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A two-phase integrated flow-stress process model for composites with application to highly compressible phases

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ABSTRACT

A new methodology is presented to integrate the simulation of flow and stress development into a unified computational modelling framework for processing of two-phase composite materials. The governing equations are developed for the general case of a composite material system that, as a consequence of curing, undergoes a transition from a fluid-like state into an elastic solid. The constitutive equations employed are such that they provide a continuous representation of the evolving material behaviour while maintaining consistency with the formulations that are typically used to represent the material at each of the two extremes. The formulation is capable of handling highly compressible phases, which is an important consideration when extending the model to a three-phase model that includes gas as a distinct phase. The model is implemented in a 2D plane strain *u-v-P* finite element code developed in MATLAB. Numerical examples are presented to demonstrate the capability of the integrated flow-stress model to predict the flow-compaction and stress development throughout the curing process of thermoset composite materials. The interactive effects of resin flow and stress development under various representative boundary conditions are investigated and comparisons are made with the predicted results obtained from the application of the stress model alone.

1. Introduction

Processing of fibre-reinforced polymeric composite materials is complex due to multitude of physical and chemical processes that occur at multiple scales during the manufacturing event. As the resin cures, it undergoes very diverse behavioural regimes such as viscous, rubber-like, and glassy behaviour at different stages of processing (Johnston et al., 1996; Hubert et al., 1999). This complex process involves various aspects such as flow of resin through the fibre-bed, thermochemical changes, heat transfer, and stress development. These phenomena are usually simulated by researchers and engineers in a so-called "integrated sub-model" based framework first applied to composite processing by Loos and Springer (Loos and Springer, 1983) and later by Bogetti and Gillespie (1991, 1992), White and Hahn (1992), and other more recent work (Johnston et al., 1996; Hubert et al., 1999; Johnston et al., 2001; Arafath, 2007). In this approach, process modelling is carried out in several independent sub-models implemented in different software modules.

Hubert et al. (1999) focused on the flow module for processing of composite materials with constituents that were assumed to be incompressible. They used Darcy's equation for flow of resin along with Terzaghi's effective stress theory (Terzaghi, 1943) for load sharing between the resin and the fibre-bed, which does not account for the deformability of the solid grains within the porous medium. In order to take into account the compressibility of the phases, the flow model developed by Biot et al. (Biot, 1941; Biot and Willis, 1957) and its extension by Zienkiewicz and Shiomi (1984) can be considered. Biot et al. (Biot, 1941; Biot and Willis, 1957) developed equations to model consolidation of the porous media taking into account the compressibility of the phases through the introduction of some physical constants for the porous media. Zienkiewicz and Shiomi (1984) presented an alternative form of Biot's model to be extended for dynamic behaviour of saturated porous media. They demonstrated the effectiveness of the model for slow compaction as well as shock excitation scenarios. The work by Gutowski et al. (1987) can be considered as one of the pioneering studies that applied such theories to consolidation of composite materials during curing. Celle et al. (2008 a, b) proposed a model for non-isothermal flow of fluid through porous media for resin infusion processes. Their model took into account deformation of the porous media as a result of applied pressure and temperature. Gigliotti (Gigliotti et al., 2007) used a thermo-chemically-elastic model in a finite element framework to predict residual stresses developed after the gel point during processing

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of composite materials. Also, Lacoste et al. (2010, 2013) incorporated a multi-scale approach for in-plane stress prediction as a result of thermal and cure shrinkage during processing of isotropic composite materials. Incorporating a two-step self-consistent scale transition for homogenization of composite materials, the stress at the microscopic level due to mismatch of properties between the fibres and matrix was also computed for a simplified cure process. Recently, Belnoue et al. (2016) proposed a framework for both squeezing and bleeding flow in uncured prepregs. Considering a micro-mechanical behavior of fibres for each flow regime, a smooth transition between squeezing (percolation) and bleeding (shear) flow was made through incorporating a multiplicative decomposition of the apparent ply viscosity. This model, which used a hyper-viscoelastic constitutive formulation, was implemented in the commercial finite element software, Abaqus/Standard.

Johnston et al. (1996, 2001) developed the stress development module within a multi-physics, 2D plane strain finite element code, called COMPRO, for polymeric composites incorporating a “cure-hardening/instantaneously linear elastic” (CHILE) material model which was later extended to fully viscoelastic behaviour of composite materials by Zobeiry et al. (Zobeiry et al., 2005; Zobeiry, 2006; Zobeiry et al., 2010; Zobeiry et al., 2016). Arafath (2007) introduced the COMPRO Component Architecture (CCA) into the commercial finite element software, Abaqus. In this modular approach, the resin flow is initially modelled for composite materials undergoing compaction (Hubert et al., 1999; Hubert, 1996) and then the resulting geometry and volume fraction of constituents are used as inputs for the subsequent stress modelling which is performed during the whole process cycle (Johnston et al., 1996; Zobeiry et al., 2005; Zobeiry et al., 2010).

In the sequential method, the interaction between the resin flow and stress development is not captured despite the fact that these phenomena occur concurrently in processing of composite materials. Furthermore, in the sequential approach, the history of pressure during the flow regime of processing is ignored at the start of the stress development module which potentially results in inaccurate prediction of the final process-induced stresses in the composite material. In this methodology, only the geometry and volume fractions at the conclusion of the flow simulation are typically considered as initial conditions for the stress development module. Mapping of the results from one state to another in this manner is a tedious and inefficient process from a computational standpoint. Moreover, not all regions of a large and complex composite part undergo the same curing process and, consequently, resin gelation does not occur uniformly over the whole spatial domain of the structure. In a non-interactive sub-model approach, however, resin gelation can only be considered to occur simultaneously for the whole composite structure at the start of the stress module and therefore local spatial and temporal variations in gelation cannot be accommodated. By contrast, when combined with a heat-transfer analysis, a non-uniform gelation (curing) of the resin can easily be accounted for in an integrated approach.

Incorporating the above mentioned main steps into a unified module that captures the various phenomena in an integrated and continuous process would help overcome the foregoing drawbacks of the sequential approach. Integrating flow and stress development in a single formulation that captures the behaviour of the material at both extremes of the fluid and solid regimes and accounts for the interplay between them enhances the efficiency and accuracy of the predicted results.

Haghshenas et al. (2017a, b) developed a framework that integrates both resin and stress development into a unified process model for composite materials. In his IFS model, modifications were made to the classical flow through porous media models (Biot, 1941; Biot and Willis, 1957; Lewis and Schrefler, 1998) to enable a seamless connection to the regime of the process simulation when the composite material is in its fully cured (solid) state. Although the above two-phase IFS model considers compressibility of its constituents, the accuracy of the model during the flow regime, especially for drained (permeable) condition, is sacrificed due to using micromechanics formulations for composite materials which inherently assume that the constituents cannot leave the system due to flow. For this reason, the model breaks down when it is applied to a composite system with constituents that have extreme bulk properties (e.g. very low bulk moduli or very high coefficients of thermal expansion).

The capability of including highly compressible materials is imperative for extension of the process model to three-phase IFS, involving gas, liquid, and solid, where the very high compressibility of the gas phase plays a significant role in the system response. Motivated by the goal of extending the current two-phase IFS model to a more general three-phase IFS model, in the current study, a novel formulation is developed for integrating the flow and stress analysis modules into a unified model for processing of composite materials with no restrictions imposed on the compressibility of its constituent phases. In this approach, the classical model for flow through porous media, which considers the compressibility of its constituents, is used in the early stages of the process when the resin is in its fluid state. However, the resin properties evolve during the curing process as it transforms from a viscous fluid into a solid. In the present formulation, the evolution of material properties and the state variables that keep track of the solidification (chemical hardening) of the resin is carried out in a continuous fashion such that at the termination of the process cycle the formulation transitions smoothly into the theoretical framework for cured composite materials that are commonly grounded on solid micromechanics models.

The conservation equations consisting of mass and momentum conservation equations are first presented. These are then followed by development of constitutive equations for a composite system containing a fully liquid (unsolidified) matrix phase that undergoes solidification during curing. Evolution of some of the mechanical properties required to represent the effect of phase transformation from liquid to solid is taken into account. Numerical examples are presented to show the effectiveness of the model in handling a wide range of matrix phase properties that exercise the robustness of the new IFS model under extreme conditions arising from compressibility of the matrix material. Specific results are generated for the case of a composite system with a matrix material that has a very low bulk modulus (highly compressible) which undergoes consolidation and a transition from an initial liquid-like state into an isotropic elastic solid. It is demonstrated that the model can cope just as easily with the early stages of the process (e.g. the compaction and debulking regime) as it does with the final stages when the composite system behaves as a solid.

2. Conservation equations

This section presents the conservation equations (balance laws) for the poroelastic two-phase system. The two-phase system considers a compressible fluid phase (which can solidify during the process) flowing through a porous medium (fibre-bed) referred to as the solid skeleton. The conservation equations include the mass and momentum conservation of the matrix phase, as well as the momentum conservation (equilibrium) of the system. These balance laws must hold at all stages of the process whether the matrix material behaves as an unsolidified fluid or when it solidifies to form a solid composite material.

2.1. Mass conservation

Assuming small strains and ignoring spatial variation of densities and phase volume fractions, the mass conservation equations