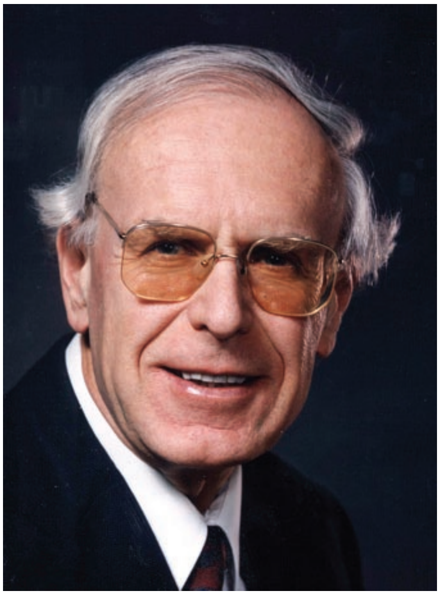
BIOGRAPHY

Biography of Zdeněk P. Bažant

Engineer Zdeněk P. Bažant is best known as a world leader in scaling research in solid mechanics (1–6). His research focuses on the effect of structure size on structural strength as it relates to the failure behavior of the structure. He also has made outstanding advances in structural stability (7), fracture mechanics (8), the micromechanics of material damage (8–10), concrete creep (11–13), and probabilistic mechanics (6, 8, 14). He was elected to the National Academy of Engineering in 1996 and to the National Academy of Sciences in 2002, 1 of only 153 members with such a dual appointment. In his Inaugural Article (1), published in this issue of PNAS, Bažant presents a simple justification of the scaling laws for the fracture of quasibrittle materials such as concrete, rock, fiber composites, and sea ice.

Bažant's work has spanned several engineering disciplines, and he has been honored with numerous awards in recognition of his accomplishments. In 1996, he received the Prager Medal from the Society of Engineering Science (SES) and the Newmark Medal from the American Society of Civil Engineers. In 1997, the American Society of Mechanical Engineers awarded him the Warner Medal, which recognizes outstanding contributions to the engineering literature. He has received four honorary doctorates and will be presented with a fifth this fall from l'Institut National des Sciences Appliquées in Lyon, France. Bažant has authored or coauthored six books and more than 450 articles in refereed journals. In 2001, he received the award of Highly Cited Researcher, which is given by the Institute for Scientific Information to only 250 authors worldwide across all engineering fields. In addition, he served as president of SES and was founding president of the International Association of Fracture Mechanics and Concrete Structures.



Zdeněk P. Bažant

Self-Education Through Determination

Born and educated in Prague, Czechoslovakia, Bažant received his undergraduate degree in civil engineering with the highest distinction from the Czech Technical University (ČVUT) in 1960. His gift for mathematics (at high school he was a National Winner of the Mathematical Olympics of Czechoslovakia) and his family's guidance undoubtedly influenced his field selection. Bažant is part of his family's fifth generation of civil engineers: his father was a professor of geotechnical engineering, and his grandfather was a professor of structural mechanics, both renowned academics at ČVUT.

Despite being first in his class as an undergraduate, astonishingly, Bažant was not accepted to graduate school. The communist dictatorship in Czechoslovakia at the time often denied higher education to political opponents. Bažant feels that he was not admitted to graduate school because he refused membership in the communist party and because he came from a family of well known, antitotalitarian intellectuals. Nevertheless, while employed full-time as a construction supervisor and bridge designer, he managed to gain admittance to external graduate study with no obligation to attend graduate courses. "I saw my advisor twice—once to tell him what I wanted to do, and then when I brought him my dissertation," Bažant remembers.

For his dissertation, he developed a new method to analyze creep effects in concrete structures responsible for the fracturing and cracking that occurs in concrete over time (11). In 1963, he was awarded a Ph.D. in engineering mechanics from the Czechoslovak Academy of Sciences in Prague. Despite his unusual graduate experience, Bažant feels that his employment as a design engineer was to his benefit: "First, although studying alone took longer, the knowledge I eventually gained was deeper, because by taking many wrong turns, I learned not only what was true but also what was untrue, and why. Thus, self-study became my life-long habit." For Bažant there was also a practical benefit: "Without being forced to experience design and construction and without realizing the oversimplifications made in practice, I would have never started thinking about the problems for which I was eventually inducted to the National Academy of Sciences: distributed fracturing and size effects." After receiving his doctorate, Bažant worked at ČVUT researching creep and degradation of fiber-polymer composites. Concurrently, he earned a postgraduate diploma in theoretical physics from Charles University in Prague in 1966 and the degree of docent in concrete structures from ČVUT in 1967.

In 1966, Bažant embarked on a series of visiting research appointments, eventually leading to his immigration to the United States. Collectively, he spent two and a half years at the Centre Experimental de Recherches et d'Études du Bâtiment et des Travaux Publics in Paris, the University of Toronto, and the University of California, Berkeley. While in Toronto, he and his wife considered returning to Czechoslovakia in 1968 during the Prague Spring, the liberation movement before Soviet troops rolled into Czechoslovakia to crush the reform movement. "We actually bought tickets to Prague, but after the Russians invaded, we changed our minds immediately," he said. Committed to staying in the United States, in 1969 Bažant joined the faculty of Northwestern University in Evanston, IL, as associate professor of civil engineering.

Bažant looked forward to the new environment: "I saw a collaborative group of young, bright, competitive, and stimulating people doing first-rate research in solid mechanics." In 1973, Bažant was promoted to full professor, and, later, he was honored with two distinguished professorial chairs: W. P. Murphy Professor of Civil Engineering and Materials Science in 1990 and McCormick School Professor in 2002. In 1981, he founded at Northwestern a research center for concrete and geomaterials and served as its first director. Bažant credits the university's environment for contributing to his success: "Northwestern has probably had the

This is a Biography of a recently elected member of the National Academy of Sciences to accompany the member's Inaugural Article on page 13400.

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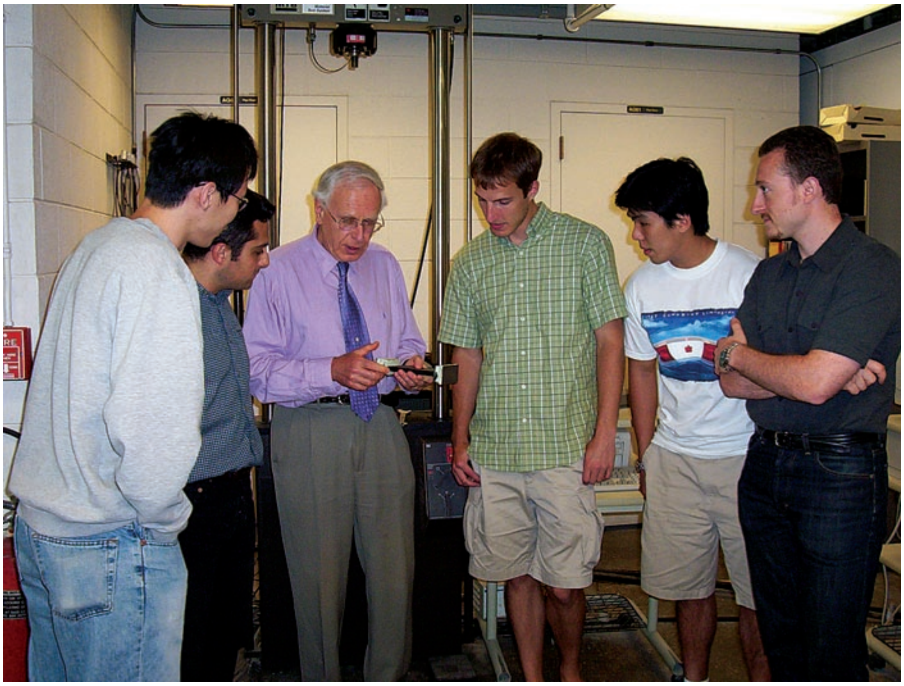
best and largest solid mechanics group anywhere."

Size Effect and Quasibrittle Failure

Of all of his work, Bažant is probably best known for his size effect law, which reflects the fact that quasibrittle failure is decided not only by material strength but also by dissipated energy (2, 3, 8). Until the 1980s, all size effects on structural strength generally were attributed to material strength randomness. In 1984, Bažant revolutionized the scaling theory by deriving a simple size effect law with broad applicability, bridging the scaling laws of plasticity and classical fracture mechanics. He demonstrated theoretically that, in quasibrittle failure that is preceded by large, stable growth of localized fracture or distributed cracking damage, the size effect mainly is caused by stress redistribution and localization of cracking damage associated with the release of energy stored in the structure. He realized that although the rate of energy dissipated at the front of a propagating fracture or at the front of a growing damage band is nearly independent of the structure size, the rate of energy released from the structure into the front would increase with the structure size if the nominal strength of the structure were assumed to be constant; from this, he concluded that energy balance can be achieved only if the nominal strength is considered to decrease with structure size, i.e., if there is an energetic size effect. Bažant with his group verified his size effect law experimentally for various important quasibrittle materials such as concrete, rock, sea ice, fiber composites, rigid foams, and tough ceramics. Bažant further demonstrated that damage caused by distributed cracking can be predicted and numerically simulated by energy-based material models with a characteristic length such as the cohesive crack model, the crack band model, and the nonlocal softening damage models. He also justified the nonlocality of material damage by the micromechanics of interacting and growing cracks (15, 16). Bažant's groundbreaking concepts have been applied to numerous disciplines, including engineering of concrete structures, ship and aircraft engineering, arctic ice engineering, geotechnical and mining engineering, petroleum engineering, nuclear safety, design of nonmetallic structures resistant to earthquake, blast, groundshock, and impact, and, most recently, to assessment of the danger of snow avalanches and landslides.



Professor Bažant, holding a specimen of carbon-PEEK composite, is examining kink band propagation in the specimen with his research assistants (from left: Qiang Yu, Gianluca Cusatis, Zdeněk Bažant, Martin Andrews, Sze-Dai Pang, and Alessandro Beghini).

Discovery Comes in Stages

In his PNAS Inaugural Article (1), Bažant presents a simple and general justification of the scaling laws of quasibrittle fracture, broadly applicable to many materials. He exploits the fact that problems of quasibrittle failure are much easier to solve theoretically at the extremes, by examining structures of infinite size and structures of vanishing size. "Brittle and ductile behaviors at these extremes are usually much easier to analyze than the behavior for real sizes. You can then sort of interpolate between these extremes, and the result is surprisingly simple, yet realistic," he explained. In his article, Bažant reviews the various applications and ramifications of this method for several types of quasibrittle materials on different scales, ranging from 10 nm to 100 km. In addition, he presents cases of structural disasters for which the disregard of size effect in design was a significant factor. "When structures are too large to test, we must learn from disasters," he said. For example, he examined the 1959 Malpasset Dam disaster: an arch dam that collapsed, flooding the ancient town of Fréjus, France, and killing more than 400 people. "The cause of collapse was that the foundation moved. Every dam is designed for some tolerable movement, but the true tolerable movement was about half of what they thought at the time," he stated. Whereas not factoring in the size effect may have contributed to some structural failures, he noted that "the size effect was not known at the time of design, so no one can be blamed for the disaster."

In addition to the work presented in his Inaugural Article (1), Bažant is working on several other lines of research. One main focus is to develop a method for realistically estimating loads to ensure extremely low probability of failure. "This probability cannot be zero," he reasons. "It's generally considered acceptable if the probability of some bridge, tall building, or aircraft frame collapsing is about 1 out of 10 million. Estimating such a tiny probability is beyond experimentation, because we'd have to test a billion identical large structures." Nevertheless, Bažant is trying to address the probability for quasibrittle failures by asymptotic arguments and computer simulations. He notes, "I would say this is one of the most challenging problems that I have faced."

In contrast to analyzing the probability of failure in large structures, Bažant also is studying the scaling of strength of polycrystalline metals on approach to the nanoscale (17). "In thin films on submicrometer scales, you see similar phenomena—size effect and gradual softening—as you do in concrete on the scale of meters," he said. In addition, Bažant continues his research on the effects of creep, nanopore water, and high temperature on concrete, subjects that he first contemplated while working on his dissertation (11–13). He recognizes that most of his advances have progressed in stages: "You try to solve a problem and, eventually, you just can't get any farther, so you work on something else. A year later, you return [to the problem], and you get a new idea. Never give up."

A Renaissance Man

A man of diverse interests, Bažant approaches his hobbies with the same zeal as he approaches his research. A fan of music, he is a regular patron of the Chicago Symphony and relaxes at home by playing his Steinway piano. Bažant has played tennis since childhood and took up windsurfing two decades ago, but downhill skiing is his greatest passion. He and his wife, Iva, a physician, make regular trips to the Rocky Mountains and the Alps. "If I am so old that I cannot ski, I will just walk the mountain. It's so beautiful," he says. In fact, decades ago, his skiing interest precipitated the series of events that led to his becoming a United States citizen.

In 1959, after a terrible skiing injury, Bažant patented a safety ski binding in Czechoslovakia named the ZPB binding. The arrangement of hinges on the ZPB binding made the release of the boot from the ski insensitive to deformation in the ski boot. This feature was especially important for the soft leather boots used at the time. He managed to get a state company to produce 30,000 pairs of these bindings, and, in the early 1960s, ZPB bindings were used by about one-third of all skiers in Czechoslovakia. The royalties, one Czech crown from each pair, amounted to more than double his annual starting salary as an engineer. In Czechoslovakia, royalties were received only during the first 3 years of a patent. "If I had been in the United States, the patent protection would be much longer (17 years) and if [the binding] did well, it might have distracted me from the path I took," he mused. As a result of his patent's success, Bažant was appointed as an equipment expert for the Czechoslovak State Commission for Skiing, which permitted him to travel to Austria to report on the Hahnenkamm ski race in 1966. "Ironically, this trip, my first trip across the Iron Curtain (which eventually led to my becoming a U.S. citizen exactly 10 years later) was because of sports rather than science," he said.

In 1976, Bažant was named Outstanding New Citizen from the Metropolitan Chicago Citizenship Council, an award of which he is extremely proud: "That was one of the greatest feelings in my life, to become a citizen, finally. Everything that I expected in coming to this country was fulfilled." Bažant thrives in the competitive research environment in the United States and appreciates that he and his colleagues have the opportunity to work on cutting-edge science: "If I stayed in communist Czechoslovakia, I probably would have worked on old-fashioned problems. I would have achieved far less if I had stayed in my native country."

Liza Q. Bundesen, *Science Writer*

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