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Impact of Changes in Damping and Spectrum Peak Broadening on the Seismic Response of Piping Systems

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ABSTRACT

The Technical Committee on Piping Systems of the Pressure Vessel Research Committee has proposed two modifications that affect seismic analysis of piping systems to regulatory guides. One modification would change damping values for piping systems specified in Regulatory Guide 1.61. The other modification would provide an alternative to the peak broadening procedure of Regulatory Guide 1.122.

In this study we quantified the reduction in piping responses of three piping systems in the Zion nuclear power plant resulting from these two modifications, separately and in combination. We concluded that:

- The proposed damping values reduce piping response substantially.
- The proposed alternative to peak broadening reduces piping response only marginally.

We calculated the seismic responses of the three piping systems by two methods: Response spectrum analysis and multi-support time history analysis. We used the proposed modifications in the response spectrum analysis. The results of the response spectrum analysis were calibrated against those of time history analysis. We found that conservatism remains under the proposed modifications.

One of the three piping systems was used to show the potential benefit of the proposed modifications. We found that both snubbers and 7 of the 10 horizontal restraints could be removed without causing stresses in the piping system to exceed code allowables. Hence, the potential benefit of the proposals is very promising.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission Standard Review Plan, Section 3.9.2 allows the response spectrum analysis procedure for the seismic design or analysis of piping systems in nuclear power plants. The input to the piping system is the enveloped, broadened in-structure spectra of all piping support locations in the structures. The damping values for these spectra are conservatively specified in Regulatory Guide 1.61, and the peak broadening procedure is specified in Regulatory Guide 1.122. These two regulatory guides introduce substantial conservatism in the seismic response spectrum analysis. Conservatism is required due to large uncertainty in the seismic analysis. Conservatism is also introduced by other areas of the analysis process, e.g., broad-band input (Regulatory Guide 1.60) and modal combination (Regulatory Guide 1.92), spectra enveloping, etc. Conservatism in these areas results in the excessive use of snubbers and rigid restraints in nuclear power plant piping systems. These restraints may increase the daily operational loads, e.g., thermal expansion, and hence reduce reliability of piping systems.

The Technical Committee on Piping Systems of the Pressure Vessel Research Committee attempted to reduce the conservatism in the analysis procedure in the Standard Review Plan for piping systems. Task Groups on Damping and Spectrum Development recommended changes in damping values (Regulatory Guide 1.61) and an alternative to spectrum peak broadening (Regulatory Guide 1.122). The proposed damping values for piping systems are the result of a regression analysis of the available data. The values are higher in the lower frequency range than those of Regulatory Guide 1.61. The alternative procedure to spectrum peak broadening uses the raw (unbroadened) spectra directly and takes account of the uncertainty of soil and structure characteristics by shifting the raw spectra over a frequency range of ±15% of peak frequency.

We adapted these two proposed modifications and performed numerous response spectrum analyses of three piping systems of the Zion nuclear power plant. These response spectrum analyses also included the current Standard Review Plan procedure. We compared the proposed modifications, separately and together, with the current Standard Review Plan procedure. We concluded that:

- The proposed change in damping values substantially reduces piping response.
- The proposed alternative to peak broadening reduces piping response only marginally.

We also compared the effect of the proposed modifications with the multi-support time history analysis procedure. Even if these proposed modifications are implemented, conservatism remains.

To determine the potential benefit of these modifications, we investigated the possibility of removing snubbers and horizontal restraints of one of the three piping systems. We found that both snubbers and 7 of 10 horizontal restraints could be removed and the piping system response under the two proposed modifications would still meet the provisions of ASME Boiler and Pressure Vessel Code Section III, Subsection NC.

IMPACT OF CHANGES IN DAMPING AND SPECTRUM PEAK BROADENING ON THE SEISMIC RESPONSE OF PIPING SYSTEMS

1. INTRODUCTION

The seismic response of piping systems in nuclear power plants is commonly separated into two parts--the inertial or dynamic response and the pseudostatic response due to relative motions of the systems supports. Various analysis procedures have been developed to calculate each portion of the response separately. The present study investigates calculational procedures and parameter values used for the calculation of the inertial response component. It also investigates the possibility of removing snubbers and restraints in piping systems. Removal of snubbers and restraints will reduce the seismic stresses due to relative support motions.

The U.S. Nuclear Regulatory Commission (NRC) Standard Review Plan (SRP) (NRC, 1981) prescribes acceptable methods to be used in the analysis of multiply supported equipment and components (e.g., piping systems) whose supports experience distinct inputs. One approach is to calculate piping system response by the response spectrum method, using as input envelopes of support motions in each of three orthogonal directions (two horizontal and the vertical). For this approach, in-structure response spectra at piping support locations are generated and broadened in accordance with Regulatory Guide (RG) 1.122 (NRC, 1978). The broadened spectra are then enveloped in each direction. Damping values for piping systems are specified in RG 1.61 [Atomic Energy Commission (AEC), 1973]. In-structure response spectra are generated for these values.

It is generally believed that this analysis procedure introduces substantial conservatism in the seismic response of piping systems. This belief was supported by a study designed to assess the calculational margin of seismic response of piping systems (Johnson et al., 1983). These authors compared the seismic response of piping calculated by two methods--response spectrum analysis and best-estimate time history analysis procedures (Bumpus, Johnson, and Smith, 1980)--and showed that considerable conservatism is embodied in the current SRP. Several areas can be identified which contribute to this conservatism, e.g., peak broadening of in-structure response spectra, conservatively specified values of damping, enveloping of in-structrure response spectra, and combination of modal responses (RG 1.92, NRC, 1976). The Technical Committee on Piping Systems of the Pressure Vessel Research Committee (PVRC) has recently proposed changes in two of these areas to reduce excess conservatism in the analysis procedure. One proposed change is in the (spectrum) peak broadening procedure (RG 1.122) and the other is in the damping values specified for seismic design or analysis of piping systems (RG 1.61). The scope of the present study was to evaluate the PVRC-proposed changes relative to piping responses calculated by response-spectrum methodology and a multi-support time history analysis procedure which is less conservative because it does not require any form of enveloping of support motions. We performed numerous response-spectrum analyses of three selected piping systems in Zion nuclear power plant, using different combinations of damping values (RG 1.61 and proposed PVRC), peak-broadening (RG 1.122), and the alternative to peak broadening (proposed PVRC). These analyses enable us to compare piping seismic responses under various combinations of damping values and peak broadening procedures. We also quantified the reduction in piping responses under these changes and assessed the potential benefit.

Section 2 describes the methods of analysis employed herein--the SRP response spectrum analysis procedure, the multi-support time history analysis procedure which uses the pseudostatic mode method, and the proposed PVRC modifications for peak broadening and piping system damping values.

Section 3 describes three piping models of the Zion nuclear power plant for which the investigation was performed. The three models vary from relatively simple to extremely complex.

Section 4 presents results of our analysis in detail. In this section, the reduction in response of piping systems due to the PVRC proposals is quantified. Comparison of reduced response with that calculated by the multi-support time history analysis procedure demonstrates that conservatism still remains for the proposed changes. The potential benefits of the PVRC proposals are illustrated by an example.

Section 5 summarizes our observations and conclusions. The proposed changed damping values (RG 1.61) of piping systems indeed reduced the responses substantially, while the proposed alternative to peak broadening (RG 1.122) did not as we would expect. Conservatism still remains after these two changes are implemented in the seismic design or analysis procedures for piping systems.

2. METHODS OF ANALYSIS

2.1 Introduction

Two methods for the seismic dynamic analysis of piping systems are identified in Standard Review Plan (SRP) Section 3.9.2. They are time history and response spectrum methods. In this study we use both methods to calculate the seismic responses of selected piping systems. The piping models for these systems are referred to as the AFW-1, RHR/SI-1, and RC-1 models. These piping systems are housed in the containment building and auxiliary fuel-handling turbine building (AFT) complex of the Zion nuclear power plant. Detailed descriptions of the piping models are given in Section 3.

We used a multi-support time history analysis procedure for the time history analysis. This procedure is embodied in the computer program SMACS (Johnson et al., 1981), whose main features are described in Section 2.2. SMACS uses the pseudostatic mode method to analyze the seismic response of piping systems.

We describe the response spectrum method in Section 2.3, including the procedures for enveloping and peak broadening of in-structure response spectra and the procedures for combining modal and directional responses of piping systems.

Finally, in Section 2.4, we describe PVRC alternative proposals for damping values and peak broadening.

2.2 Multi-Support Time History Analysis

2.2.1 SMACS Methodology

The multi-support time history analysis procedure (Johnson et al., 1981) used in our RG 1.60 analysis was that used in the Seismic Safety Margins Research Program (SSMRP). The methodology was embodied in the computer program SMACS to calculate the seismic response of structures and piping systems and the variation in these responses. SMACS performs time history analysis linking seismic input with soil-structure interaction (SSI), major structural response, and piping system response. The seismic input is defined by an ensemble of acceleration time histories in three orthogonal directions (two horizontal and the vertical) on the surface of the soil. SSI and detailed structural response are determined simultaneously using the substructure approach. Detailed structural responses in the form of time histories and peak accelerations, displacements, and forces are computed. Piping systems are analyzed using the pseudostatic mode method assuming the piping support motions obtained from the detailed structural response analyses as input.

SMACS performs repeated deterministic analyses, each analysis simulating an earthquake occurrence. By performing many such analyses and by varying the values of several input parameters, we are able to account for the uncertainty inherent in any deterministic analysis. Uncertainty was explicitly considered in each element of the seismic methodology chain--seismic input, SSI, structure response, and subsystem response (e.g., piping system). Variability in the seismic input is included by sampling to obtain a different set of earthquake time histories for each simulation. Variation in the soil-structure-piping behavior is included for each simulation by sampling values of the input parameters (shear modulus and damping of the soil, and frequency and damping of structures and piping systems). The sampling of these values is from assumed probability distributions. The samples are selected according to a Latin hypercube experimental design.

Further discussions of the SMACS methodology can be found in Johnson et al. (1981). However, since the thrust of the present study deals with comparisons of piping system responses, and since we used a pseudostatic mode approach to determine piping system response in the time history analysis, a detailed explanation of the pseudostatic mode approach to multi-support excitation analysis follows. One more point to be mentioned here and discussed further in Section 2.2.2 is that the full SMACS methodology was not applied in the present case--no variation in piping system input parameters was included. In this manner our time history analysis closely approximates the SRP procedure.

The equations of motion for a piping system subjected to applied forces or external loads can be partitioned into active degrees of freedom (x_1) and specified support degrees of freedom (x_2). The equations of motion may be written

$$\begin{bmatrix} M_{11} & 0 \\ 0 & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \quad (1)$$

where $[x_i]$, $[\dot{x}_i]$, and $[\ddot{x}_i]$ denote absolute displacement, velocity, and acceleration vectors, and $[M_{ij}]$, $[C_{ij}]$, and $[K_{ij}]$ denote mass, damping, and stiffness matrices, respectively, and where i, j = 1 or 2. P_1 and P_2 denote applied and support forces respectively. Since we are dealing with systems
subjected to seismic excitation only, i.e., with no applied forces ($P_1 = 0$), we can write Eq. (1) as

$$[M_{11}][\ddot{x}_1] + [C_{11}][\dot{x}_1] + [K_{11}][x_1] = -[C_{12}][\dot{x}_2] - [K_{12}][x_2] \quad (2a)$$

and

$$[M_{22}][\ddot{x}_2] + [C_{22}][\dot{x}_2] + [K_{22}][x_2] = [P_2] - [C_{21}][\dot{x}_1] - [K_{21}][x_1] \; . \quad (2b)$$

Assume that the absolute displacement is composed of two portions, a pseudostatic portion $[x_1^S]$ and a dynamic portion $[x_1^D]$, i.e.,

$$[x_1] = [x_1^S] + [x_1^D] \quad , \quad (3)$$

where $[x_1^S]$ is defined by

$$[K_{11}][x_1^S] = -[K_{12}][x_2] \quad , \quad (4a)$$

and thus

$$[x_1^S] = -[K_{11}]^{-1}[K_{12}][x_2]$$

$$[\dot{x}_1^S] = -[K_{11}]^{-1}[K_{12}][\dot{x}_2]$$

$$[\ddot{x}_1^S] = -[K_{11}]^{-1}[K_{12}][\ddot{x}_2] \quad . \tag{4b}$$

The pseudostatic component x_1^S can be interpreted as the response of the piping system to support motions, excluding inertial and damping effects, as we can see from Eqs. (2a) and (4a).

If we assume damping to be proportional to stiffness or assume support coupling plus pseudostatic damping forces to be negligible (i.e., $C_{12}\dot{x}_2 + C_{11}\dot{x}_1^S \cong 0$), while recognizing rigid-body motion as a stress-free state of the piping system, we can rewrite Eq. (2a) using Eqs. (3) and (4), to obtain

$$[M_{11}][\ddot{x}_1^D] + [C_{11}][\dot{x}_1^D] + [K_{11}][x_1^D] = -[M_{11}][\ddot{x}_1^S] \quad . \tag{5a}$$

Using the equation for $[x_1^S]$ in (4b), we can write Eq. (5a) as

$$[M_{11}][\ddot{x}_1^D] + [C_{11}][\dot{x}_1^D] + [K_{11}][x_1^D] = [M_{11}][K_{11}]^{-1}[K_{12}][\ddot{x}_2] \quad . \tag{5b}$$

We can interpret Eq. (5a) as follows. First we describe the pseudostatic response of the piping system as a time-varying motion without dynamic effects. However, the time-varying motion induces inertial forces on the piping system. We may treat these inertial forces as applied forces to the piping system, represented as the right-hand side of Eq. (5a). The response of the piping system to these applied forces is the solution of Eq. (5a). The form of Eq (5a) lets us interpret X_1^D as the response of the piping system subject to applied loads, $-[M_{11}][\ddot{x}_1^S]$, with no relative motion of supports.

The displacement vector $[x_1^D]$ can be represented by an eigenfunction expansion, because there exists a linear coordinate transformation that diagonalizes the mass and stiffness matrices $[M_{11}]$ and $[K_{11}]$. Then

$$[x_1^D] = [\Phi][q] \quad , \tag{6}$$

where the columns of $[\Phi]$ are the eigenvectors $[\Phi_j]$ and elements of $[q]$ are generalized coordinates. $[\Phi]$ is chosen such that $[\Phi]^T[M][\Phi] = [I]$, where $[\Phi]^T$ is the transpose of $[\Phi]$ and $[I]$ is a unity matrix.

Substituting Eq. (6) into Eq. (5b) and assuming that $[\Phi]$ can also diagonalize the damping matrix, i.e.,

$$[\Phi]^T[C_{11}][\Phi] = [\backslash 2\beta_j\omega_j\backslash] \quad ,$$

where ω_j and β_j are jth mode's natural frequency and fraction of critical damping, respectively, and $[\backslash\delta_j\backslash]$ represents a diagonal matrix, with the diagonal element δ_j, we obtain

$$[\ddot{q}] + [\backslash 2\beta_j\omega_j\backslash][\dot{q}] + [\backslash\omega_j^2\backslash][q] = [\Phi]^T[M_{11}][K_{11}]^{-1}[K_{12}][\ddot{x}_2] \quad . \tag{7}$$

With the help of $[\Phi]^T[M][\Phi] = [I]$ and $[\Phi]^T[K][\Phi] = [\backslash\omega_j^2\backslash]$, Eq. (7) can be simplified:

$$[\ddot{q}] + [\backslash 2\beta_j\omega_j\backslash][\dot{q}] + [\backslash\omega_j^2\backslash][q] = [\backslash\omega_j^2\backslash]^{-1}[\hat{\Phi}][K_{12}][\ddot{x}_2] \quad . \tag{8}$$

The matrix $[\hat{\Phi}]$ denotes the incomplete eigenfunction expansion of $[x_1^D]$; i.e., $[\hat{\Phi}]$ denotes a reduced set of the complete expansion $[\Phi]$. We used Eq. (8) to determine the dynamic response of the piping system.

Recovery of response--accelerations, displacements, support forces, and pipe resultant moments--remains to be discussed. Let us denote by P the pseudostatic influence coefficients that relate piping response to unit support motions; i.e.,

$$[K_{11}][P] = -[K_{12}] \quad . \tag{9}$$

For accelerations it is a simple matter to show that

$$[\ddot{x}_1] = [\hat{\Phi}][\ddot{q}] + [P][\ddot{x}_2] \quad , \tag{10}$$

where the first term is the dynamic or inertial response and the second is the pseudostatic response.

For displacements, support forces, and pipe resultant moments, we calculate only the piping systems' dynamic response. In this study we compare the results of response spectrum analyses with the comparable results of time history analyses, i.e., dynamic or inertial responses. The pseudostatic responses are comparable to the results of the static seismic anchor or support movement (SAM) analysis which were not compared. For accelerations, we used the total accelerations in time history analysis [Eq. (10)] for comparison because the SAM analysis is a static analysis, i.e., no accelerations are calculated.

It is also easily shown that the stress in member m, $[\sigma_m]$, can be written as

$$[\sigma_m] = [\hat{S}_{1m}][q] \quad , \tag{11}$$

where

$$[\hat{S}_{1m}] = [S_{1m}][\hat{\Phi}] \quad .$$

The matrix $[S_{1m}]$ relates support forces and pipe moments in the member m to active displacement, x_1.

2.2.2 RG 1.60 Analysis

In this study we performed SMACS analysis of piping systems subjected to a set of free-field motions called "RG 1.60." Hence, we refer to this SMACS analysis as the "RG 1.60 Analysis."

To perform a SMACS analysis, the following information must be assembled:

- Free-field motion, which models seismic input.
- Models of SSI, structures, and piping systems.
- Input parameter variations.
- Experimental design.

We discuss these items below.

Free-field motion. In the RG 1.60 analysis the seismic input was an ensemble of artificially generated time histories that met the requirements of NRC Regulatory Guide 1.60 (AEC, 1973). We used 30 sets of data that represented 30 earthquakes. Each data set was three acceleration time histories--two horizontal and the vertical. The horizontal components had equal peak accelerations of 0.18 g and the vertical component had a peak acceleration of 0.12 g. We verified for all sets that the three components were statistically independent (correlation coefficients less than 0.16). Figures 2.1-2.3 show the RG 1.60 data set response spectra (mean plus and minus one standard deviation). Notice that spectral acceleration varies little with frequency, because each time history was constrained by the same target response spectrum. Coefficients of variation (COVs) of approximately 0.1 are typical for the frequency range in which amplification occurs (1-10 Hz), and the COVs are smaller outside that range.

Models of SSI, structures, and piping systems. SSI, structure, and piping models used in this study were originally developed for the SSMRP (Smith et al., 1981). The SSI model is discussed in detail in Johnson et al. (1981); structure and piping models are discussed in Section 3. Two aspects of the development of the models are highlighted here. First, these models were developed from actual data on materials rather than from design values. Second, we selected excitation-dependent parameters, such as shear modulus and damping of the soil, to correspond to stress levels that would be produced in the various media by the range of excitations considered. We used soil properties corresponding to a peak free-field excitation of 0.18 g. Preliminary calculations indicated low levels of stress in the structures. Consequently, we used nominal damping values of 2% for the containment building and the auxiliary fuel-handling turbine building (AFT) complex. For piping systems we used the Operating Basis Earthquake (OBE) damping values specified in RG 1.61 as the nominal values (Table 2.1), because OBE values will generally govern the seismic design of piping systems if the OBE is half of the Safe Shutdown Earthquake (SSE), which is the general design practice.

Input parameter variations. As discussed in Section 2.2.1, uncertainties in seismic input, SSI, structure response, and piping system response are treated explicitly in the SMACS response calculations. A limited number of input parameters are used to incorporate uncertainty: in the seismic input, an ensemble of time histories; in SSI, the mechanism to include variablility is

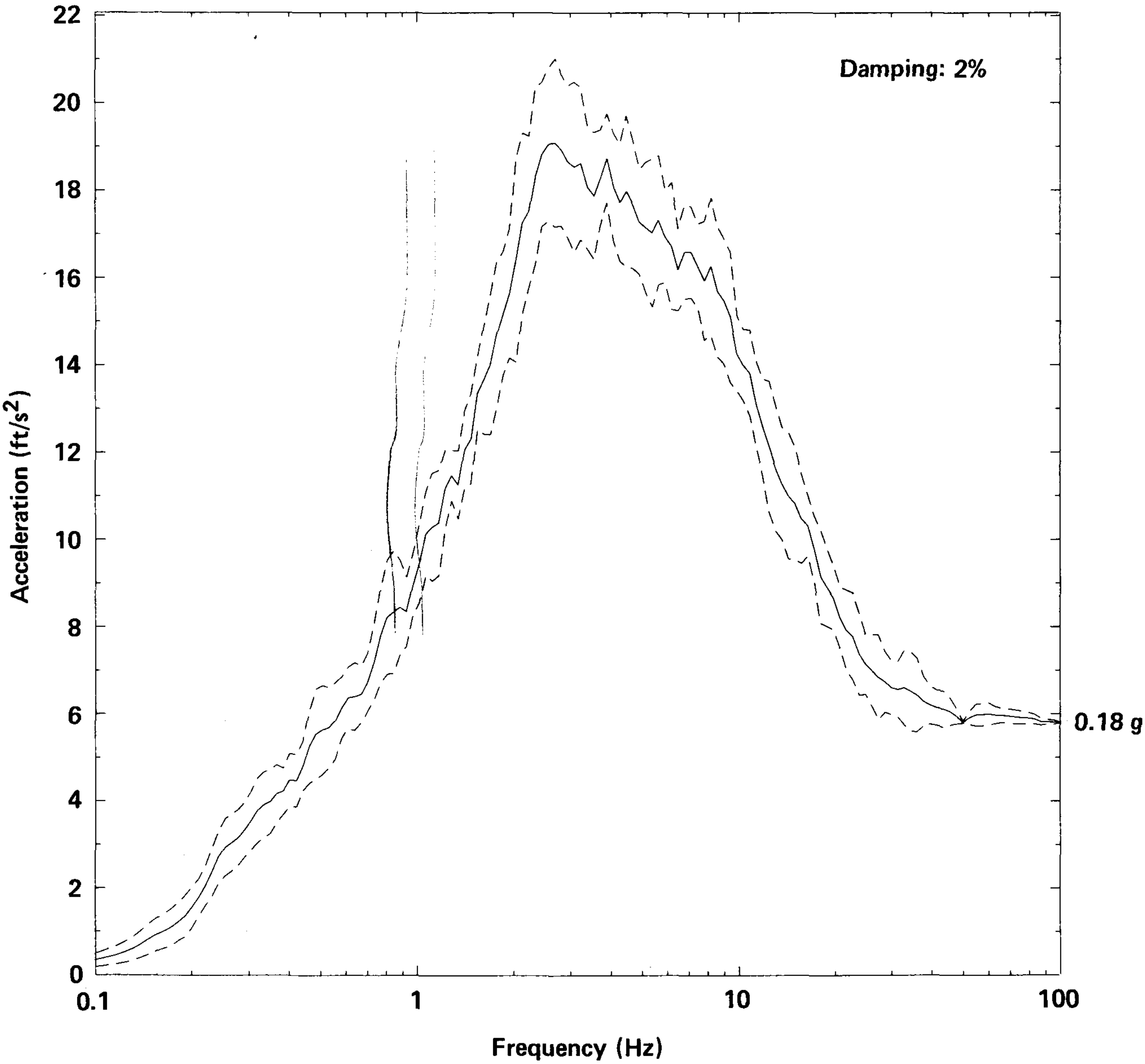


Fig. 2.1. Mean and mean-plus-and-minus one standard deviation response spectra of the RG 1.60 data set for the east-west direction.

soil shear modulus and material damping in the soil; in structures and piping systems, variations in frequencies and damping are the mechanisms. In this study we held the frequencies and damping of piping systems constant at their nominal values, i.e., no variability in the piping system parameters was included. This is consistent with the SRP requirements.

In seismic risk and probabilistic response analysis, it is helpful to distinguish between two types of uncertainty--random uncertainty and modeling uncertainty. Random uncertainty is fundamental to the phenomenon being represented. It is also irreducible given present state-of-the-art understanding and modeling of the phenomenon. Modeling uncertainty reflects

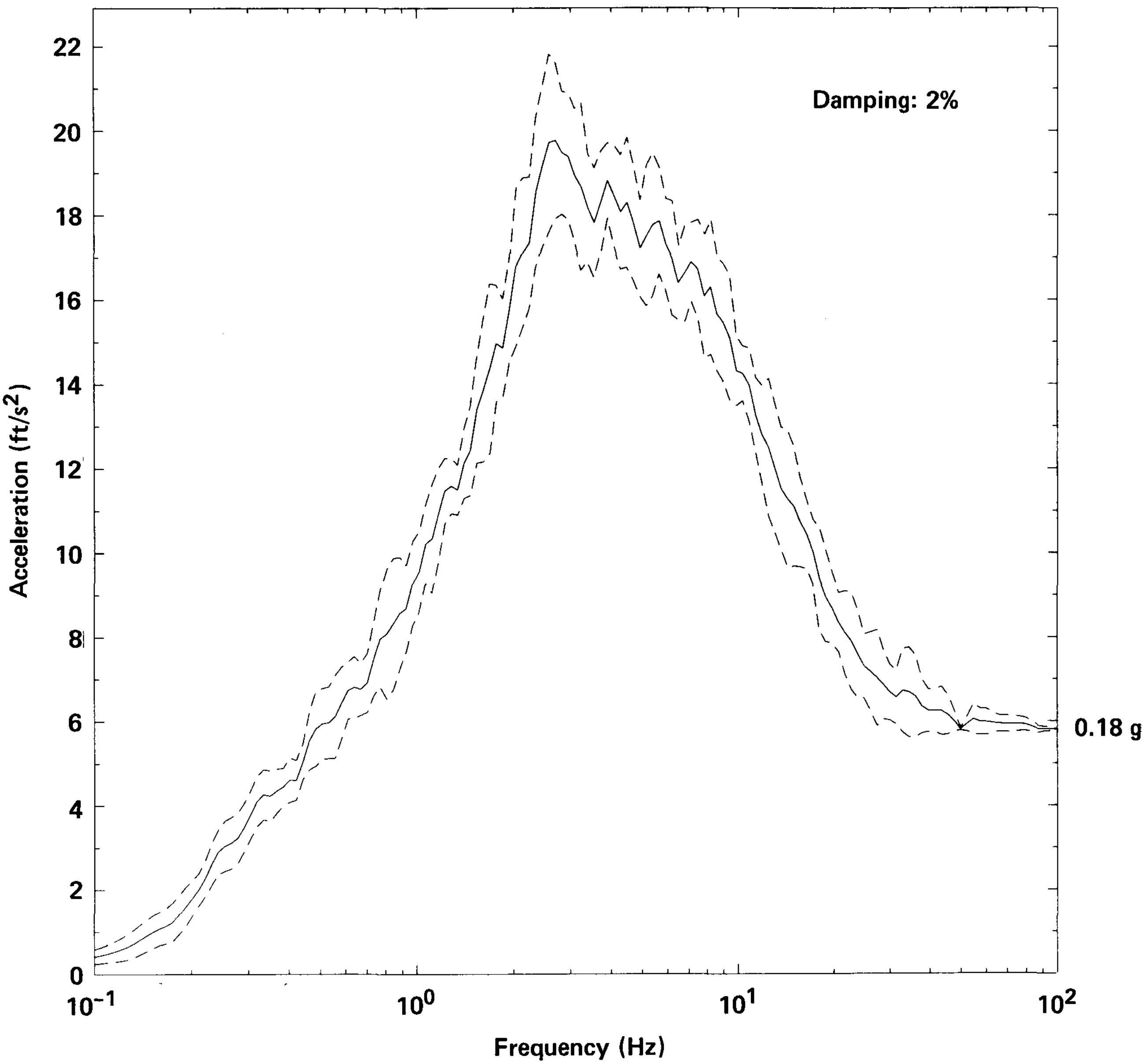


Fig. 2.2. Mean and mean-plus-and-minus one standard deviation response spectra of the RG 1.60 data set for the north-south direction.

incomplete knowledge of the response itself. Modeling uncertainty, in many cases, can be reduced within present limits of the state of the art by improved analytical models, tests, etc. The combination of random and modeling uncertainty yields total uncertainty. For the present study, variability in input parameters was selected to represent total uncertainty and assumed minimal knowledge of the Zion plant. Assuming total uncertainty on the input parameters yields larger dispersion in calculated responses. Variability in the input parameters is described by assumed lognormal distributions. Table 2.2 tabulates the COVs used in the present study.

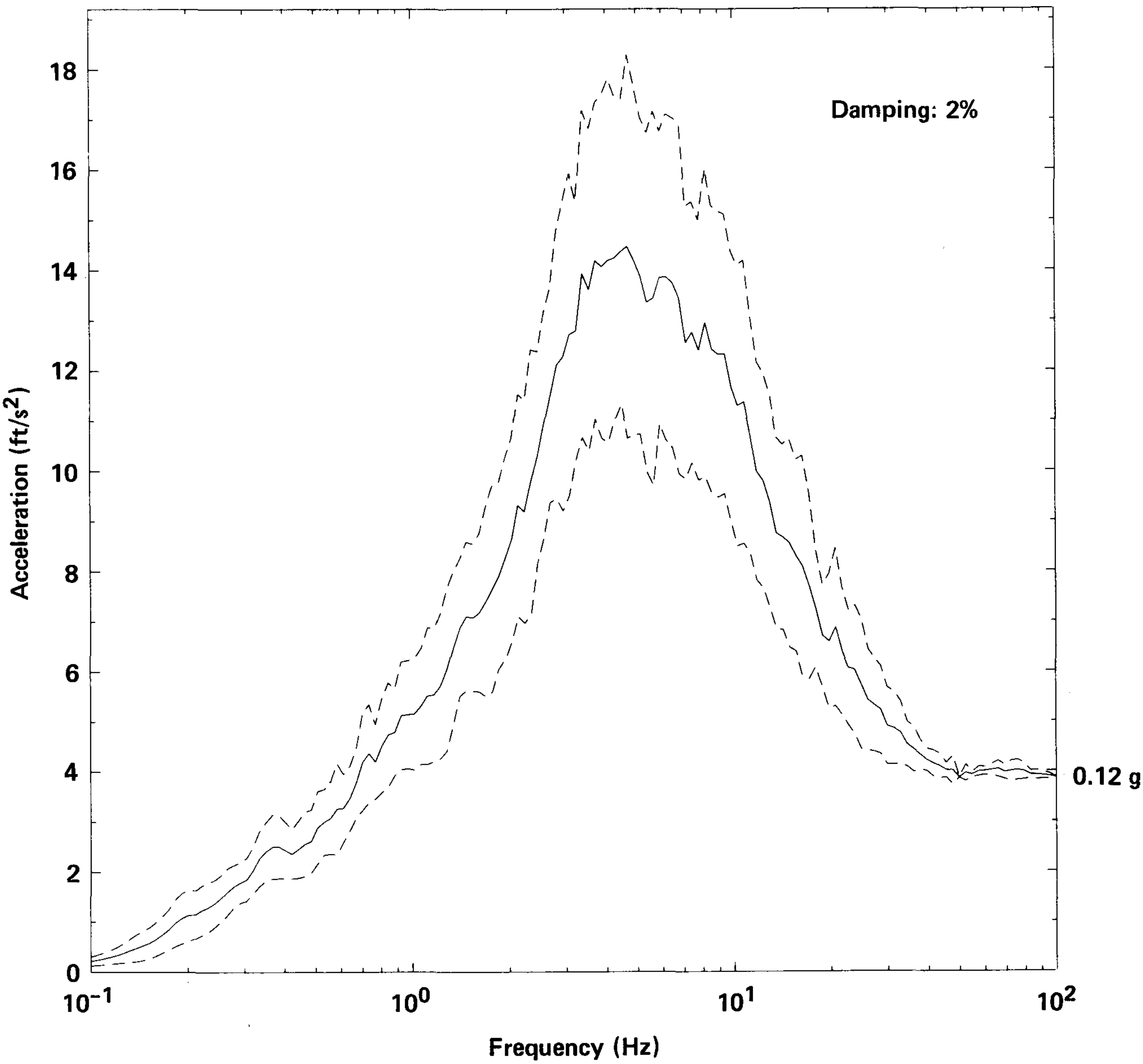


Fig. 2.3. Mean and mean-plus-and-minus one standard deviation response spectra of the RG 1.60 data set for the vertical direction.

Experimental Design. The SMACS analysis used a Latin hypercube experimental design (Iman, Conover, and Campbell, 1980). The design efficiently sampled the parameter spaces so that the number of simulations is reasonably limited. The process is described here. For our RG 1.60 analysis, 30 earthquake simulations were performed. Hence, 30 sets of earthquake time histories were selected. Next, the distribution of each variable input parameter was divided into 30 equal-probability intervals. A value was randomly selected from each interval, and the 30 values for each variable were rearranged randomly. The 30 sets of time histories and the permuted values of the variable parameters were then grouped to give 30 combinations of input values for the dynamic analyses. Therefore, in a series of 30 analyses, each time history set is

Table 2.1. Nominal damping values of piping systems.

System (model)	Damping (% critical damping ratio)
AFW-1	1
RHR/SI-1	1
RC-1	2

Table 2.2. Coefficient of variation of input parameters for the RG 1.60 analysis.

Element of seismic methodology chain	Key parameter	Coefficient of variation (COV)
Seismic input	Time history sets	(See Sec. 2.2.2)
Soil	Shear modulus	0.7
	Damping	1.0
Structure	Frequency	0.5
	Damping	0.7
Piping	Frequency	0 (no variation)
	Damping	0 (no variation)

used once, and a parameter value was selected once from each of the 30 intervals in each of the parameter distributions. The set of 30 input combinations is called a Latin hypercube sampling set. The 30 seismic analyses gave 30 values for every piping system response calculated. The median of the distribution of the 30 seismic responses was used for comparisons in Section 4.

2.3 SRP Response Spectrum Analysis

2.3.1 Development of Response Spectrum

Frequently, the response of a piping system is separated into two portions--the inertial or dynamic response and the pseudostatic response due to the relative motions of the piping supports. One acceptable and commonly used approach is to calculate the inertial response by a response spectrum analysis that takes as input the envelope of broadened individual response spectra generated from motions of all the support points in the structures. The pseudostatic response is then obtained by imposing support displacements on the piping system in the most unfavorable combination and performing a static analysis in accordance with the SRP requirement. In this study we determined only the inertial component of response of the selected piping systems by the response spectrum method described above. The first step in the process is generation of in-structure response spectra at structure node points corresponding to piping motion supports. The calculational process proceeded as follows. A set of acceleration time histories was selected from the 30 sets used in the RG 1.60 analysis (Section 2.2.2). This set of time histories closely conformed to the requirements of RG 1.60 (Figs. 2.4-2.6). SSI and structure responses were then calculated for this earthquake with SSI

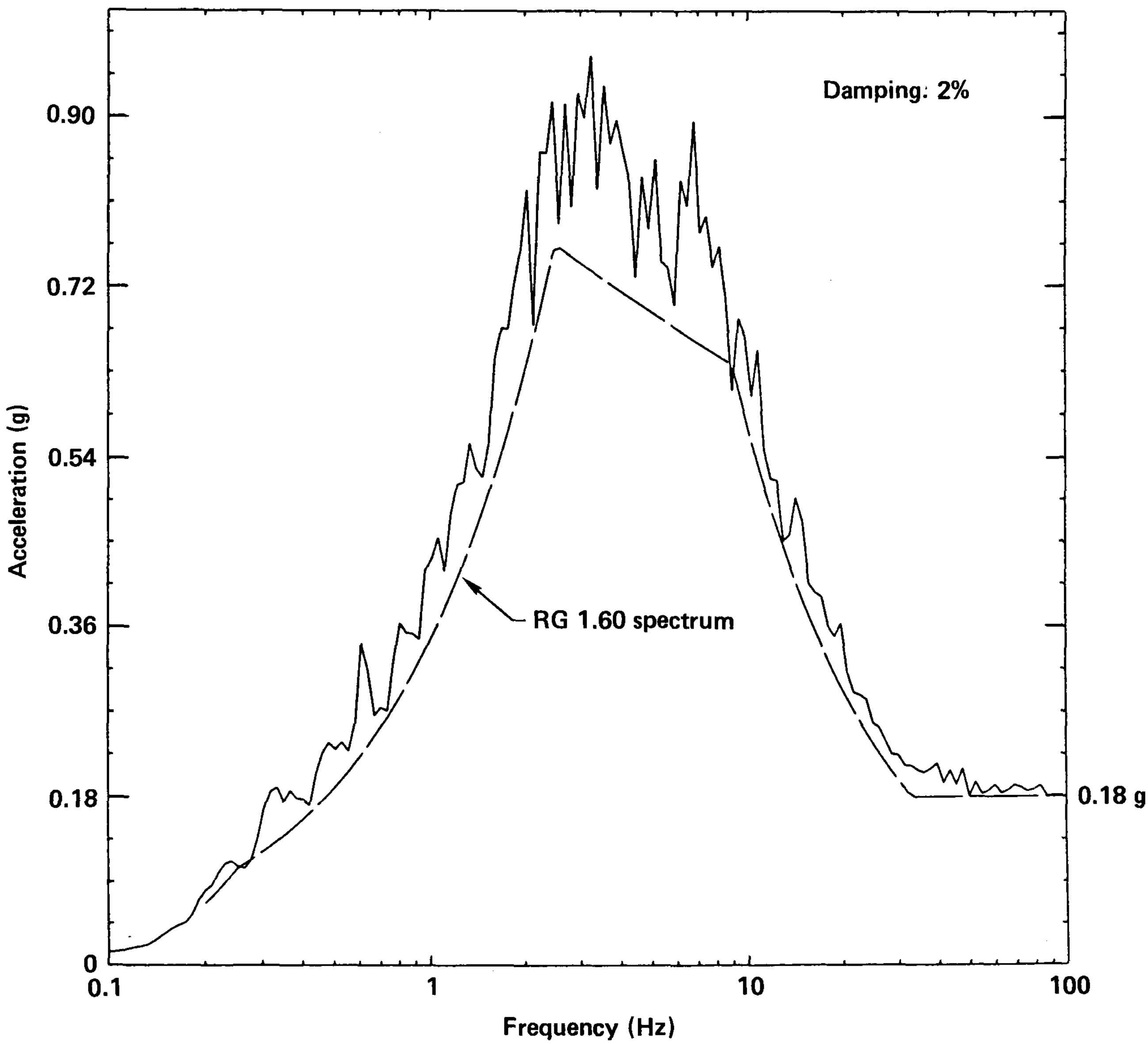


Fig. 2.4. Spectrum of the free-field motion in the east-west direction for SRP response spectrum analysis.

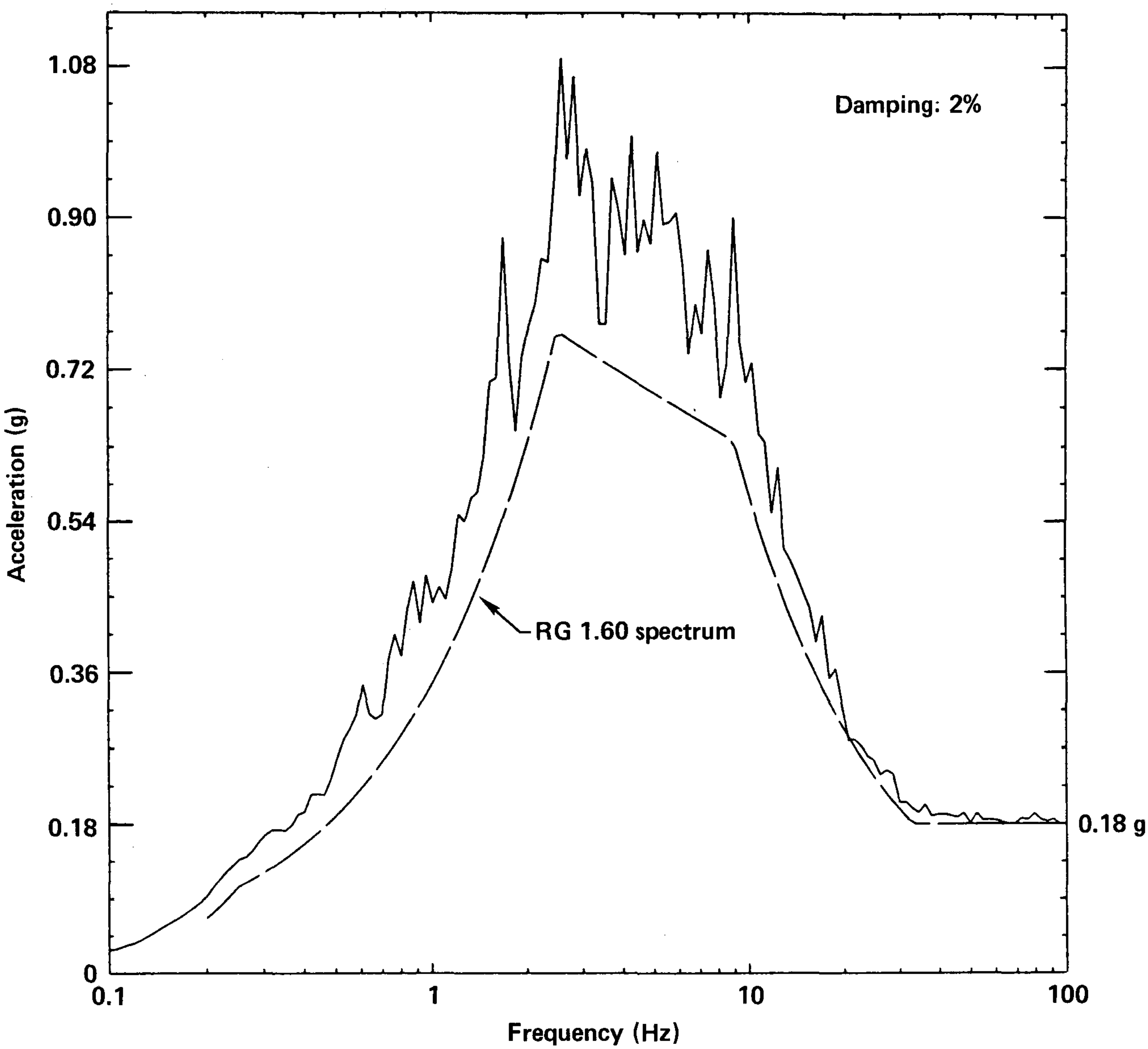


Fig. 2.5. Spectrum of the free-field motion in the north-south direction for SRP response spectrum analysis.

and structure input parameters fixed at their nominal values. Response spectra were generated at structure nodal points corresponding to piping system supports. These raw response spectra were broadened in accordance with RG 1.122 (NRC, 1978). After broadening, response spectra corresponding to the support points of the selected piping systems were grouped according to component direction (two horizontal and the vertical). For each direction, an enveloped spectrum was generated which defined the input for the subsequent response spectrum analysis. Figure 2.7 shows a typical enveloped response spectrum.

One point requires expansion at this stage relative to the generation of in-structure response spectra. Two approaches to calculating the design floor response spectra are common. In the first approach, a seismic analysis of the

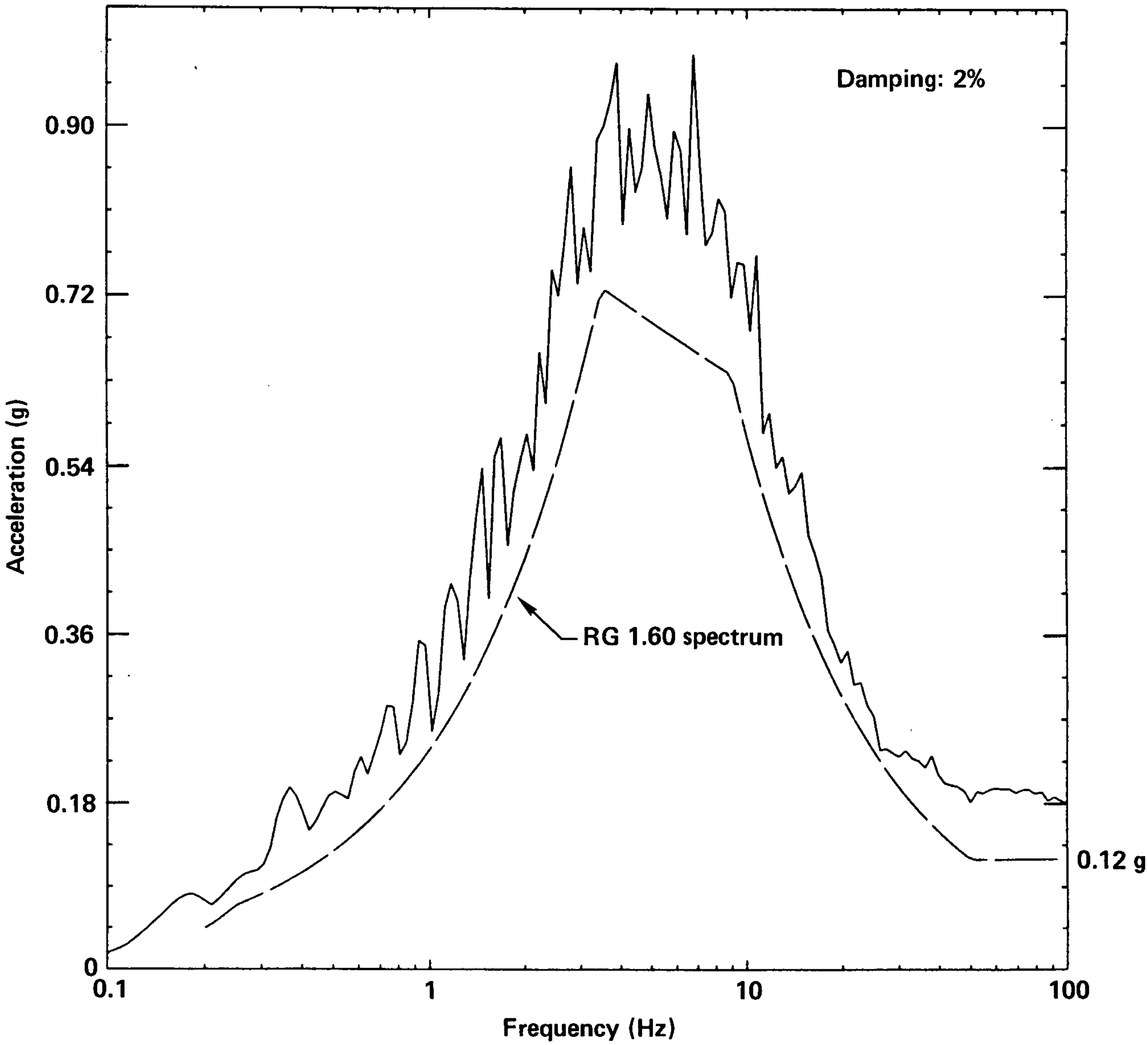


Fig. 2.6. Spectrum of the free-field motion in the vertical direction for SRP response spectrum analysis.

structure is performed separately for each direction of input motion. At a given floor location, response in all three directions is calculated for each direction of input motion. Response spectra are generated. Hence, one obtains three response spectra in each direction. The ordinates of these three response spectra for a given direction are combined according to the square-root-of-the-sum-of-the-squares (SRSS) method and the resulting response spectrum is smoothed and the peaks broadened to obtain the design floor response spectrum at the location of interest and for the given direction. The smoothed versions of these floor response spectra are the design floor response spectra. In the second approach, the mathematical model is subjected to the simultaneous action of three statistically independent spatial components of earthquake motion. The three computed and smoothed floor

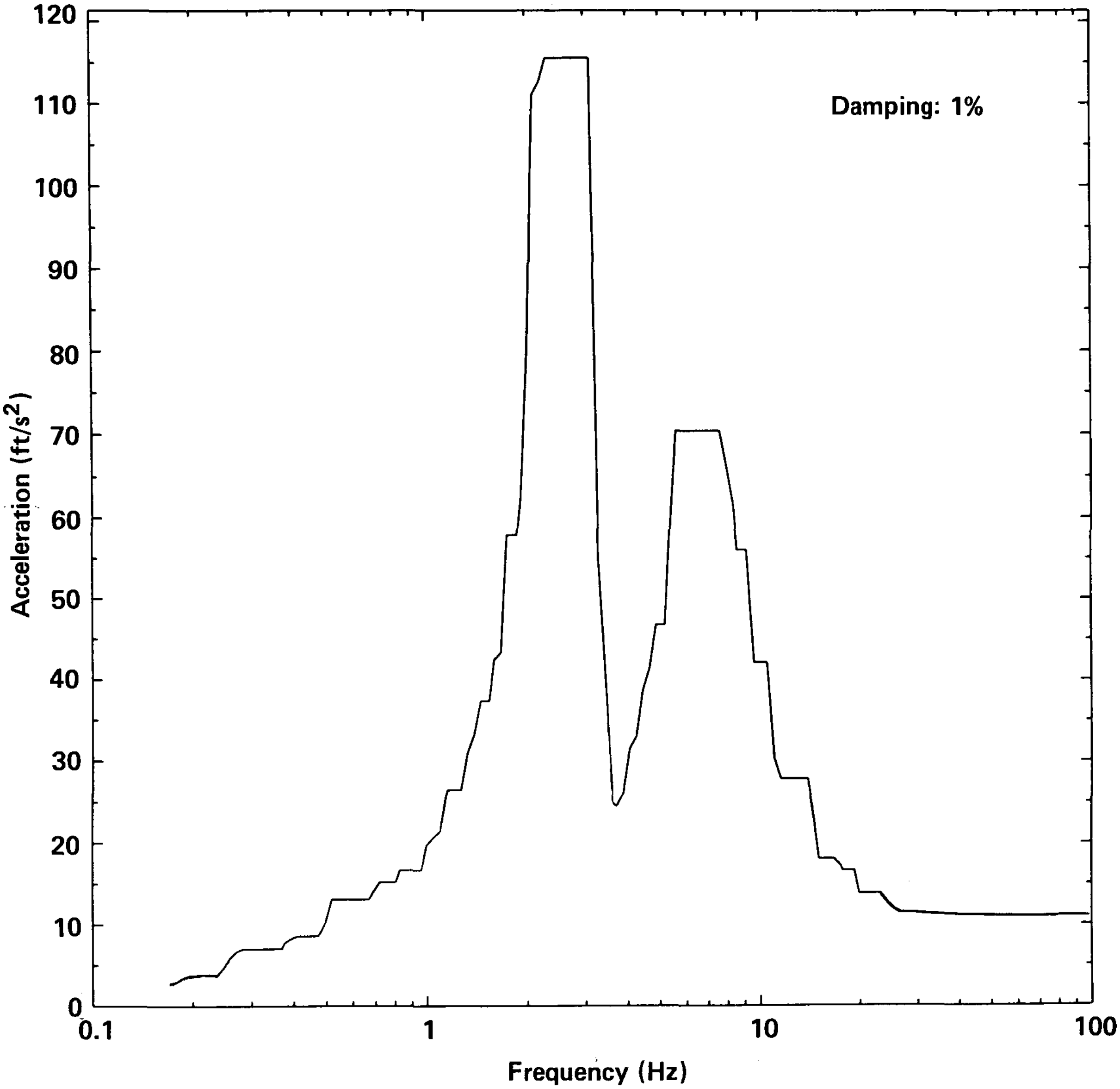


Fig. 2.7. Enveloped broadened spectrum in the east-west direction for the AFW-1 model.

response spectra at a given location are the design floor response spectra. The latter approach was taken here.

Peak broadening is an approach to account for uncertainty in the properties of structures, soil, and their mathematical model. We broadened the peaks of floor response spectra by ±15% of the peak frequency. The peak frequency is the frequency at which the spectral peak occurs. This method is an approved approach in RG 1.122.

For each piping system we enveloped the broadened response spectra of all piping support locations in the structure for each direction (two horizontal and the vertical). The damping values of these spectra were those OBE values specified in RG 1.61, because the OBE generally governs the seismic design of piping systems, as explained in Section 2.2.2. The enveloped spectra were the input to calculate the piping systems' seismic responses, e.g., accelerations, displacements, support forces, and pipe resultant moments. RG 1.61 damping values of piping systems are given in Table 2-3.

2.3.2 Response Spectrum Analysis

The seismic response spectrum analysis of a piping system subjected to a uniform excitation is a special case of multi-support analysis, as described in Section 2.2; i.e., Eq. (1) or (5a) of Section 2.2.1 can be written as

$$[M_{11}][\ddot{x}_1^R] + [C_{11}][\dot{x}_1^R] + [K_{11}][x_1^R] = -[M_{11}][D]\ddot{u} \quad , \tag{10}$$

where

$$[x_1] = [x_1^R] + [D]u \text{ , and} \tag{11}$$

$[x_1]$ is the absolute active displacement vector of the piping system and

$\ddot{u}$ is the seismic input acceleration time history of the displacement u of piping supports,

$[x_1^R]$ is the displacement vector of the piping system relative to the piping supports which move uniformly, and

[D] is a vector with zeros and ones associated with each degree of freedom.

Notice that we assumed that all piping supports moved with the same excitation u for each direction (two horizontal and the vertical), that [D] is the vector to introduce the direction of input motion, and that $[M_{11}]$, $[C_{11}]$, and $[K_{11}]$ are the mass, damping, and stiffness matrices of the piping system.

Using the eigenfunction expansion for $[x_1^R]$ and assuming the diagonalization of $[C_{11}]$, as described in Section 2.2.1, we derive the following equations:

$$[x_1^R] = [\Phi][q^R] \quad , \tag{12}$$

Table 2.3. Recommended damping values (percent of critical damping).

Pipe size	OBE or half-SSE	SSE
Large-diameter piping systems--pipe size greater than 12 in.	2	3
Small-diameter piping systems--pipe size equal to or less than 12 in.	1	2

$$[\Phi]^T[M_{11}][\Phi] = [I] \quad , \tag{13}$$

$$[\Phi]^T[C_{11}][\Phi] = [\backslash 2\beta_j\omega_j\backslash] \quad , \tag{14}$$

$$[\Phi]^T[K_{11}][\Phi] = [\backslash \omega_j^2 \backslash] \quad , \tag{15}$$

$$[\ddot{q}^R] + [\backslash 2\beta_j\omega_j\backslash][\dot{q}^R] + [\backslash \omega_j^2\backslash][q^R] = -[\hat{\Phi}]^T[M_{11}][D]\ddot{u} \quad , \tag{16}$$

where $[\hat{\Phi}]$ again is the reduced set of $[\Phi]$. The definitions of the vectors and matrices ($[\Phi]$, etc.,) are as described in Section 2.2.1.

Recall that the acceleration response spectrum is the plot of the maximum spectral acceleration, $Sa(\omega, \beta)$, of a single oscillator with damping value β subject to an excitation $\ddot{u}(t)$ versus the angular frequency ω of the oscillator. If we solve Eq. (16) by the response spectrum method, we obtain

$$[q_i^R]_{max} = \{[\Phi]^T[M_{11}][D]\}Sa_i/\omega_i^2 \quad , \tag{17}$$

where Sa_i is the spectral acceleration corresponding to the angular frequency ω_i on the response spectrum curve of the excitation $\ddot{u}$. The maximum response of the ith mode in the physical coordinates of the piping system is

$$\left[x_{1\ max}^R\right]_i = [\Phi_i]q_{i\ max}^R \quad , \tag{18}$$

where $[\Phi_i]$ is the ith column of $[\Phi]$.

Recovery of the maximum support forces and pipe moments for each mode are calculated in a fashion similar to that used in the RG 1.60 analysis [Eq. (11) in Section 2.2.1].

In a response spectrum analysis, the maximum responses of individual modes are calculated and must be combined to estimate overall response. The method of combination, as specified in RG 1.92, depends on the relative values of modal frequencies, i.e., closely spaced or not as itemized below.

If the modes are not closely spaced (frequencies within 10%), the representative maximum value of a particular response of interest for design is obtained by taking the SRSS of corresponding maximum values of the response of the element attributed to individual modes:

$$R = \left[\sum_{k=1}^{N} R_k^2\right]^{1/2} \quad , \tag{19}$$

where R is the representative maximum value of a particular response of a given element to a given component of an earthquake, R_k is the peak value of the response of the element due to the kth mode, and N is the number of significant modes considered in the modal response combination.

If the modes are closely spaced, any of three methods of combination specified in RG 1.92 may be used. They are the "Grouping Method," the "Ten Percent

Method," and the "Double Sum Method." We used the Grouping Method for our study. The grouping method defines groups of modes which are considered closely spaced. A group of modes is formed for modes with frequencies within 10% of the lowest frequency of the modes in the group. The combination of responses within a group is by absolute sum. The combination of responses outside groups (between groups and individual modes not in groups) is by SRSS.

The separately calculated piping responses for the two horizontal and the vertical directions must be combined. For directional combination we used a SRSS rule to calculate the total seismic response of the piping system.

2.4 Proposed PVRC Procedures

2.4.1 Damping

The Task Group on Damping of the PVRC Technical Committee on Piping Systems made a preliminary review of all available damping data sets (PVRC Technical Committee on Piping Systems, 1983a). The review clearly justified an increase in the specified damping values for piping systems over those specified in RG 1.61 in the lower frequency range, especially below 10 Hz.

The PVRC proposal was identified for our evaluation by the Task Group. It specifies increased damping values compared to current procedures. The proposal acknowledges that damping is frequency-dependent. This proposal assumed 5% damping for frequencies below 10 Hz, linearly varying damping from 5% at 10 Hz to 2% at 20 Hz, and 2% damping at frequencies above 20 Hz. Figure 2.8 shows the proposal and the current RG 1.61 requirements. Note that the PVRC proposal is independent of excitation level and piping size.

2.4.2 Alternative to Peak Broadening

Peak broadening of in-structure response spectra is a procedure to account for uncertainty in soil and structure characteristics. Peak broadening without a reduction in amplitude is potentially very conservative since for a given event in-structure spectra will resemble raw spectra rather than broadened with an uncertain peak spectral frequency. In an attempt to compensate for this conservatism, the Task Group on Spectrum Development of the PVRC Technical Committee on Piping Systems has proposed an alternative procedure to peak broadening (PVRC Technical Committee on Piping Systems, 1983b). The proposed alternative entails shifting the raw response spectra over a frequency range of ±15% of the peak spectral frequency, provided that at least one of the piping system's natural frequencies fall within the frequency range (Fig. 2.9). If no natural frequency falls within the range, the shifting procedure shall be used for the next highest peak of the acceleration spectrum where there is at least one of the piping system's natural frequencies in the range. The advantage of this approach is that it maintains the expected response spectra shapes from an event. Repeated response spectrum analyses of the piping system are performed with the shifted raw response spectra. Three basic cases are analyzed independent of piping system frequencies--as calculated raw response spectra and raw response spectra shifted such that the peak spectral frequency is at ±15% of its nominal value. In addition, analyses are performed with the peak spectral frequency coinciding with all piping model modes lying in the range of ±15% of the

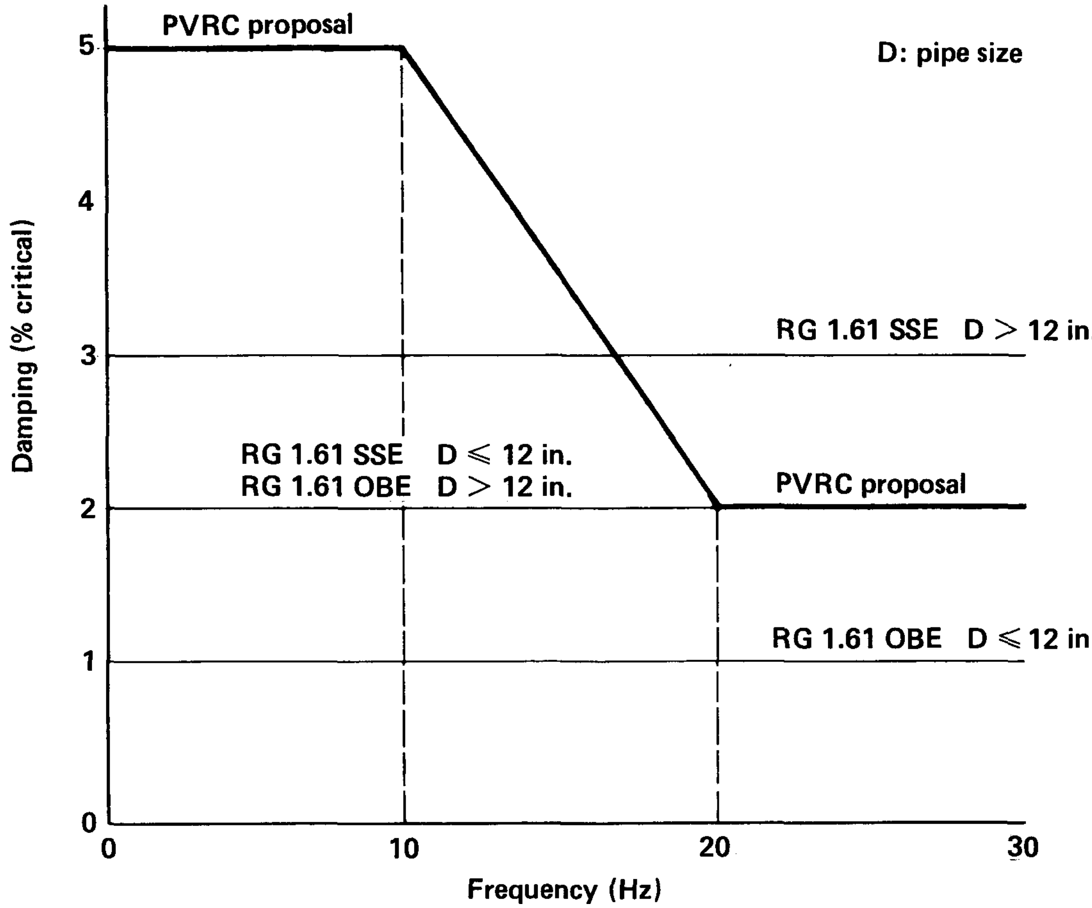
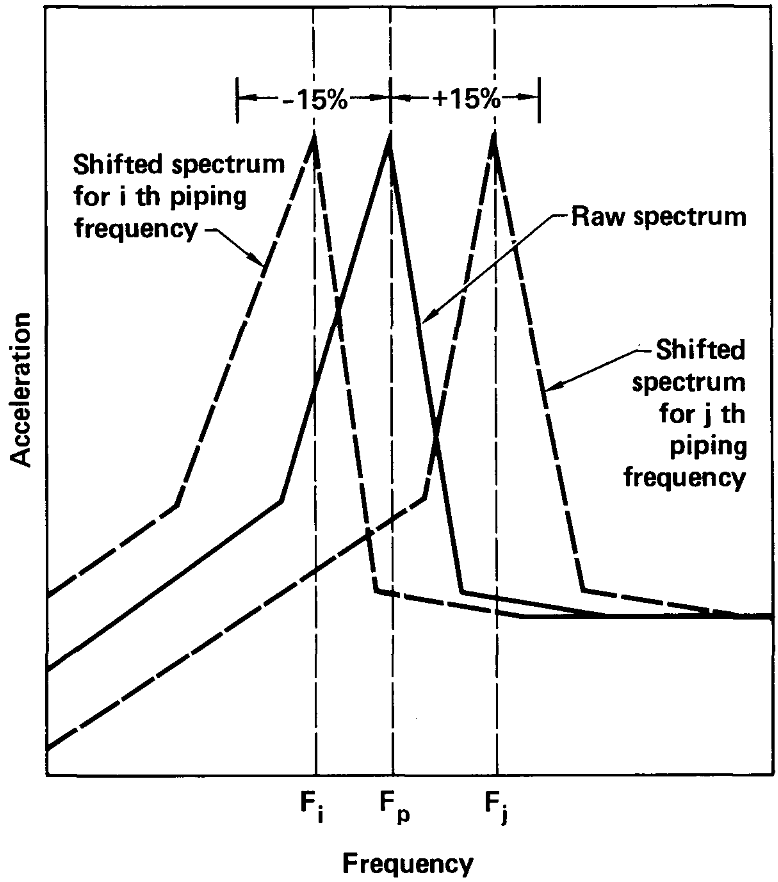


Fig. 2.8. PVRC-proposed damping values for piping systems.

peak. The response associated with each mode or element is taken as the maximum value calculated in any of the repeated analyses. Note that if no piping mode frequencies lie in the ±15% range of the peak spectral frequency, then the procedure is applied to the next highest peak. Figure 2.9 shows the process schematically.

This procedure is carried out for each direction of excitation separately and the rules of modal combination of Section 2.3.2 are applied. The resulting directional responses are combined by SRSS (again, as decribed in Section 2.3.2).



F_p = peak frequency of raw spectrum
F_i = i th piping frequency lying in the ±15% range
F_j = j th piping frequency lying in the ±15% range

Fig. 2.9. PVRC-proposed alternative to peak broadening.

3. DESCRIPTION OF PIPING MODELS

3.1 INTRODUCTION

We applied our methods of analysis to three piping systems of the nuclear power plant at Zion, Illinois (Chuang, 1981). In this section we briefly describe the structures in which the piping systems are located, the three piping models, and their key parameters. The piping models vary from relatively simple to extremely complex. These piping systems run between buildings or structures. Pipe sizes range from 3-inch to 31-inch.

3.2 ZION STRUCTURES

The piping systems of interest in this study are housed in two structures, the containment building and the auxiliary fuel-handling turbine building (AFT) complex. The AFT complex consists of connected buildings housing the turbines, fuel-handling equipment, diesel generators, etc. (Fig. 3.1). Models of these structures were originally developed for the SSMRP (Benda, Lo, and Johnson, 1981).

Containment Building. The containment building has two separate structures, the containment shell and an internal structure, on a common basemat (Fig. 3.2).

The pre-stressed concrete containment shell is modeled with beam elements. The model includes rotational inertias that affect bending and torsion of the shell. Masses and rotational inertias are lumped at node points. We include the first 13 modes in our dynamic analysis. These modes cover all the structure's natural modes below 33 Hz.

The containment shell contains a separate concrete internal structure (Fig. 3.2), which supports a four-loop pressurized-water reactor (PWR) Westinghouse nuclear steam-supply system (NSSS). The internal structure, including an appropriate representation of the NSSS, is modeled with three-dimensional finite elements (Fig 3.3). The elements are beams, trusses, plates, straight and curved pipes, etc. Masses are lumped at selected node points. We include the first 60 modes in our dynamic analysis. These modes cover all the structure's natural modes below 33 Hz.

AFT Complex. The T-shaped AFT complex is treated as being symmetrical about the vertical plane down the center of the stem of the T. A three-dimensional finite-element model of half of the complex was constructed (Fig. 3.4). The elements are plates, shells, beams, and trusses. The model has over 3800 degrees of freedom (DOF). Applying appropriate boundary conditions along the plane of symmetry and extracting symmetrical and anti-symmetrical modes led to the description of the dynamic characteristics of the structure. We included 113 modes in our dynamic analysis, which included all the structure's significant natural modes below 33 Hz.

3.3 PIPING MODELS

We considered three piping models for our study: one model of the auxiliary feedwater system (AFWS), one model of the residual heat-removal and safety injection system (RHR/SIS), and one model of the reactor coolant system (RCS). We refer to these models as the AFW-1 model, the RHR/SI-1 model, and the RC-1 model.

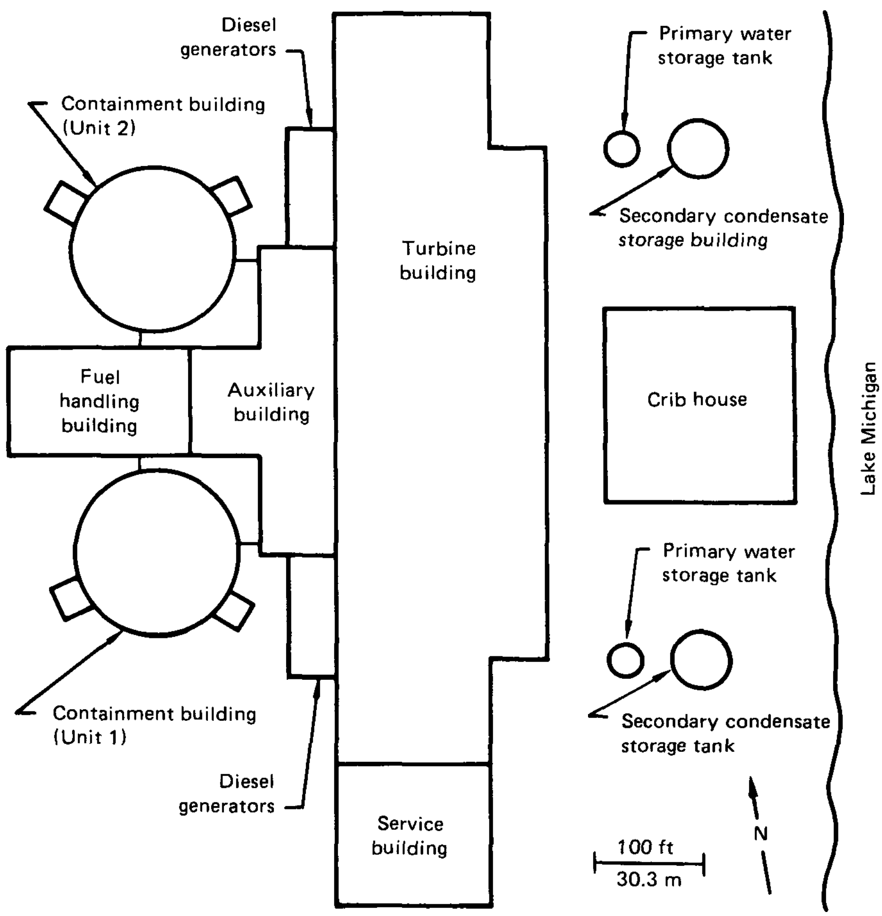


Fig. 3.1. Arrangement of building structures at the Zion plant.

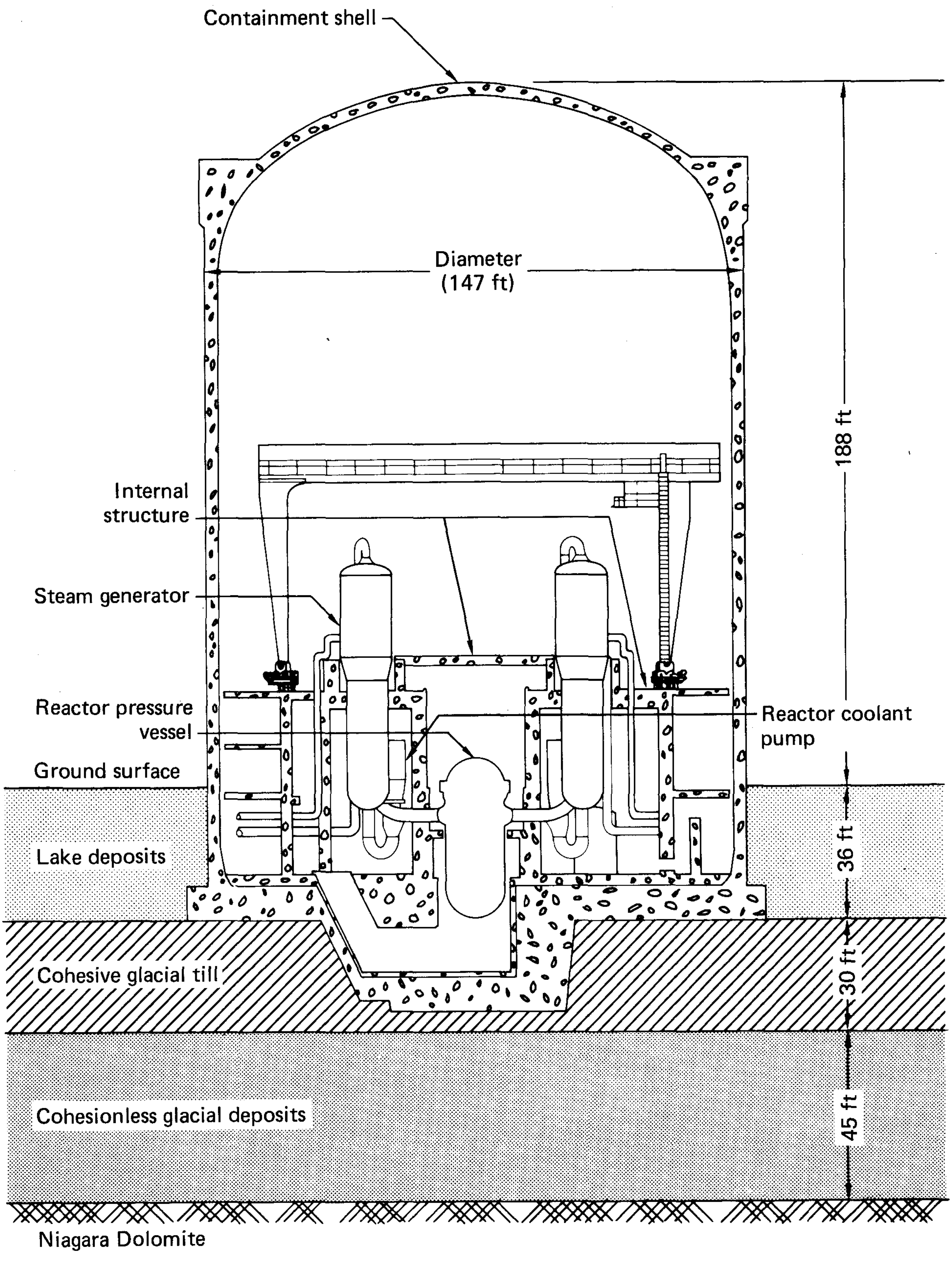


Fig. 3.2. Cross section of the containment building at Zion.

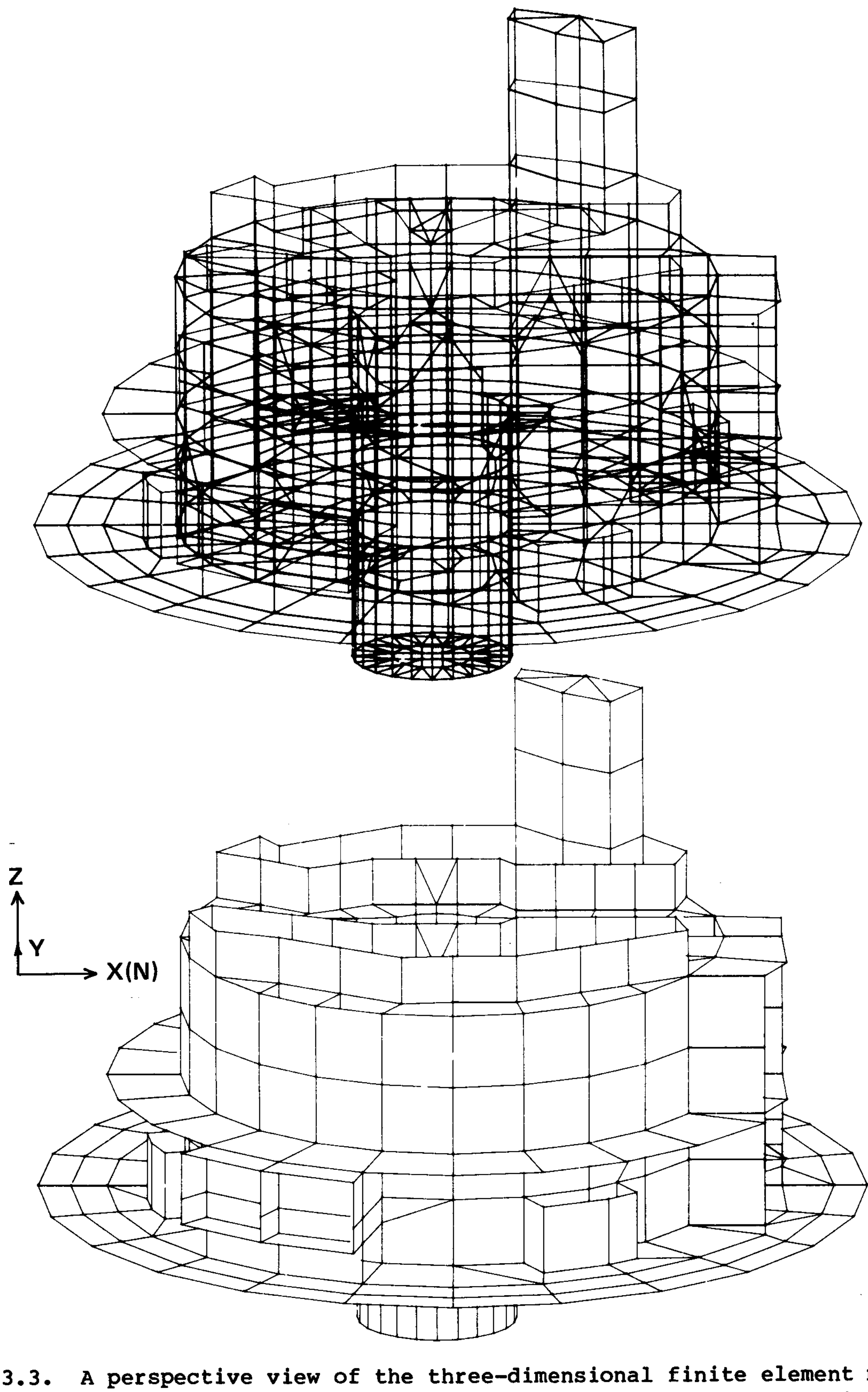


Fig. 3.3. A perspective view of the three-dimensional finite element model for the internal concrete structure in the containment building at Zion.

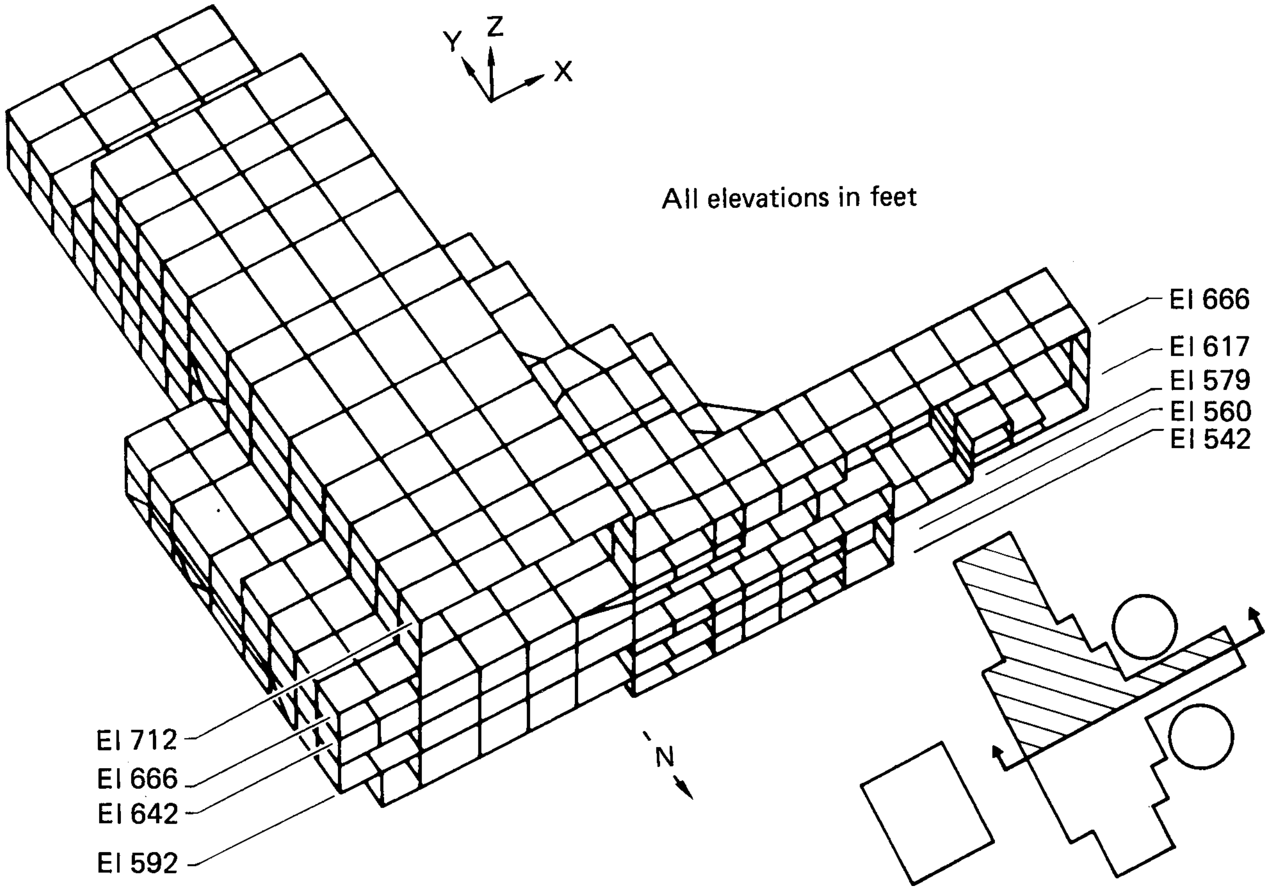


Fig. 3.4. Finite element half-structure model of the AFT complex; shaded area of the inset sketch shows the portion of the structure modeled.

The AFWS is for emergency cooling if the main feedwater system fails. The RHRS removes residual heat from the core and reduces the temperature of the reactor coolant system. The SIS cools the core and limits the metal-water interaction. The RCS transfers the heat generated in the core to the steam generators, which generate steam to drive the turbines.

AFW-1 Model. We modeled one part of the AFWS, namely, the piping from one of the four steam generators to the containment penetrations (Fig. 3.5). The AFW-1 model consists of a 16-inch main feedwater (MFW) line from steam generator nozzle to a containment penetration and a 3-inch auxiliary feedwater (AFW) line branched from the 16-inch MFW line to a containment penetration.

We describe the configuration of the supports and snubbers of the AFW-1 model in detail, since the AFW-1 model will be used in Section 4 to study the benefits of the savings on the numbers of supports/snubbers from proposed changes to RG 1.61 and RG 1.122. The 16-inch MFW line has two hydraulic snubbers installed to sustain seismic loads. In addition, both the 16-inch MFW line and the 3-inch AFW line have a number of rigid lateral restraints and vertical supports (Fig. 3.6).

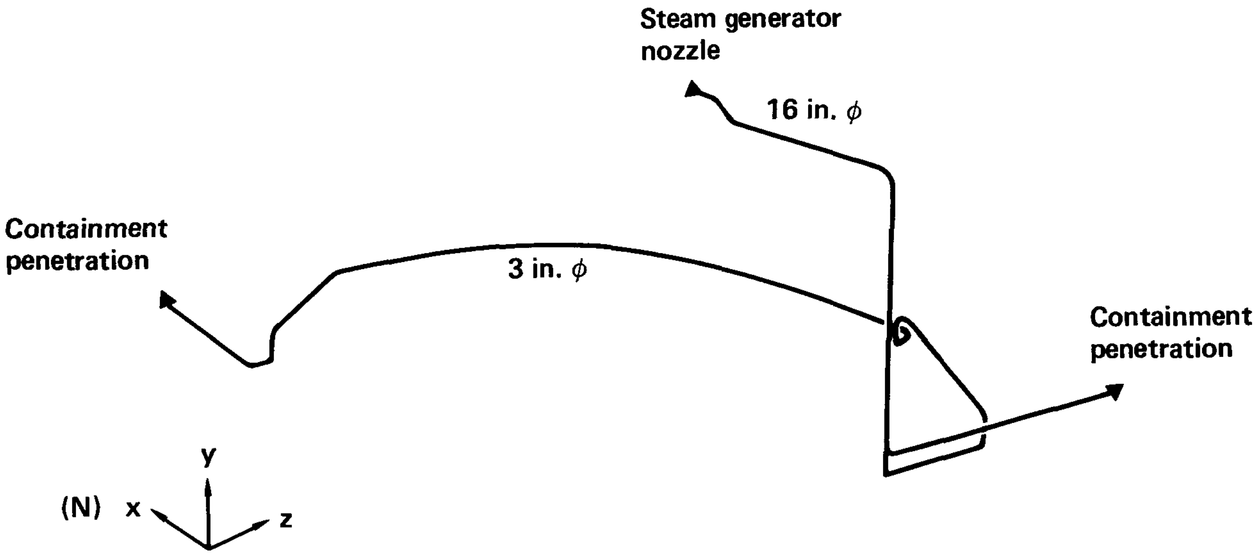


Fig. 3.5. AFW-1 model.

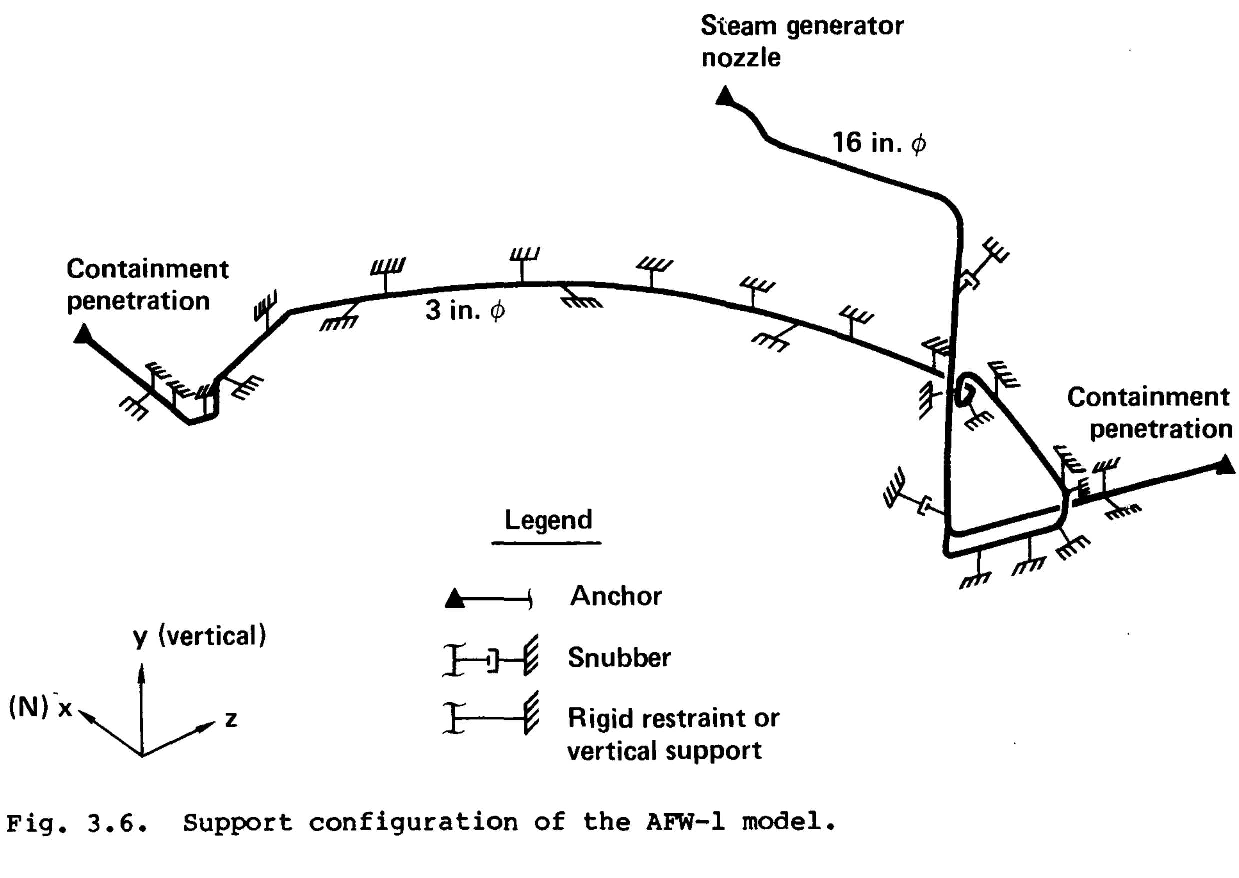


Fig. 3.6. Support configuration of the AFW-1 model.

RHR/SI-1 Model. We modeled one part of the RHR/SIS, namely, the piping inside the AFT complex and one small portion inside the containment shell (Fig. 3.7). The RHR/SI-1 model consists of a 12-inch pipe line from a wall anchor at the internal structure of the containment building to an anchor in the AFT complex, and an 8-inch pipe line from the refueling water storage tank (RWST) nozzle to the 12-inch pipe.

RC-1 Model. We modeled one part of RCS, namely, all four reactor coolant loops (RCL), six branch lines of the loops, and all major NSSS's equipment, including the reactor pressure vessel (RPV), four steam generators (SG), four reactor coolant pumps (RCP), and a pressurizer (Fig. 3.8). Each of the four reactor coolant loops consists of a 29-inch hot leg from the nozzle of RPV to SG, a 31-inch crossover leg from the nozzle of SG to RCP, and a 27.5-inch cold leg from the nozzle of RCP to RPV. These pipe sizes are the inside diameters (not the nominal pipe sizes as normally referred to).

The six branch lines are:

- The 14-inch pressurizer surge line from the pressurizer to the hot leg of the RCL No. 4.
- The 14-inch line from the hot leg of RCL No. 1 to the RHRS.
- The 8-inch SI line to the cold leg of RCL No. 1.
- The 8-inch bypass line from the hot leg to the cold leg of RCL No. 1.
- The two 4-inch pressurizer spray lines from the cold leg of RCL Nos. 3 and 4 to the pressurizer. One of these two lines joins into another going to the pressurizer.

Basis for Selection. We selected these piping models to cover a wide range of parameters, as can be seen in Table 3.1. The piping systems vary considerably in size and complexity. In terms of the number of support motions and modes considered, the RHR/SI-1 model is smallest and least complex, the RC-1 model is the largest and most complex, and the AFW-1 model is intermediate.

Table 3.1. Key parameters of the three piping models.

Piping model	Nominal pipe size (in.)	No. of nodes	No. of equations[a]	No of support motions[b]	No. of modes considered[c]	Fundamental frequ. (Hz)
AFW-1	3, 16	263	945	45	36	2.9
RHR/SI-1	8, 12	96	423	21	18	3.9
RC-1	4, 8, 14, 27.5[d], 29[d], 31[d]	760	2941	127	130	1.4

a See Sackett (1979).
b Covers motion in two horizontal and the vertical direction.
c These modes cover all the piping natural frequencies below 33 Hz.
d These are the inside diameters of reactor coolant loops.

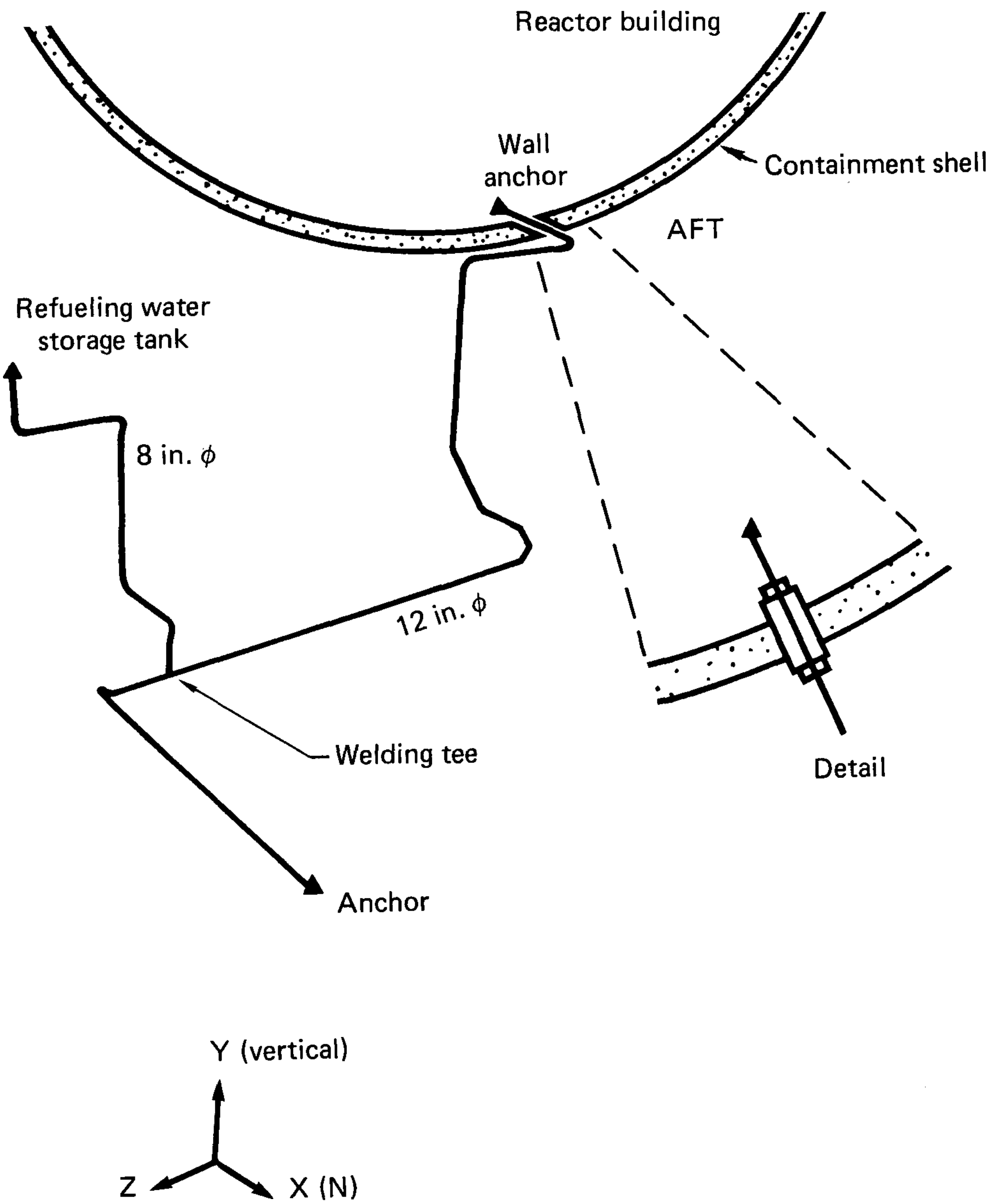


Fig. 3.7. RHR/SI-1 model.

Features of the Models. The models had several features in common:

- Piping was assumed to be linearly elastic.
- Appropriate stiffnesses were incorporated for piping supports (including rigid hangers, lateral restraints, and snubbers), except those of RHR/SI-1 model, where the piping supports were assumed to be rigid.
- Constant and variable spring hangers were not included, because their small stiffnesses were negligible compared to the stiffness of piping and other types of restraints (snubbers, etc.).

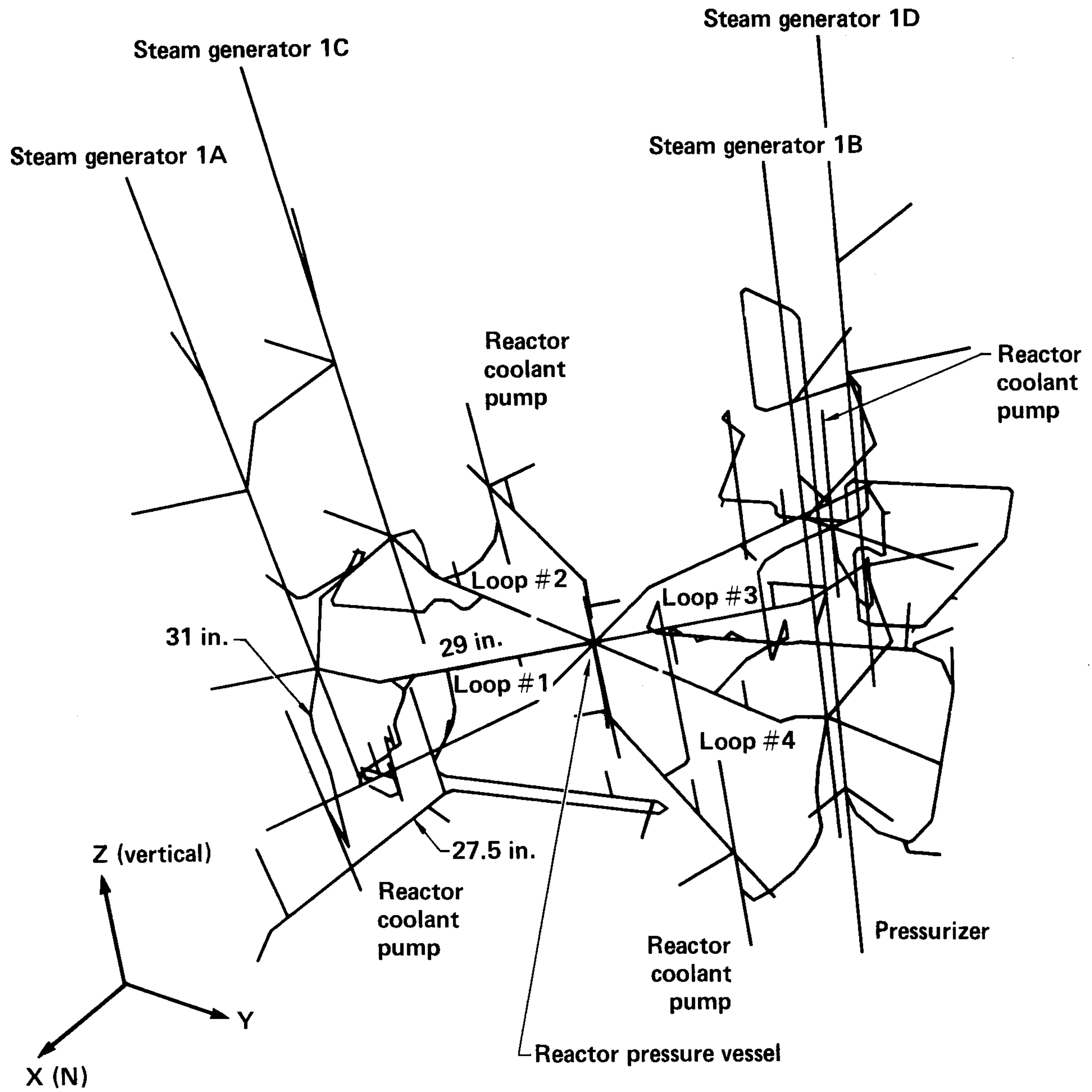


Fig. 3.8. RC-1 model.

The stiffness formulation of curved pipe (elbow or bend) elements included the effect of internal pressure on the flexibility of curved pipes. In general, we used the pipe elements of SAP4 (Sackett, 1979) to define straight and curved pipes and the boundary elements of SAP4 to simulate supports, restraints, and snubbers. However, in the RC-1 model we used truss and beam elements to describe the NSSS's equipment supports and stiffness elements to represent stiffness effects on the main steam lines and main feedwater lines. Each major component of the NSSS (RPV, SG, RCP and pressurizer) was represented by a comprehensive mathematical model. For details of this model, see Eberhardt (1980).

Responses of Models. For each piping model we calculated responses at selected nodes and elements. We concentrated on components in which high stresses generally occur, i.e., elbows, tees, reducers, etc. The number of modes was sufficiently large to permit our analysis to cover frequencies up to 33 Hz. We calculated nodal accelerations and displacements, reactions of supports, and pipe resultant moments--the amplitude of the vector sum of the two orthogonal bending moments and the torsional moment. In all, we calculated the following responses:

- 63 accelerations and displacements, 28 support reactions, and 23 pipe resultant moments for the AFW-1 model.
- 51 accelerations and displacements, 15 support reactions, and 22 pipe resultant moments for the RHR/SI-1 model.
- 51 accelerations, 94 support reactions, and 118 pipe resultant moments for the RC-1 model.

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

The Technical Committee on Piping Systems of the PVRC has proposed modifications in the specified damping values and an alternative procedure to the peak broadening of response spectra for the seismic design of nuclear power plant piping systems. These modifications are intended to reduce the conservatism and will provide more realistic seismic design guidelines. In this study we investigated the effect of these modifications on reduction of piping seismic response, their conservatism, and the benefit of possible elimination of snubbers/supports.

We performed numerous analyses with different combinations of damping values (RG 1.61 and proposed PVRC), peak-broadening (RG 1.122), and the alternative to peak broadening (proposed PVRC), enabling us to compare piping seismic responses under various combinations. Hereafter, these combinations are referred to as "damping and peak broadening," and we refer to these analyses as cases, each case representing a different combination of conditions. We included response spectrum analysis in accordance with the current SRP procedure (as described in Section 2.3); we refer to this as the Base Case or Case 1. Section 4.2 is devoted to the comparative aspect of our study, in which we compare piping system responses with various combinations of damping and peak broadening to the Base Case--three cases are reported. Compared to the Base Case, these showed a considerable piping response reduction for the proposed PVRC damping values and a smaller effect of the proposed PVRC alternative procedure to peak-broadening.

We further compared results of response spectrum analysis, using the proposed PVRC modifications in damping and an alternative procedure to peak broadening (Case 4), with results of a time history analysis (Section 4.2.2). These comparisons showed that the response spectrum analysis with the proposed damping and alternative to peak-broadening requirements were still conservative relative to the time history results, i.e., conservatism remained.

Section 4.3 is devoted to the benefits aspect of our study, in which we evaluate the ASME Boiler and Pressure Vessel code compliance (ASME, 1980) of the AFW-1 model under the PVRC proposals with some snubbers and horizontal restraints removed. We found that implementation of the PVRC proposals would permit the elimination of both snubbers and seven of the ten existing horizontal restraints of the AFW piping system (or AFW-1 model). The removal of these snubbers and restraints would also reduce the seismic stresses due to relative support movement.

4.2 COMPARATIVE ANALYSIS

4.2.1 Comparison of the Results of Proposed PVRC Modifications with SRP Procedure.

To evaluate the effect of the PVRC proposed changes, we carried out response spectrum analyses on all three piping systems, using different combinations of damping and peak broadening. We call the analyses Case 1, Case 2, etc. The various cases are shown in Table 4.1. Note that we used the OBE damping values specified in RG 1.61 rather than the SSE damping values, because OBE requirements will generally govern the seismic design of piping systems if

Table 4.1. Combinations of damping and peak broadening procedures in the comparative study.

Case	Damping	Peak broadening	Remarks
1	RG 1.61 (OBE)	RG 1.122	SRP procedure--Base Case
2	PVRC	RG 1.122	
3	RG 1.61 (OBE)	PVRC	
4	PVRC	PVRC	Proposed PVRC modifications

the OBE is half the SSE, which is the general design practice.

As explained in Section 2.2.2, the free-field motion for these analyses are artificial acceleration time histories whose response spectra envelope RG 1.60 design ground response spectrum. The various regulatory standards and procedures referred to in Table 4.1 are described in Section 2. The PVRC-proposed damping values are described in Section 2.4.

Case 1. Current SRP requirements (Section 3.9.2). Accordingly, we also refer to this as the Base Case.

Case 2. Base Case with the PVRC-proposed damping.

Case 3. Base Case with the PVRC-proposed peak broadening.

Case 4. Case 4 incorporates both PVRC proposals (damping and peak broadening).

Cases 2, 3, and 4 were compared with Case 1, the Base Case, giving a total of 9 comparisons for the three piping models--AFW-1, RHR/SI-1, and RC-1. The ratios of the piping responses (accelerations, displacements, pipe resultant moments, and support loads) under these comparisons are shown in Figs. 4.1-4.9. Figures can be compared (e.g., Figs 4.1, 4.4, and 4.7) to see the effect of the PVRC proposals--separately and combined. Figures 4.1, 4.4, and 4.7 show the comparisons of Cases 2, 3, and 4 with Case 1 for the AFW-1 model. Figures 4.2, 4.5, and 4.8 show the comparisons of Cases 2, 3, and 4 with Case 1 for the RHR/SI-1 model. Figures 4.3, 4.6, and 4.9 show the comparisons of Cases 2, 3, and 4 with Case 1 for the RC-1 model.

Figures 4.1-4.3 compare Case 2 with Case 1. The figures show a considerable reduction in response for all piping models as a result of the PVRC-proposed damping. This result is expected because:

- The damping value for frequencies less than 20 Hz is much higher than the RG 1.61 OBE values, so spectral acceleration is substantially reduced (see, e.g., Fig. 4.10 for the AFW-1 model).

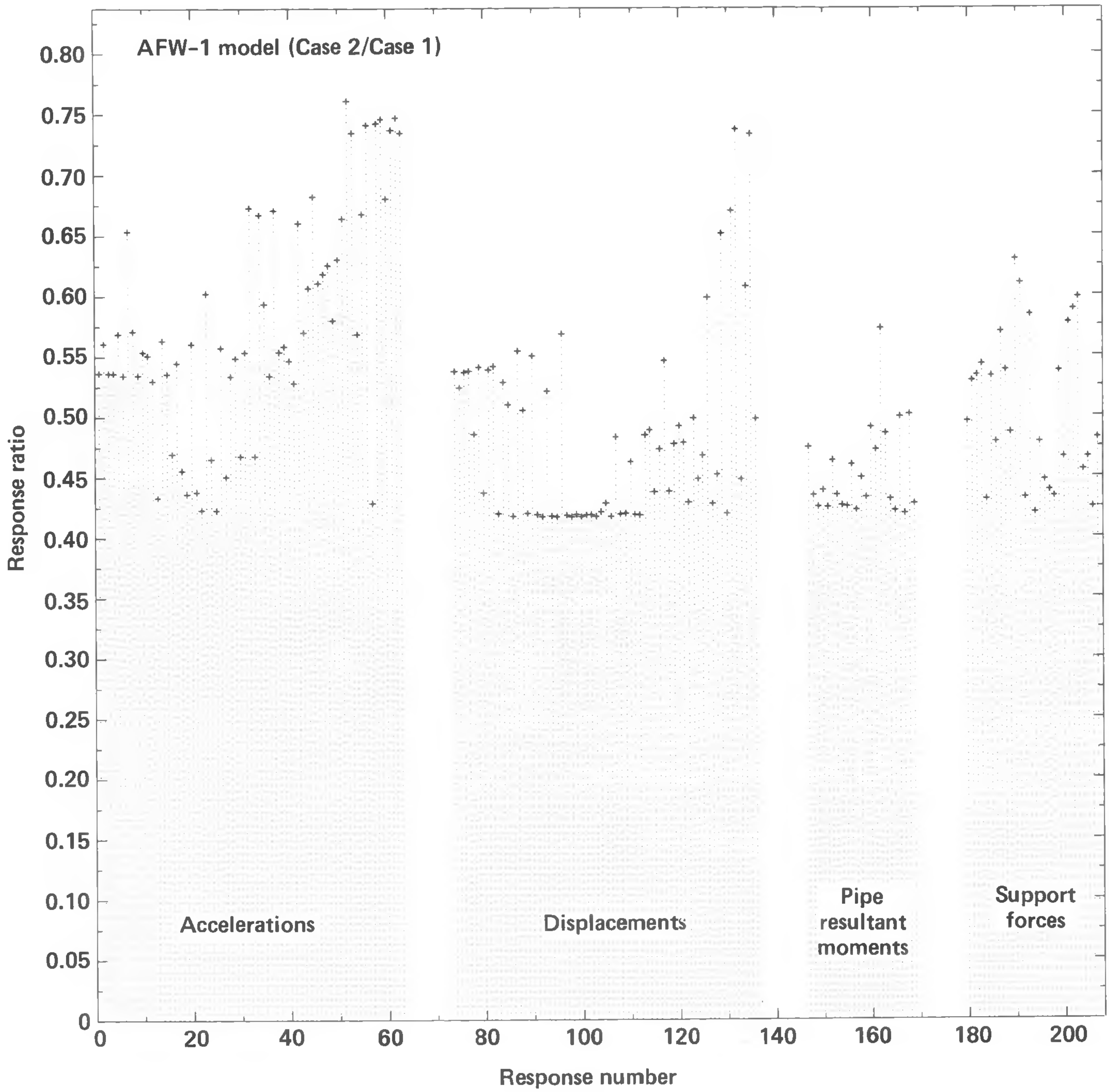


Fig. 4.1. Response ratio (Case 2/Case 1) for the AFW-1 model.

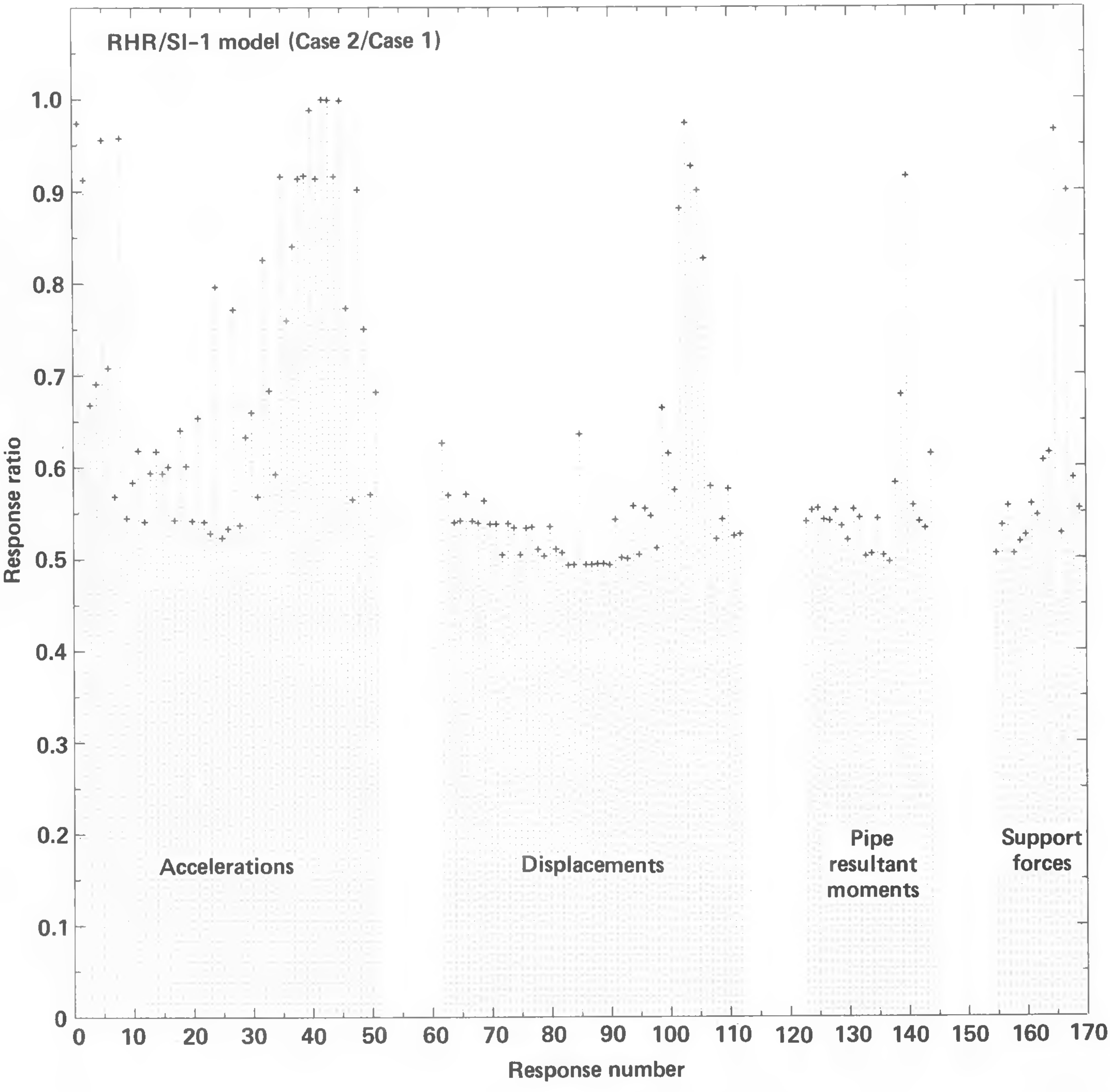


Fig. 4.2. Response ratio (Case 2/Case 1) for the RHR/SI-1 model.

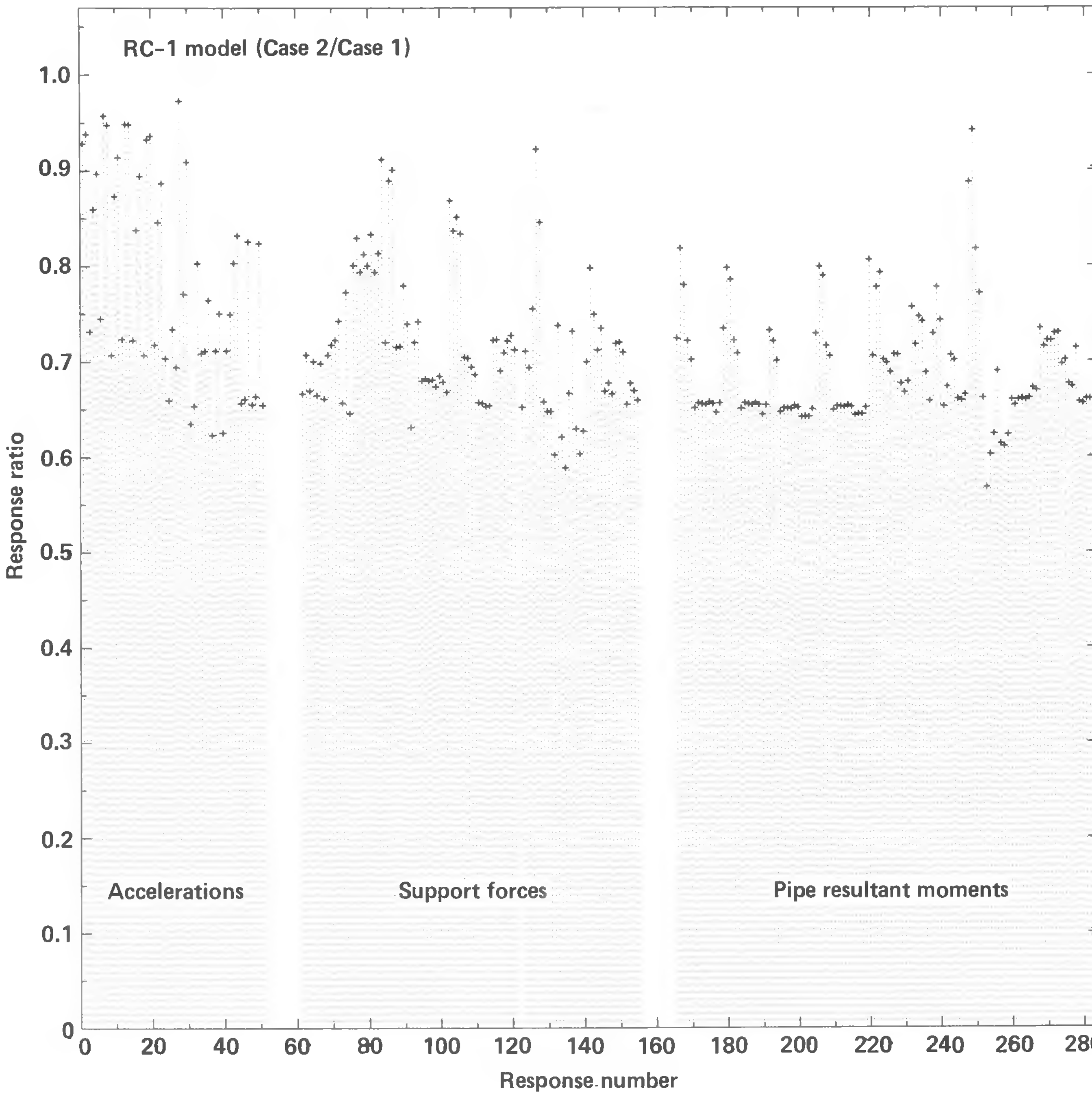


Fig. 4.3. Response ratio (Case 2/Case 1) for the RC-1 model.

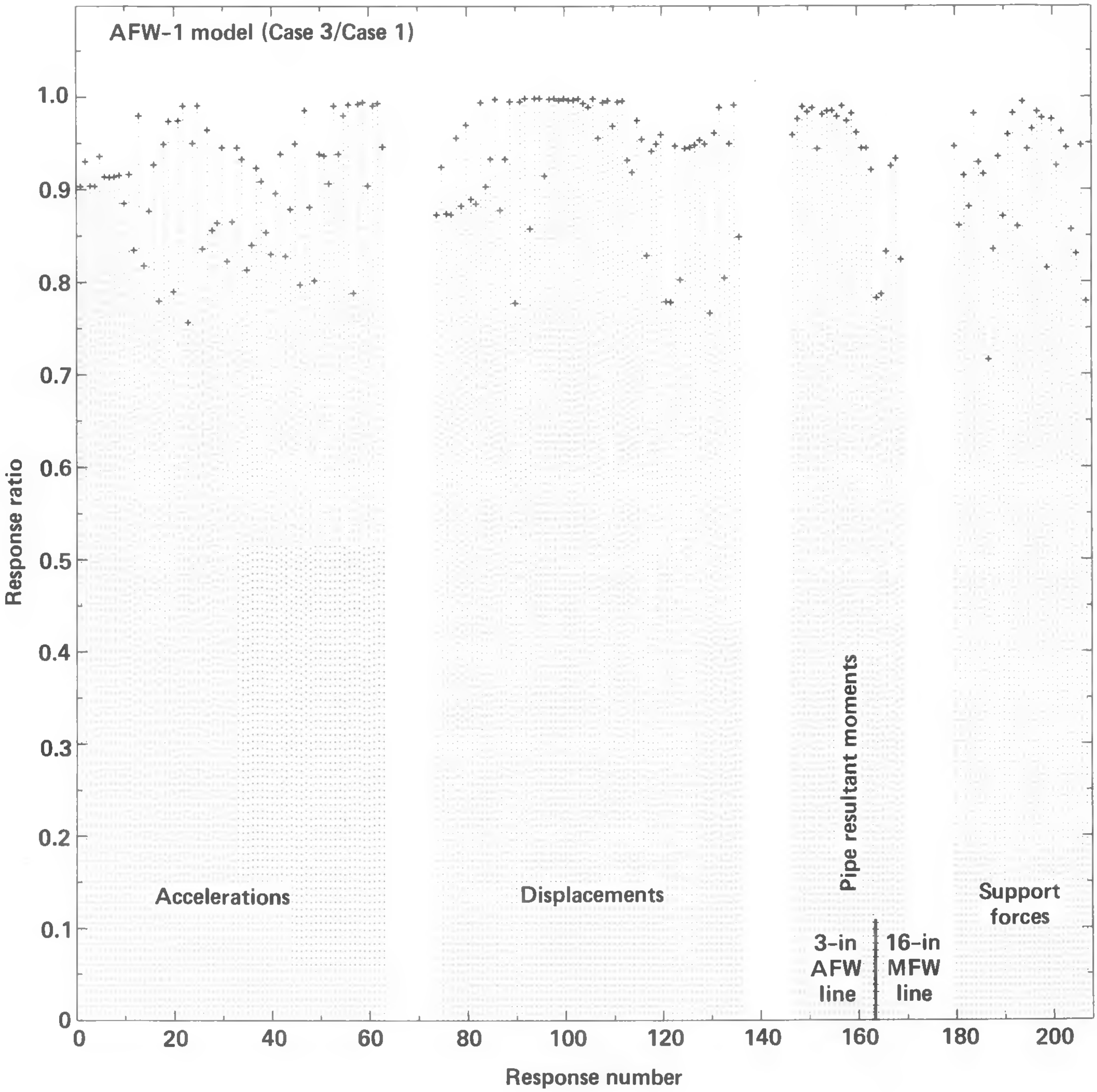


Fig. 4.4. Response ratio (Case 3/Case 1) for the AFW-1 model.

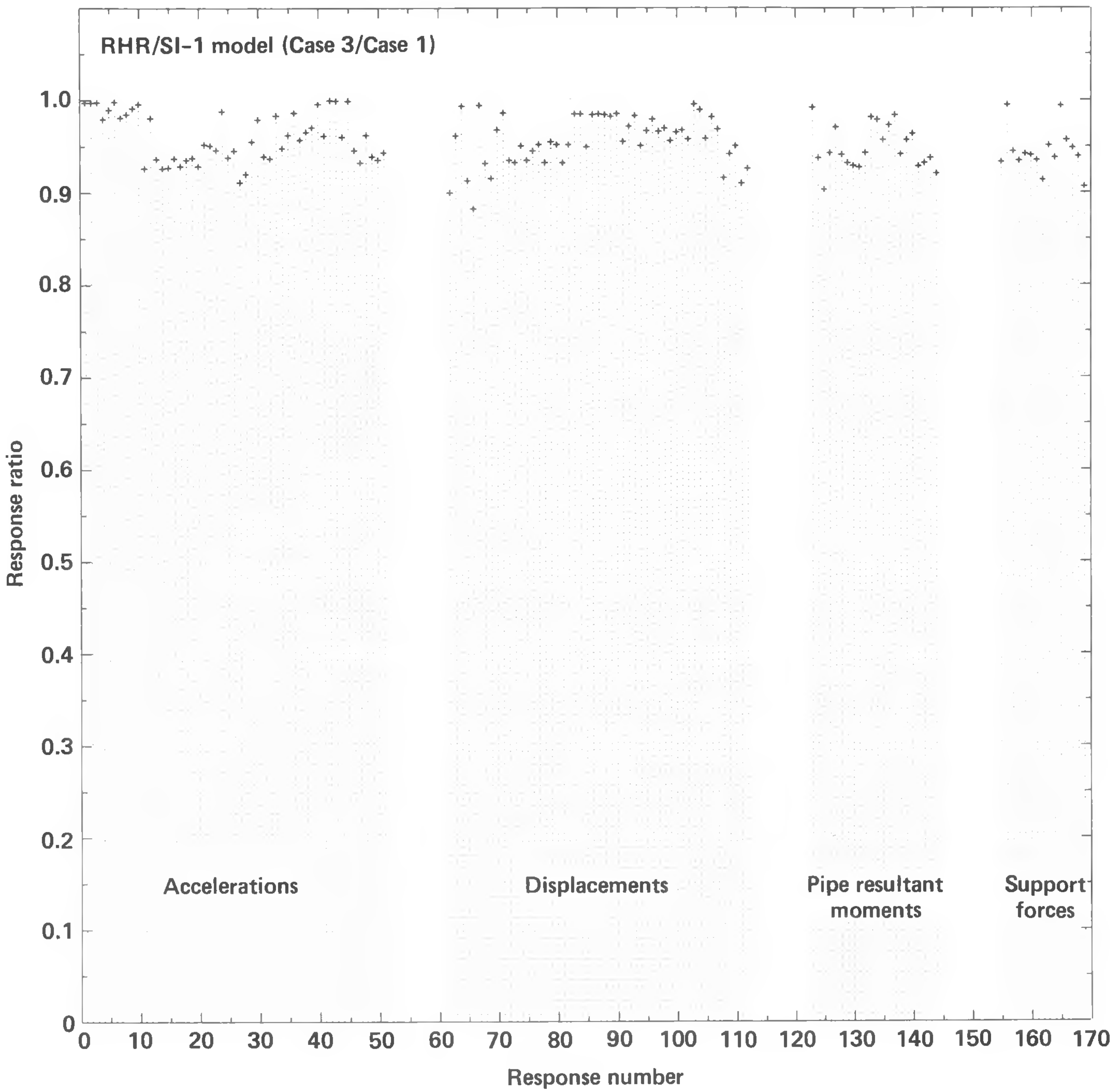


Fig. 4.5. Response ratio (Case 3/Case 1) for the RHR/SI-1 model.

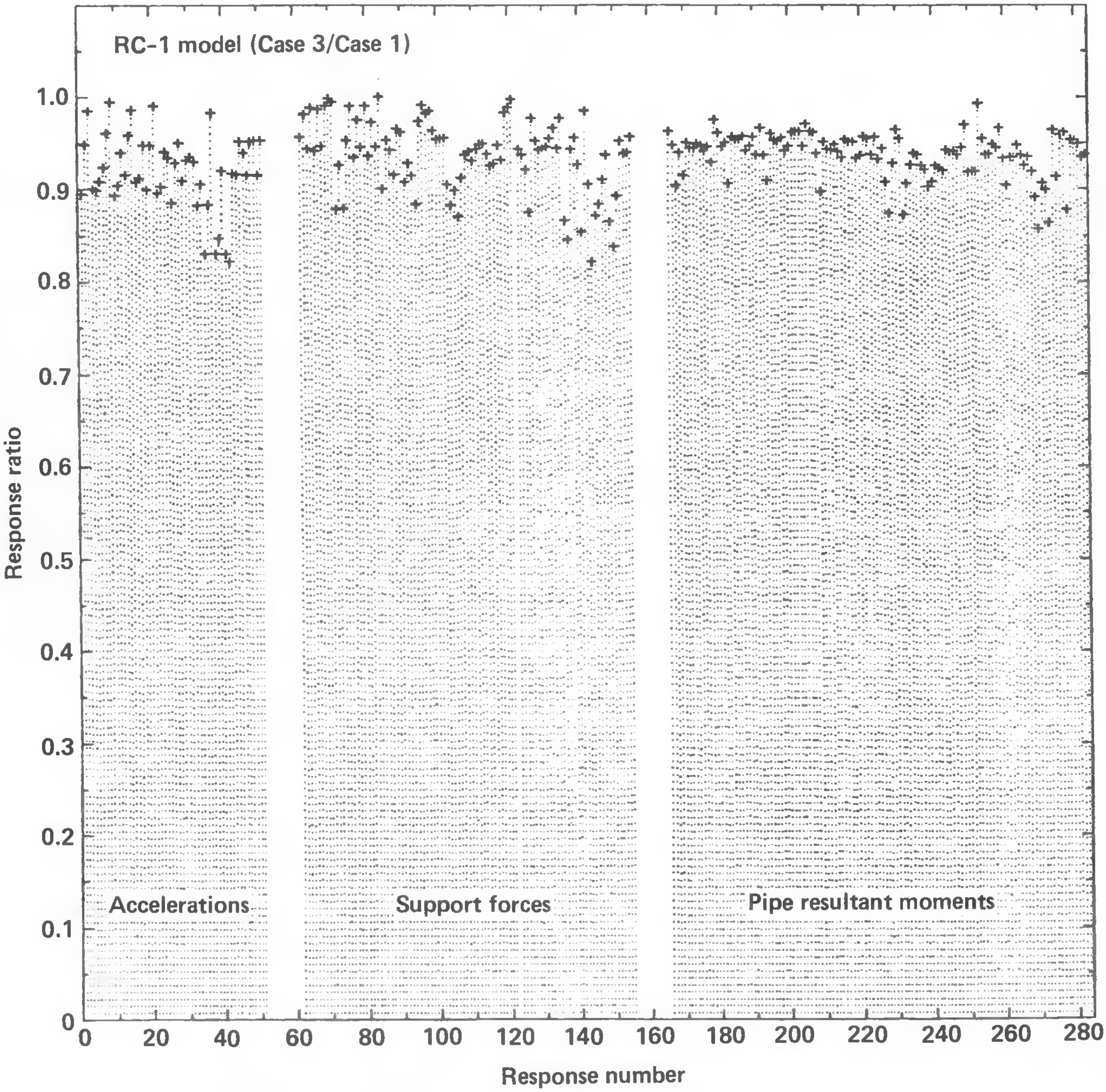


Fig. 4.6. Response ratio (Case 3/Case 1) for the RC-1 model.

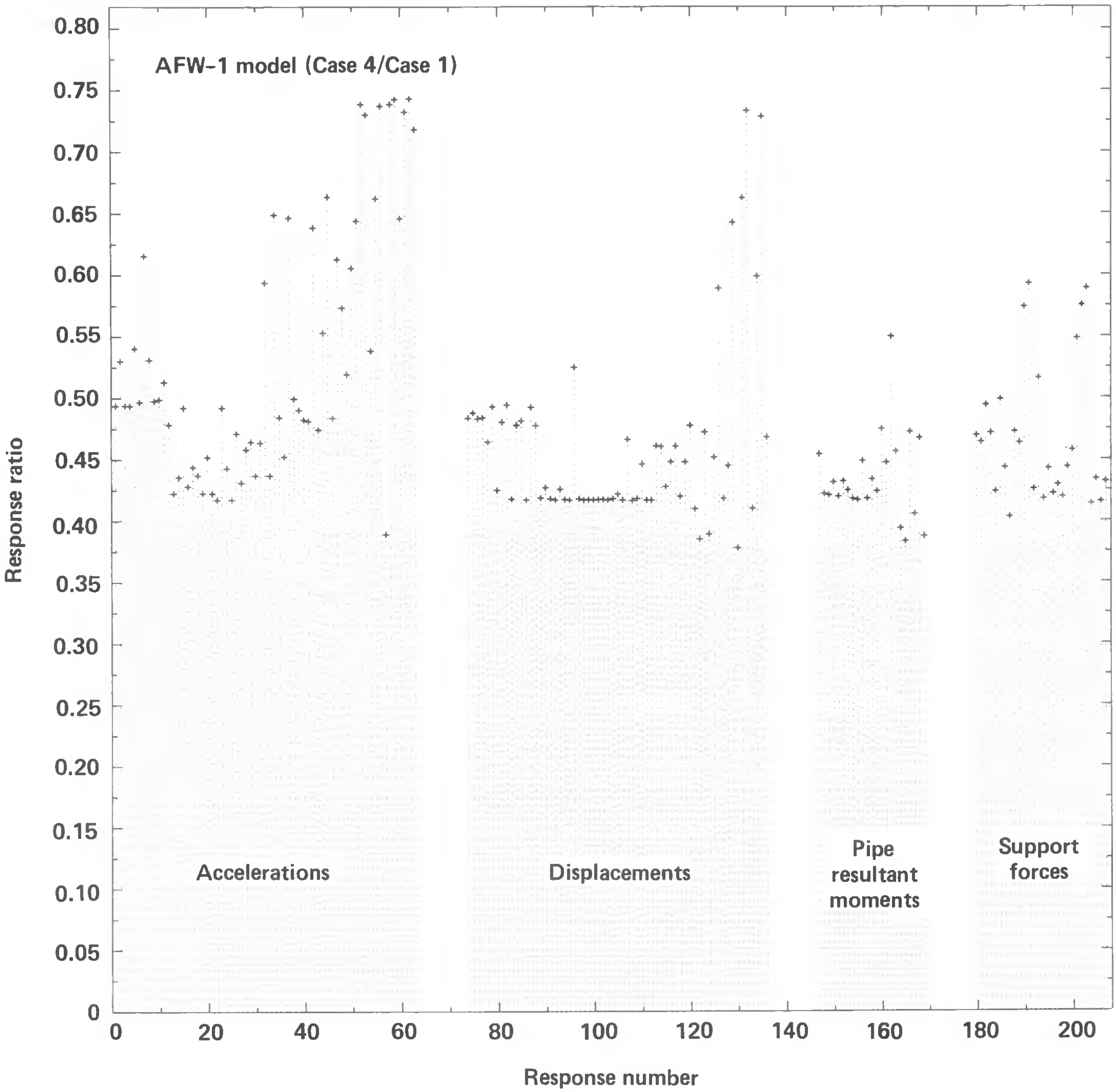


Fig. 4.7. Response ratio (Case 4/Case 1) for the AFW-1 model.

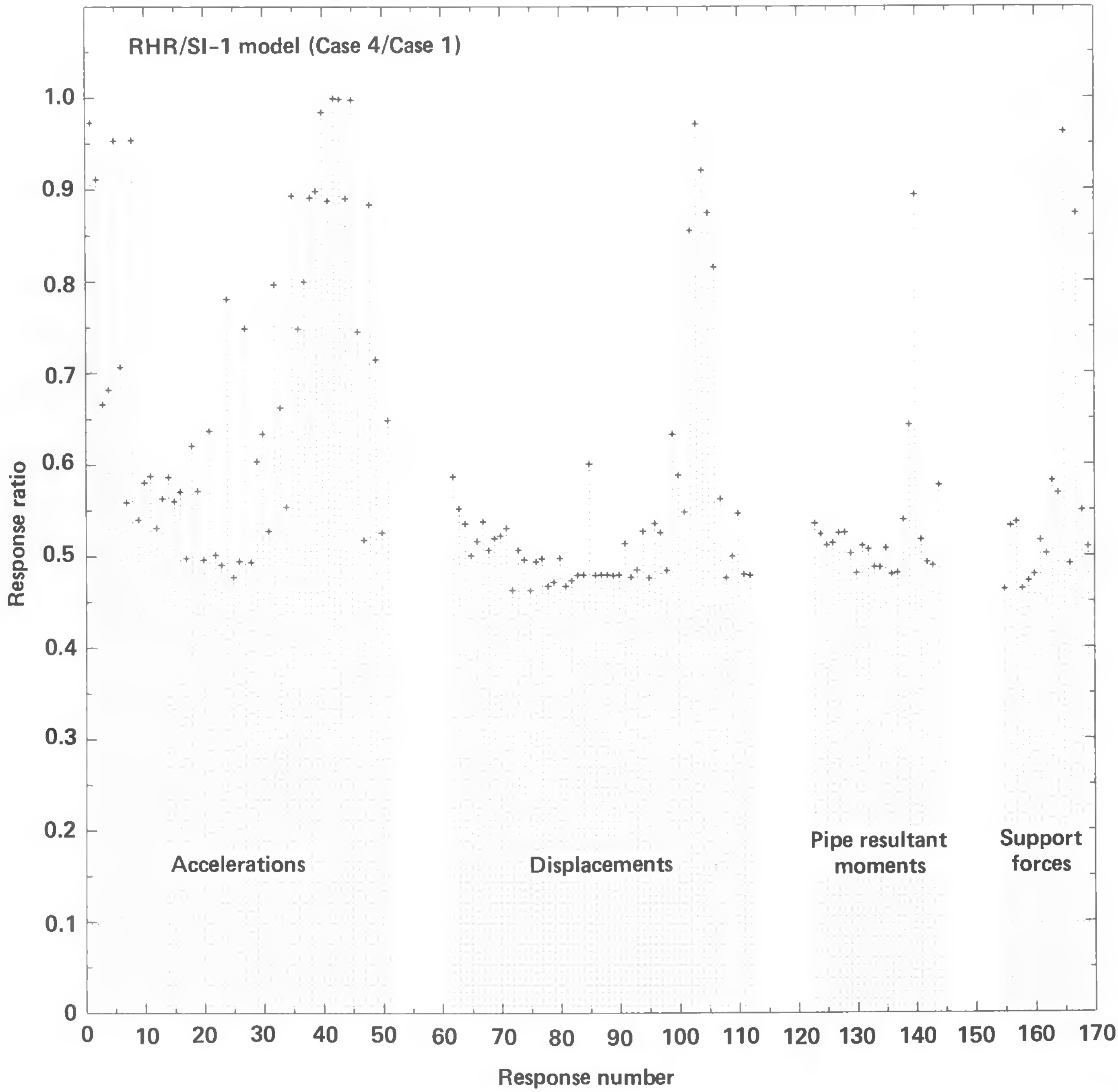


Fig. 4.8. Response ratio (Case 4/Case 1) for the RHR/SI-1 model.

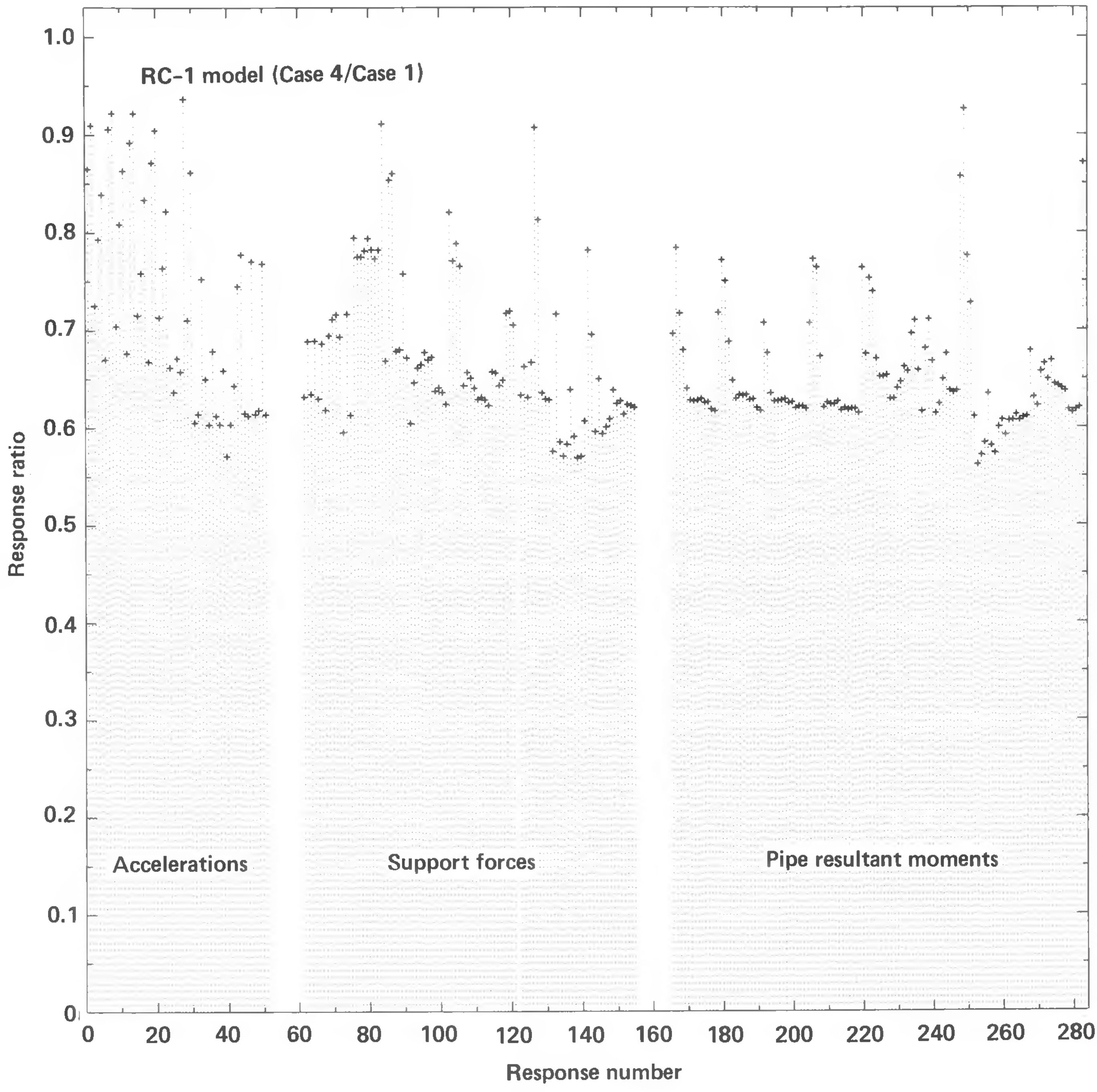


Fig. 4.9. Response ratio (Case 4/Case 1) for the RC-1 model.

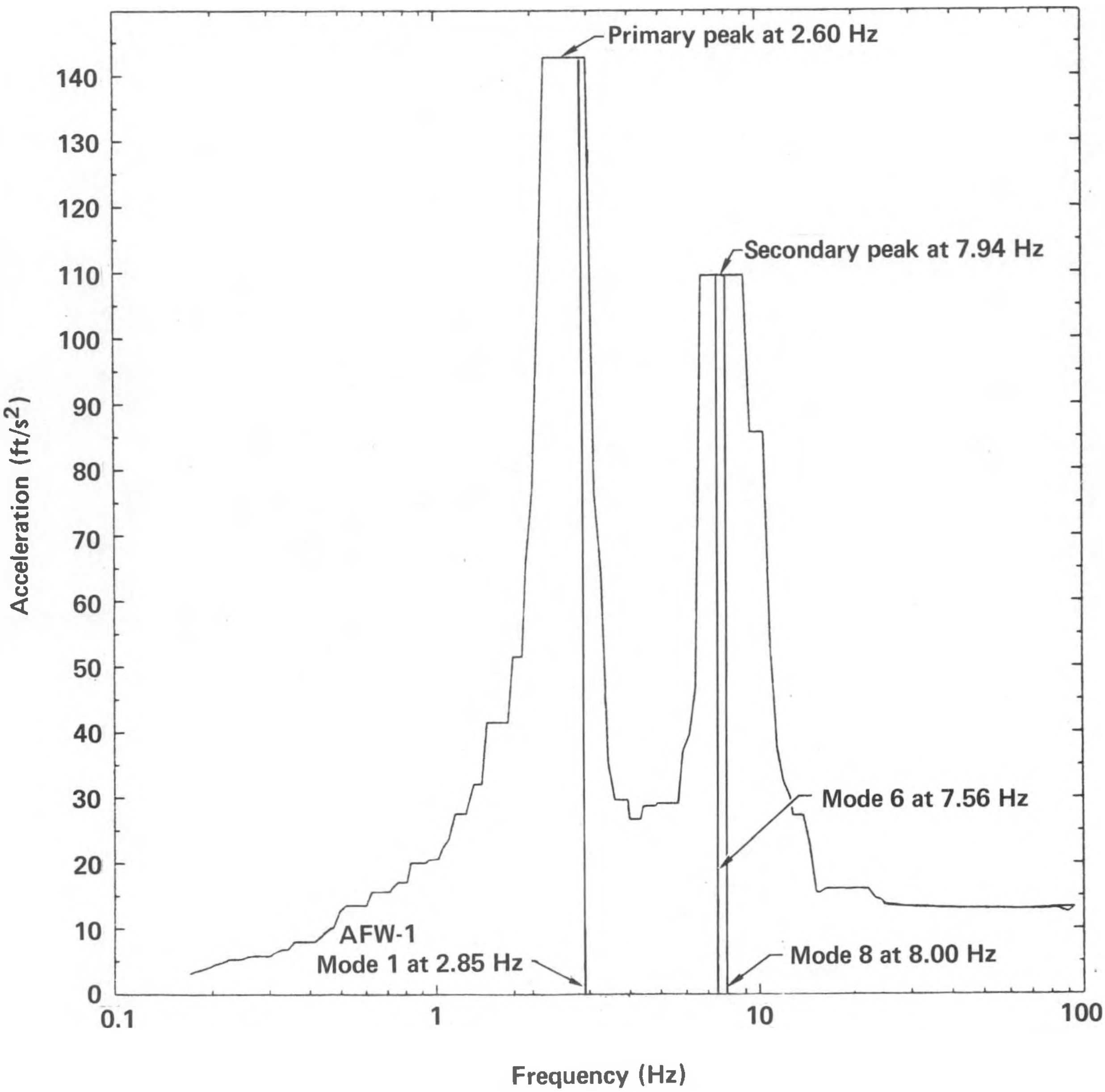


Fig. 4.10. East-west response spectrum for AFW-1 model of RG 1.61 and PVRC-proposed dampings.

- The fundamental frequencies of these three piping models are below 4 Hz, so the input to the piping models is substantially reduced (see, e.g., Fig 4.10 for the AFW-1 model). Consequently, the response is considerably reduced.

Figures 4.4–4.6 compare Case 3 with Case 1. In this comparison we see no substantial reduction in response for all piping models as a result of the PVRC-proposed alternative procedure to peak broadening. To better understand this lack of reduction in response, we performed three separate response spectrum analyses of the AFW-1 model for the Base Case, and examined the pipe resultant moments. The separate response spectrum analyses corresponded to exciting each of the three directions independently. We calculated the modal response for the 16-inch MFW line and the 3-inch AFW line and obtained one set of modal pipe resultant moments for each of the three inputs. Let us call each member of these sets R_{nx}, R_{ny}, or R_{nz}, where R_{ni} is the response of the nth mode due to the excitation in the i direction (i = x, y, or z). We combined the R_{ni} according to RG 1.92 requirements for modal combination, to obtain the combined response of each line to the x input, the y input, and the z input. Let us call this combined response R_i (i = x, y, or z). We combined R_x, R_y, and R_z according to the SRSS rule specified in RG 1.92, to obtain the total response of each line. This is denoted by R. We then expressed each R_{ni} as a percentage of R. We examined these percentages to determine dominant contributions of particular modes to total response. Thirty six modes were included in the response spectrum analysis. The first 10 modal frequencies are given in Table 4.2.

For the 3-inch AFW line we found that the responses are dominated by the first mode of the AFW-1 model excited by the x direction and we see very little reduction in response (Fig. 4.4), because only the first mode falls in the peak range of the x-input spectrum. (Fig 4.10). Therefore, both RG 1.122 peak broadening and the PVRC-proposed alternative give approximately the same result. On the other hand, response of the 16-inch MFW line is dominated by

Table 4.2. The first 10 modal frequencies, their closely spaced group, and dominance in the response of the two AFW-1 lines examined.

Mode no.	Frequency (Hz)	Closely spaced group	Dominance
1	2.85	1	3-in. MFW line
2	3.76	2	
3	4.48	3	
4	4.89	3	
5	7.27	4	
6	7.56	4	16-in. MFW line
7	7.86	4	
8	8.01	5	16-in. MFW line
9	9.05	6	
10	9.63	6	

the sixth and eighth modal responses excited by the x-direction input (Fig. 4.10). These two modes fall in the range of the secondary peak of the x-direction input response spectrum, but fall on the slopes of the secondary peak rather than coinciding with it (Fig. 4.10). Therefore, the effect of peak shifting (based on the primary peak), as described in Section 2.4, is to cause the frequency of the two dominant modes to vary their position on the slopes of the secondary peak, instead of staying on the secondary peak. Consequently the input acceleration applied to these two modes experiences larger changes as a result of the peak shifting associated with the PVRC-proposed alternative. Therefore, the reduction in response is greater for the 16-inch line than for the 3-inch line. However, the reduction in response for the 16-line, though larger than that for the 3-inch line, is still not substantial (Fig. 4-4). We observed that piping responses dominated by a single mode do not experience significant reductions due to the PVRC alternative to peak broadening, as expected.

The effect of the combined PVRC proposals (damping and peak broadening alternative) is shown by the comparison of Case 4 with Case 1 (Figs. 4.6-4.9). Again, there is a considerable reduction in piping response, but not much more than can be attributed to damping alone (Figs. 4.1-4.3). We also show the seismic (OBE) stresses of the AFW-1 model for the current SRP requirement and PVRC proposals (Cases 1 and 4, Fig. 4.11). The figure shows the absolute magnitudes rather than the ratios of comparison. The stresses for both cases are the resultant moment divided by the section modulus of piping components. The stresses are quite large. Therefore, the previous comparisons in terms of ratios of piping responses are meaningful.

We also calculated the mean and COV of the response ratio for all the comparisons. The results are summarized and presented in Section 4.2.3.

4.2.2 Comparison with Time History Analysis

Comparisons in the previous section showed a considerable reduction in piping response due to the higher damping values and alternative procedure to peak broadening proposed by PVRC. This reduction in response was measured with respect to the response spectrum analysis procedure of the SRP. An additional comparison can be made with results determined by the multi-support time history analysis procedure (Section 2.2) which conforms to the intent of SRP Section 3.9.2. For this case, recall that constant damping, as specified by RG 1.61, was used. No attempt was made in this study to implement the PVRC-proposed damping values in the time history analysis procedure, although it is a simple matter to do so. Hence, comparisons presented here are between responses calculated for the PVRC-proposed changes versus a currently acceptable analysis procedure with existing damping requirements.

Table 4.3 lists the time history analyses performed and the piping model damping values assumed. Constant damping values were assumed. For the AFW-1 and RHR/SI-1, RG 1.61 specifies 1% damping for the OBE. The PVRC-proposed damping values are greater than or equal to 2% (Fig. 2.8), independent of excitation level and pipe size. For comparison purposes, we analyzed these two piping models for 1% and 2% damping. For the RC-1, RG 1.61 specifies 2% damping for the OBE. We analyzed the RC-1 for 2% damping only.

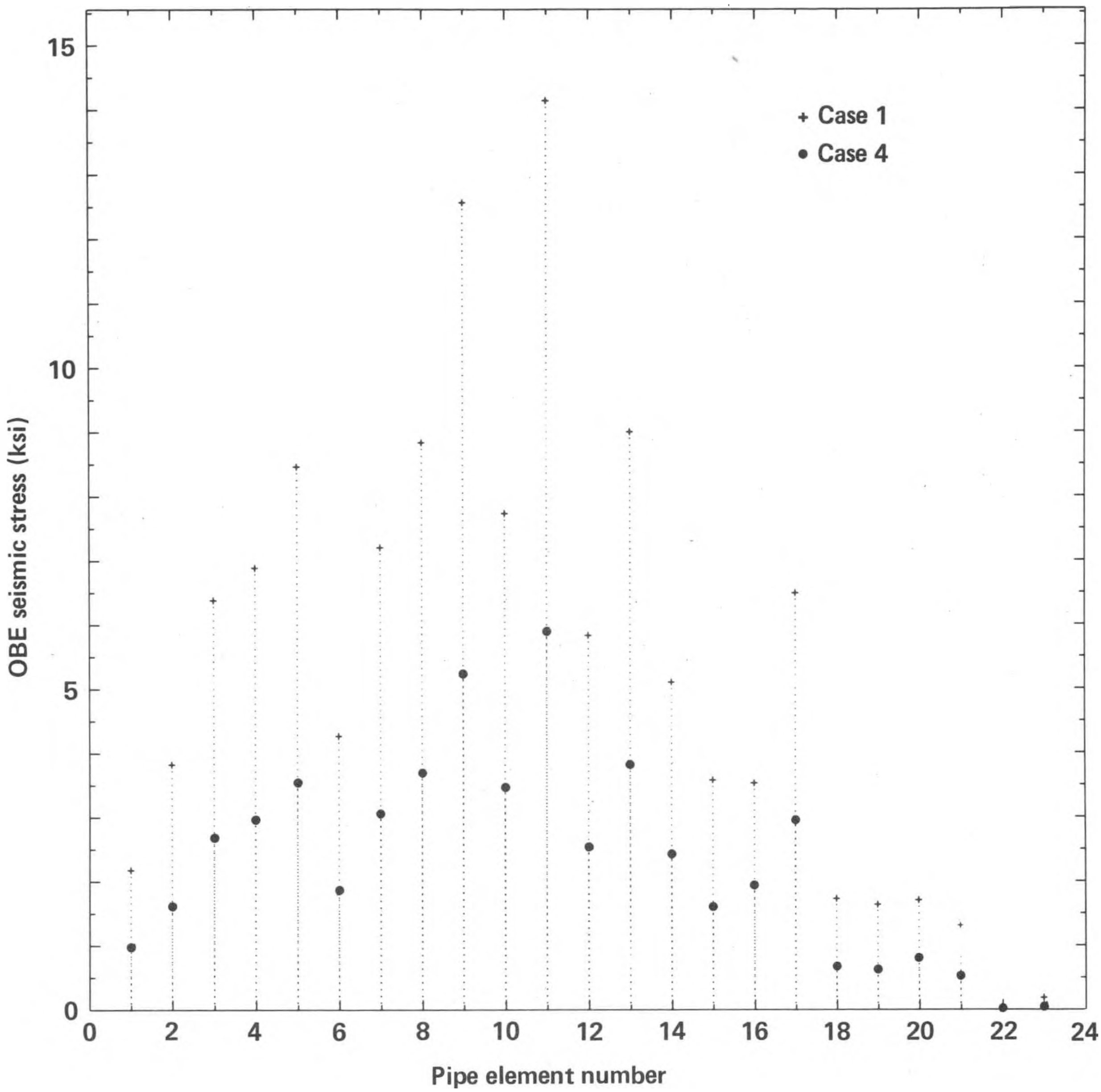


Fig. 4.11. Seismic (OBE) stresses of the AFW-1 model under the current SRP procedure and PVRC proposals (Cases 1 and 4).

Two basic comparisons were performed. First, Case 1 was compared with the time history analysis results. Figure 4.12 shows the results for AFW-1, Fig. 4.13 shows the results for RHR/SI-1, and Fig. 4.14 shows the results for RC-1. In general, large conservatism exists in the SRP response spectrum analysis procedure.

The second comparison was between Case 4 and the time history analysis results. Figure 4.15 shows the results for AFW-1, Fig. 4.16 shows the results for RHR/SI-1, and Fig. 4.17 shows the results for RC-1. These results show, in general, that responses calculated for the PVRC-proposed changes still exceed response calculated by the time history analysis procedure and existing damping values. That is, in general, the proposed changes reduce conservatism but considerable conservatism remains. For the RHR/SI-1 model, some exceptions were observed. This was expected because the RHR/SI-1 model has less variation in support motions than the AFW-1 or RC-1 and, hence, conservatisms introduced by the enveloping procedure are less. Figure 4.18 shows results for the RHR/SI-1 for 2% damping. We see that there exists considerable conservatism even for the RHR/SI-1 model if 2% damping is used for time history analysis.

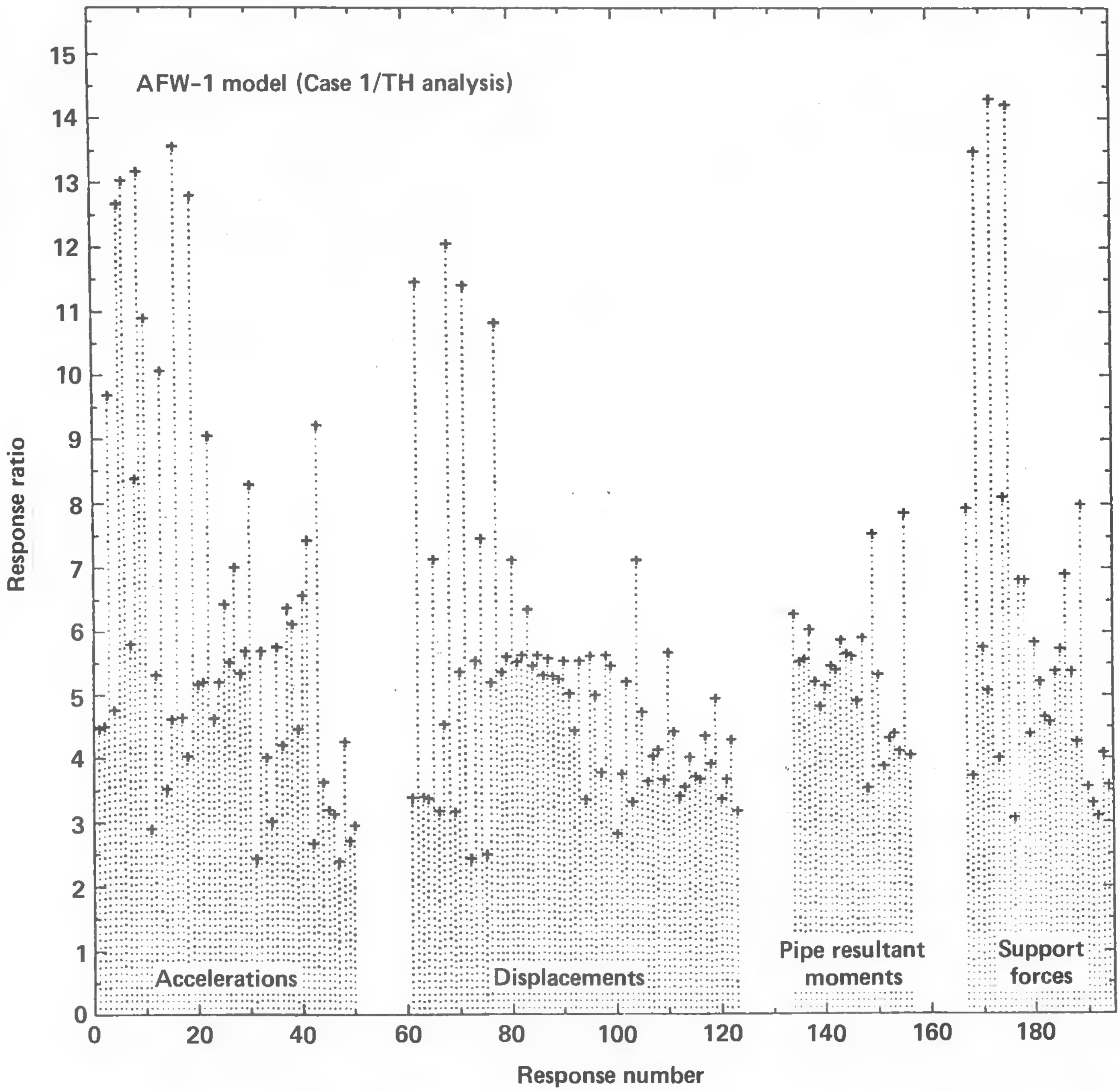


Fig. 4.12. Response ratio of Case 1 (Base Case) with time history analysis--AFW-1 model.

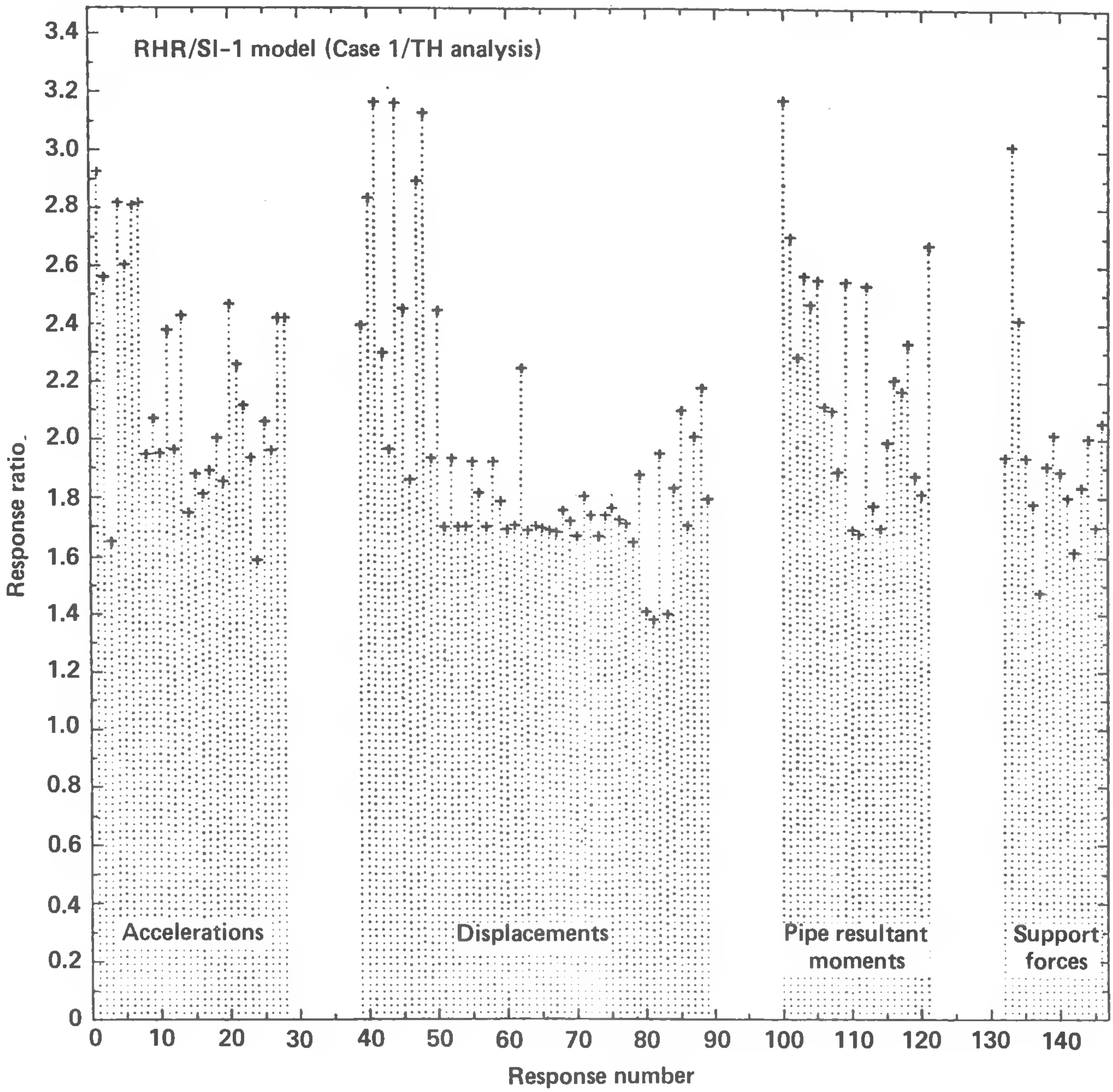


Fig. 4.13. Response ratio of Case 1 (Base Case) with time history analysis--RHR/SI-1 model.

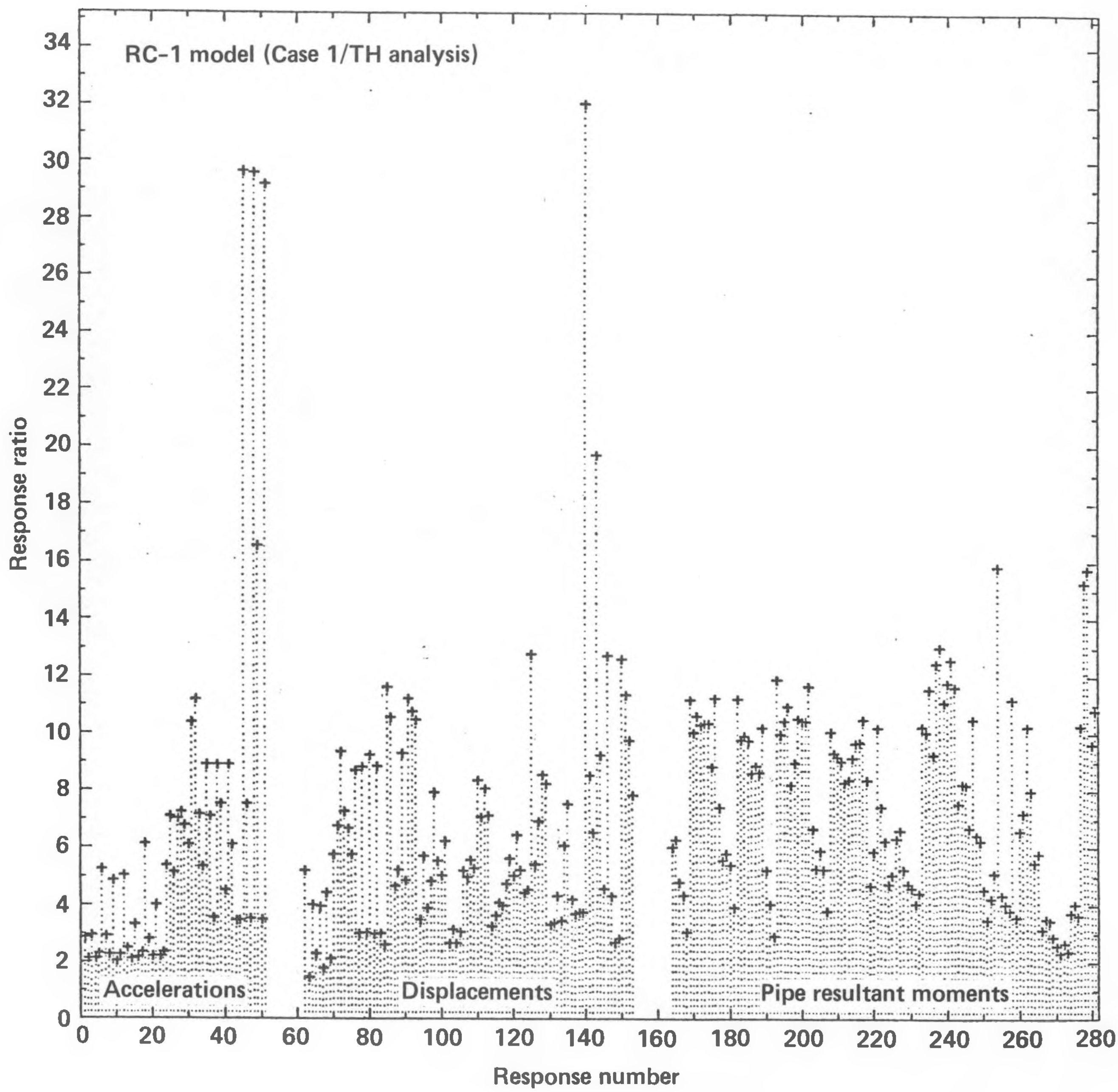


Fig. 4.14. Response ratio of Case 1 (Base Case) with time history analysis--RC-1 model.

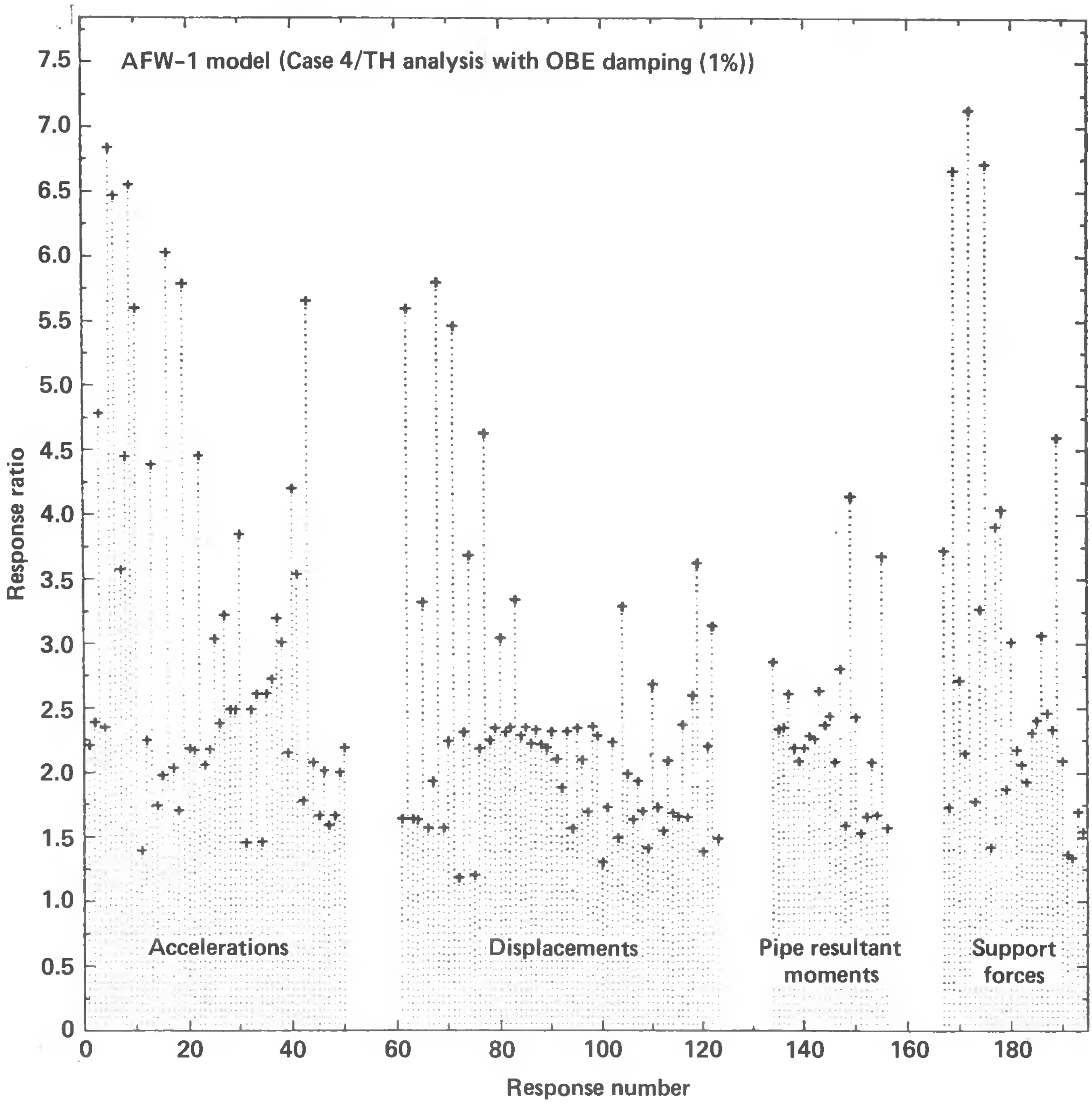


Fig. 4.15. Response ratio of Case 4 with time history analysis with RG 1.61 OBE damping (1%)--AFW-1 model.

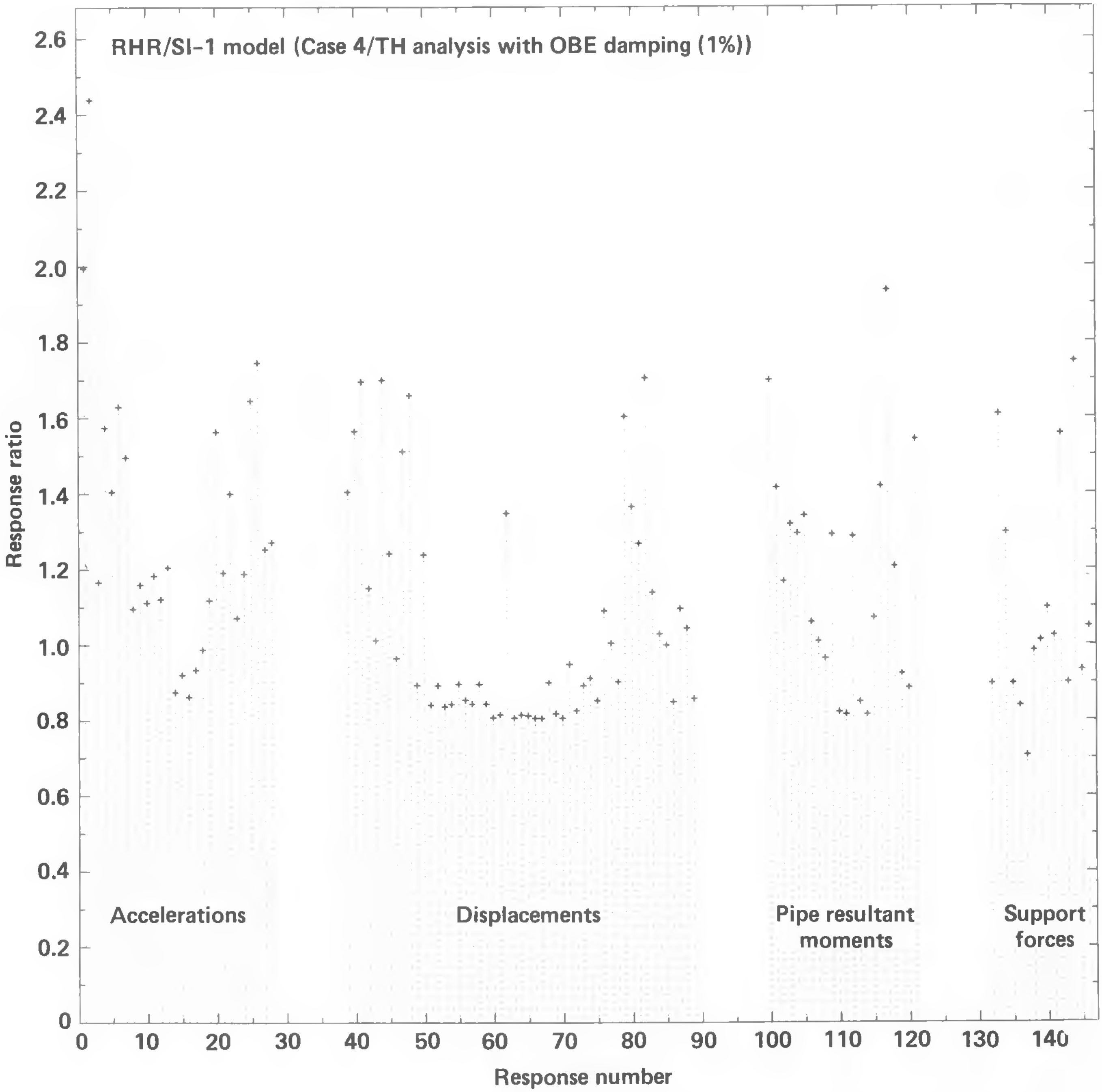


Fig. 4.16. Response ratio of Case 4 with time history analysis with RG 1.61 OBE damping (1%)--RHR/SI-1 model.

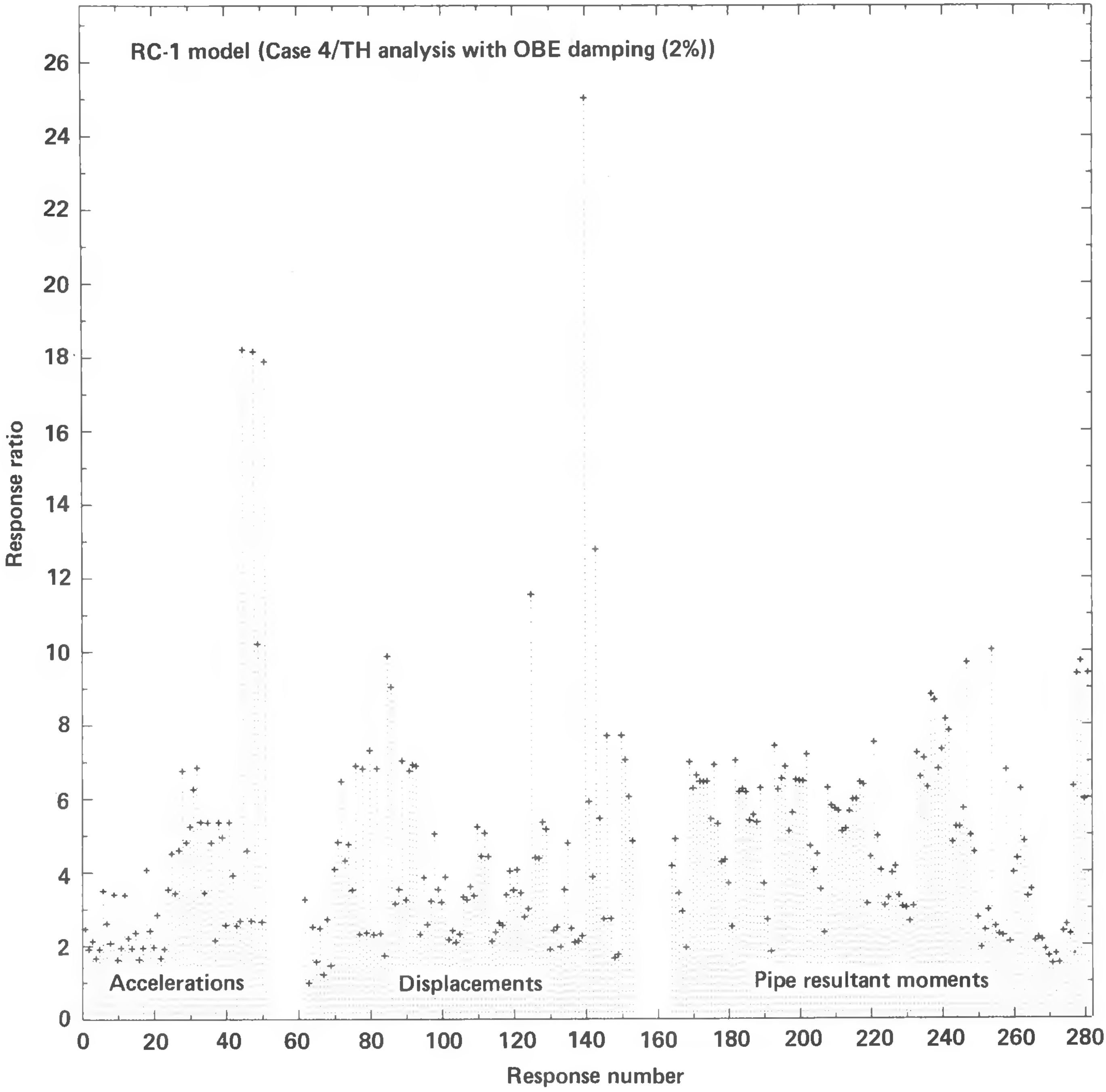


Fig. 4.17. Response ratio of Case 4 with time history analysis with RG 1.61 OBE damping (2%)--RC-1 model.

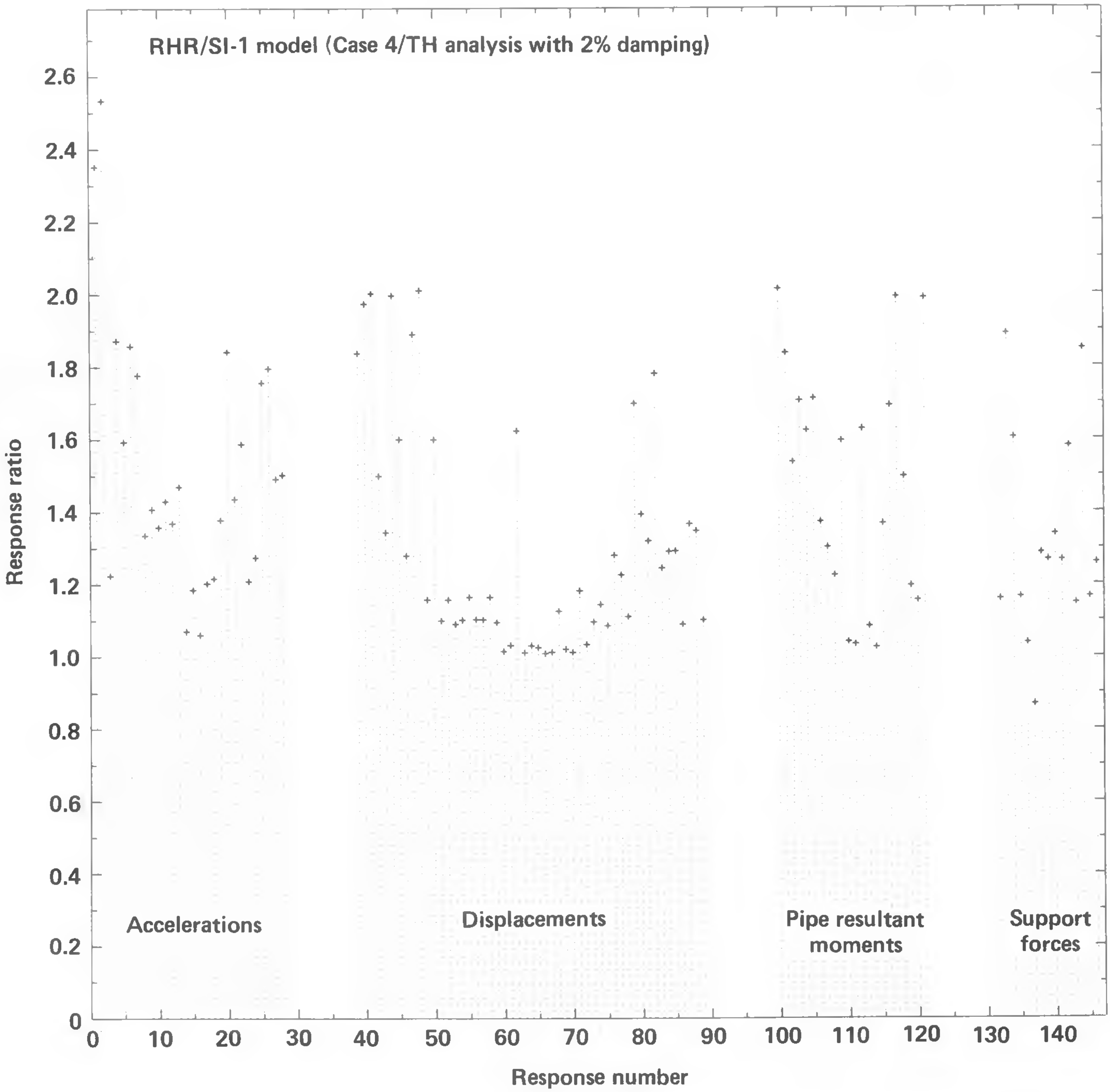


Fig. 4.18. Response ratio of Case 4 with time history analysis with 2% damping--RHR/SI-1 model.

Table 4.3. Time history analyses performed.

Piping model	Damping ratio (% critical) 1	2
AFW-1	x	x
RHR/SI-1	x	x
RC-1		x

4.2.3 Summary of Comparisons

In this section we present the mean and COV of the response ratios for all the comparative analyses in Section 4.2.1 and 4.2.2 (Table 4.3). These results quantify and summarize the response ratio. Mean response ratios for Case 2 (damping) over Case 1 (Base Case, SRP procedure) range from 0.48 to 0.79 (i.e., substantial reduction); for Case 3 (peak broadening) over Case 1 the ratios range from 0.91 to 0.96 (i.e., marginal reduction); for Case 4 (damping and peak broadening) over Case 1 the ratios range from 0.46 to 0.73 (i.e., substantial reduction under PVRC proposals). The mean ratios of the piping responses for the PVRC proposals compared with time history analysis range from 1.05 to 4.98. This indicates that conservatism remains even for the PVRC proposals. The COVs for different comparisons indicate how the response ratios disperse. Notice that COVs in Table 4.4 are generally quite small for the comparisons of Cases 2, 3, and 4 with Case 1. This indicates that the dispersion of these data is quite small. We also presented for comparison the mean ratios of the Base Case (Case 1) to the time history analysis. It is interesting to see how large the mean response ratios are. They range from 1.9 to 7.6, confirming that there exists substantial conservatism in the SRP response spectrum analysis.

4.3 BENEFITS STUDY

The comparisons of Section 4.2 are informative; however the question remains as to the impact of the proposed changes on piping system design. To investigate the potential impact of the changes on the design, the AFW-1 model was investigated in detail to ascertain whether the proposed changes could lead to a reduction in seismic restraints. The AFW-1 model had two snubbers and one horizontal restraint on the 16-inch MFW line and nine horizontal rigid restraints on the 3-inch AFW line.

We performed iterative analyses to investigate the seismic stresses for the AFW-1, starting with all snubbers and all horizontal restraints removed, and adding restraints for successive analyses. For each iteration of analysis, we evaluated the adequacy of a particular support configuration by comparing with

Table 4.4. Summary of comparisons. Mean and COV of response ratios of the three piping systems studied. Each entry is a ratio of two numbers, namely the ratio of the calculated piping system response of the first case to that of the second case.

Piping model	Response	Number of responses	Cases compared (mean ratios)					Cases compared (COVs)				
			2/1	3/1	4/1	4/TH	1/TH	2/1	3/1	4/1	4/TH	1/TH
AFW-1	Accel.	63	0.58	0.91	0.54	4.25	6.1	0.16	0.08	0.19	0.57	0.51
	Displ.	63	0.48	0.94	0.46	2.80	5.1	0.16	0.07	0.16	0.47	0.40
	Forces	28	0.51	0.91	0.47	3.52	6.1	0.13	0.08	0.12	0.60	0.51
	Moments	23	0.45	0.94	0.44	2.85	5.3	0.08	0.07	0.10	0.29	0.20
RHR/SI-1	Accel.	51	0.70	0.96	0.68	1.31	2.2	0.23	0.03	0.25	0.27	0.17
	Displ.	51	0.57	0.96	0.55	1.05	1.9	0.20	0.03	0.22	0.27	0.22
	Forces	15	0.60	0.94	0.57	1.10	2.0	0.23	0.03	0.26	0.28	0.19
	Moments	22	0.56	0.95	0.53	1.19	2.2	0.16	0.02	0.17	0.25	0.18
RC-1	Accel.	51	0.79	0.92	0.73	4.37	6.4	0.14	0.04	0.15	0.89	1.01
	Forces	94	0.72	0.94	0.68	4.30	6.3	0.10	0.04	0.11	0.73	0.65
	Moments	118	0.69	0.94	0.66	4.98	7.6	0.09	0.03	0.09	0.42	0.42

the code allowables (ASME, 1980). We arrived at a configuration with the two snubbers on the 16-inch line removed and seven horizontal restraints on the 3-inch line removed (Fig. 4.19). This support configuration of the AFW-1 model meets the code allowables for the PVRC proposals, whereas it does not meet the same allowables for the current SRP procedure (Fig 4.20). Hence, implementation of the PVRC-proposed changes would permit a reduction in the number of seismic restraints for the system studied.

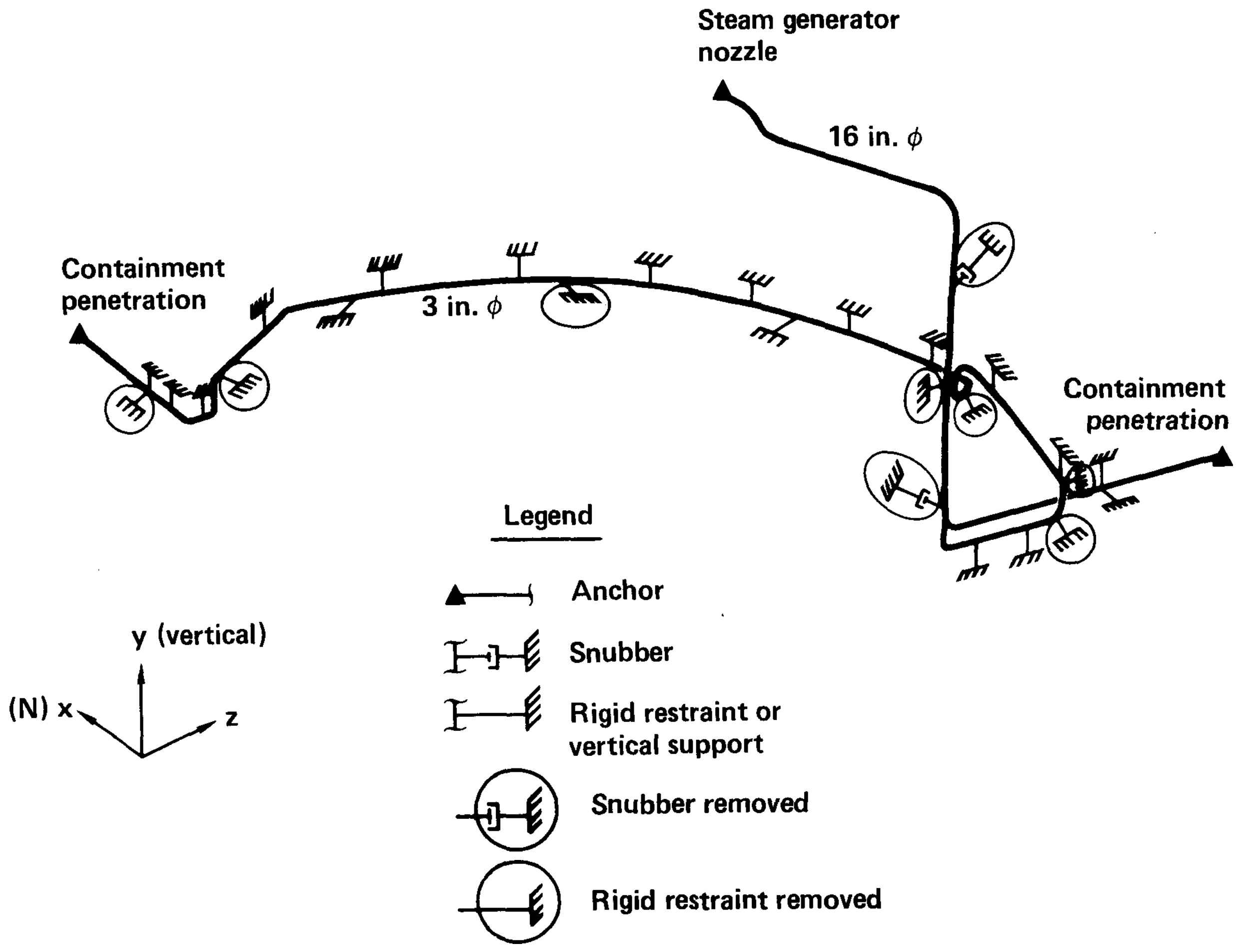


Fig. 4.19. The AFW-1 model with snubbers and restraints removed under the PVRC proposals.

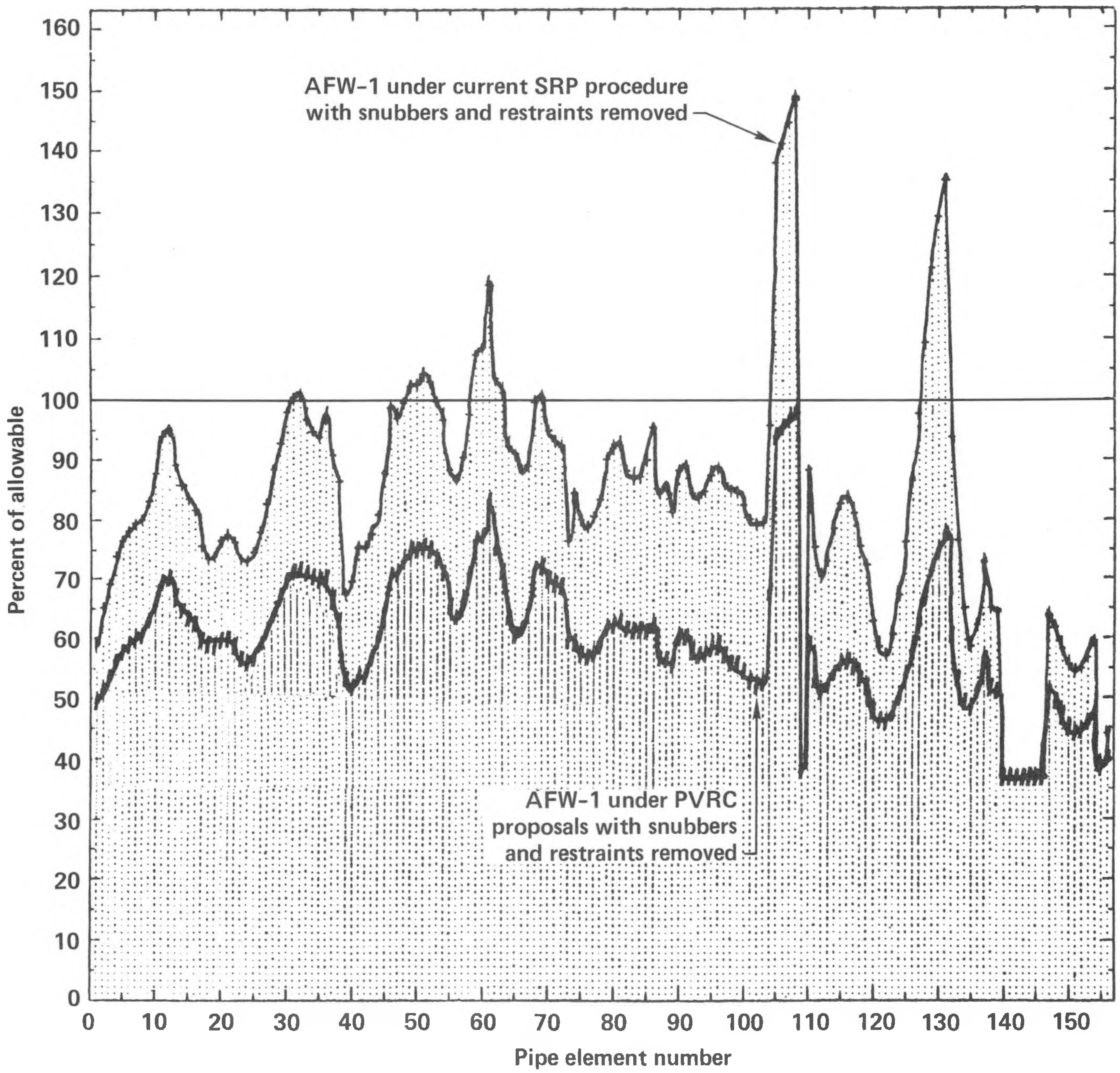


Fig. 4.20. Code evaluation of AFW-1 under the PVRC proposals.

5. CONCLUSIONS

We have shown that the changes proposed by PVRC for damping values and for an alternative to peak broadening, in the context of the selected piping systems of the Zion nuclear power plant, are advantageous. The PVRC proposals lead to substantial reductions in the calculated piping responses that we investigated.

A major reduction in response was obtained by the proposed damping values. The proposed alternative to peak broadening was marginally effective in reducing seismic response. We show that this relative lack of effectiveness of the alternative to peak broadening is due to dominant effects of one or two modes for the piping models studied.

Although the PVRC proposals reduce conservatism, a significant amount remains when compared with multi-support time history analysis procedures.

We inferred that the PVRC proposals would permit substantial savings in design of piping systems for nuclear power plants. We investigated the potential benefit of the PVRC proposals in the context of a single piping system (Zion's Auxiliary Feedwater Piping System). We found that under the PVRC proposals seven horizontal restraints and both existing snubbers could be eliminated and still permit the piping system to meet applicable standards.

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