Composites Science and Technology 105 (2014) 151–159

Contents lists available at ScienceDirect

Composites Science and Technology

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

Out-of-plane ply wrinkling defects during consolidation over an external radius

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ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form 20 June 2014
Accepted 6 October 2014
Available online 14 October 2014

Keywords:
A. Layered structures
B. Defects
C. Modelling
Wrinkling

ABSTRACT

If carbon fibre layers are prevented from slipping over one another as they consolidate onto a non-trivial geometry, they can be particularly susceptible to wrinkling/buckling instabilities. A one dimensional model for out-of-plane ply wrinkling during consolidation over an external radius is presented. Critical conditions for the appearance of wrinkles provide manufacturing strategies to eliminate such defects. Predicted wrinkle wavelengths and critical wrinkling conditions show good agreement with wrinkle defects observed in a spar demonstrator.

1. Introduction

Whilst the basic advantages of composite laminates are well proven, they are often compromised by high costs, long development time, and poor quality due to multiple defects, particularly in massive complex parts such as those found in aerospace applications. The modelling, simulation and optimisation of manufacturing processes therefore has widespread applications to the industry, with the twin objectives of improving product quality and decreasing production time.

1.1. Wrinkling of carbon fibre composites during consolidation

Typically, carbon fibre composite parts are made by layering a series of thin carbon fibre layers, pre-impregnated with resin, onto a tool surface. During this lay-up process the stack of plies is consolidated at moderate temperatures and pressures to remove air trapped between layers. This debulking process aims to ensure correct seating onto the tool surface, and to promote adhesion between plies. However, as a laminate consolidates over even a simple geometry the plies are forced to accommodate the imposed geometry of the tool surface. For example, consider consolidation over an external radius Fig. 1 (left). As the outermost ply consolidates it is forced into a tighter geometry; if the layers cannot shear relative to one another, they are put into axial compression. For plies in which the fibres align with this stress, their stiffness is particularly high. If layers can shear/slip over one another the additional length can be accommodated by producing so called 'book-ends'. If the resistance is too high, layers may form wrinkles. Fig. 1 (right) shows small amplitude wrinkles or folds, which have developed in the corner radius of a large scale component. Understanding how wrinkles form during these manufacturing processes is important because, depending on their severity, they may compromise the structural integrity of the final part, leading in some cases to expensive wholesale rejection. The formation of wrinkles not only disrupts the even distribution of fibre and resin, but most significantly can increase through-thickness stresses triggering failure at significantly reduced loads [1].

A distinction is made between *ply* and *fibre wrinkling*. In this contribution the former are observed in Fig. 1 (right), in which the ply deforms as an integral layer rather than independent fibres. The bending stiffness of a ply is much greater than that of a single fibre; consequently wrinkles in plies form over much longer wavelengths than those observed in fibres. Ply wrinkling occurs predominately in pre-impregnated materials in which each ply is laid down as an integral layer, as opposed to infusion based manufacturing processes. The thickness of a typical pre-impregnated ply is much smaller than the width, and therefore the bending stiffness out-of-plane is much smaller than in-plane. Consequently ply wrinkling is predominately out-of-plane; unlike fibre wrinkling where rotational symmetry of a single fibre means there is no preferential wrinkling direction. Various experimental contributions have considered fibre wrinkling [17,8] and to a lesser extent ply wrinkling; for example Lightfoot et al. [14] considered ply wrinkling due to shear interactions between ply and tool, whereas

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http://dx.doi.org/10.1016/j.compscitech.2014.10.007
0266-3538/

Hallander et al. [10] studied the formation of wrinkles during forming of unidirectional prepregs over complex geometries. Various publications have focused on mechanisms for fibre wrinkling, such as wrinkling due to compressive loading [18] and automated fibre placement (AFP) [2]. Previous modelling of ply wrinkles has considered wrinkling of a single textile composite whilst draping over a complex geometry using traditional finite element methods [3,21] and single ply buckling models [16]. The authors are unaware of analytical models which capture multilayered wrinkling during consolidation as studied in this contribution.

1.2. Complexities of modelling multilayered systems

The limited modelling-based work on ply wrinkling is primarily due to the inherent complexities of modelling multilayered structures. In particularly the strongly nonlinear geometric constraints of layers fitting together leads to a complex mix of both material and structural type behaviour. The primary aim of this contribution is to develop an analytical approach which captures multilayered ply wrinkling during consolidation over a non-trivial geometry. Such analysis provides insight into the mechanisms and key parameters which control ply wrinkling during consolidation, leading to greater understanding than can be obtained from simple geometric observations.

A variety of models have been proposed for the consolidation of composite laminates. Typically, these take the form of flow-compaction continuum models, which couple a nonlinear elastic response of the fibres with a Darcy-type flow model for the redistribution of resin throughout the laminate [9,11]. However, with finely-layered structures and uncured laminates, slip at the interfaces between layers can introduce highly nonlinear, anisotropic behaviour. Rapidly-varying shear stresses through the layer thickness, for example, can result from plies slipping and bending as individual layers rather than a combined laminate [16]. Current process models do not account for the anisotropy introduced by the layering, and as a result such models cannot capture layer-level phenomena such as wrinkling.

To include the mechanics of individual layers, explicit finite element calculations can be performed using special interface elements [20]. Any number of interfaces could be modelled this way, yet such approaches are naturally restricted since mesh sizes must be sufficiently small compared with the layer thickness. Some modelling based approaches have sought to include interlayer mechanics by deriving homogenised anisotropic continuum models. Such models are effective if shear properties of the interface and the layer are similar, as for example in a cured laminate. However, for larger disparities, where the layers have the potential to undergo slip and separation, such models break down. For these cases, models must not only consider the anisotropic nature of shear at the interfaces, but also the individual contributions of layers as they bend. An *alternative approach*, taken here, is to incorporate the individual contributions of layers in bending into a variational formulation. Here the interlayer geometry can be described by front propagation techniques such as the *level set method* [4], or by assuming simplified interlayer relationships [6,12] as developed in this contribution.

1.3. Overview of the paper

The paper is organised as follows. In Section 2 a one-dimensional model for wrinkling during consolidation over a corner radius is presented deriving a critical buckling load and wavelength for the wrinkle solutions. This analysis is extended by introducing the concept of a critical limb length, the limb length above which the part will form a wrinkle. Section 3 approximates modelling parameters for both consolidation behaviour and bending of unidirectional prepreg. The main results are presented in Section 4. Firstly the buckling wavelength and the critical limb lengths are compared with wrinkles in a demonstrator spar. This is followed by a parametric study of each modelling parameter, which is then related back to manufacturing processes and design decisions. The paper concludes with some general observations, a discussion of the limitations of the model and future avenues to address open questions.

2. The wrinkling model

The model comprises a stack of N plies of uniform initial thickness h and unit width, that have been laid over a tool surface characterised by the circular arc $x_t = R_t\theta$, for θ in the range $[-\pi/4, \pi/4]$, and straight limbs of length L, see Fig. 2(i). The ith layer, numbering from the outside inwards, is described by a radius of curvature R_i with arc-length parameter x_i and total length $\ell_i = \frac{1}{2}\pi R_i$.

2.1. Modelling assumptions

A number of modelling assumptions are made:

- All plies are assumed to be identical and inextensible in the fibre direction.
- Only the elastic contributions of the fibres and resin are considered in the buckling formulation.
- The analysis is limited to the consolidation over a symmetric external corner radius.
- Temperature is assumed uniform and constant throughout the laminate.
- The laminate stacking sequences is taken into account by assuming a rule of mixtures.
- The laminate wrinkles as a complete laminate, with greatest amplitude on the outside and smallest on the tool surface (as seen in Fig. 1 (right)). The model does not consider modes of deformation where a individual layer or a collection of layers wrinkle independently of the whole laminate.
- The model assumes the prebuckled state is one of uniform consolidation over the corner radius, and only considers the initial bifurcation/onset of a wrinkling instability.

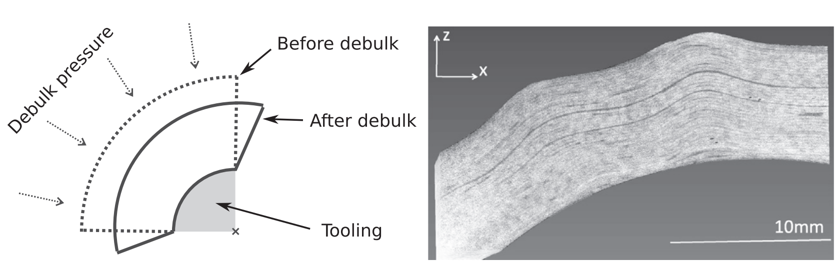

Fig. 1. (Left) A representation of the *bookend* effect, created when a laminate is consolidate over a corner radius. (Right) CT image of a corner wrinkle in the x–z plane of a spar demonstrator with half-wavelength of 5.47 mm.