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ALTERNATE MODAL COMBINATION METHODS* IN RESPONSE SPECTRUM ANALYSIS

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ABSTRACT

In piping analyses using the response spectrum method Square Root of the Sum of the Squares (SRSS) with clustering between closely spaced modes is the combination procedure most commonly used to combine between the modal response components. This procedure is simple to apply and normally yields conservative estimates of the time history results. The purpose of this study is to investigate alternate methods to combine between the modal response components. These methods are mathematically based to properly account for the combination between rigid and flexible modal responses as well as closely spaced modes. The methods are those advanced by Gupta, Hadjian and Lindley-Yow to address rigid response modes and the Double Sum Combination (DSC) method and the Complete Quadratic Combination (CQC) method to account for closely spaced modes. A direct comparison between these methods as well as the SRSS procedure is made by using them to predict the response of six piping systems. For two piping systems thirty-three earthquake records were considered to account for the impact of variations in the characteristics of the excitation. The results provided by each method are compared to the corresponding time history estimates of results as well as to each other. The degree of conservatism associated with each method is characterized.

INTRODUCTION

The response spectrum method is most commonly used to estimate the dynamic response of piping systems. In this method a response quantity is computed for each mode, each direction of excitation and each input if multiple inputs are considered. The total response is then formed by summing over all modes, inputs and directions of excitation using combination rules which should provide acceptable estimates of the true system response. Although the United States Nuclear Regulatory Commission (USNRC) has defined explicit rules to perform these combinations, new and alternate combination methods, which potentially provide better estimates of true system response, have been advanced.

This study was undertaken to respond to the USNRC Piping Review Committees recommendations [1] to investigate alternate modal combination methods and to assess the impact of their use on Nuclear Power Plant Piping design. Specifically, three methods to account for frequency dependent correlation effects and three methods to address closely spaced modes are evaluated in this study. To account for frequency effects, the methods advanced by A.K. Gupta, A.H. Hadjian and D.W. Lindley - J.R. Yow are considered. To address closely spaced modes, the Rosenblueth Double Sum Combination (DSC) method, the Complete Quadratic Combination (CQC) method and the conventional square-root-sum-of-squares (SRSS) method are considered. The adequacy or impact of these alternate methods are established by the comparison of the response spectrum estimates of response developed using these methods to time history estimates of the same response quantities.

DESCRIPTION OF CANDIDATE METHODS

Three methods to account for frequency dependent correlation effects have been evaluated. These are the methods advanced by A.K. Gupta [2], A.H. Hadjian [3] and D.W. Lindley - J.R. Yow [4].

In each of these methods the modal responses are considered to consist of two components, a rigid component, RR_i, and a damped periodic component, RP_i, where i is the mode number. All the rigid components are considered to be perfectly correlated with the input ground motion and are thus perfectly correlated with each other. The total rigid response, then, is appropriately given by the algebraic sum of all the modal components of rigid response. That is:

$$RR = \sum_{i=1}^{n} RR_i \qquad (1)$$

*This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, DC.

where n is the total number of modes.

The damped periodic components, on the other hand, are considered to exhibit the variable degree of correlation normally associated with modal responses. Their sum is provided by any of the candidate modal combination rules which properly account for intermodal correlation as a function of frequency. That is:

$$RP = \left(\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk}\, RP_j\, RP_k \right)^{1/2} \quad (2)$$

where the C_{jk} are modal coupling factors, the expression for which varies with the combination rule. In this study the DSC, CQC and SRSS combination rules are used to form this sum.

The methods differ in the specific definition of the rigid body and damped periodic modal response components and in the method used to sum between the total rigid body and total damped periodic responses to form the total response.

For the methods advanced by A.K. Gupta and Lindley-Yow the rigid and periodic response components are given by:

$$RR_i = R_i \alpha_i \quad (3)$$

$$RP_i = R_i \, (1 - \alpha_i^2)^{1/2} \quad (4)$$

where R_i is the predicted modal response corresponding to frequency f_i. For the former method the coefficients α_i are given by:

$$\alpha_i = 0, \; f_i < f_1$$

$$\alpha_i = (\log (f_i/f_1))/\log(f_2/f_1), \; f_1 \leq f_i \leq f_2 \quad (5)$$

$$\alpha_i = 1.0, \; f_i > f_2$$

with

$$f_1 = S_{a\ max}/(2\pi S_{v\ max}) \quad (6)$$

$$f_2 = (f_1 + 2\ f_r)/3 \quad (7)$$

where $S_{a\ max}$ and $S_{v\ max}$ are the maximum spectral acceleration and velocity of the input and f_r is the frequency at which the spectral acceleration returns to the zero period acceleration (ZPA). For the latter method the coefficients α_i are given by:

$$\alpha_i = ZPA/S_{ai} \text{ and } 0.0 \leq \alpha_i \leq 1.0 \quad (8)$$

where ZPA is the zero period acceleration and S_{ai} is the spectral acceleration for the mode i. In both these methods the rigid and periodic components of response are considered to be uncorrelated and therefore the total response is given by:

$$R = (RR^2 + RP^2)^{1/2} \quad (9)$$

For the method advance by Hadjian the modal coefficients are given by:

$$\alpha_i = ZPA/S_{ai} \text{ and } 0.0 < \alpha_i < 1.0 \quad (10)$$

and the rigid and periodic response components are:

$$RR_i = R_i \; i \quad (11)$$

$$RP_i = R_i \, (1 - \alpha_i) \quad (12)$$

In this method the rigid and periodic response components are assumed to be in phase and consequentially the total response is given by their absolute sum:

$$R = |RR| + |RP| \quad (13)$$

Three alternate methods are also considered to perform the combination of the periodic components of response. These are SRSS combination with no correction for closely spaced modes, the Rosenblueth Double Sum Combination rule [5] and the Complete Quadratic Combination rule [6]. In each of these methods, the damped periodic components of response are combined by:

$$RP = \left(\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk}\; RP_j\; RP_k \right)^{1/2} \quad (14)$$

where the C_{jk} are the modal coupling coefficients. For simple SRSS combination

$$C_{jk} = 1.0 \text{ for } j=k$$
$$C_{jk} = 0.0 \text{ for } j \neq k \quad (15)$$

For the DSC and CQC methods the modal coupling coefficients are functions of the natural frequencies, damping ratios and the duration of excitation involved in the system. Their derivation are theoretically based in random vibration theory and, with the coefficients taking on values ranging from 0.0 to 1.0, define the degree of correlation between modes j and k.

PROBLEM SET DESCRIPTION

The problem set consisted of the same six piping systems used in the BNL evaluations of the Independent Support Motion (ISM) method. The systems are identified as; the RHR piping model, the AFW piping model, the Z-bend piping model, and the BM1, BM2 and BM3 piping models. Each of these system models are fully described in the ISM report [7].

The RHR and AFW piping systems are housed in the containment structure of the Zion Nuclear Power Plant in Illinois. The containment structure consists of the containment shell and a separate concrete internal structure supporting a four-loop PWR nuclear steam supply system. Details pertaining to this system were made available to BNL by LLNL who analyzed it as part of the Zion SSMRP studies performed by Lawrence Livermore Laboratory for NRC [8]. In this study, the response of each of these two systems to thirty three different seismic events was determined. In each evaluation only uniform, one directional (x direction) excitation of the supports was considered. The characteristics of these problems are summarized, along with the characteristics for the remaining problems in the set, in table 1. A sketch of the RHR problem model is shown in figure 1.

The remaining four systems were selected to add depth to the study. The Z bend is a simple planar system exhibiting high natural frequencies. It simulates a system subjected to extensive laboratory testing in earlier studies. The BM1 and BM2 problems both involve the same piping model, figure 2. In BM1 the piping was considered to be part of a PWR system and the inputs to the model were derived from a 3D analysis of a PWR structure. For BM2 the piping was assumed to be part of a BWR system. The inputs for this problem were derived from a 1D stick model of a BWR structure. Lastly the BM3 model is a portion of a piping system from the HFBR Test Reactor at BNL. The input for this model was derived from a 2D frame model of a Test Reactor structure. For each of these four problems the response of the piping was determined for *uniform excitation of all supports in the X direction.*

For all problems a time history estimate of response, a response spectrum estimate of response based on the URS method and SRSS summation with absolute combination between closely spaced modes (NRC accepted procedure) and response spectrum estimates of response based on the URS method and modal combinations using the candidate methods, were developed. In each case the time history estimate of response was developed using the modal superposition method of solution and considering all modes below a cutoff frequency of 100 Hz. In the response spectrum calculations only raw or unbroadened input spectra were used and again only the modes below a cutoff frequency of 100 Hz were considered. The time history estimate of results was taken to be the best estimate of actual response and, as noted below, was used to gauge the adequacy of the response spectrum solution for each candidate method.

RESULTS AND CONCLUSIONS

The basic results of study are estimates of pipe end moment and support force for each problem. These are summarized in a tabular format where the data actually listed in the tables are the percentages by which the response spectrum estimate of a parameter exceeded the time history estimate of that parameter. This percentage is termed the Degree of Exceedance and is given by:

DOE = 100(RS-TH)TH.

where RS is the response spectrum and TH the time history estimate of response respectively. The table of support force results for the BM2 problem is reproduced as table 2. As can be seen, nine response spectrum results corresponding to the candidate methods as well as a response spectrum result corresponding to accepted methodology (Reg. 1.92) and the time estimate of results are provided. For the AFW and RHR problems, where thirty-three seismic events were considered, the tabulated results are the mean value of the DOE results over the thirty-three seismic events.

The study results have also been depicted in graphical form. Figures 3 and 4 show the results for the BM2 and RHR problems respectively. On each figure the data shown on the upper half corresponds to the support force results while the data shown on the lower half corresponds to the pipe moment results. Each data point on these figures corresponds to the estimated response for a nodal point or element in the system. If two or more points have the same magnitude, they are shown adjacent to each other. The figures thus show the distribution and dispersion of the results throughout the system. For the RHR problem, the results depicted are the mean values of the response components over thirty-three seismic events.

A review of the two figures leads to the following observations. All of the methods underestimate the time history estimate of response to varying degrees (negative DOE values). This trend would disappear or would be markedly reduced if broadened rather than raw spectra were used in the evaluations. The currently accepted method, right most data sets, shows the greatest dispersion, with the outlier points exhibiting the greatest conservatism, of all the methods. Regarding the combination of closely spaced modes, DSC vs. CQC vs. SRSS, little variation is noted. For these two problems the closely spaced modes apparently did not participate in the response. Considering the methods to account for frequency dependent correlation effects, the methods advanced by Gupta and Lindley/Yow provide essentially comparable results with the Gupta method however showing the minimum dispersion. The method advanced by Hadjian shows more dispersion than the former methods but not the larger dispersion exhibited by the currently accepted method. If dispersion alone were the criteria of judgement, the Gupta or the Lindley/Yow methods would be the methods of choice.

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NOTE:

The following Tables and Figures are a DRAFT copy. The final copies are not available yet.

Table 1 - Model Parameters

Model	Structure	No. of Equations	Pipe Size	Pipe Frequencies 1st, 2nd	No. of Seismic Events	No. of Modes Used	No. of Moments	No. of Support Forces
RHR	Zion (3D)	423	8", 12"	3.86, 8.11	33	47	22	15
AFW	Zion (3D)	945	3", 16"	2.86, 3.76	33	89	23	28
Z-Bend	ANCO Test (3D)	204	4"	8.67, 17.42	1	6	39	16
BM 1	PWR (3D)	336	2", 6"	5.05, 14.63	1	27	5[illegible]	
BM 2	BWR (Stick)	336	2", 6"	5.05, 14.63	1	27	5[illegible]	
BM 3	Test Reactor	228	3", 4", 8"	2.91, 4.39	1	32	3	

Table 2

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*              *
* BM2   MODEL  *
*              *
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EARTHQUAKE NO. 1 *SUPPORT FORCES(INERTIA COMPONENT)

ELEM NO.	FORCE CODE	FORCE (T.H.)	GUPTA DSC	GUPTA CQC	GUPTA SRSS	HADJIAN DSC	HADJIAN CQC	HADJIAN SRSS	LINDLEY + YOW DSC	LINDLEY + YOW CQC	LINDLEY + YOW SRSS	SRSS WITH CLUSTERING (REG 1.92)
1	1	.45733E+03	-8	-8	-8	-7	-7	-7	-16	-16	-16	-48
2	1	.27474E+02	9	9	9	25	25	25	17	17	17	140
3	1	.28694E+03	-20	-20	-20	-22	-22	-22	-34	-34	-34	-7
4	1	.27359E+04	-38	-38	-38	-50	-50	-60	-53	-53	-53	26
5	1	.32791E+04	1	1	1	6	6	6	3	3	3	-11
6	1	.48147E+04	-8	-8	-8	-8	-8	-8	-18	-18	-18	-34
7	1	.17247E+03	-2	-2	-2	-2	-2	-2	-4	-4	-4	-19
8	1	.25657E+03	-34	-34	-34	-43	-43	-43	-49	-49	-49	-22
9	1	.55008E+03	-28	-28	-28	0	0	0	-14	-14	-14	-37
10	1	.19476E+03	-45	-45	-45	-71	-71	-71	-53	-53	-53	-32
11	1	.26688E+03	-9	-9	-9	-9	-9	-9	-19	-19	-19	-27
12	1	.62348E+02	-48	-48	-48	-42	-42	-42	-45	-45	-45	97
13	1	.17993E+02	7	7	7	48	48	48	30	30	30	210
14	1	.40124E+02	-49	-49	-49	-44	-44	-44	-46	-46	-46	-20
15	1	.50069E+02	-23	-23	-23	-28	-28	-28	-35	-35	-34	181
16	1	.51085E+02	-49	-49	-49	-44	-44	-44	-46	-46	-46	25
17	1	.71944E+02	-22	-22	-22	11	11	11	-4	-4	-4	79
18	1	.16132E+03	-41	-41	-41	-56	-56	-56	-53	-53	-53	-21
19	1	.13626E+02	29	29	30	-55	-54	-54	30	31	32	206
20	1	.23517E+01	-10	-10	-10	28	28	28	18	18	17	497
21	1	.14619E+02	-48	-46	-48	-43	-43	-43	-46	-46	-46	-37
22	1	.31458E+03	-37	-37	-37	-15	-15	-15	-27	-27	-27	-43
23	1	.14769E+02	28	28	28	12	12	12	35	36	36	153
24	1	.58071E+02	-45	-45	-45	-70	-70	-70	-53	-53	-53	-31
25	1	.18761E+03	-41	-41	-41	-55	-65	-55	-54	-54	-54	-49
26	1	.80015E+02	-36	-36	-36	-26	-26	-26	-31	-31	-30	-21
27	1	.28164E+02	15	15	15	52	52	52	33	33	33	-2
28	1	.38605E+02	8	8	8	32	32	32	20	20	20	0
29	1	.26884E+02	20	20	21	37	37	37	30	30	30	27
30	1	.48094E+03	8	8	8	31	31	32	20	20	20	0
31	1	.20298E+04	-32	-32	-32	-39	-39	-39	-47	-47	-47	-46
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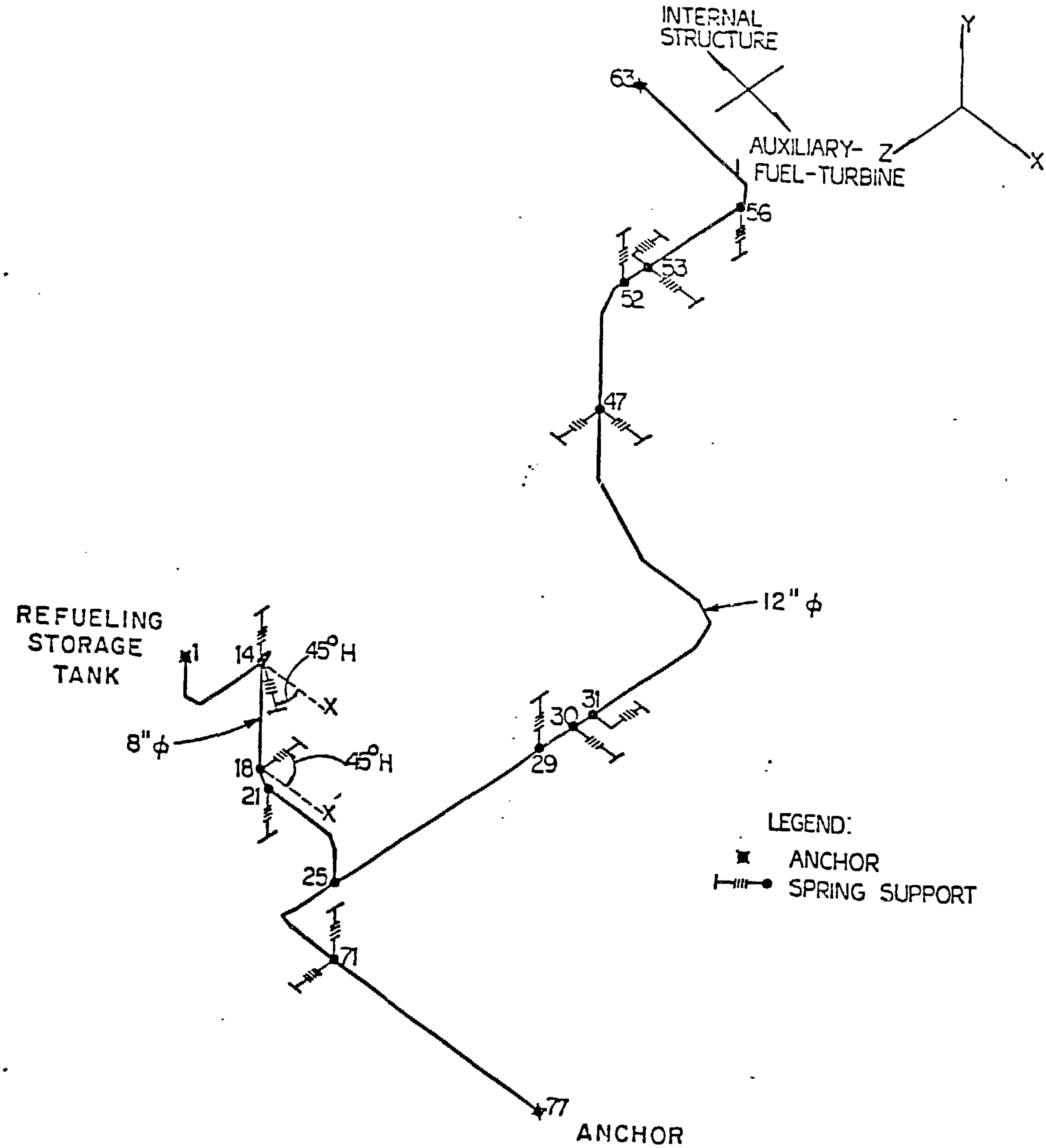


Figure 1 - RHR Piping Model

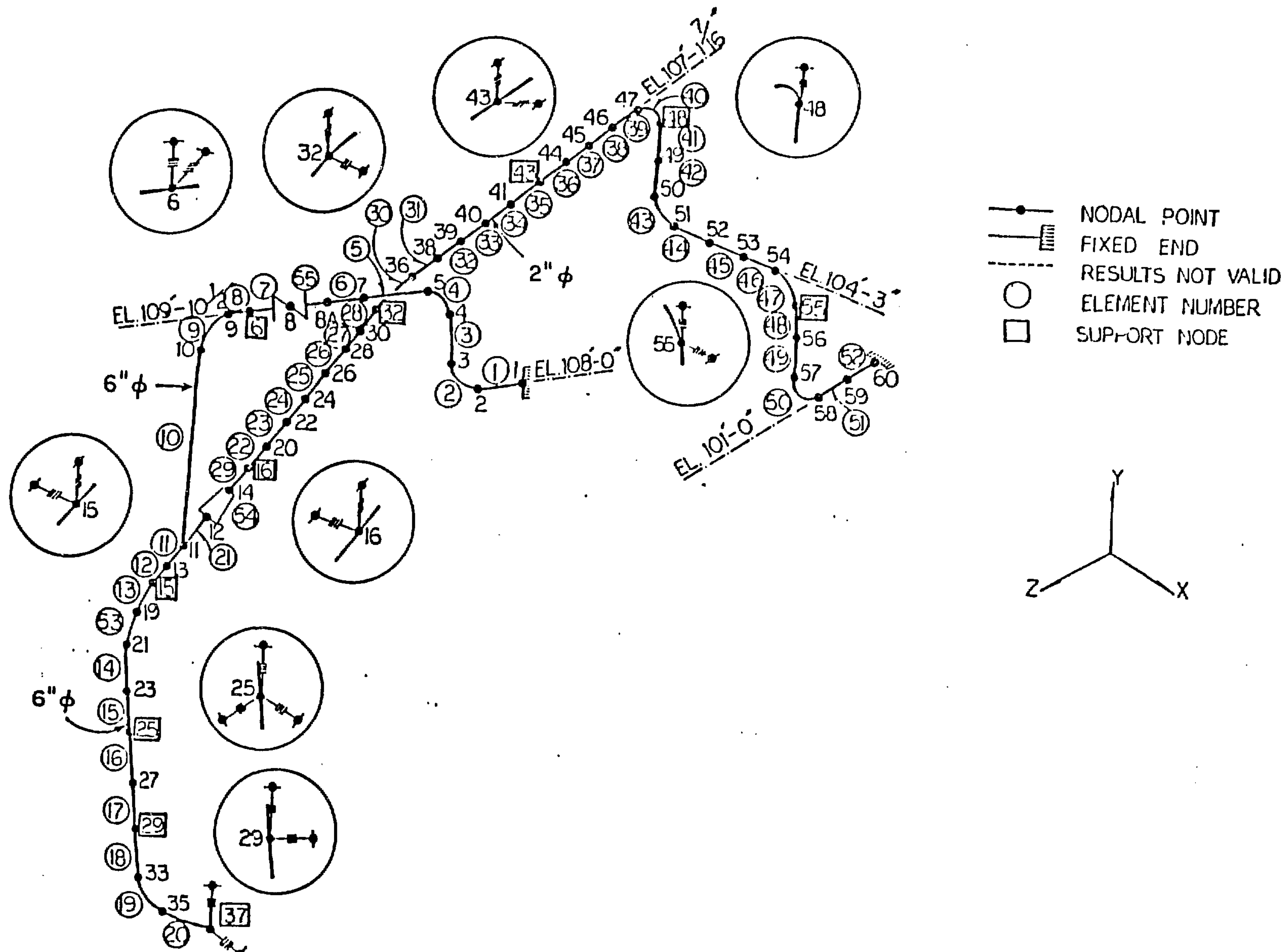
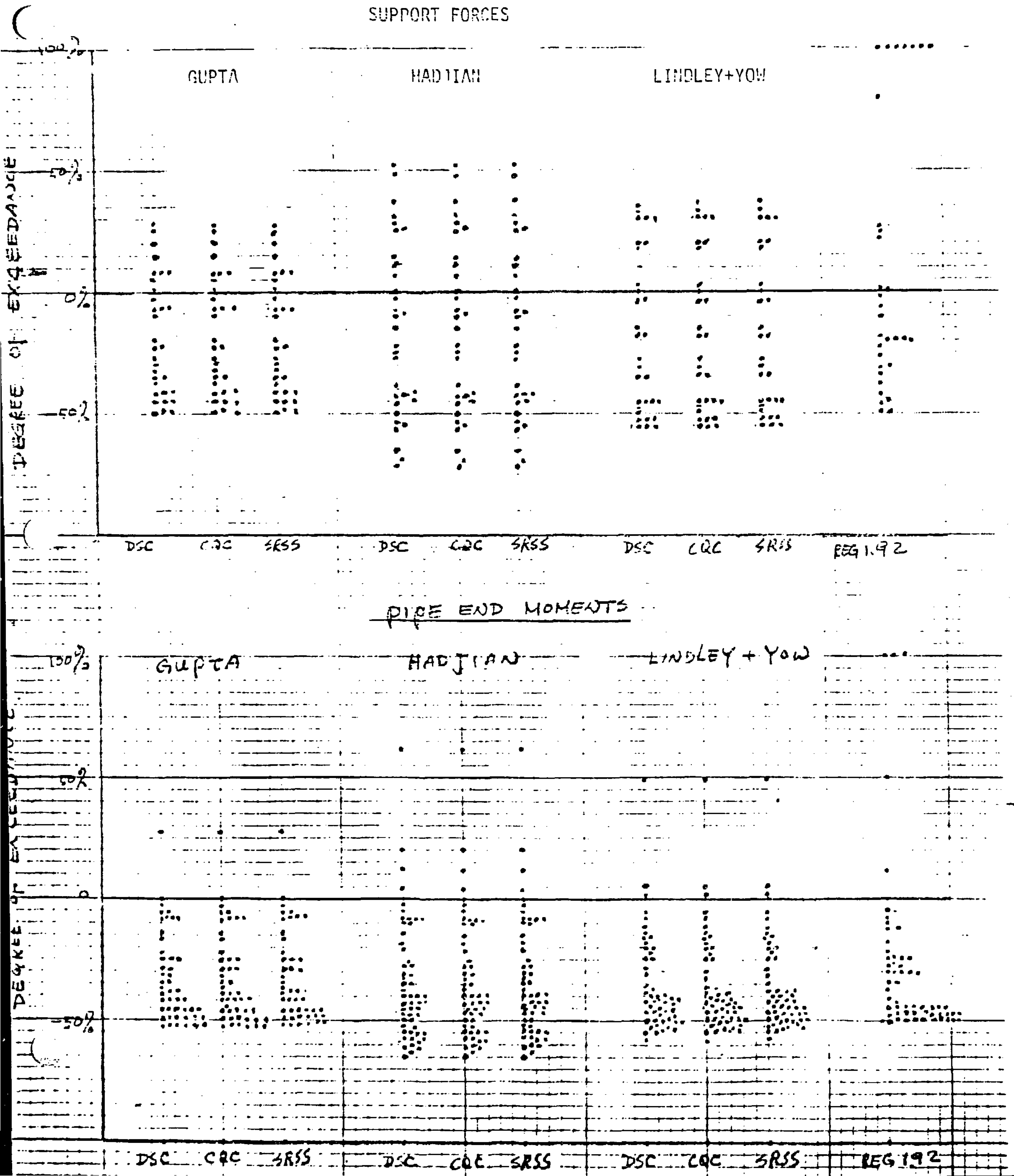


Figure 2 - BM1 and BM2 Piping Model

FIGURE 3

BM2



SUPPORT FORCES
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-50%
DEGREE OF EXCEEDANCE
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HADJIAN
LINDLEY+YOW
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CQC
SRSS
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REG 1.92
PIPE END MOMENTS
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DEGREE OF EXCEEDANCE
GUPTA
HADJIAN
LINDLEY + YOW
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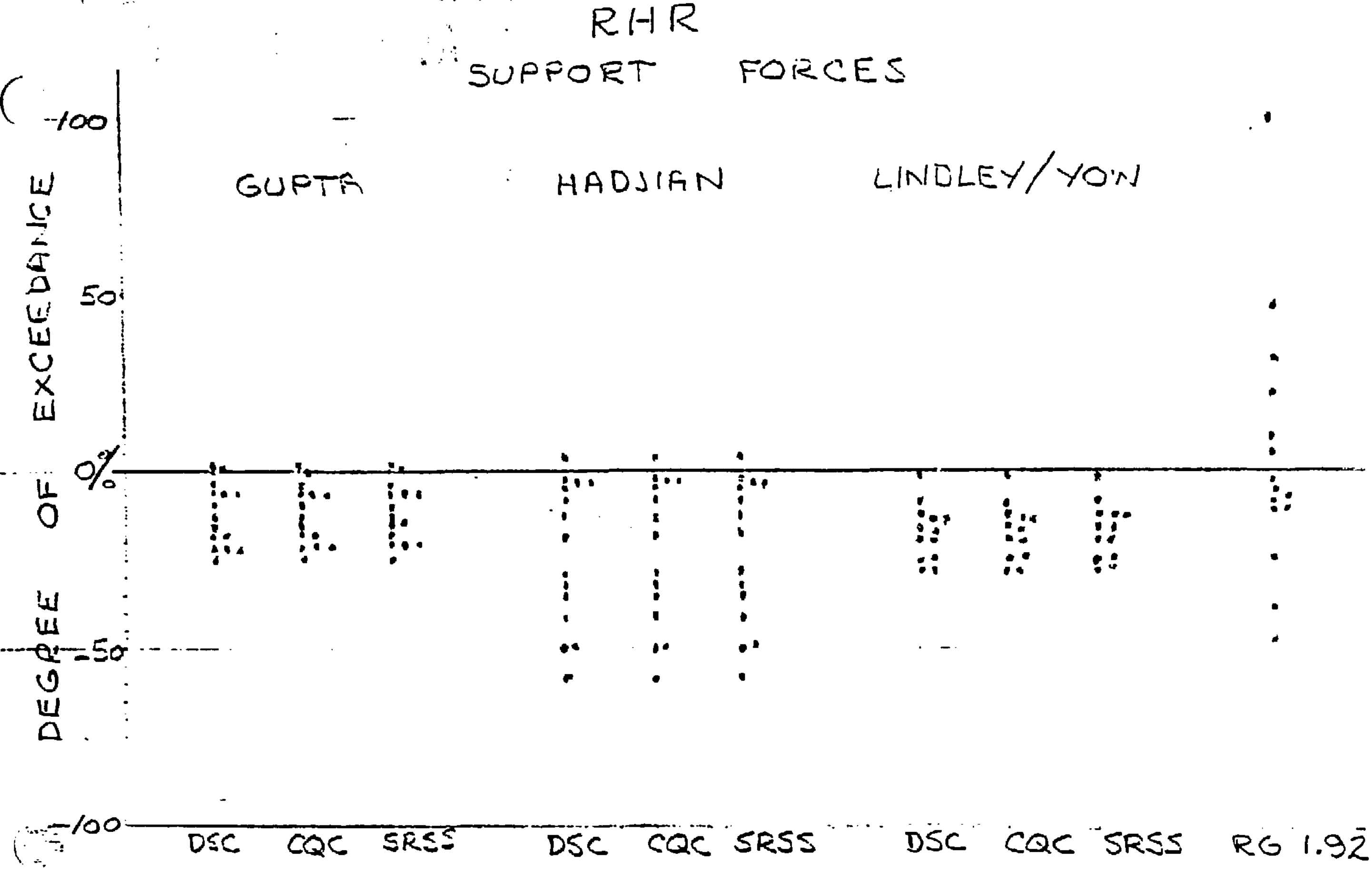
FIGURE 4


RHR
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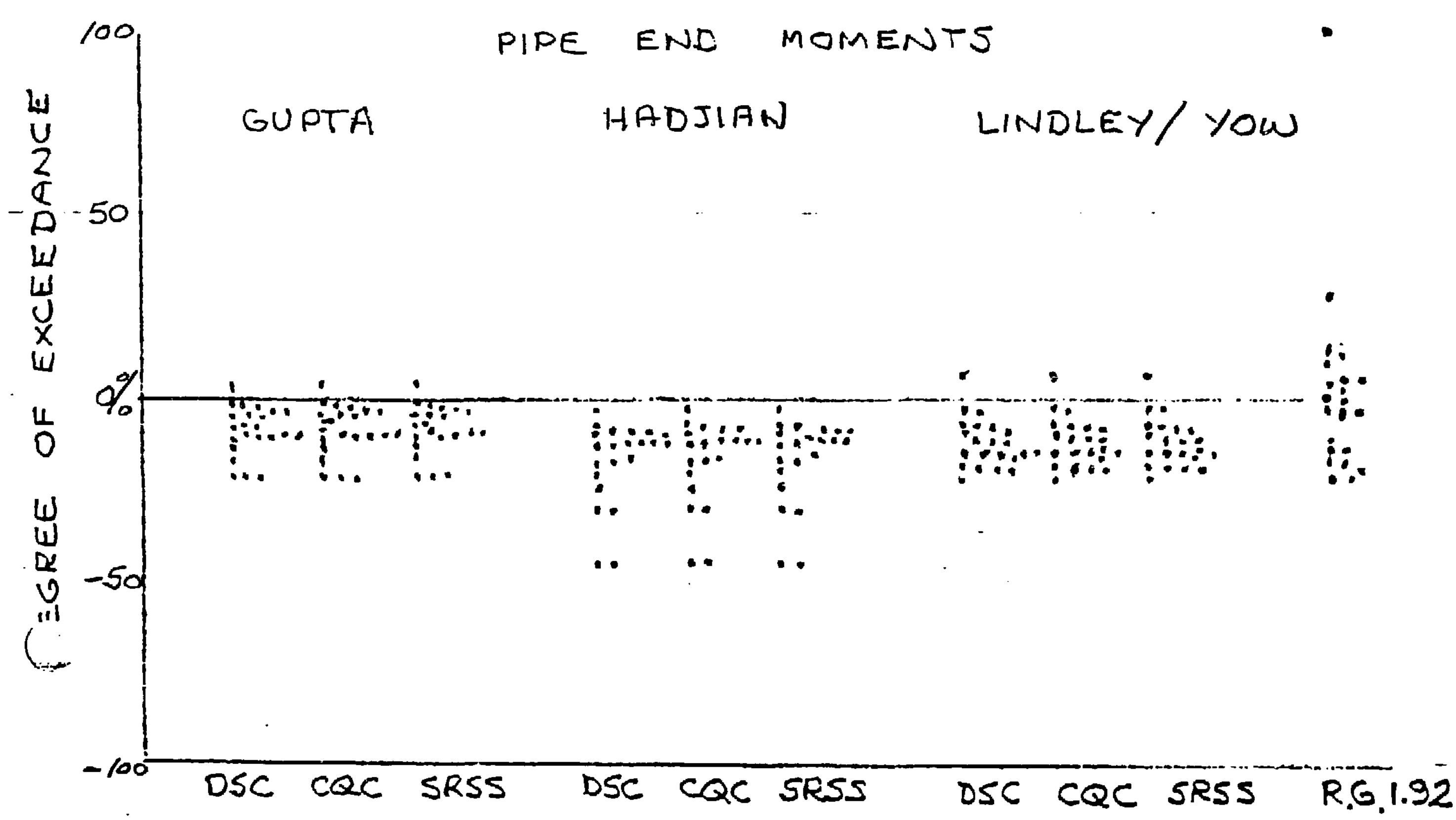
PIPE END MOMENTS
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