Viscoelastic Damping Devices Proving Effective in Tall Buildings

D. B. CALDWELL

When the World Trade Center in New York City opened its doors as the tallest building in the world in 1972, it gained instant public attention. But a design first in the 110-story twin towers was, and still is, little noticed outside the group of engineers and scientists that were close to the project.

That design feature is the 20,000 viscoelastic dampers in the structural system that absorb the punch of unusual as well as average winds. The dampers reduce perceived sway and acceleration in the upper floors. They do this job by absorbing and dissipating vibrational energy transmitted by the wind to structural members.

Although that application was 14 years ago, viscoelastic vibration damping devices are relatively new in the sense they have presently been used in only two tall buildings. Nevertheless, the devices offer a number of advantages, and for that reason were selected to be incorporated in the second structure, Seattle's 76-story Columbia Center.

The effect of damping, or the dissipation of energy from a vibrating system, is well known to every structural engineer. When wind meets the face of a tall building, air spins off around the structure in vortices that push the building back and forth, transverse to the direction of the wind. This movement is damped by air resistance, friction at joints and internal friction in the building materials. In almost all cases, engineers rely on methods such as the structural systems, mass and shape of the building, to provide damping effect.

However, something extra may be needed to bring the building closer to critical damping (where vibration stops at the end of one-half cycle). That extra something for modern steel buildings may be viscoelastic-engineered dampers. Placed between points of high relative displacement, these dampers are designed to absorb and dissipate as heat the vibrational energy that passes through them. Years ago, in the heyday of the Empire State Building, for example, damping was of little concern in structural design. Buildings then were more massive and the surfaces of exterior materials usually were rough and discontinuous, qualities that disrupt vortex shedding.

D. B. Caldwell is Senior Development Specialist, 3M (retired).

In contrast, today we erect slender, smooth buildings of glass and steel, with profiles that change little on the way up. There are exceptions, and a notable one is the Sears Tower in Chicago, the world's tallest building by a margin of 100 ft. The tower narrows three times from its base dimensions, and at the top, the floor area is only two-ninths of the area at the bottom. Wind tunnel tests showed the design of the structure would provide adequate damping, without the need for additional damping devices.

DAMPER ASSEMBLY

A typical viscoelastic damper (see Fig. 1) consists of a steel plate sandwiched between two steel tees, with a thin layer of viscoelastic material between the tee flanges and top and bottom surfaces of the plate. Exact parallel separation of the flanges is maintained by steel wire shims in the World Trade Center (special bolts are used in the Columbia Center); this ensures parallel planar motion with no twisting or tipping in the viscoelastic material. The entire assembly is tied together by a structural epoxy adhesive applied at the steel/viscoelastic interfaces. Steel surfaces are mechanically abraded and primed beforehand to prevent failures in adhesion.

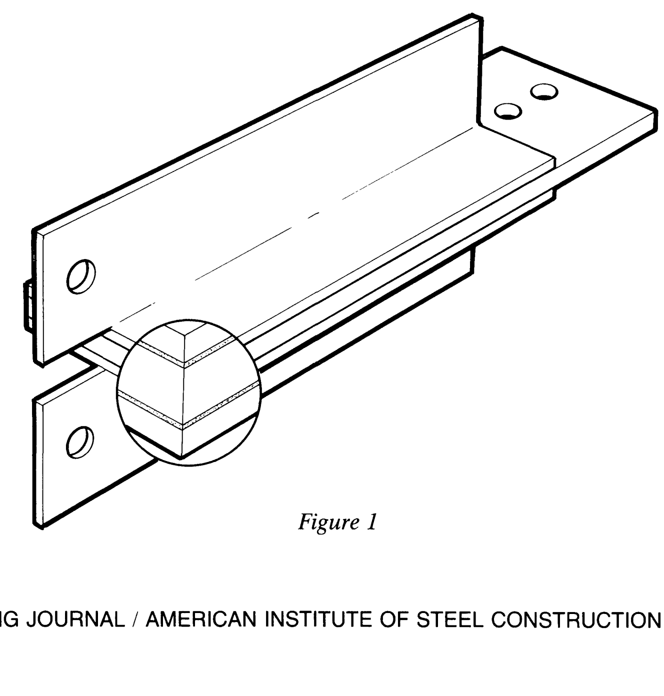

Figure 1

In the World Trade Center, the tees are bolted to seats on the outside columns; the steel plates are bolted to an extension of the bottom chord of each floor truss (Fig. 2). The dampers function when the building, excited by wind, vibrates at its natural frequency. The steel plate and tees in each damper move relative to each other along their longitudinal axis, producing sheer strain, and this energy is absorbed in the viscoelastic material. For a 100-year wind, the projected maximum displacement is 0.02 inch.

In the Columbia Center, two dampers are attached in parallel to a diagonal I-beam across selected structural modules (Fig. 3). When the building sways, the diagonal beams deflect in tension and compression, alternately pulling apart and pushing together (axially) the tees and steel plate of each damper. By design, forces on the building act only along the lines of the dampers. In combination, the diagonals and attached dampers function as a damped spring. The projected maximum displacement of this assembly in a 100-year wind is 0.08 inch.

VISCOELASTIC

What looks like a layer of clear plastic between the steel plate and tees of the assembled damper, is actually a long-chain acrylate copolymer that is both viscous and elastic. Because it is viscous, the material absorbs energy during deformation; its elasticity provides structure and stability. Energy absorbed in this copolymer in deformation eventually is released or dissipated into the environment.

Viscoelastic materials and the technology for their use have been in existence for over 40 years. For some 30 of those years, they have been used for reducing noise and fatigue in applications involving small deflections, rather than large ones such as those in the World Trade and Columbia Centers. For example, the Air Force has extended the fatigue life of stationary guide vanes at the inlet of some jet engines by wrapping the vanes with aluminum foil coated with a layer of viscoelastic material.

In another use, manufacturers have reduced saw blade noise by placing a thin viscoelastic layer between the solid area of the blade and a constraining metal layer. Other uses include acoustical control in corporate and personal aircraft and vibration control in submarines.

DESIGN CONSIDERATIONS

Damper design is a balancing act among sometimes opposing concerns, such as heat dissipation, strain, stiffness, cost and damping effectiveness. A controlling factor in this balance is the structural subsystem that contains the dampers. In the World Trade Center, for example, the design process called for a high loss factor in combination with low viscoelastic stiffness; that is, high enough to provide adequate damping, yet low enough to prevent nondissipative bending of the truss components and floor slabs. In Columbia Center, where stiffness is provided by the diagonal I-beams in the structural modules, dampers were designed to provide a certain shear loss modulus, and thus adequate energy absorption.

The first step in designing a damper is to select the viscoelastic material. The material is chosen primarily for its ability to absorb energy at the temperature and frequency at which the dampers will function. The dimensions of the material, and therefore the dimensions of the damper assembly itself, are dictated by the following:

- the dynamic properties of the materials;
- total energy to be absorbed;
- number of damper sites; and
- the shear strain imposed by the building.

As the center plate in a damper moves axially in and out of the viscoelastic material, energy is absorbed and dissi-

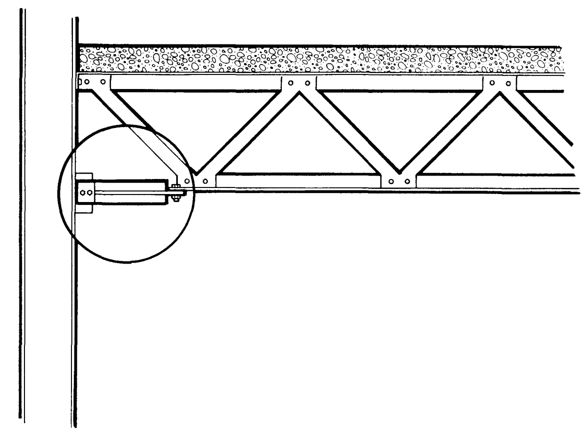

Figure 2

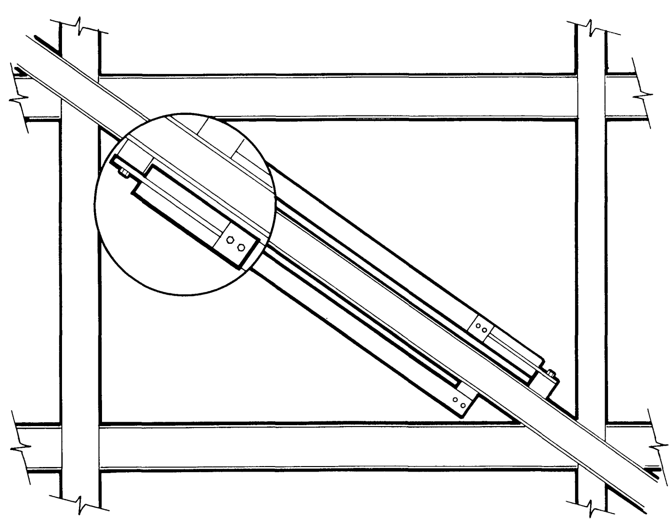

Figure 3

pated according to the equation, $W = \pi\gamma^2G''V$, where

W = energy dissipated in one cycle

γ = viscoelastic shear strain

G'' = shear loss modulus of the viscoelastic

V = viscoelastic volume

By adjusting the volume of the selected viscoelastic material (with its particular shear loss modulus), you can approach the required W, the energy each damper must absorb and dissipate to reach an acceptable percentage of critical damping for the entire structure. To understand the effect of increasing or decreasing the thickness or bonded length of the viscoelastic layers, look briefly at the variables in the energy equation.

The viscoelastic shear strain γ is the maximum cyclic displacement (zero to peak) between damper attachment points, divided by the viscoelastic thickness. The minimum allowable thickness, then, is the ratio of the maximum displacement to the maximum safe use shear strain of the viscoelastic. Beyond that, the thickness may be increased to obtain a proportionate decrease in strain. The best viscoelastic materials can withstand more than 200 percent shear strain (2 in./in.) without rupturing. However, design of the damper should be centered around a lower operating strain, at perhaps 20 to 40%, to control temperature buildup, and thus the constancy of the shear loss modulus of the viscoelastic. At lower strains, achieved by increasing the viscoelastic thickness, less energy is dissipated in the viscoelastic layers.

As previously indicated, viscoelastic thickness is a factor also in maintaining a reasonably constant shear loss modulus G'', a measure of the viscoelastic's dissipative stiffness. As thickness decreases and strain increases, temperature rises in the viscoelastic material. But G'' falls off quickly as the temperature goes up, greatly reducing damping. To maximize energy dissipation, then, the combined term γ^2G'' must be optimized. The last variable, viscoelastic volume V is the product of the thickness and shear area of the viscoelastic layers. Shear area is important because of its impact on damper cost and because it is directly proportional to the amount of energy W dissipated from a damper. Larger shear areas mean longer and wider steel components in the damper assembly, and steel is a major manufacturing cost.

Once the energy equation is balanced on paper, a test damper is assembled and tested in an electrohydraulic machine that cycles at the resonant frequency of the host building. Measured strain, shear loss modulus, energy dissipation, and other criteria of performance are compared with calculated values and, if called for, the damper is modified. In a successful design, the energy dissipated in a single damper, multiplied by the number of dampers, equals the total energy dissipation required for the building. That total is determined by computer modeling.

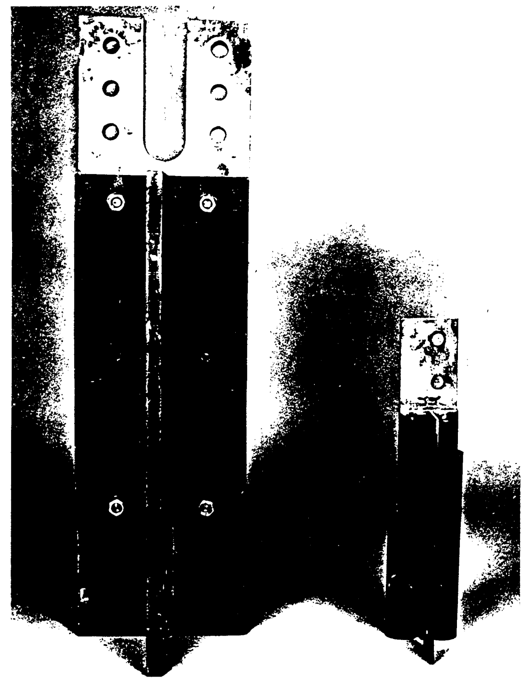

Figure 4

In comparing the final design of the dampers for the World Trade and Columbia Centers, the products varied dramatically (Fig. 4). Each of the 20,000 dampers in the World Trade Center is 4-in. wide, has a bonded length of 10 in. and dissipates about 250 in.-pounds of energy per cycle; the two viscoelastic layers are each 0.05-in. thick. Each of the 260 dampers in the Columbia Center is 12-in. wide, has a bonded length of 33 in. and dissipates about 30,000 in.-pounds per cycle; the two viscoelastic layers are each either 0.09- or 0.11-in. thick.

From laboratory tests, plus actual applications in the World Trade and Columbia Centers, it may be concluded viscoelastics will do the job of absorbing energy over many years, under a variety of environmental conditions. It may also be concluded the use of high-energy absorbing polymers in engineered dampers can help assure a dynamically stable structure.

As mentioned in the early part of this article, the use of damping devices described here are "new" in the sense they have had few applications in tall buildings. Engineers require such devices prove themselves before they are used in critical applications, and rightly so. That is beginning to happen, but because a change in the way of doing things is involved, it is a gradual process.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support received from: Leslie E. Robertson, of Robertson, Fowler & Associates, New York City, and John Skilling, of Skilling, Ward, Rogers, Barkshire, Seattle.