VOLUME 2

George Z. Voyiadjis
Editor

Handbook of Damage Mechanics

Nano to Macro Scale for Materials and Structures

Springer Reference

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With 699 Figures and 61 Tables

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Handbook of Damage Mechanics

Foreword

The field of damage mechanics has made considerable headway since its initial conception over 50 years ago as a means of associating changes of material compliance and strain localization with evolving creep damage of materials. Development of basic concepts in this field has evolved in several directions, with one stream focused on continuum thermodynamics based on damage field variables and another appealing to continuum micromechanics, attempting to account for explicit defects and microstructure and linking to cooperative behavior through elastic interactions. Although continuum damage mechanics and analytical/computational micromechanics of materials may appear to have taken distinct and parallel courses of development from the mid-1980s onward, the theoretical connections between these two paths are rich and deep, rooted in thermodynamics and kinetics. This is effectively expressed using internal state variables as a means to reduce the degrees of freedom of the model description while maintaining consistency with damaged material response at the level of a representative volume element.

This handbook thoroughly explores these connections, combining works in foundational topics such as fabric tensors to represent networks of cracks or other modes of damage with explicit modeling of microstructure and associated damage mechanisms. Authored by a series of leading international experts in the field, a unifying theme of the articles in this handbook is the treatment of structural-level degradation of response. Damage mechanics has been fruitfully applied as a practical approach for applications that involve complex aspects of distributed, evolving damage. Examples in this volume are varied:

- Low cycle fatigue via damage mechanics coupled with internal state variable crystal plasticity in polycrystalline metals
- Distributed particle/fiber cracking and interfacial debonding in particle- and fiber-reinforced composites, including both implicit and explicit consideration of damage modes
- Internal state variable modeling of distributed damage in polymers
- Damage evolution and failure of electronic materials and packaging
- Damage evolution and failure of materials subjected to extreme conditions, including dynamic loading conditions, irradiation in nuclear power plant components, and large-deformation metal forming
- Ductile fracture and damage localization in metals

In addition to applications, fundamental aspects of thermodynamics of damaged solids are addressed, including isotropic and anisotropic damage mechanics. Readers will also find substantial treatment of multiscale modeling and various approaches to homogenization of damage evolution processes. Emerging concepts in the evolution of damage, such as fractal theory and discrete damage models, round out theoretical aspects and explore the connectivity of damage mechanics with statistical physics.

Finally, the handbook provides an overview of recent experimental methods to measure evolving distributed damage in materials, with an emphasis on digital image correlation, as well as characterization and inverse modeling. The reader will find linkages between state-of-the-art theory, experiments, and applications in this volume, establishing an invaluable contribution to the literature.

I trust that you will find this *Handbook of Damage Mechanics* an inspiring and indispensable reference.

May 2014

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Preface

Damage characterization and mechanics is a broad and highly interdisciplinary field that has been continuously evolving in the last half century. This handbook is an attempt to cover the wide spectrum of topics of damage mechanics in a single book in order to reach a wide audience of readers ranging from students to active researchers in both academia and industry. This was a monumental challenge for the authors involved to overcome. An enormous group of internationally recognized authors from both academia and industry assembled from three continents to write 47 chapters on this topic and its various branches.

Tremendous developments have taken place within the research topic of continuum damage mechanics in the past 50 years. There are currently one dedicated journal to this topic as well as numerous books and thousands of research papers. In the framework of continuum damage mechanics, the collection of micro-defects (like micro-cracks, micro-voids, etc.) are treated as a continuous region within which the laws of continuum mechanics are assumed to apply. This is in contrast to what is done in fracture mechanics where individual defects are treated separately and discontinuities are allowed.

Our goal was to assimilate the existing damage mechanics knowledge of academic interest into one consistent, self-contained volume accessible to engineers in practice, researchers in this field, and interested people in academia and to motivate nonspecialists with a strong desire to learn damage mechanics. Such a task was beyond the scope of each of the collected research papers, which by nature focus on narrow topics using very specialized terminology. Our intent was to provide a detailed presentation of those areas of damage mechanics which we have found to be of great practical utility in our industrial experience, while maintaining a sufficiently formal approach both to be suitable as a trustworthy reference for those whose primary interest is further research and to provide a solid foundation for students and others first learning the subject.

Each chapter was written to provide a self-contained treatment of one major topic. Collectively, however, the chapters have been designed and carefully integrated to be entirely complementary with respect to definitions, terminology, and notation. Furthermore, there is essentially no duplication of material across chapters.

The *Handbook of Damage Mechanics* comprises 12 distinct sections including 47 chapters covering the basics of damage mechanics as well as recent research.

The topics covered include the fundamentals of continuum damage mechanics, damage in disordered media, damage in crystalline metals and alloys, damage in structures, damage in electronic packaging, damage in metal forming, micromechanics of damage in composite materials, coupled elastoplastic damage and healing mechanics in granular materials, damage under dynamic loading, experimental characterization of damage, micromechanics of damage in laminated composites, nuclear damage characterization, and recent trends in damage and healing mechanics.

One of the major features of the *Handbook of Damage Mechanics* is coverage of the latest research in the new topic of healing mechanics of materials. The handbook includes four chapters on this emerging subject. In addition, it includes three chapters on the experimental characterization of damage in materials. The fundamentals of continuum damage mechanics are presented in four chapters of the very first section.

The handbook integrated knowledge from the theoretical, numerical, and experimental areas of damage mechanics. This book mainly targets graduate students of damage mechanics, researchers in academia and industry who are active or intend to become active in this field, and practicing engineers and scientists who work in this topic and would like to solve problems utilizing the tools offered by damage mechanics. This handbook should serve as an excellent text for a series of graduate courses in mechanical engineering, civil engineering, materials science, engineering mechanics, aerospace engineering, applied mathematics, applied physics, and applied chemistry.

The handbook is basically intended as a textbook for university courses as well as a reference for researchers in this field. It will serve as a timely addition to the literature on damage mechanics and as an invaluable resource to members of the international scientific and industrial communities.

We hope that the reader will find this handbook a useful resource as he/she progresses in their study and research in damage mechanics. We would also like to wish the readers much success and welcome their suggestions for future improvement of the handbook.

Each of the individual sections of this handbook could be considered a compact, self-contained mini-book right under its own title. However, these topics are presented in relation to the basic principles of damage mechanics.

What is finally presented in the handbook is the work contributed by celebrated international experts for their best knowledge and practices on specific and related topics in damage characterization and mechanics.

The editor would like to thank all the contributors who wrote chapters for this handbook. Finally, the editor would like to acknowledge the help and support of his family members and the editors at Springer who made this handbook possible.

March 2014

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About the Editor

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George Z. Voyiadjis is the Boyd Professor at the Louisiana State University in the Department of Civil and Environmental Engineering. This is the highest professorial rank awarded by the Louisiana State University System. He joined the faculty of the university in 1980. He is currently the Chair of the Department of Civil and Environmental Engineering. He holds this position since February 2001.

Voyiadjis is a Foreign Member of the Polish Academy of Sciences, Division IV (Technical Sciences). He is the recipient of the 2008 Nathan M. Newmark Medal of the American Society of Civil Engineers and the 2012 Khan International Medal for outstanding lifelong contribution to the field of plasticity. Voyiadjis was honored in April 2012 by the International Symposium on "Modeling Material Behavior at Multiple Scales" sponsored by Hanyang University, Seoul, Korea, chaired by T. Park and X. Chen (with a dedicated special issue in the *Journal of Engineering Materials and Technology* of the ASME). He was honored in January 2013 by an International Mini-symposium on "Multiscale and Mechanism Oriented Models: Computations and Experiments" sponsored by the International Symposium on Plasticity and Its Current Applications, chaired by V. Tomar and X. Chen.

He is a Fellow of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Academy of Mechanics, and the Engineering

Mechanics Institute of ASCE and Associate Fellow of the American Institute of Aeronautics and Astronautics. He was on the Board of Governors of the Engineering Mechanics Institute of the American Society of Civil Engineers and Past President of the Board of Directors of the Society of Engineering Science. He is currently a member of the Executive Committee of the Materials Division (MD) of the American Society of Mechanical Engineers. Dr. Voyiadjis is the Chief Editor of the *Journal of Nanomechanics and Micromechanics* of the ASCE and is on the Editorial Board of numerous engineering journals. He was also selected by the Korea Science and Engineering Foundation (KOSEF) as one of the only two World Class University foreign scholars in the area of civil and architectural engineering to work on nanofusion in civil engineering. This is a multimillion research grant.

Voyiadjis' primary research interest is in plasticity and damage mechanics of metals, metal matrix composites, polymers and ceramics with emphasis on theoretical modeling, numerical simulation of material behavior, and experimental correlation. Research activities of particular interest encompass macro-mechanical and micro-mechanical constitutive modeling, experimental procedures for quantification of crack densities, inelastic behavior, thermal effects, interfaces, damage, failure, fracture, impact, and numerical modeling.

Dr. Voyiadjis' research has been performed on developing numerical models that aim at simulating the damage and dynamic failure response of advanced engineering materials and structures under high-speed impact loading conditions. This work will guide the development of design criteria and fabrication processes of high-performance materials and structures under severe loading conditions. Emphasis is placed on the survivability area that aims to develop and field a contingency armor that is thin and lightweight, but with a very high level of an overpressure protection system that provides low penetration depths. The formation of cracks and voids in the adiabatic shear bands, which are the precursors to fracture, is mainly investigated.

He has a patent, over 260 refereed journal articles, and 17 books (11 as editor) to his credit. He gave over 400 presentations as plenary, keynote, and invited speaker as well as other talks. Over 55 graduate students (30 Ph.D.) completed their degrees under his direction. He has also supervised numerous postdoctoral associates. Voyiadjis has been extremely successful in securing more than $20.0 million in research funds as a principal investigator from the National Science Foundation, the Department of Defense, the Air Force Office of Scientific Research, the Department of Transportation, and major companies such as IBM and Martin Marietta.

He has been invited to give plenary presentations and keynote lectures in many countries around the world. He has also been invited as guest editor in numerous volumes of the *Journal of Computer Methods in Applied Mechanics and Engineering*, *International Journal of Plasticity*, *Journal of Engineering Mechanics* of the ASCE, *Journal of Mechanics of Materials*, and others. These special issues focus in the areas of damage mechanics, structures, fracture mechanics, localization, and bridging of length scales.

He has extensive international collaborations with universities in France, Republic of Korea, and Poland.

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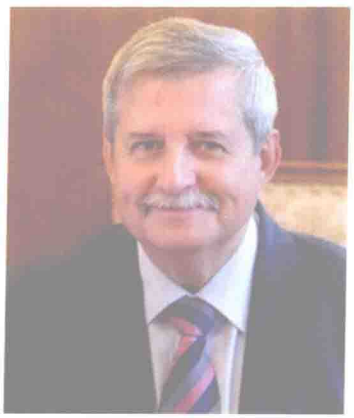

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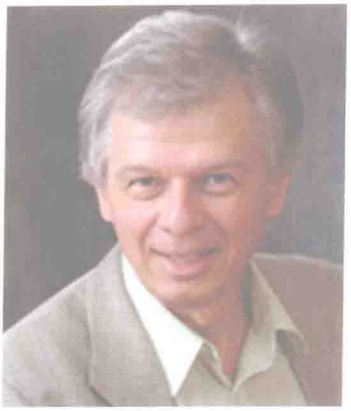

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