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Strength prediction of ply waviness in composite materials considering matrix dominated effects

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ABSTRACT

Ply waviness (PW) is a commonly observed manufacturing defect in composite materials leading to degradation of the mechanical properties. The effects of matrix systems on the strength behavior of unidirectional laminates containing ply wavinesses are analyzed for compressive loading. An analytical approach based on Hsiao and Daniel (1996) allows an estimation of stiffness and strength in dependence on waveform and material. While the geometry of the waviness can be characterized by its amplitude to wavelength ratio and its wave shape (uniform or graded), composite constituents can be considered individually. The approach according to Hsiao and Daniel is enhanced by the PUCK failure criterion Schürmann (2005) and is implemented as a graphical user interface (GUI) using the software MATLAB. The analytical approach is validated against literature data. Strength properties are individually varied, indicating that failure behavior of wavy laminates is mostly affected by matrix dominated shear strength R_{12}.

1. Introduction

1.1. General

Ply waviness is known as a wave-formed ply and/or fiber deviation from a straight alignment in a unidirectional laminate. This may arise as an undesirable manufacturing defect that commonly occurs during draping, infiltration and/or curing. Especially cost-saving manufacturing technologies as used in production lines of wind turbine blades (WTB) are prone to ply waviness. Hence misalignments and wavinesses are a commonly observed defect in spar caps of WTBs.

Under loading, ply waviness causes three-dimensional stress states that may dramatically reduce stiffness, strength and fatigue strength. Particularly in load bearing parts such as spar caps, ply waviness can lead to early global failure and kinking of the entire blade structure. Therein, ply waviness constitutes a massive risk and has to be considered conspicuously for the analysis and design process of WTBS. It is therefore necessary to first quantify the stiffness and strength reduction, depending on the waviness severity and material data. Secondly, possibilities to diminish the effects of ply waviness need to be regarded. For this purpose the impact of individual material constituents on the strength of lamina containing ply waviness have been studied.

1.2. Related work

Within the current work of the authors, both an analytical and a numerical model are being developed in order to estimate the material behavior depending on the geometrical shape and the material selection of wavy composites. A continuum damage model is being generated, taking failure mechanisms such as fiber kinking into account, which has been observed to be the initial and catastrophic failure mechanism in wavy composites [4].

A specimen's geometry has been defined by a design of experiments (DOE) study. The geometry is tuned in order to derive material data, thus preventing a structural failure of the specimen. A robust fabrication method has been developed and installed to fabricate specimen containing artificially induced waviness in reproducible quality. Experiments of tensile and compressive tests are being carried out.

This paper places emphasis on the influence of matrix relevant properties on the compressive strength of lamina containing out-of-plane waves using an analytical approach by Hsiao and Daniel.

2. Analytical method

Under loading along fiber orientation, ply waviness leads to the development of interlaminar shear stress and interlaminar tensile or compressive stress perpendicular to the fiber. These stresses may lead to inter-fiber failure (IFF), which can be influenced by the chosen matrix and fiber coating. Hence the effects of matrix

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systems on the strength behavior of unidirectional laminates containing ply wavinesses are analyzed. Compressive loads are subjected. Taking into account [1,2] the approach is reproduced and extended by the Puck failure criterion [3]. The analytical calculation is implemented as a GUI using the software MATLAB. The GUI allows an analytical estimation of the stiffness and strength behavior depending on waveform and material of the lamina.

2.1. Local and global stiffness prediction

The calculation of the stiffness is carried out by a reproduction of [1,2]. A sinusoidal, in-phase, global, out-of-plane ply wavinesses with uniform and graded amplitudes is considered. The calculation is based upon a representative volume element of length l and height h. It includes one period of a uniform or graded waviness with the amplitude A. The local inclination of the plies is defined by the angle θ:

$$\theta = \tan^{-1}\left(2\pi\frac{A}{L}\left(1-2\frac{|z|}{h}\right)\cos\left(\frac{2\pi x}{L}-\frac{\pi}{2}\right)\right) \tag{1}$$

where by angle θ for a uniform waviness arises at the special case of $z = 0$. The local stiffnesses are determined by a location-dependent transformation of the compliance matrix ${}_F\boldsymbol{S}$, from the fiber coordination system F to the global coordination system G. The transformed compliance matrix ${}_G\boldsymbol{S}$ is written by:

$${}_G\boldsymbol{S} = \boldsymbol{R}\cdot\boldsymbol{T}_{FG}^{-1}\cdot\boldsymbol{R}^{-1}\cdot{}_F\boldsymbol{S}\cdot\boldsymbol{T}_{FG} \tag{2}$$

Assuming transverse isotropy, Reuther matrix $\boldsymbol{R}$, transformation matrix $\boldsymbol{T}_{FG}$ and compliance matrix ${}_F\boldsymbol{S}$ are:

$$\boldsymbol{R} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix} \tag{3}$$

$$\boldsymbol{T}_{FG} = \begin{bmatrix} m^2 & 0 & n^2 & 0 & 2mn & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ n^2 & 0 & m^2 & 0 & -2mn & 0 \\ 0 & 0 & 0 & m & 0 & -n \\ -mn & 0 & mn & 0 & m^2-n^2 & 0 \\ 0 & 0 & 0 & n & 0 & m \end{bmatrix} \tag{4}$$

$m = \cos\theta \quad n = \sin\theta$

$${}_F\boldsymbol{S} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & -\frac{\nu_{12}}{E_1} & 0 & 0 & 0 \\ & \frac{1}{E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ & & \frac{1}{E_2} & 0 & 0 & 0 \\ & & & \frac{2(1+\nu_{23})}{E_2} & 0 & 0 \\ & \text{sym} & & & \frac{1}{G_{12}} & 0 \\ & & & & & \frac{1}{G_{12}} \end{bmatrix}_F \tag{5}$$

The local transformed stiffnesses result from the compliances with:

$${}_G\boldsymbol{S} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & -\frac{\nu_{xz}}{E_x} & 0 & 0 & 0 \\ & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_y} & 0 & 0 & 0 \\ & & \frac{1}{E_z} & 0 & 0 & 0 \\ & & & \frac{1}{G_{yz}} & 0 & 0 \\ & \text{sym} & & & \frac{1}{G_{xz}} & 0 \\ & & & & & \frac{1}{G_{xy}} \end{bmatrix}_G \tag{6}$$

Global compliances or rather stiffnesses of the representative volume element are determined by integration over the contemplated area:

$${}_G\bar{\boldsymbol{S}} = \frac{1}{h}\frac{1}{L}\int_{-h/2}^{h/2}\int_0^L {}_G\boldsymbol{S}\,dx\,dz \tag{7}$$

2.2. Local stresses

Based on the previously determined stiffnesses, respective stress distributions, arising out of an x-direction loading can be determined. Firstly the more general case of graded waviness is considered. Fig. 2.1 shows the discretization of the representative volume element.

The sections are referred to $i \in [1;N]$ in x-direction and $j \in [1;M]$ in z-direction. The central point $(x_i|z_j)$ of element ij results from:

$$\left(x_i = \left(\frac{2i-1}{2N}\right)L \middle| z_j = \left(\frac{2j-1-M}{2M}\right)h\right) \tag{8}$$

Assuming a load σ_x that is subjected to the overall volume element, each section i is considered individually. Hereby, a constant strain ${}_G\varepsilon^i$ in z-direction is assumed. Each element i is considered as a laminate with M plies and analyzed via the classical laminate theory (Fig. 2.2).

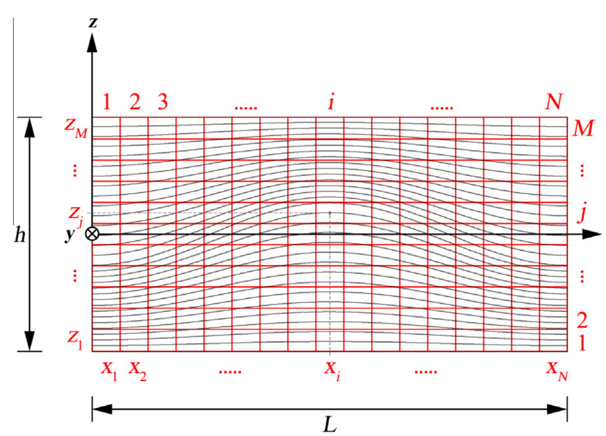

Fig. 2.1. Discretization of the representative volume element with graded waviness [5].

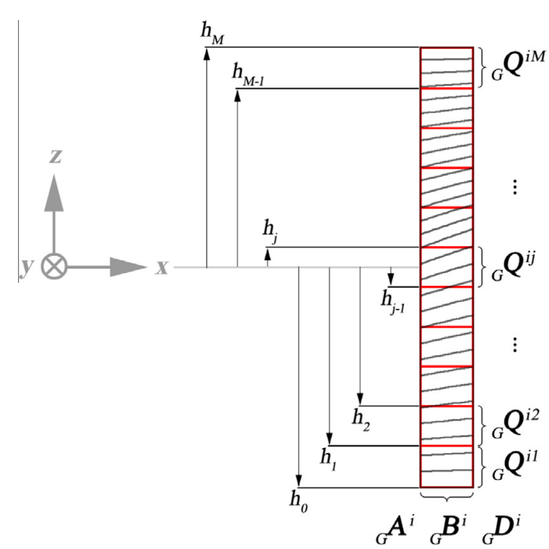

Fig. 2.2. Application of the classical laminate theory on the cut out [5].