Preface

This book covers the basic topics of computational stochastic mechanics, while focusing on the stochastic analysis of structures in the framework of the finite element method (FEM). It is addressed to students of the postgraduate programme of the School of Civil Engineering at the National Technical University of Athens (**NTUA**). It is a self-contained book and aims at establishing a solid background on stochastic and reliability analysis of structural systems, such that it will enable future engineers to better manage the concepts of analysis and design in the presence of uncertainty as imposed in almost all modern engineering requirements.

Computational stochastic[1] *mechanics* is a field of mechanics that first appeared in the 70s in order to describe mechanical systems that show unpredictable behavior due to inherent uncertainty. Since then, it has evolved into a self-contained and prolific science field and has brought forth a wide range of sophisticated and well-established methodologies for the quantification of uncertainties inherent in engineering systems. Due to the rapidly growing availability of large-scale and low-cost computer power, the intensive computational demands of these techniques are becoming more and more manageable. This fact, has made the quantification of uncertainty increasingly popular in the engineering community; the progress achieved over the last decade in applying the theory of stochastic processes within the framework of classical engineering has led into higher levels of structural reliability with respect to traditional empirical safety factor approaches, both in terms of safety and economy. As a result, design engineers can now take rational and quantified risk mitigation measures to face the random nature of various parameters (material and geometric properties, loading conditions, etc).

Parameter uncertainty quantification and methods to predict uncertainty propagation on the response of structural systems have become an essential part of the analysis and design of engineering applications. *Stochastic analysis* and in particular the Stochastic Finite Element Method (SFEM), is a valuable and versatile tool for the

[1] The word "stochastic" as in "being random" derives from the Greek verb: *stochazomai*, "aim" which in one of its versions meant "trying to guess".

estimation of the response variability and the reliability of stochastic systems. A stochastic structural system is defined as a system with inherent uncertainties in its material, its geometric properties and its boundary conditions, subjected to stochastic (and/or deterministic) excitation. Implementation of SFEM leads to the estimation of the system's response variability which is a direct measure of the sensitivity of the system's response to the scatter of uncertain input parameters. It also leads to the evaluation of its reliability, an important factor in the design procedure which investigates the likelihood of the structure to fulfilling its design requirements. Response variability and reliability are closely tied to the concepts of performance-based engineering which is currently the way to apply design criteria to structures and structural components. These criteria are associated with the frequentist violation of various performance limit states, which are in turn linked to various engineering demand parameters such as stresses, displacements, etc.

There follows a brief outline of the book:

Chapter 1 introduces the fundamentals of the stochastic process theory and its applications. The definition of a stochastic process is given first, followed by a description of its characteristic functions and moments. Moreover, the meaning of ergodicity and stationarity are discussed and a description of the power spectrum is made.

Chapter 2 describes various methods used for the simulation of a stochastic process such as point discretization methods as well as the most popular Karhunen–Loève and spectral representation series expansion methods. Methods for the simulation of non-Gaussian fields are then presented followed by solved numerical examples. The first two chapters together with the appendixes, establish the necessary background for the rest of the book.

Chapter 3 contains the stochastic version of the virtual work approach which leads to the fundamental principles of the Stochastic Finite Element Method (SFEM). The resulting stochastic partial differential equations are solved with either nonintrusive simulation methods, such as the Monte Carlo simulation, or intrusive approaches such as the versatile spectral stochastic finite element method. Both approaches have proved to be powerful tools for the analysis of stochastic finite element systems and are described in detail along with additional approximate methodologies such as the Neumann and Taylor series expansion methods. Some exact analytic solutions that are available for statically determinate stochastic structures are next presented based on the so-called variability response functions and extended to general stochastic finite element systems. Illustrative examples are provided and discussed.

Chapter 4 is devoted to reliability analysis methods with emphasis given on those developed over the past two decades. The fundamental principles and basic reliability analysis methods are presented, namely the first- and second-order moments and the Monte Carlo simulation. For practical reliability problems, the latter require disproportionate computational effort. To overcome this liability, variance reduction-based simulation methods reduce the number of the Monte Carlo simulations required for an accurate prediction of the probability of failure; importance sampling, line sampling, and subset simulation are sufficiently deployed in this book. The use of artificial neural networks as effective surrogate models in the framework of reliability analysis is finally discussed. Examples of reliability analysis in real- world applications are presented illustrating the potential of each method and its relative advantages and disadvantages.

With this book, we wish to clarify in a scientific and concise way the admittedly difficult principles of the stochastic process theory and its structural engineering applications. We tried to simplify the theory in a way that the various methodologies and computational tools developed are nevertheless fully outlined to a new audience. To this purpose three appendixes were added that address the basic probability theory and random variables. In Appendix A, the basics of set theory are described followed by definitions of probability (classical, geometric, frequentist, conditional), in Appendix B the definition of a random variable is given together with the functions that are necessary for its description while in Appendix C the modified Metropolis–Hastings algorithms is presented and a MATLAB code is provided in order for the students to efficiently implement a reliability method called subset simulation. A number of unsolved problems are included at the end of each chapter.

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