Composites: Part A 57 (2014) 67–75

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Review

Uncertainty in the manufacturing of fibrous thermosetting composites: A review

T.S. Mesogitis [a,*], A.A. Skordos [a], A.C. Long [b]

[a] School of Applied Sciences, Manufacturing and Materials Department, Composites Centre, Cranfield University, Bedford MK43 0AL, UK
[b] Division of Materials, Mechanics & Structures, University of Nottingham, University Park, Nottingham NG7 2RD, UK

ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form 4 October 2013
Accepted 2 November 2013
Available online 9 November 2013

Keywords:
A. Thermosetting resin
C. Statistical properties/methods
Probabilistic methods

ABSTRACT

Composites manufacturing involves many sources of uncertainty associated with material properties variation and boundary conditions variability. In this study, experimental and numerical results concerning the statistical characterisation and the influence of inputs variability on the main steps of composites manufacturing including process-induced defects are presented and analysed. Each of the steps of composite manufacturing introduces variability to the subsequent processes, creating strong interdependencies between the process parameters and properties of the final part. The development and implementation of stochastic simulation tools is imperative to quantify process output variabilities and develop optimal process designs in composites manufacturing.

Contents

1. Introduction

The manufacturing process of composite materials involves many uncertainties which can result in a considerable amount of scrap associated with significant cost and environmental implications. Furthermore, the existence of defects generated due to variability can compromise the performance of composite components, leading to the use of more conservative designs that do not fully exploit the performance and environmental opportunities offered by composites. These uncertainties can be summarised as follows [1,2]:

(i) Fibre architecture variations which are usually generated during production, handling or storage of pre-pregs, dry textiles and performs.

* Corresponding author. Tel.: +44 (0) 1234 752 797; fax: +44 (0) 1234 750 875.
E-mail address: t.mesogitis@cranfield.ac.uk (T.S. Mesogitis).

1359-835X/$ - see front matter
http://dx.doi.org/10.1016/j.compositesa.2013.11.004

(ii) Matrix material uncertainties caused by variations in storage conditions or uncertainties in resin composition and formulation.
(iii) Variations in environmental parameters and process conditions.

Fibre heterogeneity can significantly affect the forming/draping step [3], as well as introduce permeability and thermal property uncertainty affecting the filling and curing steps of processing. Furthermore, fibre architecture governs the structural performance of components with local variability playing a critical role in non-linear phenomena such as failure and damage. Matrix material uncertainties influence the filling and curing stages which in turn influence the quality of the final product. Variations in process parameters may affect all manufacturing steps and consequently the quality of the component. A design approach that would take these effects into account explicitly would need to be based on stochastic simulations of composites manufacturing which would allow quantification of process outcome variability as a function of material selection and process parameter definition decisions made at an early stage.

Stochastic simulation involves four main steps; (a) quantification of the input variable uncertainties (uncertainty quantification), (b) development of a stochastic model representing the variability of uncertain parameters and their cross correlation (stochastic model), (c) implementation of a model that propagates uncertainty through a deterministic process model (propagator), and (d) quantification of the output parameters uncertainty [4,5]. The input variables are considered to be either time independent random parameters which can be described by multivariate probability distributions or random fields, or time dependent stochastic processes described by stochastic differential equations. The random fields or stochastic processes are uncovered by carrying out relevant experiments.

The aim of the present paper is to summarise the state of the art on experimental and stochastic simulation methodologies and results focusing on statistical characterisation and the influence of inputs variability on the main steps of composites manufacturing including process-induced defects as well as to highlight the interdependencies between the process parameters. Uncertainty introduced by experimental methods and modelling practices is also included.

2. Stochastic simulation methods

Stochastic simulation methods can be divided into two categories; intrusive and non-intrusive. Intrusive techniques involve reformulation of the main model equations while non-intrusive techniques treat the main model as an independent model. The most common non-intrusive method is the Monte Carlo scheme, which is a sampling technique used to generate random samples of input variables values from their respective statistical distributions [4]. Since random sampling is used, a quite large number of the deterministic main model runs is usually required to ensure convergence and accuracy, leading to high computational cost, especially in the case of complex and multi-dimensional stochastic problems [6]. The Spectral Stochastic Finite Element (SSFEM) method is the most common intrusive technique [7]. It uses the Karhunen–Loève (K–L) expansion to discretise the input random field and the polynomial chaos expansion to represent the output variables using a set of orthogonal functions [7]. The coefficients of the polynomial chaos expansion are calculated using the probabilistic Galerkin approach. The domain of the solution incorporates the probability space resulting in a system of equations significantly larger than that of the deterministic problem, with the associated increase in computational costs [6]. The Probabilistic Collocation method offers an intermediate solution between Monte Carlo and stochastic finite elements. This method is similar to the SSFEM using both the K–L expansion and the polynomial chaos expansion to represent the input and output random fields, respectively. However, the unknown polynomial chaos coefficients are calculated by the probabilistic collocation approach, which is also a weighted technique for minimising residuals. The collocation points are the roots of the next higher order orthogonal polynomial for each stochastic parameter and are chosen so that the residuals between the polynomial chaos expansions and model outputs approach zero, implying that the collocation points are selected from regions of higher probability. Consequently, a system of linear equations is obtained for every output parameter. Using this sampling method, no reformulation of the deterministic model is required, which is solved several times for each collocation point. This of course has significant benefits in terms of computational efficiency when the number of stochastic components is relatively low [6].

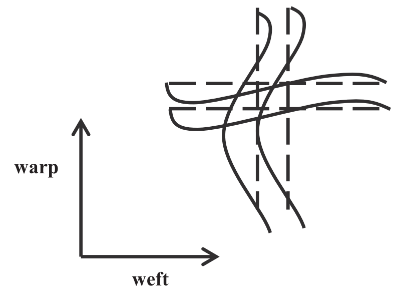

Fig. 1. Tow waviness.

The capabilities of the collocation method have been demonstrated in the context of composite manufacturing in the case of simulation of RTM filling. The results indicated the capability of the technique and its significant benefits compared to Monte Carlo [8]. More details concerning the SSFEM and the probabilistic collocation method can be found in [6,7].

3. Variability of dry textiles and pre-pregs

Variability is present in all forms of textile reinforcements including pre-pregs and dry textiles [9]. Variability in as supplied-dry reinforcements and pre-pregs is associated with tow waviness (Fig. 1), tow size and shape variations, distribution of fibres inside the tows, resin content variations and is generated during production, handling or storage [9–12]. For instance, the alignment and stiffness characteristics of the rollers used during the production of pre-pregs, can sometimes cause resin content variations, or the way pre-pregs are wrapped onto a drum for storage can cause wrinkles which in turn may result in considerable tow misalignment [9,12]. Geometrical variability of tows spreads to adjacent locations due to friction forces at tow crossovers (woven textiles) and fibre continuity [10] resulting in spatially correlated random fields of the uncertain variables. Fibre orientation variability can be described by a normal distribution [10,13–16] combined with strong spatial autocorrelation spread over several unit cells of the textile [10]. An experimental investigation of the internal geometry of 3D woven textiles using micro-computed tomography underlined the importance of variability in dry reinforcements [17]. The coefficient of variation of the dimensions of the tows and the inter-tow spacing reaches values of 16% and 6%, respectively. Experimental results on the internal geometry of a non-crimp woven fabrics show variability in the range of 4–8% for the tows dimensions, of 3–4% for tow spacing [18]. These