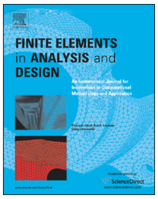
Finite Elements in Analysis and Design 78 (2014) 8–15

Contents lists available at ScienceDirect

Finite Elements in Analysis and Design

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



Process modeling of cavity molded composite flex beams

V. Bheemreddy [a], Z. Huo [a], K. Chandrashekhara [a,*], R.A. Brack [b]

[a] *Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA*
[b] *Bell Helicopter Textron, Inc, Fort Worth, TX 76101, USA*

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form
4 September 2013
Accepted 12 September 2013
Available online 10 October 2013

Keywords:
Process modeling
Cavity molding
Composite flex beam
Cure kinetics
Flow modeling
Non-isothermal prepreg-press
Level-set method

ABSTRACT

Continuous fiber reinforced composite materials are extensively being used in helicopter dynamic structures. Preimpregnated fibers or prepregs are used to produce high quality composite rotor yokes/flex beams. One process in particular known as cavity molding, is frequently used to process high quality thick composite details with exceptionally precise dimensions by using a platen press to apply heat and pressure to rigid tooling and thereby entice the prepreg within to cure into the shape of the confines of an internal cavity. The objective of the research described here is to develop a mathematical model for glass/epoxy prepreg which simulates the resin flow, heat transfer, consolidation and curing of cavity-molded flex beams which varies significantly with location. An enhanced understanding of the mechanisms involved will help significantly improve the cost-effectivity of molding process development. The current work is focused on process modeling of composite flex beams which are manufactured by cavity molding. The cure kinetics of such parts is particularly difficult to model because tool/part geometries are complex. The combined effects of heat transferred by the tool and heat spontaneously generated by the reacting thermoset during cure results in significant gradients of resin advancement throughout the part. The temperature spikes that result from internally-generated exothermic heat cannot be quickly dissipated because of the low thermal conductivity of composite. Various governing equations are presented here that describe the resin cure kinetics, thermal energy balance and flow during the process. A general-purpose, finite-element package with multiphysics capabilities is used for simulating the non-isothermal prepreg-press process, the degrees of cure and temperature field distribution at different cross-sections.

1. Introduction

Fiber reinforced polymer (FRP) composites are generally preferred over metals in high performance structural components because of: (1) superior fatigue performance, (2) high specific strengths and stiffnesses, (3) low weight, and (4) excellent resistance to corrosion. Prepregs avoid drawbacks from processes based on injection, by reducing risk of entrapment, optimal resultant fiber volume fractions, weight saving, improved fatigue performance, reduced manufacturing complexity and time. Because of these advantages, prepreg based FRP composites are widely used for the manufacture of lightweight aircraft and rotorcraft parts. However, usage of FRP composites in these applications is typically restricted to thin components and thick (>25 mm) composites are seldom made from these materials [1] because of the complexities associated with design and manufacturing. The curing of precatalyzed thermosetting resins is typically accompanied by exotherm and heat buildup during the exothermic reaction of thermoset resin based FRP composites can cause internal stresses to build-up and result in structural defects in thick composite structures. These issues are particularly significant to rotorcraft applications.

Various manufacturing techniques can be used to produce high quality finished products from prepregs. Cavity molding is one such process that can be used to facilitate the manufacture of thick composite parts. Cavity molding is very similar to prepreg compression molding process and can become particularly attractive to situations where conventional processes encounter difficulties associated with high resin viscosities. Large scale, intricate shape parts with widely varying cross-sections can be manufactured using the cavity molding process but numerous issues will be encountered when attempting to manufacture thick composites using this process. For instance, during the exotherm, a large amount of heat is generated at the center of the thick-walled thermosetting composite but because of the low thermal conductivity of the fiber and the resin and high mass to surface area ratios, this heat cannot be quickly dissipated from the center of thick composite part. Manufacture of composite parts with widely varying cross-sections typically poses numerous other difficulties that can result in premature curing, degradation in the thin cross-sections and incomplete curing in thick counter parts.

---

* Corresponding author. Tel.: +1 573 341 4587; fax: +1 573 341 6899.
E-mail address: chandra@mst.edu (K. Chandrashekhara).

0168-874X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.finel.2013.09.003

Investigation of the various phenomena occurring during composite curing gives a better understanding of these processes. Phenomena of particular importance include volumetric changes, microcracking, residual stresses and the effects of incomplete polymerization. Research in these areas can be very complex hence the current study has been limited to the investigation of the extent of cure and temperature distribution at various regions of the part during curing. Development of an adequate understanding of these phenomena requires a precise understanding of how the crosslinking of the thermosetting resin is affected by the processing conditions. Experimental investigations of the cure and rheology of the composites can be effective for understanding how a manufacturing process can result in highest quality components but this empirical approach can be very complex to set-up and time consuming to execute. Numerical modeling and simulations are much more cost effective alternatives to in-situ empirical trials for iteratively studying such processes. The current work involves numerical simulation of the cure and rheology of composites manufactured using cavity molding processes that can be particularly useful for the industrial manufacturer of thick composites.

Several researchers have worked on the modeling and simulation of composite curing process and rheology. Balvers et al. [1] set-up a generally applicable thermo-chemical model, determined cure dependent material properties of a thermoset resin and studied thermo-chemical behavior. Klunker et al. [2,3] developed and implemented a model to simulate flow in deformable porous media. Such models have also been applied to a non-isothermal prepreg-press process to predict the process behavior and thereby simplify the process design. The effect of varying specific heat capacity has also been investigated. Klunker et al. [4] worked on flow simulation of vacuum assisted resin infusion process that considered permeability to be an important parameter in the process and varying with the fiber volume content. A compaction model has been developed and implemented using the Arbitrary-Lagrangian–Eulerian-Method taking the distribution medium into consideration. Karkanas et al. [5] developed an analytical procedure for modeling the cure kinetics of a commercial epoxy resin for resin transfer molding application taking diffusion limitation effects into consideration. Sorrentino et al. [6,7] worked on modeling the cure kinetics of thick-walled composites with variable thicknesses. Ng et al. [8] measured the degree of cure, heat of reaction of viscosity of commercial resins and developed an analytical procedure to predict the kinetics of cure and rheology.

The compaction behavior of laminates was conventionally assumed to be resin dominant. However, with processes resulting in high fiber volume fractions in composite laminates, the elastic deformation behavior of preimpregnated fibers is significant in estimating accurate results. Gutowski et al. [9] were the first to consider this behavior in developing a comprehensive compaction model. Young [10] has studied the effects of compacting forces and cure cycles on the degree of consolidation. The author has developed a numerical model to simulate the consolidation and cure process of thick laminated composites. The compacting pressure was observed to be an important factor affecting the final degree of consolidation. Oh and Lee [11] have simulated temperature distribution, degree of cure, resin pressure, and time for full consolidation in thick glass/epoxy composites using three-dimensional finite element analysis. The authors have validated the developed numerical models with experimental results. Costa and Sousa [12] have developed a three-dimensional numerical model to simulate the resin flow, heat transfer, and consolidation dependent upon the compacting pressure in thick composite laminates during autoclave processing.

The focus of the present work is to develop two-dimensional cure and flow models for flex beam composite parts manufactured using the cavity molding process. Development of cure and flow models for industry specific flex beam composite parts is new and has not been investigated earlier. Cure kinetic model that is more applicable to epoxy resin used in this study, is suggested. Coupled finite element simulations are performed to predict resin flow and prepreg compaction as pressure is applied to the prepreg during cure and the resultant temperature distributions and degrees of cure at various cross-sections. In Section 2, theoretical background on the modeling of cure kinetics and rheology, and various governing equations are presented. The set-up of this numerical model is discussed in Section 3 and results are discussed in Section 4 followed by conclusions.

2. Cure kinetics and rheology

The objective of this research is to model and simulate two-dimensional cure and flow behavior during the manufacturing of composite flex beam parts. A thermo-chemical model will be constructed to simulate the cure behavior of flex beams. For modeling flow behavior, rheology models that are both temperature and time dependent will be used. The cure and flow processes occur simultaneously and so a coupled model that considers both effects will be developed and implemented. Fig. 1 shows a schematic of the methodology used in modeling the coupled cure and flow behaviors.

The inputs to the thermo-chemical model are the cure profile, temperature dependent specific heat capacity, thermal conductivity and density. The outputs from the thermo-chemical model are the temperature distribution and degree of cure of the flex beam part. The rheology model uses a temperature-dependent viscosity which calculates viscosity of the resin as a function of the temperature output from the thermo-chemical model. Overall, the coupled model calculates the cure consolidation and flow behavior of a composite flex beam. The sub-sections below detail the theoretical background of these cure and flow models.

2.1. Cure kinetics

This cure kinetics study of composite flex beams models the thermo-chemical behavior during the cure process which can be investigated experimentally or numerically. Several experimental techniques are available to investigate the extent of cure reaction and rate of reaction of the thermoset resins [1]. Differential Scanning Calorimetry and infrared spectroscopy are widely used to investigate the kinetics of cure. Numerical modeling of the cure

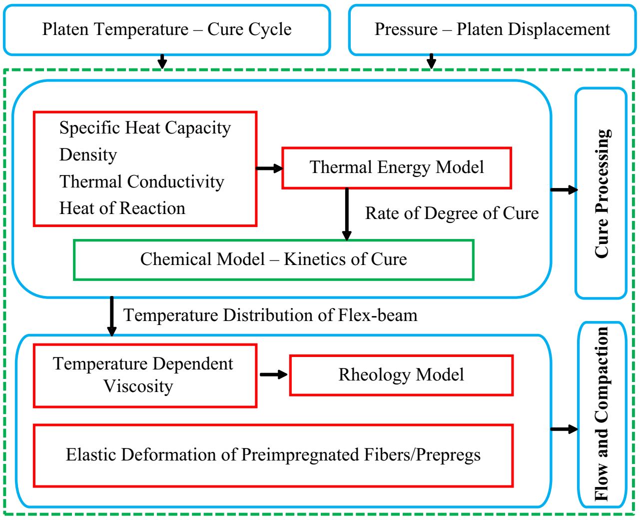


Fig. 1. Cure processing, compaction and rheology analysis methodology.