A Review of the Seismic Design and Analysis of Piping Ranging from Conventional Building Code Static Analysis to Time-History Dynamic Analysis

John D. Stevenson

ABSTRACT

This paper identifies the 5 different methods of analysis that are available for use to evaluate seismic stress in nuclear piping systems identified as Seismic Design Classes 1-5 as defined in the new ANS 2.26 and ASCE 43-05 Standards. It also provides an indication of the relative conservatism in the computed results and engineering effort as a function of the analytical methods used.

INTRODUCTION

The seismic design and analysis of nuclear facility piping covers a large range of several different types of analytical procedures and design methods and design code specified allowable stresses. These include the following:

- Static (building code design)
- Equivalent static (response spectrum)
- Modal Analysis (response spectrum)
- Modal Analysis (time history)
- Time Step Integration (time history)

which defines the methods of analysis used and the basis for seismic inertia load determination in parenthesis.

The static analysis procedure defined by the building code[1] will generally give the lowest seismic load and resultant seismic inertia stresses in the pipe and loads on the pipe supports if the F_p as defined by the ASCE 7-05 Standard(1) is used, but only is applicable to nuclear facility piping identified as SDC-2 and SDC-1 piping as defined in ASCE Std. 43-05(2) and ANS Std. 2.26(3). The other 4 methods of analysis are applicable to the SDC-3 to SDC-5 categories of piping as defined in References 1 and 2.

LOADS ON PIPING SYSTEM

Load from ASCE 7-05 (Building Code Design)

When using the ASCE 7-05 Standard a static load F_a can be defined as shown in Eq. 1 of Section 4.1 or a standard shaped ground spectra can be used as shown in Figure 1. The S_{DC} value assumes the piping system dominate frequency is in resonance with the 5.0 percent damped peak ground spectral acceleration value. The S_{DC} value selected for evaluation in this paper is 0.36g, which would be equal to a site 0.216g S_s peak ground acceleration, pga assuming a spectral amplification factor of 2.5 as defined in Table 13.6-1 of Reference 1 and S_{DC}=2/3 S_{Ms}. It should be noted that the ASCE 7-05 seismic acceleration maps define peak 5.0 percent damped peak ground spectral values at 5 Hz and 1 Hz respectively.

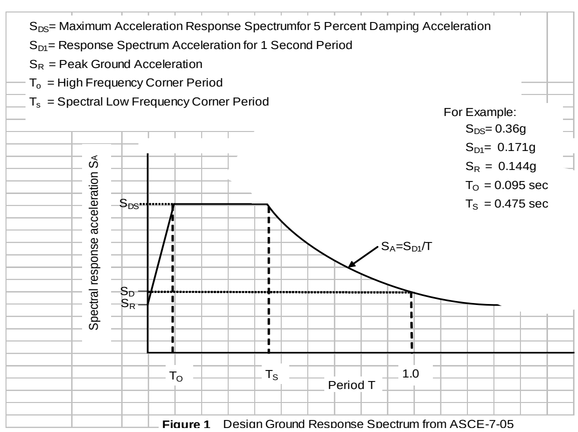

Figure 1 Design Ground Response Spectrum from ASCE-7-05

[1] For all practical purposes the ASCE 7-05(1) Standard can be substituted for the IBC-2006 Building Code for the design of SDC 1 and 2 piping systems.

Loads on the Pipe Using Equivalent Static and Dynamic Load Analyses

The seismic load on piping using the other 4 design procedures is typically based on an in-structure response spectrum as shown in Figure 2, which for the sample analysis contained in this paper is characteristic of a response spectra applicable to piping system located on the 2rd floor of a 4-story concrete frame building, which includes significant soil structure interaction. It should be noted the peak floor acceleration for the Figure 2 spectra is 0.3g, which is approximately 1.5 times the peak ground accelerations of Figure 1 and the peak spectral acceleration value is 1.5g, which is approximately 5 times the peak floor acceleration of Figure 2 and 7 times the peak ground acceleration value of Figure 1. The shape of the in-structure response spectrum used is based on typical soil structure interaction, SSI and 7 percent building damping and 5 percent piping damping.

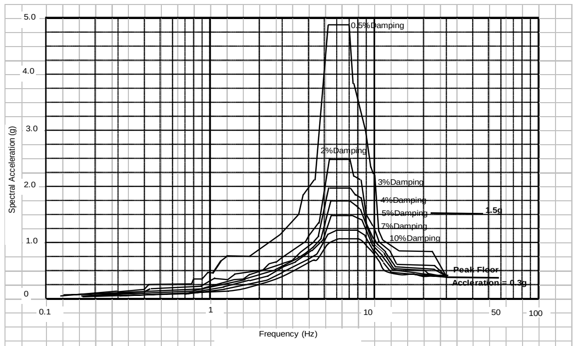

Figure 2 Typical In-Structure Acceleration Response Spectra for the 2nd Floor of a Four Story Building for 7% Building Damping and Equipment Damping as Shown for Ground Response Spectrum Shown in Figure 1

The shape of the in-structure response spectra, which is determined at the piping support location, is dependent on the damping of the piping system, dynamic characteristics (frequency and mode shapes) of the building and supporting soil, and the assumed damping characteristics of the building as well as the ground motion input to the building. For rock sites the basic seismic input to the building assumes the building foundation media is rigid. It should be noted spectral amplification between the peak floor acceleration (i.e. the high frequency rigid region in Figure 2) and the peak in-structure response spectra is significantly greater than that observed in Figure 1. This is caused by the building tendency to respond at its own dominate natural frequency in a more sinusoidal type of response motion.

For actual strong motion earthquake Magnitude 6.0 and above and site MM Intensity of V or above the actual in-structure amplification spectra damping typically ranges from 2.5 to 2.9 for median values and 2.7 to 3.2 for mean values of amplification. For pure sinusoidal motion the amplification factor as a function of damping is given as:

$$1/2\beta \qquad (1)$$

where β is percent critical damping.

For 5 percent damping:

$$1/2\beta = 1/0.05x2 = 10 \qquad (2)$$

The in-structure spectral amplification values are complicated by the requirement to consider a value of effective damping for the supporting soil and building structure. It can also be affected by the mass ratio effect as described in Reference 4, which is usually conservatively ignored.

The effect of locating piping in a structure where there is significant soil structure interaction, SSI leads to the need to consider in-structure response spectra even when the piping is located at ground surface level. This typically results in higher seismic loads on the system than would be the case if it were located at ground surface without SSI for the same values of effective building and equipment damping.

ACCEPTANCE CRITERIA

The acceptance criteria for piping depends on the particular piping design standard specified. There are one of 3 standards typically specified. The are:

- ASME B&PVC Section III, Class 1, 2 or 3[5]
- ASME B31.1, Power Piping[6]

- ASME B31.3, Process Piping[7]

The design of ASME B&PVC Section III piping is addressed in NX-3600 of Division 1 where X is B for Class 1 piping, C for Class 2 piping and D for Class 3 piping. These piping codes are generally used for piping associated with the safety of nuclear power plant reactor core and spent fuel where Class 1 is associated with piping that provides the direct coolant or contact with the nuclear fuel, Class 2 with engineered safety systems such as high and low head safety injection, chemical and volume control and residual heat removal system as well as the heat transport steam systems to the turbine. Class 3 is used for auxiliary systems in support of Class 1 and 2 systems.

The ASME B31.1 or B31.3 Codes are used primarily for other than systems related to cooling or directly interacting with large nuclear reactor fuel cores capable of core melt. They are associated with high level nuclear waste and radioactive materials classified as Seismic Design Category, SDC 1-5 of ASCE 43-05.

In Table 1 is given the characteristic acceptance criteria of the three ASME piping design codes.

Table 1 ASME Piping Design Codes Acceptance Criteria for Steel Materials

	Normal Allowable Stress		**Seismic Allowable Stress Multiplier**
Code	**Carbon**	**Austenitic**	
B&PVC III - Class 1 - 2004	$S_{mu}/3$	$2\ S_{my}/3$	3.0
B&PVC III - Class 2 - 2004	$S_u/3.5$	$2\ S_y/3$	3.0
B&PVC III - Class 3 - 2004	$S_u/3.5$	$2\ S_y/3$	3.0
B31.1 – 2004	$S_u/3.5$	$2\ S_y/3$	1.2
B31.3 - 2004	$S_u/3$	$2\ S_y/3$	1.33

Notes:

S_{mu} = Stress Intensity Specified Minimum Ultimate Strength

S_{my} = Stress Intensity Specified Minimum Yield Strength

S_u = Principal Stress Specified Minimum Ultimate Strength

S_y = Principal Stress Specified Minimum Yield Strength

PIPING MODEL DESIGN STRESSES DETERMINED BY THE 5 METHODS OF SEISMIC ANALYSIS

Figure 3 is the model of a piping system segment to be analyzed by the 5 methods identified in Section 1.0.

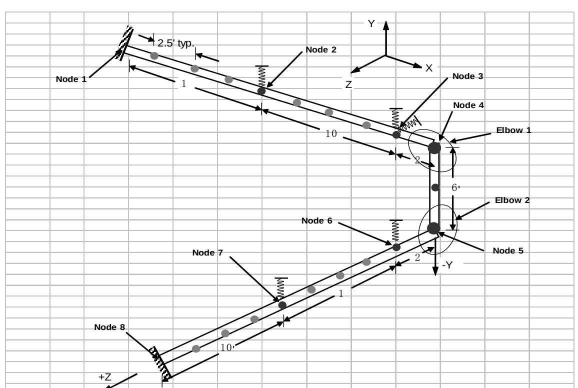

Figure 3 Dynamic Finite Element Model of Z Bend Pipe Segment

Static Analysis Using Static Code Equation

Seismic forces, F_p, applicable to the piping system is determined in accordance with Reference 1:

$$F_p = \frac{0.4 a_p S_{DS} W_p}{\frac{R_p}{I_p}} \left(1 + 2\frac{z}{h}\right) \qquad (3)$$

and F_p is not required to be taken as greater than:

$$F_p = 1.6 S_{DS} I_p W_p \qquad (4)$$

and F_p shall not be taken as less than:

$$F_p=0.3S_{DS}I_pW_p \tag{5}$$

where

a_p = component amplification factor that varies from 1.00 to 2.50 select appropriate value from Table 13.6-1 of Ref. 1 which is 2.5 in this case

F_p = seismic design force applied at the component's center of gravity or distributed relative to component's mass distribution

I_p = component importance factor that is either 1.00 for PC-1 or 1.50 for PC-2 mechanical systems or components

h = average roof height of structure relative to the base elevation = 4 in this example

R_p = component response modification factor which for ASME B31.3 or B31.1 piping is taken as 12 from Table 13.6-1 of ASCE 7-05

S_{DS} = design spectral response acceleration at short period (0.2 seconds or less), as determined in Section 11.4-1;

W_p = component weight

z = height in structure at point of highest attachment of component or system = 2 in this example

For items at or below the base height, z shall be taken as 0. For items at or above the roof, z is not required to be taken as greater than the roof height h; h=average roof height of structure with respect to base.

where:

$$S_{DS}=2/3\ S_{MS} \tag{6}$$

and

$$S_{MS}=F_aS_S \tag{7}$$

where F_a is defined in Table 11.4-1 of Reference 1; and S_s= the mapped Maximum Considered Earthquake, MCE spectral response acceleration at 0.2 second period with F_a for this example analysis taken equal to 1.0.

The force, F_p, is applied independently in the horizontal two principal directions and resultant seismic inertia forces and moments or stresses in the piping determined by applying the F_p to the piping system as a function of the distributed mass of the piping system.

It should be noted the application of the R_p factor of 12 as a divisor as defined by the Reference 1 Code Table 13.6-1, dramatically reduces the resultant seismic inertia forces, moments and stress in the pipe and loads on pipe supports. In addition, the peak floor acceleration of the Fig. 2 spectra is 1.5 times the peak ground spectra while from Fig. 3 it is 2 times the peak ground acceleration.

Equivalent Static

The equivalent static load is usually developed by taking the peak applicable spectral response (usually acceleration) and applying it to the mass distribution of the piping system in three orthogonal directions (two horizontal and one vertical). This application of inertia forces distorts the actual plus and minus mode shape directions, but can be usually shown to give conservative results.[8] This acceleration times the associated mass results in a force applied to each distributed or concentrated mass point. Application of these forces to each mass point in the model will result in equivalent static seismic stresses in the piping members connecting the mass points. It should be noted that the resultant seismic stresses are given either a (+) and (-) sensing when combined with other stresses such as dead load, live load or pressure stresses, whichever results in maximum stress and compared with maximum code allowable stresses to determine design adequacy.

The continuous beam model is used for distribution systems (pipe, duct and tubing) continuous over several supports. This type of seismic load definition and analysis is often applied to small bore piping systems typically equal to or less than 6.0 inches in diameter and ductwork 12 inches in diameter or smaller. A more stringent definition of small bore pipe of 2.5 inches nominal diameter is also often used. The 6.0 inch nominal diameter or smaller is used because piping above this diameter are of such a mass as to locally affect the design adequacy of the building structural steel that supports the pipe.

Cold tubing and small bore pipe less than 3 inches in nominal diameter (design temperature less than 150°F) are usually designed by use of spacing tables and charts, which employ an equivalent static loading procedure to define necessary lateral support spacing limitations or limiting stresses in the piping as discussed in Chapter 5 of Reference 9.

The equivalent static method usually gives very conservative results such that the ASME B&PVC Section III Appendix N[10] provides the load coefficient method to reduce the conservatism such that a coefficient K, which varies from 0.4 to 1.0, is applied to the peak spectral acceleration. However, the NRC requires the use of a 1.5 factor be applied to the peak spectral acceleration unless it can be shown that a lower coefficient is applicable.

Dynamic-Response Spectrum Modal Analysis

Dynamic response spectrum modal analysis loading assumes the system being evaluated is responding elastically otherwise natural frequencies cannot be defined. It provides a more exact definition of the applied load than the static or equivalent static procedure. It has either plus or minus directional sensing of resultant seismic stress in a particular mode; hence, a more accurately defined resultant model inertia seismic stresses.

In general, it is necessary to apply the seismic nodal forces in each mode to compute seismic stresses for each mode and then combine these stresses on a square root sum of squares basis to get resultant seismic stresses with a plus or minus sensing. Nodal accelerations of the i^{th} mass in the j^{th} mode is determined as

$$a_{ij} = \Gamma_i S_{ai} \phi_{ij} \qquad (8)$$

where

Γ_j = modal participation factor in j mode
a_{ij} = the acceleration of the I mass in the j mode of response
S_{aj} = spectral acceleration of the j mode frequency
ϕ_{ij} = the mode of the I mass in the j mode
ϕ'_{ij} = the mode shape of the I mass in the j mode in the direction of the earthquake.

For a discussion of the development of the modal participation factor Γ_j see a standard text in structural dynamics.(6)

It should be noted that both or either Γ_j or ϕ_{ij} can be positive or negative, which determines the direction or sensing of the modal force for each mode.

The seismic inertia force f_{ri} applied to the i^{th} mass in the j mode is determined:

$$f_{ij}=m_i a_{ij} \qquad (9)$$

Note that f_{ri} may be positive or negative. To obtain the correct seismic inertia stress or internal forces or moment resultant, these modal inertia forces should be applied to each mass node in each mode to the analytical model of the structure. The direction of externally applied forces is determined by the sign of the acceleration, which in turn is determined by the sign of the modal participation factors Γ modes shape ϕ as shown in Eq. (6). These resultant modal stresses or internal forces and moments are based on the assumed independence of modes, and are then combined to get the total seismic inertia stresses, internal forces or moments. The combination of independent mode shape stresses is usually on the basis of square root sum of squares as shown in Eq. (8) to obtain the resultant seismic inertia stress for a particular direction of applied earthquake.

$$S_n = \left(\sum_{j=1}^{n} (s^2{}_{ij}) \right)^{1/2} \qquad (10)$$

which assumes nodes are independent and maximum response in each node does not occur at the same instant of time.

where

s_{ij} = stress or internal force or moment from the applied modal external force f_{ij}
S_n = total stress or internal force or moment resulting from the combined modal stresses, internal forces or moments, or alternatively and conservatively the absolute sum of s_{ij} due to an earthquake in a particular direction.

The value of S_n is assumed either positive or negative when combined with other stress or internal forces or moments to obtain maximum values for a particular load combination.

The S_n value thus determined is for a single direction of an applied earthquake. The combination of all three earthquake stresses is done on an assumed SRSS basis again assuming independence of maximum response in each direction or on the basis of a 100,40,40 percent combination for all three directions two horizontal and one vertical of earthquake motion.

Modal Analysis with Time History Input

In modal analysis, the response of a linear elastic SSC is always some combination of its normal modes. In the modal analysis method, the mode shapes are used as principal coordinates to reduce the equations of motion to a set of uncoupled differential equations that describe the motion of each mode n. These equations may be written as:

$$\ddot{A}_n + 2\omega_n p_n \dot{A}_n + \omega_n^2 A_n = -\Gamma \ddot{y}_s \qquad (11)$$

Where the modal displacement or rotation, A_n, is related to the displacement o r rotation of mass point r in the mode n, x_{rn}, by the equation:

$$x_{rn} = A_n \phi_{rn} \tag{12}$$

where
ω_n = natural frequency of mode n (in radians per second
p_n = critical damping ratio of mode n
Γ_n = modal participation factor of mode n
given by:

$$\Gamma_n = \frac{\overset{n}{\Sigma} m_r \phi'_{rn}}{\overset{n}{\Sigma} m_r \phi^2_{rn}} \tag{13}$$

and ϕ'_{rn} = component of ϕ_{rn} in the direction of the earthquake.

The essence of the modal analysis lies in the fact that Eq. (9) is analogous to the classical equation of motion.

As a result, each mode may be analyzed as though it were an SDOF system and all modes are independent of each other; thus in a time history, analysis can be combined based on arithmetic sum to give the resultant time history response. By this method a fraction of critical damping, i.e., c/c_c, may be assigned to each mode and it is not necessary to identify or evaluate individual damping coefficients.

Equations of Motion with Time History Input

The dynamic time history procedure uses either time step integration by solving the equations of motion of time step modal analysis.

The response of a multi-degree-of-freedom (MDOF) linear structural system is described by the differential equation of motion expressed in matrix form.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{J\}\ddot{y}_s(t) \tag{14}$$

where $\ddot{y}_s(t)$ = ground acceleration time history; and {J} is a vector, and its components are the cosines of angles between a direction of ground motion and directions of corresponding DOF in a vector {x}. If given DOF is rotation, the corresponding component of a vector {J} is zero. In that specific case, when the displacements on all DOF are linear and parallel to ground motion direction, {J} = {1}, i.e., vector composed from ones on the diagonal.
and
[M] = mass matrix
[C] = matrix of viscous damping coefficients
[K] = stiffness matrix for the mass points of the linear elastic structure
{x} = displacement vector
$\{\dot{x}\}$ = velocity vector
$\{\ddot{x}\}$ = acceleration vector

In all typical linear matrix formulations, matrices M, C and K are symmetric and positive definite (i.e. the diagonal values dominate).

Direct integration or time-step integration is a numerical method directly applied to the solution of the differential equations of motion of linear structural system, Eq. (12), in a step-by-step manner. No uncoupling procedure is necessary to compute the response and the damping matrix need not be proportional.

There are many acceptable schemes available for numerical integration of the equations of motion, such as Newmark β-method,[11] Houbolt method[12] and Wilson method[13].

The dynamic responses of a structure at any time may be calculated from the incremental time history of excitations and the previous structural responses.

The direct integration method has the advantage of simplicity in concept and elimination of the eigen value (mode shapes) computational effort. This method, unlike the modal analysis formulation method, may also be extended to deal with nonlinear problems where, for example, stiffness is no longer a constant. For practical solutions to real problems commercially available computer programs are used.

It should be understood that unlike the response spectrum method in the time history methods, the time dependent motion relationships are maintained. To get results the full strong motion duration time history of the earthquake must be used. Appendix N of ASME B&PVC Section III(14) specifies strong motion duration of 6.0 seconds preceded by a rump-up duration of 4 seconds. This duration is characteristic of a moment magnitude 6.0 earthquake. A time-history motion with duration parameters as just described was developed, which just enveloped the Figure 2 response spectrum and was applied to the piping system segment shown in Figure 3.

Higher magnitude 7.0 earthquake typically have a moment magnitude strong motion duration of 10-15 seconds, a 7.5 moment magnitude strong motion duration of 15-20 seconds and a moment magnitude of 8.0 with a strong motion duration of 30-35 seconds, with the total durations of shaking three to four times longer than the strong motion duration. However, it should be understood that fault rupture distances for 7.5 and higher magnitude earthquake typically exceed the constant isointensity geographic dimensions, which suggest that the fault rupture can no longer be defined as a point, but rather is represented as a line.

The time history time steps are typically taken at 0.001 second intervals. Therefore, the time history response to a 13-second strong motion shaking for a magnitude 7 earthquake would be 1,300, which would generate 1,300 inertia time dependent accelerations applied to the masses of the model. In general there is no way to determine which time step would result in the highest + or – stresses or internal force or moment resultants, except to analyze the structural system through each of the 1,300 time steps.

PIPING ANALYSIS ENGINEERING EFFORT

Spacing Tables and Charts

In this method the equivalent static method is typically used when the resultant peak spectral acceleration is applied to the mass distribution of segments of constant diameter cold (T_o<150°F) 6.0 inch diameter or less pipe. The segments considered are straight, L, Z and out-of-plane and ⊥ between lateral pipe supports. All geometric combinations are evaluated. This is typically done for piping systems where dead weight support spacings are recommended by the ASME B&PVC Section III, Subsection NF(14) or ASME B31.1.

Typically, these tables and charts are prepared for lateral to vertical span ratios of 2, 3 or 4. That is to say a lateral seismic restraint will be placed every 2nd, 3rd or 4th dead weight restraint. Alternatively, tables and charts are prepared, which give the applicable distances between seismic supports.(8) The variables considered in table and chart preparation include the allowable stress in the pipe as a function of the material and design code used as well as the peak spectral acceleration values with or without a K modifier.(10)

The preparation of the tables and charts to guide piping system design will typically take 6 to 8 man months of effort. The tables and charts can be used to define design acceptability or to provide preliminary pipe support layout to be later analyzed by more rigorous methods.

Static Code and Equivalent Static Analysis

These two analytical methods are similar in that a static force is applied to the piping system layout, which is based on either ASCE-7 code formula or are taken from the applicable response spectra.

This procedure requires the static F.E. modeling of the piping system to which the static forces are applied. Most of the effort is contained in the development of static F.E. models of the piping system. This procedure is typically applied to hot pipe (T_o>150°F) and large bore pipe (D_o> 6.0 inches). The typical effort associated with modeling and analysis of the piping system is 0.3mh/ft of pipe. This effort is exclusive of the design of the piping supports.

It should be noted that hot pipe normally requires a flexibility analysis, which would require the F.E. modeling of the pipe any way.

Dynamic Analysis

In this analysis the piping will be F.E. modeled dynamically to include mass distribution and will require a dynamic load in the form of either an applied response spectra or time-history(s). This method is used when the Equivalent Static Method results in too conservative design. The analytical effort applied to the piping is typically 1 mh/ft of pipe and is typically performed only on large diameter pipe or ASME B&PVC Section III Class 1 piping.

EXAMPLE PROBLEM

The five analytical procedures have been applied to the piping system shown in Figure 3 with resultant seismic inertia stresses as shown in Table 2.

Table 2 Z-Bend Example Seismic Moments Result Summary

Analysis Method	Seismic Bending Moment SRSS($M^2xx+M^2yy+M^2zz$) [lb-in]		
	Elbow-2	Run Node 2 First support	Run Node 7 Last support
ASCE-7, R_p =1	2032	4633	4805
ASCE-7, R_p = 12	169	386	400
Equivalent Static	2258	5370	5339
Modal Analysis R.S.	272	586	586
Modal Analysis TH	230	467	588
Direct Integration TH	239	482	691

CONCLUSION

The code static method defined in ASCE 7-05 applicable to SDC 1 or 2 piping gives seismic stress resultant in the piping which are significantly less than would result from the use of a typical in-structure response spectrum elastic analysis for the same peak ground acceleration. However, this is due to the use of the R_p factor of 12 as defined in ASCE 7-05.

The response spectra and time-history methods gave results, which were similar and significantly below the values which would result from the equivalent static method.

By far the most conservative results are from the equivalent static method, which in the example used the peak acceleration of the in-structure response spectrum or a K value of 1.0. The use of a 1.5 K value increases this already conservative result at least in this sample case.

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