# Preface

The considerable influence of inherent uncertainties on structural behavior has led the engineering community to recognize the importance of a stochastic approach to structural problems. Issues related to uncertainty quantification and its influence on the reliability of the computational models, are continuously gaining in significance. In particular, the problems of dynamic response analysis and reliability assessment of structures with uncertain system and excitation parameters have been the subject of continuous research over the last two decades as a result of the increasing availability of powerful computing resources and technology. This book is a follow up of a previous book with the same subject and focuses on advanced computational methods and software tools which can highly assist in tackling complex problems in stochastic dynamic/seismic analysis and design of structures. The selected chapters are authored by some of the most active scholars in their respective areas and represent some of the most recent developments in this field.

This edited book is primarily intended for researchers and post-graduate students who are familiar with the fundamentals and wish to study or to advance the state of the art on a particular topic in the field of computational stochastic structural dynamics. Nevertheless, practicing engineers could benefit as well from it as most code provisions tend to incorporate probabilistic concepts in the analysis and design of structures. The book consists of 21 chapters which are extended versions of papers presented at the recent COMPDYN 2011 Conference. The chapters can be grouped into several thematic topics including dynamic analysis of stochastic systems, reliability-based design, structural control and health monitoring, model updating, system identification, wave propagation in random media, seismic fragility analysis and damage assessment.

In Chap. 1, A. Batou and C. Soize examine the random dynamic response of a multibody system with uncertain rigid bodies. A stochastic model of an uncertain rigid body is constructed by modeling the mass, the center of mass and the tensor of inertia by random variables. The prior probability distributions of these random variables are computed using the maximum entropy principle under the constraints defined by the available information. Several uncertain rigid bodies are linked to each other in order to calculate the random response of a multibody dynamic system.

A numerical application consisting of five rigid bodies is proposed to illustrate the theoretical developments.

In Chap. 2, V. Papadopoulos and O. Kokkinos extend the concept of Variability Response Functions (VRFs) to linear stochastic systems under dynamic excitation. An integral form for the variance of the dynamic response of stochastic systems is considered, involving a Dynamic VRF (DVRF) and the spectral density function of the stochastic field modeling the uncertain system properties. The uncertain property considered is the flexibility of the system. The same integral expression can be used to calculate the mean response of a dynamic system using a Dynamic Mean Response Function (DMRF) which is a function similar to the DVRF. These integral forms are used to efficiently compute the mean and variance of the transient system response along with time dependent spectral-distribution-free upper bounds.

A. Kundu and S. Adhikari provide the theoretical development and simulation results of a novel Galerkin subspace projection scheme for damped linear dynamic systems with stochastic coefficients and homogeneous Dirichlet boundary conditions (Chap. 3). The fundamental idea is to solve the stochastic dynamic system in the frequency domain by projecting the solution into a reduced finite dimensional spatio-random vector basis spanning the stochastic Krylov subspace to approximate the response. Galerkin weighting coefficients are employed to minimize the error induced by the use of the reduced basis. The statistical moments of the solution are evaluated at all frequencies to illustrate and compare the stochastic system response with the deterministic case. The results are validated with direct Monte Carlo simulation for different correlation lengths and variability of randomness.

An efficient approach for modeling nonlinear systems subjected to general non-Gaussian excitations is developed by X.F. Xu and G. Stefanou in Chap. 4. This chapter describes the formulation of an $n$-th order convolved orthogonal expansion (COE) method. For linear vibration systems, the statistics of the output are directly obtained as the first-order COE about the underlying Gaussian process. The COE method is next verified by its application on a weakly nonlinear oscillator. In dealing with strongly nonlinear dynamics problems, a variational method is presented by formulating a convolution-type action and using the COE representation as trial functions.

In Chap. 5 by L. Pichler et al., various finite difference (FD) and finite element methods (FEM) are discussed for the numerical solution of the Fokker–Planck equation allowing the investigation of the evolution of the probability density function of linear and nonlinear systems. The results are compared using various numerical examples. Despite the greater numerical effort, the FEM is preferable over FD, because it yields more accurate results. However, at this moment the FEM is only suitable for dimension less or equal to 3. In the case of 3D and 4D problems, a stabilized multi-scale FEM provides a tool with a high order of accuracy, preserving numerical efficiency due to the fact that a coarser mesh size can be used.

There are various approaches to deal with uncertainty propagation in stochastic dynamics. In Chap. 6, M. Corradi et al. examine some classical structural problems in order to investigate which probabilistic approach better propagates the uncertainty from input to output, in terms of accuracy and computational cost. The examined methods are: Univariate Dimension Reduction methods, Polynomial Chaos Expansion, First-Order Second Moment method, and algorithms based on the Evidence Theory for epistemic uncertainty. The performances of these methods are compared in terms of moment estimations and probability density function construction corresponding to several scenarios of reliability-based design and robust design. The structural problems examined are: (i) the static, dynamic and buckling behavior of a composite plate, (ii) the reconstruction of the deformed shape of a beam from measured surface strains.

Chapter 7 by F. Steinigen et al. is devoted to enhanced computational algorithms to simulate the load-bearing behavior of reinforced concrete structures under dynamic loading. In order to take into account uncertain data of reinforced concrete, fuzzy and fuzzy stochastic analyses are presented. The capability of the fuzzy dynamic analysis is demonstrated by an example in which a steel bracing system and viscous damping connectors are designed to enhance the structural resistance of a reinforced concrete structure under seismic loading.

W. Verhaeghe et al. use the concept of interval fields to deal with uncertainties of spatial character arising in the context of groundwater transport models needed to predict the flow of contaminants (Chap. 8). The main focus of the chapter is on the application of interval fields to a geo-hydrological problem. The uncertainty taken into account is the material layers' hydraulic conductivity. The results presented are the uncertainties on the contaminant's concentration near a river. Another objective of the chapter is to define an input uncertainty elasticity of the output, i.e. to identify the locations in the model, whose uncertainties mostly influence the uncertainty on the output. Such a quantity indicates where to perform additional in situ point measurements to reduce the uncertainty on the output the most.

Although reliability analysis methods have matured in recent years, the problem of reliability-based structural design still poses a challenge in stochastic dynamics. In Chap. 9, A. Naess et al. extend their recently developed enhanced Monte Carlo approach to the problem of reliability-based design. The objective is to optimize a design parameter $\alpha$ so that the system, represented by a set of failure modes or limit states, achieves a target reliability. Monte Carlo sampling occurs at a range of values for $\alpha$ that result in failure probabilities larger than the target and thus the design problem essentially amounts to a statistical estimation of a high quantile. Several examples of the approach are provided in the chapter.

Chapter 10 by H. Jensen et al. presents a general framework for reliability-based design of base-isolated structural systems under uncertain conditions. The uncertainties about the structural parameters as well as the variability of future excitations are characterized in a probabilistic manner. Nonlinear elements composed by hysteretic devices are used for the isolation system. The optimal design problem is formulated as a constrained minimization problem which is solved by a sequential approximate optimization scheme. First excursion probabilities that account for the uncertainties in the system parameters as well as in the excitation are used to characterize the system reliability. The approach explicitly takes into account all nonlinear characteristics of the combined structural system (superstructure-isolation system) during the design process. Numerical results highlight the beneficial effects of isolation systems in reducing the superstructure response.

The influence of structural uncertainties on actively controlled smart beams is investigated in Chap. 11 by A. Moutsopoulou et al. The dynamical problem of a model smart composite beam is treated using a simplified modeling of the actuators and sensors, both being realized by means of piezoelectric layers. In particular, a practical robust controller design methodology is developed, which is based on recent theoretical results on $H_\infty$ control theory and $\mu$-analysis. Numerical examples demonstrate the vibration-suppression property of the proposed smart beams under stochastic loading.

The field of Structural Health Monitoring (SHM) has significantly evolved in the last years due to the technological advances and the evolution of advanced smart systems for damage detection and signal processing. In Chap. 12, G. Saad and R. Ghanem present a robust data assimilation approach based on a stochastic variation of the Kalman Filter where polynomial functions of random variables are used to represent the uncertainties inherent to the SHM process. The presented methodology is combined with a non-parametric modeling technique to tackle SHM of a four-story shear building subjected to a base motion consistent with the El-Centro earthquake and undergoing a preset damage in the first floor. The purpose of the problem is localizing the damage in both space and time, and tracking the state of the system throughout and subsequent to the damage time. The application of the introduced data assimilation technique to SHM enhances its applicability to a wide range of structural problems with strongly nonlinear dynamic behavior and with uncertain and complex governing laws.

The accurate prediction of the response of spacecraft systems during launch and ascent phase is a crucial aspect in design and verification stages which requires accurate numerical models. The enhancement of numerical models based on experimental data is denoted model updating and focuses on the improvement of the correlation between finite element (FE) model and test structure. In aerospace industry, the examination of the agreement between model and real structure involves the comparison of the modal properties of the structure. Chapter 13 by B. Goller et al. is devoted to the efficient model updating of a satellite in a Bayesian setting based on experimental modal data. A detailed FE model of the satellite is used for demonstrating the applicability of the employed updating procedure to large-scale complex aerospace structures.

In Chap. 14, B. Rosič and H. Matthies deal with the identification of properties of stochastic elastoplastic systems in a Bayesian setting. The inverse problem is formulated in a probabilistic framework where the unknown uncertain quantities are embedded in the form of their probability distributions. With the help of stochastic functional analysis, a new update procedure is introduced as a direct, purely algebraic way of computing the posterior, which is comparatively inexpensive to evaluate. Such description requires the solution of the convex minimization problem in a stochastic setting for which the extension of the classical optimization algorithm in predictor-corrector form is proposed as the solution procedure. The identification method is finally validated through a series of virtual experiments taking into account the influence of the measurement error and the order of the approximation on the posterior estimate.

Chapter 15 deals with the study of SH surface waves in a half space with random heterogeneities. C. Du and X. Su prove both theoretically and numerically that surface waves exist in a half space which has small, random density, but the mean value of the density is homogeneous. Historically, this type of half space is often treated as homogeneous using deterministic methods. In this investigation, a closed-form dispersion equation is derived stochastically and the frequency spectrum, dispersion equation and phase/group velocity are computed numerically to study how the random inhomogeneities will affect the dispersion properties of the half space with random density. The results of this research may find their application in various fields, such as in seismology and in non-destructive test/evaluation of structures with randomly distributed micro-cracks or heterogeneities.

The following six chapters are devoted to earthquake engineering applications. P. Jehel et al. (Chap. 16) investigate the seismic fragility of a moment-resisting reinforced concrete frame structure in the area of the Cascadia subduction zone situated in the South-West of Canada and the North-West of the USA. According to shaking table tests, the authors first validate the capability of an inelastic fiber beam/column element, using a recently developed concrete constitutive law, for representing the seismic behavior of the tested frame coupled to either a commonly used Rayleigh damping model or a proposed new model. Then, for each of the two damping models, they perform a structural fragility analysis and investigate the amount of uncertainty to be induced by damping models.

In Chap. 17 by Y. Vargas et al., a detailed study of the seismic response of a reinforced concrete building is conducted using a probabilistic approach in the framework of Monte Carlo simulation. The building is representative for office buildings in Spain but the procedures used and the results obtained can be extended to other types of buildings. The purpose of the work is twofold: (i) to analyze the differences when static and dynamic analysis techniques are used and (ii) to obtain a measure of the uncertainties involved in the assessment of structural vulnerability. The results show that static procedures are somehow conservative and that uncertainties increase with the severity of the seismic actions and with the damage. Low damage state fragility curves have little uncertainty while high damage state fragility curves show great scattering.

Seismic pounding can induce severe damage and losses in buildings. The corresponding risk is particularly relevant in densely inhabited metropolitan areas, due to the inadequate clearance between buildings. Chapter 18 by E. Tubaldi and M. Barbato proposes a reliability-based procedure for assessing the level of safety corresponding to a given value of the separation distance between adjacent buildings exhibiting linear elastic behavior. The seismic input is modeled as a non-stationary random process and the first-passage reliability problem corresponding to the pounding event is solved employing analytical techniques involving the determination of specific statistics of the response processes. The proposed procedure is applied to estimate the probability of pounding between linear single-degree-of-freedom systems and to evaluate the reliability of simplified design code formulae used to determine building separation distances. Furthermore, the capability of the proposed method to deal with complex systems is demonstrated by assessing the effectiveness of the use of viscous dampers in reducing the probability of pounding between adjacent buildings modeled as multi-degree-of-freedom systems.

In Chap. 19, A. Elenas provides a methodology to quantify the relationship between seismic intensity parameters and structural damage. First, a computer-supported elaboration of ground motion records provides several peak, spectral and energy seismic parameters. After that, nonlinear dynamic analyses are carried out to provide the structural response for a set of seismic excitations. Among the several response characteristics, the overall structure damage indices after Park/Ang and the maximum inter-storey drift ratio are selected to represent the structural response. Correlation coefficients are evaluated to express the grade of interrelation between seismic acceleration parameters and structural damage. The presented methodology is applied to a reinforced concrete frame building, designed according to the rules of the recent Eurocodes, and the numerical results show that the spectral and energy parameters provide strong correlation to the damage indices.

As demonstrated in the previous chapter, there is interdependence between seismic intensity parameters and structural damage. In Chap. 20, A. Elenas et al. proceed to the classification of seismic damage in buildings using an adaptive neuro-fuzzy inference system. The seismic excitations are simulated by artificial accelerograms and their intensity is described by seismic parameters. The proposed system is trained using a number of seismic events and tested on a reinforced concrete structure. The results show that the proposed fuzzy technique contributes to the development of an efficient blind prediction of seismic damage. The recognition scheme achieves correct classification rates over 90%.

The book closes with a study on damage identification of historical masonry structures under seismic excitation by G. De Matteis et al. (Chap. 21). The seismic behavior of a physical 1:5.5 scaled model of the church of the Fossanova Abbey (Italy) is examined by means of numerical and experimental analyses. As it mostly influences the seismic vulnerability of the Abbey, the central transversal three-bay complex of the church was investigated in detail by means of a shaking table test on a 1:5.5 scaled physical model in the Laboratory of the Institute for Earthquake Engineering and Engineering Seismology in Skopje. In this chapter, a brief review of the numerical activity related to the prediction of the shaking table test response of the model is first proposed. Then, the identification of frequency decay during collapse is performed through decomposition of the measured power spectral density matrix. Finally, the localization and evolution of damage in the structure is analyzed and the obtained numerical results show a very good agreement with the experimental data.

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