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Thermo-elastic Properties Degradation in Damaged Laminates with High Density of Transverse Cracks

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Abstract
During the service life multidirectional laminate with an arbitrary lay-up is subjected to varying thermo-mechanical loading and in result different number on intralaminar cracks can develop in different layers of the laminate. These cracks called also transverse cracks are reducing the thermo-elastic properties of laminates. A model called GLOB-LOC model was developed in [1,2] to calculate these properties for any given damage state. This analytical calculation scheme is exact if the input information is exact. However, the expressions contain two important approximate parameters (functions) which are obtained summarizing/fitting parametric analyzes results using FEM. These parameters are proportional to the average stress state change between two cracks with respect to the undamaged stress. The parameters govern the stiffness reduction of the laminate and have the physical meaning of average opening displacement (COD) and average sliding displacement (CSD) of a crack.
The parameters COD and CSD depend mostly on neighboring layer thickness and stiffness which makes them robust parameters in the model. Unfortunately, the situation changes when the crack density (number of cracks per mm) is high and the distance between cracks is comparable with the crack size (cracked layer thickness). In this crack density range the cracks are interacting and the COD and CSD depend on the distance between them.

In this paper the crack interaction effects on laminate stiffness are analyzed using FEM. Based on FEM results a simple interaction function which depends on the cracked and neighboring layer thickness, elastic properties and the distance between cracks is suggested. This interaction function multiplied with COD of a non-interactive crack is the input parameter in analytical model for thermo-elastic properties of damaged symmetric and balanced laminates.
It is shown that these functions when used in the GLOB-LOC model give high accuracy for all thermo-elastic constants of damaged laminates.
As an example, the predicted axial modulus and Poisson's ratio of cross-ply laminates with cracks in inside 90-layer are shown for GF/EP composite in Fig.1. FEM data are shown with symbols, predictions according to the interaction function by solid curves and dotted lines represent the ply-discount model. It has to be reminded that the normalized crack density is introduced as inverse to the crack spacing normalized with ply thickness. Therefore, the values of the normalized density larger than 1 are extremely high and are with no practical interest. Data in this region are shown to demonstrate the asymptotic approaching to the ply-discount value.
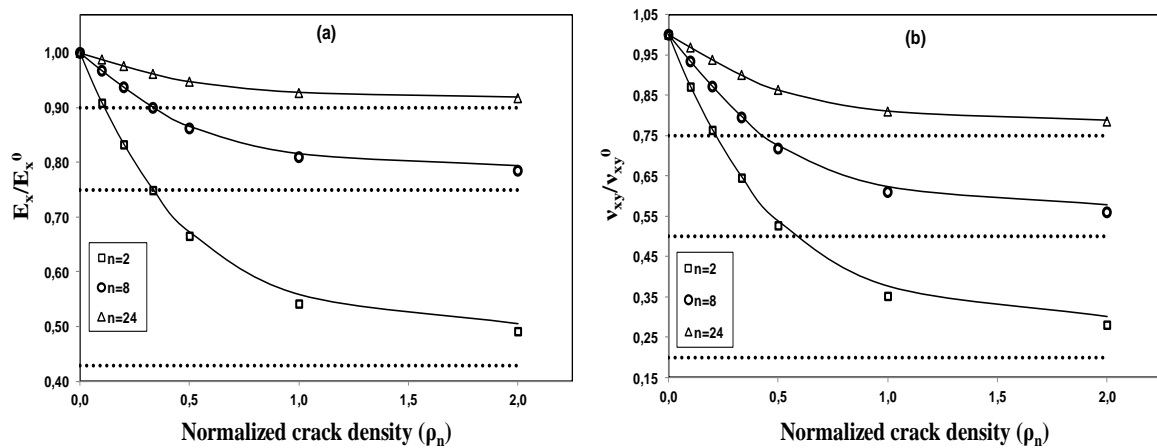
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Figure 1: **Axial elastic modulus (a) and Poisson's ratio (b) degradation in $\left[0_n / 90_8\right]_S$ GF/EP laminate.**

Most of the existing models are based on assumption that the crack distribution in the layer is uniform: the same distance between all cracks. Since optical observations show that it is not true, we present FEM simulation results to evaluate the effect of non-uniform crack distribution on elastic properties of RVE showing that the differences may be rather large. The axial modulus reduction in the uniformly damaged case is always larger than if the crack distribution is non-uniform.

A simple and accurate procedure based on using systems of periodic cracks is suggested for calculating the thermo-elastic properties of laminates with non-uniform crack distribution.

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