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Seismic Analysis of Piping Systems Subjected to Independent-Support Excitation

By

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Abstract

This paper presents a comparison of dynamic responses of piping systems subject to independent support excitation using the response spectrum and time history methods. The BNL finite element computer code 'PSAFE2' has been used to perform all the analyses. The time history method combines both the inertia as well as static effect on the piping responses due to independent support excitations at each time point, thus representing the actual responses. A sample problem is analysed subjected to two independent support excitations and the results are presented in comparison with the response spectrum methods with uniform or independent support motion.

Introduction

In the past decade, several investigators have studied the problem of independent support excitation of a piping system to identify the real need for such an analysis. Penzien and Clough [1]* have presented the matrix formulations in their book for developing a computer analysis. Memmott and Vinson [2] later implemented this in their piping code and found the methodology works well against SAP IV time history results. Vashi's [3] work identified the so-called pseudo-static and dynamic components and their importance in such an analysis. His work was directed towards the formulation details and has indicated the importance of each stress result. Later, Wu, Hussain and Liu [4] compared the results obtained by independent support response spectrum analysis against the conventional umbrella spectrum results and time history results. Recent work by Leimbach and Schmid [5] on an automated procedure for such analysis and by Leimbach and Sterkel [6] on some real piping system analyses concluded that such an analysis offers an increase in accuracy at a small increase in computational costs.

All the above studies describe the mathematical formulations for an analysis with independent support movements and identify the influence of each parameter involved without quantitative clarifications. Specifically, the pseudo-static component has been identified qualitatively without any results to show its contribution to the total response of such a system. Therefore, this work was undertaken to make a study of the approach and its impact on current design practice.

The method is formulated by a basic and rational mathematical procedure in a general form, for a realistic computation of the seismic response of a piping

*Numbers in brackets [ ] designate references in section 5 of this paper system. The conventional approach with uniform excitation is derived from this general formulation. The response spectrum method accounts for the contribution of individual excitations acting at each support group through a modified definition of the modal participation factors. In the time history method a time dependent modal load vector corresponding to each support group is defined. Both approaches, as can be seen from the formulations, predict the maximum dynamic (inertial) response of the mass points in a typical piping system. In order to complete the analysis, the pseudo-static component is determined to find the total response and hence the pipe forces/moments at each point. For the response spectrum method the static component of the response is lost during the process of developing the spectra which defines the maximum response of the system at different frequencies. The only way to include the static effects in this case is to perform a separate seismic anchor movement analysis. In the time history method, this component is calculated directly from the ground displacements by using the influence coefficient matrix. The total response is then calculated by combining these pseudo-static components to the dynamic component. In this paper some preliminary conclusions regarding the group combination methods and the pseudo-static component of the responses are discussed.

Theoretical Formulation

The equations of motion for a three-dimensional piping system subject to independent support excitation in the general matrix form can be written as:

$$\begin{Bmatrix} M_P & 0 \\ 0 & 0 \end{Bmatrix} \begin{Bmatrix} \ddot{X} \\ \ddot{Z} \end{Bmatrix} + \begin{Bmatrix} C_P & C_{PB} \\ C_{BP} & C_B \end{Bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Z} \end{Bmatrix} + \begin{Bmatrix} K_P & K_{PB} \\ K_{BP} & K_B \end{Bmatrix} \begin{Bmatrix} X \\ Z \end{Bmatrix} = \begin{Bmatrix} 0 \\ F_B \end{Bmatrix} \tag{1}$$

where, a dot over a variable denotes differentiation with respect to time, and subscripts 'P' and 'B' represent the quantities for the piping points and the boundary points respectively. The subscripts 'PB' and 'BP' denote the coupling terms between the piping and boundary points and are transpose to one another. The following are the explanations for the other variables:

M = lumped mass matrix of the piping system
C = the damping matrix
K = the stiffness matrix
X = the displacement response of the piping structure
Z = the displacement response of the support points
F_B = the Reaction Forces at the support points

Both equations can be solved directly provided the displacement and the velocity input histories at the support points are known, and the damping mechanisms can be modeled in the piping system. In practice, the ground accelerations are the only ground input known for the purpose of analysis. Also damping in both the response spectrum method and the time history method is usually introduced as modal damping instead of the general damping matrix depicted in the formulation.

It's assumed that the total response of the piping degrees of freedom consists of two individual components. One component, known as the dynamic or inertial component, is due to the inertia forces generated by the mass points in the piping system and the frequency of excitation of the ground. Thus, it is explicitly dynamic in nature. The second component, on the other hand, has nothing to do with the piping mass. It is caused by the differential ground motion between different boundary attachments when the piping system is subject to independent support motions. This component does not exist in case all support points are excited simultaneously with identical excitation. Since the ground excitation is a function of time, this component is also a function of time. It is termed the pseudo-static component because of its characteristic of deforming the piping system similar to a static ground motion.

Having this in mind, the total response may be expressed as the sum of the dynamic and pseudo-static component where

$$X = X_D + X_S \tag{2}$$

X = total response of the piping system
X_D = dynamic or inertial component of the response
X_S = pseudo-static component of the response

In order to find the static component, the dynamic components are set equal to zero in equation (1). Equation (1) then gives rise to the definition of the pseudo-static component. It is:

$$X_S = -K_P^{-1} K_{PB} Z \tag{3a}$$

$$K_{PB} X_S + K_B Z = F_{BS} \tag{3b}$$

where F_{BS} represents the support reactions due to static displacements X_S alone.

Now, substituting the value of X in terms of the static and dynamic terms as in equation (2), utilizing the relationships given in equation (3) and neglecting the support damping contributions, the following equations are obtained:

$$M_P \ddot{X}_D + C_P \dot{X}_D + K_P X_D = M_P K_P^{-1} K_{PB} \ddot{Z} \tag{4a}$$

$$K_{BP}\ X_D = F_{BD} \tag{4b}$$

where F_{BD} is the support reactions due to the dynamic displacement X_D alone.

Equation (4a) represents the equilibrium equation for a dynamic or inertial loading where Z is the input accelerations. Equations (3a) represents the static equilibrium equations where the ground displacement 'Z' is obtained from the input acceleration functions. The solutions to these equations yield the respective dynamic and pseudo-static components of the total response of the piping system.

Dynamic Response

Equation (4a) governs the dynamic or inertial response of the system subject to support excitation while equation (4b) is used to calculate the support forces due to pipe mass point inertia loadings. The solution of equation (4a) follows the normal practice. The equation set is diagonalized by operating with the modal matrix for undamped force vibrations using only a reduced number of fundamental frequencies of the system. The resulting decoupled equations are then solved separately. The decoupled normal equations are expressed in the form:

$$\ddot{q} + [2\xi\omega]\dot{q} + [\omega^2]q = \phi^T M_P K_P^{-1} K_{PB} \ddot{Z} \tag{5}$$

The above matrix equation can be rewritten in terms of modal equations as:

$$\ddot{q}_{ij}^{(k)} + 2\xi_i \omega_i \dot{q}_{ij}^{(k)} + \omega_i^2 q_{ij}^{(k)} = L_{ij}^{(k)}\ \ddot{z}_j^{(k)} \tag{6}$$

The subscript 'i' denotes the modes, 'j' denotes the support excitation direction (i.e., X, Y or Z) and superscript 'k' represents the support point (or group). Thus,

$q_{ij}^{(k)}$ = ith mode response due to jth directional excitation of the kth support point (or group)
ϕ = modal matrix of the piping system, all supports fixed
ξ_i, ω_i = ith modal critical damping and the frequency of the system
$\ddot{z}_j^{(k)}$ = jth directional excitation of the kth support point (or group)
$L_{ij}^{(k)}$ = ith modal participation factor of the jth excitation of the kth support point (or group)

$= \Sigma^N \phi_{in} M_n U_{nj}^{(k)}$, n = 1, N = number of global equations (i.e., d.o.f.) in the system

The terms $U_{nj}^{(k)}$ $(=K_P^{-1}\ K_{PB}^{(k)})$ are obtained for the kth support point (or group) in three global directions (j = 1, 2, 3) for each degrees of freedom of the system.

Using the convolution integral in solving equation (6), the response $q_{ij}^{(k)}$ can be obtained from:

$$q_{ij}^{(k)} = \frac{L_{ij}^{(k)}}{\omega_i \sqrt{1-\xi_i^2}} \left\{ \int_o^t \ddot{Z}_j^{(k)}(\tau) e^{-\xi_i \omega_i (t-\tau)} \ \mathrm{SIN} \left[\sqrt{1-\xi_i^2}\, \omega_i (t-\tau)\right] d\tau \right\} \tag{7}$$

From here, both approaches (response spectrum and time history) follow separate paths to obtain the maximum response of the system.

Response Spectrum Method

This method yields the maximum response of the system without providing the time dependence of the components of the response. Having obtained all the modal maximum values $(q_{ij})_{max}$, the maximum responses of all the piping degrees of freedom (i.e., X_p) are obtained. Other relevant quantities such as forces, moments and stresses are then evaluated for each mode due to each excitation direction at each support point (or group). Each of these quantities represents the maximum value which can be obtained at any time during the response time span of the system.

The group contributions are combined first before any modal or directional combinations. Three methods of combination were considered. These include algebraic, absolute and the SRSS methods. Once the group responses are obtained by one of the above methods, the other combinations are carried out as per usual practice.

It should be noted that the time phase among the various support groups, excitation directions and modal responses are lost during the solutions process. It, therefore, becomes necessary to make assumptions concerning the time phase and group relationships in order to select the proper combination procedure. Also, as mentioned earlier, the pseudo-static component of the total response cannot be obtained unless the ground displacement is known at each time point. With the spectrum method this is not possible.

Time History Method

This procedure involves integration of all the modal equations in equation (7) using the Wilson-θ method, an unconditionally stable step-by-step integration scheme. The integration is carried out at the same time steps for all nodes. Once the modal time histories are obtained, the piping responses are calculated at each time point. Other relevant quantities are also evaluated using these same response histories. The support reactions are obtained from equation (4b).

In order to calculate the pseudo-static response of the system, the equation given in (3) is solved. Since the term "$K_P^{-1}K_{PB}(\cdot U)$" is already determined, the static response is obtained by multiplying this term, the influence coefficients between the support point motions and the piping degrees of freedom, with the ground displacement time histories.

Having completed calculations for all the groups, the contributions from each group is added at each time point. The final solution includes the dynamic, static and total response components.

Code Implementation

The formulations described in the above section were implemented into the existing BNL finite element computer code "PSAFE2'. The updated code has the capability to solve for the response of a piping system by both the response spectrum method as well as the time history method with independent support excitation. All the support points with identical input excitations, both in magnitude and phase, form a single 'support group'. The code calculates the responses due to the ground excitation of each support group while maintaining the other supports fixed. In this procedure the responses due to all the support points within a support group are combined by the algebraic sum method according to Lin and Loceff [7]. After all the group contributions are calculated, individual group responses are combined using either of three methods available to the user. These are algebraic, absolute and SRSS methods. This is true for the response spectrum approach where the phasing between groups is lost during the process of calculation. However, for time history responses all group contributions are added algebraically at each time point.

Results and Conclusions

A typical piping system shown in Figure 1 was considered for this study. The analyses performed were selected to further verify the code against the conventional methods rather than to evaluate the independent support motion method. However, from the results some preliminary conclusions on the different methods of seismic analysis of piping systems can be made.

Figures 2 and 3 show the two time histories [8] used in the study corresponding to two floors of a building. These were obtained from a finite element analysis including soil structure interaction effects of the HFBR reactor facilities at BNL. Figures 4 and 5 are the response spectra for a particular damping value obtained from the time histories as per U.S. NRC Regulatory Guide 1.60. Figure 4 corresponds to the time history shown in Figure 2 and represents the input at the upper level of the piping system. Figures 3 and 5 correspond to the input at the lower level. The envelope spectrum, in this case, is identical to the upper level floor response spectrum, Figure 4.

The piping system was analysed using the independent support motion time history method, the independent support motion response spectrum method, and the conventional uniform support motion response spectrum method with the envelope spectrum. In the independent support motion response spectrum analyses all three combination methods (i.e., algebraic, absolute and SRSS) between the groups were used. In all the response spectrum analyses the modal and directional combinations are performed as recommended in the U.S. NRC Regulatory Guide 1.92 without considering clustering. The damping value is maintained constant in all analyses. Also, in all cases the input excitation is limited to the X-direction only. The Y-direction component is assumed to be equal to 2/3 of the X-direction input.

The independent support motion time history method yields three solutions, namely, dynamic (i.e., inertia effect), psuedo-static effects combined (i.e., static) and the total response (i.e., dynamic and pseudo-static effects combined at each time point). The independent support motion response spectrum runs, on the other hand, yield only the dynamic (or inertial) component of the response at each point of the piping system. The static component is lost since the input is a spectrum. Three separate runs were made corresponding to the three group combination methods and a separate analysis was made using the conventional response spectrum method subjected to a uniform excitation corresponding to the upper level input spectrum.

It should be evident that the best results for the piping sytem will be those developed with the independent support motion time history analysis. This is because only this method accounts for the pseudo-static component and the inertia component at each time point. In order to compare all the other results with this, a static contribution should be added to all the response spectrum results. No separate static analysis was carried out in this study appropriate to the response spectrum runs. The results obtained from the time history analysis should represent the lower bound for the static component as compared to the values that would result if other available techniques are applied to the piping system. That is, other seismic anchor movement analysis methods should yield static components of higher value than the time history results where phase is taken into account at each time step. In this study the time history static results are added to each spectrum results and the resultants should represent lower bounds for the spectrum methods. The results for all five cases are plotted in Figures 6, 7 and 8 for each component of the local moments at each point of the piping system.

As expected, the spectrum of results are bounded by two analyses for most points in the piping system. The independent time history results represent the lower bound whereas the independent support motion response spectrum analysis with group combination by the absolute sum method plus the static component represents the upper bound of the solution. It should be emphasized that the static component becomes a significant component for a system with independent support excitation. This is not true for the envelope spectrum analysis which consequentially does not yield the most conservative total response of the system. If the static component is ignored, the envelope spectrum result typically envelopes the other spectrum results.

All the pseudo-static components attain a maxima at the same time that the ground displacement component achieves its maximum value. This occurs because the static calculations are performed using a set of influence coefficients derived from a static analysis of the complete system subjected to a particular group's movements. In addition, the piping system considered in the study has only two support groups in which case the out of phase mode between the groups will always yield the worst static responses. Thus, this analysis at each time point is not necessarily required except for the time history analysis where the dynamic component is added to the static at each time point to provide accurate results.

In conclusion, it is noted that excitations from different building structures, in which case the frequency content in each excitation will be different, are expected to yield important conclusions. An additional effort on the parametric studies of various piping systems is underway to help the industry to define their criteria for designing systems under this kind of loading conditions.

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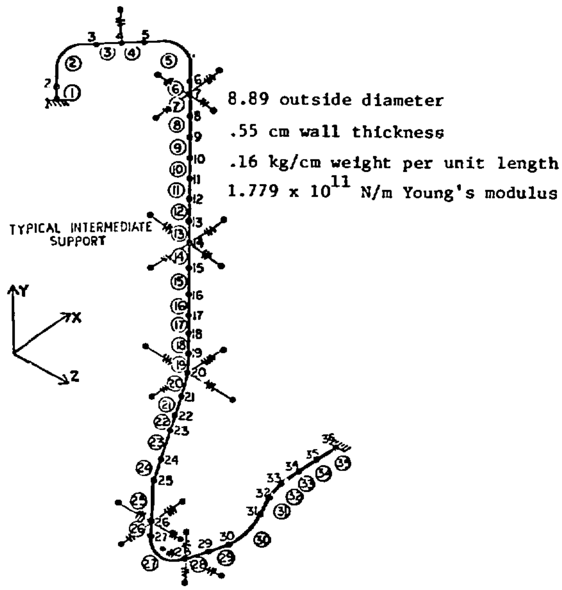

FIGURE 1. HYPOTHETICAL WATER LINE

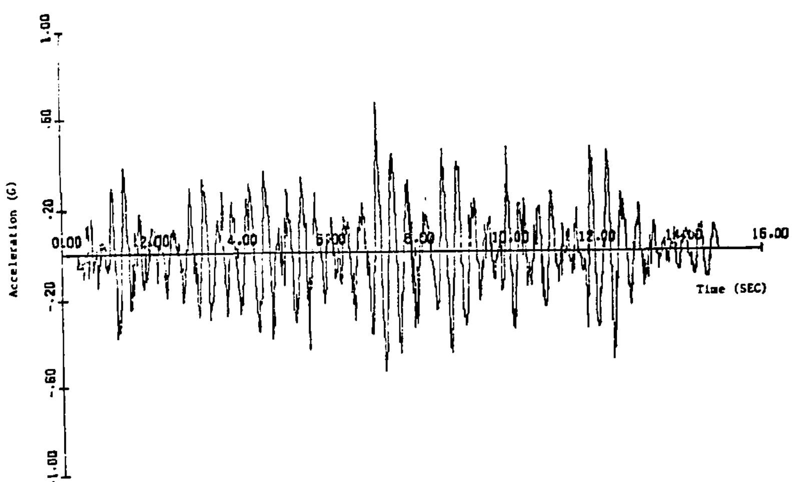

FIGURE 2. INPUT ACCELERATION TIME HISTORY FOR UPPER LEVEL

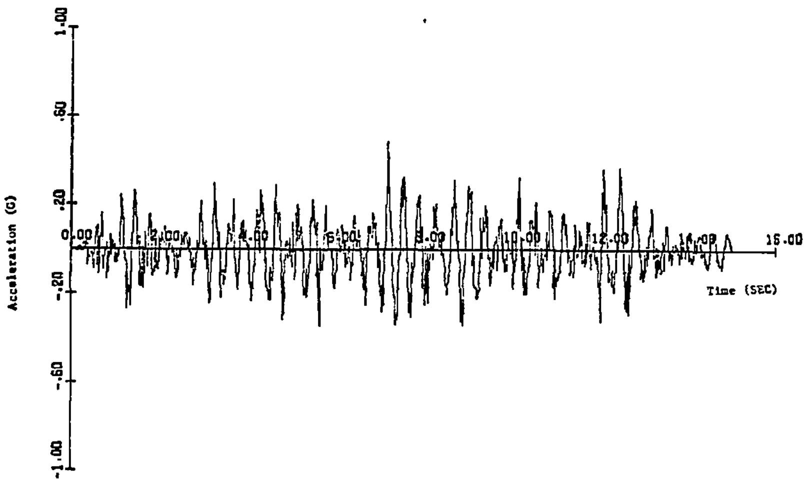

FIGURE 3. INPUT ACCELERATION TIME HISTORY FOR LOWER LEVEL

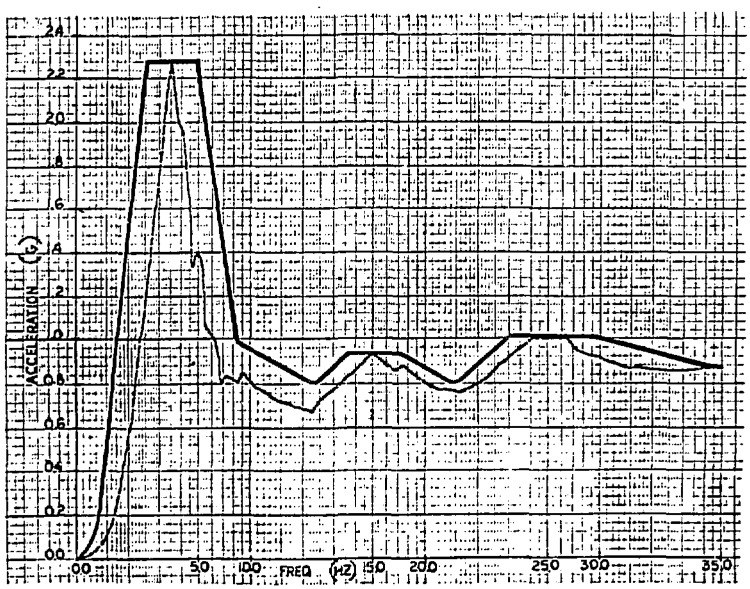

FIGURE 4. INPUT RESPONSE SPECTRUM FOR UPPER LEVEL

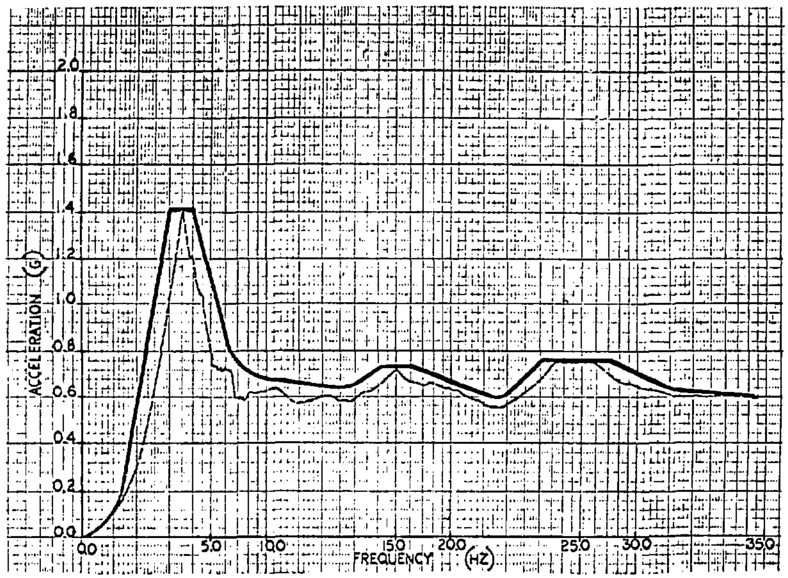

FIGURE 5. INPUT RESPONSE SPECTRUM FOR LOWER LEVEL

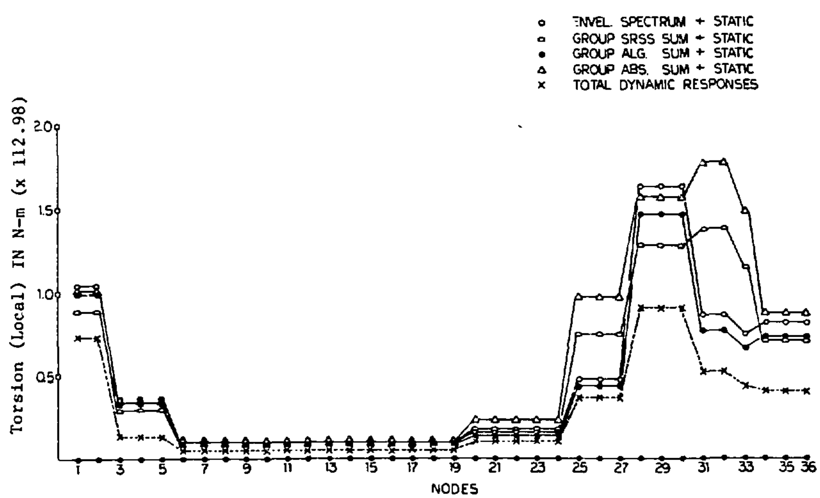

FIGURE 6 TOTAL TORSIONAL RESPONSES

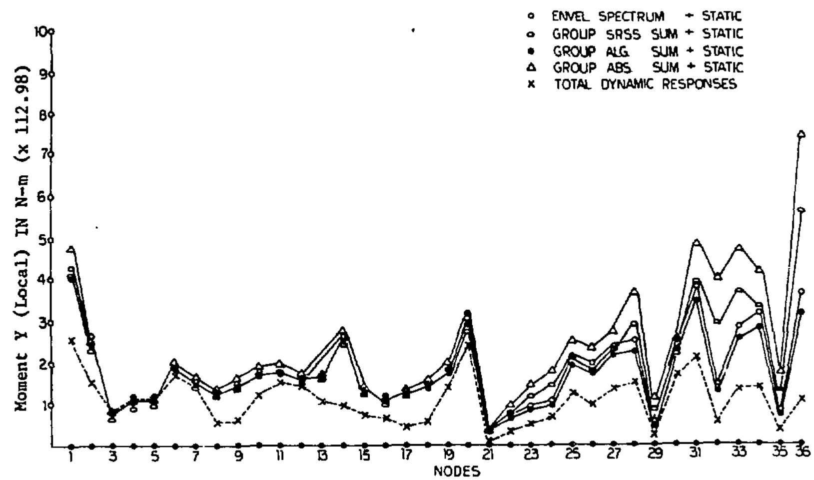

FIGURE 7 TOTAL BENDING MOMENT (My-LOCAL) RESPONSES

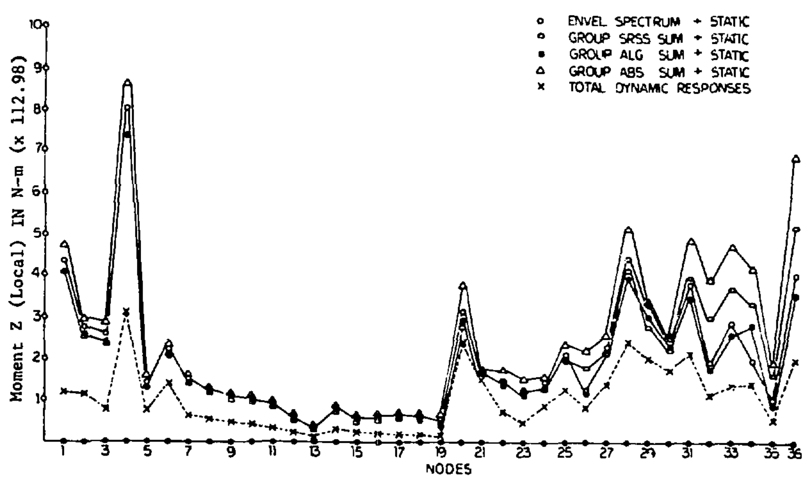

FIGURE 8 TOTAL BENDING MOMENT (Mz-LOCAL) RESPONSES