The Use of Viscoelastic Material to Damp Vibration in Buildings and Large Structures

FREDERICK C. NELSON

CONTROLLING the vibration response of structures is a problem which has received the attention of many engineers for many years. This paper discusses some recent developments of a special aspect of this general problem; namely the use of viscoelastic material to damp the low frequency vibration often associated with large scale structures and buildings.

The growing concern of structural engineers with the airborne and structure borne vibration environment of their buildings is a reflection of the growing concern of the engineering profession, as well as the general public, with the problem of noise and vibration. Economic considerations and improved design methods have resulted in a trend to lighter weight structures and higher speed machinery, both of which tend to increase vibration levels. The engineer must either develop new methods of controlling vibration or adapt or improve existing methods if the public good is to be served. As an example of adaptation, this paper describes three cases in which constrained viscoelastic layers, first employed in the aerospace industry, have been used to control the vibration of large structures.

BACKGROUND

Layers of viscoelastic material may be used in two different ways to augment the inherent damping of structures. Figure 1a 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. As anyone who has plucked a string or listened to a tuning fork knows, all structures have inherent damping which causes their free vibrations to decay. 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, in particular metals. Hence a thin coating of this high loss material can significantly increase the damping of the composite structure. A systematic study of the free layer treatment was made by Oberst[1] in 1952 and design formulas are available.[2] 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 1b 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 plates. When the plates vibrate, the damping layer undergoes oscillatory shear which results in energy dissipation. This configuration may be analyzed by specializing sandwich plate theory to the case in which the core is viscoelastic; see Mead[3] for a presentation of the theory for face plates of equal thickness. A limiting case of the sandwich configuration is also of technical interest; namely, where one face plate and the viscoelastic layer are both thin compared to the other face plate (see Fig. 1c). This is the damping tape problem† which stimulated much of the early work on constrained viscoelastic layers, in particular Kerwin's[4] 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 can again be found in Reference 2. This type of treatment is capable of producing more damping per unit of added weight than the free damping layer treatment.

Two other features of constrained and free viscoelastic layer behavior will be mentioned here even though they

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Frederick C. Nelson is Associate Professor of Mechanical Engineering, Tufts University, Medford, Mass.

* *An example of the materials available for free-layer treatment of structures is LD-400 manufactured by the Lord Manufacturing Co. of Erie, Pa. This material is a specially processed polymeric composite. At 80°F and 75 Hz, it has a storage modulus of 2 × 10^5 psi and a loss factor of 0.8.*

† *An example of damping tapes which are commercially available is "Scotch Brand" aluminum foil sound damping tape No. 428B manufactured by the 3M Co. of St. Paul, Minn. It is a pressure sensitive viscoelastic adhesive with an annealed aluminum foil constraining layer 0.008 in. thick. One layer of 428B applied to an 0.040 in. aluminum plate provides an average loss factor of 0.09 over the frequency range 100 Hz to 1000 Hz at 0°F.*

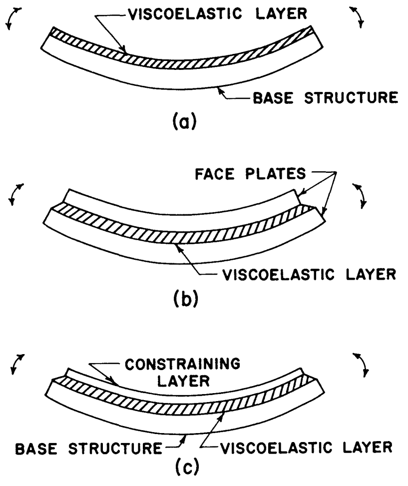

Fig. 1. Various ways of employing viscoelastic material to damp flexural vibration

are important primarily to designers of thin-walled structures. The addition of a constrained or unconstrained layer to a thin base structure can significantly increase the stiffness and mass distribution of the composite structure as well as augment its damping. The resulting change in resonant frequency can neutralize the benefits of increased damping. Criteria for assessing damping treatments from this combined point of view have been developed by Mead.[5]

A unique feature of the damping of a constrained viscoelastic layer is its dependence on mode shape. For a given viscoelastic material, there is a mode shape for which the damping is a maximum; conversely, for a given mode shape, there is a value of viscoelastic modulus for which the damping is a maximum. This feature is important if one wishes to optimize the effectiveness of constrained viscoelastic layers. Discussions of it can be found in the above work of Kerwin and Mead.

THE LOSS FACTOR

Investigations and evaluations of the damping of structures which incorporate viscoelastic material are traditionally presented in terms of loss factor. Since this term may be unfamiliar, an explanation will be given. The loss factor of many viscoelastic materials can be determined by a set-up such as shown in Fig. 2.[6] A free vibration is initiated by pulling down the center of the beam a specified amount and releasing it from rest. Figure 3 shows a typical result. After initial disturbances caused by higher modes, one obtains a damped oscillation in the fundamental free-free mode. Location of the wire supports at the nodes minimizes the support damping.

A standard measure of the damping of a transient vibration is the logarithmic decrement defined as

$$\delta = \log_e \frac{x_0}{x_1} \tag{1}$$

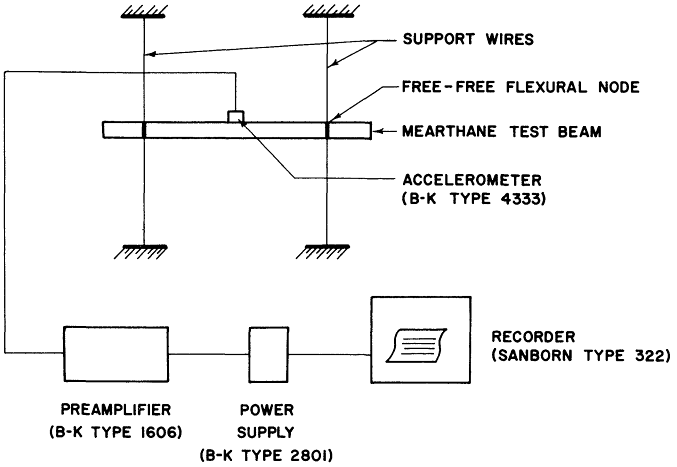

Fig. 2. Test arrangement for determining the loss factor of a viscoelastic beam

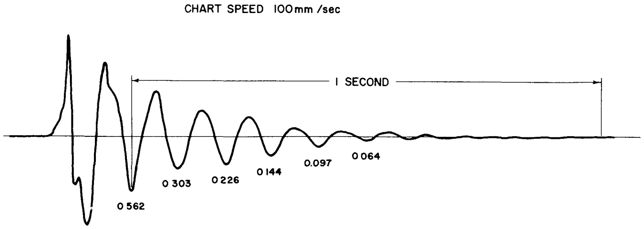

Fig. 3. Transient decay curve for beam of Fig. 2

where x_0 and x_1 are the amplitudes at the beginning and end of one cycle. For light enough damping (e.g., $\delta \leq 0.5$), the loss factor, η, is related to the logarithmic decrement by

$$\eta = \frac{\delta}{\pi} \tag{2}$$

However, more basically, the loss factor is a quantity associated with steady state sinusoidal vibration. For a viscoelastic solid under cyclic deformation, the energy dissipation can be conveniently expressed by assuming a complex modulus, e.g., in shear

$$\bar{G} = G(1 + i\eta)$$

where this equation defines the loss factor η and G is the shear storage modulus. A useful expression for η under steady state sinusoidal vibration may be obtained in terms of energies. This is

$$\eta = \frac{1}{2\pi} \frac{\text{Energy dissipated per cycle at resonance}}{\text{Peak energy stored at resonance}} \tag{3}$$

If the transient decay is exponential (e.g., linear viscoelastic or linear viscous damping), Equations (1) and (2) may be extended to cover n cycles. Then we have

$$\eta = \frac{1}{n\pi} \log_e \frac{x_0}{x_n} \tag{4}$$

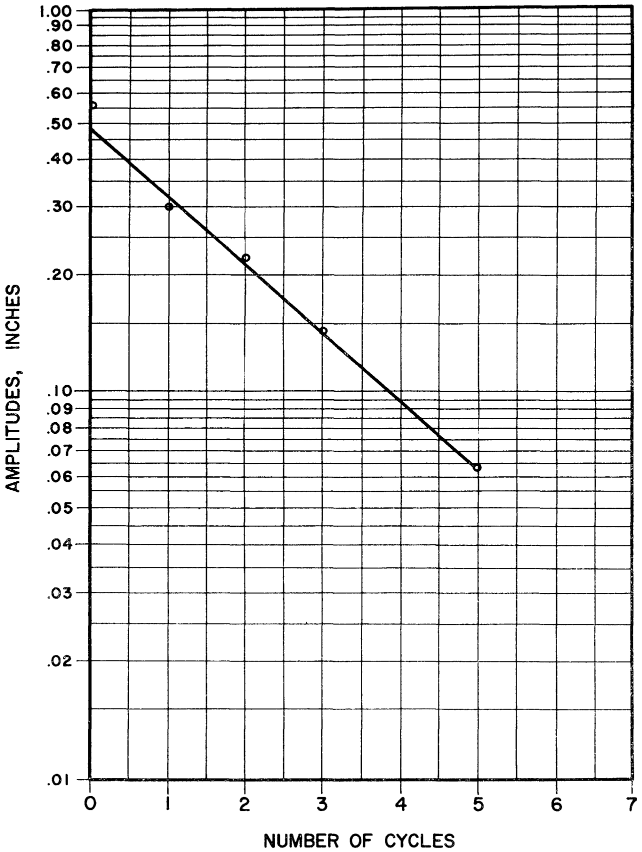

Fig. 4. Data reduction to establish loss factor for decay curve of Fig. 3

where x_0 and x_n are the amplitudes of two peaks, n cycles apart.

When reducing data from a transient response curve it is convenient to plot the amplitudes, x, on a logarithmic scale versus the number of cycles, n, on a linear scale since on a semi-log plot, Equation (4) is a straight line. If the data contains scatter, an effective η for exponential decay can be established by fairing a straight line through the data points. The data of Fig. 3 has been reduced in this manner in Fig. 4. We see that the decay is exponential and, using Equation (4), that the material loss factor* is $\eta = 0.127$. This is not a particularly high value of η for a viscoelastic material. Such materials can have loss factors ranging up to 10 with values between 1.0 and 2.0 being regarded as very good. However, compared to metallic structures the value of 0.127 is quite high. A carefully supported monolithic metal structure, such as a bar of steel hung on wires, would probably have a loss factor of the order of 0.001. A fabricated metal structure or any metal structure with practical joints or supports would probably have a loss factor in the range 0.01 to 0.10. Equation (3) shows that besides measuring the inherent damping of a structure, the loss factor depends on other parameters of the structure; for example, the stiffness. In a composite structure the relative stiffnesses of the elements determine the distribution of stored energy. The loss factor of the composite structure can be maximized by applying the viscoelastic material to the element having the largest stored energy.[2] For example, if one wished to damp the vibrations of a rib-reinforced plate which was vibrating in a mode characterized by large participation on the part of the plate and small participation on the part of the ribs, the viscoelastic material should be applied to the plate rather than to the ribs.

Loss factor data over a wide range of temperature and frequency requires equipment with much more accuracy, precision and environmental control than that considered above.**

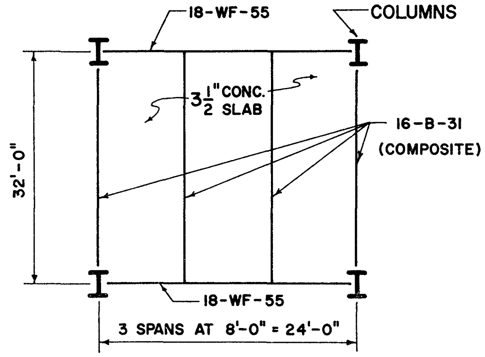

Fig. 5. Plan view of composite floor panel

FLOOR PANEL VIBRATION

Recently, an opportunity arose to employ the concept of a constrained viscoelastic layer to modify the vibration response of a floor panel in a large department store. Figure 5 shows a plan view of the panel which was treated. This panel was typical of many of the panels which comprised the floor system of the store. These floor panels were of composite lightweight steel construction and had panel fundamental frequencies in the neighborhood of 6 Hz. It is known that humans are particularly sensitive to frequencies around 6 Hz because of upper torso resonances.[7] Consequently, the vibration of these

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* *Even for a homogeneous structure, one must be careful to distinguish between the loss factor of the material* (η) *and the loss factor of the structure* (η_s). *The distinction arises because* η *implies a uniform stress field and in many structures, e.g., beams, the stress field varies in space. However, for beams composed entirely of viscoelastic material, the distinction vanishes—see B. J. Lazan, Energy Dissipation Mechanisms in Structures, with Particular Reference to Material Damping, Structural Damping, American Society of Mechanical Engineering, 1959.*

** *An example of the equipment which is commercially available for this purpose is the Model 830 Elastomer Test System manufactured by the MTS Systems Corp., Minneapolis, Minn. It measures dynamic stiffness and damping over the ranges 5 to 100 Hz and 60° to 350°F.*

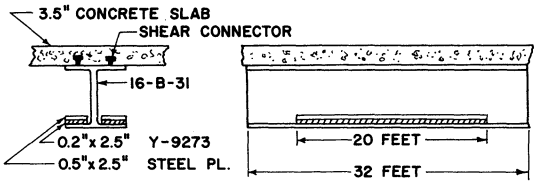


Fig. 6. Geometry of constrained viscoelastic layer applied to the floor beams of the panel in Fig. 5

floor panels due to impact (such as footfalls) was perceptible or even annoying to many occupants of the store.

Previous work on subjective reaction to floor panel vibration indicated that under impact, damping was as important, if not more important, than frequency and amplitude.[8] The greater the floor panel damping, the less noticeable was its vibration due to impact. Based on this, it seemed logical to apply constrained viscoelastic layers to increase damping and reduce the severity of human reaction.

Comparison of calculated and measured frequencies indicated that the floor beams and the concrete slab participated about equally in the fundamental mode of vibration. Because of the equal participation of the floor beams and in order to place the viscoelastic layer as far from the neutral axis of the composite section as possible, the constrained layer treatment was applied to the bottom flange of the floor beams.

An initial problem was the selection of a viscoelastic material. Indeed, when using free and constrained viscoelastic layers, there is always a problem of finding, or producing, a material which has the necessary properties in the frequency and temperature ranges of interest. The frequency and temperature dependence of the properties of a high polymer are related by physical laws.[9] In particular, if one has a material whose loss factor is high over a large frequency bandwidth it is also high over a large temperature bandwidth. This feature is very desirable in aerospace application where the excitations are broadband (jet noise has its most damaging intensities in the range 100 to 1000 Hz) and where the temperature excursions are large. Unfortunately, the price paid for large bandwidths is a reduction in loss factor. Large bandwidths were not a requirement for the problem at hand and the search could be narrowed to finding the best available material at room temperature and at 6 Hz. Since constrained layers have been used principally in the aerospace industry, property data for promising viscoelastic material existed mainly in the range of 100 Hz to 1000 Hz, but, after a careful search, Y-9273, a pressure sensitive adhesive manufactured by the 3M Co., was selected. This material has a loss factor of 1.4 and a shear storage modulus of 50 psi at 72°F and 10 Hz.

The design configuration selected is shown in Fig. 6. To apply the viscoelastic material, the beam flange was cleaned of mill scale and degreased. The Y-9273 was then applied in pre-cut strips to the flanges. Next the constraining layers, in the form of steel plates 5 in. wide, 0.5 in. thick and 20 ft long, were lowered onto the viscoelastic material. Since Y-9273 is an excellent adhesive, no bonding agent was required. The bonds were quite secure and it was not felt necessary to provide a positive holding device.

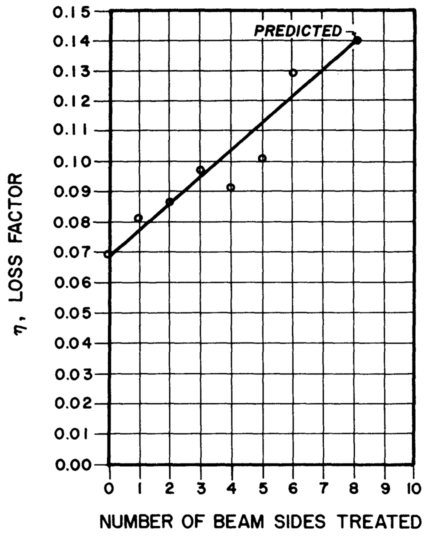
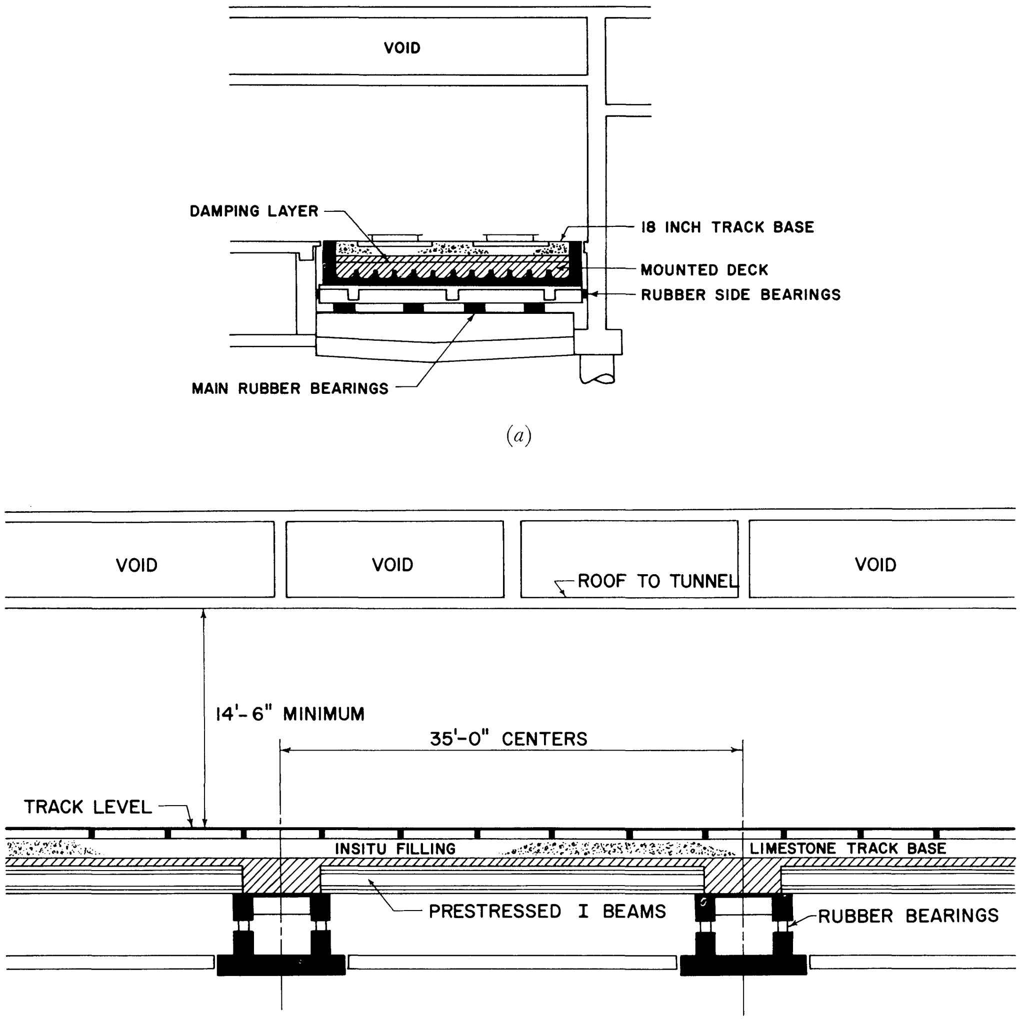


Fig. 7. Loss factor as a function of number of beam sides treated

Full scale laboratory tests[10] indicated that the arrangement of Fig. 6 should provide an increment in structural loss factor of 0.07. Only a limited attempt was made at optimization and it seems likely that the full potential of the method was not realized.

The treatment of Fig. 6 was applied to the panel of Fig. 5 at the store site. Starting with the central beams, the constrained layers were added to one side of a beam at a time and loss factor measurements were made after each application. In all, three beams were fully covered. The results are shown in Fig. 7 and indicate that with complete treatment the panel loss factor would have been increased from 0.07 to about 0.14, an increment of 0.07. The agreement among the analytical predictions, the laboratory tests and the field tests is good enough to suggest that constrained viscoelastic layers are a reliable way of augmenting the damping of large scale, low-frequency structures such as buildings.

It was also concluded that the subjective response to the floor panel was improved although the degree of improvement was uncertain. It is clear that the role of damping, as well as frequency and amplitude, in determining human reaction to the residual vibration following impact requires additional research. Such research is underway and one of its objectives is a simple relation which will enable a designer to predict whether or not his floor panels will have objectionable vibration.



(*a*)

(*b*)

Fig. 8. Longitudinal section and cross-section through suspended train deck.

RAILWAY BRIDGE-DECK VIBRATION

Another opportunity to use constrained viscoelastic layers arose in connection with the Barbican Redevelopment in the City of London. Here the problem was to minimize the noise and vibration from a series of rail lines which run under the proposed site of a number of luxury apartment houses, a concert hall, a theater and a school of music. One method would be to isolate each of the buildings by means of rubber blocks (the Odeon Cinema in London, weighing 5000 tons, has been mounted on rubber blocks[11]); however, with so many buildings involved, it seemed more economical to isolate the source of the vibration. The method chosen is shown in Fig. 8 and discussed in Reference 12.

The rail track lies on a one-half mile continuous bridge deck which is supported every 35 ft on rubber blocks. The bridge deck is constructed of prestressed concrete beams with additional concrete poured above and between the beams during erection. The inherent damping of prestressed beams is not large and one should anticipate that the bridge deck would be a sharply resonant system.

Sharp bridge-deck resonances would have two deleterious effects. The bridge deck would act as a sounding board for the train vibration and thus increase the airborne noise level. It would also reduce the effectiveness of the rubber blocks as vibration isolators and thus increase the structure-borne noise level.* To avoid both effects, it was decided to suppress the resonances of the bridge deck by incorporating a layer of viscoelastic material in the on-site poured concrete.

The selection and evaluation of the viscoelastic material was as much of a problem in this case as in the previ-

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* *The transmissibility of a vibration isolator depends not only on the properties of the isolator, but also on the properties of the source of vibration and the receiver of vibration. An isolator is effective only if its mobility exceeds that of the source and receiver. This mismatch of mobilities is reduced if either the source or the receiver becomes resonant.*

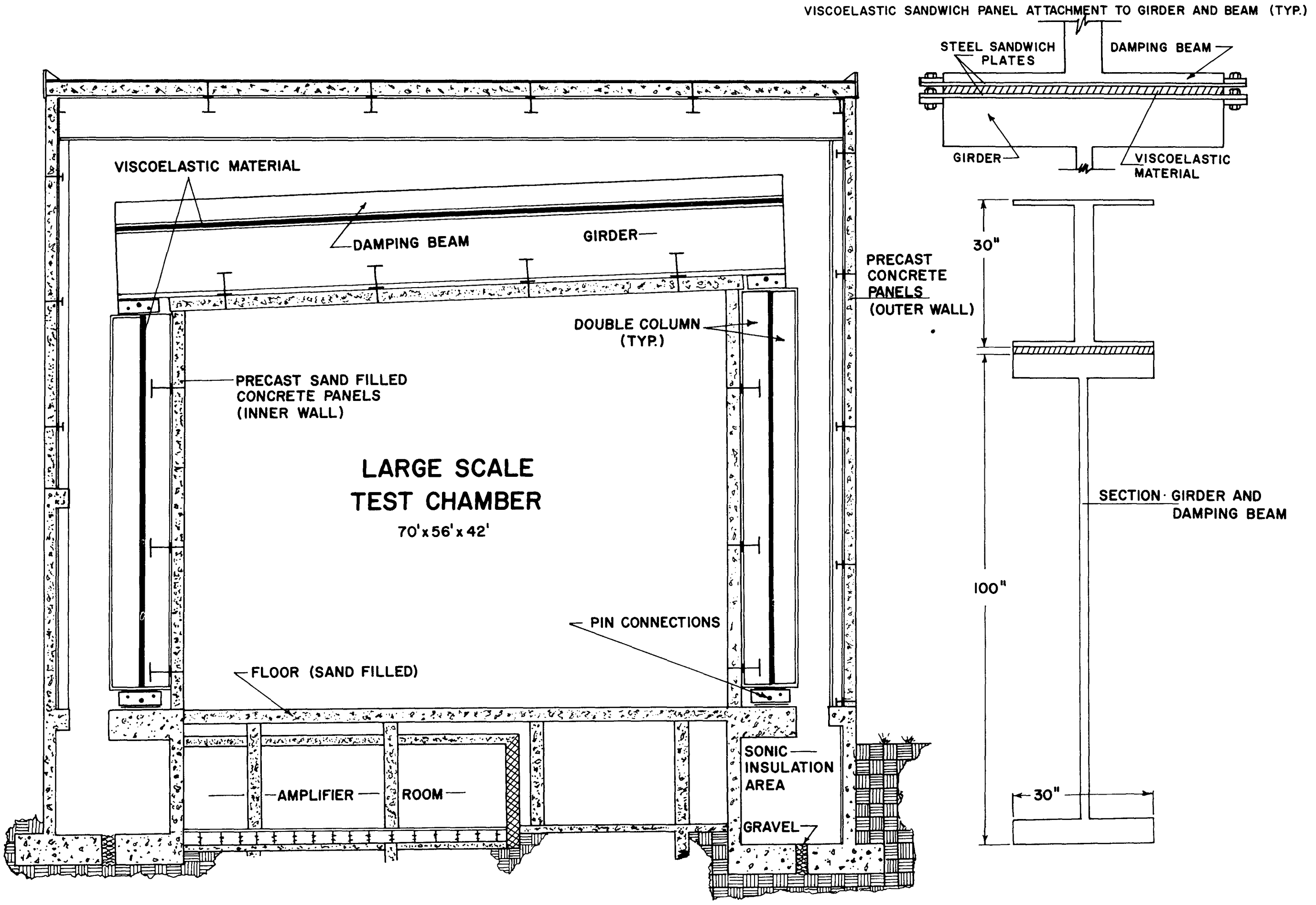

Fig. 9. Main test chamber of sonic fatigue facility

ous one. It had to be available in large quantities, adhere to concrete, be capable of being lain by the simple methods available to the contractor, and permit walking on prior to the pouring of the upper layer of concrete. The choice was bitumen reinforced with rubber latex. Tests indicated a loss factor of 1.3 and a shear storage modulus of 340 psi, both at 20.5°C and 20 Hz. Tests indicated that incorporation of a viscoelastic layer of the above properties increased the loss factor of the bridge deck from 0.07 to 0.16 and also increased the vibration isolation across the rubber blocks supporting the bridge deck to eighty-four percent.

SONIC TEST FACILITY

Perhaps the most spectacular application of constrained viscoelastic layers to a structure is the Aeronautical Systems Division Sonic Fatigue Facility at Wright-Patterson Air Force Base, Dayton, Ohio.[13] This structure, apparently the world's largest sonic fatigue facility, measures 70 ft by 56 ft by 42 ft high. Banks of sirens can subject the walls of this chamber to sound pressure levels up to 162 db relative to 0.0002 microbar over a frequency range of 100 to 1000 Hz. The broadband nature of the excitation means that one cannot avoid resonances in the reinforced concrete panels which form the walls, floor and ceiling of the chamber or in the steel structure which supports these panels (see Fig. 9). The large scale of the chamber means that the response will be rich in low frequency resonances; in fact, the fundamental resonances of the panels and steel structure lie in the range 10 Hz to 60 Hz. Again, there is the need of controlling low frequency resonances in a large structure. In this case, two damping schemes were employed. Constrained viscoelastic layers were used to damp the vibration of the steel roof girders and wall columns. The scale is enormous: the roof girders are 100 in. deep I-beams with 30 in. I-beams used as constraining layers. The viscoelastic layer is about 0.8 in. thick. Unfortunately, no information seems available as to the nature or properties of the viscoelastic material used.

The concrete wall and floor panels are damped by means of integrally cast cavities filled with sand or gravel. When the panels vibrate, waves are formed in the sand and the energy in these waves is partially dissipated by the dry friction between particles. This method is dependent on both frequency and amplitude, the damping increasing as either frequency or acceleration level is increased.

CONCLUSION

This paper has had three objectives: to acquaint structural engineers with the concept of damping augmentation by means of a constrained layer of viscoelastic material; to describe several instances in which it has been used on large scale buildings and structures; and to suggest that the method is reliable and deserving of wider use. Of course, this does not mean that no problems remain; for example, studies on the economics of viscoelastic layers in building construction and on the long time stability of such materials are badly needed. However, a great deal is presently understood about the behavior of viscoelastic layers and many individuals and organizations are actively increasing the extent and depth of this knowledge. Given the required encouragement and support, problems will yield to their efforts.

REFERENCES

1. *Oberst, M., et al.* Ueber die Daempfung der Biegeschwingungen duenner Bleche durch fest haftende Belaege, *Acustica, Vol. 2, Supplement 4, 1952, pp. 181–194; also Acustica, Vol. 4, Supplement 1, 1954, pp. 433–444.*
2. *Ungar, E. E.* A Guide to Designing Highly Damped Structures Using Layers of Viscoelastic Material, *Machine Design, Feb. 14, 1963, pp. 162–168.*
3. *Mead, D. J.* The Effect of Certain Damping Treatments on the Response of Idealized Aeroplane Structures Excited by Noise, *AFML-TR-65-284, August 1965.*
4. *Kerwin, Jr., E. M.* Damping of Flexural Waves by a Constrained Viscoelastic Layer, *Journal of the Acoustical Society of America, Vol. 31, No. 7, July 1959.*
5. *Mead, D. J.* The Practical Problems of Assessing Damping Treatments, *Journal of Sound and Vibration, Vol. 1, No. 3, pp. 270–291, 1964.*
6. *Nelson, F. C. and Ng, T. N.* Low Frequency Loss Factor in Mearthane, *Tufts University Mechanical Engineering Report 67-6, 1967.*
7. *Coermann, R. R.* The Mechanical Impedance of the Human Body in Sitting and Standing Position at Low Frequencies, *Human Vibration Research, Ed. S. Lippert, Macmillan Co., 1963, pp. 1–27.*
8. *Lenzen, K. H.* Final Report: Vibration of Steel Joist—Concrete Slab Floor Systems, *University of Kansas Center for Research in Engineering Science, Lawrence, Kan., August, 1962.*
9. *Ferry, J. D.* Viscoelastic Properties of Polymers, *John Wiley & Sons, 1961, see Chapter 11, particularly pp. 201–209.*
10. *Nelson, F. C. and Yoos, Jr., T. R.* Damping of Low-Frequency Vibration by Constrained Viscoelastic Layers, *A.S.M.E. Paper 67-VIBR-62, presented at the Vibration Conference of the Machine Design Division of thc American Society of Mechanical Engineers, March 29–31, 1967.*
11. *Morton, B. A.* Building on Rubber, *Building Technology and Management, pp. 6–9, June, 1967.*
12. *Grootenhius, P.* The Attenuation of Noise and Ground Vibration from Railways, *Journal of Environmental Sciences, pp. 14–19, April, 1967.*
13. *This facility is described in:*
    Kolb, A. W. and Rogers, O. R. The Aeronautical Systems Division Sonic Fatigue Facility, *Shock and Vibrations Bulletin, No. 30, Part 5, pp. 37–50, May, 1962.*
    and, to a lesser extent, in:
    Wolf, N. Results of Loss Factor Measurements on Steel and Concrete Beams Using a Viscoelastic or Sand Damping System *ASD-TDR-62-717, September, 1962.*