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Towards an understanding of variations in the buckling of tailored variable angle tow composite plates

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ABSTRACT

In this paper, variable angle tow (VAT) composite plates tailored to enhance buckling performance are studied with the use of stochastic finite element method to quantify uncertainties in buckling measures arising from variations in material properties and fibre tow path. Detailed formulations for predicting buckling statistics in terms of mean value and standard deviation are derived to enable a perturbation-based stochastic finite element analysis. The derivations are built on a linear variation formula for fibre tow path and plate element based on the first order shear deformation theory. They are integrated with Taylor series expansion to propagate uncertainties from inputs to buckling performance measures, including buckling eigenvalues, critical buckling coefficients, etc. A twelve-layer VAT composite plate, with optimally designed fibre tow paths under various boundary conditions, has been investigated to illustrate the uncertainty quantification procedure. The performance of the perturbation-based stochastic finite element method has been validated using Monte Carlo simulation. Influences of variations in material properties and fibre tow path are thoroughly examined to understand the variability of buckling performance of VAT composites.

1. Introduction

The freedom to obtain tailored properties is one of the most attractive features of fibre reinforced polymer composites for developing lightweight structures, achieved using well established techniques, e.g. the specific selection of new constituent materials or different compositions, designing alternative material architectures, etc. Recently, more advanced composite manufacturing techniques have emerged, such as variable angle tow (VAT) or tow steering composites, in which the fibre path is continuously varied to tailor the local stiffness properties of laminates, further enhancing their structural performance. VAT composites are receiving significant attentions from several industry sectors such as aerospace, where it has shown great potential in structures with high demands on buckling, aeroelasticity, and vibration with restricted weight allowance. However, this additional design freedom is at the expense of complexity in maintaining uniform fibre paths during manufacturing and increased computational cost. One of the main additional computational costs comes from finding the optimal fibre tow path [9,24,10,28,23]. In addition, the nature of its curved fibre courses means that they are inevitably more vulnerable to manufacturing defects, which have been recognized as the main sources of variations in structural performances, compared with unidirectional (UD) or straight fibre composites. It is thus desirable to understand the uncertainties of this type of advanced composite to provide confidences in their applications.

VAT composites are relatively new, meaning that reports on quantifying uncertainties in either material properties or structural performance are seldom available. Variations in fibre tow path have, however, been reported in [11]. Due to the hierarchical nature of composites, relatively complex manufacturing technologies are required, with the manufacturing processes becoming the primary source for introducing material and geometric uncertainties. As a type of product using Automated Fibre Placement (AFP) technologies, VAT composites may share many manufacturing defects and variations in their properties with conventional composites. In general, variability exists in the constituent material properties arising from defects, such as fibre misalignment, waviness, etc. [22]. It has been widely accepted that defects and their inherent variations are some of the main sources of damage initiation [8]. The formations of defects were investigated in [2,17]. For instance, one of the processes known to influence the formation of fibre path defects is the consolidation of laminates manufactured by AFP. Moreover, these defects are random in nature. Uncertainty in the geometry of fibre preforms manufactured with Automated Dry Fibre Placement and its effects on permeability were

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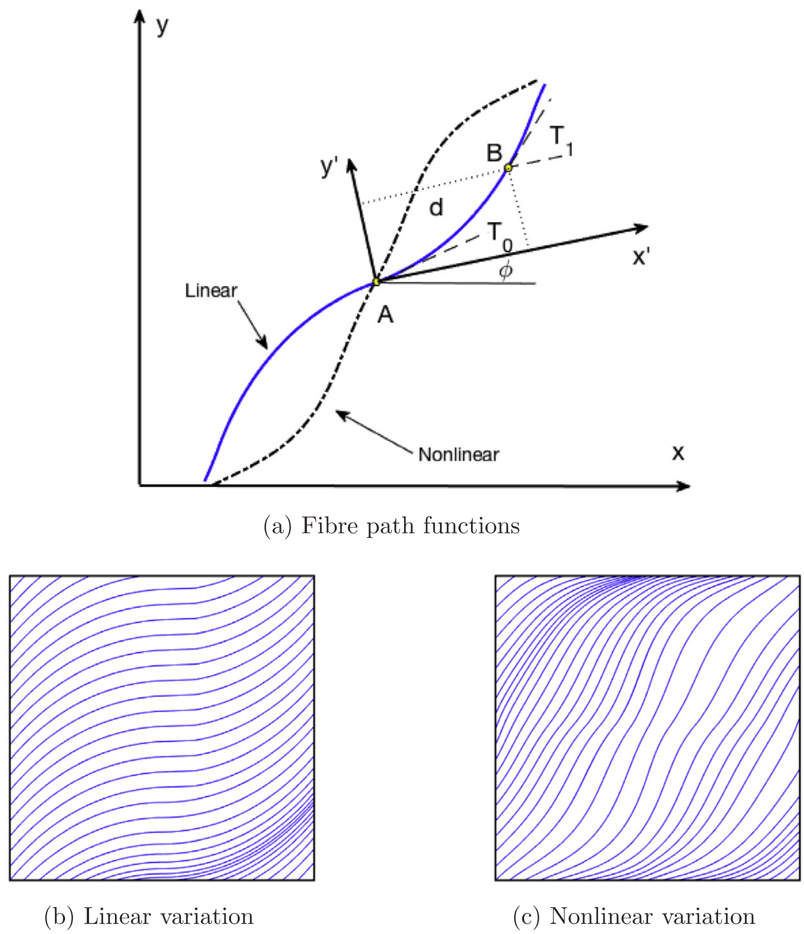

Fig. 1. Configuration of the variable angle tow composite laminate.

studied in [18]. The influence of manufacturing uncertainties on mechanical and/or physical properties of conventional composites, e.g. UD or textile, has been continuously investigated through numerical and experimental approaches, e.g. [4,1,30,29]. In the present study, the influences on buckling performance are of interest.

Uncertainty-driven probabilistic buckling analysis has been historically researched for composite structures. Lin [15] investigated the buckling failure probability evaluation of laminated composite plates subjected to different in-plane random loads using the stochastic finite element method, with the feasibility and accuracy of the results validated using results obtained from Monte Carlo Simulations (MCS). Using alternative methods, reliability predictions of laminated composite plates with random system parameters subjected to transverse loads have also been made [16]. Singh et al. [25] studied the effects of random material properties on the buckling of composite plates. Orifici and Bisagni [21] used a perturbation-based technique to investigate the impacts of imperfections on the buckling of composite cylindrical shells. Chen and Guedes Soares [3] conducted a reliability analysis of post-buckling performance. In addition to mechanical load induced buckling, other actions, e.g. temperature-induced buckling has also been reported. Lal et al. [13] investigated the effects of random system properties on the thermal buckling of composites. Lal et al. [12] further conducted a stochastic post-buckling analysis of laminated composites subjected to hygro-thermal–mechanical loading. The effect of random system properties, plate geometry, stacking sequences, supporting conditions, and fibre volume fractions on hygro-thermal–mechanical buckling load of the laminated shells and panels were investigated using a first order perturbation-based stochastic finite element method (PSFE). Most recently, Li et al. [14] conducted a stochastic thermal buckling analysis using a perturbation technique to propagate uncertainties from the constituent material scale to the structural scale. It is noted that the perturbation-based finite element method is the most commonly adopted technique for probabilistic buckling analysis. However, all the aforementioned studies have only investigated conventional unidirectional fibre reinforced polymer composites. No equivalent studies appear to have been conducted for VAT composites.

In this study, the perturbation-based stochastic finite element method is adopted to develop an uncertainty quantification approach to investigate the buckling characteristics of VAT composite plates subject to mechanical loads e.g. uniform end shortening displacement. The first-order shear deformation theory, which enables to consider transverse shear strain that can provide sufficiently accurate prediction of the structural response for the medium thickness laminated plates, is used as the basis to develop the stochastic finite element method. As the primary objective of the present study is to understand the variations in buckling performance, relatively simple VAT composite plates with a linear variation to define fibre tow path (see Fig. 1b based on the formula proposed by Gürdal et al. [7] are considered to investigate the mechanical characteristics of such structures. However, the method described in this paper can be straightforwardly applied to VAT composites with more complicated fibre path functions, such as Lagrangian polynomials (see Fig. 1c) proposed by Wu et al. [28]. In the present study, the formulation for propagating uncertainties from material properties e.g. moduli and Poisson's ratios and fibre tow path e.g. rotation angle in the linear variation formula to buckling performance measures, i.e. eigenvalue and critical buckling coefficients, is derived