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Composites Science and Technology 67 (2007) 3242–3252

COMPOSITES SCIENCE AND TECHNOLOGY

www.elsevier.com/locate/compscitech

Predictive modelling for optimization of textile composite forming

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Received 23 January 2007; received in revised form 21 March 2007; accepted 30 March 2007
Available online 20 April 2007

Abstract

Wrinkling often occurs during textile composite forming and is a major problem for manufacturers. The prediction of this defect is, therefore, of major importance for the design and optimization of textile composite structures. Numerical simulations of forming for textile composites over a hemisphere have been conducted using a rate/temperature-dependent hybrid FE model. The hybrid FE model incorporates a fully predictive multi-scale energy model which determines the shear resistance of the textile composite sheet. The effects of varying the normal force distribution across the edges of the blank and blank size, together with the effect of changes in forming temperature on the final fibre pattern and wrinkling behaviour, are investigated. Predictions are evaluated against press-formed components. The results from the simulation and the experiments have good correlation and show that wrinkling can be minimized by optimizing the force distribution around the edge of the manufacturing tool and by careful choice of forming temperature.

Keywords: A. Textile composites; B. Modelling; C. Finite element analysis; Stamp forming

1. Introduction

Wrinkling (i.e. buckling of fibres), during the forming of textile composites, tends to significantly degrade the performance characteristics of the final product [1]. A number of parameters could affect wrinkling, such as variations in processing conditions (particularly holding force distribution and temperature), ply placement and alignment, matrix rheology and fibre architecture. All of these factors can affect the deformation behaviour during forming (particularly shear compliance and occurrence of wrinkling), leading to variations in the formed fibre pattern. These factors will, in turn, affect component mechanical performance. It is necessary to know if the material can be formed into the desired shape without wrinkling, and under what processing conditions this can be achieved. It is difficult to achieve an optimum fibre pattern using experiments alone [2]. Accurate simulation of the draping process can significantly reduce component development times. Hence, numerical simulation becomes an indispensable tool for engineers to design and optimize structural components. Through parametric studies, finite element analysis can predict optimum forming parameters. Predicted fibre patterns can subsequently be used for prediction of the mechanical behaviour of formed components.

There is considerable research activity related to composite forming simulation [3–7], resulting recently in a number of dedicated international conferences and symposia (e.g. ESAFORM). However whilst most approaches may be distinguished by choice of material model or treatment of boundary conditions, models typically can be categorized as either kinematic or mechanical (finite element based). Kinematic draping algorithms [8–10] provide a rapid solution, but take no account of material properties. These algorithms are only able to predict the deformation of a system without any strain energy (assuming fibres are inextensible, neglecting bending and shear stiffnesses). Obviously, results obtained by the geometrical approach are only a first order approximation of textile composite behaviour. Moreover, this method does not account for process boundary conditions. This means that such codes

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0266-3538/$ - see front matter
doi:10.1016/j.compscitech.2007.03.040

are generally more suited to hand lay-up rather than automated forming operations.

Finite element (FE) models can represent material behaviour and processing conditions, but take longer to compute and require significant material property data [11–13]. Whilst there has been much activity in the areas of material modelling and forming simulation, what has not been demonstrated is a sensible design approach utilizing forming simulation codes. For example, whilst ply wrinkling may be predicted using mechanical forming codes, there are no clear guidelines as to how to proceed when wrinkling occurs. A full FE simulation is required to assess the effects of process variables such as material temperature, blank holding force and material properties on forming performance. For these reasons, work is currently in progress at Nottingham University to develop numerical codes and finite element models with accurate material property constitutive equations [14–16]. This will allow users to simulate all aspects of press-forming including the influence of material properties, mould geometry and processing parameters.

In this study, we focus on prediction of the effects of process boundary conditions, blank size and forming temperature on the forming quality of a hemisphere using a rate/temperature-dependent hybrid FE model. The study has two major objectives. The first is to determine the effects of clamping force conditions, blank size and forming temperature on the wrinkling and tow patterns. The second is to obtain a better an understanding of how the material sheet responds to different forming conditions to find the best way to form a part on a mould surface, avoiding wrinkle formation. The study can facilitate optimization of processing parameters; provide materials characterization data; and evaluate final products with a realistic representation of material and forming processing parameters. This paper starts with an analysis of wrinkling mechanisms, followed by a description of experimental methods and FE simulation, and ends with analysis and discussion of FE simulation and experimental results.

2. Wrinkling mechanisms

The significantly large differences in the stiffness of fibres and the polymer matrix results in two possible ways in which wrinkling could occur during textile composite forming.

From the view point of micro/meso-scale deformation, several researchers including Long et al. [17] identified in-plane and inter-ply shear as the important mechanisms governing forming of aligned fibre composites. The formed fibre pattern is governed mainly by the trellis effect, i.e., local intra-ply shearing between initially orthogonal fibres. Tam and Gutowski [18] demonstrated that wrinkling will occur when the material shear angle required to form a particular geometry is too high. Potter [19] also reported that instantaneous buckling occurs when the fabric warp and weft lock. Trellising results in continuously changing yarn/unit cell structure [17]. If the fabric continues to be deformed, local shear and in-plane compressive forces build up. This is compensated by buckling or out-of-plane deformation [1].

On the other hand, from the viewpoint of global deformation, the dominant deformation mechanism during textile composite forming is out-of plane bending (shell-type curvature). During a forming process, a sheet material is deformed into a complex part (shell); the part sustains compressive stresses as well as tensile forces produced by the normal tool contact force and blank holding force, and the force varies over the circumference of a cross-section of the part due to anisotropic material properties. In addition, in the deformed part, the Gaussian curvature is non-zero; regions of double curvature involve membrane stretching stresses and shearing stresses. Therefore, the force (compressive stress) causing buckling comprises two main components: membrane force and loading force due to contact with tools. Wrinkles should be homogeneous in the circumferential direction for an isotropic material. However for an orthotropic woven fabric, the response of the material to the compressive stress depends on the orientation of the stress with respect to the fibres. The material can accommodate the stress by compressing if the stress orientation is along the bias direction. If the compressive stress is aligned with the fibre direction, the material could buckle and so wrinkling may occur.

It is of crucial importance to understand that the material responds differently to boundary conditions for the two wrinkling mechanisms. For the first case, the change in tow architecture during deformation depends strongly on the in-plane tension in the material, which can be controlled using a pressure blank-holder (see Section 3.2) and is also dependent on blank size. The blank-holder maintains tension within the material sheet during forming. Different holder force distributions can cause different stress fields in the material sheet, consequently affecting tow rearrangement and wrinkling. For the second case, the viscoelastic shell wrinkling behaviour is a result of geometry, material stiffness and, more importantly, in-plane loading distribution across the edges of the blank. Similarly, both wrinkling mechanisms are significantly influenced by forming temperature. Assuming a constant surface and through-thickness temperature distribution before press-forming, the fibres are relatively unconstrained by the molten matrix. This allows mechanisms such as resin percolation, transverse flow, inter-ply slip and intra-ply shear to occur during forming. These mechanisms are strongly dependent on the matrix viscosity, which in turn depends on temperature. An increase in temperature would cause the viscosity of the resin to decrease, causing a reduction in shear force and consequently an increase in allowable shear deformation, leading to a decrease in wrinkling.

Wrinkling can be predicted either when the in-plane shear exceeds a measured locking angle (for kinematic models) or when in-plane compressive forces occur along the tow direction (for mechanical models). In reality, it is