Mechanics of Quasi-Brittle Materials and Structures

A Volume in Honour of
Professor Zdenek P. Bazant 60th Birthday

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1999

HERMES

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Foreword

This volume, honouring Zdenek P. Bazant on his 60th birthday, features most of the papers presented at the Workshop on Mechanics of Quasi-Brittle Materials and Structures. This Workshop, in honour of Zdenek, was held during March 27-28, 1998, at his alma mater, the Czech Technical University in Prague (CVUT). It was organised in collaboration with the Laboratoire de Mécanique et Technologie at Ecole Normale Supérieure de Cachan, France, and sponsored by Electricité de France, Stavby silnic a zeleznic, Stavby mostri Prague, and Vodni stavby Bohemia.

Born in Prague on December 10, 1937, Zdenek studied engineering at Czech Technical University in Prague (CVUT), receiving the degree of Civil Engineer (Ing.) in 1960 (with a straight A record, first in class). In 1963, he obtained a Ph.D. in mechanics from the Czechoslovak Academy of Sciences, and in 1966 a

postgraduate diploma in physics from Charles University, both in Prague. In 1967, he attained habilitation at CVUT as « Docent » in concrete structures. Through all his graduate studies, he was employed full-time as a design engineer and construction supervisor; he designed six bridges, one of them a prestressed box girder over Jizera near Korenov, noteworthy for its highly curved spans (each with a 30° central angle). During 1964-1967, he conducted research in polymer-fibber composites in the Klokner Institute of CVUT, served as adjunct assistant professor, and continued consulting in structural engineering.

In the fall of 1966, the French government awarded Zdenek an ASTEF fellowship for a six-month visit of CEBTP, Paris. Zdenek feels lucky that his advisor and mentor was the famous Robert L'Hermite. Since that time, Zdenek has always maintained close contacts with French researchers and has had a number of French assistants and collaborators (G. Pijaudier-Cabot, J. Mazars, C. Huet, L. Granger, E. Becq-Giraudon, Y. Berthaud, F.-J. Ulm and others). As a result of his stay in France, Zdenek started his activity in RILEM.

The year 1967 was critical for Zdenek. He left his native land and moved to America. After spending two years on visiting appointments at the University of Toronto and the University of California, Berkeley, he joined in September 1969 the faculty of Northwestern University as Associate Professor of Civil Engineering. He became full Professor in 1973 and was named to the W.P. Murphy distinguished professorial chair in 1990. During 1981-88, he was the Director of the Center for Geomaterials, and during 1974-78 and 1992-96, he was the Structural Engineering Coordinator.

Zdenek has made lasting contributions to mechanics of solids and concrete engineering which received wide attention (as documented by his extraordinarily high citation index, now running about 550 annually). Since 1958, he published over 380 research papers in refereed journals. In 1991, he published (with L. Cedolin) an important book on Stability of Structures, which is the first to cover systematically stability problems of fracture, damage and inelastic behaviour, and has been acclaimed in reviews by leading mechanics experts. Bazant's latest book (with J. Planas, 1998) on Fracture and Size Effect is the first to present a systematic theory of size effects in quasibrittle failure, and his book (with M. Kaplan, 1996) on Concrete at High Temperatures is the first to systematically treat mathematical modelling in this field.

Bazant is by now well known for his size effect law and the nonlocal concept for strain-softening materials. Until 1984, the observed size effects on structural strength were explained by Weibull's statistical theory, but this changed after Bazant showed theoretically, and verified experimentally, that for quasibrittle failures preceded by large stable crack growth (as observed in concrete, rock masses, tough composites, sea ice and other quasibrittle materials), the size effect is caused mainly by the release of energy stored in the structure. He introduced the size-effect method to identify non-linear fracture characteristics (adopted as RILEM Recommendation). He was the first to demonstrate, beginning in 1976, that finite element codes that

model distributed cracking by means of strain-softening stress-strain relations are plagued by spurious mesh sensitivity, ill-posedness and localisation, and lack size effect. His simple remedy, the energy based crack band model, found wide use in industry and is being introduced in commercial codes (e.g., DIANA, SBETA). As a more general remedy, he pioneered, beginning in 1983, the nonlocal continuum models, as well as gradient models for damage localisation, and later justified them physically by microcrack interactions.

In his lab, Bazant generated an extensive experimental basis for the quasibrittle size effect. He extended the size effect law to rate dependence (discovering the reversal of softening to hardening after a sudden increase of loading rate), to compression failures (columns, borehole breakout, fiber laminates) and to bending fractures of sea ice plates. He showed that, for quasibrittle materials, Paris' law for fatigue crack growth requires a size effect correction. He extended the plastic « strut-and-tie » model for failures of reinforced concrete structures (such as diagonal shear) to size effect by incorporating quasibrittle fracture mechanics. He also elucidated the size effect and fracture mechanics aspects of quasibrittle compression failures, particularly reinforced concrete columns and microbuckling kink bands in unidirectional fiber composites. He demonstrated further how the previously accepted Weibull-type statistical strength theory of size effect can be extended to nonlocality. Bazant also produced a series of progressively more powerful non-linear triaxial constitutive models for concrete and soils. Extending G.I. Taylor's idea from plasticity to damage, he developed the microplane constitutive model for concrete and soils, which is used in some large codes (EPIC) and is proving more realistic than the classical plasticity-type models. In this context, he found a new and more efficient (21-point) Gaussian integration formula for a spherical surface (published in a mathematics journal, it has also been used in computational chemistry and radiation problems).

Furthermore, Bazant solved the three-dimensional elastic stress singularity and edge angle for crack-surface intersections, and the singularity at the tip of a conical notch or inclusion. He derived conditions of localisation into ellipsoidal domains and layers; clarified the thermodynamic basis of the criterion of stable post-bifurcation path; demonstrated bifurcation and crack arrest occurring in systems of parallel cooling or shrinkage cracks; derived consistent micropolar continuum approximation for buckling of regular lattices; demonstrated and quantified spurious wave reflection and diffraction due to a changing finite element size (which found implications in atomic lattice studies and in geophysics, and was recently republished in a special volume of most important papers by the American Society for Exploration Geophysics). In 1971, Bazant clarified the correlation among three-dimensional continuum stability theories associated with different finite strain measures, such as Green's, Biot's and Hencky's, which had hitherto been thought to be in conflict. This, for example, showed the Engesser's and Haringx's formulas for shear buckling to be equivalent. He formulated a new finite strain tensor with compression-tension symmetry giving a close approximation to Hencky's but easier to compute.

Extending the work of Trost, Bazant, in 1972, formulated and rigorously proved the age-adjusted effective modulus method, which allowed approximately solving the system of integral equations for ageing creep effects in concrete structures by a single quasi-elastic analysis. This method became standard, embodied in American (ACI) and European (CEB-FIP) recommendations and featured in many books. As consultant to the Nuclear Reactor Safety Division of Argonne National Laboratory, he developed thermodynamically based models for creep, hygrothermal effects, coupled heat and mass transport and pore pressure in concrete, widely used to analyse nuclear accident scenarios. He formulated the solidification theory for creep of concrete which treats short-term ageing as a volume growth of a non-ageing constituent (cement gel) in the pores of cement stone, and the microprestress theory which describes long-term ageing and cross-couplings with diffusion processes (drying, heating) by relaxation of self-equilibrated prestress in the microsctructure generated chemically and by water adsorption. He explained various phenomena in creep of concrete by surface thermodynamics of water adsorption in gel pores. He elucidated various stochastic aspects of concrete creep, developed a Latin hypercube sampling approach to assess the effect of uncertainty of creep parameters on structures, often used in design of sensitive structures, and conceived a Bayesian model for updating these predictions based on short-time measurements. Adapting the concept of ergodicity, he formulated a spectral method for determining the effects of random environmental humidity and temperature on an ageing structure. He clarified creep and shrinkage effects on nuclear reactor containments. Bazant's efficient exponential step-by-step algorithm for concrete creep (1971), based on converting an integral-type to rate-type creep law, has found use in various finite element codes. Bazant's contributions to creep, humidity effects and their statistical analysis are important for improving durability of infrastructures as well as for designing more daring structures with high-performance concretes.

Bazant is a member of the National Academy of Engineering (elected in 1996, he was cited for *contributions to solid mechanics, particularly structural stability and size effects in fracture*). He received honorary doctorates (Dr.h.c.) from Czech Technical University, Prague (1991) and Universität Karlsruhe, Germany (1998). In 1996, the Society of Engineering Science awarded him the Prager Medal, given for *outstanding contributions to solid mechanics*. In 1997, ASME awarded him the W.R. Warner Medal, which honors *outstanding contributions to the permanent literature of engineering; cited for important contributions to solid mechanics, focusing on the size-effect law for failure of brittle structures, modeling of material damage from softening, local and nonlocal concepts, stability and propagation of fracture and damage in material and thermodynamic concepts associated with stability of non-elastic structures*. In 1996, ASCE awarded him the Newmark Medal (which honors *a member who, through contributions to structural mechanics, has helped substantially to strengthen the scientific base of structural engineering; cited for fundamental contributions to the understanding of constitutive behaviour of structural materials, non-linear fracture mechanics and stability of structures*). Other honors include: 1975 L'Hermite Medal from RILEM (cited for *brilliant*

developments in mechanics of materials, thermodynamics of creep and stability theory, bridging experimental and theoretical research); Huber Research Prize (1976), T.Y. Lin Award (1977) and Croes Medal (1997) from ASCE; Guggenheim (1978), Ford Foundation (1967), JSPS (Japan 1995), Kajima Foundation (Tokyo 1987), NATO Senior Scientist (France 1988) Fellowships; A. von Humboldt Award (Germany 1989); 1991 National Science Council of China (Taiwan) Lectureship Award, 1992 Best Engineering Book of the Year Award (Association of American Publishers), Meritorious Publication Award (1992) from Structures Engineers Association, Medal of Merit (1992) (for advances in mechanics) from Czech Society for Mechanics; Outstanding New Citizen from Metropolitan Chicago Citizenship Council (1976); and 1990 Gold Medal from Building Research Institute of Spain (cited for outstanding achievements in the fields of structural engineering and mechanics of concrete). He was elected an Honorary Member of that Institute (1991), of Czech Society of Civil Engineers (Prague 1991) and of Czech Society for Mechanics (1992), and a Fellow of American Academy of Mechanics, American Society of Mechanical Engineers (ASME), American Society of Civil Engineers (ASCE), American Concrete Institute (ACI) and RILEM (International Union of Research in Materials & Structures, Paris).

Zdenek has been very active in engineering societies. He was, (1991-93), the first president of the International Association. for Fracture Mechanics of Concrete Structures (IA-FraMCoS), incorporated in Illinois. In 1993, he was president of the Society of Engineering. Science. During 1983-94, he was division coordinator in International Association for Structures Mechanics in Reactor Technology (IA-SMiRT). He has been an inspiring leader and determined organizer, forming new committees in several societies and producing (with several committees he chaired) influential state-of-art reports. He served, (1988-94), as Editor-in-chief of ASCE Journal of Engineering Mechanics. He is a Regional Editor of the International Journal of Fracture, and a member of editorial boards of 14 other journals. He chaired the ACI Committee on Fracture Mechanics, Concrete Structures Division of the International Association for Structural Mechanics in Reactor Technology, ASCE-EMD Programs Committee and ASCE-EMD Committee on Properties of Materials. In RILEM, he currently chairs a committee on creep and a committee on scaling of failure. He organised and chaired IUTAM Prager Symposium (Evanston 1983), 4th RILEM International Symposium on Concrete Creep (Evanston 1986); FraMCoS1 (Breckenridge 1992); and co-organized and co-chaired NSF Workshop on High Strength Concrete (Chicago 1979), NSF Symposium on Concrete Creep (Lausanne 1980), AFOSR Workshop on Localisation (Minneapolis 1987), France-U.S. Workshop on Strain Localisation and Damage (Paris-Cachan 1988), RILEM 5th International Symposium on Concrete Creep (Barcelona, 1993), NSF-Eur. Union Workshop on Quasi-Brittle Materials in Prague (1994), etc. An Illinois Registered Structural Engineer (S.E.), he has been consultant for many firms and, during 1974-1996, has served as staff consultant on nuclear reactor structures to Argonne National Laboratory.

Zdenek P. Bazant comes from an old family of engineers and intellectuals. Zdenek is the fifth generation civil engineer in the line of Bazant's. His grandfather Zdenek Bazant was professor of structural mechanics at the Czech Technical University in Prague (CVUT), where he served as the dean and rector, and was member of the Czechoslovak Academy of Sciences. His father Zdenek J. Bazant was the chief engineer of Lanna, the largest construction firm in pre-war Czechoslovakia, and then for thirty years professor of foundation engineering at CVUT and a widely sought consultant. Zdenek's wife Iva, whom he married in Prague in 1967 (just two days before leaving for America), works as a physician in a State of Illinois hospital. Their son Martin, with a doctorate in physics from Harvard University, just started teaching at M.I.T., and their daughter Eva pursues graduate studies in public health at Columbia University.

Most of all, Zdenek always emphasises the great help in research he received from his outstanding doctoral students (40 completed Ph.D.'s so far). He is proud that 18 of them became professors (in the USA, France, Spain, Turkey, Japan, Korea, Taiwan, etc.). Five became deans, five directors of research institutes. Others distinguished themselves in industry.

Zdenek has many human qualities which are appreciated by all the people he has been working with. He has always cared for his students and co-workers. He believes that being a professor does not only mean being successful in research and teaching. It also means helping co-workers at developing their own original way of thinking and assisting them in finding, depending on their interests, the best place for the future. In other words, Zdenek knows that advising does not stop at the end of a Ph.D. defense or a stay at Northwestern. It is almost a life-time effort and Zdenek has always been up to it, collaborating with many former students on new research problems for years after they left Northwestern.

For his co-workers, he is not only an outstanding scientist and an experienced advisor, but also a very much appreciated friend. We are all looking forward to celebrate many more Zdenek's birthdays in the future!

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