Probabilistic Mechanics of Quasibrittle Structures

Strength, Lifetime, and Size Effect

Quasibrittle materials are becoming increasingly important for modern engineering. They include concretes, rocks, fiber composites, tough ceramics, sea ice, bone, wood, stiff soils, rigid foams, glass, dental and biomaterials, as well as all brittle materials on the micro or nano scale. Their salient feature is that the fracture process zone size is non-negligible compared to the structural dimensions. This causes intricate energetic and statistical size effects and leads to size-dependent probability distribution of strength, transitional between Gaussian and Weibullian.

Probabilistic Mechanics of Quasibrittle Structures discusses the ensuing difficult challenges for safe design.

Drawing upon years of practical experience and using numerous examples and illustrative applications, the authors cover:

- Rigorous theory with detailed derivations yet no superfluous mathematical sophistication.
- Extensive experimental verifications and realistic approximations for design.
- Fracture kinetics and its size effect.
- Multiscale analytical transition to the material scale.
- Statistics of structural strength and lifetime, size effect and reliability indices.
- Ramification to gate dielectrics breakdown with analogous mathematical formulation.

Born and educated in Prague (Ph.D. 1963), Zdeněk Bažant joined Northwestern University in 1969, where he has been W.P. Murphy Professor since 1990 and simultaneously McCormick Institute Professor since 2002, as well as Director of Center for Geomaterials (1981–1987). He was inducted to NAS, NAE, American Academy of Arts & Sciences, Royal Society London; to the academies of Italy, Austria, Spain, Czech Republic, Greece and Lombardy; and to Academia Europaea and European Academy of Sciences & Arts. He is an honorary member of ASCE, ASME, ACI, and RILEM; received seven honorary doctorates as well as the von Karman, Timoshenko, Prager and Newmark medals among many honors; was awarded the Austrian Cross for Science and Art 1st Class from president of Austria; and was president of SES, IA-FraMCoS and IA-ConCreep. He has authored six books and over 600 papers. In 2015, ASCE established ZP Bažant Medal for Failure and Damage Prevention, and ZP Bažant Prize for Engineering Mechanics was created in Czech Republic. He is one of the original top 100 ISI Highly Cited Scientists in Engineering (www.ISIhighlycited.com).

Dr. Jia-Liang Le is currently Associate Professor of Civil, Environmental, and Geo-Engineering at the University of Minnesota. He obtained his Ph.D. in structural mechanics from Northwestern University in 2010. He received the Best Paper Award of the 48th U.S. Rock Mechanics/ Geomechanics Symposium, the 2015 Young Investigator Award from the U.S. Army Research Office, and the 2017 ASCE Leonardo da Vinci Award. His research interests include fracture mechanics, probabilistic mechanics, scaling, and structural reliability.

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Zdenek P. Bazant , Jia-Liang Le
Frontmatter
More Information

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Strength, Lifetime, and Size Effect

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Dedicated to the memory of Alfred Martin Freudenthal (1906–1977), widely regarded as the founder of the field of structural safety and reliability, encompassing both the theories of probability and statistics and the theories of mechanics of materials and structures.

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Frontmatter
More Information

Contents

Cambridge University Press
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Zdenek P. Bazant , Jia-Liang Le
Frontmatter
More Information

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978-1-107-15170-3 — Probabilistic Mechanics of Quasibrittle Structures
Zdenek P. Bazant , Jia-Liang Le
Frontmatter
More Information

Foreword

Failure of materials was recognized centuries ago as a critical component of structural mechanics and consequently of structural design. Efficient (minimum amount of materials) and economical (minimum cost) designs are based on the basic principle of taking full advantage of the strength of the materials used, while at the same time carefully avoiding any type of material failure.

Whether or not they were able to quantify it, adequately, engineers realized very soon that material failure involved a high level of uncertainty. Later on, based on advances in the mathematical theory of probability, researchers in the field of mechanics identified two basic types of material behavior as far as failure is concerned – ductile and brittle failures – and were able to establish rigorous probabilistic models for both. The Gaussian and Weibull probability distributions have been the standard models for these two types of material failure, respectively.

However, there has always been a transition area between ductile and brittle failures with a behavior that was orders of magnitude more complex and challenging to model: it has been named “quasibrittle behavior.” The two standard models for ductile and brittle failure were clearly not adequate in this transition area, and on top of that, there is a very wide range of materials falling in this category at the scale of laboratory testing and normal structures: concrete, various composites, toughened ceramics, many rocks, coal, ice, rigid foams, biological shells, bone, cartilage, dental ceramics, and many others. Furthermore, at the nano- and micrometer scales, virtually all materials become quasibrittle.

The first author of this book – one of the giants in the field of mechanics – has been instrumental over the years in developing a rigorous theoretical framework modeling the failures of structures made of quasibrittle materials. In a long series of seminal scientific papers, he has identified the challenges involved and has introduced a number of groundbreaking theories and models to address them. He and his coauthor, who, despite being much younger, has already impacted the field by his own seminal contributions, have provided in this volume the definitive treatment of this formidably challenging field, and in the process have established the complete theory of any type of material failure, ranging between the two limiting cases of ductile and brittle behaviors.

In particular, I would like to highlight the equal emphasis and importance given by the authors to the two disciplines of mechanics and probability, and their ingenious and highly successful blending of the two in a fully integrated theoretical framework. The volume is a true pleasure to read and will become immediately an indispensable tool for every scientist, scholar, and engineer interested in this critically important field.

George Deodatis
Santiago and Robertina Calatrava Family Endowed Chair and Chair,
Department of Civil Engineering and Engineering Mechanics, Columbia University
President, International Association for Structural Safety and Reliability, 2009–2013

Preface

Although some would vehemently deny it, many specialists would agree that, since the 1977 death of Freudenthal,[1] the research field of structural safety and reliability has been in a schism.

Alfred Freudenthal, the founder of this field of research in the 1960s, perceived the fields of (1) structural safety and (2) mechanics and physics of materials and structures as inseparable. He mastered both, and treated both to the depth of knowledge in his time. Since that time, unfortunately, most researchers have immersed themselves in one of these two fields in great detail and with high sophistication, while treating the other aspect simplistically and superficially. The connection has been weak.

On one side, there have been probabilists who develop and successfully market complex computer programs to assess safety, reliability, and lifetime of concrete structures without recognizing that failure probability of concrete structures cannot be predicted with simplistic or obsolete material models that eschew fracture mechanics and energetic size effect. Or there have been statistically minded experimenters who conduct extensive histogram testing of the strength of ceramics but ignore the scale effects, micromechanics, and microscale physics of failure.

On the other side, there have been mechanicians who construct highly refined constitutive and computational models for the mechanics of failure of concrete, geomaterials,

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[1] Born in Poland in 1906, Alfred Martin Freudenthal received his engineering and doctoral degrees in Prague, in 1929 and 1930, respectively. His dissertation dealt with the theory of plasticity. He worked in Prague as a structural engineer in a well-known engineering design firm, collaborated with Prof. J. Melan, a leading bridge designer at that time, and simultaneously, in 1934, collected another engineering degree in Lwow. From 1936 to 1946 he was one the chief engineers of the new port of Tel Aviv and, after 1938, also a professor of bridge engineering at the Hebrew University of Technology in Haifa. In 1948 he arrived in the United States as a visiting professor at the University of Illinois, and between 1949 and 1969 he was a professor of civil engineering at Columbia University, New York, and then, until his death in 1977, a professor at George Washington University, Washington, DC.

A selection of his papers, published in 1981 by the American Society of Civil Engineers, shows a remarkably evenhanded attention to the mechanical behavior of materials and structures on one side, and the structural safety, reliability and fatigue on the other side, with both aspects intertwined as if they were one. His seminal works deal with viscoelasticity and nonlinear creep, plastic shells, orthotropic sandwich plates and shells, shrinkage stresses, concrete creep, consolidating media, strength of airframes, shear dilatancy in rock, seismic waves, work-hardening law for metals, relaxation spectra, second-order strain effects in metals, physical and statistical aspects of metal fatigue and residual stresses, fundamental theory of structural safety, safety of prestressed concrete, cumulative damage, lifetime estimation, random failure of structures with multiple load paths, reliability of reactor components, extreme value risk analysis, reliability of aircraft and of offshore platforms in seismic regions, structural optimization, and risk control.

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Frontmatter
More Information

and composites without recognizing that far greater prediction errors stem from simplistic or nonexistent treatment of the randomness of the material as well as the loads.

The present book attempts a step to rectify this schism. In a unified theoretical framework, it deals with the quasibrittle structures, which are those consisting of quasibrittle (or brittle heterogeneous) materials. These are commonplace materials, used more and more widely and increasingly important for modern technology, including much of high-tech. They encompass concretes (as the archetypical case), rocks, fiber composites, tough ceramics, sea ice, bone, wood, stiff soils, rigid foams, and so forth, as well as all brittle materials on the micrometer scale. They are characterized by a fracture process zone that is not negligible compared to the typical structural dimensions. This feature causes an intricate energetic size effect, which is intertwined with the classical statistical size effect, the only kind of size effect known in classical fracture mechanics of brittle materials. Compared to metals and ceramics, a probabilistic theory of strength, lifetime, and size effect of quasibrittle structures has been developed much more recently. Its comprehensive presentation, based mostly on previous studies at Northwestern University and the University of Minnesota, is the objective of this book.

Although the main purpose of this book is a comprehensive mathematical exposition of the subject, the book is also suitable as a text for an advanced course, as all the results are mathematically derived and the focus is on understanding rather than just description. Moreover, parts of the book can be covered in graduate courses dealing with the modeling of failure of various materials and structures, as featured in the curricula in civil, mechanical, aerospace, nuclear, offshore, geotechnical, and ocean engineering, as well as materials science and geophysics. Chapters 1–3, Sections 6.1, 6.4, 6.6, 12.1, 12.2, 13.1, 13.3, and Appendices A–C can also be covered in a broader graduate course on Quasibrittle (or Cohesive) Fracture and Scaling, which the first author has been teaching at Northwestern since the 1980s, and which the second author later introduced at the University of Minnesota.

Working on the journal articles that underlie our book, we benefited from outstanding collaborators, particularly Sze-Dai Pang, Marco Salviato, Miroslav Vořechovský, Jan Eliáš, Drahoš Novák, Augusto Cannoe Falchetto, Mihai Marasteanu, Joseph Labuz, Roberto Ballarini, Johnathan Manning, Bing Xue, and Mathieu Pieuchot. They deserve our deep thanks. The results presented here could not have been achieved without generous funding from the US National Science Foundation, the US Department of Energy, the Army Research Office, the US Department of Transportation, the Boeing Co., the Minnesota Department of Transportation, and the Center for Transportation Studies at the University of Minnesota, for all of which we are very grateful.

We also want to express our deep appreciation of the stimulating research environments provided by Northwestern University and the University of Minnesota. Last but not least, we wish to express our wholehearted thanks to our wives, Iva M. Bažant and Miao Pan, for their loving support of our research endeavor.

Zdeněk P. Bažant and Jia-Liang Le
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