Structural and System Reliability

Based on material taught at the University of California, Berkeley, this textbook offers a modern, rigorous, and comprehensive treatment of the methods of structural and system reliability analysis. It covers the first- and second-order reliability methods for components and systems, simulation methods, time- and space-variant reliability, and Bayesian parameter estimation and reliability updating. It also presents more advanced, state-of-the-art topics such as finite-element reliability methods, stochastic structural dynamics, reliability-based optimal design, and Bayesian networks. A wealth of well-designed examples connect theory with practice, with simple examples demonstrating mathematical concepts and larger examples demonstrating their applications. End-of-chapter homework problems are included throughout.

Including all necessary background material from probability theory, and accompanied online by a solutions manual and PowerPoint slides for instructors, this is the ideal text for senior undergraduate and graduate students taking courses on structural and system reliability in departments of civil, environmental, and mechanical engineering.

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Preface

This book is the outcome of teaching the subject of structural and system reliability at the University of California for more than 40 years. I was hired there as Assistant Professor in 1978 and tasked with the responsibility of developing the field of risk and reliability analysis in civil engineering. Over the subsequent years, I collected, produced/co-produced, and refined the material that forms the core of this book. Of course, I was influenced by the developments in the field as I encountered them in the literature or through interactions with colleagues both within and outside the university. I was also assisted by the many excellent students who did their research in this field under my supervision. Aside from a graduate course on structural and system reliability, I developed and taught undergraduate courses on engineering data analysis and engineering risk analysis, and a graduate course on stochastic structural dynamics, all of which employed probabilistic methods. Parts of this book are influenced by my teaching of these courses, also.

My motivation for writing this book lies in my strong belief that the topic of structural and system reliability is in need of a textbook that presents the material in a clear and well-organized way, without unnecessary mathematical formalism, and in a manner that facilitates self-learning through clear exposition of background theories followed by demonstrative examples. For this reason, the book contains many worked-out examples, each designed to demonstrate one or more fundamental concepts. The material seeks to provide a contemporary treatment of the subject.

The first 11 chapters of the book form the core of the teaching material. They include detailed numerical examples and end-of-chapter problems. The focus is on developing structural reliability methods, including the first- and second-order reliability methods (FORM and SORM), a host of sampling methods, models and methods for time- and space-variant reliability analyses, and Bayesian parameter estimation and reliability updating. Earlier methods, such as the second-moment reliability method (FOSM), are also presented for their historical interest. Methods for characterization and reliability assessment of systems are presented in a broad way, appropriate for both structural systems and infrastructure systems. Also included, in considerable detail, are methods for assessing reliability sensitivity and variable importance measures.

The last four chapters of the book, which are on the topics of finite-element reliability analysis, stochastic dynamics of nonlinear structures, reliability-based optimal design, and Bayesian networks for structural reliability assessment and updating, are presented more as state-of-the-art reviews than textbook material. These topics are still developing, and I hope that these chapters will motivate some readers to pursue further research and development in these areas.

My own entry into this field was somewhat accidental. As a new doctoral student at the University of Illinois at Urbana-Champaign, in the fall of 1972, I visited Professor Alfredo H.-S. Ang, who was looking for a research assistant. He asked whether I had a background in probability theory. I said that I did not. He told me that the project he had was in risk and reliability analysis and that it required a background in probability theory, going on to say that it was all right that I did not have such a background but that I would have to take his courses to learn it. He was so honest as to admit that some civil engineering faculty thought this field "useless," but he disagreed and saw a bright future. He then gave me Bruce Ellingwood's newly completed doctoral thesis to read, to give me an idea what the topic was about. With my lack of a background in probability, naturally I did not understand much of Bruce's thesis. But I was sufficiently intrigued to give the subject a try. I took two courses with Professor Ang that semester, one on risk analysis and decision-making and the other on structural reliability. The probabilistic approach in both courses appeared to me to be logical and easy to grasp and devoid of the somewhat dogmatic and mysterious approaches I had seen in other courses. That set the direction of my entire academic career.

Looking back, I am amazed at how far the field has developed. The need for risk and reliability assessment in engineering has become paramount in order to assure the safety and operability of engineered facilities and for optimal use of resources. With the advent of sensor technologies and advances in data analytics, even broader opportunities for the use of risk and reliability methods for decision-making are available. It is clear that Professor Ang's prediction in 1972 was correct.

To master this subject, the student must have a strong understanding of applied probability and statistics. Although it is desirable that the student have such a background before reading this book, it is possible to gain the necessary proficiency by thoroughly absorbing the material in Chapters 2 and 3. Additional material on random processes and random fields is presented in Chapters 11, 12, and 13. While that material is sufficient for the topics covered in this book, these are rich topics that go far beyond what is presented here. References for further reading are listed throughout the book.

The solution of non-trivial structural reliability problems requires the use of specialized software. In Chapter 1, several software packages for this purpose are mentioned. Among them are CalREL, FERUM, and OpenSees, which have been developed at the University of California, Berkeley (with FERUM further developed at the Université Clermont Auvergne, France), and are freely available as described in Chapter 1. Additional computational tools for reliability analysis and uncertainty quantification are being made available by the new generation of academics and researchers in this field, as also described in Chapter 1. Indeed, the resources available for studying and applying the methods of structural and system reliability are infinitely larger than what was available when I started.

It is my hope that students and instructors will find this book worthy of their consideration and use. I also hope that researchers and practicing engineers will find the exposition sufficiently clear for self-learning and use in their research and practice.

Acknowledgments

I have benefited from the counsel and assistance of many individuals who have indirectly contributed to the creation of this book. First among them is Alfredo H.-S. Ang, who introduced me to this field. His courses at the University of Illinois were instrumental in inspiring me to continue working in this area. He also encouraged me to apply for the position at UC Berkeley and I am sure his reference played a significant role in my hiring.

UC Berkeley has offered an ideal environment for academic pursuits. I was fortunate to be in a department with top-notch faculty. Even though the vast majority of them were working far from the probabilistic area, interactions with them were always inspiring and helped me broaden my perspective on the use of probabilistic methods. I greatly enjoyed collaborating with my colleagues Vitelmo Bertero, Yousef Bozorgnia, Jonathan D. Bray, James M. Kelly, Steve Mahin, Jack Moehle, Carl Monismith, Paulo Monteiro, Khalid Mosalam, Jerome L. Sackman, Ray Seed, Nick Sitar, Bozidar Stojadinovic, Robert Taylor, and Edward Wilson on various papers. I am particularly grateful to Jerome L. Sackman, who was a mentor, a collaborator, and a very dear friend throughout my career at Berkeley. I also benefited enormously from collaborations with colleagues from outside our department, including Richard Barlow of the Industrial Engineering and Operations Research Department, Douglas Dreger of the Department of Earth and Planetary Science, and Elijah Polak of the Department of Electrical Engineering and Computer Science. Outside UC Berkeley, I have been influenced by many colleagues in the field of structural and system reliability, chief among whom is Ove Ditlevsen at the Technical University of Denmark; discussions with him always helped my thinking reach new depths. I am grateful to my colleagues Robert Taylor and Sanjay Govindjee for offering valuable comments on Chapter 12.

There is no question that the major influence on my academic work and the writing of this book has come from my students at UC Berkeley. I have been extremely fortunate to have an exceptionally intelligent and dedicated group of students. The learning experience has always been mutual. In fact, a good teacher must be a good learner and I have learned as much from my students as they have learned from me. Those of my students who have had important impact on this book include Wiggo Smeby, Masoud Zadeh, Takeru Igusa, Alejandro Asfura, Jorge Crempien, Rodrigo Araya, Chih-Dao Wung, Pei-Ling Liu, Jyh-Bin Ke, Hong-Zong Lin, Yan Zhang, Dariush Mirfendereski, Chin-Man Mok, Charles Menun, Petros Keshishian, Mehrdad Sasani, Paolo Gardoni, Johannes O. Royset, Heonsang Koo, Kee-Jeung Hong, Terje Haukaas, Junho Song, Kazuya Fujimura, Sanaz Rezaeian, Michelle Bensi, Katerina Konakli, Iris Tien, Marco Broccardo, Mayssa Dabaghi, and Binbin Li. Aside from these doctoral students, I have had the good fortune of hosting an excellent group of postdoctoral visitors and visiting doctoral students in my research group. Among them, the following have had influence on what is presented in this book: Philippe Geyskens, Bruno Sudret, Jean-Marc Bourinet, Anthony Hanel, Daniel Straub, Salvatore Sessa, Luca Garré, Umberto Alibrandi, Iason Papaioannou, Matteo Pozzi, Nikolay Dimitrov, James-A. Goulet and Ziqi Wang. Many of these doctoral students and postdocs are now prominent academics in the field of risk and reliability analysis. Furthermore, two of Junho Song's students from Seoul National University, Ji-Eun Byun and Eui-Hyun Choi, provided valuable assistance in developing the example problems in Chapter 8. In addition, Michelle Bensi, Iason Papaioannou, Junho Song, and Daniel Straub reviewed parts of the manuscript and made valuable comments. I express my sincere thanks to them all.

Finally, I must express my deep gratitude to my own family: my parents, who instilled in me the love for education and learning; my children, who thought their father was "always working" and tolerated my frequent absences; and to my dear wife Nelly who has steadfastly supported me all along and to whom this book is dedicated.