TECHNIQUES FOR THE DESIGN OF HIGHLY DAMPED STRUCTURES

F.C. NELSON
Department of Mechanical Engineering,
Tufts University, Medford, Massachusetts 02155, U.S.A.

SUMMARY

In only a few instances does theoretical mechanics provide formulas whereby the damping of a structure can be accurately calculated. If knowledge of the damping is important for proper design, the damping is usually estimated from experience. When the structure is built and tested one takes the damping one gets. It is the purpose of this paper to discuss some ways in which one might design the structure to get the damping one wants. In particular, it will discuss ways in which structures can be designed to have high damping. For broadband excitation, as encountered in the seismic excitation of nuclear reactor structures, resonances can not be avoided and damping plays an important role in determining the dynamic forces imposed on such structures. One would like ways of designing a structure for high damping so that its seismic loading can be reduced.

There are four principal sources of structural damping: the damping inherent in the material, energy dissipation at joints, energy dissipation in the surrounding fluid, and radiation of energy away from the structure. Many engineers mistakenly assume that the damping of a structure is determined by the choice of its material when in fact the inherent damping of the material is usually the least important source. The joints of a built-up structure are usually the controlling factor in determining the structure's damping. This paper will review the various energy dissipation mechanisms associated with the motion of dry interfaces. The paper will then discuss the extent to which lubricates and layers of interfacial material (such as polymer films or metal foils) can be used to increase the damping at joint interfaces.

Certain viscoelastic polymers possess material damping which is much larger than that of metals or concrete. This suggests that if they can be incorporated into the elements which form the structure, the damping of the structure will be significantly increased. An effective way of doing this is to apply layers of high damping polymers to the surfaces of structural elements or to insert polymer layers within the structural elements. Recently these techniques have been successfully used for large scale, low frequency structures. The paper will discuss two examples of the application of this technique to large scale structures: a concrete bridge deck and a metal, frame-type machinery foundation.

While increasing the damping, the use of the above techniques can reduce the stiffness of a structure. To avoid this, a parallel arrangement of components can be used: one component to provide stiffness and the other component to absorb energy. The energy absorption component can operate as a dynamic absorber or a damped absorber. The primary interest of the paper will be on damped absorbers which have been used to augment the structural damping of large structures during seismic events by the plastic deformation of bars or strips of steel. Some mention will be made of the use of multiple, damped dynamic absorbers.

INTRODUCTION

The purpose of this paper is to discuss several techniques for the design of highly damped structures, techniques which have proven successful for large scale, low frequency steel and concrete structures which are typical of nuclear power reactors and their components. The ability to augment structural damping can be useful in increasing the seismic withstandibility of structures. Seismic excitation is broadband in its frequency content and will excite many structural resonances. Broadband damping will limit these resonant responses and thereby reduce the seismic load on structures and their components.

This paper will discuss three techniques: the design of structural joints and interfaces to promote damping; the use of layers of viscoelastic material; and the employment of damping links. The emphasis is on explaining the ways in which these techniques work and in describing the ways in which they have been used. The theoretical details are left to the references.

DAMPING AT JOINTS AND INTERFACES

The damping of a built-up structure is primarily a function of how it is joined together rather than the material from which it is made. Energy dissipation in joints which permit slip, such as a bolted joint, is much larger than that in joints which prevent slip, such as a welded joint, see Fig. 1. Thus if one is trying to design a highly damped structure and if bolted joints are permissible, they are to be preferred.

However, the conscious use of bolted joints to promote damping will often conflict with other structural requirements. As will be shown below, a bolted joint designed for optimum damping will be relatively loose and thus may degrade the stiffness of the structure. Also joint slip produces debris and this may give rise to fretting corrosion. Nevertheless, if a highly damped structure is desired, the high damping potential of a bolted or riveted joint can not be ignored.

When two dry surfaces are compressed they contact one another only at a series of discrete localized regions. Friction is due to the deformation and fracture of these contacting regions. When a cyclic tangential load is applied to an interface compressed by a constant normal force, three types of interaction can be identified.

(1) Cyclic plastic deformation of the contact regions only. There is no relative slip anywhere in the joint. This is an unslipped joint. The energy dissipation is finite but small.

(2) The joint has regions of relative slip and regions of no relative slip. This is a partially slipped joint. As the level of tangential load is increased, the slip regions progress along the interface until the joint is fully slipped.

(3) A fully slipped joint. The magnitude of the friction force (F) in a fully slipped joint can be predicted by Coulomb's law of friction

$$F = \mu N$$

where μ = coefficient of friction for the mating surfaces and N = normal force across the interface.

A fully slipped joint has the greatest potential for damping and will be discussed further. Investigations are available for unslipped joints,[1], and for partially slipped joints, [2], and they will not receive any further attention in this paper.

In a fully slipped joint, the direction of F is opposite to the relative velocity. Hence the damping force will be nonlinear. If the nonlinearity introduced by friction is small, the response to sinusoidal excitation may be assumed to be sinusoidal. Then the equivalent viscous damping coefficient (C_{eq}) is given by

$$C_{eq} = \frac{4\mu N}{\pi \Omega X} \qquad (1)$$

where Ω is the forcing circular frequency and X is the slip amplitude. The energy dissipated per cycle (D) is

$$D = 4\mu N X \qquad (2)$$

From (2), D = 0 when N = 0 (i.e., a free joint) and D = 0 when X = 0 (i.e., a locked joint). Hence there is a joint tightness which maximizes D. If, as experiments in [3] indicate, X and N are linearly related; in particular,

$$X = -(X_F/N_L)\,N + X_F \qquad (3)$$

where

X_F = slip amplitude of free joint

N_L = normal force required to lock the joint

then maximum D occurs at $N = 1/2\ N_L$ and is equal to

$$D_{MAX} = \mu N_L X_F = F_L X_F \qquad (4)$$

where F_L is the friction force required to lock the joint against full slip.

Therefore one is likely to achieve optimum damping from a bolted joint by adjusting the joint preload to one-half the value which prevents full joint slip. A bolted joint which slips at all, much less one for which $N = 1/2\ N_L$ and hence $X = 1/2\ X_F$, may be unacceptable because of the resultant reduction in structural stiffness. This can be overcome by removing the joint from the main structural load path, and inserting it into a parallel load path. Ways of accomplishing this depend on the ingenuity of the designer. One way, adapted from [4], is shown in Fig. 2.

Joints subjected to squeezing or rocking motions have also been investigated, [5]. Here the normal force is the time-varying independent variable. The tangential slip generated by normal force variation is usually very small and hence the joint damping is usually negligible. The damping and dynamic stiffness can be increased to useful levels by introducing interface lubrication or by inserting interfacial materials such as polymer films or metal foils. The increase in stiffness is apparently due to an increase in the effective contact area between the mating surfaces while the increase in damping is due to the oscillatory shearing of the oil or viscoelastic material. Of course, if the interfacial layer is too thick, it will govern the joint stiffness and produce a softer rather than a stiffer joint. An idea of what can be accomplished by this technique is shown in Table I which is adapted from [6].

DAMPING BY VISCOELASTIC LAYERS

Layers of viscoelastic material may be used in two different ways to augment the inherent damping of structures. Figure 3a illustrates the unconstrained or free layer treatment. As the base structure (usually a beam or plate) vibrates, the layer of viscoelastic material undergoes stretching and compression. One of the distinguishing features of a viscoelastic material is that within certain temperature and frequency limits its inherent damping can be several orders of magnitude larger than that of common construction materials. Hence a thin coating of this high loss material can significantly increase the damping of the composite structure. A study of the free layer treatment for beams was first made by Oberst in 1952 and design formulas are available, [7]. For a given loss factor of the viscoelastic coating, maximum damping requires as stiff a coating as possible and therefore many of the materials developed for this purpose are high polymers stiffened by various fillers.

Figure 3b illustrates the other way of using viscoelastic material to augment the damping of a beam or plate. The high loss material is "sandwiched" between two cover plates. When the structure vibrates, the damping layer undergoes oscillatory shear which results in energy dissipation. A limiting case of the sandwich configuration is also of design interest; namely, where one face plate and the viscoelastic layer are both thin compared to the other face plate (see Fig. 3c). This is the damping tape problem which stimulated much of the early work on constrained viscoelastic layers, in particular, Kerwin's work in 1959. In contrast to the free layer case, maximum damping of structures using a constrained viscoelastic layer requires a relatively soft viscoelastic material. Design formulas for constrained layers can also be found in [7]. This type of treatment is capable of producing more damping per unit of added weight than the free damping layer treatment.

The damping of viscoelastic materials is sensitive to temperature and frequency. This dependence will be reflected in the damping performance of the structure. Therefore, care is required to match the temperature and frequency of the structure to the peak damping region of the material. In addition, the design of constrained viscoelastic layers requires careful attention to geometric factors. One must ensure that as much shear energy as possible is stored in the viscoelastic layer. Most analyses contain a stiffness parameter, R, which is proportional to the ratio of the shear stiffness of the viscoelastic layer to the extensional stiffness of the cover plates. As shown in Figure 4, if the layer is relatively soft ($R \to 0$), large shears are produced in the layer but since the modulus of the layer is low, little energy is stored and little energy is dissipated. If the viscoelastic layer is relatively stiff ($R \to \infty$), little shear deformation occurs in the layer and, again, little energy is stored and little energy is dissipated. Clearly, there is an optimum value of R. It can be shown that this optimum varies with the loss factor of the viscoelastic material used. Hence, proper design of a constrained viscoelastic layer requires a careful match between material properties and structural geometry.

The use of viscoelastic layers to damp the vibration of large scale, low frequency structures has proven successful in several applications. An opportunity to use constrained viscoelastic layers in a concrete structure arose in connection with the Barbican redevelopment in the City of London, [8]. The structure was a continuous railway bridge deck supported every 35 ft. The deck was made of prestressed concrete beams and little inherent damping would have been expected. To provide damping, a constrained viscoelastic layer was incorporated as shown in Figure 5. This required a damping material which adhered to concrete and onto which further wet concrete could be poured to complete the sandwich. A bitumen reinforced with rubber latex proved successful. A single layer of this material increased the damping ratio about 2 1/2 times without significantly altering the natural frequency of 16 Hz.

Two examples of use of this technique for large scale steel structures are reported in [9]. In one structure, a 70 ft. by 56 ft. by 42 ft. high sonic test facility, the wall and roof girders were damped with constrained viscoelastic layers. Figure 6 shows a cross section of the 100 inch-deep I-beams used as roof girders; the constraining layer was a 30 inch-deep I-beam. This treatment was successful in controlling resonances in the 10 Hz to 60 Hz range.

The design of large steel and concrete structures containing viscoelastic layers will receive tremendous impetus when finite element computer programs containing damping layer elements become widely available. The most current and advanced state-of-the-art seems to be that described in [10]. A computer program, ASTRE, based on [10], is briefly described in [11].

DAMPING LINKS

As was mentioned above, it is often convenient to incorporate a damper as a structural link parallel to the main load path. These damping links can dissipate energy by friction, as above, or by material hysteresis. Auxiliary dampers have long been used to control machinery vibration. Since many reviews of this technology exist, e.g. [12], they will not be dealt with here.

Damping links in the form of viscoelastic shear dampers have been used in the 110 story World Trade Center Building in New York City. About 10,000 of these dampers were used as links between the floor trusses and the building frame, see Fig. 7. Their purpose is to limit wind induced vibration of the buildings in the 0.1 Hz range. The design of these dampers is discussed in [13].

Recently, [14], it has been suggested that links using the plastic deformation of metal to absorb energy can be used to control the seismic response of large structures. Several types of energy absorbers have been built and tested; Figure 8 shows a design which absorbs energy by the hysteresis associated with the plastic torsion and bending of a rectangular steel bar. It has been proposed to use these links to reduce the seismic motion of the 200 foot high central piers of a railway viaduct.

One of the features of this concept of augmenting structural damping is that they are replaceable. That is, if the structure were subjected to a severe wind storm or to an earthquake, the links could be inspected and, if necessary, replaced.

CONCLUSION

By and large, structures are designed on the basis of strength, stability or dynamics. One takes whatever damping one gets. Techniques are now available to design a structure for the damping one wants. These techniques need additional development but they presently offer a valuable design option.

REFERENCES

[1] ROGERS, P.F., BOOTHROYD, G., "Damping at Metallic Interfaces Subjected to Oscillating Tangential Loads", ASME paper No. 74-WA/PROD-9 (1974).

[2] GOODMAN, L.E., "A Review of Progress in Analysis of Interfacial Slip Damping", Structural Damping, ASME Symposium (1959).

[3] EARLES, S.W.E., BEARDS, C.F., "Some Aspects of Frictional Damping Applied to Vibrating Beams", Int. J. Mach. Tool Des. Res., vol. 10, pp. 123-131 (1970).

[4] BEARDS, C.F., "Structural Damping by Slip in Joints", Shock and Vibration Digest, vol. 7, no. (1), pp. 113-119 (1975).

[5] ANDREW, C., COCKBURN, J.A., WARING, A.E., "Metal Surfaces in Contact Under Normal Forces: Some Dynamic Stiffness and Damping Characteristics", Proc. Instr. Mech. Engrs., vol. 182, pt. 3K, pp. 72-100 (1967-68).

[6] FAGERSTROM, W.B., "Dynamic Stiffness and Damping of Machined Interfaces and their Effect on the Dynamic Stiffness of a Structure", Ph.D. Thesis, Univ. of Wisconsin (1972).

[7] UNGAR, E.E., "A Guide to Designing Highly Damped Structures Using Layers of Viscoelastic Material", Machine Design, pp. 162-168, Feb. 14 (1963).

[8] GROOTENHUIS, P., "The Attenuation of Noise and Ground Vibrations from Railways", J. of Environmental Sci., pp. 14-19, April (1967).

[9] NELSON, F. C., "The Use of Viscoelastic Material to Damp Vibration in Buildings and Large Structures", AISC Eng'g J., pp. 71-78, April (1968).

[10] PAULARD, M., TROMPETTE, P., LALANNE, M., "Response of Thick Structures Damped by Viscoelastic Material with Application to Layered Beams and Plates," presented at the 45th Shock and Vibration Symposium, Dayton, Ohio, Oct. (1974).

[11] NELSON, F.C., GREIF, R., "Damping in Shock and Vibration Programs", to be published in Shock and Vibration Computer Programs, a monograph of the Shock and Vibration Information Center, Office of Naval Research, Washington, D.C.,U.S.A.

[12] REED, F.E., "Dynamic Vibration Absorbers and Auxiliary Mass Dampers", chapter 6, Shock and Vibration Handbook, McGraw-Hill (1961).

[13] MAHMOODI, P. "Structural Dampers", J. Struct. Div., ASCE, pp. 1661-1672 (1969).

[14] SKINNER, R.I., KELLY, J.M., HEINE, A.J., "Energy Absorption Devices for Earthquake Resistant Design", Proc. of Vth World Conf. on Earthquake Eng'g, pp. 2924-2933 (1974).

TABLE I

Stiffness and Damping Results for a nonsliding, normally loaded, single interface joint

joint preload: 4000 lbs.
dynamic load: ± 3000 lbs. @ 100 Hz
metal surfaces: cast iron
surface roughness: 600 microinch, arithmetical average

Interfacial Material	stiffness lb/μin.	loss factor
none	29.7	0.032
Lead Foil 0.004" thick	113.0	0.053
Polyethylene film 0.0034" thick	37.6	0.114
Silicone Fluid 10^6 Centistokes	30.8	0.071

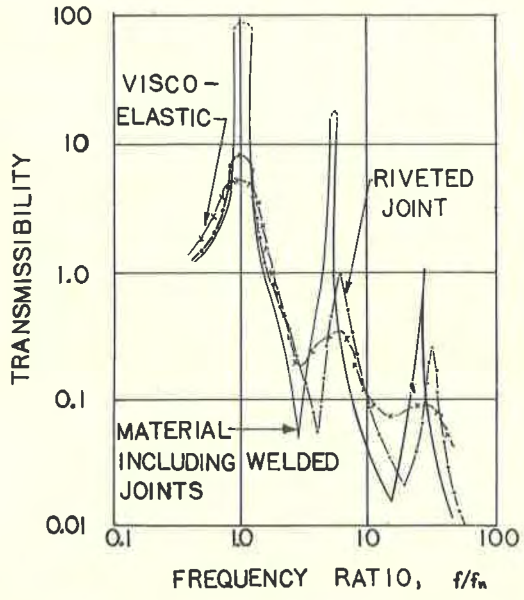


FIGURE 1 Transmissibilities for various methods of joint fabrication

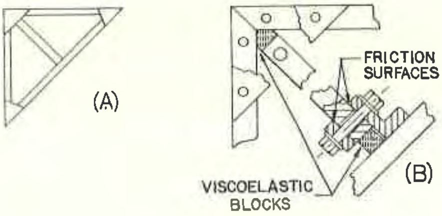
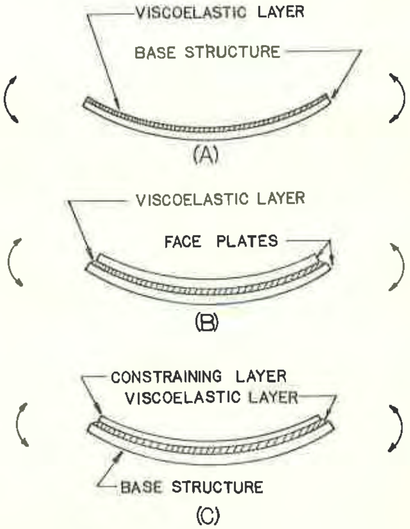


FIGURE 2 (a) example structure
(b) modification to example structure to increase damping



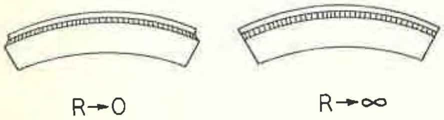


FIGURE 4 Viscoelastic layer deformation at low and high values of R

FIGURE 3 Ways of employing viscoelastic material to damp flexural vibration

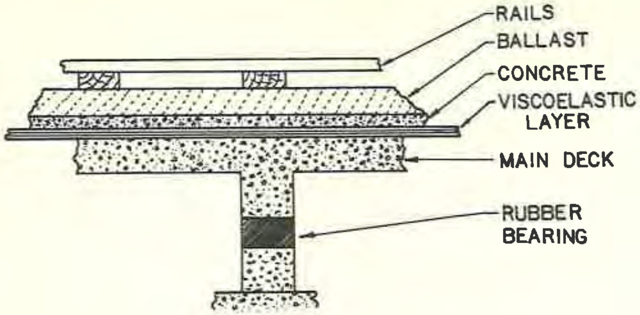


FIGURE 5 Damping treatment of bridge deck

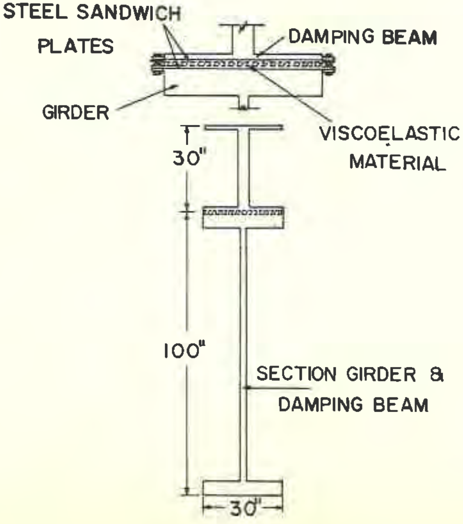


FIGURE 6 Damping treatment of roof girder

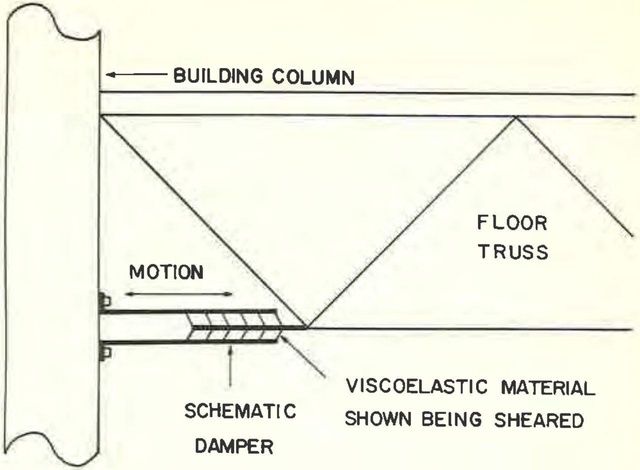


FIGURE 7 Location of viscoelastic shear dampers in floor truss

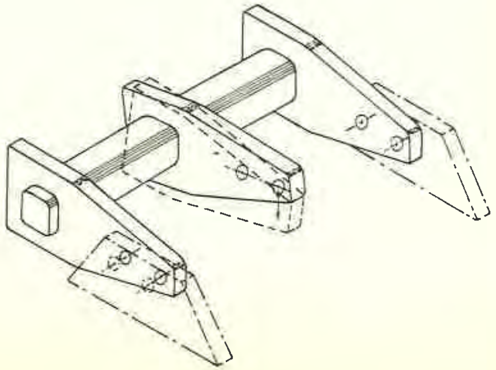


FIGURE 8 Torsional Energy Absorbing link