BAD VIBRATIONS

The ancient craft of bridge design still holds surprises

BY MASON INMAN

In the middle of rush hour on Aug. 1, at 6:04 p.m., traffic zoomed across the westbound span of the I-35 Mississippi River bridge in Minneapolis. By 6:05, the 40-year-old structure had buckled and broken, dumping most of the bridge into the river and killing 13 people. Though it came as a shock, this was in retrospect an accident waiting to happen, experts say. The Minneapolis bridge had been poorly maintained, with cracks in its iron arches that had been patched up over the years. And the bridge's design lacked redundancy.

"This is a classic example of how ... a single failure can lead to a collapse," says Spiro Pollalis, a bridge designer who teaches at Harvard University. "At the time [the bridge was built], it was considered an acceptable risk," he adds. "Now we try to be more careful."

Whether because of obsolete design or disrepair, thousands more U.S. bridges are similarly at risk, according to the American Society of Civil Engineers' 2005 "Report Card for America's Infrastructure." Yet the majority of bridges built in the 1950s and 1960s are still holding up, even though they typically carry much more traffic than they were designed to handle.

With increasingly sophisticated computer tools and wind tunnel tests, and more-detailed understanding of steel, concrete, and other materials, engineers have a better grasp than ever of how bridges work. But some recently built bridges have surprised their designers by showing disturbing and unexpected vibrations.

Every new bridge that's different from those that have been built before—with a longer span, say, or a novel design—represents a leap into the unknown. "Until you build structures, they really are like scientific hypotheses," says Henry Petroski, a civil engineer and historian at Duke University in Durham, N.C. "If it's never been done before, no matter how many theoretical supports you have, the proof is only in building it."

LESSONS LEARNED The most famous bridge collapse in history—caught on film and burned into engineers' memories—was the 1940 failure of the Tacoma Narrows suspension bridge, south of Seattle. Nicknamed "Galloping Gertie" because of the way its roadway wriggled in the wind, the bridge failed spectacularly after being open just 4 months. High winds induced the bridge's extraordinarily slender deck—the horizontal span that carried the roadway—to twist back and forth, wrenching the structure past its breaking point. "That was obviously an inferior design," says Khaled Mahmoud, president of Bridge Technology Consulting in New York City. "It did not provide enough stiffness for the bridge."

CORBIS

TWIST AND POUT — The original Tacoma Narrows bridge fluttered in the wind until it snapped.

The disaster impressed on engineers the need to understand bridges' aerodynamics—that is, the way they respond to wind-generated forces. Today, engineers typically conduct wind tunnel tests of full-scale sections of a bridge's decks and sometimes also of a scale model of the entire bridge, occasionally set in a mock-up of the surrounding landscape. Computer modeling can complement such empirical tests, and allow engineers to factor in the inevitable imperfections in steel beams and other parts, says David Goodyear of the San Francisco engineering firm T.Y. Lin International.

Such methods have not only made traditional bridge designs safer but have allowed architects and engineers to try innovative designs that may be more cost-effective but are also more difficult to analyze.

These trends are behind the increasing popularity of so-called cable-stayed bridges, which typically sport towers of solid concrete that anchor high-tension cables running in straight lines down to the deck, either splayed like the ribs of a handheld fan or parallel to each other like harp strings. Usually the cables run from both sides of the tower down to the roadway in a symmetrical pattern, so the forces pulling on the tower from each side are in balance.

But that general form allows a wide variety of designs. Some cable-stayed bridges have separate spires on either side of the roadway; others have a single tower in the center of the bridge, with cables running to both sides of the roadway. Some have a triangular arch over the roadway. And some even have a leaning tower that balances the tension in the cables with its own weight. Compared with suspension bridges, cable-stayed bridges give engineers much more "freedom of expression," Petroski says.

They're also typically cheaper. A suspension bridge needs large anchors sunk into the ground at both ends to support the tension of the cables. In a cable-stayed bridge, by contrast, tension is balanced where the cables meet at the central tower, and no external anchoring is needed. Such bridges must have taller, thicker towers and stiffer decks than suspension bridges do, but can use thinner, shorter cables.

A recent innovation could make cable-stayed bridges even more attractive. Figg Engineering Group in Tallahassee, Fla., has pioneered a "cradle" in which cables are routed through a curved tube set inside the central tower rather than being anchored to the tower. This seemingly subtle change has big repercussions. It makes the bridge simpler and allows individual strands of a multistrand cable to be pulled out and inspected while the bridge is in use.

With this system "you can test new kinds of cables in the context of a new bridge, and if they fail, you can replace them," says Petroski. On the Penobscot Narrows Bridge, between Bangor and Brewer, Maine, one of two bridges in the United States that use the cradle system, engineers have installed test strands of carbon-fiber composite in a few of the cables.

CHARISMATIC CABLES — Eye-catching cable-stayed bridges, like Boston's Zakim-Bunker Hill Bridge, are becoming city showpieces.

SHIMMIES AND SHAKES

Although the calamity that befell the Tacoma Narrows bridge has not been repeated, some cable-stayed bridges have suffered wind-induced trouble of a novel kind. In the mid-1980s, reports came in that moderate winds of about 20 to 50 kilometers per hour could set these bridges' cables fluttering. The phenomenon usually happened only during light or moderate rain—something that puzzled engineers for years.

These vibrations can make cables sway by more than a meter at their midpoints—not enough to bring a bridge crashing down, most experts say, but potentially enough to shorten a bridge's life span through wear and tear on the cables and their anchors.

In the early 1990s, a combination of lab tests and field measurements suggested that moderate winds can cause rain to trickle in rivulets down the cables, which typically have a smooth plastic coating. The resulting change in the cable's profile can affect the way it reacts to wind, creating an aerodynamic instability that sets the cable vibrating at some resonant frequency, somewhat like a guitar string. "While the cause is known, it still remains impossible to predict the cable-excitation process from first principles," says Anton Petersen of COWI, an engineering firm in Kongens Lyngby, Denmark, that consults on many of the world's biggest bridges. "The physical mechanism responsible ... is still an active area of research," he says.

A team led by Emmanuel de Langre at the École Polytechnique in Paris recently developed the first mathematical model to predict how the rivulets will run on a cable vibrating in the wind. Their model, described in the October *Journal of Wind Engineering and Industrial Aerodynamics* supports earlier ideas that wind pressure, along with friction between the water and the cable, causes the rivulets to form.

Engineers have been installing retrofits to deal with vibrating cables. "We don't have any cases where the problems were not corrected," Harvard's Pollalis says.

One solution has been to add cables that run between the main stay cables. Tying the cables together creates a more complex aerodynamic response and removes the simple resonance that can lead to vibration.

More popular now are dampers, like shock absorbers, that attach to the stay cables near where they connect to the deck. China's Dongting Lake Bridge, a midsize cable-stayed bridge in northeast Hunan Province, was the first to employ a new kind of sophisticated damper incorporating a magnetorheological fluid. When the cables start to vibrate, it triggers the damper to turn on a magnetic field. This causes the fluid—which has iron nanoparticles suspended in it—to stiffen, putting resistance on the cable. Tests show that it works better than earlier dampers, according to a study by Jan-ming Ko and his colleagues at the Hong Kong Polytechnic University in the April 2006 *Journal of Intelligent Material Systems and Structures*. Other researchers are working on subtler ways of fixing these vibrations, using bumps, wires, or flanges that wrap in a helix around the cables to break up the flow of water.

Another kind of vibration, familiar but still capable of causing surprises, can afflict pedestrian bridges. Engineers know to design bridges so that they don't have a natural vibration frequency close to 2 Hertz, because that's the frequency that an average person's footsteps hit the ground. Soldiers have long been ordered to break step when crossing a bridge so as not to set it oscillating. Failure to take that precaution seems to have contributed to the collapse of at least two suspension bridges. One in Manchester, England, collapsed in 1831 with 60 soldiers on it, and in 1850 the Dordogne Bridge in France fell, killing more than 220.

A variant of this old problem resurfaced when London's Millennium Bridge opened to fanfare in 2000. Hundreds of people surged across, but within minutes, many of them were hugging the handrails as the bridge slithered back and forth like a snake. After only a couple of days, officials shut the bridge.

The bridge's engineers at the London-based firm Arup studied the bridge, checked the literature, and found that the same thing had happened before on at least a few other pedestrian bridges. However, as they said in a report about the Millennium Bridge, "these cases have not been widely published and as a result the phenomenon has not become known to practicing bridge engineers."

Even after Arup retrofitted the bridge with dampers that prevented the swaying, the reason for it was obscure. Researchers surmised that the instability might begin because of people's tendency to push sideways a little with each step as they walk. In the Nov. 3, 2005 *Nature*, a team led by applied mathematician Steven Strogatz of Cornell University showed how feedback between pedestrians and the bridge could turn this effect into wholesale swaying. A few people falling into step by chance could make the bridge sway a little. Then other people would tend to fall into step because synchronizing one's pace with the bridge is more comfortable than fighting the sway—except that this positive feedback would only make the bridge sway more.

These problems with swaying footbridges and vibrating cables are more of a nuisance than a real danger, most experts say. But it's hard to know what would happen if they weren't dealt with. "Swaying could have led to failure of Millennium Bridge," Petroski says.

GOING FURTHER Despite computer modeling and wind tunnel tests, vibrations in new bridges caused by pedestrians, wind, and rain came as a surprise to engineers. "There's always a question whether scale models really reflect the full bridge," Petroski says. The models are typically built of wood, fishing line, and other materials totally different from steel and concrete, but they are tuned to have stiffness and elasticity similar to what's predicted for the real bridge, says Guy Ferguson of RWDI, a wind-engineering firm in Guelph, Ontario.

Whether computers can supplant empirical models remains debatable. With improvements in computational fluid dynamics to describe wind flows, "maybe in 10 years, [computer simulations] may take over from wind tunnel tests," Goodyear says. But others disagree. "We're still a long way away from that," Ferguson says. "There's so much going on in a wind tunnel—to model it accurately [on a computer] is next to impossible."

Even as computer simulations improve, more surprises could spring up as engineers push bridges to longer spans, and try out simpler, cheaper, or more daring designs. One idea that's been floating around for a few decades is for a buoyant tunnel that sits just under the surface of the water. A team of Italian and Chinese engineers is aiming to build such a tunnel to span the 3-km Jintang Strait on the coast of Zhejiang Province, China. The engineers call it an Archimedes bridge, after the ancient Greek mathematician who first understood the principle of buoyancy.

The Archimedes bridge would stay in place through buoyancy, counteracted by cables tethering it to the floor of whatever body of water it crosses. Such a bridge would be much cheaper than a suspension bridge, and might be the only way to cross spans longer than a few kilometers, argues Federico Mazzolani of the University of Naples in Italy. "In principle, we can cross a span of 20–30 km without any difficulties."

ISTOCKPHOTO

LEANING TOWER OF SEVILLE — Architect Santiago Calatrava went out on a limb with the unusual Alamillo Bridge in Spain.

"But nobody wants to be the first one to build it," he adds. For now, Mazzolani and his colleagues are aiming to build a much smaller prototype, a pedestrian bridge in a lake in China, just 100 m long and a couple of meters underwater. "We will use it as a full-scale laboratory," Mazzolani says, to try out the manufacturing and see how the tunnel reacts to vibrations. But he has his sights on distant shores. "After the prototype is built, it will be a revolution in bridge design."

For modest-size bridges, engineers are confident they understand the mechanics well enough to take more liberty with the designs, blurring the line between architecture and engineering, Pollalis argues. "You can take this in two directions," he says. "You can make things cheaper and more efficient, or you can make them more appealing. But people aren't so interested in having things cheaper." The growing popularity of cable-stayed bridges, Petroski argues, is in part because communities want distinctive, signature bridges.

As the recent collapse of the bridge in Minneapolis showed, it's not just the design of a bridge that gives it a long life but also how it's maintained. But the two may be tightly intertwined. "My old adviser ... used to say, if you want a bridge to last, make it beautiful, because people will want to preserve it," Goodyear says. "If it's ugly, people will want to tear it down." ■

OF NOTE

TECHNOLOGY

A smaller magnetometer

A sensor the size of a rice grain can detect magnetic fields as small as those produced by brain waves, researchers report.

John Kitching of the National Institute of Standards and Technology in Boulder, Colo., and his colleagues filled a millimeter-wide silicon cylinder, sealed by glass at both ends, with a gas of about 100 billion rubidium atoms. Under normal conditions, shining a laser through the container causes the spins of the atoms to line up.

The presence of a magnetic field, however, tips the atoms out of alignment. The disoriented atoms absorb some of the light from the laser beam, so by measuring how much light passes through the cylinder, the scientists can infer how misaligned the rubidium atoms are. The misalignment provides a measure of the strength of the magnetic field, the researchers report in the November *Nature Photonics*.

Kitching says these tiny sensors could be used noninvasively to measure brain waves or fetal-heart waves.

The detectors "are small, can run on low power, and could be very low cost," he says. "That's what gives them such great possibility for applications." —S.C.W.

BIOLOGY

Eastern farms have native-bee insurance

Watermelon fans can stop biting their nails, at least around the Delaware Valley region. Even if the beleaguered honeybees disappear, native bees should be able to buzz in and take care of most of the crop by themselves, says a new study.

It's a compelling example of biodiversity as insurance, says Rachael Winfree of Princeton University.

U.S. farmers who need pollinators for their crops use European honeybees (*Apis mellifera*). Those bees have had their troubles lately, with parasitic mites and colony-collapse disorder, among other ills (*SN: 7/28/07, p. 56*). But the United States has hundreds of species of native bees that drop in on farms.

Within the past 5 years, two studies have analyzed the role of native bees as pollinators on watermelon farms. The studies found that the natives assisted but that their numbers were rarely large enough to pollinate entire crops, reports Claire Kremen of the University of California, Berkeley and her colleagues. Where wild lands were scarce within a bee's flight from the field, native bees were scarce too.

Kremen's studies took place in and near the intensely managed agricultural lands of California's Central Valley. In the new