Uncertainty Quantification in Laminated Composites: A Meta-model Based Approach

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Preface

Who should read it and why? Natural and engineered materials have acquired an unprecedented role in the history of human civilisation. Entire eras have been named after predominant materials, such, as the stone age, bronze age, and iron age to mention a few. Composite materials are the defining advanced materials in the current era with the exceptional promise of applicability in a number of high-end areas such as aerospace, marine, automotive, construction and defence sectors. Composite materials convincingly demonstrate that their mechanical properties can be tailored to specific engineering demands and therefore perform superiorly compared to conventional metallic materials. From a design perspective, this advantage arises through a fundamental mathematical fact that the mechanical properties of composite materials are functions of significantly more parameters compared to their metallic counterparts. However, the advantages of composite materials come at a cost that the designers and analysts have to deal with many parameters. This gives rise to two major problems. Firstly, considering many parameters simultaneously makes the design process computationally more expensive. Secondly, perhaps more importantly, the increase in the number of parameters leads to an unavoidable escalation of uncertainty associated with these parameters. One way to address both of these problems simultaneously is to use metamodels which effectively 'replace' the original physics-based computationally expensive model with a data-based computationally inexpensive model. The aim of this book is to introduce predominant techniques in this direction.

This book is the first comprehensive text on the treatment of uncertainties in the modelling and analysis of composite materials. The authors have drawn on their considerable research experience to produce this book. The text is written from an engineering standpoint, comprising fundamental and complex theories that are relevant across a wide range of metamodeling techniques. The book introduces faculties, researchers and students about the confluence of composite structure theory, uncertainty modelling and propagation and metamodeling approaches. The pedagogical objective of this book is to systematically present the latest developments in the metamodeling techniques and explain how they can be used in conjunction with composite structures. The focus has been on the mathematical and computational aspects. This book will be relevant to aerospace, mechanical and civil engineering disciplines and various sub-disciplines within them. The intended readers of this book include senior undergraduate students and graduate students doing projects or doctoral research in the field of composite structures. Researchers, Professors and practicing engineers working in the field of composite structures will also find this book useful.

Existing works and the need for this book: There are some excellent books which already exist in the field of composite materials. For example, the book by Reddy (2003) covers essential details on analytical techniques and physics-based modelling of laminated composites. Uncertainty quantification has gained immense attention from the research community in the recent years. Extensive works from different disciplines such as mathematics, statistics, engineering and applied sciences have led to some excellent books on uncertainty quantification. As an example, the book by Smith (2014) gives a comprehensive account of uncertainty quantification approaches from a general multidisciplinary point of view. Meta-modelling is a classical topic which has seen a significant explosion over the past two decades due to the increasing demand for inexpensive computational tools. As a result, there are excellent books available to the readers on this topic. We refer to the books by Myers et al. (2016) and Forrester and Keane (2008) for a detailed exposure on statistical and mathematical aspects underpinning the metamodeling techniques for computational models. Although there are outstanding books available *separately* on the topics of composite structures, uncertainty quantification and metamodeling, to date there is no book which comprehensively discusses the role of metamodeling techniques for efficient uncertainty quantification and sensitivity analysis of composite structures in a unified manner. This book was conceived by us to *fill this essential gap* in the literature. We hope that this text will be an invaluable reference for next-generation engineers and researchers working in the area of design, analysis and manufacturing of composite materials for a wide range of practical applications. As significant research works have gone into uncertainty quantification in composite structures recently and many seminal papers have been published, the book also covers some of these latest developments with the introduction of fundamentals in a concise way. The attention in the book is mainly focussed on theoretical and computational aspects, although some reference to experimental works is given. Using this book, engineering and applied science graduate students and researchers will be able to implement and develop metamodels for applications in composite structural mechanics.

What will you find in this book? This book covers the essential fundamentals, applications and important references related to different metamodeling approaches specifically applicable to the aspect of uncertainty quantification in composite structures. Chapter 1 gives a general introduction to the need for considering uncertainty in engineering. The Chapter 2 of this book gives an overview of uncertainty quantification and a general review of the literature related to uncertainty quantification in composite structures. Chapter 3 presents a bottom-up approach to analyse the effect of stochasticity in material and structural parameters of a composite plate on the dynamic responses based on high dimensional model representation technique. Chapter 4 and 5 deals with the stochastic dynamic analysis of singly curved and doubly curved composite shells respectively. Chapter 6 deals with an environmental effect (thermal uncertainty) on the stochastic dynamic analysis of composite laminates, while chapter 7 addresses one of the crucial aspects of mechanical structures arising during the operational conditions (rotational uncertainty). Often application-specific requirements are needed to be met in engineering structures such as cutouts in plate and shells. Chapter 8 deals with the stochastic dynamics of composite laminates with cutouts. Chapter 9 presents a stochastic dynamic stability analysis of composite shells with uncertain material and geometric properties. Chapter 10 presents the stochastic dynamics and stability analysis of sandwich panels. Probabilistic approaches of uncertainty quantification are followed in Chapter 3 to 10. A metamodel based non-probabilistic uncertainty propagation scheme for composites is presented in Chapter 11. Different metamodel based uncertainty propagation schemes are discussed in Chapter 3 to 11, while the comparative performance of the metamodels for analysing composite structures is presented in Chapter 12 and 13. The scope of this book includes the aspect of uncertainty modelling as well as critical evaluation of the efficient metamodel-based uncertainty propagation approaches for composite structures.

Brief history and acknowledgements: This book on uncertainty quantification in laminated composites is a result of last ten years of research by the authors in the area of probabilistic engineering mechanics. The book's initial chapters began taking shape when Dr Dey, an expert in composite mechanics, joined Swansea University as a postdoctoral research fellow to work on uncertainty propagation in large composite structures. During this time, Dr Dey collaborated with Dr Mukhopadhyay, who had experience in metamodeling methods and computational mechanics. The inception of this book emerged from the fusion of three key technical areas which were historically disconnected in nature, namely, uncertainty modelling and propagation (Prof Adhikari), composite structures (Dr Dey) and metamodeling for multi-parameter systems and computational mechanics (Dr Mukhopadhyay). Without the timely merger of such complementary expertise, this book would have never taken the shape.

In this context, it could be noted that Dr Dey and Dr Mukhopadhyay have contributed equally in this book.

The authors are deeply indebted to numerous colleagues, students, collaborators and mentors. We are genuinely thankful to all of them for numerous stimulating scientific discussions, exchanges of ideas and on many occasions direct contributions towards the intellectual content of the book. Support and encouragement from colleagues within Swansea University's Zienkiewicz Centre for Computational Engineering, such as Professor M. I. Friswell, Professor P. Nithiarasu, Dr H. H. Khodaparast is greatly acknowledged. Particular thanks to Dr P. Higino, Dr G. Caprio and Dr A. Prado from Embraer (Brazil) for their intellectual

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We have been fortunate to receive grants from various companies, charities and government organisations including an Advanced Research Fellowship from UK Engineering and Physical Sciences Research Council (EPSRC), the Wolfson research merit award from The Royal Society, the Philip Leverhulme Prize from The Leverhulme Trust, research grants from Embraer, NRN Wales and a Zienkiewicz Scholarship from Swansea University. Without these funding, it would have been impossible to conduct the works leading to this book.

Sudip Dey
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CHAPTER 1

Introduction

> *"Uncertainty is the only certainty there is, and knowing how to live with insecurity is the only security".*
>
> — John Allen Paulos

If we think deeply, sun-rise or sun-set never ever occurs. In reality, there is no new year or end of year and thus there is no century. Actually, all of us have framed everything as per our convenience. We always try to formulate our surroundings in the form of a theory-law-hypothesis or an equation or algorithm. The perpetuity of these deterministic frameworks based on the model of certainty does not exist in the universal-continuum of time scale. The Sun and earth rotate to their own tune of rotation. In many of the cases, we cannot even identify the variability/change in pattern due to the unimaginable vastness of such systems both in terms of space and time. Since the dawn of civilization all models introduced are meant for some specific purposes, such as the solar model initially proposed by Pythagoras and Aristotle (500 BC) was meant for the purpose of assessment of weather needed for crop production. Later on, Ptolemy (300 BC) proposed a new solar model which claimed to have corrected the previous solar model. Even though the earlier models served the intended purpose to some extent, both the models are found to be wrong as compared to the present solar model (refer to Fig. 1.1). Thus there exists a deficiency in the accuracy of our understanding of the physical systems in many cases. We human beings have formulated all the uncertain facts and transformed them into the cage of certainty for our convenience. Hence, many of the theories, laws, hypothesis, and formulae (from Aristotle to Hawking) become questionable if we change its domain, assumptions and boundary conditions.

The convenient simplified models have their limitations in accurate predictions and often differ from the true values. For centuries, researchers have been abiding

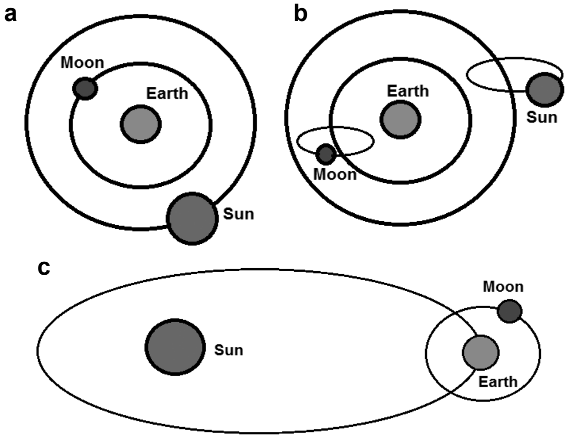

Fig. 1.1 Solar models.

by and spending their valuable time either to demonstrate or to validate those certain (/deterministic) models, which are actually uncertain in the domain of space and time. However, uncertainty being an inevitable characteristics of this universe, it is almost impossible to model a system accurately in a deterministic manner. Rather, it is a rational idea to try to quantify the effect of such uncertainty by considering it as an integral part of the model and deal with the consequences. This approach of modelling physical systems equips us to be prepared for the possible combination of outcomes by providing a detailed account of the variation from deterministic values of responses (i.e., the output quantity of interest). In case of engineering systems, if the design is carried out by considering the effect of source-uncertainties and prospective service-life conditions (such as environmental effects and damages) instead of blatantly avoiding them, the possibility of failure can be minimized (/ controlled) based on a strong scientific foundation.

Let us take a simple example to understand the influence of source-uncertainty. When we flip a fair coin, the probability of getting head or tail is 50%; but what happens if there is a soft muddy floor. It may lead to some possibilities wherein the coin will fall neither head nor tail, i.e., the coin may fall vertical. In such cases, it will not be 50% probability of getting either head or tail. Moreover, due to manufacturing uncertainties the coin may not be perfectly unbiased. This may also deviate the outcome from the general expectation. Likewise, the probability of getting one in dice having six faces is 1/6. But if the similar conditions (such as soft muddy surface, manufacturing uncertainty of the dice) are imposed here, there can be some possibilities wherein the dice will not show any specific face, or the probability of different outcomes would vary. Hence, the exact probability of getting one in those cases can’t be predicted. In a similar fashion, all the physical or mathematical models are formulated based on certain boundary conditions and assumptions, which are often not strictly valid.

1.1 Source-uncertainty in engineering systems

If we think in a scale of time, the observations (/realizations) at a present time are precise and unique; while the sparsity of impreciseness (/uncertainty in prediction) increases as we go away from the present moment towards the direction of past or future (refer to Fig. 1.2). Various practical issues of life should be able to cope with the uncertainties that may originate from different aspects of design, implementation and operational conditions. The past, present and future are the unidirectional horizon of time, wherein plenty of areas can be cited to illustrate the scope of quantifying the hidden uncertainty, such as:

- Forecasting of weather in a particular place over a common span of time.
- Gain or loss on investment in financial markets, e.g., stock markets.
- Measurement error implicitly influencing the accuracy of machines or instruments.
- Response of structural systems related to various fields of engineering, such as aerospace, mechanical and civil.
- Validation and verification of material modelling in engineering.
- Success of new product, services, firms or person in the time-scale of future.
- Winning in games or gambling.
- Occurrences of events, incidents, births, deaths, accidents.
- Day to day activities like walking, sleeping, sitting, reading, writing, eating.
- Movement of particles such as atoms, molecules from Dalton's atomic theory to modern quantum mechanics.
- Actions, reactions and reflex in any biological systems.
- Human behaviour and activities.

In particular, the areas of engineering, which are most susceptible to different forms of uncertainty, are listed below:

❑ *Design of Machine elements or components (linear and non-linear model)*
  - Design of joints (Any fasteners subjected to random load).
  - Power transmission unit design (Shaft coupling for torque transmission).

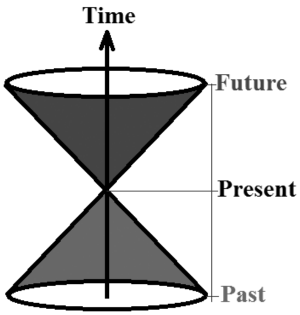

Fig. 1.2 Past-present-future domain with respect to time scale.

  - Bearing design (Journal/Ball/Roller bearing).
  - Vehicles Dynamics (Tire Technology).
  - Pressure vessel design subjected to uncertain load.

- ☐ *Biomedical or Bioengineering*
  - Human glucose metabolism/Diabetic Model.
    - Model for inflow of insulin by injection.
    - Model for inflow of glucose from ingested food.
  - Molecular/Cellular/Organisms/Communities and Ecosystems.
  - HIV model, Ebola virus model, Polio model, etc.
  - Human Blood Pressure model.
- ☐ *Control Engineering for robust design*
  - Temperature–Moisture Controller for air-conditioner.
  - Speed: Fuel consumption Controller for automobiles.
  - Speed: Cleanliness (dirt-removal) Controller for washing machine.
  - Illumination: Power Controller for Light emitting diode (LED) light.
- ☐ *Aerospace and Structural Engineering*
  - Bending Characteristics.
  - Vibration analysis (Free/Forced).
  - Inverse Problem/Design Optimization.
  - Structural Health Monitoring.
  - Reliability Analysis.
- ☐ *Environmental Engineering*
  - Weather Model (rain/snowfall/humidity/temperature).
  - Earthquake Model.
  - Atmospheric climate (Layerwise) Model.
- ☐ *Coastal/Marine Engineering*
  - Tide/Flood control.
  - Marine traffic control.
- ☐ *Geo-technical Engineering*
  - Contamination migration problem (by uncertain diffusion process).
  - Sedimentation of clay/silt due to uncertain hydraulic transportation.
  - Inaccurate measurement of the properties of soil and their spatially varying characteristics.

This book is focused on the aspect of source-uncertainties in advanced lightweight structures such as composites and efficient approaches to quantify their effects on global responses for a safe, yet economic design. A brief overview of the uncertainty quantification of composites following an efficient metamodeling approach is provided in the following sections of this chapter.

1.2 Importance of uncertainty quantification in composite structures

Composite structures are extensively used in modern aerospace, marine, construction and automobile applications due to their high strength, stiffness, lightweight and tailorable properties. Even though laminated composite structures have the advantage of modulating large number of design parameters to achieve various application-specific requirements, this concurrently brings the challenge of manufacturing the structure according to exact design specifications. Large-scale production of such structures according to the requirements of industry is always subjected to significant variability due to unavoidable manufacturing imperfections (such as intra-laminate voids, incomplete curing of resin and excess resin between plies, porosity, excess matrix voids, variations in ply thickness and fibre parameters), lack of experiences and complexity of the structural configuration. The issue aggravates further due to uncertain operational and environmental factors and the possibility of incurring different forms of damages and defects during the service life.

In general, an additional factor of safety (FOS) is incorporated by the designer to account for such unpredictable global responses, which may lead to either an ultraconservative or an unsafe design. A river and bridge model (refer to Fig. 1.3) is introduced to explain this further. Due to the presence of different forms of uncertainties (referred as the river of uncertainty in a collective form), the designed outcome and the real outcome differ for an engineering system. For a particular value of FOS, if the design is more conservative the real outcome would be less prone to failure (refer to Fig. 1.3a) and vice versa (refer to Fig. 1.3b). However a high value of FOS would be required if the design is less conservative, yet the system is required to be less prone to failure (refer to Fig. 1.3c). The above three cases normally lead to either an unsafe or uneconomic design because of the fact that the river of uncertainty is not adequately explored in this approach of analysis. An economic, yet safe design requires the in-depth analysis of the uncertainty associated with the system, as shown in Fig. 1.3d. If the level of uncertainty for a system is appropriately quantified, then the value of FOS can be adopted based on the importance of the system in a more robust manner. Moreover, probabilistic description for the response of the system could be obtained for the adopted value of FOS. As laminated composites are often used in various functionally important structures (such as aircrafts), it is important to quantify the uncertainties associated with the responses of the structure. If the actual outcome of an engineering system is considered, there could be four distinct situations in terms of attaining the design specification and variability from the target (refer to Fig. 1.4). The objective is to achieve a design outcome which is on target and has low variability. As the variability cannot be nil in case of real-life engineering systems, the objective becomes to minimize it and subsequently quantify the effect of such variability (/uncertainty) following a strong mathematical stochastic paradigm.

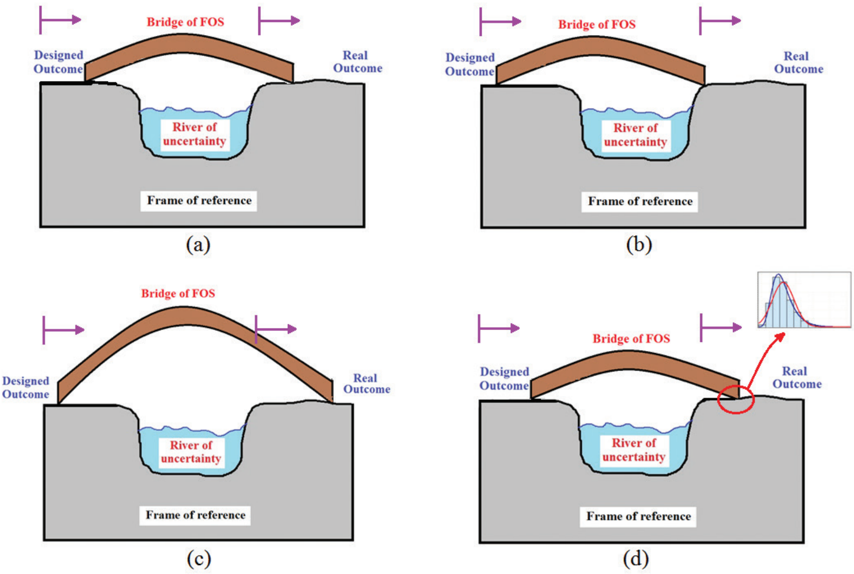

Fig. 1.3 River and bridge model of uncertainty.

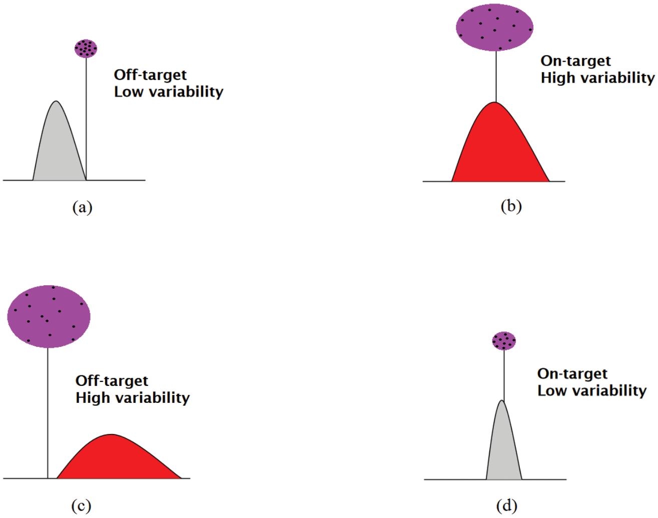

Fig. 1.4 Realistic design aim of engineering structures.

In general, uncertainties are classified into three categories, namely aleatoric (because of variability in the structural system parameters), epistemic (because of lack of information of the structural system) and prejudicial (because of the absence of variability characterization of the structural system). A detail description of different categories of uncertainty is provided in Chapter 2. Composite structures being susceptible to multiple forms of uncertainties, damages and environmental variations, the structural performances are often subjected to a significant element of risk. Thus it is of prime importance in case of composite structures to quantify the effect of source-uncertainties so that an inclusive design paradigm could be adopted to avoid any compromise in the aspects of safety and serviceability. The whole context of uncertainty quantification in various global responses of composite structures, which are increasingly being used in different industries, is summarized in Fig. 1.5. A concise discussion of the most prominent approaches for uncertainty quantification in composite structures is furnished in the next paragraph.

Following several decades of deterministic studies related to the static and dynamic responses of laminated composite structures (Reddy 2003, Chakrabarti et al. 2013, Mandal et al. 2017), the aspect of considering the effect of uncertainty in material and structural attributes have recently started receiving due attention from the scientific community. Both probabilistic (Sakata et al. 2008, Goyal and Kapania 2008, Manan and Cooper 2009) as well as non-probabilistic (Pawar et al. 2012) approaches have been investigated to analyse the effect of variability in the material and structural properties of composite structures. Plenty of researches have been reported based on intrusive methods to quantify the uncertainty of composite structures (Lal and Singh 2010, Scarth and Adhikari 2017); wherein the major drawback can be identified as the requirement of intensive analytical derivation and lack of the ability to obtain complete probabilistic description of the response quantities for systems with spatially varying attributes. Moreover, many of these approaches are valid only for a low degree of stochasticity in the input parameters. A non-intrusive method based on Monte Carlo simulation,

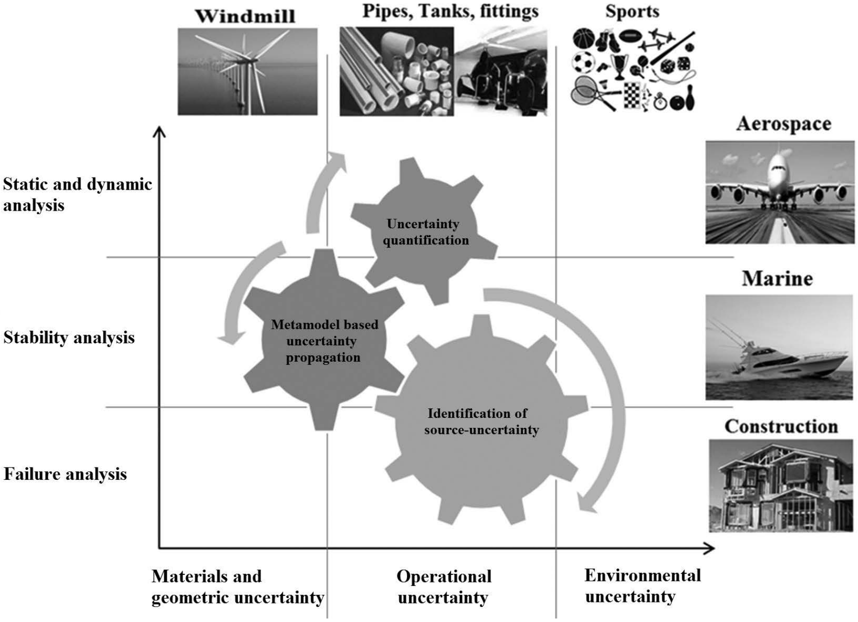

Fig. 1.5 Uncertainty quantification in various global responses of composite structures.

as adopted by many researchers (Dey et al. 2015a), can obtain comprehensive probabilistic descriptions for the response quantities of composite structures and these methods can account for much higher degree of stochasticity in the input parameters. A brief description of the Monte Carlo simulation method is provided in the next section.

1.3 Monte Carlo simulation

Uncertainty quantification is part of modern structural analysis problems. Practical structural systems are faced with uncertainty, ambiguity, and variability constantly, as discussed in the preceding sections. Even though one might have unprecedented access to information due to the recent improvement in various technologies, it is impossible to accurately predict future structural behaviour during its service life. Monte Carlo simulation, a computerized mathematical technique, lets us realize all the possible outcomes of a structural system leading to better and robust designs for the intended performances. The technique was first used by scientists working on the atom bomb; it was named after Monte Carlo, the Monaco resort town renowned for its casinos. Since its introduction in World War II, this technique has been used to model a variety of physical and conceptual systems across different fields such as engineering, finance, project management, energy, manufacturing, research and development, insurance, oil and gas, transportation and environment.

Monte Carlo simulation furnishes a range of prospective outcomes along with their respective probability of occurrence (refer to Fig. 1.6). This technique performs uncertainty quantification by forming probabilistic models of all possible results accounting for a range of values from the probability distributions of any factor that has inherent uncertainty. It simulates the outputs over and over, each time using a different set of random values from the probability distribution of stochastic input parameters. Depending upon the nature of stochasticity, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it can provide a converged result depicting the distributions of possible outcome values of the response quantities of interest. Each set of samples is called an iteration or realization, and the resulting outcome from that sample is recorded. In this way, Monte Carlo simulation provides not only a comprehensive view of what could happen, but how likely it is to happen, i.e., the probability of occurrence.

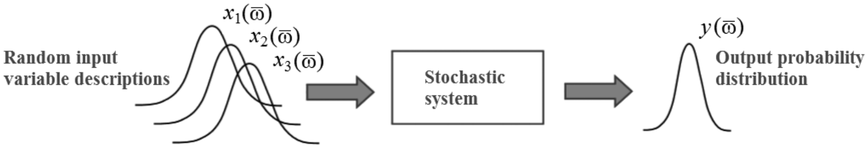

Fig. 1.6 Schematic representation for Monte Carlo simulation based analysis of a stochastic system with three input parameters (x_i, $i = 1, 2, 3$) and one output parameter (y). Here $\bar{\omega}$ represents the stochastic character of a parameter.

The mean or expected value of a function $f(x)$ of an n dimensional random variable vector can be expressed as

$$\mu_f = E[f(x)] = \int_{\Omega} f(x)\phi(x)dx \tag{1.1}$$

Similarly the variance of the random function $f(x)$ is given by the integral below,

$$\sigma_f^2 = Var[f(x)] = \int_{\Omega} (f(x) - \mu_f)^2 \phi(x)dx \tag{1.2}$$

The above multidimensional integrals, as shown in equations (1.1) and (1.2) are difficult to evaluate analytically for many types of joint density functions and the integrand function $f(x)$ may not be available in analytical form for the problem under consideration. Thus the only alternative way is to calculate it numerically. The above integral can be evaluated using MCS approach, wherein N sample points are generated using a suitable sampling scheme in the n-dimensional random variable space. The N samples drawn from a dataset must follow the distribution specified by $\varphi(x)$. Having the N samples for x, the function in the integrand $f(x)$ is evaluated at each of the N-sampling points x_i of the sample set $\chi = \{x_1, \ldots\ldots\ldots\ldots, x_N\}$. Thus, the integral for the expected value takes the form of averaging operator as shown below

$$\mu_f = E\left[f(x)\right] = \frac{1}{N}\sum_{i=1}^{N} f(x_i) \tag{1.3}$$

Similarly, using sampled values of MCS, the equation (1.2) leads to

$$\sigma_f^2 = Var\left[f(x)\right] = \frac{1}{N-1}\sum_{i-1}^{N}\left(f(x_i) - \mu_f\right)^2 \tag{1.4}$$

Thus the statistical moments can be obtained using a brute force Monte Carlo simulation based approach, which is often computationally very intensive due the evaluation of function $f(x_i)$ corresponding to the N-sampling points x_i, where $N \sim 10^4$. The noteworthy fact in this context is the adoption of a metamodel based Monte Carlo simulation approach that reduces the computational burden of traditional (i.e., brute force) Monte Carlo simulation to a significant extent, as discussed in the next section.

1.4 Meta-modelling approach for uncertainty quantification

Uncertainty quantification based on Monte Carlo simulation is a popular approach because of its ability to obtain a comprehensive probabilistic description of the response quantities. However, the major lacuna of this approach is that a Monte Carlo simulation requires thousands of expensive model evaluations to be carried out corresponding to the random realizations. Thus, in case of the systems where the model evaluations are expensive (such as finite element simulation), direct Monte Carlo simulation has limited practical use because of its computational intensiveness.

In general for complex composite structures, the performance function is not available as an explicit function of the random design variables unlike various other engineering problems with closed-form solutions (Mukhopadhyay and Adhikari 2017a, Mukhopadhyay et al. 2017b, 2017e, 2018c). The performance functions or responses (such as natural frequencies, buckling loads, etc.) of the composite structure can only be evaluated numerically at the end of a structural analysis procedure such as the finite element method, which is often time-consuming and computationally expensive. To mitigate this lacuna, a meta-modelling approach can be adopted, wherein the uncertainty propagation is realized following an efficient mathematical medium. The metamodel based uncertainty propagation strategy can develop a predictive and representative mathematical model relating each response quantity of interest to a number of input variables. These metamodel equations are used to determine the global response characteristics corresponding to given values of input variables, instead of having to repeatedly run the time-consuming original simulation model (such as finite element analysis). The metamodel thus represents the result (or output) of the structural analyses encompassing (in theory) every reasonable combination of all input variables. From this, thousands of combinations of all design variables can be created (via simulation) and a pseudo analysis for each variable set can be performed by simply adopting the corresponding metamodel.

In general, the metamodels are employed to reduce the number of function evaluations based on actual simulation/experimental models in a Monte Carlo simulation, which needs large number of realizations corresponding to random set of input parameters (Metya et al. 2017, Mukhopadhyay et al. 2016f, Mahata et al. 2016). Metamodels are also quite popular in the area of optimization and inverse problems that involves multiple function evaluations (Mukhopadhyay et al. 2015b, 2016d). The development of metamodels is performed in three typical steps: selection of the representative sample points (which are able to collect all information of the whole design space in an optimal way) to construct a surrogate of the original simulation model, evaluation of responses (i.e., output) corresponding to each sample point and formulation of the mathematical or statistical model to obtain input-output relationship based on the sample set (containing a set of input parameters and corresponding output parameters). The performance of a metamodel (i.e., accuracy in prediction and computational efficiency) depends on various factors such as: dimension of the input parameter space (i.e., number of input parameters), number and quality of sample points for metamodel formation, degree of nonlinearity involved with the system and different forms of errors involved in metamodel formation (refer to Fig. 1.7). This book follows a metamodel based approach to quantify the effect of uncertainty in various global responses of composite structures.

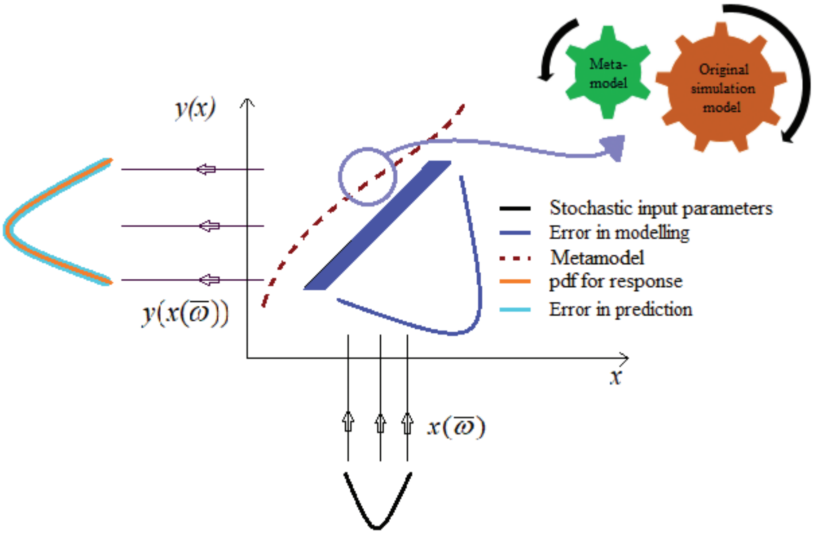

Fig. 1.7 Metamodel based analysis of stochastic systems. (Here $x(\overline{\varpi})$ and $y(x(\overline{\varpi}))$ are the symbolic representation of stochastic input parameters and output responses respectively. $\overline{\varpi}$ denotes the stochasticity of parameters.)

1.5 Motivation and scope of the book

Uncertainty quantification in composite materials and structures, initiated from industrial needs due to inevitable variation in global responses of such structures from the deterministic predictions, has gained immense attention from the research community over the last few decades. This book aims to present an efficient uncertainty quantification scheme for laminated composite structures following meta-model based approaches for stochasticity in material and geometric parameters. Several meta-models are studied for this purpose and comparative results are presented for different global responses of composite structures including the effect of various environmental (such as temperature) and operational (such as rotation) conditions. Stochastic response of composite structures with application-specific design requirements such as cutouts is presented following the metamodel based approach. Both probabilistic and non-probabilistic approaches are discussed. Results for sensitivity analyses are presented to provide a complete understanding of the relative importance of different material and geometric parameters in global responses of the structure. To account for the effect of different forms of errors and uncertainty in metamodel formation, a collective effect of noise is presented in the metamodel based uncertainty quantification algorithms for composite structures.

Motivated by the influence of inevitable source-uncertainties in composite structures and the computational challenges involved therein, as outlined in the preceding sections, this book is written to address both the aspects of modeling different forms of uncertainties in composites as well as efficient computational approaches for uncertainty propagation. After providing a general overview of uncertainty quantification and stochastic analysis of composite structures in Chapters 1–2, rest of the chapters in this book are concentrated on various specific aspects related to uncertainty analysis of laminated composites and metamodel based algorithms for uncertainty quantification. The Chapters 3–10 of this book are focused on probabilistic approach of uncertainty quantification in composite laminates and sandwich structures, while the Chapter 11 deals with a non-probabilistic approach of uncertainty quantification in composites. The aspects of uncertainty and sensitivity of the material, geometric, environmental and operational factors for different responses of composite structures are analyzed in the Chapters 3–11. Various application-specific requirements (such as cutouts, twist and skewed geometry) in modern high-performance structural systems are analyzed. The effect of noise is analyzed in surrogate based uncertainty quantification algorithms for composites. Chapter 12 provides a critical assessment of different kriging model variants for the uncertainty quantification of composite structures. Different meta-models are used for formulating the uncertainty quantification schemes in various chapters of this book. Finally, comparative assessment of these meta-models is presented in Chapter 13. A concise summary explaining the contributions of each of the chapters in this book is given below.

The Chapter 2 of this book gives an overview of uncertainty quantification and a general review of the literature related to uncertainty quantification in composite structures. Different probabilistic and non-probabilistic methods of stochastic structural analysis are briefly presented in this chapter. After providing a concise review of the deterministic models for analyzing composite structures, the recent works on the aspect of uncertainty quantification in composite structures are discussed. The present standing of research in this area is assessed critically and the contribution of this book is justified in that context. Even though a comprehensive literature review is presented in Chapter 2, Chapters 3–13 also cite relevant studies specific to the topic of a particular chapter.

The effect of material and geometric uncertainty on the dynamic responses of composite plates is investigated in Chapter 3. A bottom up surrogate based approach is employed to quantify the variability in free vibration responses of composite cantilever plates due to uncertainty in ply orientation angle, elastic modulus and mass density. The finite element method is employed incorporating effects of transverse shear deformation based on Mindlin's theory in conjunction with a random variable approach. Parametric studies are carried out to determine the stochastic frequency response functions (SFRF) along with stochastic natural frequencies and modeshapes. In this study, a surrogate based approach using General High Dimensional Model Representations (GHDMR) is employed for achieving computational efficiency in quantifying uncertainty. This chapter also presents an uncertainty quantification scheme using commercial finite element software

(ANSYS) and thereby comparative results of stochastic natural frequencies are furnished for UQ using GHDMR approach and ANSYS.

In Chapter 4, we have concentrated on the stochastic dynamic responses of singly curved composite shells including the effect of twist angle in the geometry. The effect of transverse shear deformation is incorporated in the probabilistic finite element analysis considering an eight noded isoparametric quadratic element with five degrees of freedom at each node. The finite element model is coupled with the response surface method based on D-optimal design to achieve computational efficiency. A sensitivity analysis is carried out to address the influence of different input parameters on the output natural frequencies. The fibre orientation angle, twist angle and material properties are randomly varied to obtain the stochastic natural frequencies.

Chapter 5 presents an efficient stochastic free vibration analysis of composite doubly curved shells. The stochastic finite element formulation is carried out considering rotary inertia and transverse shear deformation based on Mindlin's theory. The sampling size and computational cost in the probabilistic analysis is reduced by employing a Kriging model based approach compared to direct Monte Carlo simulation. Besides detail investigation on the stochastic natural frequencies corresponding to low frequency vibration modes, the stochastic mode shapes and frequency response functions are also presented for a typical laminate configuration. The effect of noise on the kriging based uncertainty propagation algorithm is addressed. Results are presented for different levels of noise in a probabilistic framework to provide a comprehensive idea about stochastic structural responses under the influence of simulated noise.

Chapter 6 investigates the effect of rotational uncertainty under operating condition in the dynamic responses of composite shells. A response surface method based on central composite design algorithm is used for the quantification of rotational and ply-level uncertainties. The stochastic eigenvalue problem is solved by using QR iteration algorithm. An eight noded isoparametric quadratic element with five degrees of freedom at each node is considered in the finite element formulation. Sensitivity analysis is carried out to address the influence of different input parameters on the output natural frequencies. The sampling size and computational cost is reduced by employing the present surrogate based approach compared to direct Monte Carlo simulation. The stochastic mode shapes are also depicted for a typical laminate configuration.

Chapter 7 deals with the uncertainty caused by inevitable random variation of environmental factors such as temperature. The propagation of thermal uncertainty in composite structures has significant computational challenges. This chapter presents the thermal, ply-level and material uncertainty propagation in frequency responses of laminated composite plates by employing a surrogate model which is capable of dealing with both correlated and uncorrelated input parameters. In the present generalized high dimensional model representation (GHDMR) based approach, diffeomorphic modulation under observable response preserving homotopy (D-MORPH) regression is utilized to ensure the hierarchical orthogonality of high dimensional model representation component functions. The stochastic range of thermal field includes elevated temperatures up to 375 K and sub-zero temperatures up to cryogenic range of 125 K.

The aspect of an application-specific design requirement in engineering structures (cutouts) is illustrated in Chapter 8. This chapter deals with the effect of cutout on stochastic dynamic responses of composite laminates. Support vector regression (SVR) model in conjunction with Latin hypercube sampling is used in this investigation as a surrogate of the actual finite element model to achieve computational efficiency. The convergence of the present algorithm for laminated composite curved panels with cutout is validated with original finite element (FE) analysis along with traditional Monte Carlo simulation (MCS). Variations of input parameters (both individual and combined cases) are studied to portray their relative effect on the output quantity of interest. The layer-wise variability of structural and material properties is included considering the effect of twist angle, cutout sizes and different geometries (such as cylindrical, spherical, hyperbolic paraboloid and plate). The sensitivities of input parameters in terms of coefficient of variation are enumerated to project the relative importance of different random inputs on natural frequencies. Subsequently, the noise induced effects on SVR based computational algorithm are presented to map the inevitable variability in practical field of applications.

In Chapter 9, a stochastic dynamic stability analysis of composite panels is presented considering the effect of non-uniform partial edge loading. The system input parameters are randomized to ascertain the stochastic first buckling load and zone of resonance. Considering the effects of transverse shear deformation and rotary inertia, first order shear deformation theory is used to model the composite curved panels. Moving least square method is employed as a surrogate of the actual finite element model to reduce the computational cost. Statistical results are presented to show the effects of radius of curvatures, material properties, fibre parameters, and non-uniform load parameters on the stability boundaries.

Chapter 10 focuses on the stochastic analysis of laminated soft-core sandwich panels including the effect of skewness in the geometry. An efficient multivariate adaptive regression splines based approach for dynamics and stability analysis of sandwich plates is presented considering the random system parameters. The propagation of uncertainty in such structures has significant computational challenges due to inherent structural complexity and high dimensional space of input parameters. The theoretical formulation is developed based on a refined C0 stochastic finite element model and higher-order zigzag theory in conjunction with multivariate adaptive regression splines. A cubical function is considered for the in-plane parameters as a combination of a linear zigzag function with different slopes at each layer over the entire thickness while a quadratic function is assumed for the out-of-plane parameters of the core and constant in the face sheets. Both individual and combined stochastic effect of skew angle, layer-wise thickness, and material properties (both core and laminate) of sandwich plates are considered. Statistical analyses are carried out to illustrate the results of the first three stochastic natural frequencies and buckling load.

A non-probabilistic uncertainty propagation approach (fuzzy) for composites is presented in Chapter 11. Probabilistic descriptions of uncertain model parameters are not always available due to lack of data. This chapter investigates on the uncertainty propagation in dynamic characteristics (such as natural frequencies, frequency response function and mode shapes) of laminated composite plates by using fuzzy approach. A non-intrusive Gram–Schmidt polynomial chaos expansion (GPCE) method is adopted in the uncertainty propagation, wherein the parameter uncertainties are represented by fuzzy membership functions. A domain in the space of input data at zero-level of membership functions is mapped to a zone of output data with the parameters determined by D-optimal design. The obtained meta-model (GPCE) can also be used for higher α-levels of fuzzy membership function. The most significant input parameters such as ply orientation angle, elastic modulus, mass density and shear modulus are identified and then fuzzified. Fuzzy analysis of the first three natural frequencies is presented to illustrate the results and its performance. The proposed fuzzy approach is applied to the problem of fuzzy modal analysis for frequency response function of a simplified composite of cantilever plates. The fuzzy mode shapes are also depicted for a typical laminate configuration. The GPCE based approach is found more efficient compared to the conventional global optimization approach in terms of computational time and cost.

Chapter 12 presents a critical comparative assessment of Kriging model variants for surrogate based uncertainty propagation considering stochastic natural frequencies of laminated composite shells. The five Kriging model variants studied here are: Ordinary Kriging, Universal Kriging based on pseudo-likelihood estimator, Blind Kriging, Co-Kriging and Universal Kriging based on marginal likelihood estimator. First three stochastic natural frequencies of the composite shell are analysed by using a finite element model that includes the effects of transverse shear deformation based on Mindlin's theory in conjunction with a layer-wise random variable approach. The comparative assessment is carried out to address the accuracy and computational efficiency of the five Kriging model variants. Comparative performance of different covariance functions is also studied. Subsequently the effect of noise in uncertainty propagation is addressed by using the Stochastic Kriging. Representative results are presented for both individual and combined stochasticity in layer-wise input parameters to address performance of various Kriging variants for low dimensional and relatively higher dimensional input parameter spaces. The error estimation and convergence studies are conducted with respect to original Monte Carlo Simulation to justify merit of the present investigation. The study reveals that Universal Kriging coupled with marginal likelihood estimate yields the most accurate results, followed by Co-Kriging and Blind Kriging. As far as computational efficiency of the Kriging models is concerned, it is observed that for high-dimensional problems, CPU time required for building the Co-Kriging model is significantly less as compared to other Kriging variants.

Chapter 13 presents an exhaustive comparative investigation on different metamodels for critical comparative assessment of uncertainty in natural frequencies of composite plates on the basis of computational efficiency and accuracy. Both individual and combined variations of input parameters have been considered to account for the effect of low and high dimensional input parameter spaces in the surrogate based uncertainty quantification algorithms including the rate of convergence. Probabilistic characterization of the first three stochastic natural frequencies is carried out by using a finite element model that includes the effects of transverse shear deformation based on Mindlin's theory in conjunction with a layer-wise random variable approach. The results obtained by different metamodels have been compared with the results of direct Monte Carlo simulation (MCS) method for high fidelity uncertainty quantification. The crucial issue regarding influence of sampling techniques on the performance of metamodel based uncertainty quantification has been addressed as an integral part of this chapter.

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