Composite Structures 152 (2016) 464–476

Contents lists available at ScienceDirect

Composite Structures

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

Damage analysis of out of plane undulated fiber composites

Sina Eskandari *, F.M. Andrade Pires, P.P. Camanho, A.T. Marques

Faculdade de Engenharia, Universidade do Porto, Rua Doutor Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 21 April 2016
Accepted 18 May 2016
Available online 18 May 2016

Keywords:
Out of plane undulation
Continuum damage model
Fiber waviness
Failure strength
Larc failure criteria

ABSTRACT

It is very important to widen the design capacity by analyzing different configurations of composite materials. Out of plane undulated fiber composite is one category of the variable stiffness composites which has attracted research community attention. Waved fibers in this type can be as an unintentional result of production process or a deliberate design purpose. In this research, a 3 dimensional constitutive model is proposed for continuum damage analysis of through thickness curvilinear fiber composites. Larc failure criteria is used in order to determine the damage onset which is a well-established criteria for composite structures. The model is developed by 2 different approaches. In the first approach, it is assumed that the wave shape is fixed during the analysis, while in the second one the geometrical non-linearity is taken into account. Damage evolution is based on the Maimi continuum damage model. Several numerical examples are implemented and results are compared together and the experimental data. There is a good agreement between the second approach and the experiments. Finally a parametric study is conducted and the results are reported.

1. Introduction

Exploring the performance of different categories of composite materials provide the opportunity to discover new applications for this kind of materials and enhancing the current usages. Variable stiffness composite structures are a kind of composites which are being used in aerospace and wind turbine industries. They are involved higher design and manufacturing costs. The higher design cost is due to the inordinately large number of design variables required to define variable orientations and thicknesses and additional constraints required for maintaining the continuity in the structure, which implies a need for higher computational resources compared to the constant stiffness design [1,2]. Variable stiffness can be as a result of design desires which are constructed by tow placement machine or unintended consequence of manufacturing process. The variation in the stiffness can be caused by different sources as thickness change across lamina, material change, or fiber undulation. The focus of this research is on the later one. Fiber undulation or waviness can be in plane of lamina or out of plane through thickness.

Part of the research available in the literature has devoted to model the stiffness distribution of the undulated fiber composites. Hyer and Lee [3] approached in-plane undulated fiber composites by modeling the laminate as a group of finite elements with piece-wise continuous fiber directions to implement the waviness. They tried to achieve an optimized design for buckling resistance of the laminate. While a substantial increase of buckling load was produced, the optimal designs had a configurations that would be difficult or impossible to manufacture. Nagendra et al. [4] looked specifically at the Cincinnati Milacron tow-placement machine and proposed a method for modeling the fiber orientations. The goal of their research was to develop a method of optimizing tow paths. The paths were defined by passing a single curve through a set of control points based on a single cubic NURBS (Non-Uniform Rational B-Splines) curve. Another method of defining the tow paths was presented by Abdalla et al. [5] and Gurdal [6]. In this method, the fiber-orientation angles varies linearly along the length of the composite laminate. A reference path was defined that passed through the center of a flat rectangular plate. The path was then shifted a uniform distance to define fiber paths for the entire plate. In an extension of that research, Waldhart [7] examined two different possible methods of using the formulation proposed by Gurdal. The first method was the same shifted method used by Abdalla et al. [5] and the second method was to create new paths that are parallel to the reference fiber. An interval-search method was used to determine the distance of the adjacent paths from the reference path. In order to increase the number of design variables and hence expand the available design space, fiber paths can be expressed in terms of more complex functions such as Lobatto polynomials, as has been done by Alhajahmad et al. [8]. In the formulation presented by Alhajahmad et al. the definition

* Corresponding author.
E-mail address: dem11005@fe.up.pt (S. Eskandari).

http://dx.doi.org/10.1016/j.compstruct.2016.05.062
0263-8223/

of non-linear fiber angle variation along both spatial surface coordinates is possible. Klees et al. [9] use hierarchical shape functions, based on Lobatto polynomials, to express fiber angle distributions over the plate. Similarly to the formulation presented by Alhajahmad et al. [8], the number of design variables can be increased by increasing the polynomial order. An additional advantage of the formulation presented by Klees et al. [9] is that curvature estimates, which are required to apply manufacturing constraints, can be efficiently computed.

Once the structural stiffness distribution has been defined, the desired response information must be calculated which is typically done using analytical, semi-analytical, and numerical methods. The Ritz method, which is a semi-analytical direct method for finding approximate solution to boundary value problems, has been applied extensively in the past, to compute vibration and buckling modes of variable stiffness composites. However, to compute buckling modes of variable stiffness laminates, the complex pre-buckling plane stress state must first be modeled. Martin and Leissa [10] are among the first to develop a procedure based on the Ritz method to determine both stresses and displacements for sheets with arbitrary fiber spacing. Kassapoglou [11] presents a Rayleigh–Ritz solution to compute buckling loads of panels with an arbitrary number of patches. The energy of a panel is formulated in terms of the out-of-plane displacements. Minimizing the energy with respect to the unknown coefficients in the expression for displacement results in an eigenvalue problem the solution of which yields the buckling load.

Hyer and Lee [3] is the first to use the finite element method to design variable stiffness structures. Due to its general applicability, this approach is used extensively for variable stiffness design. Finite difference discretization has also been implemented by Khani et al. [12] to solve several structural problems. Superior structural performance of variable stiffness design versus constant stiffness design have been demonstrated for different properties such as buckling capacity [3,5,13], elastic behavior [14], stiffness [15], compressive buckling and first-ply failure [16], maximum fundamental frequency [17] and post-buckling progressive damage [18]. Variable stiffness design also provides flexibility for trade-off between different structural properties [19]. Akhavan et al. [20] also analyzed the damage onset and deflection of in-plane curvilinear fiber under vibration and impact by means of Tsai–Wu criteria. The tow model in this work is also from [5].

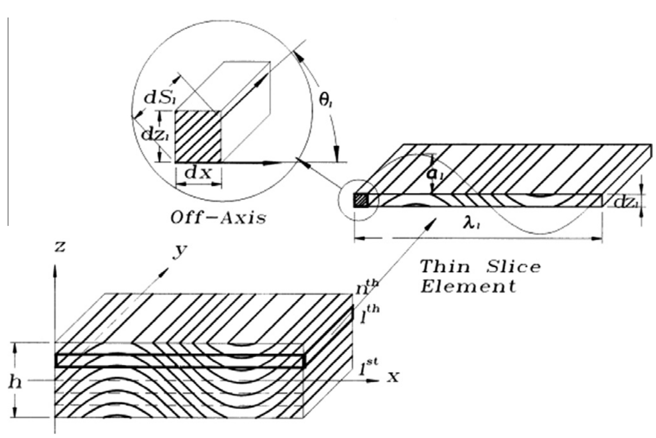

Fig. 1. Schematic of out of plane undulated fiber composite [29].

Table 1
Larc04 failure criteria in fiber failure mode.

Loading condition	FI_F
$\sigma_{11} \geqslant 0$	$\frac{\sigma_{11}}{X^T}$
$\sigma_{11} < 0$ and $\sigma_{2m2m} < 0$	$\left\langle \frac{\tau_{12}^m + \eta^L \sigma_{22}^m}{S_{is}^L} \right\rangle$
$\sigma_{11} < 0$ and $\sigma_{2m2m} \geqslant 0$	$(1-g)\frac{\sigma_{22}^m}{Y_{is}^T} + g\left(\frac{\sigma_{22}^m}{Y_{is}^T}\right)^2 + g\left(\frac{\tau_{12}^m}{S_{is}^L}\right)^2$

Most of the applications of composite materials have been limited to thin sections. However, there is growing interest in thick composite materials especially for primary structures. Fiber waviness is one of the manufacturing defects frequently encountered in thick composite structures. It results from local buckling of prepreg or from wet hoop-wound filament strands under the pressure exerted by the overwrapped layers during the filament winding process or from the lamination residual stress built up during curing [21]. Its characteristics can be represented by the through thickness undulation of fibers within a thick composite laminate. A number of studies have been conducted on the behavior of composites with out of plane fiber waviness. Shuart [22] considered both in-plane and out of plane waviness in an analytical and experimental investigation for multi-directional laminates and analyzed failure of selected compression loaded specimens. A general non-linear theory is presented for predicting a laminate compressive strength and failure mode. The theory also includes fiber scissoring. Bogetti et al. [23] developed an analytic model, based on a three-dimensional laminated media analysis, to predict the effective nonlinear laminate behavior associated with ply waviness. They studied the influence of ply waviness with nonlinear shear material response on the mechanical performance of composite laminates. The nonlinear analysis revealed significant nonlinearity in the stress/strain response of both the wavy ply and crossover region configurations investigated. Telegadas and Hyer [24] conducted finite element analysis to study influence of layer waviness on the stress state in hydrostatically loaded cylinders. Chou et al. [25] predicted the tensile stress–strain response of wavy fiber composites. An elastic constitutive model was developed for flexible fiber composites composed of continuous curved fibers and ductile matrices. The prediction of non-linear stress/strain responses of the composites was performed by a stepwise incremental analysis. Hsiao and Daniel [21,26,27] investigated the compressive behavior of thick composites with fiber waviness. An investigation has been done on the effect of fiber waviness on the stiffness and strength reduction of unidirectional composites under compressive loading using constitutive relations developed by Hsiao and Daniel [21]. These studies analyzed the elastic behavior of the material by analytic method using integration of the compliance, ***S***, over one period of wave as:

$$\bar{\epsilon}_x = \frac{1}{L}\left\{\int_0^L S_{xx} dx\right\}\bar{\sigma}_x. \tag{1}$$

This integration will lead to 5 relations for integration constants in linear case and 12 constants for non-linear case that makes computer programming tedious and time consuming due to high number of parameters and equations. Hsio et al. [27] also calculated the damage onset in the material based on the elastic formulation developed by Hsiao and Daniel [21]. The failure criteria used in that research is Tsai–wu which is not a well-established criteria for composites.

Mandell et al. [28] analyzed the effects of fiber waviness on wind turbine blades. Since blades must be produced at a low finished cost, only relatively inexpensive resins, reinforcement sand processes are competitive. The low cost materials and processes combined with strength-driven designs produce a significant concern with the effects of flaws on the various strength-based properties. They reported the effects of both in-plane and through-thickness fiber waviness under compressive static and fatigue loading.