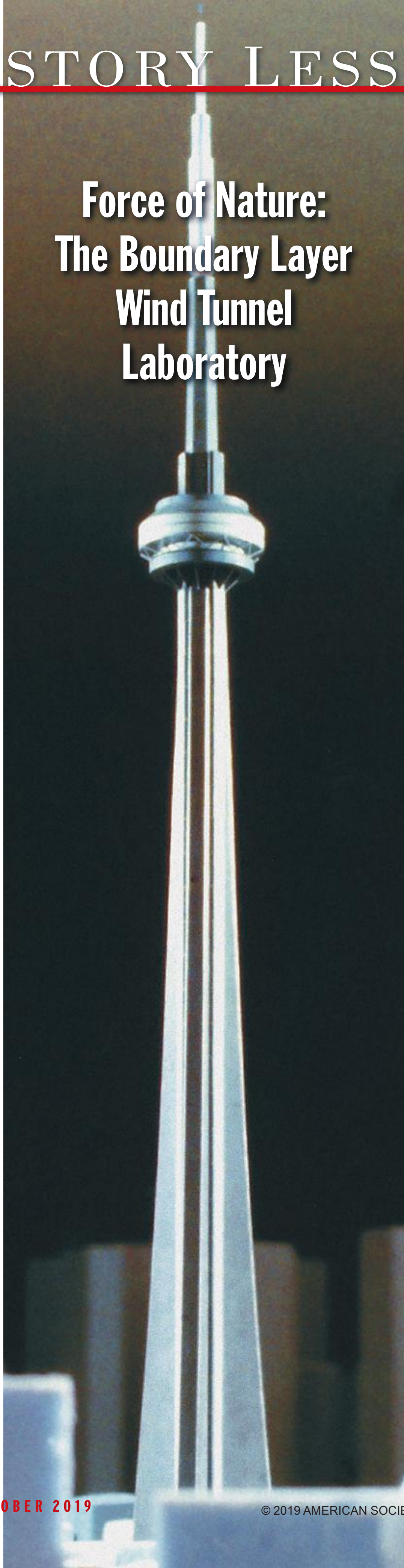
Force of Nature: The Boundary Layer Wind Tunnel Laboratory



Testing at the Boundary Layer Wind Tunnel Laboratory helped shape a more elegant design for the CN Tower in Toronto.

COURTESY OF THE BOUNDARY LAYER WIND TUNNEL LABORATORY/UWO

WIND TUNNELS, which can generate wind at a reduced scale for research purposes, have been used by the aviation industry since the beginning of the 20th century. "However, the wind through which airplanes fly is markedly different from that near the earth's surface, where we construct our buildings and structures," says Nicholas Isyumov, Ph.D., P.Eng., a professor emeritus of civil and environmental engineering at Western University in London, Ontario, Canada, and a consulting director of the Boundary Layer Wind Tunnel Laboratory (BLWTL)—the first wind tunnel built explicitly to test the effects of wind on the built environment. The BLWTL, located at Western, was recognized in 2018 as a National Historic Site by the Canadian Society for Civil Engineering and as an international landmark in ASCE's Historic Civil Engineering Landmark program.

When engineers began to focus on the effects of turbulent wind on structures in the middle of the 20th century, they revolutionized a new civil engineering specialty, wind engineering, that has profoundly shaped high-rises, bridges, and ordinary buildings ever since.

The key figure in the development of this specialty was Canadian engineer Alan Davenport. Born in India and raised in South Africa, Davenport obtained bachelor's and master's degrees in mechanical sciences from Cambridge University, in the United Kingdom, earned a master's degree in civil engineering from the University of Toronto and a doctorate from the University of Bristol, in the United Kingdom. He began his academic career at Western.

Davenport's doctoral work centered on wind action on long-span bridges and guyed masts. "He'd done some full-scale measurements on the Severn Bridge in England and realized that wind was highly turbulent and that the wind loads you really needed to be designing structures for must include that turbulence component," says J. Peter C. King, Ph.D., P.Eng., F.CSCE, currently a consulting director of the BLWTL. "At the time, there really were no codes that took that into account."

Davenport, King says, "wrote a number of seminal papers that described his theories on how you should be treating wind loads on structure." In 1963 he presented a paper at the first International Symposium on Wind Effects on Buildings and Structures in Teddington, England, United Kingdom, that drew the attention of Leslie E. Robertson, P.E., Dist.M.ASCE, the lead structural engineer of the twin towers at the World Trade Center. Robertson asked Davenport to join the design team as a wind expert. Davenport worked on the project for two years, shuttling between Ontario and New York City.

Wind tests on models of the twin towers were completed at two sites: the National Physical Laboratory (NPL) in the United Kingdom and Colorado State University, the latter of which had a wind tunnel that was used to study environmental issues for the U.S. military. Davenport, along with Jack E. Cermak, Ph.D., P.E., Hon.M.ASCE, who was then a professor of civil engineering at Colorado State, oversaw modifications on the tunnel.

King says Davenport "recognized there was a real niche for wind engineering for tall buildings and bridges," and obtained a small grant to build a boundary-layer wind tunnel and lab, which opened in 1965 at Western. In the boundary layer, which is the portion of the atmosphere ranging from ground level to about 3,000 ft, wind flow is not smooth but turbulent and gusty.

The BLWTL was not the first facility to investigate the boundary layer, but it was the "first [one] actively used or designed to deal with real structures," says Isyumov. "If the load varied in time, if it was a dynamic load—like that due to wind or an earthquake—the response of structures could be much more severe than that due to a static load."

Isyumov says that the BLWTL brought together three areas of study that had largely been separate: how bridges and slender structures such as tall chimneys behave, the importance of measurements taken by meteorologists (whose concerns were climatology and flight), and structural engineering. Structural engineers, he points out, "knew that structures under load deflect, deform, are stressed, et cetera, and that they behave differently under different kinds of loads."

All three areas of study, Isyumov says, were "reasonably well established but not necessarily talking to each other. Our lab was able to tie them together...into one field that we now call wind engineering."

As Isyumov explains, the requirement for modeling this kind of boundary-layer wind in wind tunnels was first described by Martin Jensen of the Danish Technical University in the late 1950s. Such testing "requires that the ratio of the characteristic dimension of wind to the characteristic dimension of the building or structure be the same in [the] model and prototype scale." This ratio came to be called the Jensen Number.

One of Davenport's chief accomplishments was the development of a "wind loading chain" model, which studied the interrelatedness of five key elements in modeling wind's impact on structures: wind climate, terrain, aerodynamic data, dynamic effects, and criteria. Criteria described the comfort level of occupants at the upper levels of a tall structure and pedestrians near a tall building at ground level.

According to the nomination form submitted to ASCE for its landmark program, wind studies performed at the BLWTL integrated historic wind-climate data from local sources near the proposed structure and described the data in statistical terms. Davenport and his team pioneered probabilistic methods for quantifying at a particular site the wind climate, including wind speed and direction. He also introduced the use of the Monte Carlo method—which introduces random inputs to models of complex systems to produce probable outcomes—to more reliably predict the winds associated with tropical storms.

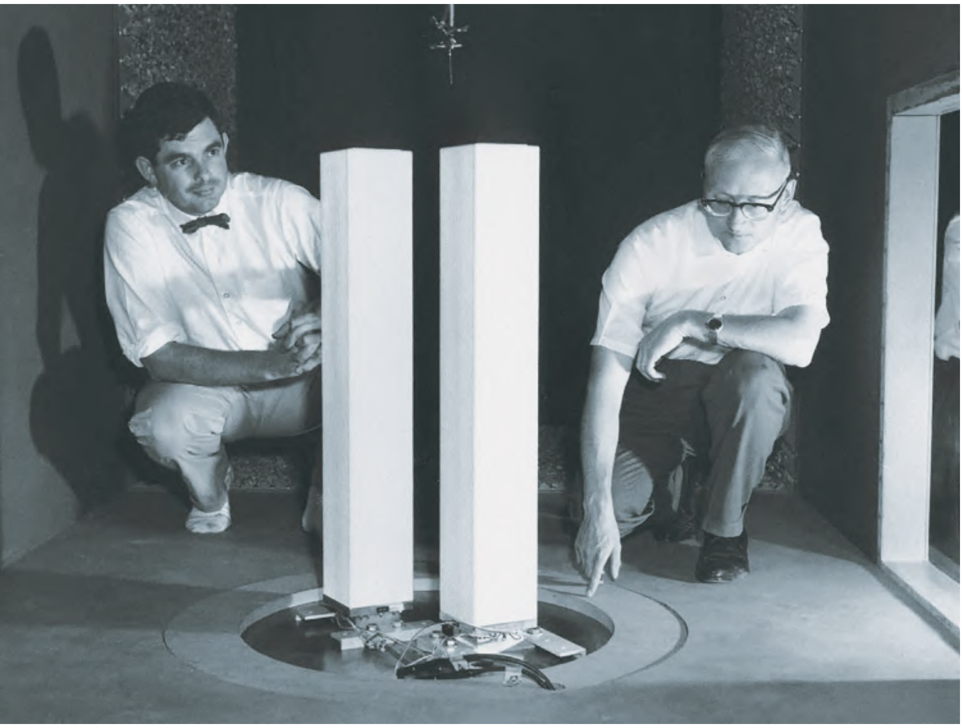
To account for terrain, the lab pioneered topographical models and completed some of the first studies "using numerical methods to profile wind behavior over hills and ridges," the nomination document states.

To collect aerodynamic data, engineers had to "model the effects of the natural wind at a reduced geometric scale," the document states. These techniques included a "taut strip model," which facilitated the study, for example, of the "three-dimensional response of long-span bridges under turbulent wind; the high-frequency force-balance technique, first developed as the base-balance technique, a major contribution to the measurement of dynamic forces exerted on a structure; the pneumatic averaging technique, used to measure area-averaged fluctuating wind pressures on buildings; and high-speed pressure scanners that were adapted from the aeronautical industry to facilitate the simultaneous measurement of pressures at high frequencies."

To study dynamic effects, which were, as the nomination form noted, "wind-induced resonant vibrations that create a potential for load increases on a structure," the lab developed new techniques. These included pneumatic averaging to "distinguish between the low-frequency and resonant components of the dynamic wind load" on wind-sensitive structures.

The last element in Davenport's chain was the "integrity of the structure, the comfort of building occupants, and the usability of the area surrounding the structure," which Davenport collectively termed "criteria," the form states.

The first tunnel at the BLWTL was 100 ft long and 8 ft wide and had an adjustable roof that could move from 5.5 ft to 7.5 ft. in height. The tunnel's fan could generate wind at speeds of up to



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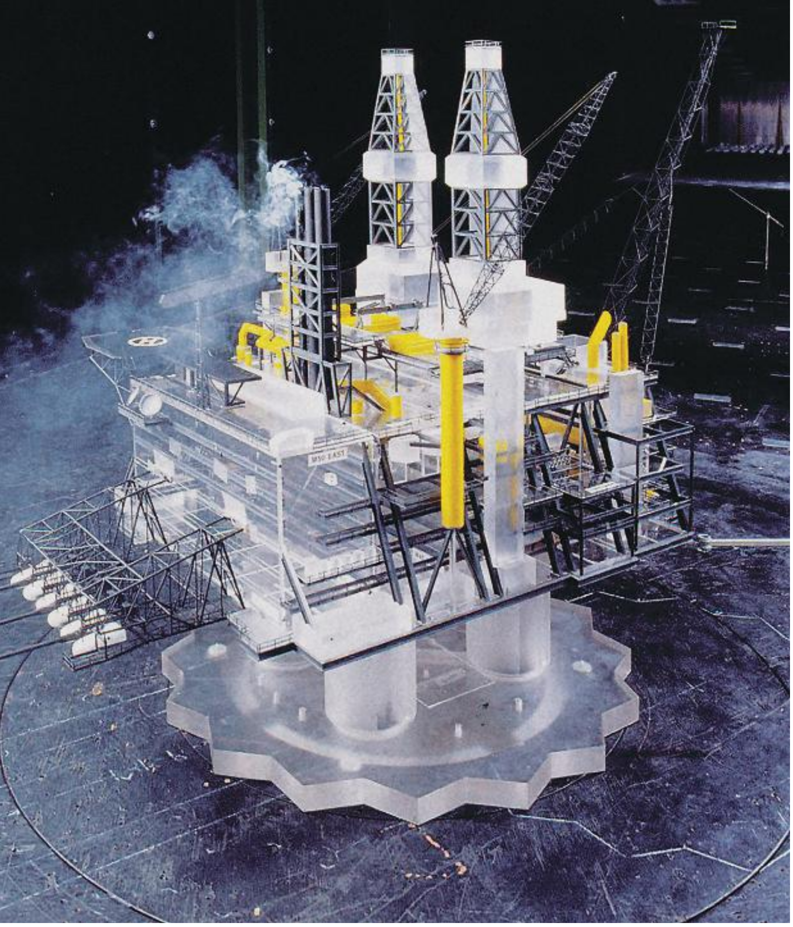
Alan Davenport, *at left*, worked with Jack E. Cermak to test models of the twin towers to be built as part of New York City's World Trade Center.



30 mph. According to the Canadian Society for Civil Engineering, "The adjustable roof height allows accurate simulation of pressure gradients, and the long test section allows turbulent boundary layer flow to naturally develop over roughness elements on the wind tunnel floor."

The tunnel was not much longer than the NPL tunnel in the United Kingdom and about the same size as the Colorado State tunnel. Researchers at Colorado State were "looking at pollutant dispersion—gas emanating from a stack," King explains. "You'd measure the concentrations downwind. So you need a longer fetch downwind from the turntable, {which is} the main test section." At the BLWTL, "the turntable is at the end of the fetch," he says.

At the lab, models are mounted on a 6 ft diameter turntable within a 10 ft diameter "proximity model" of the local surroundings, King says. To simulate roughness on the floor—which creates the turbulence—engineers at first used Masonite sheets—a type of engineered wood—with wooden or Styrofoam blocks. Eventually, the lab shifted to more automated means—computer-controlled and pneumatically operated from the floor—to generate different kinds of turbulence.

In 1984, the second wind tunnel at the Boundary Layer Wind Tunnel Laboratory opened, with a long-wave water tank that could conduct tests on offshore structures, *above.* The facility's first wind tunnel, *below*, comprised a large fan, at left in the rendering, that generated 30 mph winds that traveled along a 100 ft test section, becoming turbulent while passing over roughness elements constructed on the wind tunnel floor.

Before long, the BLWTL was conducting tests for the tallest structures in the world, including Chicago's Willis Tower (then the Sears Tower), which opened as the world's tallest building in 1973, and the even-taller CN Tower, which opened in Toronto in 1976 and is still North America's tallest freestanding structure. Work at the lab helped refine the CN Tower's shape, from an imposing, three-legged structure to a "much more pleasing and slender structure," says Isyumov. Wind engineers conducted research in parallel with the development of the design. New ideas were tested in the wind tunnel, and decisions were made with the benefit of the test results, he says.

The tunnel reflected changes in building technologies throughout the 20th century, shaping a new generation of building codes struggling to keep pace.

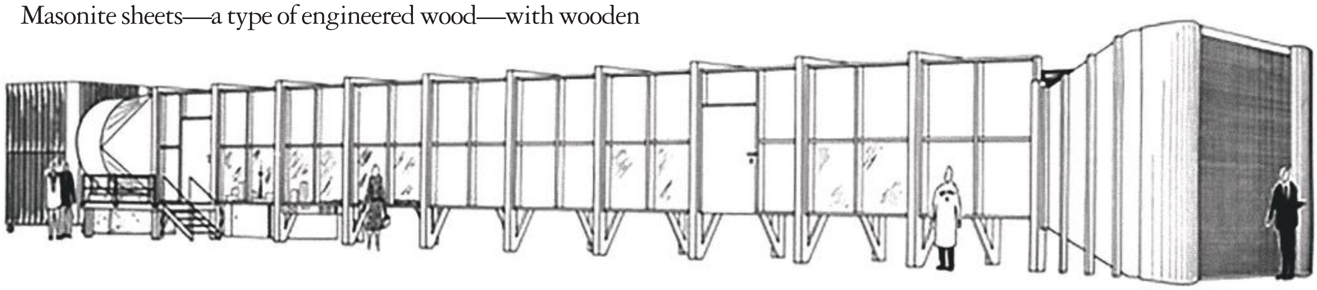
"If you were to build the Coliseum or a pyramid, {it wouldn't matter} whether you did a wind tunnel test or not," says Isyumov. "But as we started to build structures that were lighter and more flexible, more dynamically responsive, the building codes became inadequate for {these} unusual structures."

Early building codes in cities such as New York and Chicago did not consider wind loads. For example, the New York City building code at one time specified a constant pressure of 20 psf at above 200 ft, with no load at lower heights. In the case of a tall structure like the Willis Tower, "There would have been a distinct possibility {the tower} would have had problems if it had been built to the Chicago code," Isyumov says. "It would not have been sufficiently strong," because codes at the time didn't address dynamically active structures.

As Davenport understood with his criteria category, the goal of wind engineers working on tall buildings is not only to improve their structural integrity but also to improve their habitability—especially on the upper floors. Testing gave "designers a very clear warning that structures vibrated, and maximum loads were influenced by these forces" in ways that "people would have found uncomfortable," Isyumov says.

By the 1980s, the lab was in such high demand that the tunnel was "running flat out," King says. "We needed a second wind tunnel just to keep up with the demand of the service." In

COURTESY OF THE BOUNDARY LAYER WIND TUNNEL LABORATORY/UWO, *ALL THREE*



Before its construction in 2012, the Margaret Hunt Hill Bridge, in Dallas, which features a 1,870 ft cable-stayed main span with a uniquely twisting cable design, was tested at the Boundary Layer Wind Tunnel Laboratory.

1984, the BLWTL opened a second, larger wind tunnel, occupying more than 12,000 sq ft and capable of a maximum wind speed of 60 mph. It also featured a closed-circuit design. The first tunnel is an open circuit, meaning its wind is generated by the fan and circulates through the tunnel and then through lab itself. "It's not very efficient because of all the instrumentation and clutter in the room," says King. "It's much better in wind tunnel design to make a closed-circuit design—the wind just stays in the wind tunnel itself. You can control it much better."

Additionally, a low-speed test section with a 200 ft long wave tank was installed in the second tunnel, with wave paddles at one end and a beach at the other, to allow engineers to study wind and wave interactions and the effects of wind on offshore structures, such as oil platforms. According to a BLWTL capability statement, the low speed was also well suited for studies of long-span bridges, the dispersion of pollutants, and rain and snow.

The models being tested advanced as well. Pressure models were once made of acrylic, King says, with pressure taps, or sensors, that were drilled in by hand. Now it's all done with rapid prototyping—a digital process that involves converting 3-D images to machine instructions for producing a physical model. This reduces the cost of model building.

Instrumentation has also improved. Years ago, mechanical pressure scanners could only look at one pressure tap at a time; researchers were restricted by the number of taps that could be examined with the mechanical scanners. Now, the lab has three electronic pressure systems (each with more than 1,000 pressure sensors) that allow simultaneous measurements on the surfaces of multiple models to be studied simultaneously. A test that might have taken 36 hours a few decades ago now takes one.

The BLWTL has tested hundreds of projects, including the Walt Disney Concert Hall in Los Angeles, the Spanish opera house Palau de les Arts Reina Sofia, Greece's Olympic Athletic Center of Athens (Spyros Louis), and high-rises across the world, including buildings in London, Shanghai, and Dubai, United Arab Emirates.

Work at the lab led to critical improvements in buildings, including Citigroup Center in New York City and the John Hancock Tower in Boston. For the 4 mi long, cable-stayed Sunshine Skyway Bridge that was built in 1987 south of St. Petersburg, Florida, Davenport and King "developed some buffeting load theories that could define wind loads much better. They were a series of dynamic loads that accounted for interaction between wind and different modes of vibration," King says.

The bridge project represented "one of the first times that the wind tunnel work was really integrated into the design," King says. The process did more than just confirm the design; it enabled the bridge designers and lab engineers to participate together and feel they really accomplished something important in the design, he says.

Just as important was the normalization of wind testing for more prosaic structures. From the 1960s through the 1980s, King says, wind tunnels primarily tested the longest or tallest structures. "People didn't believe [that] for an apartment building, you needed to do wind tunnel testing," he says. Now there are wind requirements in every jurisdiction and for a variety of ordinary building types such as apartments and office buildings of moderate heights. And there is more focus on the pedestrian wind environment around the base of those buildings.

In the wake of the BLWTL's success as a center for both wind tunnel testing and education, wind testing facilities, private and public, have become more commonplace. "Every country has their own wind engineering group that offers services to their own country," says King.

The BLWTL remains a respected force in the industry; the lab still conducts tests of about 50 projects a year and has a staff of 10 engineers, technicians, and administrative personnel.

Davenport passed away in 2009. Colleagues remember him as a visionary scientist—he authored more than 200 scientific articles and was the founding editor of the *Canadian Journal of Civil Engineering*—as well as a great leader with a knack for recognizing talent and putting teams together. Worldwide, the development of wind design codes is based on Davenport's theories. "Every major design code in the world treats the wind the same way—the way that Alan developed," says King.

Wind tunnels themselves still have a certain allure. But if the prospect of occasionally standing in a wind tunnel, while it's going, sounds like a perk of the job, think again. "At full speed, or sixty miles an hour, it's like standing up in a convertible. It's not fun," King says. "You have to lean into the wind at a forty-five-degree angle so you don't get blown away." —T.R. WITCHER

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