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# Macro-mechanical damage modeling of fibrous composite materials accounting for non-linear material behavior

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ABSTRACT

In the present paper, a new macro-mechanical model for tracing damage-evolution in composite materials is proposed. The present model represents a new extension and a new approach to a previous model (Ghazi-Farid model), which can be applied for a general state of stress. The model is verified by comparing its results with those corresponding to Ghazi-Farid model for different composite materials and it seems to give very close correlations. The proposed model can be applied to both elastic and inelastic materials as well as generally orthotropic fibrous composite nonlinear-materials.

It was concluded that shear damage is always higher than any other damage types due to the high nonlinear-material shear behavior, which causes high plastic strain-energy density. Damage in a composite lamina causes a reduction in its stiffness. Therefore, a new quantum-damage variable is proposed: " tangential quantum-damage variable " to quantify the overall-damage in a composite lamina. Percentage reduction of composite stiffness depends mainly on the amount of resulting damage irrespective of fiber-orientation angle. So, a new trend for the behavior of composite materials is introduced which states that the relation between damage-evolution and corresponding stiffness-reduction follows a certain behavior and it is independent of fiber-orientation. Each composite material has a unique trend which is verified using three different composite materials; Boron-Epoxy-Narmco 5505, Graphite-Epoxy 4617/Modmore-II, and Carbon-Epoxy AS4/3501−6.

A new damage-term is introduced as: "directional damage-variable", to simplify tracing damage in the case of a uniaxial off-axis loading. The new damage-variable was used to predict damage-evolution in the three laminas made of the indicated composite materials. It is concluded that, Graphite-Epoxy 4617/Modmore-II has the minimum damage at all stress levels and Boron-Epoxy-Narmco 5505 has the maximum damage. The importance of the new damage-term makes it easier to predict damage and make preferences between several composite materials subjected to uniaxial off-axis loading.

## 1. Introduction

Composite materials or so called advanced materials will partially replace conventional materials in civil engineering structures to attain higher stiffness/density and higher strength/density ratios and gain better corrosion and wear resistance in addition to many other advantages. Composite materials have many applications in the field of industry, such as aircraft industry, marines and many other applications. Due to increasing applications of composite materials in the industry for the last past decades, the necessity of understanding the behavior of those materials has been increasing. Since most composite materials exhibit nonlinear behavior, this challenge encouraged researchers to develop different models to predict the behavior of composites and possible failure mechanisms. Development of damage in composite materials due to matrix micro-cracks, voids, interfacial de-bonding and other deteriorations, all of these make the material to behave nonlinearly. Many models were proposed to predict the damage in composites based on different failure mechanisms and approaches. A new model is made to trace the damage in fibrous composite materials depending on derivative equations from the stress-strain relations.

Over the last century, many researchers studied the failure of composite materials, they have been trying to make a good prediction of the performance of these materials. In order to achieve

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this, they defined many terms such as the damage-factor. These terms are used to model failure of the material.

Lemaitre et al. [1] mentioned eight different methods to quantify the damage defined as the effective surface density of cracks in any plane of Representative Volume Element (RVE). The authors assumed damage in materials would be formed in micro-cracks or micro-cavities, breakage of bounds and cracks in matrix-polymers. Two approaches were carried out in their study; direct measurements such as micrographic picturing and indirect measurements using destructive and non-destructive testing procedures. The different measuring methods gave reasonable different results. The differences may be attributed to different definitions of damage mechanisms. In a very recent work, Garcea et al. [2] carried out a three-dimensional non-destructive testing using X-ray computed tomography (CT), to examine and quantify defects due to damage in polymer composites.

Abu-Farsakh [3] developed a new material model accounting for the non-linear behavior of fibrous composite materials and it was compared with the Jones-Nelson material model [4]. In which the secant mechanical property was assumed to be a function of the plastic strain energy density of an equivalent linear elastic system which replaced the total strain energy term in the Jones- Nelson model. The model was verified using experimental data published in Cole et al. [5].

Kattan et al. [6] developed a micromechanical composite model to investigate damage in a uniaxial loaded unidirectional fiber-reinforced composite laminate. Their research constituted the first step towards the development of a consistent micromechanically based damage theory for composite materials. The damage defined based on effective stress concept. Damage was separated into matrix damage and fiber damage as a local damage definition. The local-overall relation for damage-evolution was derived based on micromechanical considerations. The relation between local damage-variable to the overall damage-variable depended on the matrix volume fraction.

Abu-Farsakh et al. [7] developed a new model for predicting damage and crack-density ratios in fibrous composites. Damage in material principle-directions was determined based on mathematical equations utilizing the strain-energy density obtained from the stress-strain curve directly. Equations were formulated using the secant model (non-linear model) mentioned in Abu-Farsakh [3]. A reasonable approach to estimate the crack-density ratios for any fiber-orientation loaded up to failure was introduced based on total strain energy approach of an equivalent linear elastic system as mentioned in Abu-Farsakh et al. [8]. Results of damage-factor and crack-density ratios were compared with experimental data for Boron-Epoxy, Graphite-Epoxy, $[0/90]_s$ and $[\pm45]_s$ metal-matrix laminates.

Barbero et al. [9] proposed a new model for damage-evolution in polymer matrix composites. Nine-model parameters were proposed for damage evolution. The authors implemented the finite element program Abaqus utilizing the eight-node solid element (Hexahedron Element) used for the analysis. Results were compared with experimental data obtained from standard tests of $[0/90]_s$ and LTM45EL-SM laminates for shear tests, also [±45]s and LTM45EL-SM laminates for axial loading tests. Their model predicted the non-linear behavior of the polymer-matrix composites and shown to be in good agreement with the experimental data obtained with standard tests.

Voyiadjis et al. [10] proposed a new concept of small damage within the framework of continuum damage mechanics. A new damage-variable was presented in terms of the elastic stiffnesses of the material. Overall and local damage approaches were examined and compared mathematically. In a further work, Voyiadjis et al. [11] formulated fabric damage-tensors for evolution of damage resulting from micro-cracks distribution within the framework of thermodynamics. Two different sets of micro-cracks were considered in the same representative volume element (RVE). One set was the micro-crack length and the second set was the micro-crack orientation. The proposed model was applied to laminates subjected to uniaxial tensile loading only.

Jalalvand et al. [12] proposed a new finite element approach for modeling damage modes in Glass-Carbon unidirectional (UD) hybrid laminates subjected to tensile loading. The new approach was used to imitate the development of damage and to make a map of damage-mode for Glass-Carbon UD hybrid laminates. In their work, it was shown that, the glass fibers in the thinner laminate, failed before those in the thicker laminate due to stress concentration effect. Kushch et al. [13] proposed two micromechanical models; analytical and finite element models (FEM), to investigate the propagation of local damage in fibrous composites due to interface debonding.

Elnekhaily et al. [14] studied the onset of failure in composite materials subjected to transverse tensile loading. It was found that, the strain that is needed to form the first cavitation in the matrix was increased with increasing matrix/fiber stiffness-ratio. On the other hand, it was decreased with decreasing the uniformity of fiber-distribution through thickness.

## 2. Scope and objectives

The present study aims at deriving a mathematical damage model to quantify the damage factor ($\Phi$) in fibrous composites for the case of general state of in-plane stresses ($\sigma_x$, $\sigma_y$, $\tau_{xy}$) accounting for the non-linear behavior of a composite material. And, it also aims at predicting the degradation of strength and stiffness of a composite lamina. Hence, to reach a formula for estimating damage in a composite lamina in order to make preferences between several available composite materials.

## 3. Nonlinear-material model

In general, a composite material exhibits a nonlinear stress-strain behavior in at least one principle material-direction, as shown in Fig. 1. A new material model for accounting the nonlinearity of composites was proposed originally by Abu-Farsakh [3], which deals with the secant mechanical property ($E_s$) instead of the tangential mechanical property ($E_t$). The new model can be applied to both elastic and inelastic materials as well as generally orthotropic fibrous composite nonlinear-materials. The physical significance of the model is that; it can represent the stress-strain relation

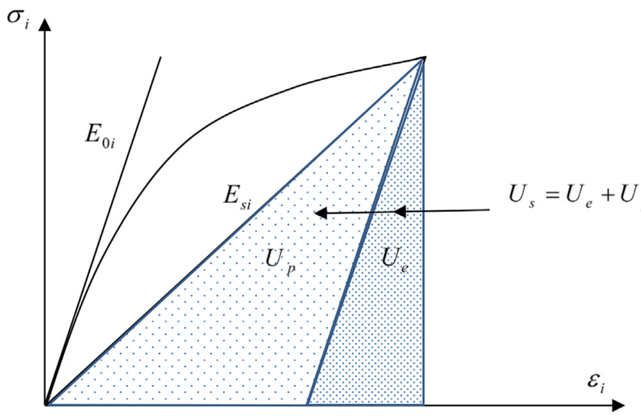

**Fig. 1.** Typical nonlinear stress-strain curve for *i-th* mechanical-property showing the energy terms.