dominated by one mode at 3.51 Hz.

Another important observation is that the structure is characterized by 66 modes between 10.45 Hz and 33 Hz, all of which are "closely spaced" i.e., within 10 percent of the frequency of adjacent modes. Over 95, 95 and 80 percent of total mass for the North-South, East-West and Vertical directions, respectively, are included in the amplified frequency range of the input motion.

3.0 RESULTS: VARIOUS MODAL COMBINATIONS VERSUS CQC

Tables 2, 3, and 4 present the comparisons of four different methods of combining modal responses (ASUM, 1OPC, SRSS, CQC) and one time history analyses for the CSP. In these tables, ASUM means that all modes are combined by absolute summation; 10 PC means that modes are lumped into frequency groups, with at least a ten percent frequency shift between groups (as per R.G. 1.92) and modes within a group are absolute summed, and separate groups are SRSSd; SRSS means all modes are combined by Square Root of the Sum of the Squares; CQC means all modes are combined by Complete Quadratic Combination using the formulation presented in (2); T-H means results are calculated by mode superposition Time History analysis. Each of the response spectra results (ASUM, 10 PC, SRSS) are ratioed to the Time History results. There were a total of 836 force and moment comparisons, 264 accelerations comparisons and 264 displacement comparisons performed.

Table 2 presents mean ratios of seismic responses due to the three directions of earthquake. The three directions of earthquake are combined by SRSS, as per R.G. 1.92. Tables 3 and 4 present these comparisons due to individual directions of earthquake.

The following conclusions are drawn from Table 2:

- ASUM is naturally the most conservative. It overpredicts CQC results, on average, by 190 percent.
- 10PC (the R.G. 1.92 method) overpredicts CQC, on average, by 131 percent. Design forces are overpredicted, on an average, by 121 percent. In effect, the R.G. 1.92 method causes a nominal 0.25g motion to be as severe as a 0.55g motion. This calculation technique introduces <u>unnecessary</u> and <u>costly</u> conservatism into the seismic design process.
- SRSS compares closely to CQC (within a few percent), on average (but see below).

It is useful to compare these ratios before the three directions of earthquake are combined.

Tables 3 and 4 show that ASUM, 10PC and SRSS methods are consistently better at predicting responses in the direction of the earthquake (in-plane) than responses transverse to the earthquake (out-of-plane). The R.G. 1.92 (10PC) method disturbingly overpredicts out-of-plane response on average from 227 percent to 582 percent, depending on earthquake direction and the type of response parameter. Even SRSS suffers from this problem (overpredictions from 21 percent to 60 percent). This point was well brought out by Wilson et al in (2), where they note that SRSS or ASUM methods fail conservatively for out-of-plane response prediction for asymmetric three dimensional structures. Although three directional SRSS to CQC ratios compare closely in the present analysis, this is only accidental, as there are wide discrepencies of in-plane (too low) and out-of-plane (too high) comparisons. This "averaging" effect of in-plane and out-of-plane responses cannot be guaranteed for all types of structures, and hence, SRSS should not in general be used for design. Note that the results in Table 3 are based on a smaller sample size than in Table 2. Table 3 includes all responses for the concrete cells. Comparisons for the steel braces and the concrete floor diaphragms are similar.

Tables 3 and 4 also show that SRSS is a non-conservative predictor for in-plane responses for this structure. Inspection of Table 1 shows that this occurs because this structure has many closely spaced modes, requiring absolute summation (when mass participation factors are of the same sign).

4.0 <u>RESULTS: CQC VERSUS TIME HISTORY</u>

The results presented herein were validated by performing time history analyses using the mode superposition technique. The same mathematical model was used in both the response spectra and time history analyses. Synthetic time histories were developed having similar shape as the required smooth design response spectra. Generated spectra consistent with these synthetic time histories do not give an exact match to the smoothed design spectra; consequently for the CQC/T-H comparison consistent spectra were used. Time constraints limited this comparison to North-South and East-West time history analyses.

Tables 3 and 4 present the results of the CQC versus Time History comparison. As can be seen, CQC proves to be an excellent predictor for both in-plane and out-of-plane responses.

The CQC versus Time History ratios in Tables 3 and 4 are averages of a large sample. For licensing consideration, it is also important to look at the scatter in the ratios. Table 5 gives the standard deviations associated with the mean ratios given in Tables 3 and 4. The in-plane scatter is smaller than the out-of-plane scatter. No single in-plane CQC/T-H ratio was less than 0.90.

5.0 CONCLUSIONS

A large complex three-dimensional structure has been rigorously analyzed using the CQC, ASUM, SRSS and R.G. 1.92 (10PC) response spectra techniques. Over 1000 comparisons were made between these techniques. If the structure had been designed based upon the R.G. 1.92 technique, then unnecessary and costly conservatism of over 100 percent would have been introduced. If the structure had been designed based upon the SRSS technique, then some under and over design would have occurred in various areas of the structure. The CQC technique for all practical purposes would result in adequate and not unduly conservative design for all areas of the structure.

The CQC results were compared against explicit time history results. Excellent agreement was found. No CQC design forces were more than 10 percent below equivalent Time History design forces. For design, the calculated seismic response needs to be increased to account for missing mass. Missing mass corrections can be made with either pseudo-static analysis methods, such as in (3), or with "narrow banded" CQC methods, such as in (4). Details of such corrections are beyond the scope of this paper.

These results present strong evidence supporting acceptance of CQC as an alternative to R.G. 1.92 mode combination techniques.

6.0 REFERENCES

1. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.92, Revision 1, 1976.

2. Wilson, E.L., Der Kiureghian, A., Bayo, E.P., "A Replacement for the SRSS Method in Seismic Analysis," Earthquake Engineering and Structural Dynamics, Vol. 9, No. 2, 1981.

3. Powell, G.H., "Missing Mass Correction in Modal Analysis of Piping Systems," Smirt Paper K10/3, Berlin, 1979.

4. Der Kiureghian, A., "On Response of Structures to Stationary Excitation," Earthquake Engineering Research Center, Berkeley, EERC-79-32, 1979.

Table I. Modal Masses (78 Modes)

	MODAL MASS		
FREQUENCY (Hz)	NORTH-SOUTH (%)	EAST-WEST (%)	VERTICAL (%)
1.27	.0	2.1	.0
2.43	.0	2.0	.0
2.55	.1	2.8	.0
3.19	.7	.1	.0
3.51	7.3	.4	.0
4.18	.3	3.2	.0
7.34	1.3	9.6	.0
7.42	.0	42.6	.0
7.94	4.2	8.3	.0
8.42	.7	7.3	.0
8.51	.0	.2	.0
9.33	59.3	.0	.0
10.45	4.5	.0	.0
10.87	.0	.0	.9
10.98	2.4	.7	.1
11.90	.0	.0	.1
12.56	.3	1.6	.3
13.39	.4	.2	4.0
13.58	.6	.9	17.0
13.78	.8	.1	.8
14.39	.2	.8	1.3
14.85	1.0	1.7	.9
15.20	.1	.9	.0
15.92	.0	.3	.0
16.12	.2	3.2	.2
16.57	.0	.8	.3
17.05	.0	.3	.7
17.20	.1	1.9	.1
17.67	.3	.8	3.2
17.89	.7	.0	1.5
18.09	.8	.8	.5
18.41	.2	.0	.0
18.79	.7	.3	1.6
19.13	.0	.4	.3
19.31	.2	.0	5.9
19.85	.7	.0	.0
20.21	.3	.0	.1
20.25	.5	.0	.1
20.40	.0	.3	3.9
20.66	.4	.0	1.1
21.14	1.6	.0	.7
21.37	.1	.2	.3
21.67	.8	.0	.1

Table 1. Modal Masses (78 Modes)
(Continued)

FREQUENCY (Hz)	MODAL MASS NORTH-SOUTH (%)	EAST-WEST (%)	VERTICAL (%)
21.91	.0	.0	1.6
22.01	.0	.3	8.5
22.31	.0	.4	.3
22.87	.2	.1	1.1
22.91	1.1	.0	1.4
23.33	.3	.4	3.9
23.43	.3	.3	1.0
23.50	.2	.1	.1
23.73	.2	.1	.8
24.45	.5	.1	4.8
24.57	.1	.3	1.2
25.07	.0	.0	.1
25.30	1.2	.0	.6
25.60	.0	.1	.7
25.74	.1	.0	2.4
25.94	.0	.0	1.3
26.52	.0	.0	.7
26.58	.0	.0	.2
26.79	.0	.0	3.1
27.36	.8	.1	1.0
28.03	.0	.1	1.4
28.44	.0	.0	.0
28.92	.0	.1	.0
29.10	.0	.2	.3
29.18	.1	.2	.1
29.75	.0	.0	.0
29.89	.0	.2	.0
30.45	.0	.0	.1
30.77	.3	.1	.4
30.98	.1	.0	.6
31.31	.0	.1	.1
32.09	.0	.2	.0
32.40	.2	.2	.4
32.88	.0	.0	.6
32.98	.3	.0	.1
	98.1	98.7	84.6

Table II. Comparisons: Mean Ratios of All Design Data
Due to Three Directions of Input

	ASUM CQC	10PC CQC	SRSS CQC	Observations
All Components	2.90	2.31	1.02	1364
Forces and Moments	2.86	2.21	1.04	836
Acceleration	3.61	3.18	1.04	264
Displacement	2.30	1.77	0.94	264

TABLE III. Comparisons: Mean Ratios of All Forces and Moments Due to Single Earthquake Input

	ASUM CQC	10PC CQC	SRSS CQC	CQC T-H	Observations
NS - Total	3.81	2.77	1.15	1.03	304
- In-Plane	2.18	1.46	0.92	0.98	114
- Out-of Plane	4.79	3.56	1.29	1.05	190
EW - Total	3.70	2.58	1.05	1.05	304
- In-Plane	2.06	1.43	0.78	1.00	114
- Out-of-Plane	4.68	3.27	1.21	1.07	190
VT - Total	5.24	5.03	1.26	N/A	304
- In-Plane	2.26	2.26	0.69	N/A	38
- Out-of-Plane	5.66	5.43	1.34	N/A	266

TABLE IV. Comparisons: Mean Ratios of All Accelerations Due to Single Earthquake Input

	ASUM CQC	10PC CQC	SRSS CQC	CQC T-H	Observations
NS - Total	4.74	3.92	1.26	1.07	264
- In-Plane	2.59	2.00	0.91	1.04	88
- Out-of-Plane	5.81	4.88	1.43	1.08	176
EW - Total	5.21	4.34	1.31	1.00	264
- In-Plane	2.76	2.05	0.89	0.98	88
- Out-of-Plane	6.44	5.49	1.51	1.00	176
VT - Total	6.29	5.44	1.45	N/A	264
- In-Plane	2.44	2.43	0.70	N/A	44
- Out-of-Plane	7.06	6.82	1.60	N/A	220

TABLE V. CQC/T-H Comparisons: Standard Deviations

	Force and Moments	Acceleration
NS - Total	.09	.14
- In-Plane	.03	.05
- Out-of-Plane	.11	.16
EW - Total	.13	.12
- In-Plane	.06	.08
- Out-of-Plane	.15	.13

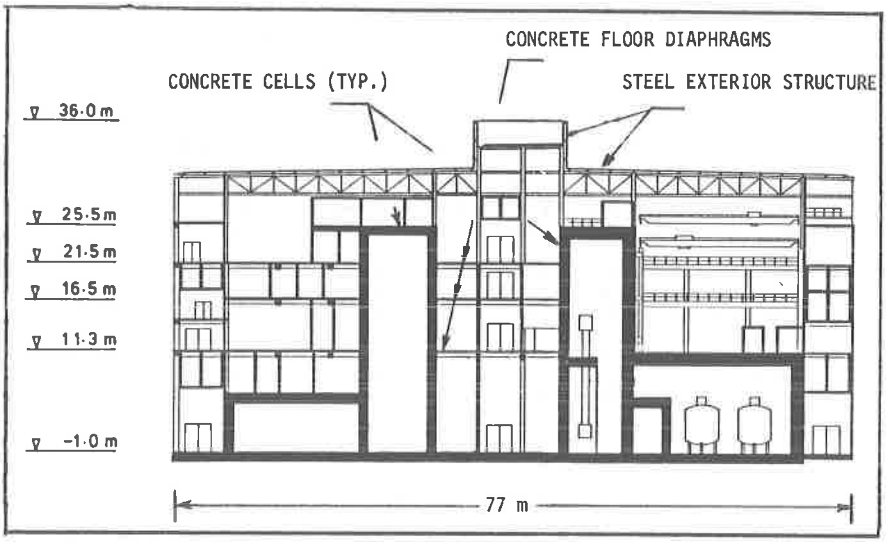
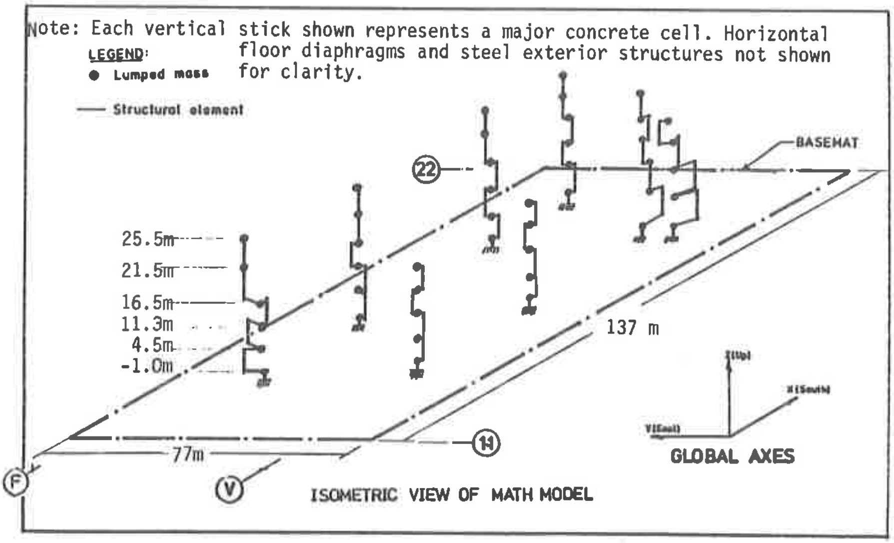


FIGURE 1. SECTION VIEW OF CHEMICAL SEPARATION PLANT



Note: Each vertical stick shown represents a major concrete cell. Horizontal floor diaphragms and steel exterior structures not shown for clarity.

FIGURE 2. MATHEMATICAL MODEL OF CHEMICAL SEPARATION PLANT