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A stochastic approach to model material variation determining tow impregnation in out-of-autoclave prepreg consolidation

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ABSTRACT

Material variations are always present even though out-of-autoclave prepregs are machine-made. They strongly determine the consolidation and may eventually lead to voids within the final part, depending on applied process conditions. To capture any contingencies, stochastic differential equations are derived to describe various interacting phenomena in OoA consolidation. In a second step the probabilistic space is discretized using the Karhunen–Loève truncation and the Probabilistic Collocation method is applied in order to use deterministic solvers for flow and compaction problems. The initial degree of impregnation is represented by an Ornstein–Uhlenbeck process and calibrated with CT-images.

1. Introduction

The increasing demand for composite materials as well as the request for sustainability promoted the replacement of pressurized autoclaves by conventional ovens for the consolidation of prepreg material. The lack of pressure makes part fabrication vulnerable to voids. Gas cannot be dissolved in the resin, as performed during autoclave processing where the external pressure can reach up to 8 bar. To counteract a quality degradation when parts are consolidated in a vacuum bag-only, thermoset out-of-autoclave (OoA) prepregs have a special purpose design. Prepreg materials are initially only partly impregnated, consisting of dry and resin rich areas. Dry areas are permeable, establish channels and allow gas to be evacuated. After an initial vacuum hold time, heat is applied and resin supplied by resin rich areas infiltrates the dry microstructure. Full prepreg impregnation is desired before gelation, but concurrently evacuation channels have to stay permeable sufficiently long to ensure that no gas remains in the laminate. In unidirectional (UD) prepregs, unimpregnated areas are considered to form a permeable layer in between layers of resin rich areas. The initial degree of impregnation (IDOI) indicates the percentage of wet fibres across the thickness. Fig. 1 shows that the boundary between wet and dry areas, i.e. the flow front, is irregularly distributed and accordingly the IDOI. A higher local IDOI implies a smaller distance for the resin to flow, which might close evacuation channels at an early stage. Therefore, it is not acceptable with OoA processing to neglect the material's inherent spatial impregnation variation in simulations.

1.1. Background

Various flow and compaction models are available in the literature, a significant amount for conventional prepreg consolidation. Most thermoset composite flow/compaction models assume a fully saturated fibre bed and simulate resin flow through a porous medium (fibre bed) using Darcy's law [1–3]. Though based on the same phenomena, available models cannot be transferred directly to OoA prepregs. The partly impregnated microstructure of the uncured OoA prepreg introduces a new aspect to the consolidation process: air evacuation through the dry fibre network. This determines the progression of the consolidation process. Pressure conditions within the dry areas determine the pressure gradient at the resin flow front and accordingly the impregnation velocity. Therefore, the interaction of air evacuation, time and temperature dependent resin viscosity, and fibre bed compaction affect the resin pressure and the permeability of the porous structure.

The effect of material and process parameters on final part quality was researched experimentally. Not only cure cycle ramp rate, dwell temperature, and out-time affecting the resin viscosity evolution determine the consolidation process [4,5]. Also fibre bed architecture, degree of air evacuation, consolidation pressure differential [6] and moisture content [7] were proven to be relevant for the final part quality, as summarized in [8]. This reveals the importance of capturing all the phenomena and interactions in an OoA process model. Several flow models were developed for

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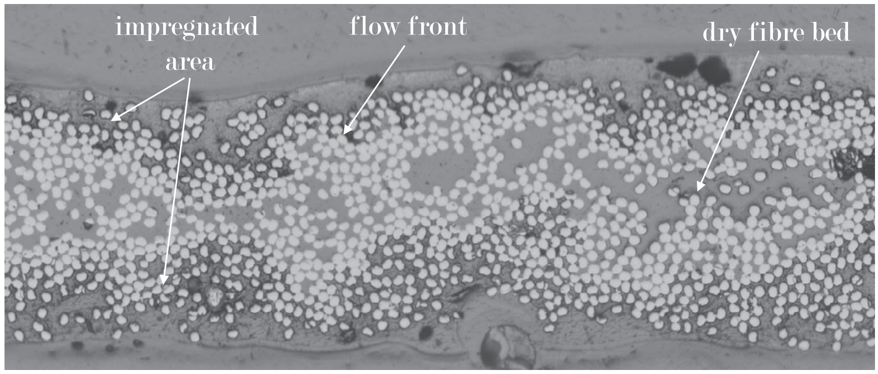

Fig. 1. Microscopy picture of an uncured UD prepreg.

partly impregnated prepregs. Most simulate the resin flow through fibre tows using Darcy's law. However, gas evacuation through dry tows was not incorporated [9,10]. Similarly, a model for gas evacuation from prepregs was developed using Darcy's law, but was not combined with a resin flow and fibre bed compaction model [11]. Material and process variability issues were not studied in models developed for OoA prepregs. The consideration of uncertainties in composite material parameters was solely found in models for RTM processes [12] and concentrated on variations in fibre volume fraction. The mathematical realisation used in [12], applying the Karhunen–Loève (KL) representation and Probabilistic Collocation method (PCM) to solve stochastic differential equations, was pioneered by Ghanem and Spanos [13] and then applied to a wide range of problems involving input uncertainties. The IDOI characterizes the initial constitution of an OoA prepreg. Even though this parameter has to be determined in a model for OoA prepregs when considering dry areas, in literature it was assumed to be spatially constant throughout the material [14]. This does not reflect the OoA prepreg materials, and cannot capture the spatially diverse impregnation process of the composite. Overall, there is a need for an integrated process model for OoA prepreg material that combines the key phenomena during consolidation and accounts for material variability.

In a previous study [15], we developed a 1D model specifically for partly saturated UD prepregs that considers the interaction between air evacuation, fibre bed compaction and resin infiltration. Capturing material variations requires at least a 2D representation of the initial material constitution and the subsequent consolidation process. To overcome the limitations of the previous models, a 2D model is introduced within this study, considering the spatially unsteady IDOI of the uncured prepreg.

1.2. Objectives and structure

The objective of this work is to develop a comprehensive 2D consolidation model that integrates air evacuation through dry fibres of a partially saturated microstructure, fibre bed compaction and resin flow under non-isothermal conditions. Most notably material variability within prepregs and its effect on void formation is captured. The study is organized in four parts. First, a deterministic 2D consolidation model was developed for a 2D representative volume element (RVE) of the prepreg structure. It accounts for the interaction of the key phenomena in OoA consolidation. Second, the initially partly impregnated microstructure was represented by a random field using the Ornstein–Uhlenbeck process. Third, the embedment of the deterministic model in a stochastic environment was conducted. Overall the model aimed to predict the average void content of an OoA prepreg material associated with the applied process parameters. Finally, a parametric study was conducted to investigate the sensitivity to ambient pressure conditions and the convergence of the model.

2. Methods

2.1. Deterministic 2D consolidation model

Various interacting phenomena are captured in the model to represent the consolidation of OoA prepregs. Driving forces of the process phenomena are temperature changes according to the applied cure cycle and the application of vacuum while the ambient pressure P_{atm} remains constant. The initial UD prepreg consists of fibre bundles that are assumed to merge into a planar, permeable fibre bed layer which is partially infiltrated with resin. The flow front is considered to be irregularly distributed. During the early stage of processing, only vacuum is applied and air is evacuated from dry areas while high resin viscosity is assumed to prevent resin flow and inhibits fibre bed movement in infiltrated regions. As soon as heat is applied resin viscosity changes and the cure process is initiated. For simplicity, the resin's behaviour is considered to be Newtonian. Flow rates can be calculated by 2D Darcy's law and depend on the resin viscosity, fibre bed permeabilities and the pressure gradient within the resin. The fibre bed is non-rigid. Fibre volume fraction and resin pressure are a function of time and position. They determine in-plane and through-thickness resin flow which is assumed to be saturated. For simplification the marginal resin outflow in OoA prepregs is neglected within the model. All body forces, inertial forces and capillary forces are neglected so that the pressure at the resin flow front is solely determined by the gas pressure P_{gas}. Modelling a two-dimensional (x, z)-flow field using only the upper half of the prepreg is sufficient when assuming the prepreg material to have a symmetry at the ply mid-plane. In-plane air evacuation at room temperature was described using a 1D model based on Darcy's law and the ideal gas law. A closed-form solution was developed by [11], describing the mass fraction of air remaining in the laminate Δ_M as a function of time t, initial pressure P_0, air viscosity μ_{air}, permeability K, and the distance of the described location to the closest vacuum vent L:

$$\Delta_M = \exp^{-0.9\left(\frac{t \cdot P_0 \cdot K}{\mu_{air} \cdot L^2}\right)}. \tag{1}$$

This leads to a reduction in tow pressure P_{gas}. Accordingly, the effective stress in the fibre bed increases which involves a compression and results in an increasing fibre volume fraction within the tow.

As depicted in Fig. 2, the RVE consists of three regions: the dry fibre bed, the impregnated fibres and resin rich areas. Two functions border those regions, the flow front $x_f(x, t)$ and the fibre bed edge $x_e(x, t)$. They change during the consolidation once heat

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