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A three-phase integrated flow-stress model for processing of composites

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ABSTRACT

An extension of the previously developed two-phase integrated flow-stress process model for composites is presented here to account for the presence of the gas phase. The extended model incorporates the multi-physics phenomena involving flow of both the resin and gas phases through the fibre-bed as well as the previously considered thermochemical transformations during resin cure. The model is implemented in a 2D plane strain *u-v-P* finite element code developed in MATLAB. Numerical examples with varying initial contents of gas and resin are presented to demonstrate the capability of the three-phase integrated flow-stress model to predict the flow-compaction and stress development during the curing process of thermoset composite materials. The interactive effects of resin flow, gas flow and stress development are investigated in order to shed light on the efficacy of the model in capturing the overall response of the composite material during processing.

1. Introduction

Manufacturing of composite structures enables production of complex-shaped and large-scale structures from the raw materials in one step. In order to predict the outcome of the produced part including any process-induced defects (e.g. residual stresses, shape distortions, voids etc.) and the resulting variations in material properties, it is important to have predictive models that can capture the behaviour of the composite structure as it undergoes the complete sequence of events during manufacturing. An accurate process simulation tool, that incorporates the interactive multi-physics phenomena involved during processing, can help mitigate the manufacturing risks and associated costs. The complex behaviour of composite materials as a result of the evolving properties of their various constituents poses challenges to their predictive modelling during processing.

Processing of composite materials involves various phenomena such as flow of resin and gas through the fibre-bed, thermochemical changes and phase transformations during resin cure, and the resulting build-up of residual stress and dimensional variations in the final part. These phenomena are usually simulated through the application of independent sub-models, such as resin flow (Hubert et al., 1999; Celle et al., 2008a,b) or stress (Johnston et al., 1996, 2001; Zobeiry et al., 2005; Gigliotti et al., 2007; Zobeiry et al., 2010; Lacoste et al., 2010, 2013; Bogetti and Gillespie, 1991, 1992). In the sequential approach, first applied to composite processing by Loos and Springer (1983) and later by Bogetti and Gillespie (1991, 1992), resin flow is first modelled during the early stages of the process when the composite material undergoes compaction due to the application of pressure and temperature. The deformed geometry and volume fraction of the constituents as the outcome of the flow model are then used as input (or initial conditions) for the subsequent stress analysis of the curing solid composite. The independent modelling of the resin flow and mapping the results onto the subsequent steps makes the simulations very inefficient and tedious for users. Furthermore, in the sequential approach, the interaction and overlap between resin flow and cure-induced residual stress development is not captured even though these occur concurrently in processing of composite materials.

By combining the governing equations for flow of resin with the previously formulated pseudo-viscoelastic constitutive models for the solid, Haghshenas et al. (2017a, b) successfully bridged the two regimes of polymer resin behaviour as it transforms from a viscous fluid to a viscoelastic/elastic solid during the cure cycle. Niaki et al. (2016, 2017) built on the work by Haghshenas to integrate flow of resin and stress development in composite materials within a new formulation (with no restrictions imposed on the compressibility of the constituents) into a unified two-phase (fibre and resin) model that captures both phenomena in a continuous manner. They verified the accuracy of the model at both extremes of the process cycle when the resin behaves as a liquid as well as its fully solidified state when it forms into a homogenized solid composite material. Also, the significance of using the integrated approach to obtain accurate prediction of residual stresses for a curing composite material was demonstrated through comparison with results obtained using the stress module alone.

In composite materials, presence of voids and spaces that are filled

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with gas, represent an important manufacturing quality issue. Porosity, defined as volume fraction of voids, is considered to be a process-induced defect that can potentially lead to deterioration of the structural performance of the final part. Availability of modeling tools that can quantify the total amount and spatial distribution of porosity trapped in composite structures after they undergo processing is highly desirable in order to take required precautions to minimize it or limit its occurrence to locations that are far removed from critical regions of the structure. This requires a detailed understanding of composite materials and their constituents' behaviour during such processes.

The work by Kardos et al. (1986) can be considered as one of the pioneering work on porosity in prepreg composites. Bubble growth as a result of moisture dissolution was studied and the effect of temperature and pressure was investigated to propose a pressure-temperature-humidity stability map to identify the condition for porosity formation during the cure cycle. Boey and Lye (1990, 1992) studied the effect of high pressure in an autoclave as well as vacuum bagging in order to reduce the void content in thermoset composites. The bending strength and modulus of composite parts manufactured under different process conditions were also analyzed where an increase in the strength was reported as a result of post-curing. Thorfinnson and Biermann (1986, 1987) investigated processing parameters that affect the laminate void content and found that controlling the degree of resin impregnation was important as partial resin impregnation of the prepreg creates gas transport pathways within the laid-up laminates. Lundström and Gebart (1994) and Lundstrom et al. (1993) experimentally investigated the influence of different process variables on the void content in resin transfer molding and showed the significance of the vacuum assistance during mould filling in reducing the void content in the composite material. This behaviour was explained with a simple theory based on the ideal gas law. Ruiz et al. (2006) and LeBel et al. (2014) investigated the effect of injection flow rate to minimize the void formation in resin transfer moulding processes. Based on a double scale flow model and the capillary number, an optimization algorithm was proposed that can be used to maximize the performance of injection tools in composite processing. Farhang and Fernlund (2015) performed a characterization study of void and porosity in prepregs undergoing Out-of-Autoclave (OOA) processing. Multiple sources of porosity formation in composite materials as well as several alternatives to bring it under an accepted level have been discussed in the literature. Despite extended experimental investigations into porosity and gas transport phenomena, a multiphase modelling approach that explicitly considers the gas phase in composites processing is still unavailable. Numerical modelling of voids formation in composites process modeling is limited to Liquid Composite Molding (LCM) processes. Wang et al. (1986), Fracchia et al. (1989) and Bruschke and Advani (1990) developed a Control Volume-Finite Element Method (CV/FEM) method for Resin Transfer Molding (RTM) process. Later, Bruschke and Advani (1990) and Kuentzer et al. (2007) extended their model to be used for a dual-scale porous media. Darcy's law was assumed for flow of resin through pores between the tows and a separate one-directional linear flow was considered for flow through the pores inside the tows. Using this method, they were able to consider the partially saturated region between the macroscopic flow front and the fully saturated region in RTM (Simacek and Advani, 2003) and Vacuum Assisted RTM (VARTM) (Kuentzer et al., 2007). This method was implemented as Liquid Injection Molding Simulation (LIMS) program and used successfully for industrial LCM applications. A more complex version of this approach was developed by Tan and Pillai (2012a, b, c) where a two-dimensional flow was assumed for micro-scale flow inside the tows. Trochu et al. (1992, 1993) used a non-conforming element that serves as the CV as well in order to overcome the need for separate CV in the resin transfer model.

In none of the above mentioned studies, is the transport of the gas phase during composites processing considered. Composite materials usually undergo a debulking process at room temperature that involves flow and removal of entrapped air and other gaseous volatiles. Furthermore, compaction of composite materials during the curing process requires consideration of the presence and flow of residual gas from previous steps as well as gases produced during the in- or out of-autoclave processing. For simulation of such processes it is essential to account for the gas phase and its flow in the formulation of the governing equations. The evolution of porosity during the curing cycle as influenced by gas flow, thermal effects, and resin hardening, necessitates consideration of a three-phase integrated flow/stress model. For gas transport simulation in composite materials, the same principles of multiphase fluid flow previously utilized in modelling partially saturated soils (Lewis and Schrefler, 1998; Bear and Cheng, 2010) can be adopted for simulating uncured composite materials undergoing manufacturing process.

Khoei and Mohammadnejad (2011) presented a three-phase, liquid-gas-solid, finite element model for seismic analysis of earth and rockfill dams using the Biot's effective stress model (Biot, 1941; Biot and Willis, 1957; Zienkiewicz and Shiomi, 1984). Oettl et al. (2004) used a three-phase deformable finite element model for dewatering simulation of fully or partially saturated soils using compressed air. In their work, equilibrium of the multiphase system and mass balance for each fluid phase, combined with momentum balance equations, are taken as governing equations of the model. Nagel and Meschke (2010) presented a finite element formulation for partially saturated deformable soils as a three-phase model where the liquid phase was assumed to be incompressible. The governing equations of the model were based on the mass conservation of fluids combined with equilibrium of the three-phase system along with the relationship between the capillary pressure and the degree of saturation, Darcy's law for two-phase flow, and the effective stress formulation. Schümann (2010) also showed that the built-in module for two or three-phase models in the commercial finite element code, Abaqus, can be extended through implementing a user-defined element (UEL) subroutine for unsaturated soils based upon the three-phase model developed by Holler and Meskouris (2006).

In this article, the two-phase integrated flow-stress model (2IFS) previously developed by the authors (Niaki et al., 2016; Niaki, 2017) for saturated flow, is extended to a three-phase model (3IFS). The three-phase system initially consists of a liquid phase (e.g. resin), a gas phase (e.g. air or water vapor), and a solid phase (e.g. fibre/fibre-bed), where the liquid resin phase undergoes solidification during curing thus transforming from a liquid to a cured, fully solid resin. In this article, the conservation equations governing the response of the three-phase system are first presented. Subsequently, constitutive equations are developed in such a way that accounts for hardening of one of the fluid phases as the composite material undergoes curing. A summary of governing differential equations is presented followed by their weak form used as the basis for finite element implementation. To assess the performance of the 3IFS model some numerical examples are presented that discriminate the effect of the presence of the third phase; namely gas, on the response of a composite material during processing.

2. Conservation equations

The three-phase composite system considers two compressible fluid phases (one of which can solidify during the process) flowing through a porous compressible medium (fibre-bed) referred to as solid-skeleton. Conservation equations governing the response of the poroelastic, three-phase system presented in this section must hold at all stages of the process whether the solidifying fluid phase behaves as an unsolidified fluid (liquid-like behaviour) or when it solidifies to form a three-phase homogenized solid composite material.

2.1. Mass conservation

Assuming small strains and ignoring spatial variation of densities and phase volume fractions, the mass conservation equations for a system that entails a compressible solid phase, S, and two compressible