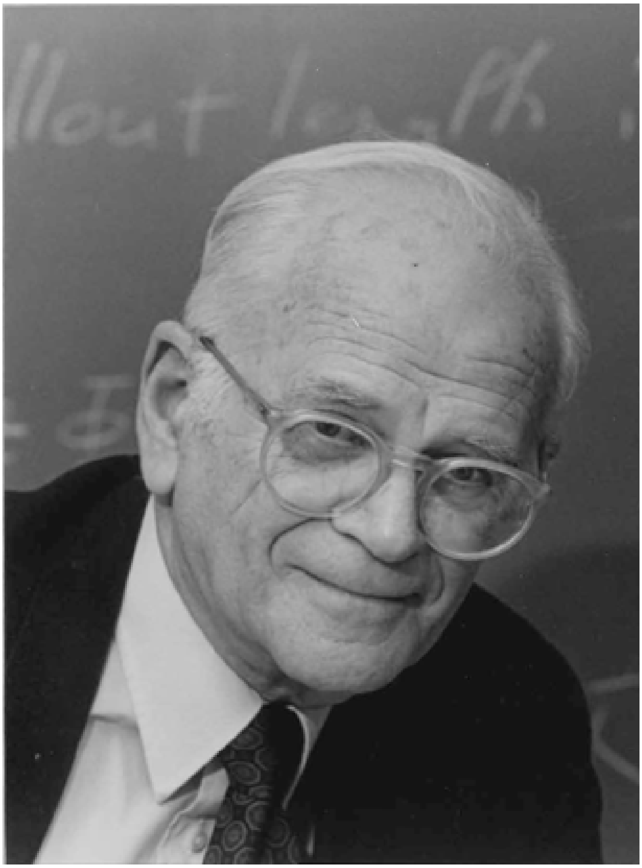
NATIONAL ACADEMY OF SCIENCES

BERNARD BUDIANSKY
1925—1999

A Biographical Memoir by

JAMES R. RICE

Biographical Memoir



Bernard Budiansky

BERNARD BUDIANSKY

March 8, 1925–January 23, 1999

BY JAMES R. RICE

BERNARD BUDIANSKY WAS a person of great charm, wit, and intelligence. He was an unabashed enthusiast about his profession, family, friends, and many other good things in life. He made innovative contributions to nearly every subfield of solid mechanics—the science of how materials and structures stretch, bend, shake, buckle, and break. His work as an engineer and applied mathematician strongly influenced structural engineering and materials technology, and also seismology and even biomechanics. He assumed emeritus status in 1995 in his positions as Gordon McKay Professor of Structural Mechanics (since 1961) and Abbott and James Lawrence Professor of Engineering (since 1983) in the Division of Engineering and Applied Sciences at Harvard University.

Budiansky was born in New York City on March 8, 1925, to Russian immigrant parents, who soon separated, and was raised by his mother and grandfather. He obtained a bachelor of civil engineering degree from City College of New York (CCNY) in 1944 when he was barely 19, a remarkable fact which, characteristically, none of his colleagues seem to recall his mentioning.

He was a child of the heroic era of large engineering structures, and his love of structural mechanics was to be lifelong. But while at CCNY he became equally enamored with mathematics and physics, and could not fail to be attracted by the then-new challenges of aeronautical structural mechanics. Accordingly, he jumped at a first job offer as an aeronautical research scientist with a newly formed unit of the Structural Research Division of NACA at Langley, Virginia, concerned with high-speed flight. [NACA, the National Advisory Committee for Aeronautics from 1917 to 1958, became NASA (the National Aeronautics and Space Administration) in 1958.]

Although Budiansky departed New York at a tender age, the city's imprint on him was indelible. His love for the city, its cultural references, its humorists (Henny Youngman, a special favorite), and its life style was to stay an integral part of him, along with an abiding pride in his generation at CCNY.

During the NACA years, Budiansky began his rapid rise to eminence with a new understanding of the dynamics of elastic plates, shells, and their combination in various thin-walled structures essential for aviation. His first published work there was on buckling of clamped plates (e.g., 1946), a topic on which he was to contribute extensively over the next few years. He also contributed on combined torsional and compressional bucking of thin-walled tubes, on buckling of structures on multiple supports or with multiple stiffeners, on developing a torsional stiffness criterion for preventing flutter of wings in supersonic flight, and on studies of divergence instability of swept wings. The vexing problems of flutter remained a focus over his entire time at NACA (1954).

He took an educational leave from NACA in 1947 to enroll in the newly established graduate program in applied mathematics at Brown University; but he lingered there no longer than at CCNY, completing his Sc.M. in 1948 and Ph.D.

in 1950. (Years later when Brown established a graduate citation to recognize distinguished graduate alumni, Budiansky was the first recipient.) Shortly before the leave from NACA, he had begun work with S. B. Batdorf (1949) on describing macroscopic plastic stress-strain response of metals in terms of slip in individual crystalline grains, and that same subject was to be the topic of his Ph.D. thesis, directed by William Prager, at Brown. Later (1959) he would use that work as the basis of a famous reappraisal of the validity in certain circumstances of the deformation, or total strain, formulation of plasticity, relative to oversimplified but commonly used formulations of the physically correct incremental class, which did not incorporate yield surface vertex features that are thought to descend from the crystalline slip basis of plastic flow.

Budiansky returned to Langley in 1950, and in 1952 was appointed head of the Structural Mechanics Branch. That year was far more memorable because he married the charming, erudite, and mathematically trained Nancy Cromer, a South Carolinian who worked in the group assisting with computations at NACA. They made for an enduringly warm and wonderful couple, deeply interested in literature and the arts, in politics, travel, and good food. She was also a cheerful participant in his enthusiasm for horse races.

His work at NACA continued with studies of vibrations and wave propagation in thin-walled structures, on buckling of plate structures that were deformed into the plastic range, on plastic stress concentrations around cut-outs, on effects of aerodynamic heating on the effective torsional stiffness of thin wings, and on the ever-present problem of flutter (1954). One can best understand how he felt about those formative years at NACA by quoting his own words, in a speech in connection with his receipt of the 1989 Timoshenko Medal of the Applied Mechanics Division, American

Society of Mechanical Engineers (taken from "Reflections" by Bernard Budiansky, Applied Mechanics Division Newsletter, ASME, spring 1990):

> To conclude these reflections, I would like to flip quickly through some verbal snapshots of a few of the people who have enriched my professional life. I had a remarkable trio of bosses in my first job in the Structures Research Division of NACA in 1944: Pai-Chuan Hu, a fresh Ph.D. in Engineering Mechanics from the University of Michigan, whose knowledge and intellect were awesome; Sam Batdorf, a renegade physicist, whose insightful way of thinking about problems in applied mechanics has been an enduring inspiration; and the big boss, the Chief of Structures Gene Lundquist, a great pioneer of structures research whose legacy as a research leader has been enduring. It was an exciting time at NACA, in those pre-space days of aeronautical research, and my experience there has left me fiercely supportive of scientific civil servants, who are at least as smart and hard-working as those in the private sector, but often are slandered by invidious comparisons. I was lucky to meet and even interact technically with some famous people at NACA outside my field of structures, like Ed Garrick, Carl Kaplan, and the great aerodynamicists Robert T. Jones and Adolph Busemann, who had independently conceived of swept wings for high-speed flight—Jones in America, Busemann in Germany. Jones told me how to calculate the lift on a swept wing, so that I could go on to study its aeroelasticity. Busemann got sufficiently interested in plasticity to join Lyell Sanders, John Hedgepeth and me in many happy hours of exploration of 6-dimensional stress space. Busemann had a marvelous, infectious technical vocabulary in English; an eavesdropper would have heard us earnestly discussing Humpty-Dumpties, meaning hyperspheres; stalactites, meaning hypervectors; and stalagmites, vectors pointing the other way!

Budiansky came to Harvard in 1955 as a tenured associate professor of structural mechanics in what was then called the Division of Engineering and Applied Physics (and, since 2007, called the School of Engineering and Applied Sciences). His renowned wit and clarity quickly established him as one of the finest teachers in that unit, even if his forcefulness and passionate expressions of opinion were found a bit intimidating by those who had not yet discovered the underlying warmth. The acerbic nature of his wit, and perhaps growing impatience, did loom larger in his later years. He remained as fulfilled as ever with his lectures to graduate students, who knew of him already as a legend, but expressed frustration that the undergraduates just didn't seem to be getting his jokes any more. We colleagues joked among ourselves that perhaps they were too scared to laugh.

In his time at Harvard he dedicated himself to building the mechanics program. He helped recruit the late George Carrier, whom he had known at Brown, and his NACA colleague, the late J. Lyell Sanders, and indeed had a major role in recruiting the current tenured members of the group. Budiansky's area of solid and structural mechanics at Harvard has been influential on the world stage somewhat out of proportion to its size, and a distinguished academic, when learning of his death, referred to that area as "the house that Bernie built." Nothing could be closer to the mark. Indeed, his dedication and charm made the entire Harvard group in mechanics and associated applied mathematics an unusually cohesive group of faculty members. In a university laden with what some suspect to be strong egos, and with primary connections being to fellow specialists typically residing elsewhere, it is rather unusual to see largish groups of faculty members who actually seem to enjoy one another's company. That caught the eye of former dean of the Faculty of Arts and Sciences, Henry Rosovsky, who once remarked that the eight or so Harvard mechanicians, whom he saw frequently together at lunch, were the largest group of faculty he ever saw together except at meetings. Budiansky was the glue for that.

In addition to his work on plasticity mentioned above, the primary early focus of his work at Harvard was on structural engineering fundamentals, especially for shell structures (e.g., 1960, 1966, 1968). Some very well-known contributions, made in part with his Ph.D. student and later faculty colleague John W. Hutchinson, were on the sensitivity to initial imperfections (1966). These could greatly reduce the buckling load of a real structure relative to that of, say, a perfect cylinder or spherical shell. He also helped clarify the mathematical foundations of thin-shell theory (1968).

Another stream of work that he initiated in the early years at Harvard was on estimating the overall elastic and thermoelastic properties of heterogeneous solids, including technological composite materials (1965, 1970). That work had hundreds of citations, but even more widely cited were a later series of papers with his Harvard geophysical faculty colleague Richard J. O'Connell, on extending those concepts to clarify the way fissures and joints in rocks affect the propagation of seismic waves (1974, 1976[2]). That has become a standard basis for inferring rock properties in the earth and constraining the extent of their fluid infiltration.

Budiansky's work in his last 20 years was focused primarily on problems in the domain of materials science and engineering. That was on explaining mechanical properties of solids in terms of microscopic mechanisms, but mechanisms, in the cases of interest to him, involving processes at scales far above the atomic, for which the most effective approach was to apply continuum mechanics at that microscopic scale. He referred to that important area as "micromechanics" (1983[2]). He was one of its pioneers, and contributed, among other topics, to widely cited works in explanation of the toughening of normally brittle ceramics and composite materials.

His works in that domain were often done in collaboration with one or more of John Hutchinson of Harvard; Anthony G. Evans of the University of California, Santa Barbara; Norman Fleck of Cambridge, U.K.; and John C. Amazigo of Nigeria. They addressed such topics as the following:

toughening of otherwise brittle ceramics by inclusions that could undergo a stress-induced dilatant phase transformation (1983[1]); stress distributions and matrix failure processes in fiber composites (1984, 1986); resistance to macrocrack growth by particulae inclusions or by broken fibers that initially bridge a growing fracture (1988, 1994); notch strength of brittle-matrix composites; and internal kinklike buckling and compressive failure of fiber-reinforced composites (1993, 1995).

Budiansky's interests in mechanics were broad, and he had a host of other contributions. Those included experiments on plastic response to changes in multiaxial stressing direction, theory of wave propagation in composites, conservation integrals in elasticity theory (1973), interaction of slip on Earth faults and creep in the lithosphere (1976[1]), pressure-sensitivity of clad optical fibers, crack face closure in fatigue crack growth (1978[1]), sheet metal forming processes (1978[2]), void growth and collapse in viscous solids, integral equations in elastodynamics, nondestructive evaluation of solids for crack-like defects, and elastic response of the lung (1990).

His final paper (1999) like his first one (1946) was in the domain of structural mechanics: on the minimum weights achievable for compression structures.

Appropriately, Budiansky was elected to the National Academy of Sciences in 1973 and the National Academy of Engineering in 1976. He was also elected a foreign member of the Royal Netherlands Academy and of the Danish Center for Applied Mathematics and Mechanics. He won the highest scientific awards for achievement in mechanics, namely, the Timoshenko Medal (1989) of the American Society of Mechanical Engineers (ASME) and the von Kármán Medal (1982) of the American Society of Civil Engineers (ASCE), and won the ASME Medal recognizing "eminently distinguished engineering achievement." He was Dryden lecturer (1970) of the American Institute of Aeronautics and Astronautics (AIAA), Townsend Medalist (1974) at CCNY, and Eringen Medalist (1985) of the Society of Engineering Science. Further, he was elected to fellow-grade membership in the ASME and the AIAA, and was a member of the ASCE, the American Geophysical Union, and the International Society for Interaction of Mechanics and Mathematics. He received honorary doctor of science degrees from Northwestern University and from the Technion in Haifa.

He served from 1966 to 1970 on the NASA Research and Technology Advisory Subcommittee on Aircraft Structures, which included the time of the first Apollo landing on the moon, and from 1978 to 1984 on the NASA Space Systems and Technology Advisory Committee. From 1985 onward he was a member of the Aeronautics and Space Engineering Board of the National Research Council.

Bernard Budiansky was a wonderful and valued colleague and friend—funny, acerbic, and kind, a great original whose likes we can hardly expect to see again. He delighted in sharing his enthusiasm for current literature, good food, and other pleasures with graciousness and charm. Intellectually and as a scientist he was still in his prime when cancer took him at 73. Nancy and their children, Michael and Stephen, survive him.

SELECTED BIBLIOGRAPHY

1946

With P.-C. Hu. The Lagrangian multiplier method of finding upper and lower limits to critical stresses of clamped plates. NACA Report 848. Langley Field, Va.: NACA Langley Memorial Aeronautical Laboratory.

1949

With S. B. Batdorf. A mathematical theory of plasticity based on the concept of slip. NACA Technical Note 1871. Langley Field, Va.: NACA Langley Memorial Aeronautical Laboratory.

1954

With J. M. Hedgepeth and R. W. Leonard. Analysis of flutter in compressible flow of a panel on many supports. *J. Aeronaut. Sci.* 21(7):475-486.

1959

A reassessment of deformation theories of plasticity. *J. Appl. Mech.* 81:259-264.

1960

Sloshing of liquids in circular canals and spherical tanks. *J. Aerospace Sci.* 27(3):161-173.

1965

On elastic moduli of some heterogeneous materials. *J. Mech. Phys. Solids* 13(4):223-227.

1966

With J. W. Hutchinson. A survey of some buckling problems. *AIAA J.* 4(9):1505-1510. Reprinted 2003 in *J. Spacecraft Rockets* 40(6):918-923.

1968

Notes on nonlinear shell theory. *J. Appl. Mech.* 35(2):393-401.

1970

Thermal and thermoelastic properties of isotropic composites. *J. Compos. Mater.* 4: 286-295.

1973

With J. R. Rice. Conservation laws and energy-release rates. *J. Appl. Mech.-Trans. ASME* 40(1):201-203.

1974

With R. J. O'Connell. Seismic velocities in dry and saturated cracked solids. *J. Geophys. Res.* 79(35):5412-5426.

1976

[1] With J. C. Amazigo. Interaction of fault slip and lithospheric creep. *J. Geophys. Res.* 81(26):4897-4900.
[2] With R. J. O'Connell. Elastic-moduli of a cracked solid. *Int. J. Solids Struct.* 12(2):81-97.

1978

[1] With J. W. Hutchinson. Analysis of closure in fatigue crack growth. *J. Appl. Mech.-Trans. ASME* 45(2):267-276.
[2] With N. M. Wang. Analysis of sheet-metal stamping by a finite-element method. *J. Appl. Mech.-Trans. ASME* 45(1):73-82.

1983

[1] With J. W. Hutchinson and J. C. Lambropoulos. Continuum theory of dilatant transformation toughening in ceramics. *Int. J. Solids Struct.* 19(4):337-355.
[2] Micromechanics. *Comput. Struct.* 16(1-4)3-12.

1984

With G. F. Carrier. High shear stresses in stiff-fiber composites. *J. Appl. Mech.-Trans. ASME* 51(4):733-735.

1986

With J. W. Hutchinson and A. G. Evans. Matrix fracture in fiber-reinforced ceramics. *J. Mech. Phys. Solids* 34(2):167-189.

1988

With J. C. Amazigo and A. G. Evans. Small-scale crack bridging and the fracture-toughness of particulate-reinforced ceramics. *J. Mech. Phys. Solids* 36(2):167-187.

1990

With E. Kimmel. Surface-tension and the dodecahedron model for lung elasticity. *J. Biomech. Eng.-Trans. ASME* 112(2):160-167.

1993

With N. A. Fleck. Compressive failure of fiber composites. *J. Mech. Phys. Solids* 41(1):183-211.

1994

With Z. C. Xia, J. W. Hutchinson, and A. G. Evans. On large-scale sliding in fiber-reinforced composites. *J. Mech. Phys. Solids* 42(7):1139-1158.

1995

With N. A. Fleck and L. Deng. Prediction of kink width in compressed fiber composites. *J. Appl. Mech.-Trans. ASME* 62(2):329-337.

1999

On the minimum weights of compression structures. *Int. J. Solids Struct.* 36:3677-3708.