Preface

At the dawn of the twenty-first century, 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 extensive research over the last two decades as a result of the increasing availability of powerful computing resources and technology. This book 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 16 chapters which are extended versions of papers presented at the recent COMPDYN 2009 and SEECCM 2009 Conferences. The chapters can be grouped into several thematic topics including dynamic response variability and reliability of stochastic systems, risk assessment, stochastic simulation of earthquake ground motions, efficient solvers for the analysis of stochastic systems, dynamic stability and stochastic modeling of heterogeneous materials.

In Chapter 1, G.I. Schuëller gives an overview of the well established deterministic model reduction techniques (Guyan reduction, component mode synthesis) and approaches for efficient uncertainty propagation in structural dynamics. The recent advances in the combination of these two fields are reviewed and methodologies for the consideration of uncertainty when using model reduction schemes are presented. The capabilities of a Karhunen-Loève expansion of the substructure matrices and of a random combination of substructures are investigated. It is shown that the proposed approaches can combine high accuracy with a substantial reduction of the computational cost compared to Monte Carlo simulation (MCS) of the full model.

In Chapter 2, S. Krenk and J. Høgsberg present a design principle for resonant control of a SDOF system by second order filters. The basic idea is the introduction of a resonant force with frequency tuning that results in splitting the original resonant mode into two modes with equal damping ratio. The design procedure is developed for resonant displacement and acceleration feedback, respectively, based on a combination of "equal modal damping" and approximately equal response amplitudes of the two modes. The procedure is extended to collocated resonant control of the lower modes of MDOF systems. An explicit design approach for the control parameters of MDOF systems is developed that includes the effect of the higher modes via a quasi-static approximation. The efficiency of resonant damping is illustrated by application to a benchmark example for stochastic wind load on a high-rise building.

S.K. Au presents a novel approach for improving importance sampling in the estimation of the first passage probability of nonlinear hysteretic systems subjected to stochastic earthquake excitations (Chapter 3). Instead of using fixed design point excitations, the importance sampling distribution is constructed using a stochastic process, called "adapted process". A stochastic control algorithm is developed for the adapted process where the objective function reflects the expected energy needed to next yield as well as the exit velocity. The variance reduction efficiency of the "optimal" control law is investigated through a numerical example involving a SDOF elasto-plastic structure. It is shown that the proposed approach leads to substantial reduction of the "unit COV" of the importance sampling estimator while maintaining the required computational effort at a reasonable level (comparable to that of Markov Chain Monte Carlo-based approaches).

Another approach to the solution of the first passage problem for earthquake engineering applications is provided by M. Barbato in Chapter 4. This chapter describes the representation of the complex envelope process for transient response of linear structures and illustrates the use by the first passage problem. The Vanmarcke and modified Vanmarcke approximate solutions to the first passage problem are compared with the classical Poisson approximation and MCS results for an idealized linear elastic model of a steel building. The failure condition is expressed in terms of inter-storey drifts outcrossing specified deterministic thresholds. The retrofit of the benchmark structure with viscous dampers is also considered, allowing to illustrate the use of the closed-form approximations of the failure probability for non-classically damped linear elastic systems. The results presented show that the two Vanmarcke approximations can improve considerably the estimates of the failure probability for the first passage problem when compared with the simpler Poisson approximation.

A computationally efficient method for the stochastic analysis of large linear structural systems subjected to seismic actions is developed by P. Cacciola and G. Muscolino in Chapter 5. The method is based on modal analysis for the evaluation of stochastic response along with a modal correction approach, which includes the contribution of the neglected modes. Furthermore, a previously developed method for the evaluation of spectrum-compatible evolutionary power spectra of ground motions is presented. Some numerical results show the accuracy and efficiency of the proposed technique for determining the spectral moments of the response.

In Chapter 6, S.M. Elachachi et al. investigate the effect of soil spatial variability (correlation length, coefficient of variation) on the reliability of buried networks subjected to earthquake loading. The reliability analysis is performed using a Response Surface Model (RSM) and the reliability index is calculated for serviceability and ultimate limit states. The dynamic response of a buried pipe subjected to natural ground motion records is computed taking into account a longitudinal variability of the properties of the soil. It is shown that the magnitude of the induced stresses and thus the reliability of the pipe are mainly affected by four parameters: a soil-structure length ratio, a soil-structure stiffness ratio, a structure-joint stiffness ratio (relative flexibility) and the magnitude of soil variability (coefficient of variation).

The problem of reliability-based optimization of structural systems under stochastic loading is treated by H. Jensen et al. in Chapter 7. In the proposed approach, a standard gradient-based algorithm with line search is used, allowing to explore the space of the design variables most efficiently. Subset simulation is adopted for the purpose of estimating the corresponding failure probabilities. The gradients of the failure probability functions are estimated by an approach based on the local behavior of the performance functions that define the failure domains. Numerical results show that only a moderate number of reliability estimates has to be performed during the entire design process. A numerical example with deterministic system properties is provided to show the effectiveness of the proposed approach.

Meta-models are a powerful tool for the solution of complex realistic problems in stochastic dynamics. L. Pichler et al. present a mode-based meta-model for the reliability assessment of linear dynamical systems (Chapter 8). The reliability analysis is carried out through the application of the meta-model for estimating the modal properties which are then subsequently required to perform a mode-superposition analysis. The proposed approach is proved to be accurate and computationally efficient in both cases of deterministic and stochastic loading. The verification of the results for the reliability assessment carried out with the meta-model is performed with a full finite element (FE) analysis and shows a good agreement of the response over the whole duration of the stochastic ground acceleration.

The effect of uncertain system properties on structural response and reliability is examined by G. Stefanou and M. Fragiadakis in Chapter 9. An efficient approach combining MCS with translation process theory is presented for assessing the nonlinear stochastic response and reliability of a steel moment-resisting frame subjected to transient seismic actions. The structure is modeled with a mixed fiber-based beam-column element, whose kinematics is based on the natural mode method. The adopted formulation leads to the reduction of the computational cost required for the calculation of the element stiffness matrix, while increased accuracy compared to traditional displacement-based elements is achieved. The uncertain parameters of the problem are the Young modulus and the yield stress, both described by homogeneous non-Gaussian translation stochastic fields. Under the assumption of a pre-specified power spectral density function of the stochastic fields, a parametric investigation is carried out providing useful conclusions regarding the influence of the correlation length of the stochastic fields on the response variability and reliability of the frame.

Although reliability analysis methods have matured in recent years, the number of available techniques to evaluate the risk of complex structural systems is limited. In Chapter 10, F. Petrini et al. investigate the problem of Aeolian risk assessment of slender structures in the framework of performance-based wind engineering. A classification of the main sources of uncertainty is attempted and the importance of some of them (epistemic uncertainty of the aerodynamic coefficients, model uncertainty of aeroelastic forces, influence of model uncertainty on risk assessment) is examined with reference to an example case, a long span suspension bridge.

The concept of evolutionary power spectrum is important in the context of stochastic simulation of earthquake ground motions. Chapter 11 by D. Schillinger and V. Papadopoulos presents a novel approach called "method of separation" for the accurate estimation of evolutionary power spectra of non-homogeneous strongly narrow-band stochastic fields encountered in various engineering applications. The method is developed for power spectra separable in space-frequency but can also efficiently treat a class of non-separable spectra. The method of separation is based on the geometrical similarity of functions. It leads to the estimation of evolutionary power spectra from a series of samples based only on sample mean square and on an estimate of the homogeneous Fourier power spectrum. The limitations of existing methods (short-time Fourier, wavelet and Wigner-Ville transforms) are avoided and a very good localization in both space and frequency is achieved. Numerical examples including analytical benchmark spectra as well as spectra corresponding to measured geometric imperfections of I-section beams illustrate the superiority of the proposed approach in comparison to other established techniques.

An energy-based envelope function is proposed in Chapter 12 by S. Sgobba et al. enabling to characterize the time-varying amplitude of strong ground motion and to generate realistic stochastic accelerograms corresponding to a given earthquake scenario. This envelope function is directly related to the Arias intensity of the ground motion and has a functional form similar to that of a lognormal probability density function. In conjunction with suitable peak factors, the envelope function may also be used to predict the distribution of PGA values corresponding to a given earthquake scenario.

The development of robust and efficient solution algorithms is crucial for the treatment of large-scale realistic problems involving uncertainties. A novel numerical algorithm for the solution of stochastic partial differential equations (SPDEs) arising in the context of stochastic mechanics is presented by H. Matthies and E. Zander in Chapter 13. The algorithm exploits the natural tensor product structure between basis vectors describing the physical/deterministic behavior and a basis describing the stochastic response of the system. A sparse representation of input and output is achieved using singular value decomposition (SVD). This sparse format is preserved throughout the computation and is also used to reduce the amount of computation. A numerical example involving the 1D diffusion equation is presented to illustrate the efficiency of the approach. It is shown that for a sufficiently accurate representation of the solution, the required storage is reduced by 90% and by 50–80% as intermediate storage is concerned.

The problem of dynamic stability is treated in Chapter 14. J. Náprstek and C. Fischer investigate the dynamic stability behavior of a non-linear auto-parametric system with three degrees of freedom (used as a simple mathematical model of a slender structure on elastic subsoil exposed to strong vertical excitation). Certain intervals of the excitation frequency are identified where the semi-trivial solution loses its dynamic stability and the strong horizontal response components become important. Post-critical states of both deterministic and chaotic type are thoroughly analyzed with respect to excitation frequency and amplitude. It is observed that the response amplitudes can remain in acceptable limits when adequate excitation (in terms of frequency and amplitude) acts throughout a short time interval. It is mostly not the case when the excitation has an infinite duration and the response is approaching to the steady state.

The last two chapters of the book are devoted to the rapidly evolving area of stochastic modeling of heterogeneous materials. A. Ibrahimbegovic et al. (Chapter 15) discuss the failure analysis of civil engineering structures built of heterogeneous materials. The structured FE mesh approach (consisting of constant stress triangular element that can contain two different phases and phase interface) is proved to be much more efficient than the non-structured mesh representation of material heterogeneities for the case of 2D two phase materials. This feature is of special interest for probabilistic analysis, where a large amount of computation is needed in order to provide the corresponding statistics. One such case of probabilistic failure analysis is also considered in this chapter, where the geometry of the phase interface remains uncertain since it is obtained as the result of the Gibbs random process. This computation is further used to provide the appropriate probabilistic description of material parameters of phenomenological model of localized failure in terms of correlated random fields. Subsequent Monte Carlo computations of failure phenomena in simple tension test performed with such probabilistic phenomenological model clearly show the capability of the presented approach to recover the size effects anywhere within a range between the two classical bounds which are Continuum Damage Mechanics and Linear Fracture Mechanics.

The book closes with a stochastic mechanics approach by D. Schwarzer and C. Proppe for the calculation of the statistics of eigenfrequencies in heterogeneous beams made of metal foam (Chapter 16). The spatial variation of the linear elastic material properties of metal foam is quantified using random fields generated by the spectral representation and Karhunen-Loève expansion methods. The probability distribution and the correlation structure of the random fields are derived from data. MCS of eigenvibration problems of beams of different length are performed. The computed eigenfrequencies are compared to experimental data. From this comparison, it can be concluded that the heterogeneity of the material microstructure affects the macroscopic properties. The mean values of the eigenfrequencies are smaller than those of beams with homogeneous material of similar mean material properties. A scatter of the eigenfrequencies is also observed, a fact that has to be taken into account when using parts consisting of metal foam.

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