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Stochastic natural frequency analysis of damaged thin-walled laminated composite beams with uncertainty in micromechanical properties

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ABSTRACT

This paper presents a stochastic approach to study the natural frequencies of thin-walled laminated composite beams with spatially varying matrix cracking damage in a multi-scale framework. A novel concept of stochastic representative volume element (SRVE) is introduced for this purpose. An efficient radial basis function (RBF) based uncertainty quantification algorithm is developed to quantify the probabilistic variability in free vibration responses of the structure due to spatially random stochasticity in the micromechanical and geometric properties. The convergence of the proposed algorithm for stochastic natural frequency analysis of damaged thin-walled composite beam is verified and validated with original finite element method (FEM) along with traditional Monte Carlo simulation (MCS). Sensitivity analysis is carried out to ascertain the relative influence of different stochastic input parameters on the natural frequencies. Subsequently the influence of noise is investigated on radial basis function based uncertainty quantification algorithm to account for the inevitable variability for practical field applications. The study reveals that stochasticity/ system irregularity in structural and material attributes affects the system performance significantly. To ensure robustness, safety and sustainability of the structure, it is very crucial to consider such forms of uncertainties during the analysis.

1. Introduction

Laminated composites have gained huge popularity because of their weight sensitivity, high-strength and stiffness to weight ratios and long-term cost effectiveness. Such structures are extensively used in aerospace, marine, construction and other industries due to their application specific tailorable material properties. It is widely known that thin walled composite beams are used broadly in various applications of structural engineering, such as helicopter blades, wings, trusses in space structures, submarine hulls, cooling tower shafts, medical tubing, connecting shafts, transmission poles, tail boom of helicopter and tube like structures in missiles. Because of their inherent complexity, a laminated composite beam is difficult to manufacture accurately according to its exact design specifications, resulting in undesirable uncertain responses due to random material and geometric properties. Generally uncertainties are broadly classified into three divisions, 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) [1–3]. The performances of composite structures are influenced by the quality control processes, operating conditions and environmental effects. It can be observed that there are uncertainties in input forces, system descriptions, computation as well as model calibration. The production of composite laminates is subjected to large variability because of unavoidable fabricating imperfections, operational factors, inaccurate experimental data, lack of experience, etc. Furthermore, because of various forms of damages and defects, effective material properties may vary substantially from the specified values. As a cumulative effect, the vibration characteristics of such composite structures show significant variability from the deterministic values. Therefore, the structural performance is subjected to a significant element of risk from safety and serviceability point of view. Moreover, uncertainties in input parameters can propagate through different modelling scales and influence other parameters and the final system output can have a substantial cascading effect because of the accumulation of the risk [4]. Such variability can result in significant deviations from the expected outputs (deterministic design values).

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Hence, it is of prime importance to characterize the probability distribution of the response parameters of interest (such as natural frequencies) by accounting for the variability in stochastic input parameters.

Since late eighties, research activities are dedicated towards the development of appropriate analysis for thin-walled composite beams [5,6]. Bauld and Tseng [7] studied the static structural behavior of a thin-walled composite orthotropic member under various load patterns. Bauchau [8] studied thin walled composite beam models with effects of shear deformability. Cortínez and Piovan reported vibration and buckling analysis of thin-walled composite beams with shear deformability [9]. Various other studies on composite beams are found to be concentrated on deterministic analysis concerning statics and dynamic responses including aeroelastic effects [10–16]. An extensive review of literature on laminated composites reveals that most of the studies carried out so far are based on a deterministic framework, in spite of the possibility of significant probabilistic variability in the responses of such structures due to inevitable stochasticity in material and geometric parameters. Recently attempts have been made to carry out stochastic analysis for different responses of composite plates and shells [17–19]. The treatment of uncertainties to quantify the same for thin walled circular composite beam has received little attention. Of late, Piovan et al. have investigated the effects of parametric uncertainty on dynamics of thin-walled laminated composite beams [20]. However, most of the recent research follows a random variable based approach that neglects the spatially random variation of material properties. Consideration of random fields for modelling uncertainty in composite structures is practically more relevant. Moreover, consideration of spatially varying damage that often develops in the operational environments has not been accounted in scientific literature yet.

This paper presents a realistic analysis on stochastic natural frequency of thin-walled laminated composite beams with spatially varying matrix cracking damage in a multi-scale framework. A typical schematic description of damage development in composite laminates isdepicted in Fig. 1, where the five identifiable damage mechanisms are indicated in the order of their occurrence [21]. In the early stages of damage accumulation, multiple matrix cracking dominates in the layers which have fibres aligned transverse to the applied load direction. Static tensile tests on cross-ply laminates have shown that the transverse matrix cracks can initiate as early as at about 0.4–0.5% applied strain depending upon the laminate configuration. Thus in the present investigation, spatially random distribution of matrix cracking is considered along with other stochastic input parameters to characterize the natural frequencies of thin-walled composite beams. The crucial issue of expensive computation involved in uncertainty quantification of composite structures and the development of radial basis function based uncertainty quantification algorithm to mitigate this lacuna is discussed in the following paragraph.

One of the most prominent approaches followed for uncertainty quantification in composite structures is the Monte Carlo simulation (MCS) based approach. MCS is a computerized mathematical technique which allows to account for risk in quantitative analysis and decision making. This technique is mainly utilized to generate the uncertain variable output frequency using large number of samples. MCS technique can be broadly used to quantify the uncertainty of laminated composites in which thousands of FEM simulations are required to be carried out. Therefore, this technique has limited practical use because of its computational intensiveness unless some form of efficient modelling technique is applied to mitigate this lacuna. Moreover, due to consideration of matrix cracking damage in the present analysis, the entire process of obtaining natural frequency for a particular realization of Monte Carlo sample becomes a multi-step procedure (in the first step of the analysis, the effective material properties of damaged composite are obtained; subsequently these effective material properties are fed in the finite element model to compute global mass and stiffness matrices and thereby the natural frequencies) making it even more time consuming. An efficient radial basis function [22,23] based uncertainty quantification approach is developed in this article to quantify the probabilistic variability in free vibration responses of the structure due to spatially random stochasticity in the micro-mechanical and geometric properties along with matrix-cracking damage. In the present approach, the effect of uncertainty is accounted in the elementary micro-level first and then these effects are disseminated towards the global responses via surrogates of the actual FEM models.

To the best of the authors' knowledge, there is no scientific literature available which deals with stochastic structural dynamics based on radial basis function for uncertainty quantification of

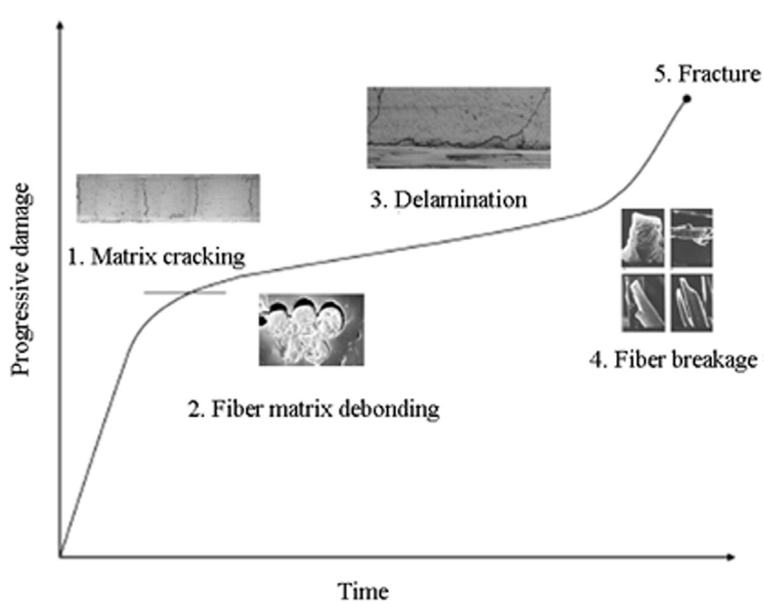

Fig. 1. Occurrence of progressive damage in composites.