Annoying Floors
Help coming to keep floors from being too flexible for comfort

Blame it on the bunny hop. At least, in the final analysis. And there was lots of analysis of the structural kind after a Mary Kay cosmetics party at the Charlotte Convention Center where the ballroom started to “shake, rattle and roll” during the line dance. Even worse, just as tables trembled and water glasses wobbled, there was an alarming blast as if from a shotgun. The Mary Kay party turned into chaos as people bolted toward the door.

The architect for the then-four-month-old convention center soon got that dreaded phone call from the client. “Good gracious, yes, we were disturbed when we got the call,” said architect Harry D. Sherrill, recalling the April 1995 incident. Sherrill was project manager for the FWA Group, Charlotte, N.C.

The news was especially unsettling because the design team had informed the client that activities like aerobics would make the floor shake, and had even suggested deeper floor framing. The client’s response was, “Just give us the code,” says Lawrence G. Griffis, director of structural engineering for Walter P. Moore & Associates, Houston. So Moore designed a steel frame with a typical 90-ft-square bay, 10-ft-deep trusses and 10-ft-deep beams working compositely with a 5½-in-thick slab on metal deck.

A blizzard of tests followed the party chaos to assure the structure was safe. Mary Kay even provided its video of the party so the forensic team could watch, and even listen to, the event. Ultimately, FWA, Moore and an independent testing consultant determined that the second-level ballroom and the building in general were structurally sound and perfectly safe—even for the bunny hop.

Then why all the fuss? In the synchronized line dance, “both feet leave the floor in unison,” says Griffis, causing the floor to flex. Revealing the acceleration and feared collapse.

And the blast? The culprit may have been pyrotechnics set off coincidently on the exhibit floor below during Anway products motivational event. It may also have been “bolt banging...”
Triggered by the bunny hoppers, the frame's truss-beam connection may have slipped into bearing, says Griffis.

In the end, the designers were exonerated and no one got sued. The recommendation to the owner: Either spend big bucks to stiffen the floor or simply advise users of the ballroom's limitations. And, reserve high-impact activities for the slab-on-grade.

Griffis also stressed to the owner that shaking floors are typically a comfort issue. And comfort falls under the category of building serviceability, which is defined by Thomas M. Murray, a guru on "annoying" floors and professor of structural steel design at Virginia Tech, Blacksburg, Va., as anything related to the building structure—sway, noise, vibrations—that is not safety-related.

Ironically, the public's awareness of serviceability has been boosted by high-profile collapses, including the 1981 Kansas City Hyatt walkway, says Linda M. Hanagan, assistant professor in the Dept. of Civil and Architectural Engineering at the University of Miami, Coral Gables, Fla., and Murray's colleague. "Not that Kansas City had anything to do with serviceability," she emphasizes, but the average person mistakenly thinks it did.

Engineers stress that too-flexible-for-comfort floors rarely collapse, unless the structure happens also to have a design or construction flaw, as in Kansas City. "If you have zero damping and you hit something with a forcing frequency that is the same as the natural frequency of the structure, it will collapse," explains Hanagan. "But structures don't have zero damping," she adds.

Nevertheless, if tenants are anxious or dissatisfied, it becomes "a significant economic issue for building owners," adds Bruce R. Ellingwood, professor and chairman of Johns Hopkins University's civil engineering department, Baltimore.

Annoying floors have gotten more common over the past 30 or so years because of composite construction, better computer analysis and higher-strength, lighter-weight construction materials, says Emmanuel E. Velivasakis, vice president of Thornton-Tomasetti/Engineers, New York City. The consequence is very-low natural floor frequencies that harmonize with frequencies induced by occupants. "LRFD will make it even worse," Velivasakis warns.

Help is on the way. There have been refinements in controls to calm shaking, and the industry is paying more attention to serviceability. Next month, the first-ever recommended design criterion will be published for cold-formed C-shape-supported floors, based on tests Murray just completed for the Nashville-based Light Gauge Steel Engineers Association through the NAHB Research Center. The goal, says Nader R. Elhajj, project manager at NAHB Research Center, Upper Marlboro, Md., is to introduce the procedures into the one and two-family dwelling code.

Also in June, the American Institute of Steel Construction, Chicago, and the Canadian Institute of Steel Construction, Willowdale, Ont., are publishing the first design guide dedicated to floor vibrations due to human activity. And on June 16, AISC will kick off seminars on serviceability in steel design, to be held in 49 cities through next March. "We're coming out to talk about this because it affects our business," says Robert F. Lorenz, AISC director of education.

Murray, who will do half the floor lectures, also just developed modeling software to take some of the mystery out of floor design for serviceability. "Tom's approaches are good, and simple enough to be of use to the average practicing engineer," says Griffis. He adds that for special uses, more sophisticated software is available.

The are two types of floor vibrations, says Murray. Steady state vibrations from machinery are best dealt with by isolating equipment. Transient vibrations from low-impact activities, such as walking and dancing, and high-impact activities, such as athletics, are best muted by eliminating or relocating the culprit activity, relocating the irritated occupant, stiffening or damping the structure, or some mix of the above.

Each situation has to be custom-designed and there is no foolproof solution. Predicting a floor's response to unknown future activity and building contents is difficult, and occupant tolerance will always remain subjective, says Murray. For instance, older people are typically more sensitive than younger ones; tolerance levels change depending on the building type; and sensitivity is greater when sitting than standing, and when sitting for a longer rather than a shorter period of time.

Floor hives can interfere with operations and experiments in hospitals, laboratories and factories. In office buildings, theaters, arenas, malls and long-span or cantilevered structures, shaking can interfere with building performance and reduce worker productivity. Computer monitors rattle, lamps sway and ductwork and the like tremble, making noise. Vibrations from a single floor can actually shake up an entire building.

Often, the problem arises when use changes. Velivasakis describes the conversion of a 45-story building's top-floor, 200-psf mechanical room to an aerobic space. The activity was setting one of the elevator shaft columns in resonance, "shaking the building down to the second floor," he says.

Retrofits can be expensive. In addition to buying and installing material, there are costs for removing and replacing finishes. And often, buildings are occupied and work must be done at night and on weekends. Fixing an asbestos-laden building opens another can of worms, as does welding indoors.

It's best to design a more-serviceable floor up front, say engineers. That costs approximately $5 per sq ft of floor space, says James M. Fisher, vice president of the 50-person engineer, Computerized Structural Design, Milwaukee. The figure includes an inch thicker slab, and added steel and foundation costs.

There's a snag. Often, as in Charlotte,
the client "doesn't want to pay for anything beyond the minimum code requirements," says Terry D. Steelman, director of design for Ballinger, a Philadelphia-based architect-engineer. And value engineering out cost doesn't help floor serviceability either, he adds.

As with nonperforming curtain walls, private owners prefer to shove annoying floors under the rug. But when a problem occurs—whether a month or several years after occupancy—tenants blame landlords and landlords complain to designers, sometimes threatening a lawsuit. "Just because you end up with a bad floor doesn't mean the structural engineer is at fault," says Hanagan. "Our obligation is to provide minimum design load for a type of building," she adds. "If you give serviceability a low priority, engineers will overlook it."

Architect Jim W. Sealy, a Dallas-based building code consultant, is pragmatic about serviceability. "If you can make the client's pro forma work, you can design a building that doesn't vibrate," he says. If a client doesn't want to spend the money, a good practitioner will inform the client that the floors will vibrate, he adds.

Some designers think architecture schools should give floor vibrations more attention. While engineers are taught to consider floor vibrations, architectural graduates "don't have a clue" about the subject, says Steelman.

Ballinger has to raise the level of awareness of its architectural recruit to consider floor vibrations with other parameters early in design. Steelman adds. Typically, the project architects then present their clients with options, including tradeoffs in cost and floor performance, along with a recommendation.

For special cases, such as a health club in an office building, Ballinger calls in Cerami & Associates Inc., a New York City-based acoustic engineer that also consults on floor vibrations. One approach for a health club is to put a floor on springs, says Neil Moisey, a Cerami associate principal.

As in most architecture schools, serviceability is all but ignored in U.S. building codes. But Canada's national code has nonbinding provisions, and often, U.S. engineers refer to them and to standards developed elsewhere. The problem, says Murray, is that other countries require "much stiffer floors. It's a cultural thing." That's why Murray "finetuned" the Mether-Reister perceptibility scale to be more in line with American higher thresholds of tolerance.

Some engineers think vibration provisions should be code. "We've added everything else," says Matthias P. Levenson, principal at Weidlinger Associates, New York City. "It's an issue of good practice.

Mal P. Sacks, a principal in The Engineering Ltd., Toronto, who uses Canadian code supplement to design U.S. damping systems, agrees with Murray. "The information is out there," he says. "But it's so why not use it? It's helpful."

But Ellingwood, who tried to get serviceability into U.S. codes for 18 years, thinks most consulting engineers don't want even meaningful serviceability requirements codified. When he tried to get serviceability checking provisions into the code specification—the same for the code, he says he was "blown out of the water." When the subject is "eyes either glass or people get big." he says. Ellingwood.
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STIFFENING For high-impact activity, as in ballroom installation (at left), engineer Allen recommends adding columns or making beams deeper.

was based on a simple heel-drop test. Allen's test for aerobics was based on walking excitation. The criterion is now based less on specific impact and more on resonance, says Murray.

Resonance occurs when the forcing frequency—the frequency of the human activity—matches the floor's natural frequency. Both typically range between 1.5 and 3.5 Hz. To illustrate resonance, hold a slinky toy at one end and bounce it at different rates, and "you'll suddenly hit a place where the loose end is going all over the place," says Murray. That's the nasty resonance frequency.

To retrofit for aerobics, Allen believes in stiffening a structure by adding beam depth, columns or posts. That makes the floor's natural frequency higher than the forcing frequency, he says.

For walking activity, however, damping, which is considered less intrusive and most cost-effective, often works because the force is small compared to the size of the structure. A problem is that annoying floor motion is nonetheless minuscule and that makes improvements difficult to accomplish, says Murray. "If the floors were moving up or down in inches, it would be easy to fix," he explains. But floor amplitudes of 0.04 in. (1 millimeter) down to 0.015 in. offer little motion to work with.

Damping can be either passive or active, which requires a power source. When a floor shakes, an active system feeds accelerometer measurements into a computer that then directs a set of hydraulic jacks or other equipment to quell vibrations. Active controls are less commonly used because not only do they require a power source and a computer they need servicing.

A common passive control is a tuned mass damper. These TMDs used to reduce building

UNDER BALLROOM New York City hotel has posts with viscoelastic material.

does take credit for the general service-ability guidelines in Appendix B of the American Society of Civil Engineers Standard 7-95.

Architect Rai A. Fernandez, a senior project manager with Miami-based architect-engineer Bermello-Jamali & Partners Inc., is against mandating serviceability. "Your comfort level and mine may be very different," he says.

LITIGIOUSNESS Murray and Sealy are also against serviceability in codes because it is a comfort, not a safety issue, and as such, not easily quantifiable. And because of litigiousness, many engineers feel clients would use serviceability provisions, binding or not, "as a club to beat them over the head," says Ellingwood, adding, "I can sympathize with that."

Murray may not believe in mandating serviceability, but he does think the design tools need improvement. The AISC-CISC design guide, which he co-authored, even includes a section on sensitive equipment by Eric E. Ungar, chief engineering scientist at Acen-tech Inc., Cambridge, Mass.

The guide combines the historically different approaches of Murray and co-author David E. Allen, Canada's now-retired expert on high-impact aerobics-induced floor vibrations. Formerly, Murray's mathematical model for walking activity...
way but much smaller, floor TMDs, operate much like a car’s shock absorber by fastening a mass block to a structural component using a spring and a damper containing a viscous material. The material dissipates energy as heat.

**Dissipated** During damper installation, its natural frequency is tuned so that it is slightly less than the frequency of the original structure. The amount of energy dissipated is related to the size of the TMD’s mass.

Typically, the viscous material is an oily substance, which can leak. To avoid that, 3M Co., St. Paul, Minn., is developing a TMD using a solid polymer, says Ming-Lai Lai, a 3M research specialist. The patented viscoelastic TMD weighs about 10 lb and will handle 100 lb, says Lai. It “worked very well” in tests at Virginia Tech, but none have been sold.

Hanagan, while earning her doctorate under Murray at Virginia Tech, developed an active control called an electromagnctic shaker or mass actuator. The inertial effect of the actuator can be programmed to counteract the movement of the floor. “When you send voltage, magnets push from the induction coil, causing displacement in mass,” says Hanagan. For the same amount of mass as a TMD, the actuator offers 30 times the control, says Hanagan, who is refining control algorithms to get even more from a single actuator. Currently, the cost of a setup for 100 sq ft or one bay is about $18,000. There are no permanent installations.

However, there are permanent TMDs, and they have proven themselves over time. Weidlinger Associates designed an installation of four 20-kip TMDs to calm the four corner, cantilevered dance floors of the Terrace on the Park building in Flushing, N.Y., that was built on “stilts” for the 1964 World’s Fair.

For ease of acquisition and installation, each damper was made of un reinforced concrete, field-assembled structural steel and off-the-shelf hardware. The mass blocks are stacked, 220-lb steel plates, for easy delivery, says Levy. They are set on a steel-encased concrete box that sits on springs. Two 19-ft-long guide posts, which run from the floor of a closet to a roof floor beam above, were spliced twice to fit into the freight elevator.

The $200,000-plus project, completed in 1991, had all the headaches of a retrofit. Crews, restricted to one service elevator, had to wrap up work by 2:30 p.m. every day, to leave the caterer enough time to prepare for evening events. That included hiding any evidence of work.

Being unable to predict exact dancing-triggered vibrations, the TMD’s natural frequency was tuned close to but not exactly at the excited floor frequency under actual conditions, explains Levy. Tests showed that the TMDs reduced floor vibrations by 60% to barely perceptible levels. And restaurant-goers stopped complaining, he adds.

For a 28,000-sq-ft, too-flexible ballroom with 112-ft spans at the Marriott Marquis Hotel in Manhattan, Weidlinger opted for passive controls but not a TMD. The firm specified adding Bimeta steel pipes under three girders at the floor’s center. Each pipe is connected to a girder by a viscoelastic material, which breaks the structural continuity of the strut, says Levy. Vibrations are reduced as the material is sheared with each floor oscillation and mechanical energy is converted to heat. The $100,000 installation cut floor deflections in half and reduced perceived vibration levels from distinctly to slightly perceptible. Ten years have passed without any complaints, reports Levy.

Another successful retrofit, about 10 years old, is in New York City’s LaGuardia High School. There, activity in a third-floor gymnasium was disturbing school administrators in offices directly below and students using a theater below that. “We found that the fundamental frequency of the gym floor, at 4.5 Hz, was in resonance with the second harmonic of the forcing function frequency, 2.3 Hz, as though the gymnaasts were loading the floor on every downward swing,” says Velivasakis, whose firm designed the fix. The gym floor had little damping, which would have helped absorb and attenuate vibrations, he adds.

Columns could not be added, as they would interfere with the theater, so Thornton-Tomasetti devised a system of TMDs installed under the gym floor. Building occupants reported “dramatic improvement,” though gym activity is still noticeable, says Velivasakis.

Despite reported successes, Murray and Hanagan are skeptical about offering any guarantees to clients that even a design by an engineer experienced in floor calming will actually work. And, they say lots more research into serviceability design is necessary. “Bottom line,” says Murray, “is that it is still very much a developing art.”

*By Nadine M. Post in Blacksburg and Coral Gables*