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THE EFFECT OF PLASTIC BEHAVIOR ON DAMPING IN PIPING SYSTEMS[a]

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ABSTRACT

Due to energy dissipated by plastic action, the equivalent damping that must be used in stress analyses to predict moments and stresses is much higher than damping for elastic response. High strain damping data from eight different sources were plotted on a common basis as a function of ductility to estimate damping levels at system failure. At the strain levels when systems fail, equivalent damping values are estimated to be 30 to 50% of critical. This results in a response margin of actual input acceleration to linear elastic computed acceleration (using 5% of critical damping) of from 2.5 to 3 for seismic excitations and from 6 to 10 for sinusoidal excitations.

INTRODUCTION

The Idaho National Engineering Laboratory (INEL) has been conducting a research program to assist the United States Nuclear Regulatory Commission (USNRC) to determine best-estimate damping values for use in the design and analysis of nuclear piping systems (Ware and Arendts, 1985, and Ware, 1987a). In addition to the damping at elastic stress levels, it is desirable to know the damping at response levels where the pipe is undergoing plastic deformation, to assess the safety margins inherent in the design process.

Although the linear elastic concept of damping is not strictly defined for elastoplastic piping system vibrations, an equivalent damping is used to estimate the response margins in predicted piping system behavior. The equivalent damping concept is based on the computed linear damping that would cause amplifications of an elastic system to match the available experimental data. A simplified theoretical explanation and test results of high excitation level tests from eight sources were correlated on common bases to describe damping at high strain levels (Ware, 1987b,c).

ANALYTICAL DEVELOPMENT

Traditionally, ductility has been a measure of the strain to fracture of a tensile specimen of a material. The measure of ductility has been the percent elongation or the reduction of area of the material. This concept is a measure of the <u>local</u> plastic strain, or a <u>local</u> ductility. More recently, a term called the allowable ductility has been introduced and defined as the ratio of the allowable displacement (x_m) to the effective elastic

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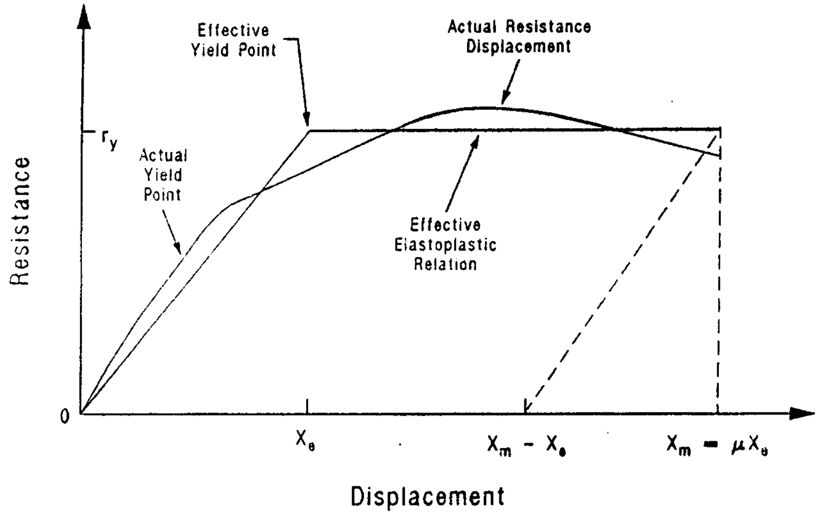

Figure 1. Resistance-displacement curve.

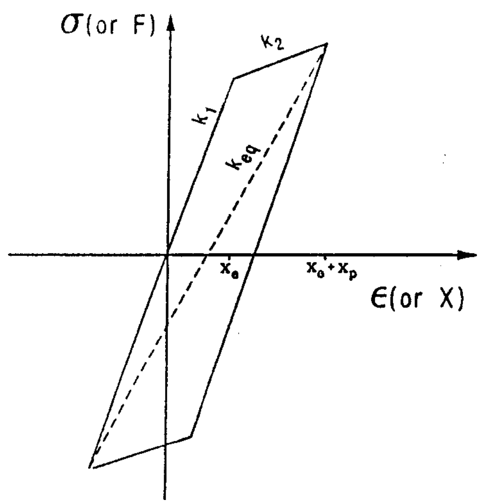

Figure 2. Bilinear force-displacement (or stress-strain) curve.

displacement (x_e) (see Figure 1).

$$\mu = x_m / x_e \quad (1)$$

This concept is that of a <u>system</u> ductility, as it uses the overall system displacement, rather than the local strain. The effective yield point is found by extending the initial elastic deformation line to its intersection with the limit or collapse load line. In this paper the term ductility will be defined as the ratio of the total displacement to the elastic displacement.

<u>Damping and Frequency Shift with Ductility</u>

Damping is proportional to the energy loss per vibration cycle and can be expressed mathematically (Thompson, 1981) as:

$$c = E_d / (4 \pi E_t) \quad (2)$$

where E_d and E_t are the energy dissipated per cycle and the total system energy, respectively. The bilinear stress-strain curve shown in Figure 2 will

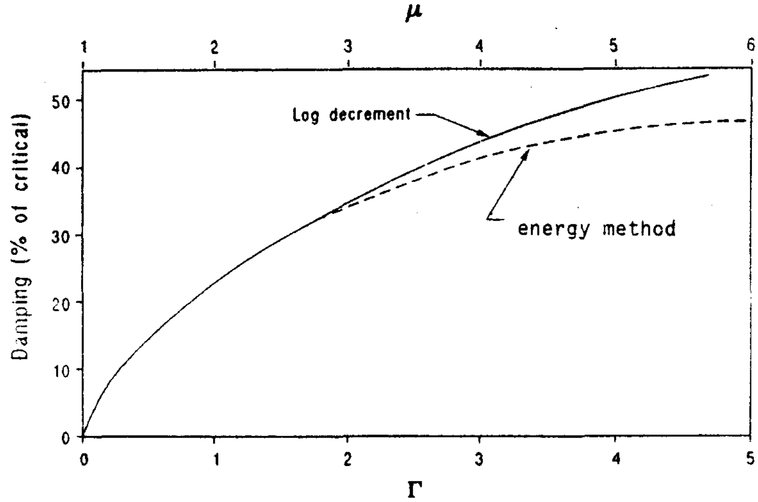

Figure 3. Plastic damping.

be used to approximate plastic damping. The effective linear stiffnesses of the resistance-displacement curve of Figure 1 are denoted by k_1 and k_2 in Figure 2. This simplification does not account for the pipe shape, nor the plastic zones that would develop. It is assumed that the tensile and compressive yield strengths are equal from repeated cycling. The equivalent linear stiffness k_{eq} can be expressed as:

$$k_{eq} = 2\ (k_1 + \Gamma k_2) \ /\ [2 + (1 + \beta)\Gamma] \qquad (3)$$

where $\Gamma = x_p / x_e = \mu - 1$, and $\beta = k_2 / k_1$.

Applying Equation 2, the plastic damping is (Ware, 1987b):

$$c = \Gamma(1 - \beta)(2 + \beta\Gamma) \ /\ \{\pi(1 + \beta\Gamma)[2 + (1 + \beta)\Gamma]\} \qquad (4)$$

For an elastic-perfectly-plastic material, $k_2 = 0$ and $\beta = 0$:

$$c = 2\Gamma / \{\pi(2 + \Gamma)] \qquad (5)$$

Damping by the logarithmic decrement method is based on the ratio of the amplitude of successive cycles follows:

$$c = 1 / (2\pi m) \ln (x_n / x_{n+m}) \qquad (6)$$

For the case of the first two successive half-cycles in the vibrational decay for an elastic-perfectly-plastic system, the damping is

$$c = \ln(\mu) / \pi \qquad (7)$$

Damping versus ductility based on the logarithmic decrement and energy methods are plotted in Figure 3 for an elastic-perfectly-plastic material.

Not only will there be a damping change, but there will also be a frequency shift due to the system softening as ductility increases. This can also be described in an approximate manner by considering the elastic stress-strain curve in Figure 1. The elastic natural frequency is $\Omega = [k_1 / M]^{1/2}$. In the plastic range the frequency can be approximated by the elastic frequency, so the ratio of the plastic to elastic frequency can be approximated by Equation 8. Representative plots are shown in Figure 4.

$$\Omega_p/\Omega = (k_{eq} / k_1)^{1/2} = \{2\ (1 + \beta\Gamma) \ /\ [2 + \Gamma(1 + \beta)]\}^{1/2} \qquad (8)$$

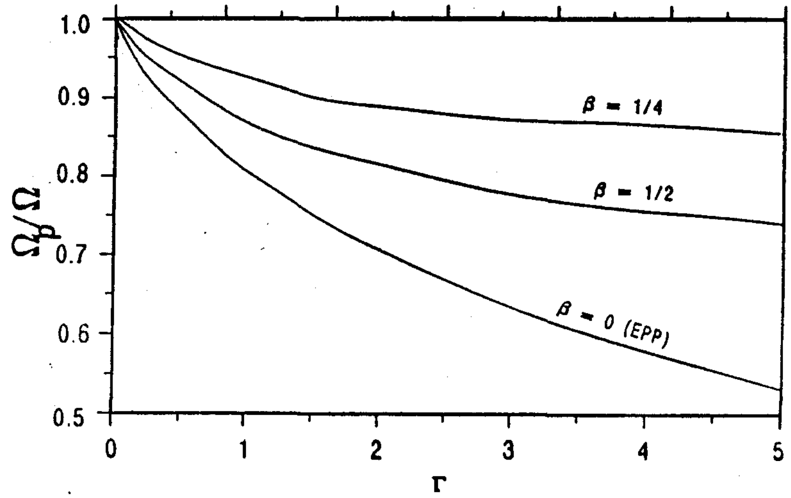

Figure 4. Frequency shift due to ductility.

TEST DATA

The vibrational behavior of piping systems at high strains has been characterized by limited testing until the past few years. Data from eight test sources were gathered and evaluated (Ware, 1987b,c): straight piping systems tested by Westinghouse Electric Corporation, the INEL, the University of Akron, and the Central Electricity Generating Board (United Kingdom); and systems with bends and elbows tested by Kraftwerk Union (KWU), GE (preliminary results), and the Hanford Engineering Development Laboratory (HEDL). A summary is presented in Table 1.

The test results were normalized to start at zero damping at a ductility of 1 and are plotted in Figure 5. The theoretically derived curve based on energy dissipation by a fully plastic section appears to give an upper bound to the data. Data for straight piping systems generally follow the theoretical curve which was based on the straight section becoming fully plastic once yield strength was reached. Systems with bends or elbows that have a stress

TABLE 1. CHARACTERIZATIONS OF PIPING SYSTEMS WITH HIGH STRAIN DATA

ORGANIZATION	SYSTEM	DIAMETER (IN)	LME[a]
Westinghouse	test	1/2	no
INEL	3-in	3	no
	8-in	8	no
	5-in	5	no
U of Akron	test	1 1/2	no
CEGB	test	1	no
KWU	several	0.4 to 2.4	yes
GE/ETEC	system 1	6	yes
HEDL	liquid metal	1	yes
GE/ANCO	component	6	no

a. LME is the presence of line-mounted (or on-line) equipment.

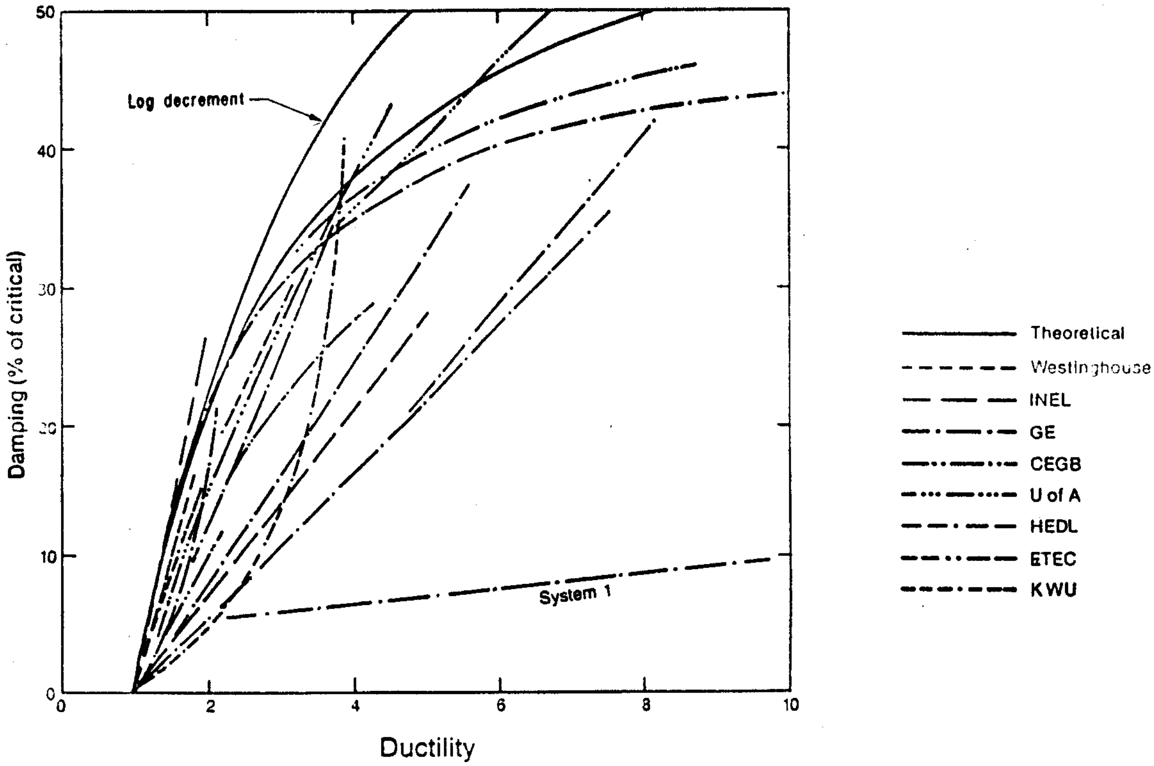

Figure 5. High strain level damping from tests.

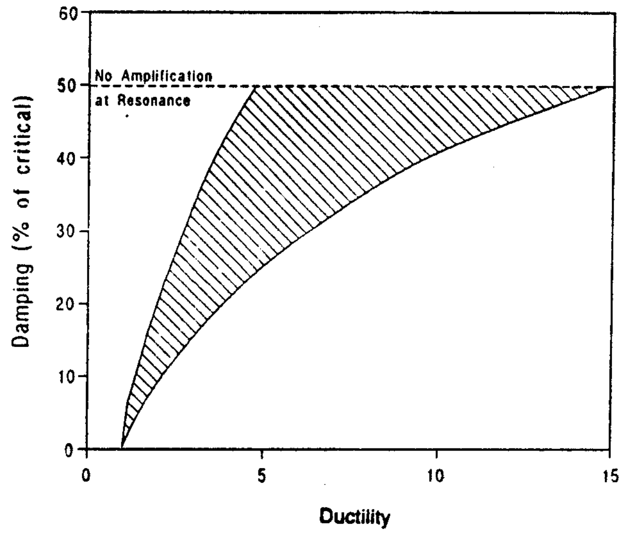

Figure 6. High strain level damping estimate.

concentration such that the full piping cross-section is not fully plastic, and for which the maximum reported strain is highly localized, have lower damping values. Similarly, for thinner pipe walls (lower schedule pipe) in which localized thinning may occur, the damping is reported to be lower by GE. While the GE component test results seem to be in line with the previous data, the system 1 damping reported is substantially less than all the other data. In this test the damping was only 10% of critical at a measured strain of 1% (10,000 micro in./in.).

Figure 6 shows the expected range of damping at high strain levels. The left edge of the shaded area represents a straight pipe section becoming fully plastic and is based on both a theoretical prediction and actual test results. The right limit of the shaded area is appropriate for a bend or elbow where the section does not become fully plastic. It conforms to a bilinear force/displacement curve as shown in Figure 3. The shaded area includes all the data except for the GE system 1 results.

Based on using 5% of critical damping with linear elastic analysis, the test data indicates a minimum acceleration response margin of 2.5 for seismic events and 6 to 10 for harmonic motion. ASME Code Case N-411 damping is appropriate for levels of damping around the yield strain, even for simple piping systems with little or no support-induced damping. At a ductility level of 2, the damping would be 10% of critical or greater, and at a ductility of 5 would be 25% or greater.

CONCLUSIONS

Damping has been shown to increases at higher ductilities using two theoretical concepts. The increase depends on changes in the system stiffness during plastic motion. During this time there will be a progressive decrease in system frequency. Test data for straight pipes tend to follow the theoretical curves, while the damping is lower for systems with bends and elbows. Based on test data for systems at failure, ASME Code Case N-411 has a minimum response margin of 2.5.

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