System predicts how tall structures respond to vibrations, may help monitor stress over time

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(Left to right): M. Nafi Toksöz, professor in the Department of Earth, Atmospheric and Planetary Sciences (EAPS); Oral Buyukozturk, professor in the Department of Civil and Environmental Engineering (CEE); and Hao Sun, a postdoc in CEE. The Green Building, behind them, has 36 accelerometers that record vibrations and movements on selected floors, from the building's foundation to its roof. Credit: Jose-Luis Olivares/MIT

When a truck rumbles by a building, vibrations can travel up to the structure's roof and down again, generating transient tremors through the intervening floors and beams.

Now researchers at MIT have developed a computational model that makes sense of such ambient vibrations, picking out key features in the noise that give indications of a building's stability. The model may be used to monitor a building over time for signs of damage or mechanical stress. The team's results are published online in the journal Mechanical Systems and Signal Processing.

"The broader implication is, after an event like an earthquake, we would see immediately the changes of these features, and if and where there is damage in the system," says Oral Buyukozturk, a professor in MIT's Department of Civil and Environmental Engineering (CEE). "This provides continuous monitoring and a database that would be like a health book for the building, as a function of time, much like a person's changing blood pressure with age."

Buyukozturk's co-authors Hao Sun, a CEE postdoc who was the paper's lead author; Aurélien Mordret, a postdoc in the Department of Earth, Atmospheric and Planetary Sciences (EAPS); Germán Prieto, the Cecil and Ida Green Career Development Assistant Professor in EAPS; and M. Nafi Toksöz, an EAPS professor.

Taking vital signs

The team tested its computational model on MIT's Green Building—a 21-story research building made completely from reinforced concrete. The building was designed in the 1960s by architect and MIT alum I.M. Pei '40, and stands as the tallest structure in Cambridge, Massachusetts.

In 2010, Toksöz and others at MIT worked with the United States Geological Survey to outfit the Green Building with 36 accelerometers that record vibrations and movements on selected floors, from the building's foundation to its roof.

"These sensors represent an embedded nervous system," Buyukozturk says. "The challenge is to extract vital signs from the sensors' data and link them to health characteristics of a building, which has been a challenge in the engineering community."

To do this, the team first built a computer simulation of the Green Building, in the form of a finite element model—a numerical simulation that represents a large physical structure, and all its underlying physics, as a collection of smaller, simpler subdivisions. In the case of the Green Building, the researchers built a high-fidelity finite element model, then plugged various parameters into the model, including the strength and density of concrete walls, slabs, beams, and stairs in each floor.

As the model is designed, researchers should be able to introduce an excitation in the simulation—for example, a truck-like vibration—and the model would predict how the building and its various elements should respond.

"But the model uses a lot of assumptions about the building's material, its geometry, the thickness of its elements, et cetera, which may not correspond exactly to the structure," Buyukozturk notes. "So we are updating the model with actual measurements to be able to give better information about what may have happened to the building."

Hao Sun holds an example of a sensor. “I would envision that, in the future, such a monitoring system will be instrumented on all our buildings, city-wide,” says Sun. “Outfitted with sensors and central processing algorithms, those buildings will become intelligent, and will feel their own health in real time and possibly be resilient to extreme events.”. Credit: Jose-Luis Olivares/MIT

Mining for features

To more accurately predict a building's response to ambient vibrations, the group mined data from the Green Building's accelerometers, looking for key features that correspond directly to a building's stiffness or other indicators of health. To do this efficiently, the team developed a new method with the seismic interferometry concept that describes how a vibration's pattern changes as it travels from the ground level to the roof.

"We look at the foundation level and see what motions a truck, for instance, caused there, and then how that vibration travels upward and horizontally, in speed and direction," Buyukozturk explains.

The researchers added this equation to their model of the Green Building and ran the model multiple times, each time with a set of measurements taken by the accelerometers at a given point in time. In all, the group plugged into the model vibration measurements that were taken continuously over a two-week period in May 2015.

"We are continuously making our computational system more intelligent over time, with more data," Buyukozturk says. "We're confident if there is damage in the building, it will show up in our system."

Intelligent buildings

So how has the Green Building fared since its construction more than 50 years ago?

"The building is safe, but it is subject to quite a bit of vibration, particularly in the upper floors," Buyukozturk says. "The building, which is built on soft soil, is long in one direction and narrow in the other with stiff concrete walls on each end. Therefore, it manifests torsional movements and rocking, especially on windy days," he says.

The team plans to verify its computational model with experiments in the lab. The researchers have constructed a 4-meter-tall replica of a building structure, which they will outfit with accelerometers. They will study the effects of ambient vibrations, as well as how the structure responds to hammer strikes and other seismic stimuli. The team is also erecting a large steel structure in Woburn, Massachusetts, about the size of a cellphone tower, and will carry out similar experiments that will ultimately help to refine the researchers' computational model.

"I would envision that, in the future, such a monitoring system will be instrumented on all our buildings, city-wide," says lead author Hao Sun. "Outfitted with sensors and central processing algorithms, those buildings will become intelligent, and will feel their own health in real time and possibly be resilient to extreme events."

More information: Hao Sun et al. Bayesian characterization of buildings using seismic interferometry on ambient vibrations, *Mechanical Systems and Signal Processing* (2017). DOI: 10.1016/j.ymssp.2016.08.038

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