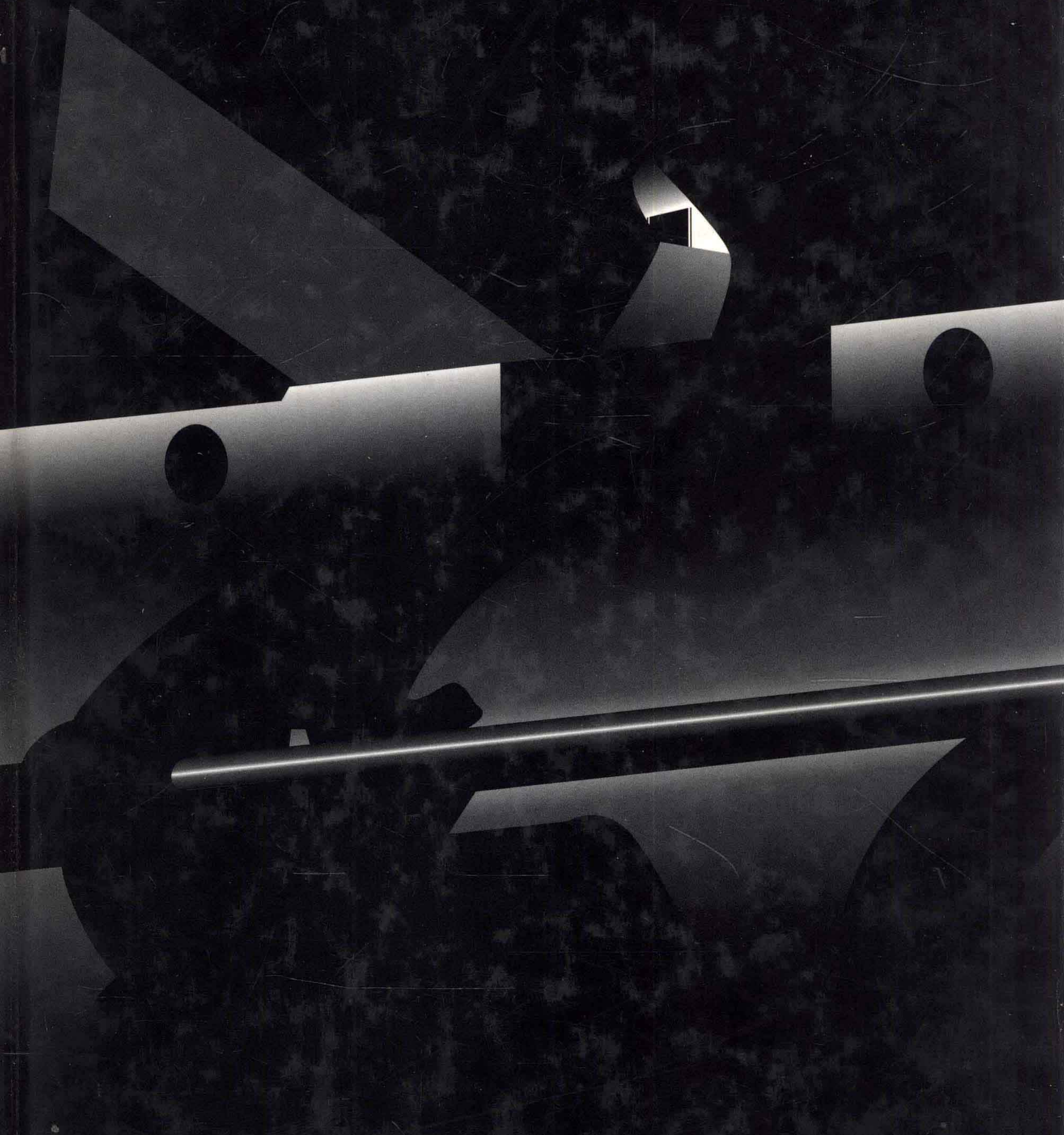
PROBABILISTIC STRUCTURAL MECHANICS HANDBOOK

THEORY AND INDUSTRIAL APPLICATIONS



EDITED BY C. (RAJ) SUNDARARAJAN

Probabilistic Structural Mechanics Handbook

Theory and Industrial Applications

Edited by C. (Raj) Sundararajan, Ph.D.

Consultant

Houston, Texas

CHAPMAN & HALL

I(T)P An International Thomson Publishing Company

New York • Albany • Bonn • Boston • Cincinnati • Detriot • London • Madrid • Melbourne • Mexico City
Pacific Grove • Paris • San Francisco • Singapore • Tokyo • Toronto • Washington

Cover design: Trudi Gershenov

Printed in the United States of America

For more information, contact:

Chapman & Hall
One Penn Plaza
New York, NY 10119

International Thomson Publishing
Berkshire House 168-173
High Holborn
London WC1V 7AA
England

Thomas Nelson Australia
102 Dodds Street
South Melbourne, 3205
Victoria, Australia

Nelson Canada
1120 Birchmount Road
Scarborough, Ontario
Canada M1K 5G4

International Thomson Editores
Campos Eliseos 385, Piso 7
Col. Polanco
11560 Mexico D.F. Mexico

International Thomson Publishing Gmbh
Konigwinterer Strasse 418
53228 Bonn
Germany

International Thomson Publishing Asia
221 Henderson Road #05-10
Henderson Building
Singapore 0315

International Thomson Publishing - Japan
Hirakawacho-cho Kyowa Building, 3F
1-2-1 Hirakawacho-cho
Chiyoda-ku, 102 Tokyo
Japan

1 2 3 4 5 6 7 8 9 10 XXX 01 00 99 98 97 96 95

Library of Congress Catloging-in-Publication Data

Sundararajan, C.
Probabilistic structural mechanics handbook / C. Sundararajan.
p. cm.
Includes bibliographical references and index.
ISBN 0-412-05481-7
1. Structural stability--Statistical methods. 2. Stuctural dynamics--Statistical methods. 3. Probabilities. 1. Title.
TA656.S86 1994
624. 1'7--dc20 94-18578
CIP

British Library Cataloguing in Publication Data available

Please send your order for this or any other Chapman & Hall book to
Chapman & Hall, 29 West 35th Street, New York, NY 10001, Attn: Customer Service Department.
You many also call our Order Department at 1-212-244-3336 or fax you purchase order to 1-800-248-4724.

For a complete listing of Chapman & Hall's titles, send your request to
Chapman & Hall, Dept. BC, One Penn Plaza, New York, NY 10119.

Probabilistic Structural Mechanics Handbook

CONTRIBUTORS

Professor Bilal M. Ayyub
Department of Civil Engineering
University of Maryland
College Park, MD 20742

Mr. Kenneth R. Balkey
Nuclear Technology Division
Westinghouse Electric Corporation
Pittsburgh, PA 15230-0355

Professor Ted Belytschko
Department of Mechanical Engineering
Northwestern University
Evanston, IL 60208

Mr. Bruce A. Bishop
Nuclear Technology Division
Westinghouse Electric Corporation
Pittsburgh, PA 15230-0355

Dr. A. C. Bornhauser
Zentralabteilung Produktion und Logistik
Siemens AG
13629 Berlin, Germany

Professor W. M. Bulleit
Department of Civil and Environmental Engineering
Michigan Technological University
Houghton, MI 49931

Mr. O. J. V. Chapman
Rolls-Royce and Associates
Derby, England DE2 8BJ

Dr. A. D. Crossland
Rolls-Royce and Associates
Derby, England DE2 8BJ

Professor Dan M. Frangopol
Department of Civil, Environmental, and Architectural Engineering
University of Colorado at Boulder
Boulder, CO 80309-0428

Professor Fabian C. Hadipriono
Department of Civil Engineering
Ohio State University
Columbus, OH 43210

Professor Achintya Haldar
Department of Civil Engineering and Engineering Mechanics
University of Arizona
Tucson, AZ 85721

Dr. David O. Harris
Engineering Mechanics Technology, Inc.
San Jose, CA 95129

Professor Owen F. Hughes
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Professor P. Johnson
Department of Civil Engineering
University of Maryland
College Park, MD 20742

Dr. William Stephen LaPay
Nuclear Technology Division
Westinghouse Electric Corporation
Pittsburgh, PA 15230-0355

Professor N. C. Lind
Department of Mechanical Engineering
University of Victoria
Victoria, British Columbia V8W 3P6, Canada

Professor W. K. Liu
Department of Mechanical Engineering
Northwestern University
Evanston, IL 60208

Dr. Y. J. Lua
Applied Research Associates, Inc.
Raleigh, NC 27615

Professor S. Mahadevan
Department of Civil Engineering
Vanderbilt University
Nashville, TN 37203

Professor Pavel Marek
Department of Civil Engineering and Applied Mechanics
San Jose State University
San Jose, CA 95192

Professor Richard H. McCuen
Department of Civil Engineering
University of Maryland
College Park, MD 20742

Professor Robert E. Melchers
Department of Civil Engineering and Surveying
The University of Newcastle
Newcastle, N.S.W. 2308, Australia

Professor Fred Moses
Department of Civil Engineering
University of Pittsburgh
Pittsburgh, PA 15261

Dr. Wolfgang Muller
Laboratory for Technical Mechanics
University of Paderborn
33098 Paderborn, Germany

Professor E. Nikolaidis
Department of Aerospace & Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Professor A. S. Nowak
Department of Civil and Environmental Engineering
University of Michigan
Ann Arbor, MI 48109

Dr. R. Ramme
Zentralabteilung Produktion und Logistik
Siemens AG
13629 Berlin, Germany

Dr. M. K. Ravindra
EQE International, Inc.
Irvine, CA 92715

Professor Andrew Scanlon
Department of Civil and Environmental Engineering
Pennsylvania State University
University Park, PA 16802

Dr. F. A. Simonen
Pacific Northwest Laboratory*
Richland, WA 99352

Dr. Rolf Skjong
Det Norske Veritas Research
N-1322 Hovik, Norway

*Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Dr. Herb Smith, Jr.
McDonnel Douglas Aerospace—East
McDonnel Douglas Corporation
St. Louis, MO 63166

Dr. C. Sundararajan
Consultant
Houston, TX 77396

Dr. Lawrence A. Twisdale
Applied Research Associates, Inc.
Raleigh, NC 27615

Dr. P. J. Vickery
Applied Research Associates, Inc.
Raleigh, NC 27615

Dr. Truong V. Vo
Pacific Northwest Laboratory*
Richland, WA 99352

Professor G. J. White
Department of Naval Architecture, Ocean and Marine Engineering
U.S. Naval Academy
Annapolis, MD 21012

Professor Paul H. Wirsching
Department of Aerospace and Mechanical Engineering
University of Arizona
Tucson, AZ 85721

Mr. F. Joel Witt
Consultant
Greensburg, PA 15601

*Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Probabilistic Structural Mechanics Handbook

CONTENTS

1

INTRODUCTION

C. (RAJ) SUNDARARAJAN

Probabilistic structural mechanics (PSM) is an evolving and expanding field within structural engineering. The past four decades have seen significant advances in this field and still considerable research and development activities are in progress. This handbook presents a comprehensive set of chapters dealing with the wide spectrum of topics in the theory and applications of probabilistic structural mechanics.

The first 20 chapters deal with basic concepts and methodologies of probabilistic structural mechanics. Each of these chapters contains a tutorial-type discussion of the subject and highlights of advanced developments. A comprehensive list of references is included in each chapter. Interested readers may obtain more detailed information from these references. The final 10 chapters deal with the applications of probabilistic structural mechanics in various industries and for various types of structures. A list of references is provided in each of these applications chapters also.

The **stress–strength interference method** is one of the earliest methods of structural reliability analysis. Although more advanced and less restrictive methods of reliability analysis have been developed in recent years, the stress–strength interference method is still widely used in many industries because of its simplicity and ease of use. Chapter 2 discusses this method and provides a table of useful formulas for the quick and easy computation of structural reliability.

The **first-order** and **second-order reliability methods** (FORM and SORM) provide attractive mathematical tools for the reliability analysis of a wide class of problems. Although these methods are computationally more involved than the stress–strength interference method, they are less restrictive, require less simplifying assumptions, and are valid for a broader class of problems. FORM and SORM are the subjects of Chapter 3. The first-order second moment (FOSM) method and the advanced mean value (AMV) method are also discussed therein.

Monte Carlo simulation (MCS) has long been used for the solution of probabilistic and statistical problems in many fields of engineering, science, and mathematics. This method has also been used for probabilistic structural analysis for many years. Although MCS is versatile and can solve virtually any probabilistic structural mechanics problem that has an underlying deterministic solution, the cost of the analysis is prohibitively high for complex problems, especially if very low probabilities are involved. A number of variance reduction techniques (VRTs) have been developed during the past two decades to reduce the required computational effort. Advances in computer hardware have also brought down the cost of computing. Thus the advances in computer hardware and developments in variance reduction techniques have made it possible to perform probabilistic analyses of many complex structural engineering problems at reasonable cost. **Simulation-based reliability methods** is the subject of Chapter 4. Direct Monte Carlo simulation and variance reduction techniques such as the importance sampling method, stratified sampling method, adaptive sampling method, Latin hypercube sampling method, antithetic variates method, conditional expectation method, generalized conditional expectation method, and response surface method are discussed.

Probabilistic analysis techniques such as FORM, SORM, and simulation can be combined with classic finite element analysis to solve a variety of probabilistic structural mechanics problems. Chapter 5 discusses the **probabilistic finite element method**. Applications of the method to linear and nonlinear response analysis and reliability assessment are discussed. A brief discussion of the probabilistic boundary element method is also presented, with an application to reliability assessment.

Methods of structural reliability analysis discussed in Chapters 2 to 5 are applicable to any type of failure mode—yielding, plastic collapse, excessive deformation, buckling, fracture, fatigue, creep, etc. Some surveys indicate that approximately 80% of all structural failures may be attributed to fracture and fatigue. The random scatter in fracture and fatigue properties of structural materials is usually even wider than that in other material properties. So probabilistic methods are especially apt for fracture and fatigue analyses. **Probabilistic fracture mechanics** and **probabilistic fatigue analysis** are the topics of Chapters 6 and 7, respectively. Material properties and methods of analysis are discussed with applications.

The preceding chapters deal primarily with the reliability of individual structural components. However, there are many structures that consist of a number of structural components (structural members). A typical example is an offshore oil platform consisting of many dozens of tubular members. Damage or failure of a single member due to accident or deterioration may not necessarily mean the failure of the structure. If the structure has redundancies, it may still be able to carry the loads, but at a reduced level of reliability (residual reliability). Chapter 8 discusses the **probabilistic analysis of structural systems**, that is, structures composed of many members. In addition to describing methods of reliability analysis, the chapter also discusses wide-ranging topics such as the development of design code rules to include redundancy effects, requalification of existing structures to carry higher than design loads, reliability optimization, and the assessment of residual reliabilities of structures after an accident or after years of aging in a corrosive or other hostile environment.

Chapter 9 considers structural reliability within the context of the **reliability and risk assessment of engineering systems**. An engineering system, for example, an industrial plant, consists not only of structures but also of mechanical, electrical, and electronic components and equipment. The structural reliabilities should be considered within the "global framework" of the engineering system. Failure of a single structure in a system may not necessarily produce system malfunction or failure because of the redundancies built into most systems. Two or more structural failures or a structural failure and one or more nonstructural component failures may be necessary. Therefore structural failures and their probabilities are best considered within the totality of the system and not as an isolated incidence. Reductions in structural failure probabilities and the benefits of such reductions in terms of increased system reliability or reduced system risk should be considered within the context of the system as a whole. In fact, structures in a system or plant can be ranked according to their importance to system reliability and the higher-ranked structures can be designed to higher reliability levels or inspected and maintained at more frequent intervals to achieve higher reliabilities. Methods of system reliability analysis such as failure modes and effects analysis, fault tree analysis and event tree analysis, and methods of ranking structures are discussed in Chapter 9. A number of applications in which structural reliabilities play an important role in the overall engineering system reliability are also presented.

Chapters 2 to 8 consider only (or at least principally) the random variations in physical quantities such as material properties, structural parameters and loads, and their effects on structural performance and reliability. **Human errors** in design, construction, fabrication, and maintenance can also affect structural performance and reliability. In fact, human error could be a more significant factor than random variations in physical properties. Human errors and their effects on structural reliability is the subject of Chapter 10.

Structural performance and reliability can be improved by a preservice inspection and then periodic in-service inspections during the life of the structure. Nondestructive examination techniques such as magnetic particles, radiography, acoustic emissions, eddy currents, and ultrasonics are used. These examination techniques are not 100% correct every time. They may miss a flaw present in the structure or give a false alarm. In order to use the results of nondestructive examination effectively and correctly in the reliability assessment of structures, a knowledge of the reliability of nondestructive examination techniques is essential. **Reliability of nondestructive examination techniques** is discussed in Chapter 11.

Probabilistic structural mechanics is expanding and evolving by adapting new theories and techniques emerging in other fields of engineering and sciences. Chapters 12 to 14 discuss three such areas of development, namely, expert opinion surveys, fuzzy set theory, and neural networks.

Expert opinion has been used in military intelligence, economics, medicine, and weather forecasting with differing levels of success. Expert opinion is used in probabilistic structural mechanics when structural failure probability prediction through statistical analysis of historical failure data or through structural reliability analysis techniques such as those discussed in Chapters 2 to 8 is impossible, impractical, or prohibitively expensive. The considerable amount of research done in other fields of applications has been adapted for use in probabilistic structural mechanics. Much of the use of expert opinion in probabilistic structural mechanics is for applications in the nuclear power industry, but the gas industry has also used expert opinion to estimate failure probabilities of interior gas piping in residential and commercial buildings. Expert opinion surveys are the subject of Chapter 12. Methods of conducting expert opinion surveys and the analysis and aggregation of expert opinions are discussed.

Fuzzy set theory is a new branch of mathematics (circa 1965). Although the classic deterministic and probability theories of mathematics are suited for the analysis of quantitative (numerical) information, fuzzy set theory is best suited for the analysis of qualitative information. For example, it is difficult, if not impossible, to provide a probability distribution for the quality of workmanship in a construction project. But an experienced construction engineer may be able to characterize it qualitatively as "excellent," "good," "acceptable," or "poor." Such subjective, qualitative information cannot be incorporated in the structural reliability analysis, using probability theory. But fuzzy set theory can be used for this purpose. Chapter 13 discusses the fundamental concepts of fuzzy set theory and its applications in probabilistic structural mechanics. The first impression many structural engineers have of fuzzy set theory is that it is of no practical use in probabilistic structural mechanics. But if one approaches it with an open mind, he or she may find it to be a useful tool to complement probability theory. We purposely included a chapter on fuzzy set theory and its applications in this handbook in order to create an interest in the subject among probabilistic structural mechanics researchers. This area of probabilistic structural mechanics is still in early stages of development and much work is yet to be done.

The most recent advance in computer software technology is **neural networks**. Use of this new technology in probabilistic structural mechanics is the subject of Chapter 14. This area of probabilistic structural mechanics is still in its infancy and much work is yet to be done. The pioneering application and results presented in the Chapter show the potential of neural networks in probabilistic structural mechanics.

Chapters 15 to 18 discuss applications of probabilistic structural mechanics in design codes development, structural optimization, in-service inspection planning, and life expectancy prediction. These generic applications cross industry lines and structural types. They are applicable to any type of structure in any industry—whether buildings or bridges, nuclear plants or naval vessels, equipment supports or aircraft structures.

Most of the current design codes are based on deterministic principles. However, the random variabilities in structural strength and loads are recognized and are implicitly considered by specifying a safety factor between nominal strengths and nominal loads. Safety factors are specified on the basis of the collective judgment of the code developers. Although these safety factors have served society well by providing for the design of safe structures, failure probabilities of structures designed according to these codes are not known (without performing a structural reliability analysis). There is no one-to-one relationship between the safety factor and structural reliability; the latter depends not only on the safety factor but also on the load–response relationships, failure criteria, and random variabilities in material properties and loads. Therefore structures designed to the same code specifications do not necessarily have the same level of reliability; some structures are overdesigned (higher reliability) and some are underdesigned (lower reliability). **Probability-based design codes** attempt to derive code specifications that would result in an approximately uniform level of reliability for all structures designed according to the code. Chapter 15 discusses the basic philosophy and development of probability-based design codes.

Code-based designs are acceptable for the vast majority of structures. But there are special situations in which minimum weight designs or other types of optimal designs are important. For example, minimum weight design is of interest in aircraft structures, not only because of the initial material savings but also because of fuel savings throughout the life of the aircraft. Special structures such as space stations, which are not governed by any design code, may also be designed to achieve maximum reliability within budget constraints. **Reliability-based structural optimization** is the subject of Chapter 16. Optimization techniques are described with illustrative examples. Although reliability optimization techniques are well developed, they have not yet found inroads into industrial applications.

Periodic in-service inspections are an important part of maintaining the reliability of operating structures above specified levels even as time progresses and the structures age. Because the very purpose of in-service inspections is to maintain an adequate level of reliability over the service life of the structure, setting the inspection interval on the basis of reliability analysis is a logical step. Unlike the conventional practice of specifying inspection intervals on the basis of past experience and engineering judgment, **reliability-based** (or **risk-based**) **inspection** strategies are more rational and the structure is neither overinspected nor underinspected; the inspection interval is just sufficient to maintain the required level of reliability. Chapter 17 discusses the use of probabilistic structural mechanics in inspection and maintenance planning.

The infrastructure and industrial facilities built during the 1950s and 1960s in the United States and many other countries are aging and deteriorating. Estimation of the remaining life and methods for extending the life are becoming increasingly important. Probabilistic methods are well suited for life expectancy prediction and life extension planning. Even if a structure has reached the end of its design life (on the basis of the original design calculations), it does not necessarily mean that the structure is unsafe or unfit for service. Probabilistic methods can be used to compute the reliability at the end of design life, and if this reliability is at an acceptable level the structure could continue in service. Even if the structural reliability is reaching close to unacceptable levels, life extension strategies such as improved or more frequent inspection and maintenance or strengthening of selected structural members could be instituted and their beneficial effects on the reliability of the structure could be quantified by probabilistic structural analysis. **Probability-based life prediction** is the subject of Chapter 18.

Chapters 19 and 20 deal with the reliability of structures during natural disasters such as **earthquakes, tornadoes,** and **hurricanes.** Although earthquake loads and wind loads are included in most design codes, severe earthquakes and extreme wind conditions well above design levels can occur, although very infrequently, and cause widespread damage to structures. Consequences are not only property damage but also injuries and loss of life. Insurance companies have to consider the probabilities and consequences of natural disasters. Government agencies and industries have to consider the damage to critical facilities and the potential consequences to public health and the environment. Thus the estimation of the probability of occurrence of natural disasters, probability of structural damage during such events, and the overall risk due to such damage are of interest. These topics are discussed in Chapters 19 and 20 with reference to earthquakes and extreme-wind events, respectively.

Probabilistic methods of structural analysis are now used in a broad spectrum of industries. Some industries have probabilistic concepts integrated into the design codes whereas in many other industries probabilistic methods are used to resolve special problems. Chapters 21 to 26 discuss applications of probabilistic structural mechanics in a number of industries.

The nuclear power industry is one example in which probabilistic structural mechanics is used to resolve special problems and licensing issues. Also, structural failure probabilities have been combined with mechanical, electrical, and electronic component failure probabilities to predict the public risks due to commercial nuclear plant operations. Probabilistic structural analysis is also used to investigate the adequacy of the codes, regulations, and procedures used in the design of nuclear power plant structures. In-service inspection planning is yet another application. These and other applications in the nuclear power industry are discussed in Chapter 21.

Chapter 22 discusses applications to **pressure vessels and piping**. The impetus for the use of probabilistic structural mechanics in pressure vessels and piping came from safety concerns in the nuclear power industry. The probabilistic methods developed by the nuclear power industry have also been adapted for applications to nonnuclear pressure vessels and piping. Both nuclear and nonnuclear applications are discussed in Chapter 22. Applications discussed include the resolution of safety issues in nuclear power plants, remaining life prediction, evaluation of life extension strategies, minimum weight design, and in-service inspection planning.

The use of new, advanced composite materials, the ever-increasing performance demands, and the need for high reliability and safety during missions have all been the impetus for the application of probabilistic structural mechanics in the military aircraft industry. The commercial aircraft industry is also following suit. Applications of probabilistic structural mechanics in the **aircraft industry** is the subject of Chapter 23. In addition to the usual reliability computation from load and material property statistics, reliability evaluation of complex, built-up structures on the basis of certification test results and the failure probability analysis of a fleet of aircraft using flight hour and field inspection data are also discussed. With cuts in military budgets and economic crunch in the aviation industry, aircraft are being used beyond their initial design life. Life prediction is also discussed in the chapter.

As with military aircrafts, military naval vessels have also to meet increasing performance and reliability demands. A number of research projects on the use of probabilistic methods are ongoing. The commercial ship industry is also taking notice. Chapter 24 discusses the probabilistic analysis of **ship structures**. Applications in design, in-service inspection, and life prediction are discussed.

The **offshore oil production industry** has been in the forefront of developing and using probabilistic methods of structural analysis and design. As oil platforms move into deeper and deeper waters, new structural concepts and construction technologies are being used. Together with concerns about oil spills, workers safety, and the economic impact of platform damage, these factors prompted interest and research in the use of probabilistic structural mechanics to design and operate safer, more reliable, and more economical offshore platforms. Chapter 25 discusses this subject. Fatigue reliability assessment, incorporation of in-service inspection findings to update reliability estimates, reliability optimization, requalification of older platforms, and probability-based design codes are some of the topics discussed in the chapter. It is estimated that the use of probabilistic methods has saved the oil industry hundreds of millions of dollars in the design and operation of offshore platforms.

Use of probabilistic methods in the analysis, design, and maintenance of **bridges** has been the subject of research for many years. Many thousands of bridges in the United States and other countries are aging. Their remaining lives have to be estimated and in the majority of cases the older bridges have to be renovated or new bridges built. Probabilistic structural mechanics could play a vital role in the life expectancy prediction, renovation, and new construction. A comprehensive discussion of the applications of probabilistic methods to design, reliability assessment, inspection planning, and life prediction of bridges is provided in Chapter 26.

Chapters 27 to 30 discuss probabilistic structural mechanics applications in steel, concrete, timber, and ceramic structures, respectively.

Use of probabilistic methods in **steel structure** design is now well matured. Probability-based codes (load and resistance factor design [LRFD] codes) are in use in the United States, Canada, and many European countries. Chapter 27 discusses and comments on LRFD code rules for steel structures. Material properties data and some results from simulation-based reliability assessment are also presented.

Probabilistic approaches to the design of **concrete structures** is also well developed and LRFD codes are in use in the United States and elsewhere. Concrete structures are the subject of Chapter 28. In addition to a discussion of LRFD code rules, a Bayesian approach for estimating the compressive strength of *in situ* concrete in existing structures is presented. Safety assessment of aging infrastructure and industrial facilities requires an estimate of the strength of existing concrete structures and this Bayesian approach is an effective and economical method for such estimates.

Studies on the use of probabilistic methods for **timber structure** design have been ongoing for about two decades and probability-based design codes have been developed. Timber structures are the subject of Chapter 29. Material properties, probability-based design codes, and reliability assessment of structural members, connections, wood joist floors, wood stud walls, trusses, bridges, and transmission poles are discussed.

Ceramic structures are being used increasingly in many applications in which high temperature and corrosion resistance are important. Applications of probabilistic methods to ceramic structures are not as mature as in steel or concrete structures. However, probabilistic methods are well suited for ceramic structures because of the wide scatter in material properties relevant to the dominant failure mode—brittle fracture. The application of probabilistic structural mechanics to ceramic structures is the subject of Chapter 30. Material properties, probabilistic analysis of brittle fracture, and development of lifetime diagrams are discussed.

The editor believes that this handbook will serve not only as a useful reference book but also as a catalyst for interactions between researchers and applications engineers, and among applications engineers in different industries. Such interactions should be conducive to creating an environment for basic and applied research that would meet the current and projected needs of the applications engineers. We have purposely included both theoretical and industrial applications chapters in this handbook, so that practising engineers would be exposed not only to applications in their respective industries but also to recent advances in probabilistic methodologies and computational tools and be tempted to use them in their projects. Also, this book could promote cross-industry fertilization whereby engineers from one industry learn about applications in other industries and adapt them for their own applications. As an example, there are methods and software used in offshore structures design and maintenance that would lend themselves easily to applications in aircraft structures or pressure vessels and piping.

This book also exposes researchers, professors, and graduate students to probabilistic structural mechanics applications in a wide spectrum of industries. This exposure would help them identify future research and training needs, as applications of probabilistic structural mechanics are broadening in scope and increasing in numbers.

The initial impetus for probabilistic structural mechanics applications has been safety concerns. With increasing public demand for safer products and safer industrial operations, use of probabilistic methods