Composites: Part A 78 (2015) 102–112

Contents lists available at ScienceDirect

Composites: Part A

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

Predictive model for the detection of out-of-plane defects formed during textile-composite manufacture

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ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form 15 July 2015
Accepted 18 July 2015
Available online 7 August 2015

Keywords:
A. Fabrics/textiles
B. Buckling
B. Defects
C. Finite element analysis (FEA)

ABSTRACT

A hybrid finite element model using a discrete mesoscopic approach was previously developed and has since demonstrated its ability to capture the tensile and shear behaviors of textile reinforcements for composites. The aim of the present research is to implement flexural properties into a non-homogenous beam/shell model such that the formation and shape of out-of-plane defects can be well predicted. A method for linking the measurement of bending rigidity to the determination of a compressive modulus is presented and simulations are used to demonstrate the ability of the modeling approach to predict the amplitude and curvature of out-of-plane waves. A comparison of the simulation results to experimental data shows the finite element model accurately captures this out-of-plane phenomenon.

1. Introduction

Composite materials have many characteristics that make them an attractive option in a variety of industries including aerospace, automotive, construction, marine, and wind energy [1]. Lightweight parts and structures can be engineered from composites while maintaining high stiffness and strength; they can additionally be tailored to complex geometries and designed to have attractive performance characteristics, such as corrosion and fatigue resistance [2]. The main factor limiting their rapid growth is the high cost associated with composites [3]. However, recent advances in automation techniques facilitate high-volume production and, with the expansion of the composite market, prices of raw materials are decreasing. With such improvements driving down expenses, the penetration of composite materials in the marketplace has potential to grow significantly [4–9].

There are some challenges associated with textile composite production that are a nonissue for conventional materials. While there are several common manufacturing defects (Fig. 1), out-of-plane deformations (a.k.a., wrinkles, kinks, buckles, puckering, through-thickness misalignment), specifically, are recognized to significantly compromise the strength of the cured structural part in the local vicinity of the defect [10]. Adjustments in processing parameters or modifications to design specifications (e.g., tooling geometry and material selection) can prevent the onset of such through-thickness fiber misalignments.

Traditionally, experimental parametric studies are employed to isolate the effect of each processing parameter on wrinkle formation. With the sensitivity of each factor characterized and understood, a potentially appropriate combination of processing conditions can be identified and defect-free components can be fabricated [11]. However, these experimental procedures can be costly and time consuming. An alternate methodology is to use a virtual model to explore and assess the sensitivity of each parameter on part quality. Therefore, it is valuable to have a simulation tool that can consider the mechanical behavior of a fabric such that it can accurately represent the fabric bending properties and predict the locations where waves, wrinkles, or folds are likely to form. The simulation can then be used to explore how changes in the processing parameters can eliminate the formation of such defects while maintaining the overall structural intent of the part, thereby guiding the design of the manufacturing process.

The finite element method is very amenable to the development of such a simulation tool for fiber-reinforced composites because it can account for the mechanical behavior of the fabric and the complex boundary conditions experienced during manufacturing. A simulation tool that provides orientation information of fabric constituents throughout the manufacturing process can: (1) produce a full-field prediction of the fiber compressive forces, (2) identify localized buckling sites, and (3) track progression of out-of-plane defects. The model results can then be used to make modifications to the tooling and processing conditions to inhibit the onset of defects like those shown in Fig. 1. Ultimately, this simulation tool will result in improved structural integrity of the cured composite due to its ability to identify steps in the manufacturing process that

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http://dx.doi.org/10.1016/j.compositesa.2015.07.011
1359-835X/

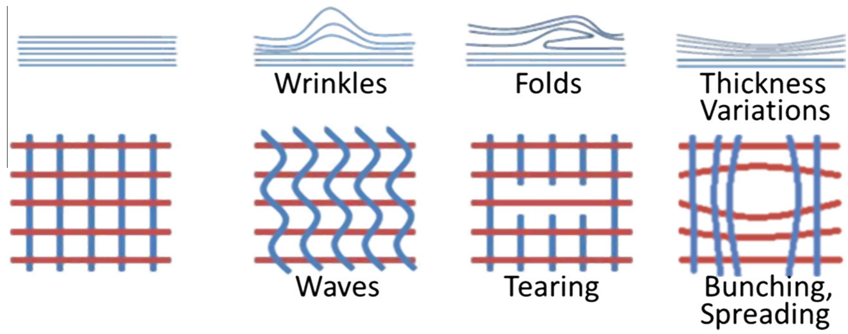

Fig. 1. Through-thickness and in-plane defects commonly found in textile composites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lead to defect formation. Furthermore, the model can be used for parametric studies that provide insight into the mitigation of such defect formation.

2. Background

2.1. Manufacturing out-of-plane defects

A composite defect can be any irregularity in structure or material causing a part to deviate from its intended design specifications. Such anomalies can be introduced into the composite as early as fabrication of its raw materials but, more commonly, they are a product of the manufacturing process or are a function of unreasonable design constraints [12]. Out-of-plane defects, specifically, are known to develop during part manufacture.

Potter et al. identified several causal effects that initiate fabric wrinkling in textile composites [12,13]. Commonly, geometric constraints initiate onset of out-of-plane defects [12]. For example, in molds with internal curvature (e.g., wind turbine blades) wrinkles and folds manifest in the part because oversized planar plies are forced to conform to curved three-dimensional geometry; to accommodate the excess material, fabric tows must displace out-of-plane. Even in the simplest of cases (e.g., L- or C-brackets), any radius is a catalyst site for wrinkle onset [12].

When multiple plies are formed to the same simple geometric bend (i.e., radius or corner), additional factors come into play. While individual plies will still experience compressive/tensile differential through the thickness, further complications are introduced when relative slip between layers is hindered. If inter-ply slip is not facilitated, the textile layers can experience severe buckling. Yet, unless wrinkles in the bend are cohesive and organized for a number of plies, there will be no substantial detriment to the global stiffness. There is, however, a direct effect on the local response resulting from fiber misalignment in the radius. Furthermore, wrinkles in the bend can contribute to spring-in angles of thin corner sections [12].

Through-thickness fiber misalignment is recognized to significantly compromise a structure's mechanical properties, such as fatigue strength, stiffness and yield strength. For example, the wind energy industry has experienced complications from wrinkle and wave defects that reduce turbine blade fatigue life. These blades can experience catastrophic failure due to fiber misalignment resulting from unintended out-of-plane features [14]. Furthermore, Hallett et al. demonstrated that wrinkles in composite coupons severely reduce the compressive strength by 33%, regardless of wave angle, and observed premature delamination under tensile loading due to straightening of misaligned fibers causing increased inter-laminar shear [15–17]. Therefore, it is clear that measures should be taken during the forming process to inhibit this tow buckling.

When this wrinkling phenomenon manifests during forming applications (e.g., thermostamping), it can be controlled by the addition of lateral restraint (e.g., matched die) or modification of forming temperature, tooling velocity, contact-to-free edge distance (e.g., blank size), and pre-tensioning (e.g., binder pressure) [3,11–13,18]. Traditionally, parametric studies are performed to investigate and isolate the effect of each of these parameters on final part quality; once the effects of each factor are well understood, the processing conditions can be shrewdly prescribed to fabricate defect-free composite components [11]. While experience and experimental trial-and-error can be effective, these parameters can be easily modified in a finite element simulation to quickly and efficiently identify a workable set of processing parameters and design configurations (e.g., tooling geometry, material choices, and ply orientations).

2.2. Finite element approach

In comparison to an experimental approach, time, financial, and human resources can be spent more effectively and efficiently by using a credible simulation tool in which processing parameters and tooling geometry are easily varied to understand their effects on the final morphology and structure of the cured composite [11]. While there are various commercial software applications with capabilities to perform draping simulations, these products are limited to a kinematic analysis to predict the progressive blank displacement and do not account for the mechanical behavior of the fabric. Such geometric approaches accommodate only shear deformation of the textile as the mesh grid is mapped to a new surface geometry by means of "fishnet" algorithms [19]. While geometric approaches are fast and efficient, they do not consider the boundary conditions of the manufacturing process (e.g., binder pressure) or the mechanical properties of the material (e.g., bending stiffness) [19]. Though using the finite element method is more computationally taxing than a purely geometric model [20], such a mechanical analysis is preferable to achieve high-quality results that can provide insight into the detection, location, and magnitude of defects resulting from part manufacture.

Modeling the fabric reinforcement can be challenging due to the multi-scale complexity of the fiber interactions. For this research, the fabric is modeled at a mesoscopic scale using a discrete approach developed by Jauffrès et al. that employs a hypoelastic element description with an explicit formulation [21]. An explicit solver, chosen for its robust contact algorithms, was determined to be more amenable to forming simulations than implicit solvers [21]. This modeling technique has been applied to a variety of textile architectures including woven and non-crimp fabrics. The