REVIEW OF STRUCTURAL DAMPING MECHANISMS

by

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I. INTRODUCTION

The term damping, as used in this paper, defines the energy dissipation properties of a material or system under cyclic stress. In most cases, a direct conversion of mechanical energy to heat is involved. This definition specifically excludes such energy transfer devices as dynamic absorbers or so-called dynamic "dampers."

As mentioned in the introductory remarks, the damping properties of a structural configuration may greatly affect the stress induced in the structure excited at resonance, either by periodic or random forces. The exciting force on a structural system with low damping may be greatly amplified by resonance, thus leading to fatigue inducing conditions as discussed in another paper. If, therefore, resonant vibrations are likely to be present, it is generally highly desirable to design high damping into the structural system. The purpose of this paper is to discuss the various mechanisms and approaches which can be utilized to increase (a) the damping inherent in a structural system and (b) the damping added to a structural part by various types of surface treatments.

Damping may be classified in various ways. For convenience, in this paper damping is broken down into two major headings which shall be identified as (a) material damping and (b) system damping.

Material damping, sometimes called internal friction, integral damping, or hysteretic damping, is related to the energy dissipation in a volume of macro-continuous media. System damping, by contrast, involves configurations of distinguishable parts or the interaction among various phenomena. Among the types of systems in which damping under cyclic stress may be important are: (a) structural systems involving various types of joints, interfaces, or fasteners; (b) electro-mechanical systems involving interactions between electrical or electromagnetic phenomena and physical bodies, for example, magnetic hysteresis and eddy currents; and (c) hydro-mechanical and acoustical systems involving fluid flow, for example, acoustical damping and radiation, oil flow through orifices, and dash-pot effects.

This paper is concerned primarily with the various damping mechanisms inherent in a structure and further reference will not be made to electro-mechanical, hydro-mechanical, or acoustical damping (discussed by Dr. Kerwin in his paper). The emphasis on this paper is on what may be defined as inherent structural damping:- that built into the structure.

One important mechanism in structural damping is hysteretic effects within the material of which the structure is fabricated. Thus, the damping properties of structural materials are discussed first.

II. MATERIAL DAMPING

Materials are not perfectly elastic even at very low stress levels. Inelasticity in materials manifests itself in a variety of different ways. Under cyclic stress, for example, inelastic behavior will result in the dissipation of damping energy. Under these circumstances, stress-strain hysteretic loops, such as that illustrated in Figure 1, will be formed.

Many different types of inelastic mechanisms and hysteretic phenomena have been identified (1). For purposes of this paper, the damping classification given in Table I seems most appropriate.

Referring to the main heading of Table I, the various damping phenomena and mechanisms may be identified under two main headings: "dynamic hysteresis" and "static hysteresis." Dynamic hysteresis is discussed first.

Many aspects of dynamic hysteresis, sometimes identified as viscoelastic, rheological, and rate-dependent hysteresis, have been studied during the past two decades. All of these terms refer to the properties of a material having an essentially linear stress-strain law which is describable by a differential equation containing stress, strain, and time derivatives of stress or strain. This differential equation need not be linear. Furthermore, it can include terms which allow for permanent set in the material, such as OB after cycle OAB in Figure 1.

One important type of dynamic hysteresis, a special case which Zener (2) has labeled "anelasticity", does not include allowances for permanent set after a long time. This means that if the load is suddenly removed at point B in Figure 1, after cycle OAB, strain OB will gradually reduce to zero as the specimen recovers (or creeps negatively) from point B to point O.

The terms anelasticity and internal friction (damping in anelastic materials) has been reasonably well accepted by physical metallurgists for over a decade. However, the more general types of damping, identified here as viscoelastic and rheological hysteresis, do not have a well-accepted name. This type of damping is discussed by Dr. Oberst in his paper.

A distinguishing characteristic of internal friction and the more general case of viscoelastic damping is its dependence on time derivative effects. Thus, the hysteresis loops tend to be elliptical in shape rather than pointed as in Figure 1. Furthermore, the loop area is definitely related to the dynamic or cyclic nature of the loading and the area of the loop is dependent on frequency. In fact, the stress-strain curve, for an ideally viscoelastic material becomes a single value curve (no hysteretic loop) if the cyclic stress is applied slowly enough to allow the material to be in complete equilibrium at all times (oscillation period very much longer than relaxation times). Thus, no hysteretic damping is produced by these mechanisms if the material is subjected to essentially static loading. Stated differently, the static hysteresis is zero.

"Static hysteresis", in contrast with dynamic hysteresis, involves stress-strain laws which are insensitive to time, strain rate, stress rate, or other derivatives. Thus, in a material in which static hysteresis dominates (dynamic hysteresis, if present, is insignificantly small) the value of strain in attained almost instantly for each value of stress and prior stress history (direction of loading, amplitudes, etc.), independent of loading rate. Under cyclic loading, pointed loops similar to Figure 1 are formed and if the stress is reduced to zero (point B) after cycle OAB, then OB remains as a permanent set or residual deformation. Furthermore, the shape of the hysteretic loop is independent of frequency.

The two principal mechanisms which lead to static hysteresis are magnetostriction and plastic strain as shown in Table I. Also shown are the simplest representative mechanical models for each of the behaviors classified. In these models S is a spring having linear elasticity (linear and single-valued stress-strain curve), D is a linear dash-pot which produces a resisting force proportional to velocity, and C is a coulomb friction unit which produces a constant force whenever slip occurs within the unit, the direction of the force being opposite to the direction of motion. More sophisticated models have been found to predict reliably the behavior of some materials (2), particularly polymeric materials (3).

The various inelastic mechanisms with each of the above classifications have been discussed in prior publications (1) and will not be reviewed here. However, in order to facilitate comparisons to be made later with other structural damping mechanisms, it is desirable to indicate magnitudes of damping which can be expected from hysteretic effects in materials. Such data are given in the bottom half of Table I, the units used being defined below:

σ_d = induced stress in material; psi

D_d = specific damping energy at induced stress σ_d, in - lbs per cu - in per cycle (see Reference (1))

E = modulus of elasticity

η = loss factor = $ED/\pi\sigma_d^2$

σ_e = fatigue strength of material, psi

σ_L = a limiting stress approximately 80% of σ_e; psi

Various criteria for comparing the damping properties of material have been used (4,5). It has been shown that a convenient and significant method for comparing the damping properties of structural materials is to plot damping energy D_d versus ratio of induced stress to fatigue strength (ratio σ_d/σ_e). Such a plot is shown in Figure 2 for a variety of common structural materials. For the large group of structural materials which were not particularly selected for high damping (excludes materials having large magnetoelastic or plastic strain damping) and for a variety of test conditions, the data lie within a fairly well established band shown in Figure 2. The approximate "geometric" mean curve is shown as the dot-dash in Figure 2. Even though this is a two segment line, it can be defined with sufficient accuracy by the following single equation:

$$D = (\sigma_d/\sigma_e)^{2.3} + 6\,(\sigma_d/\sigma_e)^{8} \qquad \text{Equation (1)}$$

Also shown in Figure 2 for comparison purposes are four materials having especially high damping. Materials 1 and 2 are the magnetoelastic alloys Nivco 10 and 403 alloy. Nivco 10 retains its high damping up to the stresses shown (data not available at higher stresses). However, the 403 alloy reaches its magnetoelastic peak at a stress ratio of approximately 0.2 and increases less rapidly beyond this point, up until plastic strain damping becomes dominant (at stress ratio of approximately 0.8), beyond which damping increases very rapidly. By contrast, material 3, a manganese copper alloy with large plastic-strain damping, retains its high damping up to and beyond its fatigue strength. Material 4 is a 'typical' viscoelastic adhesive (3M tape No. 466) for which a cyclic shear strain of unity is assumed to lie within the fatigue strength (experiments show that a shear strain well above unity does not cause deterioriation in the adhesive even after millions of cycles). Dr. Oberst will discuss damping in viscoelastic materials in greater detail in his paper.

Since these damping data are plotted to a logarithmic scale, the superiority of the high damping materials is not dramatically revealed by Figure 2. However, Nivco 10, for example, has a damping thirty times as large as the average structural material in the stress range shown in Figure 2, and the damping of viscoelastic materials is over ten times that of Nivco. These observations on viscoelastic adhesives will be discussed further later.

III. DAMPING AT STRUCTURAL INTERFACES

In order to clarify the various types of damping inherent in a structural configuration, it is desirable to ask the following question: Beyond the damping energy dissipated internally by the materials of which the structural members are made, what is the principal mechanism by which structural joints dissipate energy? The unique characteristic of a joint, insofar as damping is concerned, is its interfaces or mating surfaces which are maintained in contact. Thus, it is the damping associated with various interface effects that should receive close scrutiny.

For purposes of this paper, two types of interfaces shall be identified: (a) a dry or lubricated contact surface (metal-to-metal contact, or metal-to-liner-to-metal contact; or (b) an adhesive type interface (metal-to-adhesive-to-metal joint).

Next, let us consider the simple types of relative motions which can take place between mating surfaces at an interface to produce damping effects. A review of the general behavior of typical joints in typical load environments indicates that two types of relative motion should be considered: (a) a separation of mating surfaces (motions perpendicular to the interface); and (b) interface shear effects (relative motions of mating members in the plane of the interface). These types of motions may be illustrated by referring to the top of Figure 3, which shows a double cantilever beam (A and B) in contact along its common surface or interface and fixed at its left end. Under exciting force $F_g \sin \omega t$ beams A and B may either: (a) separate at the common interface leaving a gap of cyclically varying width; or (b) slide relative to each other as illustrated by "S" in top right figure. Of these two types of motions, the one which appears to offer the greater potential for dissipating energy safely is relative shear at the interface.

Reasonably general equations for slip damping have been developed recently (6). However, since the purpose of this paper is to convey general damping concepts for engineering guidance, only one special case shall be considered to illustrate the important parameters.

The case to be discussed is the bileaf cantilever beam AB under uniform pressure P as shown in Figure 3. At very small values of exciting force F_g (or at very large interface pressures), the friction between beams A and B is sufficient to prohibit slip, and the bileaf behaves as though A and B were one solid beam without an interface. However, if the exciting force is increased (or if pressure P is reduced) slip will occur causing an offset at the end of the beams labeled S. Under cyclic exciting force, slip S at the end of the beam and also along the entire interface will also be cyclic and provide a mechanism for dissipating damping energy. This energy is a function of both the slip and shear stress at the interface. Under large pressure P the shear stress is large but slip small; whereas under small pressure P the shear stress is small but the slip is large. Since damping energy depends on a product of shear stress function and a slip function, maximum damping will occur at some intermediate or optimum pressure. The equation for defining the damping energy dissipation associated with this interface slip has been developed and is plotted in Figure 3b for one special joint considered theoretically and experimentally. This figure shows the total damping D_o^s due to interface slip only as a function of interface pressure P and ratio of induced stress σ_d in the beam to its fatigue strength σ_e. The maximization of damping at an optimum pressure of 80 psi is clearly shown in this figure. Another feature of this figure (to be contrasted later with material damping) is that the damping does not change abruptly with stress.

The relative magnitudes of slip and material damping cannot generally be compared directly due to the basic differences in the mechanisms involved. The material damping in a part depends not only on its material composition and constitution but also on stress amplitude, the volume-stress function of the part, and other factors discussed in prior publications (5). Slip damping at an interface depends on another set of parameters, which include the coefficient of friction, pressure, shear stress, and strain distribution. Furthermore, material damping occurs throughout the volume of a part (a volume integral), whereas slip damping occurs at an interface surface only (a surface integral). Thus, the two types of damping are not directly comparable. Parts and joints can easily be conceived in which either slip or material damping will dominate. Nevertheless, in order to clarify the important parameters in damping, it is desirable to make simplified comparisons between material and slip damping. In these comparisons only two important parameters shall be considered, interface pressure and maximum stress. Other factors such as member geometry, coefficient of friction, and types of vibration are held constant.

For comparison purposes, material damping for the same beam assembly, computed for a "representative" material defined by Equation (1) (also see Figure 2) is shown in Figure 3a . The main features this figure has are: (a) damping increases rather abruptly at a stress in the vicinity of the fatigue limit; and (b) interface pressure does not significantly affect material damping.

Both material and slip damping are plotted in Figure 3c with the line OAD indicating the intersection between the two surfaces. The projection of this line on the basal plane OA'D indicates the combinations of stress and pressure in which each type of damping dominates; in region S at near optimum pressure and at intermediate stress the slip damping is the larger, whereas in region M at extremely high or low pressure or at high stress the material damping dominates.

Mr. Mead will discuss further some of the practical implications of slip damping in his paper.

Dry slip can provide an effective mechanism for dissipating energy. It is generally found, however, that a design optimized for maximum dry slip damping may sometimes develop serious fretting and corrosion effects in the interface regions subjected to large cyclic slip. Such interface surface deterioration may not only cause the joint to drift from optimum conditions but may also initiate fatigue cracks, the very thing that high damping in a system exposed to resonant vibration is intended to mitigate. In short, the cure may lead to a condition worse than the original disease.

In view of this difficulty with dry interface slip, consideration was given to the possibility of lubricated interfaces (7) and inserts of plastic and other types of "non-fretting" materials at interfaces (8). However, it was still difficult to avoid fretting and maintain optimum conditions for maximum damping in practical joints which dissipate large damping. This led to the consideration of an adhesive type interface of sufficient thickness to permit the relative shear motions between metal surfaces to be absorbed as shear strain within the adhesive itself (no relative motion between adhesive and the metal adherents). This is the principle of sound deadening tape, which has been in use for about a decade (9). However, there was, until recently, very little interest in the utilization of adhesive damping in structural joints. The potential contribution of this approach became more apparent recently when it was found that the damping capacity of viscoelastic adhesives (as a material) in shear is very large (10), as discussed by Dr. Oberst in his paper. Furthermore, it was also found that viscoelastic adhesives can withstand very large cyclic shear strain without deterioration (10). This combination indicates that a properly optimized adhesive joint (thickness, for example, adjusted properly in accordance with its stiffness and other properties) can dissipate very large damping energy. Furthermore, this damping mechanism not only avoids corrosion and fretting problems but also simplifies the problem of maintaining optimum conditions during service. This damping mechanism and its use and optimization in systems or configurations is discussed by Dr. Mentel in his paper.

IV. SURFACE ADDITION APPROACHES

So far we have considered only inherent structural damping:- that built into the structure. This approach is characterized by "design optimization" to suggest the proper proportions and materials for a configuration which must have high damping. However, in practice it is usually difficult to change an existing design. Yet there is often room to add a surface treatment to increase the damping of a member which otherwise cannot be changed radically. Examples of such a "surface addition" approach are damping coatings, damping tapes, spacing layers, sandwich additions, and other types of layered construction (9). Various types of surface additions have been tried in the past. Three of the more important types are described below.

One of the earliest approaches for increasing the damping of panels is to add a thick layer of viscoelastic or similar type of material (identified by heavy cross-hatching in Figure 4) to a panel. As the panel is subjected to cyclic bending deflections ± d, cyclic direct strain (tension-compression) is developed in the viscoelastic layer, as shown in Figure 4 by the difference in the lengths of line A' B' (>A B) and A"B" (<A B). Although reasonably satisfactory in some types of panel noise problems, this approach for increasing damping is sometimes inefficient since the cyclic strain in the viscoelastic coating is usually small and only a small percentage of the damping capacity of the viscoelastic layer is utilized. Dr. Oberst will discuss this further in his paper.

A second "conventional" surface addition approach for increasing damping involves the addition of so-called "sound damping tape." This is a configuration shown schematically in Figure 5, consisting of a thin layer "A" of viscoelastic adhesive (thickness exaggerated in figure for clarity) and a backing band of tape "T", usually aluminum or some other metal. The mechanism of energy dissipation in this case is one of shear in the viscoelastic layer as shown schematically by the distortions in the cross-hatch bands. As the beam flexes, the viscoelastic layer, located well above the neutral axis and restrained by the backing tape, receives a cyclic shear, as shown in the figure, and thus dissipates energy. However, as in the case of the viscoelastic coating shown in Figure 4, only a very small percentage of the damping which the viscoelastic layer is capable of dissipating can generally be realized. For most thin beams or panels, the distance between the neutral axis of bending and the plane of the viscoelastic adhesive is so small that the cyclic shear strain imposed on the adhesive is well below its limits; thus, the energy dissipation is also well below the capacity of the adhesive.

An improvement on the damping tape method shown in Figure 5 involves a spacing layer (9,11) shown in Figure 6a. This spacer locates the viscoelastic layer further from the neutral axis and thus increases the cyclic shear associated with a given cyclic flexing. Theoretically, the damping energy which can be dissipated by the adhesive shear mechanism can be greatly increased by such a spacing layer. However, there are some practical limitations. In order to be effective, the spacing layer must be reasonably thick. Furthermore, most applications require a low density material to avoid excessive weight and cost. Unfortunately, low density spacing layers, or core materials, have relatively low shear modulus. Thus, as illustrated in Figure 6b , much of the cyclic shear which would otherwise be transmitted to the viscoelastic adhesive may be lost as shear strain in the core material. For a rigid spacing layer (Figure 6a) all the cyclic shear strain γ_o is felt by the adhesive, whereas for a low density spacing layers have relatively low shear modulus (Figure 6b), the available total cyclic shear γ_o is partially dissipated in the core (part γ_c) leaving only part γ_a for the adhesive layer. Thus, as in the previous cases, the adhesive will be subjected to relatively small cyclic shear and the full potential of the viscoelastic adhesive is again not realized.

Other types of surface additions which more effectively utilize the damping potential of an adhesive layer are currently under study.

V. CONCLUDING REMARKS

In the past, either the natural frequency of a system or its exciting frequency could generally be adjusted to avoid resonant conditions. However, this is no longer possible in many types of aero-space vehicles. In particular, many types of random excitation, especially those of acoustical origin, cover such a wide frequency band that resonant vibrations can no longer be avoided.

The design concepts of former years are inadequate to deal with the fatigue problem associated with resonance amplification. Although "beefing-up" a structure for increased strength and stiffness has "fixed" resonance fatigue difficulties in some cases, this approach cannot be considered a long term engineering solution. Not only is the cost and weight penalty large in such an approach, but also it is totally inadequate to meet the problems encountered in many of the newer types of aero-space vehicles. Thus, the greater utilization of structural damping as an engineering property to control resonance is a necessity. Looking to the future, it will still be necessary, of course, to stiffen panels and other configurations by using sandwich and other similar build-ups. However, if the maximization of damping is also considered to be a design objective, in addition to the stiffness increase, then a much larger gain in resonant fatigue strength can be realized than using either criterion alone to the exclusion of the other.

Whereas in the past the damping of a structural assembly was often increased by the addition of separate energy absorption units (dash-pots and the like) or energy transfer devices (dynamic absorbers), this approach no longer provides an engineering solution for many of the newer types of configurations and resonance conditions. Looking to the future, the design concept of <u>optimizing a configuration for maximum inherent structural damping</u> (damping built into the structure itself) must be emphasized.

The experimental and analytical knowledge on the major sources of <u>inherent structural damping</u> (hysteresis in structural materials, interface slip, and interface adhesive shear) have now reached a point where application to structural design is practicable. Interface slip must, however, be used with caution because of the fretting and corrosion it may produce.

The relative importance of hysteresis in the structural materials and interface adhesive shear as damping mechanisms depends on the configuration, how it is optimized, and the force regimes considered. In most cases, however, structural materials are selected and shaped for properties other than large damping, whereas the interface adhesive may be especially selected and the layer thickness optimized for large damping. In such an optimized design, the contribution of interface adhesive shear to the total damping of a structural system can be very significant.

Looking to the future, the greater utilization of interface adhesive shear as a damping mechanism, both in an optimized configuration and in surface addition, should be encouraged.

VI. CLOSURE

The papers which follow discuss some of the more important structural damping mechanisms and their engineering utilization. Dr. Oberst discusses, in his paper, various types of viscoelastic coatings, an area in which he has pioneered. This is followed by an analysis by Dr. Mentel of the damping associated with interface adhesive shear in a structural joint. Finally, Mr. Mead will review some of the experimental observations he has made on actual structural configurations which are characteristic of current aircraft design.

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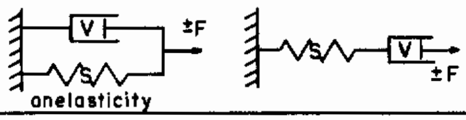
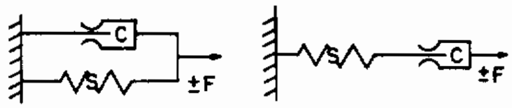
TABLE I CLASSIFICATION OF TYPES OF HYSTERETIC DAMPING OF MATERIALS

	TYPES OF MATERIAL DAMPING		
Name Used Here	DYNAMIC HYSTERESIS	STATIC HYSTERESIS	
Other Names	Viscoelastic, rheological, and rate-dependent hysteresis	Plastic, plastic flow, plastic strain and rate-independent hysteresis	
Nature of Stress-Strain Laws	Essentially linear. Differential equation involving stress, strain, and their time derivatives	Essentially nonlinear, but excludes time derivatives of stress or strain	
Special Cases and Description	<u>Anelasticity</u>. Special because no permanent set after sufficient time. Called "internal friction"		
Simplest Representative Mechanical Model	Voigt unit Maxwell unit 		
Frequency Dependence	Critically at relaxation peaks	No, unless other mechanisms present	
Primary Mechanisms	Solute atoms, grain boundaries. Micro- and macro-thermal and eddy currents. Molecular curling and uncurling in polymers.	Magnetoelasticity	Plastic strain
Value of "n" in $D = JS^n$	2	3 - up to coercive force	2-3 up to σ_L 2 to >30 above σ_L
Variation of η with Stress	No change, since n-2=0	Proportional to σ since n-2=1	Small incr. up to σ_L Large incr. above σ_L
Typical Values for η	Anelasticity: < .001 to .01 Viscoelasticity: < 0.1 to > 1.5	0.01 to 0.08	.001 to .05 up to σ_L .001 to > 0.1 above σ_L
Stress Range of Eng. Importance	Anelasticity - low stress Viscoelasticity - all stresses	Low and medium. Sometimes high	Medium and high stress
Effect of Fatigue Cycles	No effect	No effect	No effect up to σ_L Large changes above σ_L
Effect of Temperature	Critical effects near relaxation peaks	Damping disappears at Curie Temp.	Mixed. Depends on type of comparison
Effect of Static Preload		Large reduction for small coercive force	Either little effect or increase

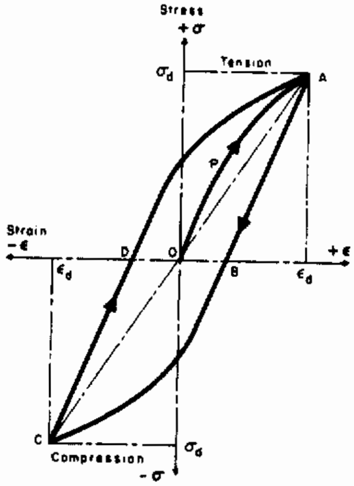


Fig. 1 Typical Stress-Strain Hysteretic Loop for a Material Under Cyclic Stress.

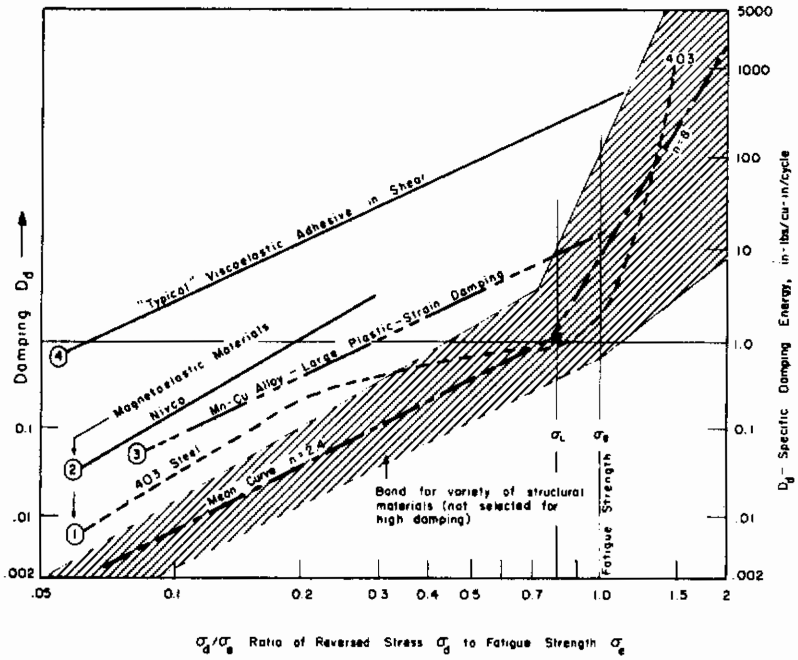


Fig. 2 Range of Damping Properties for a Variety of Structural Materials.

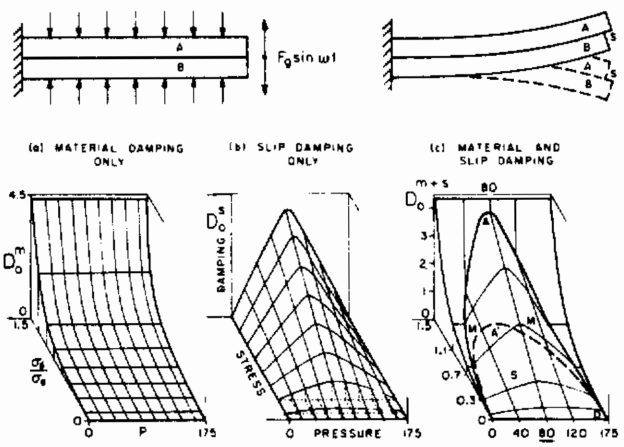


Fig. 3 Material and Slip Damping of a Bileaf Cantilever Beam Under Uniform Interface Pressure.

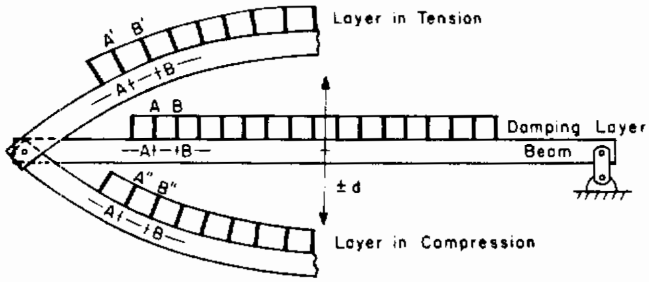


Fig. 4 Viscoelastic Coating Which Dissipates Hysteretic Damping Energy Under Cyclic Direct Stress (Tension - Compression).

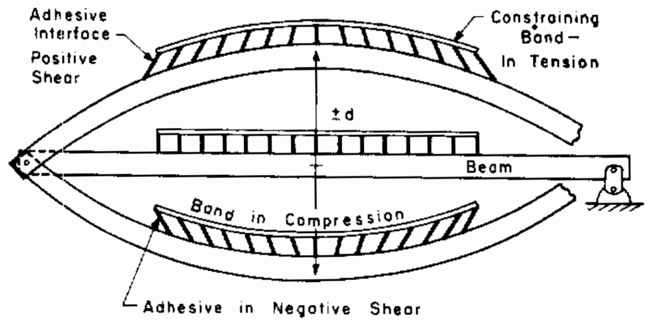


Fig. 5 "Damping Tape" which Dissipates Hysteretic Damping Energy Under Cyclic Shear Strain in Adhesive Between Beam and Constraining Tape.

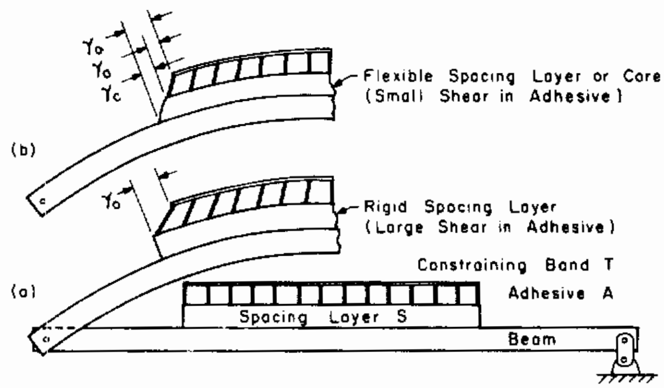


Fig. 6 Damping Tape on Spacing Layer.