Composite Structures 185 (2018) 212–220

Contents lists available at ScienceDirect

Composite Structures

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

The effect of free-edges and layer shifting on intralaminar and interlaminar stresses in woven composites

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A R T I C L E I N F O

Keywords:
Woven composites
Finite element method
Intralaminar stresses
Interlaminar stresses
Free-edge effects
Multiscale modeling

A B S T R A C T

The free-edge effects and relative layer shifting in the interlaminar and intralaminar stresses of plain woven composite laminates under uniaxial extension is investigated numerically using a finite element approach. A computational framework of the free-edge problem for periodic structures with finite width is applied to woven laminates. First, two-layered laminates with three different shifting configurations are studied considering repeating unit cells simulating finite and infinite width. For each configuration, two different widths are considered by trimming the model at different locations in order to investigate different free-edge effects. Then, two four-layered laminates with no shifting and a maximum shifting configuration are analyzed to illustrate the effect of neighboring layers in the stresses. For each shifting configuration, different delamination mechanisms are expected. When considering more layers, it is found that the stacking configuration affects the state of stress and the free-edge effects depending on the shifting. In general, a different behavior than that of unidirectional tape laminates is found, since the interlaminar and intralaminar stresses can be higher than those generated at the free-edges. Particularly, for the maximum shifting configuration results are in agreement with experimental results in the literature where no debonding between yarns was observed at the free-edges.

1. Introduction

Fiber reinforced woven composites are commonly used in structural applications with complex geometries offering low production costs in comparison to unidirectional tape laminates. However, their use has been restricted by the lack of understanding of their structural integrity, quantifying its damage and predicting its evolution [1]. Delamination as a result of interlaminar stresses is a common failure mechanism [2,3] which is typically triggered at the free-edges when composite tape laminates are under uniaxial extension. Among the first observations and solutions of free-edge effects were those made by [4,5] in unidirectional tape laminates, which later motivated numerous investigations [6–10]. It is well accepted that the interlaminar stresses arise due to the mismatch between adjacent layers and cannot be captured with classical laminate theory, but numerical solutions are required instead [8–10].

The free-edge effects in woven composites have not been thoroughly discussed in the literature and when performing experimental testing under uniaxial extension it is typically assumed that the maximum stresses are generated at the free-edges, assuming a similar behavior as in unidirectional tape laminates [11–13]. To the best of our knowledge, the only work that has studied free-edge effects in woven composites has been Owens et al. [14]. They studied the effect of finite thickness and finite width on four-layered woven laminates with different waviness ratios (WR = t_h/λ) for a given thickness, t_h, and a wave length, λ. Their results suggested that for low values of WR, free-edge effects were more pronounced, but in both cases, different than in tape laminates.

The relative layer shifting between layers has been shown to have an important effect in woven composites. Ito and Chou [12] studied layer shifting experimentally testing laminates with no-shifting, maximum shifting and random shifting configurations under uniaxial tension. They found delamination or debonding between fiber bundles in the free-edges, in turn related with the strength of the laminate [11,12,15] except for the maximum shifting configuration. Among other things, layer shifting can also reduce the interlaminar shear stress between neighboring laminas [12,16] and affects the macroscopic strain field [17]. Therefore, it has been suggested that in order to capture the physics of the failure process, shifting should be considered when performing simulations [18]. However, it is worth to mention that other geometrical imperfections due to manufacturing might arise, such as nonuniform distribution of undulation angle, variability of layer thickness, and voids, to mention a few, which could lead to more complex representative volume elements, see e.g. [19,20]. All these imperfections may also influence the stress distribution within the laminate and should be taken into account in later studies.

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https://doi.org/10.1016/j.compstruct.2017.11.014
Received 30 June 2017; Received in revised form 9 October 2017; Accepted 6 November 2017
Available online 07 November 2017

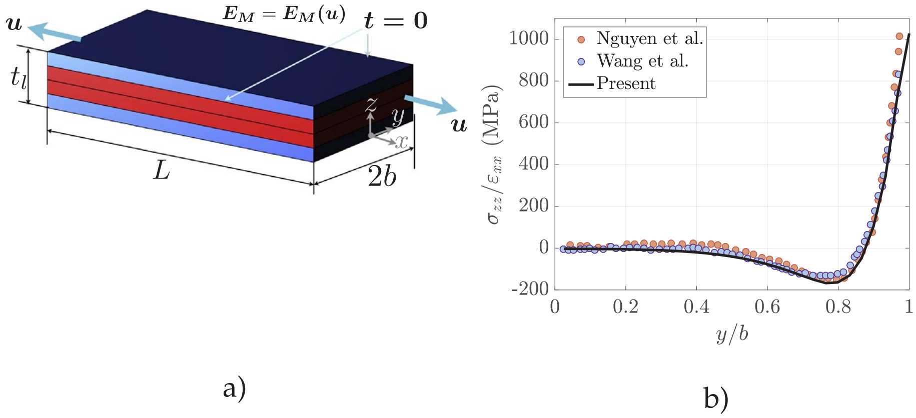

Fig. 1. Example of a typical free-edge effect in a $[0/90]_s$ tape laminate under uniaxial extension. a) Schematic representation, b) benchmark of the results herein compared to the solutions of Nguyen et al. [10] and Wang et al. [22].

The present investigation focuses on the relative layer shifting and its effect on the intralaminar stresses responsible for yarn debonding in the same layer, interlaminar stresses responsible for yarn debonding between layers and free-edge effects in plain woven composite laminates. First, the effect of relative layer shifting between layers is discussed in a two-layered plain woven composite. The free-edge effect is studied by representing a specimen with finite width, with appropriate boundary conditions, as it will be described later. Afterwards, these two layers are considered as a part of a four-layered laminate under two different shifting arrangements in order to study the effect of neighboring layers.

2. The free-edges as a boundary value problem

2.1. A brief introduction

The so-called free-edge effects were first observed and reported by Pagano and Pipes [4] in tape laminates subjected to uniaxial extension. This effect arises near the free-edges due to stress imbalances and the local Poisson's ratio mismatch between layers. As an example, consider a $[0/90]_s$ laminate as that shown in Fig. 1a with length L, width $2b < L$ and total laminate thickness $t_l \ll 2b$ that is subjected to a macroscopic uniaxial extension in the x-direction. At the free-edges ($y = 0$ and $y = 2b$), the macroscopic surface traction is zero ($\boldsymbol{t} = 0$). On the other hand, plane-stress conditions prevail at the interior of the laminate where in-plane stresses might differ between layers due to the different ply orientations and stacking order. Thus, in order to satisfy equilibrium and the macroscopic traction-free conditions at the free-edges, high out-of-plane interlaminar stresses arise at these zones vanishing at a distance of approximately t_l according to the Saint–Venant principle [21]. Then, free-edges become common places for triggering delamination, see [4] for further details and a complete study. It is worth to mention that benchmark models capturing these free-edge effects were first implemented in a $[0/90]_s$ laminate finding agreement with the well-known solutions presented by Nguyen et al. and Wang et al. [10,22], Fig. 1b.

2.2. A computational approach of the free-edge problem

The aforementioned free-edge problem can be written as a boundary value problem in the absence of body forces as,

$$\nabla\cdot\boldsymbol{\sigma}_M = 0 \text{ on } \Omega \tag{1a}$$

$$\boldsymbol{t} = \boldsymbol{\sigma}_M\cdot\boldsymbol{n}_y = \boldsymbol{0} \text{ on } \Gamma_{edge} \tag{1b}$$

$$\boldsymbol{t} = \boldsymbol{\sigma}_M\cdot\boldsymbol{n}_z = \boldsymbol{0} \text{ on } \Gamma_{bt} \tag{1c}$$

$$\boldsymbol{u} = \boldsymbol{u}_p \text{ on } \Gamma_p \tag{1d}$$

where ∇ is the gradient operator, $\boldsymbol{\sigma}_M$ is the macroscopic Cauchy stress tensor in Voigt notation, $\boldsymbol{n}_i$ is the outwards normal to each surface in the i-direction, being $i = x,y$, $\boldsymbol{u}$ are the displacements, $\boldsymbol{u}_p$ are the prescribed displacements, Ω is the domain and Γ the union of sub-boundary regions with subscripts *edge*, *p* and *bt* referring to the lateral free-edges, prescribed displacements, and bottom-top boundaries, respectively. The weak solution of the boundary value problem denoted by Eqs. ((1)) is obtained by finding the displacements $\boldsymbol{u}$ such that,

$$\int_\Omega \boldsymbol{\sigma}_M : \delta\boldsymbol{E}_M = \int_\Gamma \boldsymbol{t}\cdot\delta\boldsymbol{u}$$
$$\forall\ \delta\boldsymbol{u} \in \mathbb{U},$$
$$\mathbb{U} = \{\boldsymbol{u}:\ \boldsymbol{u} \in [\mathbb{H}^1(\Omega)]^m, \boldsymbol{u} = \boldsymbol{u}_p \text{on } \Gamma_p\} \tag{2}$$

where $\boldsymbol{E}_M = \boldsymbol{u} \otimes \nabla$ is the average Cauchy infinitesimal strain tensor on the macroscale, and $\delta\boldsymbol{E}_M = \delta\boldsymbol{u} \otimes \nabla$ holds. $\mathbb{H}(\Omega)^1$ is the Sobolev space of order m, and Eq. (2) is discretized using the standard Galerkin method. The Dirichlet boundary conditions $\boldsymbol{u}_p$ can be prescribed as displacements on the macroscale, which in turn, can be related to the macroscopic strain $\boldsymbol{E}_M$ and a micro-fluctuation displacement part $\tilde{\boldsymbol{u}}$ related to the periodicity. Details are provided in the following section.

2.3. Boundary conditions, periodicity and free-edges in periodic structures

Free-edge effects in woven composites have been suggested to be different than those presented in unidirectional tape laminates due to the complex state of stress that arises as a result of the undulation of the yarns [14]. Furthermore, woven composites are periodic structures and modeling its behavior is typically done using homogenization theory with a repeating unit cell (RUC) on the microscale together with the representation of periodicity of displacement, related to the average macroscopic strain $\boldsymbol{E}_M$. It is known that for periodic structures with a given boundary Γ, periodic boundary conditions in the appropriate directions can be written in terms of the micro-fluctuation displacement $\tilde{\boldsymbol{u}}$ as,

$$\tilde{\boldsymbol{u}} = \tilde{\boldsymbol{u}}^+(\boldsymbol{X}^+) = \tilde{\boldsymbol{u}}^-(\boldsymbol{X}^-) \tag{3}$$

where the superscripts + and $^-$ represent opposite boundaries on Γ and $\boldsymbol{X}$ are the reference coordinates. Periodicity in the z-direction is not considered since the exact number of laminas is used [23,24]. Thus, if periodicity is considered simultaneously in the x-y-directions, an infinite length and infinite width is being represented and if periodicity is only considered in the x-direction, infinite length and finite width is being represented. Notice that when finite width is considered, the nodal constraints in the y-direction (free-edges) are released and the traction $\boldsymbol{t}$ vanishes on the free edges,

$$\boldsymbol{t} = \boldsymbol{\sigma}_M\cdot\boldsymbol{n}_y = \boldsymbol{0} \text{ on } \Gamma_{edge} \tag{4}$$

In contrast, it does not vanish when periodicity in such boundary is prescribed. Thus, we study the free-edge effects in this periodic structure by comparing these two cases. This physical representation of the free-edge effect is shown schematically in Fig. 2. In order to impose