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STRUCTURAL DAMPING VALUES AS A FUNCTION OF DYNAMIC RESPONSE STRESS AND DEFORMATION LEVELS *

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Damping as it is normally defined is the means by which the response motion of a structural system is reduced as the result of energy losses. However, as used in the context of nuclear plant design, the effects of changes in structural stiffness, geometry, support configuration, and modulus of elasticity are also usually lumped under the general heading of damping in current design methods. For convenience in structural design, damping is usually assumed as viscous in nature and in recognition of its use in modal response spectrum dynamic analysis is normally expressed as a percent of critical.

In general, it should be understood that damping as used in design or analysis of nuclear plants is an experimentally determined factor which is used to make the results of linear elasticity analysis of dynamic systems agree reasonably well with observed experimental results. In this paper, damping data existing in the open literature applicable to nuclear power plant structures and equipment is summarized and statistically analyzed. Results of this analysis is used to develop damping trend curves which predict applicable damping values to be used in design at various levels of stress or deformation.

1. Introduction

Damping as it is normally defined is the means by which the response motion of a structural system is reduced as the result of energy losses. However, as used in the context of nuclear plant design, the effects of changes in structural stiffness, geometry, support configuration, and modulus of elasticity are also usually lumped under the general heading of damping in current design methods. For convenience in structural design, damping is usually assumed as viscous in nature and in recognition of its use in modal response spectrum dynamic analysis is normally expressed as a percent of critical.

Material damping is usually identified as that damping associated with hysteresis energy loss in the materials as it experiences stress cycling. This form of damping is extremely small for steel typically in the range of 0.04 to 0.2 percent of critical and 0.25 to 0.5 for concrete up to yield of the material [1]. It also tends to be relatively insensitive to stress level up to yield of the material. Even above yield material damping values tend to remain relatively low for structural grade steel where work hardening in the plastic range results in linear loading and unloading of the material in tension or compression during additional cycles.

A second form of reduced response is typically identified as structural damping and includes material damping effects plus that due to friction and joint slippage and other small nonlinear or detuning effects such as changes in boundary conditions and modulus of elasticity within the limit of working stress levels (i.e., 40 to 60 percent of yield in steel and 40 percent of compressive ultimate strength in concrete.

Finally there is impact damping which includes impact or banging in the closing of gaps in supports and changes in geometry. Such damping estimate typically range between 5 and 10 percent critical for steel piping and values as high as 25 percent have been used for fuel elements. Damping values used in design are usually limited to material plus structural effects when elastic or linear analysis is assumed. When nonlinear analysis is used which considers gaps and banging between supports, impact damping as well is usually considered.

Damping can have a very significant effect on seismic design requirements for components near or at resonance conditions. Typically a change from 0.5

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percent to 2 percent damping would reduce seismic load requirements in the potential resonance region by a factor of 2.0 or more. However, damping for components more than one octive removed from the limit of resonance region has relatively little effect on resultant response loads.

Damping values for materials and structural components are normally determined experimentally by the free decay, the bandwidth, magnification factor or response methods as described in ref. [1]. In such experimental determination of damping in real structural systems it is usually not possible to distinguish between measured material and structural damping. In design of nuclear plant facilities usually two or three sets of damping values must be developed:

(a) the damping of the building structure,

(b) the damping of the mechanical and electrical equipment and distribution systems and

(c) and damping in the foundation media except in those cases where nuclear structure are found on rock having a shear wave velocity in excess of 1200m/sec.

In general, it should be understood that damping as used in design or analysis of nuclear plants is an experimentally determined factor which is used to make the results of linear elastic analysis of dynamic systems agree reasonably well with observed experimental results.

2. Historical development

The first damping values generally considered in nuclear power plant design were those suggested by Housner [2]. These values as shown in table 1 were used extensively in the U.S. and Japan for seismic analysis during the period 1963 through 1968. These values which were single valued for all modes, stress and earthquake levels were normally used with the Housner type response spectra as shown in fig. 1.

Table 1
Typical Housner type and current Japanese damping values

	Percent
1. Piping	0.5
2. Welded steel	1.0
3. Structural steel building frames	2.0
4. Prestressed concrete	2.0
5. Reinforced concrete	5.0

Starting in 1969 Newmark suggested the use of different ground response spectra [3,4] and in conjunction with the use of these new spectra as shown in fig. 2 he suggested a new set of damping values be used as shown in table 2. As can be seen by the table, Newmark made damping a function of stress level. This in turn made seismic analysis an iterative procedure since seismic load could not be determined until stress was defined which was not possible until load was defined. For this reason, the nuclear industry in the U.S. strongly resisted adoption of the Newmark damping values. In Japan, the tendency was to continue to use the Housner damping values. Finally, in 1973 a compromise was worked out between the U.S. nuclear industry and the U.S. Nuclear Regulatory Commission where damping was made a function of earthquake, either OBE or SSE. The rationale being that under OBE loads allowable stress are lower therefore implicitly damping values should be lower than those permitted for the SSE load condition. The process is also self-correcting. If a damping value is selected for the analysis of a component which cannot be supported by the stress level developed, the damping should be lower which would increase the seismic load hence the stress in the component. Thus in the limit, the actual stress approaches the maximum allowable stress permitted in the OBE or SSE load cases and the limited damping value defined would be justified. This compromise appeared as Regulartory Guide 1.61 and continues to form the criteria for definition of damping values currently used in U.S. nuclear power plant design. These damping values are shown in table 3 and are used with ground response spectra defined in Regulatory Guide 1.60 as shown in fig. 3.

It should be understood that the damping values presented in R.G. 1.61 are described as interim values. In general, these values should be considered as conservative lower bound values suitable for design in the absence of the research necessary to better quantify damping values. As more data on damping directly applicable to nuclear power plant components, systems and structures is generated, it is anticipated the R.G. 1.61 design values will be modified. A more mean centered (upper range limit) recommendation amping values

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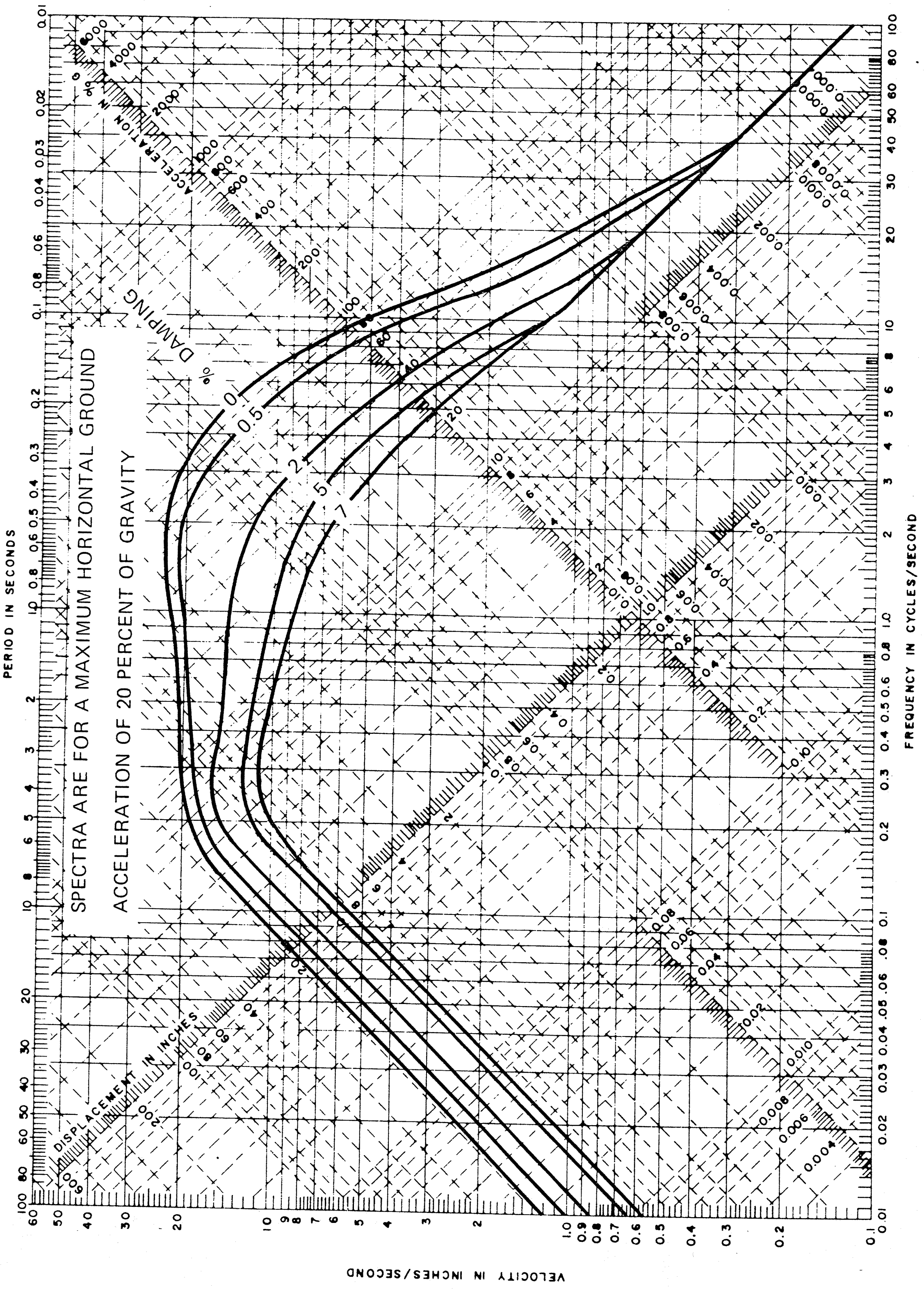
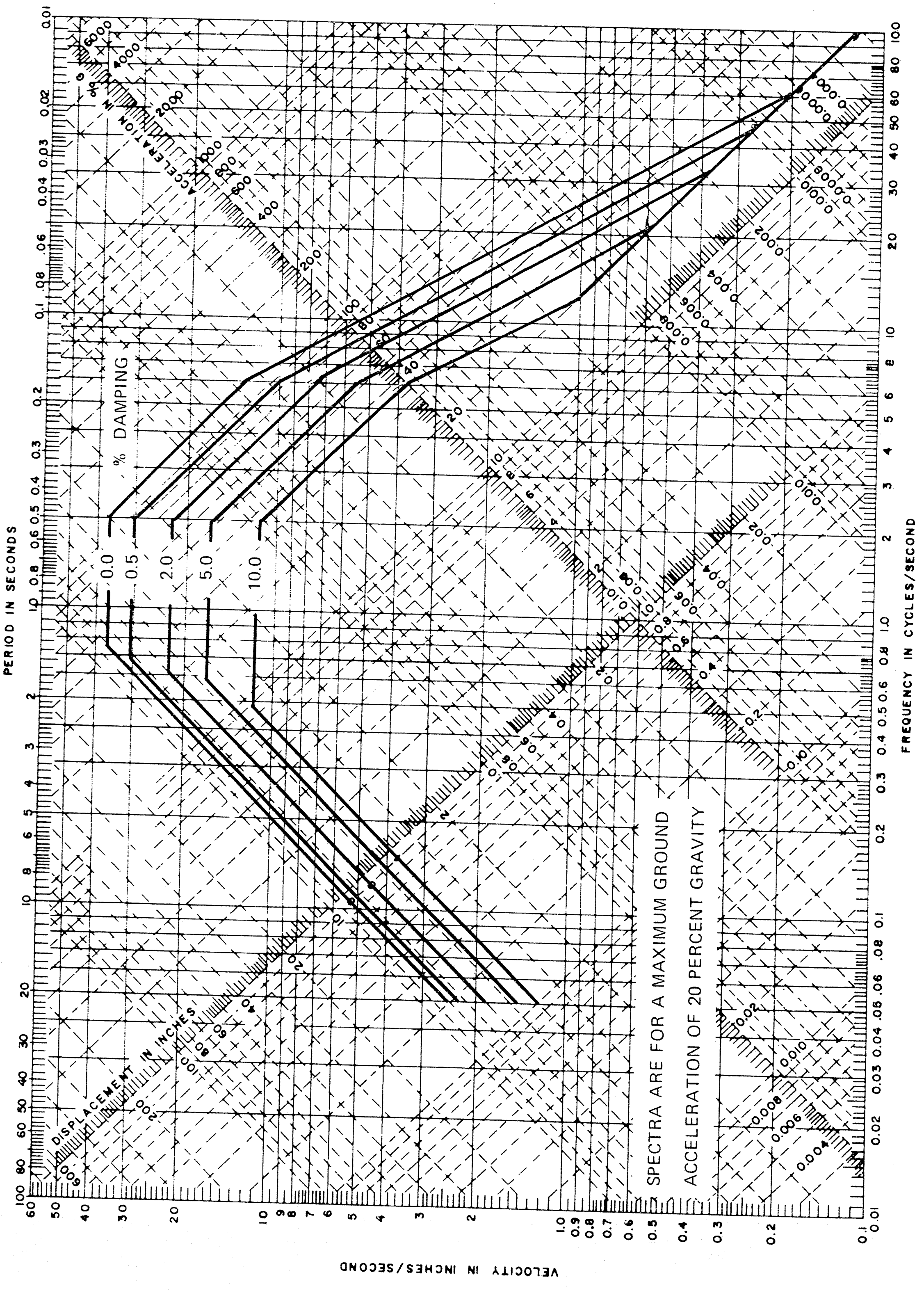


Fig. 1.


PERIOD IN SECONDS
FREQUENCY IN CYCLES/SECOND
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% DAMPING
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0.5
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SPECTRA ARE FOR A MAXIMUM GROUND
ACCELERATION OF 20 PERCENT GRAVITY

Fig. 2.

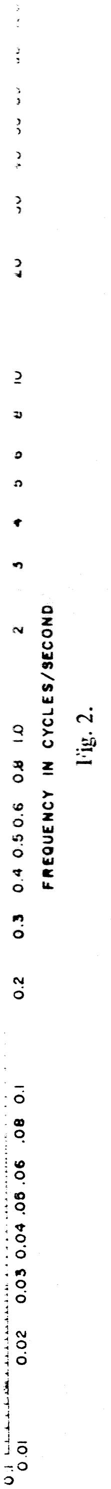


Fig. 2.

Table 2
Typical Newmark type damping values

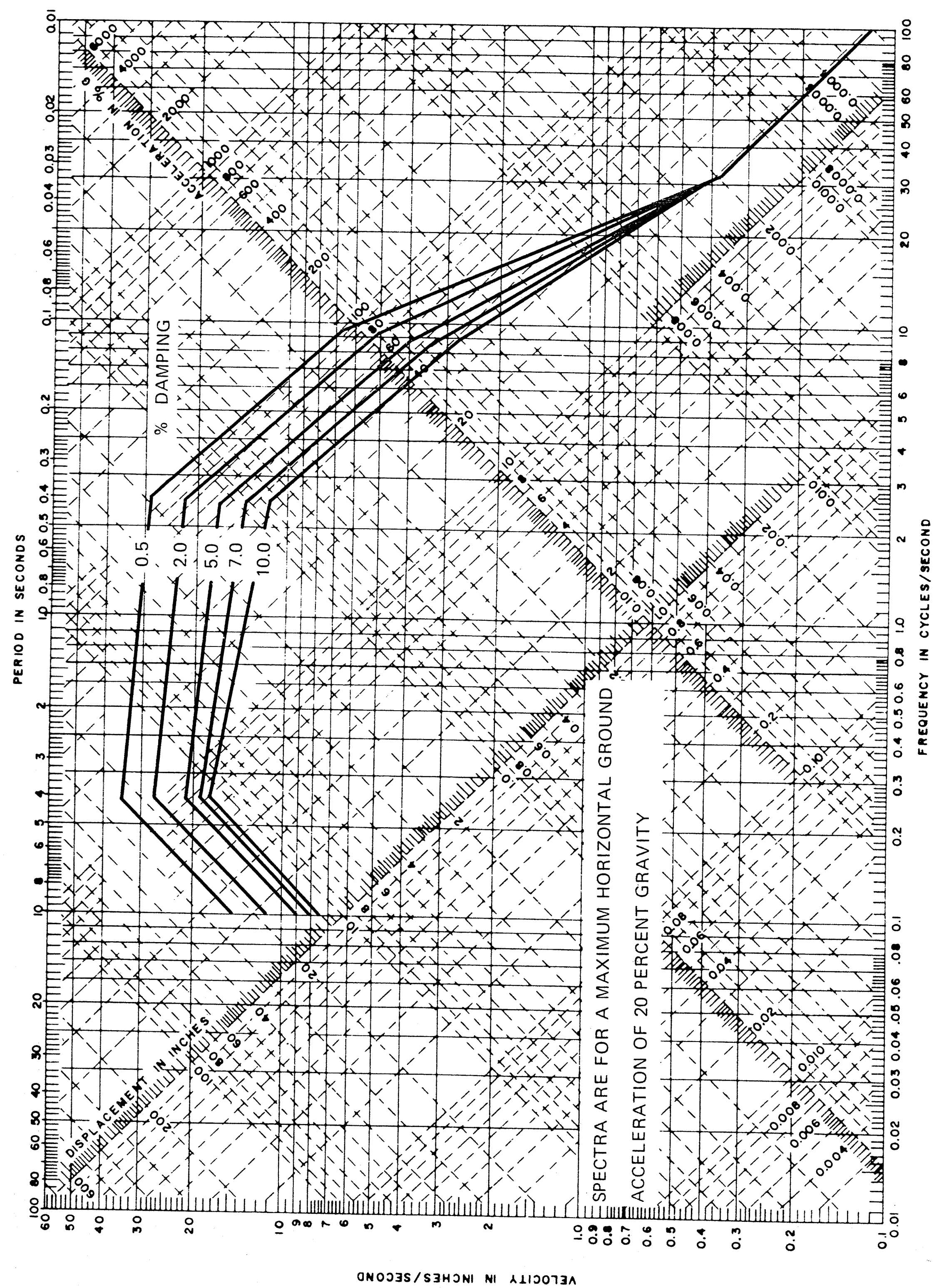
Stress level	Type and condition of structure	Percentage of critical damping
1. Low, well below proportional limit stresses below 1/4 yield point	a. Vital piping	0.5
	b. Steel, reinf. or prestr. conc., wood; no cracking no joint slip	0.5 – 1.0
2. Working stress, no more than about 1/2 yield point	a. Vital piping	0.5 – 1.0
	b. Welded steel, prestr. conc., well reinf. concr. (only slight cracking)	2
	c. Reinf. concr. with considerable cracking	3 – 5
	d. Bolted and/or rivited steel, wood structs with nailed or bolted joints	5 – 7
3. At or just below yield point	a. Vital piping	2
	b. Welded steel, prestr. concr. (without complete loss in prestress)	5
	c. Prestr. concr. with no prestress left	7
	d. Reinf. concr.	7 – 10
	e. Bolted and/or riveted steel, wood structs, with bolted joints	10 – 15
	f. Wood structs with nailed joints	15 – 20
4. Beyond yield point, with permanent strain greater than yield point limit strain	a. Piping	5
	b. Welded steel	7 – 10
	c. Prestr. conc., reinf. conc.	10 – 15
	d. Bolted and/or riveted steel, or wood structs	20
5. All ranges (Effective total modal damping in the rocking and translation modes)	Rocking of entire structure [a]	
	a. On rock, c = 6000 fps	2 – 5
	b. On firm soil, c = 2000 fps	5 – 7
	c. On soft soil, c = 2000 fps	7 – 10

[a] Higher damping values for lower values of seismic velocity, c.

of damping made by Newmark and Hall is found in ref. [7] which is reproduced herein as table 4.

3. Other current damping criteria

In addition to the damping values presented in R.G. 1.61 which are limited to structural components in air, there is generally a need to define damping associated with soil structure interaction, components in water and effective damping of structures made up of different materials and more recently, damping associated with higher mode response resulting from higher frequency, impact and impulse dynamic loads other than earthquake.


PERIOD IN SECONDS
FREQUENCY IN CYCLES/SECOND
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7.0
10.0
SPECTRA ARE FOR A MAXIMUM HORIZONTAL GROUND
ACCELERATION OF 20 PERCENT GRAVITY

Fig. 3.

Table 3
Regulatory Guide damping values (percent of critical damping)

Structure or component	Operating basis earthquake or $\frac{1}{2}$ safe shutdown earthquake	Safe shutdown earthquake
Equipment and large-diameter piping systems [b], pipe diameter greater than 12 in	2	3
Small-diameter piping systems, diameter equal to or less than 12 in	1	2
Welded steel structures	2	4
Bolted steel structures	4	7
Prestressed concrete structures	2	5
Reinforced concrete structures	4	7

[a] In the dynamic analysis of active components as defined in Regulatory Guide 1.48, these values should also be used for SSE.
[b] Includes both material and structural damping. If the piping system consists of only one or two spans with little structural damping, use values for small-diameter piping.

3.1. Soil–structure interaction damping

Prior to 1969 in the U.S., soil–structure interaction when considered normally used the elastic half space or lumped mass spring theory. In these cases damping values for both radiation damping and material damping were usually those derived from ref. [8] and damping values in the 20 to 40 percent radiation and 2 to 5 percent material damping range were not uncommon. In 1969, the U.S. Nuclear Regulatory Commission began to arbitrarily limit total soil–structure interaction damping to a total of 15 percent as an upper limit regardless of the values suggested by standard references and made no distinction between

Table 4
Recommended damping values

Stress level	Type and condition of structure	% Critical Damping
Working stress, no more than about $\frac{1}{2}$ yield point	a. Vital piping	1 – 2
	b. Welded steel, prestressed concrete, well reinforced concrete (only slight cracking)	2 – 3
	c. Reinforced concrete with considerable cracking	3 – 5
	d. Bolted and/or riveted steel, wood structures with nailed or bolted joints	5 – 7
At or just below yield point	a. Vital piping	2 – 3
	b. Welded steel, prestressed concrete (without complete loss in prestress)	5 – 7
	c. Prestressed concrete with no prestress left	7 – 10
	d. Reinforced concrete	7 – 10
	e. Bolted and/or riveted steel, wood structures, with bolted joints	10 – 15
	f. Wood structures with nailed joints	15 – 20

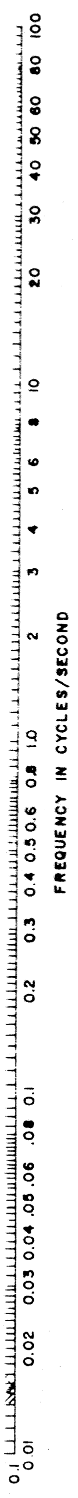

Fig. 3.

Table 5
Lumped representation of structure–foundation interaction, circular base

Motion	Equivalent spring constant	Equivalent damping coefficient
Horizontal	$k_x = \dfrac{32(1-\nu)\,GR}{7-8\nu}$	$c_x = 0.576 k_x R\sqrt{\rho/G}$
Rocking	$k_\psi = \dfrac{8GR^3}{3(1-\nu)}$	$c_\psi = \dfrac{0.30}{1+B_\psi} k_\psi R\sqrt{\rho/G}$
Vertical	$k_z = 4GR/(1-\nu)$	$c_z = 0.85 k_z R\sqrt{\rho/G}$
Torsion	$k_t = 16GR^3/3$	$c_t = \dfrac{\sqrt{k_t I_t}}{1+2I_t/\rho R^5}$

ν = Poisson's ratio of foundation medium, G = shear modulus of foundation medium, R = radius of the circular base mat, ρ = density of foundation medium, $B_\psi = 3(1-\nu)I_0/8\rho R^5$, I_0 = total mass moment of inertia of structure and base mat about the rocking axis at the base, I_t = polar mass moment of inertia of structure and base mat.

radiation and material damping. This had the effect of significantly increasing seismic response of soil founded plants using elastic half space or lumped mass methods of analysis and gave impetus to the development of finite element methods of soil–structure interaction where the equivalent of radiation damping was provided by energy transmitting boundaries and material damping was kept well within 15 percent limit. As was later determined [9,10] the arbitrary limitation on total damping of 15 percent also had the effect of a significant and incorrect shift of resonant response frequency when the elastic half space or lumped mass method were used.

By 1973, Hadjian [9,10] was able to demonstrate that at least for surface and shallow buried structures using radiation damping without the arbitrary 15 percent limitation it was possible to get equivalent results using elastic half-space as compared to the finite element method. Since 1974, it has again been permissible by the NRC to use damping values as suggested by standard reference [8,11] or as developed from experimental evaluation at the site. As published in the U.S. Nuclear Regulatory Commission Standard Review Plan 3.7.2 [2], a free field finite element analysis or the lumped mass spring analysis may be used although the lumped mass method is limited to application to surface and shallow buried plants. More recently the Nuclear Regulatory Commission has been requiring, during its licensing review, both a free field finite element analysis and lumped mass method for determining soil site structural response. Research is currently being sponsored by the Nuclear Regulatory Commission to better determine the applicability and limitation of both the finite element as well as compliance function – lump mass methods of representing foundation–structure interaction [20].

Suggested damping values for use in lumped mass–spring methods of analysis are given in tables 5 and 6 [11]. Again it should be emphasized the U.S. Nuclear Regulatory Commission does not currently place a upper limit or damping values for soils used in soil–structure interaction analyses. The values used, however, must be verified by test or by authoritative reference [8,11,34].

3.2. Damping of components at high frequency and in higher modes

Of increasing importance in nuclear plant design is the development of design damping values for components at relatively high frequency and in higher modes of response. This results from the development of design response spectra for high frequency loading phenomena such as airplane crash, safety relief valve discharge, LOCA transients, blast waves and postulated missile impacts. Such loadings typically give rise to development of relatively high response accelerations in the 35 to 100 Hz range which exceeds those accelerations defined from seismic loads. Based on the limited experimental data currently available, [28–32] it appears damping increases as a function of increased frequency and in higher modes until some frequency range (i.e., 40–50 Hz) is reached and then begins to decline. One possible explanation for such a damping behavior pattern, if indeed such a pattern exists, would result from the situation that damping experiments tend to be run at constant amplitude. In these higher modes, these amplitudes or displacements would give rise to higher stress levels resulting in greater nonlinearities which would thereby result in increased damping values. This characteristic is countered by the observation in the progressively higher mode

Table 6
Lumped representation of structure–foundation interaction, rectangular base

Motion	Equivalent spring constant	Equivalent damping coefficient	
Horizontal	$k_x = 2(1+\nu)\,G\beta_x\sqrt{BL}$	Use the results for circular base with the following equivalent radius R	
Rocking	$k_\psi = \dfrac{G}{1-\nu}\beta_\psi BL^2$		
Vertical	$k_z = \dfrac{G}{1-\nu}\,\beta_z\sqrt{BL}$	(1) $R = \sqrt{BL/\pi}$	for translation
Torsion	Use take 1 for $R = \sqrt[4]{16BL(B^2+L^2)/6\pi}$	(2) $R = \sqrt[4]{BL^3/3\pi}$	for rocking

ν and G are as defined previously, B = width of the base mat perpendicular to the direction of horizontal excitation, L = length of the base mat in the direction of h horizontal excitation, β_x, β_ψ, β_z = constants that are functions of the dimensional ratio (L/B), see fig. T6 (after Richard et al., 1970).

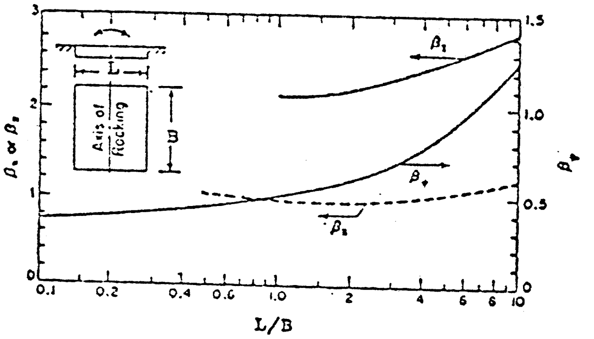

Fig. T6. Constants β_x, β_ψ and β_z for rectangular bases.

there is less energy being transmitted to the supports or boundaries of the component. As a result, material damping would tend to dominate at higher modes and thereby effective damping would be reduced.

3.3. Damping of components in water

Early studies of the resonant response of components submerged in water [12,13] have suggested there is a significant increase in apparent damping for such components. Until 1977, the U.S. Nuclear Regulatory Commission had been permitting a 2 percent increase in damping associated with water submerged component particularly associated with spent fuel rod seismic analysis. However, during 1977 a study performed by Lawrence Livermore Laboratories for the Nuclear Regulatory Commission recommended that the increased damping should not be allowed, and since the publication of this report [14] generally no increase as a result of water submergence has been permitted by the U.S. Nuclear Regulatory Commission. Results of recent tests performed on the CANDU reactor core [15] suggest that damping in water versus air is highly dependent on the shape of the submerged component [16] and an increase in damping in water compared to air should be permitted as a function of the shape of the submerged object.

3.4. Modal damping of structures made up of different materials

The methods used are typically those suggested in the U.S. Nuclear Regulatory Standard Review Plant

Section 3.7.2 [17].which are summarized herein.

For the composite modal damping approach, two techniques of determining an equivalent modal damping matrix or composite damping matrix are commonly used. They are based on the use of the mass or stiffness as a weighting function in generating the composite modal damping. The formulations lead to:

$$\overline{\beta}_j = \frac{\{\phi\}^{\mathrm{T}}[\overline{M}]\{\phi\}}{\{\phi\}^{\mathrm{T}}[M]\{\phi\}}, \qquad (1)$$

or

$$\overline{\beta}_j = \frac{\{\phi\}^{\mathrm{T}}[\overline{K}]\{\phi\}}{\{\phi\}^{\mathrm{T}}[K]\{\phi\}}, \qquad (2)$$

where $[K]$ = assembled stiffness matrix, $\overline{\beta}$ = equivalent modal damping ration of the jth mode, $[\overline{K}]$, $[\overline{M}]$ = the modified stiffness or mass matrix constructed from element matrices formed by the product of the damping ratio for the element and its stiffness or mass matrix, and $\{\phi\}$ = jth normalized modal vector.

For the models that take the soil–structure interaction into account by the lumped soil spring approach, the method defined by eq. (2) is acceptable. For fixed base models, either eq. (1) or (2) may be used. Other techniques based on modal synthesis [18] have been developed and are particularly useful when more detailed data on the damping characteristics of structural subsystems are available. The modal synthesis analysis procedure consists of

(1) extraction of sufficient modes from the structure model,

(2) extraction of sufficient modes from the finite element soil model,

(3) performance of a coupled analysis using the modal synthesis technique, which uses the data obtained in steps (1) and (2) with appropriate damping ratios for structure and soil subsystems.

This method is based upon satisfaction of displacement compatibility and force equilibrium at the system interfaces and utilizes subsystem eigenvectors as internal generalized coordinates. This method results in a nonproportional damping matrix for the composite structure and equations of motion have to be solved by direct integration or by uncoupling them by use of complex eigenvectors.

Another technique which is also considered acceptable for estimating the equivalent model damping of a soil structure interaction model is given by Tsai [19].

5. Direct computation of damping values

Damping values as used in seismic analysis of structures, components and soil–structure interaction are well defined in U.S. criteria since 1973 as shown in table 3. These are based on values recommended by Newmark, Blume and Kapur [5] as shown in table 2. Direct comparison of recommended damping values with actual test results on nuclear power plant facilities is difficult since load and stress levels used in the tests are normally much less than those that would result from actual typical earthquake strong motion in order to assure no overstress of the equipment during the insitu test. This normally results in inertia stresses induced in components and piping during test below 0.10 yield stress. For concrete, a lower bound stress level of 0.25 times yield stress is used consistent with test stress levels reported in Appendix B.

A summary of damping test data appearing in the literature which is particularly applicable to nuclear power plant mechanical components is given in Appendix A of this paper. A grouping of the data given in Appendix A and typical damping trends as a function of increased load or acceleration intensity observed during tests which generally show an increase are shown in Appendix B.

An excellent summary of damping data and variability applicable to all types of concrete and steel buildings is presented in Appendix B [27]. Also, a summary of damping as a function of deformation of nuclear reactor coolant system components can be found in ref. [21]. From the statistical data, mean values and the damping trend curves given in Appendix B, a mathematical formulation as a function of seismic stress level has been developed as shown in Appendix B. By use of these formulations, it is possible to predict damping values as a function of seismic stress levels. The best estimate damping values given in table 7 which are based on the formulations developed in Appendix B, are significantly higher than the design values that would be permitted by R.G. 1.61 but are in better agreement with best estimate values recommended by Newmark and Hall [7]. It should also be understood that the data base presented in Appendix A in general is quite small so that the damping values base presented in table 7 cannot be used with a high degree of confidence, particularly es

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Table 7
Comparison of available nuclear station experimentally measured damping and regulatory requirements and recommendations

I. Best estimate or mean value damping values

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Reactor system piping	3.4	2.0	8.1	2.0	10.0	3.0	3.0	12.7	16.2
Mechanical components	3.8	3.0	5.7	2.0	6.5	4.0	7.0	7.7	9.1
Concrete structures	5.2	5.0	7.5	4.0	13.9	7.0	10.0	18.7	25.0

Column headings
(1) Average of measured data for stress levels at or less than 0.1 yield for components and piping and 0.25 yield for concrete from table B.1.
(2) Suggested Newmark and Hall values at approximately 0.5 yield ([7]).
(3) Measured damping values normalized to 0.5 yield stress using procedures shown in Appendix B.
(4) Regulatory Guide 1.61 values for stress levels of approximately 0.67 yield (OBE).
(5) Measured damping values normalized to 0.67 yield stress using procedures shown in Appendix B.
(6) Regulatory Guide 1.61 values for stress levels of approximately 0.90 yield (SSE).
(7) Suggested Newmark and Hall values at approximately 0.9 yield ([7]).
(8) Measured damping values normalized to 0.9 yield stress (faulted: buildings; emergency: component supports).
(9) Measured damping values normalized to 1.2 yield stress (faulted: component supports).

at the high stress range at or beyond yield. There is much additional data available particularly from electrical component testing which is considered proprietary and therefore is not currently available. It is hoped that this data may be available in the future to better define the damping value suggested in this paper.

6. Conclusions and recommendations

In order to improve the overall safety and reliability of nuclear power plants it is absolutely essential that extreme load design requirements such as earthquake which effect and tend to be detrimental to normal operation, reliability and safety be as realistically defined as is possible. The cause of nuclear safety is not well served if restraint of piping to carry over estimated seismic loads results in thermal fatigue failure during normal operations. An improvement in our understanding and definition of realistic damping values used in design is an important step in increasing overall nuclear safety.

The damping data to be gathered in the current Heissdampfreaktor Seismic Test being sponsored by the German Federal Minister for Research and Development and the Indian Point Unit No. 1 tests being sponsored by the Electric Power Research Institute in the U.S. are badly needed steps in the direction of developing additional experimental damping data directly applicable to nuclear plant components and structures. However, more data is required which is directly applicable to prestressed as well as reinforced concrete, nuclear plant distribution systems (i.e., large and small, hot and cold piping, cable trays, HVAC duct) and mechanical and electrical equipment at stress levels up to and exceeding yield or its equivalent before any major modification of current seismic damping design values are likely to be permitted by National Regulatory Agencies.

Appendix A. Summary of tests of in situ nuclear power systems to determine frequency and damping response [1,2]

A. CVTR reactor

	Structure/component	Excitation	Response in	Levels in/s	G	Type of response mode	Frequency (Hz)	Damping (% critical)
1.	Concrete containment building: 114 ft high. 58 ft. diameters, 50% buried	$10^3 - 10^4$ lb	10^{-3}	10^{-1}	10^{-2}	Translation	8.3 – 9.5	6.0
2.	Operating floor inside side containment building	$10^3 - 10^4$ lb Harmonic vibrators	10^{-2}	10^{-1}	10^{-2}	EW Translation NS Translation Torsion	4.0 6.8 4.0	6.0 9.0 6.0
3.	Stack: 150 ft high	Ambient	10^{-3}	10^{-1}	10^{-1}	Translation	20, 24, 40	1.0

B. Enrico Fermi

	Structure/component	Excitation	Response in	Levels in/s	G	Type of response mode	Frequency (Hz)	Damping (% critical)
1.	Steel containment 100′ high, 72′ diameter, steel and concrete below grade, 50% buried		10^{-4}	10^{-2}	10^{-2}	Translation	13.0 16.0	6.0
2.	Intermediate heat exchanger, 24″ high, 60″ diameter steel vessel with large diameter (30″, 12″) piping attached. Cantilevered off a skirt, but in close contact with concrete wall		10^{-3}	10^{-2}	10^{-3}	Translation	3.0	10.0
3.	Secondary sodium pump, 19″ high, 5′ diameter motor and pump, attached at bottom by plate, and at top by light steel beams; some attached piping	Up to 25 lb detonation at 1000 ft (single detonation)	10^{-3}	10^{-2}	10^{-2}	Translation	7.9	3.0
4.	Sodium/Water genera- 200″ high, 100″ diameter; many small pipes attached, held to middle and bottom by steel frame and struts.		10^{-3}	10^{-2}	10^{-2}	Translation	15.0	10.0
5.	Fuel transfer machine		10^{-3}	10^{-2}	10^{-2}	Translation	8.0	6.0

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[1] Only components having fundamental frequencies below 25 Hz are included.
[2] Frequencies shown are fundamental frequencies.

	Structure/component	Excitation	Response in	Levels in/s	G	Type of response mode	Frequency (Hz)	Damping (% critical)
C. SAN ONOFRE reactor unit No. 1.								
1.	Containment, 140' diameter steel sphere, continuously supported on lower 30% by below grade concrete cradle	Harmonic vibrations $10^3 - 10^4$ lbs	10^{-4}	10^{-2}	10^{-4}	Rocking on soil	SE: 4.8 NW: 7.0	16.0 18.0
2.	Pressurizer, 42' high, 8' diameter steel pressure vessel, cantilever off skirt, 10 000 slugs filled with water	Harmonic vibrations $10^{-5} - 10^{-4}$ g	10^{-2}	10^{-2}	10^{-3}	Rocking on skirt	NW: 2.4 NE: 2.9	2.0 1.5
		Harmonic vibrations 10^{-3} g on containment	10^{-4}	10^{-2}	10^{-3}	Translation	16.0 19.0	2.5 1.0
		Earthquake 9/70 less than 0.01 g peak ground acceleration	~10^{-1}	~10^{0}	~10^{-1}	Rocking on skirt	NW: 2.4 NE: 2.7	2.0 1.5
3.	Steel containment sphere	Harmonic vibrators 10^{-3} g on containment	10^{-4}	10^{-2}	10^{-3}	Translation and rocking	11.3	0.05
4.	Reactor vessel, 38' high, 13' diameter thick walled vessel containing reactor core; supported at three points above center of gravity by keys	Harmonic vibrations 10^{-4} g on containment	10^{-4}	10^{-2}	10^{-4}	Translation and rocking	7.3	1.5
5.	Steam generator-coolant pump system affecting more than one component). Steam generator (SG) is 45' high, 11' diameter, steel pressure vessel with internal tube sheets. Pump is 25' high, 9' diameter. Both SG and pump connected by large diameter (30") thick wall 3") piping with typical lengths of 100". These pipes also connect them to the reactor vessel. Vertical support by stringers off steel frames. Transverse support comes from the connecting piping. SG also restrained by keys.	Harmonic vibrators and 10^{-4} in on containement	10^{-3}	10^{-2}	10^{-3}	Steam generator translation	1.88	1.5
			10^{-2}	10^{-1}	10^{-1}	Pump piping pump steam generator translation	2.84 3.15 3.95 5.7 8.0	1.5 1.5 1.5 1.5 1.5
		Earthquake 2/71 10^{-2} g ground motion	10^{-1}	10^{0}	10^{-1}	Steam generator Pump Piping Pump Steam generator Translation	2.0 2.9 3.1 4.0 5.7 8.0	

Structure/component	Excitation	Response in	Levels in/s	G	Type of response mode	Frequency (Hz)	Damping (% critical)
D. EGCR reactor							
1. Core, cylindrical array of graphite bars 16" × 16" 20' feet high, 15' diameter, held top, middle, and bottom. Use of keys causes nonlinear response.	Harmonic vibrators $10^{-4} - 10^{4}$ lbs up to 2 000 lb detonation at 300 ft	10^{-3}	10^{-2}	10^{-3}	Translation	EN: 4.6 NS: 3.9 EW: 13.6	1.0 1.0 – 3.0 1.0
2. Concrete exhaust stack; 200' high, approximately 30' diameter	Ambient	–	–	–	Translation	0.9 4.0	1.0 1.0
3. Concrete containment building, 200' high, 30% buried, 100' diameter, 10^{6} slugs	Harmonic vibrators $10^{3} - 10^{4}$ lbs	10^{-3}	10^{-2}	10^{-3}	Rocking Rocking Torsion	EW: 4.7 NS: 4.2 8.2	1.5 – 2.0 2.0 – 3.0 2.0
	up to 2 000 lb detonation at 300 ft	10^{-2}	10^{-1}	10^{-1}	Rocking Rocking	EW: 4.5 NS: 4.0	2.0 – 4.0 2.0 – 5.0
4. Steam generator, 45' high, 9' diameter, steel pressure vessel with heavy walls (3–4 in), tube sheet inside, supported on skirt from bottom, several attached pipes.	Harmonic vibrators $10^{4} - 10^{3}$ in on containment	10^{-3}	10^{-2}	10^{-3}		EW: 4.6 NS: 3.9 EW: 13.6	1.0 1.0 – 3.0 1.0
	Up to 2 000 lb detonation at 300 ft	10^{-2}	10^{-1}	10^{-1}	Rocking Rocking	EW: 6.0 NS: 5.8	1.0 1.0
	Snapback in NS direction	10^{-1}	10^{-0}	10^{-0}	Rocking Rocking	EW: 5.4 NS: 5.1	2.0 – 3.0 2.0 – 3.0
5. Pipe attached to steam generator, 45' long, unsupported, 22" O.D., 3/8 inch wall.	Up to 2 000 lb detonation at 300 ft resulting in 10^{-6} g on steam generator and containment; snapback produced same results	10^{-2}	10^{-0}	10^{-1}	Translation, perp. to pipe	12.0	2.0 – 3.0
E. Indian Point unit 2							
1. Steam generator – approximately 65 ft long and 16 ft dia. with an empty weight of approx. 330 ton	Electro–dynamic shaker–sine beat	10^{-2} to 3.7×10^{-2}		–	Tangential radial	3.15 2.48	3.0 5.0
2. Cross over leg between steam generator and coolant pump	Electro–dynamic shaker–sine beat	3×10^{-3}	–	–	Significant coupling with steam generator internals	35.1	5.0
3. Coolant pump		1.9×10^{-2} 1.8×10^{-2}	–	–	Tangential radial	4.5 5.3	0.95 1.3

ency	Damping (% critical)
4.6	1.0
3.9	1.0 – 3.0
3.6	1.0
0.9	1.0
4.0	1.0
4.7	1.5 – 2.0
4.2	2.0 – 3.0
8.2	2.0
4.5	2.0 – 4.0
4.0	2.0 – 5.0
4.6	1.0
3.9	1.0 – 3.0
13.6	1.0
6.0	1.0
5.8	1.0
5.4	2.0 – 3.0
5.1	2.0 – 3.0
12.0	2.0 – 3.0
3.15	3.0
2.48	5.0
35.1	5.0
4.5	0.95
5.3	1.3

Structure/component	Excitation	Response in	Levels G in/s		Type of response mode	Frequency (Hz)	Damping (% critical)
F. Madras atomic power project	1 to 4.4 × 10^3 lbs pluck test						
1. Air ejector conde		–	–	–	Trans.–Longitudinal	24.7	2.7
		–	–	–	Trans.–Transverse	23.8	2.2
2. L.P. heater		–	–	–	Trans.–Longitudinal	17.9	6.7
					Trans.–Transverse	10.0	4.5
3. Air receiver		–	–	–	Trans.–Longitudinal	13.1	5.2
					Trans.–Transverse	13.1	5.2
4. Main condenser extrac. pump		–	–	–	Trans.–Longitudinal	9.7	3.1
					Trans.–Transverse	12.3	6.2
5. L.P. flash tank		–	–	–	Trans.–Longitudinal	21.7	3.5
					Trans.–Transverse	22.8	2.8
6. Reheater drain pump		–	–	–	Trans.–Longitudinal	21.1	3.0
					Trans.–Transverse	20.0	4.6
7. Turbine oil cooler		–	–	–	Trans.–Longitudinal	6.21	3.9
					Trans.–Transverse	6.21	3.9
G. Rajasthan power project	1 to 4.4 × 10^3 lbs pluck test						
1. Glen steam condenser		–	–	–	Trans.–Longitudinal	8.6	6.5
					Trans.–Transverse	6.0	6.5
2. Turbine oil cooler		–	–	–	Trans.–Longitudinal	7.3	2.3
					Trans.–Transverse	7.3	2.3
3. B.S.R. drain tank		–	–	–	Trans.–Transverse	24.9	4.0
4. Reheater drain tank		–	–	–	Trans.–Longitudinal	13.5	1.9
					Trans.–Transverse	1.9	3.5
5. Air ejector condenser		–	–	–	Trans.–Longitudinal	8.7	3.5
6. Pump house pump		–	–	–	Trans.–Longitudinal	16.7	3.3
					Trans.–Transverse	13.7	2.8
7. Condensate extractor pump		–	–	–	Trans.–Longitudinal	20.1	2.6
					Trans.–Transverse	21.6	1.8
8. Reheater		–	–	–	Trans.–Longitudinal	7.6	6.5
					Trans.–Transverse	6.2	7.4
9. Separator		–	–	–	Trans.–Longitudinal	6.0	3.1
10. Deairator and storage tank		–	–	–	Trans.–Longitudinal	11.6	3.8
					Trans.–Transverse	7.1	1.7
11. H.P. process water		–	–	–	Trans.–Longitudinal	22.7	3.8
					Trans.–Longitudinal		
12. Compressor		–	–	–	Trans.–Longitudinal	17.9	8.5
					Trans.–Transverse	17.4	6.5
13. Chilled HX		–	–	–	Trans.–Longitudinal	9.1	4.4
					Trans.–Transverse	18.0	4.2
H. Diablo canyon							
1. Boric acid tank	Harmonic vibrators	–	–	0.2	E–W Bending	15.0	2.5
2. Diesel generator		–	–	0.2	N–S Rocking	17.0	5.0
3. Component cooling HX		–	–	0.1	Transv. Bending	8.8	3.4
4. CO_2 cardox system		–	–	0.2	Vertical	9.8	3.7
5. Containment spray pump		–	–	1.1	–	11.7	0.6
6. pressurizer		–	–	0.6	–	22.0	3.5
7. Safety injection pump		–	–	0.3	–	5.5	14.8
8. Let down line (small pipe)		–	–	0.05	–	4.2	6.5
9. Component cooling surge tank		–	–	0.26	Trans.–Transverse	21.0	2.0
10. Liquid hold up tank		–	–	1.0	Trans.–Ovaling	8.2	0.4

Appendix B. Grouping of nuclear power plant data and development of damping trend curves as a function of deformation, stress or strain level and development of an explicit formulation of damping as a function of stress level

B.1. Introduction

In Appendix A is presented a summary of the published data concerning damping of mechanical components used in nuclear power plant facilities. This information has been grouped by component in table B.1, and statistically analyzed. In addition, since so little data is available from reported tests on nuclear plant facilities and most nuclear plant concrete structure are composed of shear walls supplemental data from the testing of 22 conventional concrete shear wall buildings [25] and laboratory testing of shear walls [26] has been included in table B.1.

In figs. B.1 – B.11 are presented existing plots of damping versus loading phenomena in the form of deformation, stress or strain. Figs. B.1 – B.6 are based on in situ testing of nuclear power plant equipment and figs. B.7 – B.11 report the results of laboratory tests on simple structural systems.

Since all testing results shown in table B.1 were at low stress levels, a value of $0.10\,f_y$, is selected as a conservative stress level applicable to the mean of mechanical component and piping data groups shown in table B.1. For concrete structures a stress level of $0.25\,f_y$ is selected since it is more consistent with test stress levels shown in fig. B.11. The slopes of the damping trend curves shown in figs. B.1 – B.11 have been determined as shown in table B.2. The mean increase in damping from table B.2 for mechanical component (heat exchangers and valves) trends curves is 12.6 percent for each doubling of deformation, stress or strain levels.

Table B.1
Grouping of nuclear power plant damping statistical data and determination of lower bound damping values

Category	damping (% critical)	Seismic stress level
I. Reinforced concrete structures		
A. Concrete Containment Structures		
(1) CVRT	6.0	$<0.10\,f_y$
(2) EGCR (3300 fps, shear wave velocity	3.3	$<0.10\,f_y$
B. Partial steel and concrete containment		
(1) Enrico Fermi	6.0	$<0.10\,f_y$
C. Containment internal concrete structure		
(1) CVTR	7.0	$<0.10\,f_y$
D. Concrete buildings – (Shear wall type construction)– summary of building tests		
No. of buildings		
2	1.5	
3	2.5	
2	3.5	
2	4.5	
1	5.5	
5	6.5	
4	7.5	
1	8.5	
1	9.5	
1	12.5	

Table B.1 (Continued)

Catetory	Damping (% critical)	Seismic stress level
E. Concrete shear walls – Test data on 5 samples – 10 test points each sample		
1	4.0	0.25 f_y
1	3.0	
1	2.5	
1	2.3	
1	2.0	
Sample size $n = 31$ Sample mean $(\bar{x}) = 5.2$ Sample standard deviation $(s) = 2.64$ C.O.V. = 0.508		
II. Mechanical equipment		
A. Vessels and tanks		
(1) San Onofre No. 1 pressurizer	1.8	<0.10 f_y
(2) San Onofre No. 1 reactor vessel	1.5	
(3) MAPP air receiver	5.2	
(4) RAPP BSR drain tank	3.2	
(5) RAPP reheater drain tank	2.7	
(6) RAPP deairator and storage tank	2.8	
(7) Diablo Canyon pressurizer	3.5	
(8) Diablo Canyon boric acid tank	2.5	
(9) Diablo Canyon comp. cooling surge tank	2.0	
(10) Diablo Canyon liquid holdup tank	0.4	
Sample size $n = 10$ Sample mean $(\bar{x}) = 2.56$ Sample standard deviation $(s) = 1.29$ C.O.V. = 0.503		
B. Heat exchangers		
(1) Enrico Fermi intermediate HX	10.0	<0.10 f_y
(2) Enrico Fermi sodium/water HX	10.0	
(3) San Onofre No. 1 steam generator	3.0	
(4) EGCR steam generator	2.5	
(5) Indian Point No. 2 steam generator	4.0	
(6) MAPP air ejector condenser	2.5	
(7) MAPP L.P. heater	5.6	
(8) MAPP flash tank	3.2	
(9) MAPP turbine oil cooler	3.9	
(10) RAPP steam condenser	6.5	
(11) RAPP turbine oil cooler	2.3	
(12) RAPP air ejection condenser	3.5	
(13) RAPP reheater	7.0	
(14) RAPP seperater	3.1	
(15) RAPP chilled HX	4.3	
(16) Diablo Canyon comp. coolant HX	3.4	
Sample size $n = 16$ Sample mean $(\bar{x}) = 4.68$ Sample standard deviation $(s) = 2.92$ C.O.V. = 0.624		

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Table B.1 (Continued)

Category	Damping (% critical)	Seismic stress level
C. Pump		
(1) Erico Fermi secondary sodium pump	3.0	<0.10 f_y
(2) San Onofre No. 1 reactor coolant pump	2.5	
(3) Indian Point No. 2 reactor coolant pump	1.2	
(4) MAPP main condenser extraction pump	4.7	
(5) MAPP reheater drain pump	3.8	
(6) RAPP pump house pump	3.3	
(7) RAPP condensate ext. pump	1.9	
(8) Diablo Canyon containment spray pump	0.6	
(9) Diablo Canyon safety injection pump	14.8	
Sample size $n = 9$ Sample mean $(\overline{x}) = 3.98$ Sample standard deviation $(s) = 4.25$ C.O.V. = 1.068		
III. Piping		
A. A. Large integrated pipe system > 12" diameter		
(1) San Onofre No. 1 RCS	3.0	<0.10 f_y
(2) EGCR stream line	2.5	
(3) Indian Point No. 2 cross over leg	5.0	
(4) Diablo Canyon steam line	3.1	
Sample size $n = 4$ Sample mean $(\overline{x}) = 3.4$ Sample standard deviation $(s) = 1.1$ C.O.V. = 0.324		
B. Small pipe		
(1) Diablo Canyon loop 2 let down line (~2")	6.5	<0.10 f_y
(2) Tsuruga 6 to 16" pipe line	5.9	<0.10 f_y
Sample size $n = 2$ Sample mean $(\overline{x}) = 6.2$ Sample standard deviation $(s) = 0.42$		
IV Miscellaneous		
(1) Enrico Fermi fuel transfer machine	6.0	<0.10 f_y
(2) EGCR graphite core	1.3	
(3) RAPP H.P. process pump motor	3.8	
(4) RAPP compressor	7.5	
(5) Diablo Canyon diesel generator	5.0	
(6) CO_2 CARDOX CO_2 system	3.7	
V. Summary of Mechanical Components		
(1) Vessels and tanks $(\overline{x})$	2.56	$(s) = 1.29$
(2) Heat exchangers $(\overline{x})$	4.68	$(s) = 2.92$
(3) Pumps $(\overline{x})$	3.98	$(s) = 4.25$
Mechanical component sample mean $(\overline{x})$ C.O.V. = 0.740	11.22/3 = 3.81	$(s) = 8.4/3 = 2.82$

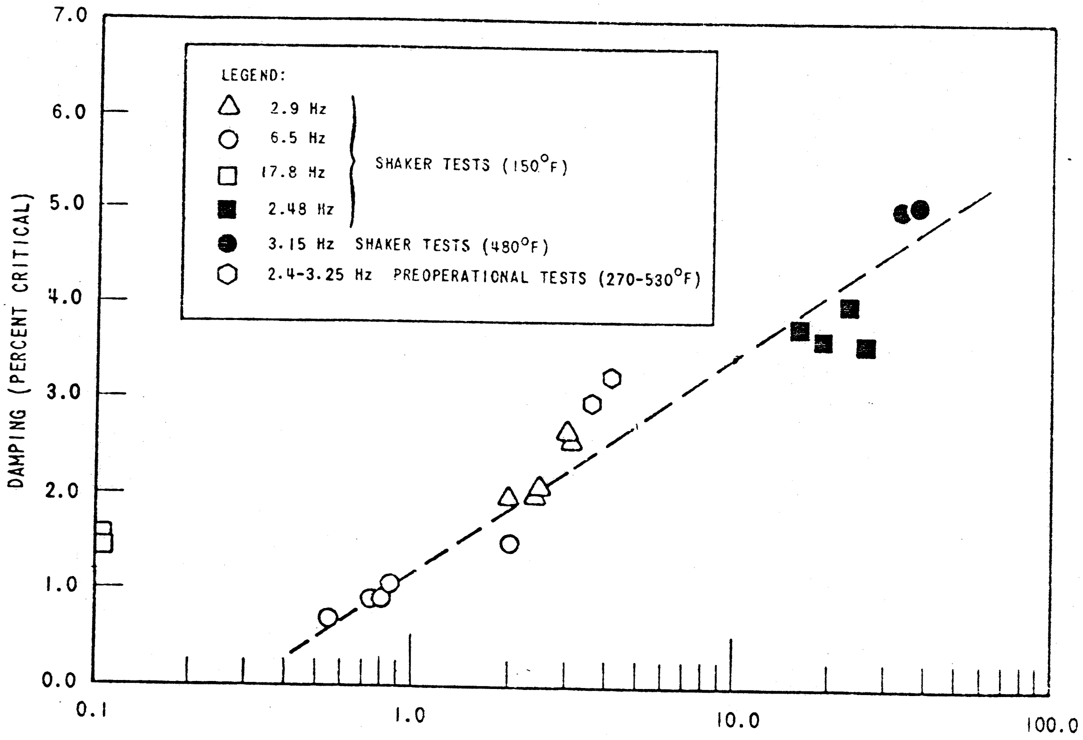

Fig. B.1. Steam generator damping values, radial modes.

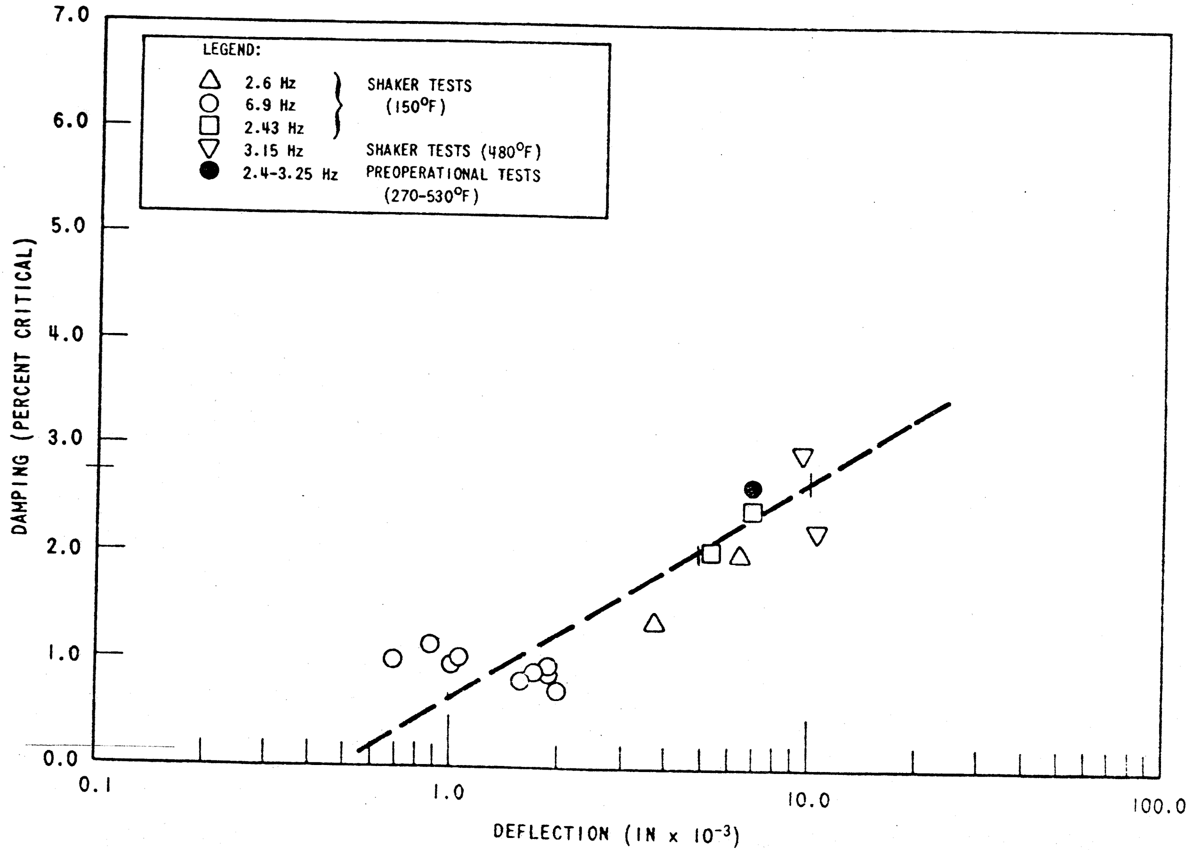

Fig. B.2. Steam generator damping values, tangential modes.

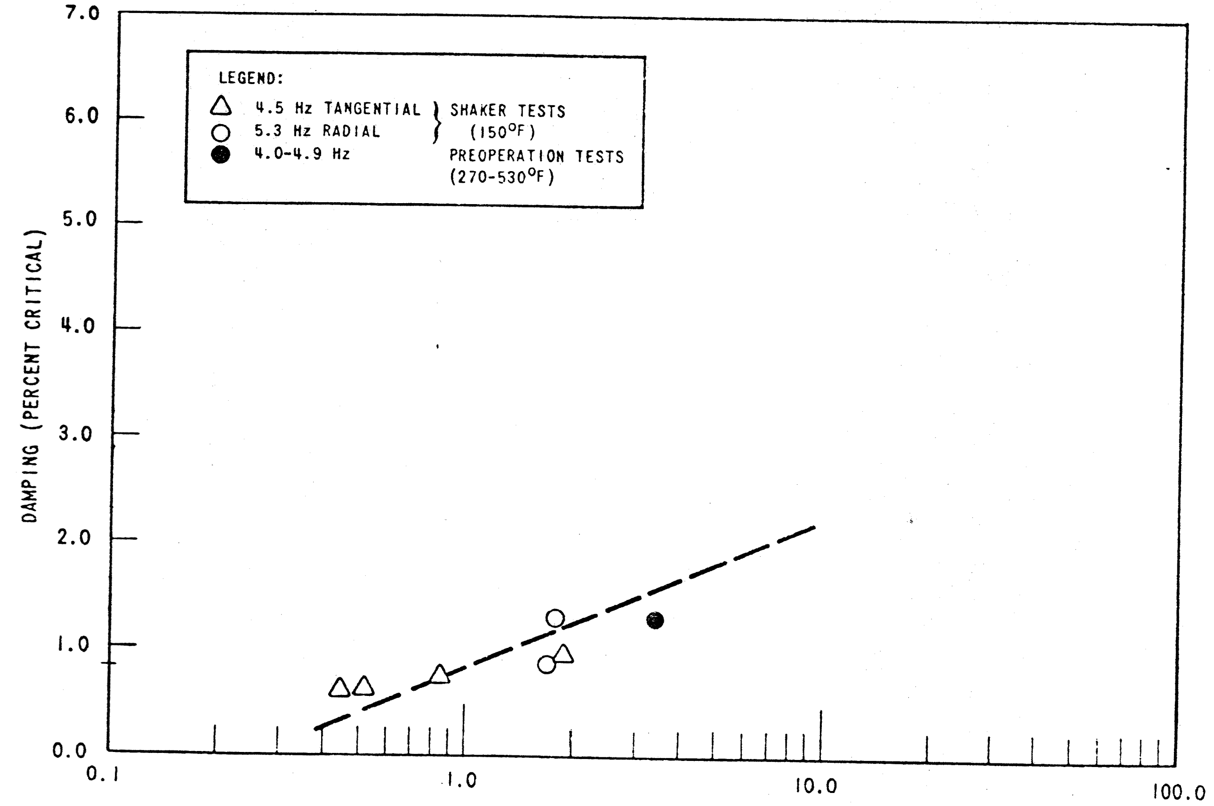

Fig. B.3. Reactor coolant pump damping values.

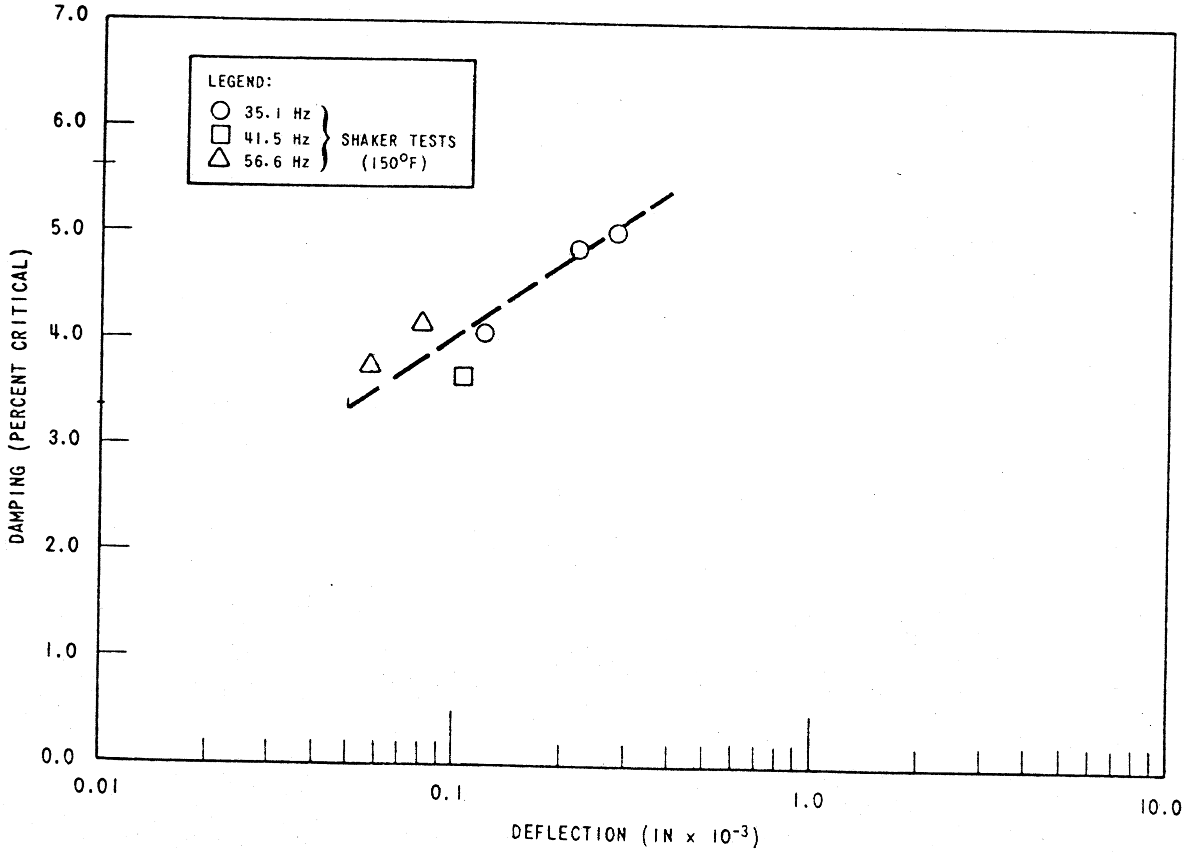

Fig. B.4. Cross-over leg damping values.

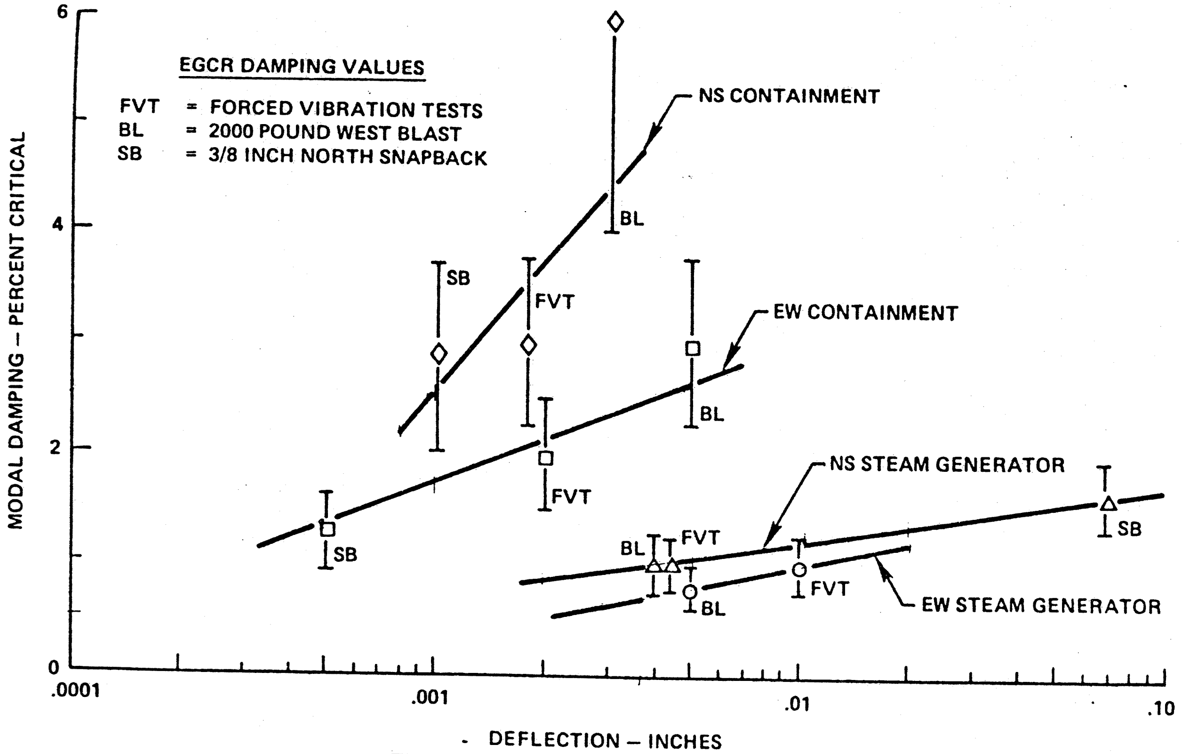

Fig. B.5. Modal damping versus amplitude.

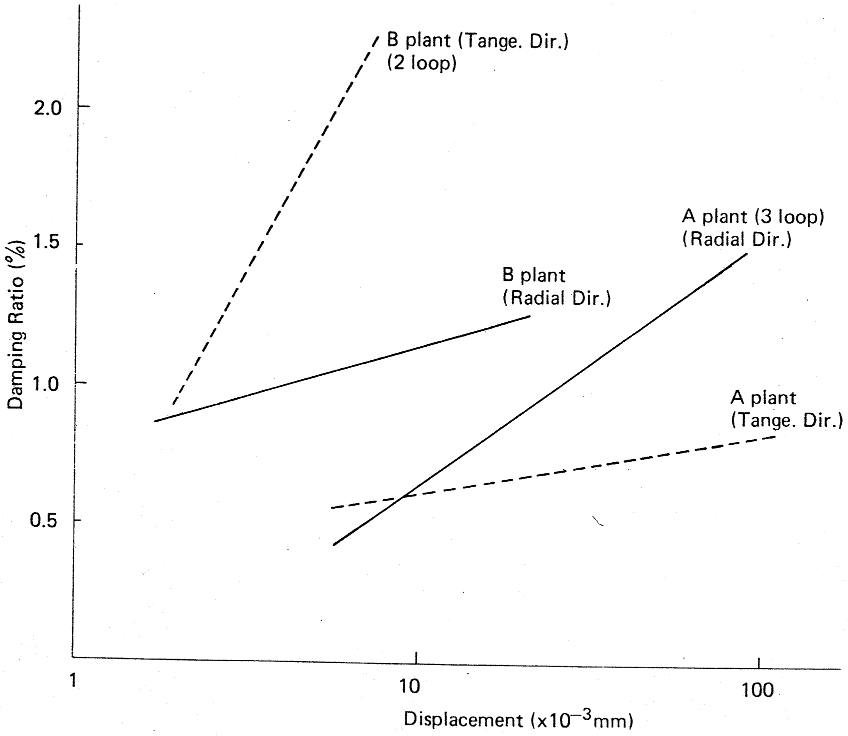

Fig. B.6.

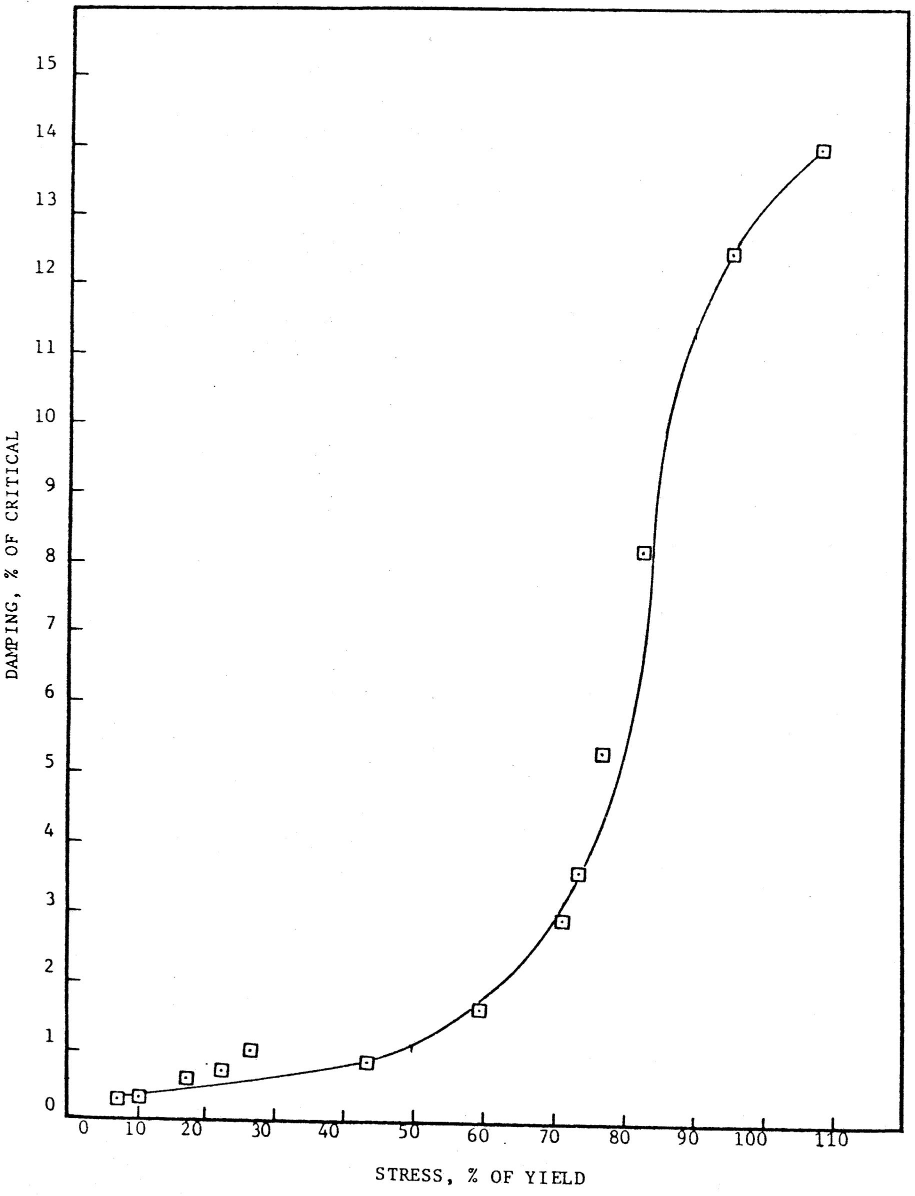

Fig. B.7. Results of fixed-end 1/2" o.d. pipe damping tests.

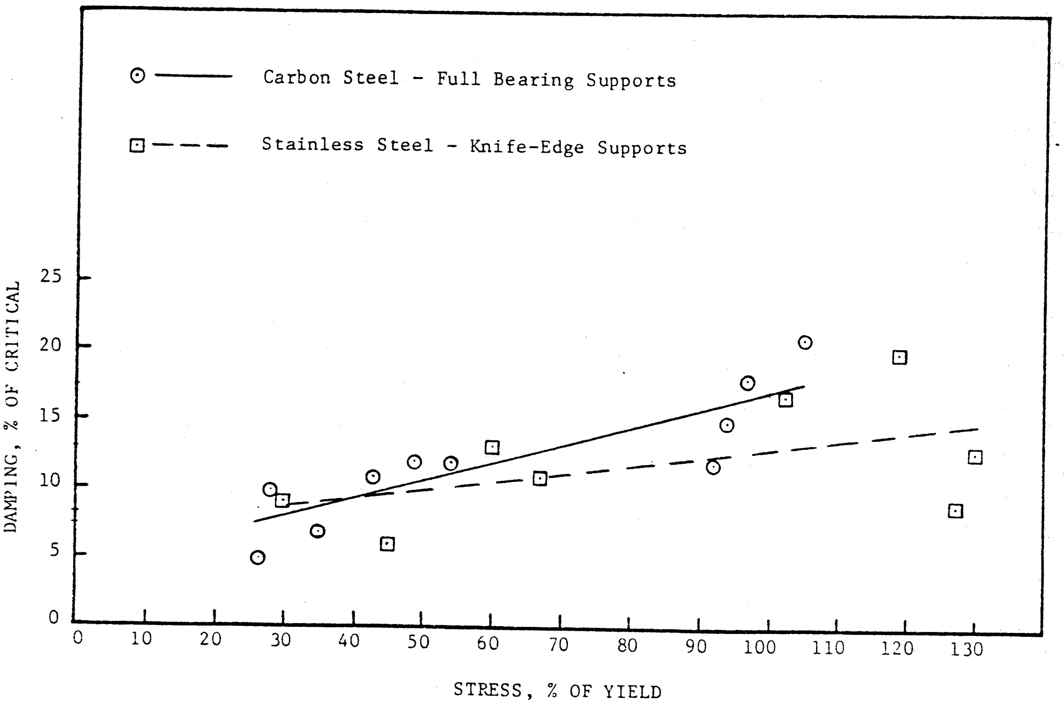

Fig. B.8. Results of simply-supported 1/2″ o.d. pipe damping tests.

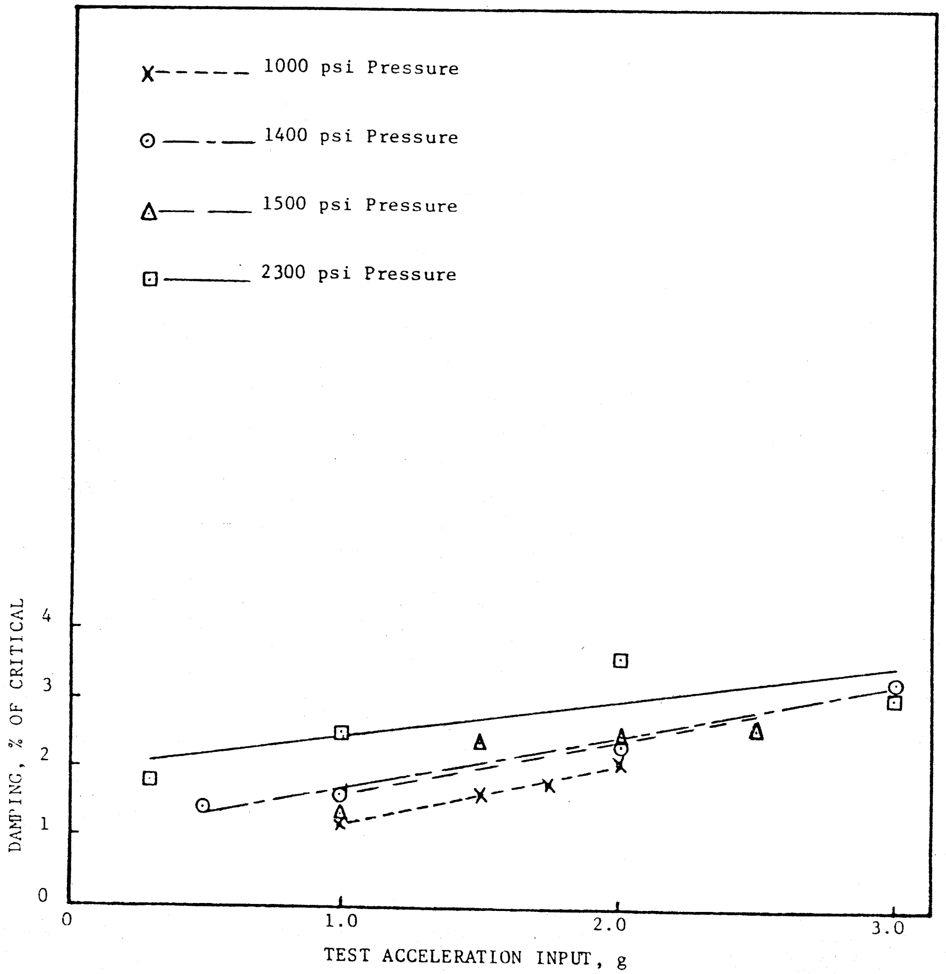

Fig. B.9. Partial results of 2″ o.d. pipe damping tests.

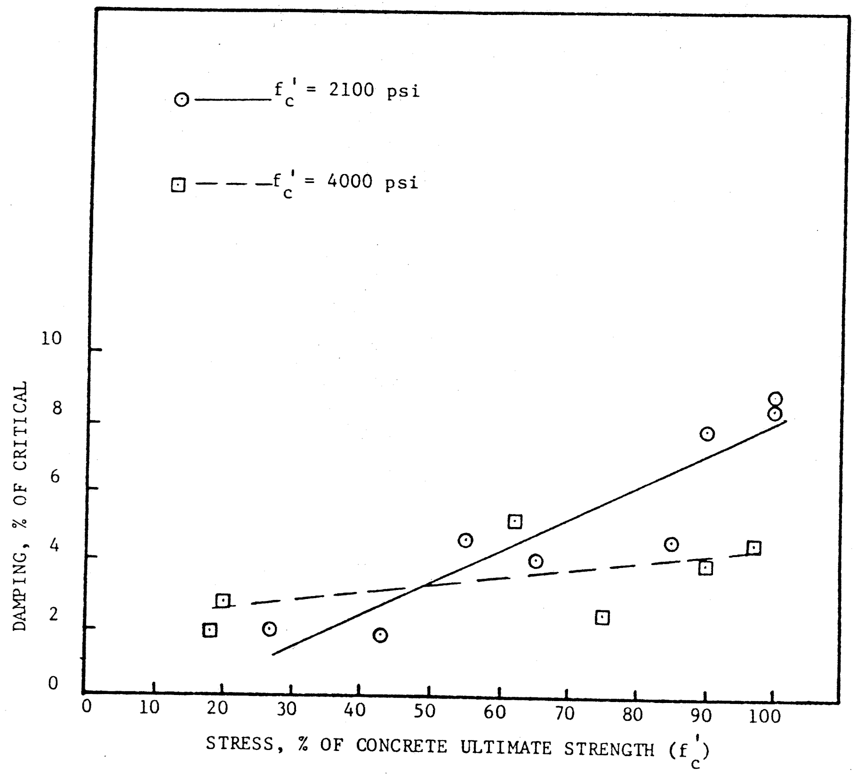

Fig. B.10. Results of reinforced concrete beams damping tests.

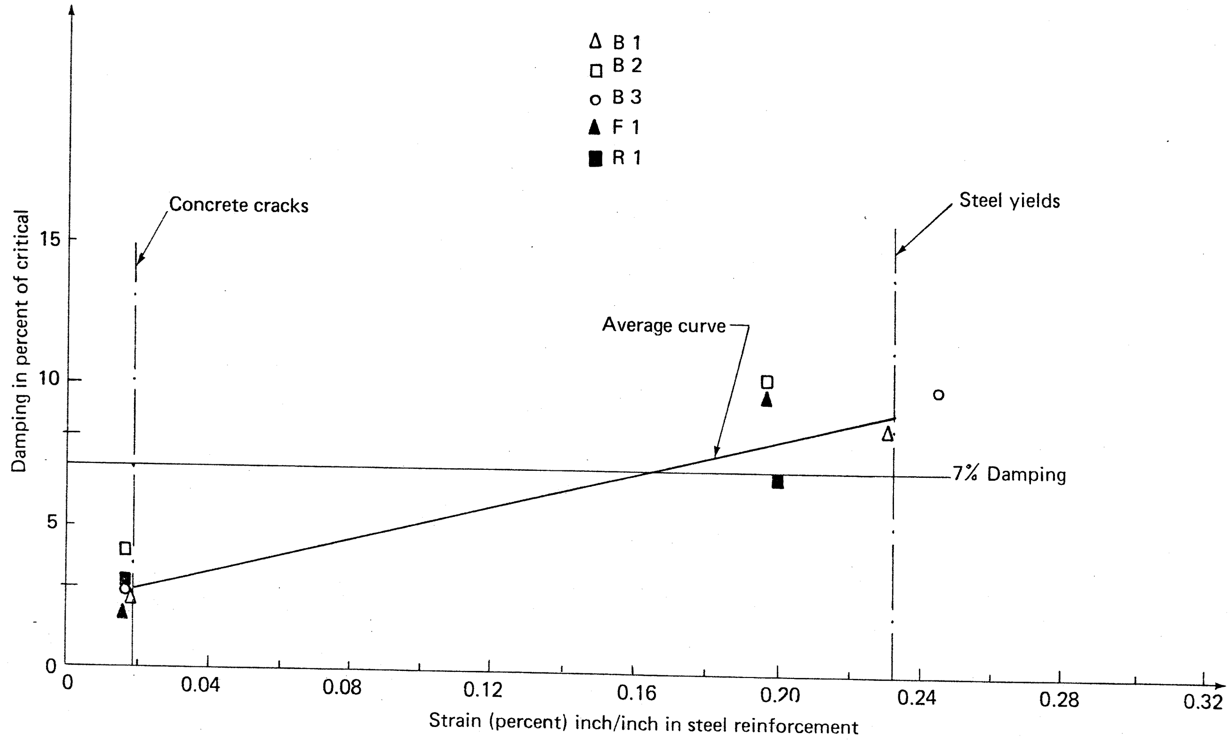

Fig. B.11.

Table B.2
Slope of percent critical damping trends as a function of loads levels

Description	Slope percent damping increase [b]	Reference
A. Heat exchanger		
1. IPP unit 2^W steam generator radial modes	23.0	Fig. B.1. (ref. [6])
2. IPP unit 2^W steam generator tangential modes	21.0	Fig. B.2. (ref. [6])
3. EGCR steam generator N–S modes	4.5	Fig. B.5. (ref. [33])
4. EGCR steam generator E–W modes	8.0	Fig. B.5. (ref. [33])
5. 2 Loop PWR steam generator radial direction	3.5	Fig. B.6. (ref. [24])
6. 2 Loop PWR steam generator tangential direction	26.0	Fig. B.6. (ref. [24])
7. 3 Loop PWR steam generator tangential direction	3.5	Fig. B.6. (ref. [24])
8. 3 Loop PWR steam generator radial direction	9.0	Fig. B.6. (ref. [24])
Sample size $n = 8$; sample mean $(\overline{x}) = 12.3$; Sample standard deviation $(s) = 9.4$		
B. Pump		
1. IPP unit No. 2 reactor coolant pump	15.0	Fig. B.1. (ref. [6])
Summary of A and B sample mean $(\overline{x}) = 12.6$		
C. Piping		
1. IPP unit No. 2 cross over leg	24.0	Fig. B.4. (ref. [22])
2. 0.5 in carbon steel simply supported pipe [a]	250.0	Fig. B.8. (ref. [22])
3. 0.5 in stainless steel simply supported pipe [a]	125.0	Fig. B.6. (ref. [22])
4. 2.0 in simply supported pipe – 1400 psi internal pres.	46.0	Fig. B.9. (ref. [22])
5. 2.0 in simply supported pipe – 2300 psi internal pres.	33.0	Fig. B.9. (ref. [22])
D. Containment		
1. ECGR containment N–S	41.0	Fig. B.5. (ref. [33])
2. ECGR containment E–W	12.0	Fig. B.5. (ref. [33])
E. Concrete beam		
1. Beam $f'_c = 2100$ psi [a]	180.0	Fig. B.10. (ref. [22])
2. Beam $f'_c = 4000$ psi	50.0	Fig. B.10. (ref. [22])
3. Shear walls	40.0	Fig. B.11. (ref. [25])

[a] Excluded from sample statistics since individual statistic is not representative of nuclear plant components of interest.
[b] Slope is measured as percent increase in damping for each doubling of load (stress, strain, deformation) level.

Table B.3
Summary of statistics for histograms of damping determinations – for building (ref. [27])

Structural type	Amplitude small					Amplitude large					Amplitude all				
	n	$\overline{x}$	s^2	s	C.O.V.	n	$\overline{x}$	s^2	s	C.O.V.	n	$\overline{x}$	s^2	s	C.O.V.
Reinforced concrete	104	4.26	10.49	3.23	0.76	17	6.63	17.99	4.24	0.64	121	4.60	12.06	3.47	0.76
Steel	41	1.68	1.18	1.08	0.65	12	5.65	6.47	2.54	0.45	53	2.58	5.09	2.26	0.87
Composite construction	47	2.72	1.31	1.14	0.42	23	3.23	3.08	1.76	0.54	70	2.89	1.91	1.38	0.48
All	192	3.33	7.36	2.71	0.81	52	4.91	10.71	3.27	0.67	244	3.67	8.45	2.01	0.79

For piping and concrete the mean increase is damping for each doubling of input loading is 33.4 and 45.0 percent respectively. The formulation of damping values as a function of deformation, stress or strain is as follows.

$$\beta_{\sigma_x} = \beta_{\sigma_a}\{1 + K_i\,(x - a)/a\}\,, \quad 0.10\,f_y < \sigma_x < 1.2\,f_y\,, \qquad \text{(B.1)}$$

where

β_{σ_x} = Best estimate or mean percent critical damping at stress level x,

β_{σ_a} = Best estimate or mean percent critical damping from table B.1 test data stress levels,
a = 10% of yield stress for steel components and piping,
a = 25% of yield stress for concrete,

K_i = Slope of damping trend curve increase of damping with every doubling of load level from table B.2, K_1 = 0.126 for steel components, K_2 = 0.343 for large piping, K_3 = 0.450 for concrete,

x = Percent of yield stress,

In table 7 can be found a summary comparison of damping values developed from eq. B.1 with various stress levels compared to Regulatory Guide 1.61 requirements and the recommendation of Newmark and Hall [7].

While not directly applicable to this study, for comparison purposes a statistical summary of damping values and their variability for concrete, steel and composite building structures is present in table B.3 [27].

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