All Shook Up

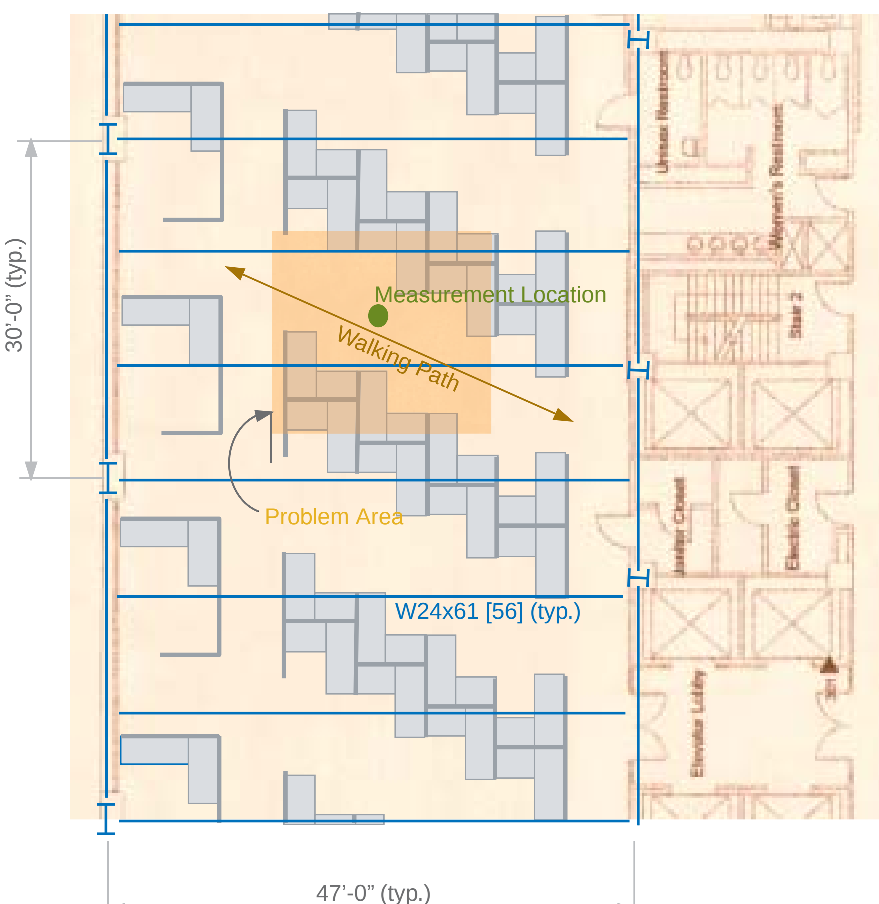
By Hillary A. Lichtenstein

When a convoy of 18-wheelers rolls by, no one is surprised to feel the ground shake. But what if merely tapping your foot was enough to make your entire office floor vibrate?

This was just the problem at a Voorhees, NJ, office building. Built in 1972, the building experienced no vibration problems until the walls on one floor were removed to accommodate open-plan offices. When the new tenants occupied the space in 2002, building management received an earful of vibration complaints.

"In the case of the New Jersey building, one office worker had a nervous twitch in his leg and it bounced all day long," explained Jerry Duffy, a consultant for Vibration Specialty Corporation (VSC). "The floor was extremely sensitive to movement after the walls were removed, and this small movement was enough to get the floor really moving." He explained that floor vibration is a very common problem in open-office spaces, but it is less likely in older buildings that feature heavy office partitions. However, once walls are removed on a floor, floor vibrations often become much more noticeable.

What made the problem especially vexing was that there was no hint of a vibration problem in the three decades since the building was constructed in the early 1970s.



Built in 1972, this office building never experienced a vibration problem until this floor was converted to an open-office layout.

Diagnostic Tests

Initially, the complaints were chalked up to one "picky" person. However, after more complaints were received the owners paid to have the facility analyzed—and they were surprised to discover they indeed had a problem, even after 30 years of successful building operations. An accelerometer was placed at the center of the problem area and it was discovered that the acceleration amplitudes were greater than the 0.005 g recommended by Thomas Murray, Ph.D., P.E. of Virginia Tech in AISC's *Design Guide 11: Floor Vibrations Due to Human Activity*.

"If you jump on a floor," Duffy explained, "the initial movement will occur no matter what. What makes people uncomfortable is the 'ringing' of the floor for a few seconds after that first movement. If you're sitting in front of a computer screen for eight hours, it's going to become quite bothersome."

VSC was originally called to the building to see if the building's rooftop pumps and air handling equipment were the cause of its vibration problems. "We didn't know what to expect when we went in to check out the problem," said Duffy. "So, we measured vibration throughout the building in identified problem areas." Vibration measurements were taken while the equipment operated, but no definitive conclusions could be drawn.

Back for a second investigation, VSC worked backwards to figure out the problem. One test done by VSC involved installing a vibration absorber, which is a tuned spring. The absorber didn't help and was soon taken out. Another test used stiffeners and wooden posts to ease the problem. While that approach quieted the vibrations on the problem floor, it transmitted vibration down to the floor below.

"There was so much floor vibration that a tenant one floor below could see

Software **Solutions**

Jason Ericksen, S.E., director of AISC's Steel Solutions Center (SSC) and Todd Alwood, SSC advisor, spoke with **Chris Minichiello**, P.E., vice president of RISA Technologies and **Allen Adams**, S.E., chief structural engineer of RAM International to hear about floor vibration capabilities of their respective software products.

Q How does the software implement the guidelines from AISC's *Design Guide 11*?

Minichiello: As a standard part of every design, RISAFloor checks every floor-framing member for its vibration characteristics right along with the strength and deflection calculations. Adjustments for stiffness, effective width, interior edges and other special cases are automatic. The analysis includes results for individual beam panels and combined beam-girder panels. The user can then plot frequencies and accelerations graphically to quickly determine where floor vibration issues might arise. The engineer determines how to address vibration problems in design.

Adams: The Beam Design module of the RAM Structural System V9.0 (January 2005) will identify bays with framing configurations that should be checked for vibration behavior. The user then selects a bay and verifies the information and assumptions that will be used in the vibration analysis. A program called FloorVibe—developed by Thomas Murray, P.E., of Structural Engineers, Inc., one of the co-authors of *Design Guide 11*—implements those guidelines. FloorVibe will be automatically launched from the RAM Structural System, with the bay information passed from one program to the other. The vibration analysis is then done for each floor panel. FloorVibe V1.2 will be bundled with the RAM Structural System V9.0 for clients with a current support agreement.

Q For which activities does the software check the floor?

Minichiello: The current version of RISAFloor (released April 2002) evaluates vibration serviceability to walking excitation. RISAFloor V2.0, due out in January 2005, adds checks for sensitive equipment and rhythmic activities.

Adams: In the upcoming release of the RAM Structural System V9.0 (January 2005), the link to FloorVibe will be available. At that time the user will have all the capabilities of FloorVibe (Structural Engineers, Inc.), including walking excitation, sensitive equipment and rhythmic excitation. Vibration analysis can be performed on floor systems consisting of composite and noncomposite hot-rolled and built-up steel beams, steel joists and SMI Smartbeams.

Q How does your software deal with irregular or skewed framing?

Minichiello: All members are evaluated—even those with skewed and irregular framing. The criteria are followed as closely as possible in these areas. Per *Design Guide 11*, RISAFloor averages joist lengths and bases calculations on smaller girder frequencies. A further option is to pass the framing to RISA-3D to perform a finite element analysis and determine member frequencies for irregular framing.

Adams: *Design Guide 11* serves two functions. First it identifies framing configurations that have experienced problems in the past and, second, sets forth a procedure to evaluate these configurations. Basically, the regular or nearly regular framing is the type of framing that has the most potential for vibration problems. RAM identifies such bays where vibration is a potential concern and performs the vibration analysis by launching FloorVibe. Vibration involves a complex interaction between the slab, beams, girders and even the columns. In order for the vibration to reach a point where it is perceptible, each of those elements and members must be acting in unison, in resonance. If they are not, the vibrations are unlikely to reach a point where they are significantly perceptible. Bays of irregular and skewed framing do not act in unison because their individual fundamental frequencies conflict, and hence generally do not need to be analyzed for vibration. RAM marks these areas, and analysis is not performed. ★

	RISA Technologies	RAM International
program	RISAFloor V1; RISAFloor V2	RAM Structural System V9.0
released	V1, April 2002; V2, January 2005	January 2005
references	AISC *Design Guide 11*	AISC *Design Guide 11*
reports	reports complete panel/bay results for each member	looks at vibration in each panel/bay
capabilities and checks	girders alone; beam panels and combined beam-girder panels; V1 checks walking; V2 also checks rhythmic & sensitive equipment; ability to use FEA in RISA-3D to find frequency.	checks walking, rhythmic, & sensitive equipment on composite and noncomposite hot-rolled and built-up steel beams, steel joists and SMI Smartbeams; integrated w/ FloorVibe V1.2 (Structural Engineers, Inc.).
graphics	graphical display of frequency and acceleration	graphical indication of analysis required per bay
website	**www.risatech.com**	**www.ramint.com**

ripples of water in a goldfish bowl every time an upstairs tenant walked the floors," said Duffy.

Expert Opinion

VSC sought more solutions. They tried reducing the amplitudes of floor vibrations by adding mass (they rolled 1,000-lb elevator weights onto the floor), but that didn't help. Numerous experiments were conducted with several devices from a variety of companies, but nothing seemed to work. "Adding columns seemed to be the most significant recommendation," said Duffy, "but it would have been expensive and would significantly reduce usable floor space. Also, they could have built more partitions, but that would have dramatically altered the desired office setting." Likewise, beam stiffening was rejected since it would have been costly and also would have required tearing out the suspended ceiling below, which would have disrupted the occupants on the lower floor.

A search of the Internet for alternative solutions turned up a possible answer to the building's vibration woes—a device called an "active control system" built by Linda Hanagan, Ph.D., P.E., a Penn State architectural engineering professor and floor vibration researcher.

Hanagan explained that during the early 1970s—at the time this building was constructed—proper floor vibration criteria were not readily available. Also, open-plan offices weren't nearly as common. "Design methods have really changed over the years, and lighter floors and open floor plans can make a difference in a building's floor vibration behavior," said Hanagan. "Now," she continued, "well-established criteria exist in AISC's *Design Guide 11*. A problem floor can generally be avoided if it's designed to satisfy the criteria in the guidelines."

Researching a Cure

Every structure will have some degree of vibration, but those vibrations are not usually a problem as long as the structure's damping and stiffness characteristics are within a certain range. For example, the frequency of someone walking is usually about 2 Hz or a multiple of 2 Hz. If the fundamental frequency (or resonant frequency) of a floor structure is also about 2 Hz, then the walking motion can case the floor to resonate (the amplitudes of the vibration will become very large) unless the structure has sufficient damping characteristics.

Floor vibrations in the 4 Hz to 8 Hz range—where humans are most sensitive—are most often associated with significant discomfort. "Major organs in the chest cavity resonate in that frequency range," said Duffy. Since floors also have resonant frequencies in this range, people are disturbed by even very small amplitudes of floor vibration. In the New Jersey office building, the readings indicated that the natural frequency of the floor system was 4.7 Hz. At this frequency, a sinusoidal motion with peak amplitudes as small as 0.003" will be perceptible and possibly disturbing.

Vibration frequency is proportional to $(k/m)^{1/2}$, where k = stiffness and m = mass. Removing the walls from a floor plate affects damping, stiffness and mass. "The removal of walls," said Hanagan, "can have a significant negative impact on the floor's vibration behavior." According to Hanagan, when older office buildings are remodeled as large spaces with open floor plans, they may experience vibration problems that were never evident before.

The Treatment

Hanagan's solution is what she calls an "active control system." The active control device is composed of four primary parts: an electromagnetic proof-mass actuator, an amplifier, a velocity sensor, and an electronic feedback controller. The velocity sensor detects the motion of the floor; the electronic feedback controller responds to the velocity signal by sending a control signal to the actuator; the control signal makes the reaction mass of the actuator move to generate the control forces that add damping and counteract the resonant motion of the floor. In the case of the New Jersey building, the active control system uses a 100-lb weight attached to a 20"-high linear motor.

Richard Pietropoli, senior vice president of Arden Group (parent company of Arden Echelon Partners, LLC, mangers of the New Jersey building), purchased Hanagan's device. VSC, along with Hanagan, installed and tested it.

"We came in on a Saturday to try it out, and it was up and running within hours," said Duffy. "The system just sits on floor, and we covered it to make it look like a file cabinet. It's really a self-contained unit, and it can be placed anywhere you have a problem." In fact, Hanagan noted the device could even have been installed in the ceiling cavity below. The device has been successfully operating in the building since November 2002.

The Bill

Costs associated with fixing vibration problems after the building is already constructed can be high, but the legal fees that may surface if the tenant sues building management can be even higher. Although Hanagan's system was a one-of-a-kind creation that came with a pretty steep price tag (about $35,000), it still cost less than the attorney's fees for litigation.

"This case study illustrates that if you build a floor that doesn't meet acceptable vibration criteria, the floor might be problem years from now," said Hanagan. She suggests that if a buyer chooses an already constructed building, they should consider making vibration assessment and remediation part of the cost evaluation.

In new construction, it's often difficult to convince building owners and developers to go with a slightly more expensive floor system that results in better vibration characteristics. "Unfortunately, many developers are persuaded that floor vibration is a serious concern only after their first costly legal struggle." "However," Hanagan adds, "the old adage still apples: an ounce of prevention is worth a pound of cure." ★

Hillary A. Lichtenstein is a former assistant editor of Modern Steel Construction.

AISC members and ePubs subscribers can download a free copy of *Design Guide 11: Floor Vibrations Due to Human Activity* by visiting **www.aisc.org/vibration**.

An active control system for reducing unwanted floor vibrations. The system installed in the New Jersey office building was approximately 20" tall and "camouflaged" in an enclosure to blend with the office furniture.