Acoustics • Shock • Vibration • Signal Processing **January 2002 Newsletter**

Happy New Year!

Buildings must withstand gravity, wind, and earthquake loads.

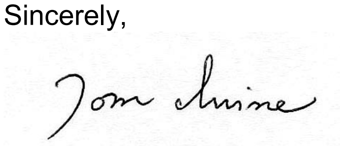
Both wind gusts and earthquakes can excite a building's natural frequencies, causing a resonant response. In extreme cases, a building may even have a structural failure or collapse.

This issue examines three buildings with respect to dynamic environments.

The first building is the Citicorp Tower in New York City. This building has a tuned mass damper designed to counteract building swaying caused by wind gusts. These wind gusts could potentially reach hurricane speeds.

The next building is the Olive View Hospital in Sylmar, California. This hospital partially collapsed during the 1971 San Fernando Earthquake. It was later demolished. A new Olive View Hospital was built in 1976. The new hospital successfully withstood the 1994 Northridge Earthquake.

Sincerely,



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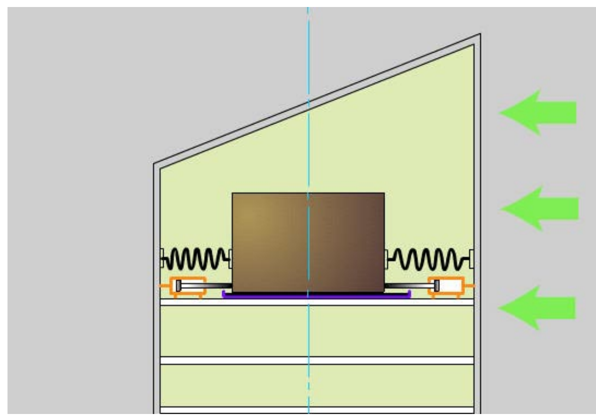
Feature Articles



Vibrationdata Announces

Shock & Vibration Response Spectra & Software Training Course

Course Benefits

This training will benefit engineers who must analyze test data, derive test specifications, and design isolation systems, with respect to shock and vibration environments.

Engineers in the aerospace, automotive, medical, petroleum, and semiconductor industries can apply the course materials to solve real-world vibration problems.

Course Description

- The course includes viewgraph presentations as well as hands-on software training
- Each student will receive a licensed copy of MIT's EasyPlot software
- Each student will receive software programs which perform the following calculations:

  Power Spectral Density (PSD), Fast Fourier Transforms (FFT), Shock Response Spectrum (SRS), and digital filtering

- Students will receive data samples so that they can practice using the software programs
- Students are also welcome to bring their own data samples

Dates for 2002 Courses

January 10-12, March 13-15,
April 17-19, May 15-17,
June 12-14, July 10-12,
September 10-12,
November 5-7

Location

Mesa Commerce Center
1930 S. Alma School #B-219
Mesa, Arizona 85210

Students may also arrange for onsite training.

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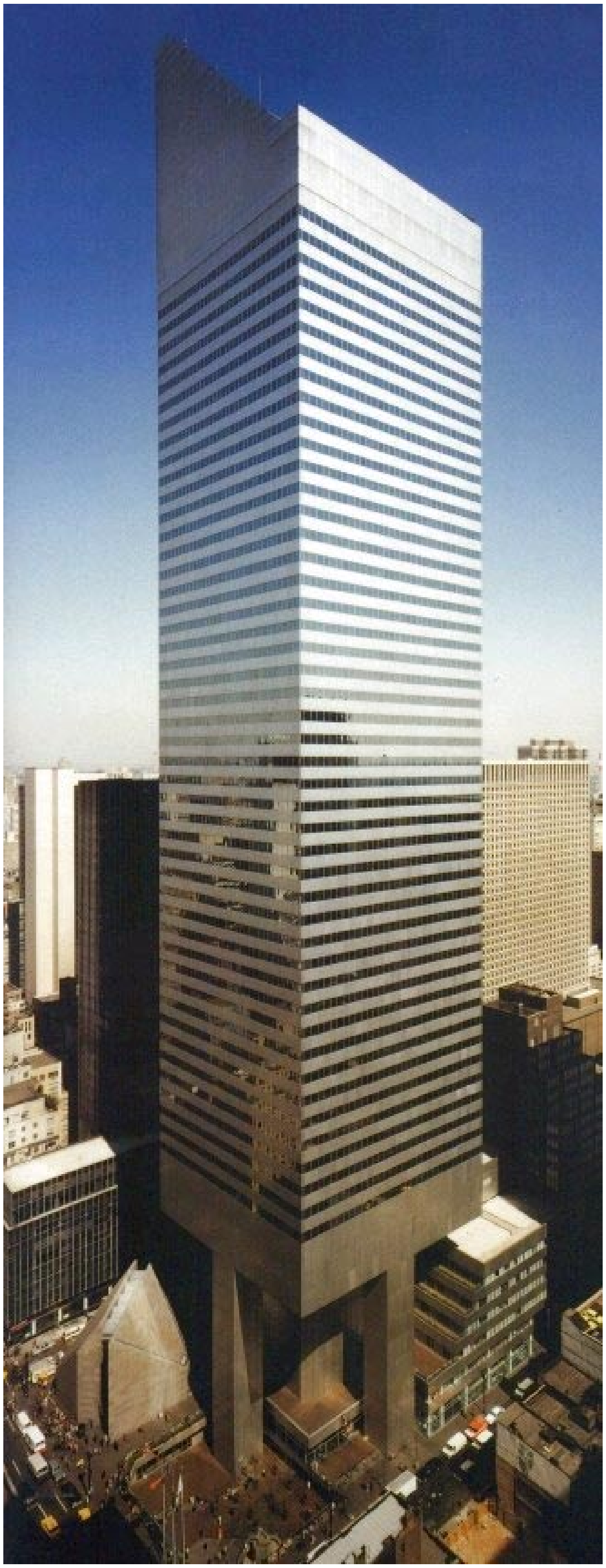

Figure 1-1.

The Citicorp Building Tuned Mass Damper

By Tom Irvine

Introduction

The Citicorp Tower is located in Midtown Manhattan, New York City. It was opened in 1977.

It has 59 stories, with a height of 915 feet (279 meters). It is constructed from steel beams, with aluminum and glass cladding.

William LeMessurier was the chief structural engineer.

The St. Peters Lutheran Church congregation owned a portion of the land that was needed for the Tower. The original St. Peter's Church was built on this land in 1862. The congregation agreed to sell some of the land to Citibank provided that a new church would be built in place of the old one with "nothing but free sky overhead." Furthermore, the congregation also required a hospitality plaza.

To accommodate these requirements, the Tower was designed so that it is 10 stories above street level on four 17.5-foot columns and a central core. The columns are like stilts.

Furthermore, the four base columns are located beneath the middle of each edge, rather than beneath the four corners. This unusual design is show in Figure 1-1.

Wind Loading

Buildings in New York City must withstand hurricane winds, with gusts up to 100 miles per hour.

The current city building code requires that the buildings must withstand wind pressure of 40 pounds per square foot, per Reference 1. Note that the pressure is proportional to the wind velocity squared.

The Empire State Building, for example, has a very stiff steel frame structure, with beams and columns that are rigidly connected. Furthermore, it is clad with heavy masonry walls, made from limestone and granite. The friction between the wall sections and structural elements provides a relatively high amount of damping. As a result of its high mass, high stiffness, and high damping; the Empire State building is able to resist wind loading.

Most skyscrapers built since World War II, however, are clad with aluminum and glass. Cost is perhaps the main reason for this trend. Consequently, these buildings have mass, stiffness, and damping values that are relatively low. These buildings thus tend to be more susceptible to wind loading, than traditional masonry-clad buildings.

In the Citicorp Tower, the wind load plus one half of the gravity load is directed to the trussed fame on the outside of the Tower. The core carries the remaining gravity load.

Specifically, the building frame has a unique set of diagonal steel cross-beams set in a chevron pattern to transfer the loads to the base columns.

A design goal for the Citicorp building, however, was to minimize the weight of the beams and columns.

As a result, the Citicorp Tower is an unusually lightweight building, with twenty-five thousand tons of steel in its skeleton. In contrast, the Empire State Building has a sixty-thousand ton superstructure.

For most buildings, the main concern in regard to wind loading is the comfort of occupants on the upper floors, who might become seasick if the building swayed too much. Even aluminum and glass-clad buildings are strong enough that structural collapse is unrealistic, barring a tragic terrorist act.

For particularly sensitive buildings, such as the Citicorp Tower, structural collapse is a vital concern, although this possibility was not fully addressed until one year after the building had been completed.

Citicorp Tower Dynamic Properties

The Citicorp Tower has a period T = 6.5 seconds, which corresponds to a natural frequency fn = 0.15 Hz, according to Reference 2. Wind gusts can excite this natural frequency.

The building's Inherent damping ratio is 1%, not including the effect of the tuned mass damper.

Tuned Mass Damper Theory

Isaac Newton wrote as his first law of motion that a mass either remains at rest or moves at a constant velocity unless acted upon by an unbalanced force. This law is also referred to as the principle of inertia. A tuned damper consists of a concrete block weighing many tons, set on a thin layer of oil at the top of the building. Steel springs and shock absorbers connect the mass to the building's outer walls.

As the building begins to sway back and forth, the inertial mass tends to remain still, relative to a fixed point on the ground outside the building. The building thus slides under the mass on the oil layer. As this happens, the springs on one side of the mass are compressed and thus try to push the building back to its rest position. At the same time, the springs on the other side are stretched and try to pull the building back. This explanation is taken from Reference 3.

Now consider that video camera is mounted on the building floor and pointed at the mass. A person watching the video would think that the building remained still while the mass oscillated. Again, the mass tends to remain still relative to a fixed point on the ground. The mass does experience a relative displacement, however, as measured from a moving point at the top of the building.

Furthermore, the mass damper system must be tuned to have the same natural frequency as the building's natural frequency, in order to optimize the vibration attenuation.

The building and mass damper motion is illustrated in Figures 1-2 and 1-3.

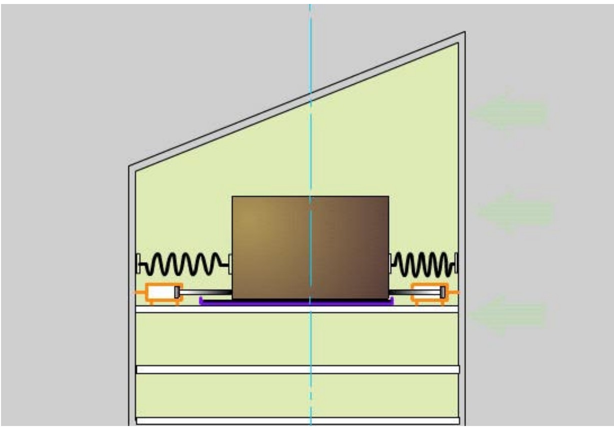

Figure 1-2. Building's Far Left Position

The wind pushes the building to the left. The mass remains still relative to a fixed point on the ground outside the building. The mass experiences a displacement to the right, however, relative to the building's moving walls.

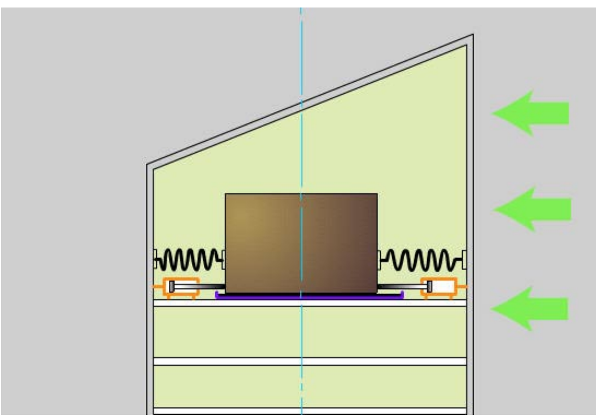

Figure 1-3. Building's Far Right Position

The building sways back to the right, past its rest position. The mass continues to remain still relative to a fixed point on the ground.

Citicorp Tuned Mass Damper

The Citicorp Tower was designed with a tuned mass damper in order to control the swaying induced by wind. It was the first building to have such a system.

The 400-ton mass damper is located in a room at the top of the Citicorp building. The block is supported on a series of twelve hydraulic oil bearings.

The mass damper is tuned to be "biaxially resonant" with a variable operating period of 6.25 sec, and with a margin of ±20%. Its damping rate is adjustable from 8% to 14%.

Furthermore, the springs are designed to have a peak displacement of ±55 inches (1.4 meters).

The damper is designed to reduce the building sway by 50%. This reduction corresponds to increasing the basic structural damping by 4%, to a total of 5%.

The damper system is activated whenever the horizontal acceleration exceeds 0.003 G for two consecutive cycles. This acceleration corresponds to a peak-to-peak displacement of 2.6 inches (6.6 cm) assuming that the swaying is occurring at the natural frequency of 0.15 Hz.

Once activated, the damper continues until the acceleration does not exceed 0.00075 G in either lateral axis over a 30-minute interval.

For activation, a separate hydraulic system raises the block mass about 3/4 inch (2 cm) to its operation position in about 3 minutes.

Design Problem and Modification

Note that wind causes tension in the building's structural members, while the gravity load causes compression. The joints must be strong enough to withstand the differential loading.

William LeMessurier, the chief structural engineer, had specified welded joints for the diagonal braces. The contractor, however, used bolts instead, which were significantly cheaper and faster to install. The bolted joints were weaker than the specified welded joints. Nevertheless, this substitution was considered within the realm of standard engineering practice.

In 1978, William LeMessurier realized the potential consequence of the bolted joints. He performed some calculations and carried out some wind tunnel tests on a scale model of the building.

The resulting data revealed that the that the building had a 50% chance of collapsing if exposed to a sustained wind speed of 70 mph (113 km/hr) for five minutes. Such a wind event had the probability of occurring once in sixteen years.

When the steadying influence of the tuned mass damper was factored in, the probability dwindled to once in fifty-five years. But the damper required electric current, which might fail as soon as a major storm hit.

The first step was to provide an emergency generator for the damper.

Next, the structural problem was fixed by a massive effort to weld two-inch thick steel plates over each of the joints. This reinforcement project lasted from August unit October.

A dangerous situation threatened to develop, however, in the middle of the project. Shortly before dawn on Friday, September 1st, weather services reported that Hurricane Ella, was off Cape Hatteras and heading for New York. Fortunately, the storm veered out to the sea.

References

1. A. Hayashi, Winds of Change, Scientific American, January 2002.
2. J.J. Conner, Introduction to Structural Motion Control, MIT Web Book, July 2001.
3. M. Levy and M. Salvadori, Why Buildings Fall Down, Norton, New York, 1992.

Seismic Response of the Olive View Hospital

By Tom Irvine

Introduction

The Olive View Hospital is located in Sylmar, California. It was built in 1964, in compliance with the earthquake codes of that time. It partially collapsed, however, during the 1971 San Fernando Earthquake. It was later demolished.

A new Olive View Hospital was designed in 1976. The new hospital successfully withstood the 1994 Northridge earthquake, although with some peril.

This article discusses the structural response of each hospital to its respective earthquake event.

1971 San Fernando Earthquake

The San Fernando Earthquake occurred on February 9, 1971. It had a magnitude of 6.5. The shaking lasted about 60 seconds. The resulting death toll was 65.

The Olive View Hospital sustained heavy structural damage as a result, even though it was considered to be earthquake-resistant. Four five-story wings pulled away from the main building and three stair towers toppled.

The building's failure was due to both design and workmanship flaws.

As the ground shakes, a building's mass elements undergo acceleration, thus developing inertial loads. The dynamic loads from these reactive elements must be carried across floors diaphragms to vertical elements in the lateral load system, and then to the foundation, and finally to the ground.

The building must have a continuous load path from the roof to the foundation to safely carry these loads.

The Olive View Hospital building had vertical shear walls in its upper stories to carry the inertial loads. The first floor, however, did not have shear walls. Instead, the load was carried by the first story columns down to the foundation.

This discontinuous design thus has a "soft first story." As a result the first story columns failed, as shown in Figures 2-1 through 2-3.

One of the first story columns underwent 0.81 meters of lateral displacement in a clear height of 4.27 meters, resulting in an interstory drift index of 0.19.

Poor workmanship also contributed to the building's failure. The first story columns were spirally reinforced, but the spiral ended prematurely at the top of each column. Thus the spiral did not connect to spandrel girder. As a result, a "plastic joint" was created that was unable to provide the needed lateral confinement.

Figure 2-1.

Figure 2-2.

Figure 2-3.

(Figures 2-2 and 2-3 are courtesy of the University of Berkeley)

The Olive View Hospital suffered other structural failures as well.

A cantilever beam protruding from a roof is shown in Figure 2-4. The beam underwent such a high bending stress that it fractured as shown in Figure 2-5.

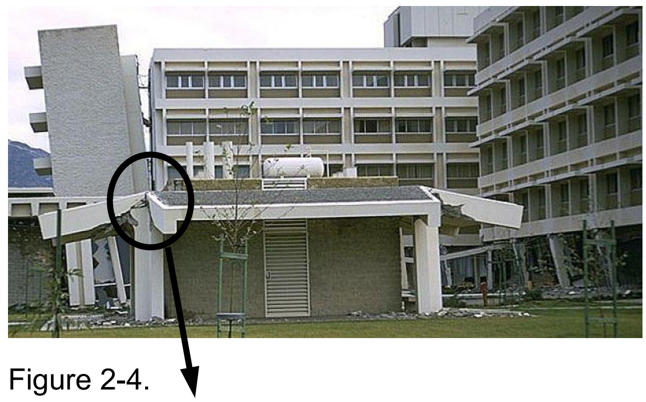

Figure 2-4.

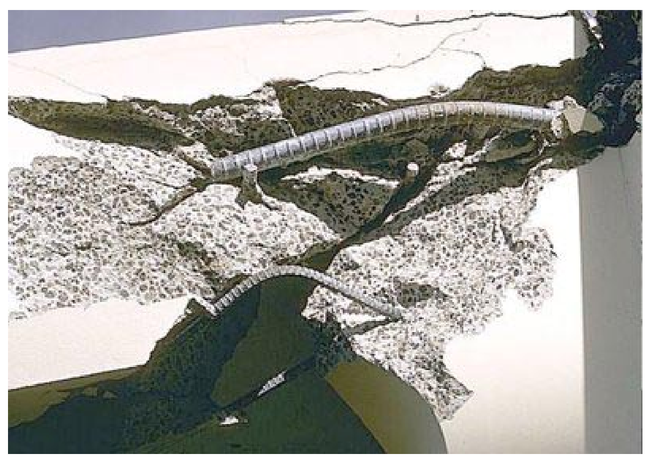

Figure 2-5.

(Figures 2-4 and 2-4 are courtesy of the University of Virginia)

The bending stress causes both axial tension and compression. The top bar in Figure 2-5 was subject to high tension. The lower bar buckled in compression.

New Olive View Hospital, Designed in 1976

The new Olive View building, shown in Figure 2-6, was designed to withstand increased levels of ground motion, based on the lessons of its predecessor. It is very strong and stiff. The foundation consists of spread footings and concrete slab-on-grade for the first floor. The first and second stories are built of concrete shear walls 25 centimeters thick. Steel shear walls are used for remaining upper stories.

Figure 2-6.

1994 Northridge Earthquake

The Northridge earthquake occurred at 4:30 a.m. local time on January 17, 1994. Northridge is located about 30 km northwest of Los Angeles.

This earthquake had a 6.8 magnitude. The hypocentral depth was 19 km. The duration was about 10 seconds to 20 seconds. The earthquake occurred along a "blind" thrust fault, close to the San Andreas Fault. Note that a blind fault is a fault that does not extend to the surface. It is thus buried.

Accelerometers were mounted in the Olive View Hospital and on the adjacent ground. The peak ground level was 0.91 G. The peak roof level was 2.31 G. These values are taken from Reference 2-1. The hospital thus amplified the ground motion.

The building structure's fundamental frequency is estimated at 2.5 Hz in the north-south direction. This building undergoes a rocking mode at this frequency.

The dominant earthquake excitation at the hospital's foundation was in the 2 to 3 Hz domain. The dominant frequency is largely a result of the local soil conditions. It thus represents the site ground response to the seismic waves.

Thus the building natural frequency and the site excitation frequency were nearly the same, causing the building to undergo a resonant response.

Despite the resonance, the hospital structure successfully withstood the Northridge earthquake. A water pipe broke, however, forcing evacuation.

The hospital's structural damping limited the resonant response. One of the damping mechanisms may have been radiation damping whereby the building dissipates energy into the surrounding soil. The measured damping for the Northridge event was 10% to 15% (north-south) and 5% to 10% (east-west).

Significantly lower damping values were measured in the hospital for the 1987 Whittier Earthquake. The Whittier event produced lower ground motion than the Northridge event, however.

Thus, the hospital has a nonlinear damping response, where the damping increases is some proportion to the ground motion amplitude.

Again, Olive View Hospital withstood the earthquake with no major structural damage. This is considered a great success.

Nevertheless, the hospital's resonant response was undesirable. It indicates that greater attention must be paid to the site response frequencies during the design of new buildings.

<u>Reference</u>

2-1. USGS Response to an Urban Earthquake Northridge '94, Prepared by the U.S. Geological Survey 1 for the Federal Emergency Management Agency (FEMA) Open-File Report 96-263, 1996