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Elastoplastic CDM model based on Puck's theory for the prediction of mechanical behavior of Fiber Reinforced Polymer (FRP) composites

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A B S T R A C T

In this paper, the plane stress version of the Puck's failure theory is used as an indicator of the intra-laminar meso-damage initiation. The thermodynamically consistent damage evolution law is defined to accumulate the damage leading to the subsequent stiffness degradation coupled with the isotropic hardening plasticity. The model is formulated in incremental form keeping in view the implementation by following the plasticity theory which is later used in the Return Mapping Algorithm (RMA). In the implicit scheme based on the Newton-Raphson approach, the consistent tangent operator is derived for the current model. The developed model has been implemented in ABAQUS/Standard via UMAT subroutine in a strain-driven problem where strain tensor is provided as an independent argument into the solution scheme. The non-linear mechanical behavior and ultimate failure of Carbon Fiber Reinforced Polymers (CFRPs) laminates are predicted for the small strain time-independent boundary value problem. The results are compared with the experimental results collected from the previously published literature which exhibit better correspondence.

1. Introduction

The accurate though easier reliable modeling of mechanical behavior of Fiber Reinforced Polymers (FRPs) composite structures is a challenging and arduous task to accomplish in the today's stringent industrial requirements that strive persistently to seek cost-effective solutions. The contributing factors in the complexity are the heterogeneity, anisotropy and the multi-scale nature of the composite structures which usually need many characterization tests for the qualification of the structures to be introduced into their intended service conditions. To minimize the testing in the development and to squeeze the qualification timeline of the project and, hence cost, reliable numerical tools shall be synergized with the characterization plan in order to compete in the market. For the efficient use of the composite structures up to the ultimate failure, complete failure analysis shall be carried out including the damage initiation and saturation till the final rupture [1]. The conventional design approach which declares a laminate to be failed or safe is based on the First Ply Failure (FPF) criterion and is very conservative [2]. The structures based on FPF approach are usually over-designed which augments the weight of the structures, one of the critical design parameters in transportation: such as aerospace, automobile, etc.

In principle, the non-linear material behavior is characterized by two different mechanical phenomena regardless the material is metal or composite as reported in [3]. The first source of non-linearity is the plasticity which in case of metals is the slippage of the dislocations along the slip planes whereas in composites is the irreversible deformation in the softer matrix material. The second cause of the non-linearity is the possible accrued damages which encompass all the micro-voids/cracks, fiber/matrix de-cohesion, etc. Upon the damage accumulation and growth by the exerting load the drop in the elastic modulus and also in the plastic hardening is governed by applying the coupled constitutive equations of damage and plasticity [4]. The damage and plasticity ultimately induce inelastic strains which can be additively decomposed into elastic strain vector $\varepsilon^{\mathbf{e}}$, plastic strain vector $\varepsilon^{\mathbf{p}}$, and inelastic strain vector due to damage $\varepsilon^{\mathbf{d}}$ [3]. Voigt notation is followed throughout the formulation for the stress, strain and stiffness tensors in the present model where due to symmetry the stress and strain tensors are treated as vectors. The total strain vector ε can be read as:

$$\varepsilon = \varepsilon^{\mathbf{e}} + \varepsilon^{\mathbf{p}} + \varepsilon^{\mathbf{d}} \quad (1)$$

Most of the models based on the Continuum Damage Mechanics (CDM) do not consider the inelastic strains caused by the irreversible micro-damages as they assume that all the inelastic strain is due to the plasticity of the matrix in the composites. For instance, the phenomenological elastoplastic damage model proposed by Ladevèze et al. [5] is very efficient in the prediction of transverse tensile and shear non-

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linear mechanical behavior of FRPs. Though this model [5] portrays the complete non-linearity caused by the combined effect of the micro-damages and plasticity with significant accuracy from the very beginning depending on the thermodynamic force thresholds, as is generally the actual case in composites, it demands some additional parameters. In the response to minimize the unconventional testing for model identification, there are models [6–12] which make use of the readily available material properties both for damage initiation and evolution. Such models incorporate failure criterion as the damage initiation surface normally in the form of strength parameters.

The progressive failure models developed by Vaziri et al. [12], Chen et al. [6,13], and Vasiukov et al. [8] are some of the elastoplastic/damage models which are based on the aforementioned philosophy in which a ply is treated as homogenous orthotropic continuum known as meso-scale for Uni-Directional (UD) plies based laminates. Chen et al. [6] selected one parameter plastic potential for plane stress case with isotropic hardening function that has been developed in [14] and used in [15]. Vasiukov et al. [8], used the modified Hoffman criterion having hydrostatic pressure sensitivity and non-linear kinematic hardening in 3D stress space. When plasticity potentials are used for composites, plasticity flow only develops in matrix and is blocked in the direction of fibers. In the above models [6,8,13], Hashin's failure theory [16] has been used for the damage initiation like in most of other models: for instance in [11]. Improved ultimate breaking strength along with the matrix non-linearity for Open Hole Tension (OHT) coupon of T300/1034-C Carbon epoxy were reported in [6,8], in comparison to the previous models [7,17–19]. In addition, Maimí et al. [7,17] utilized the LaRC03 criterion and employed in-situ ply strength in the damage activation functions. These models which are based on the failure theories usually pose the convergence problems and the solution aborts prematurely once the Fiber Fracture (FF) or Inter Fiber Fracture (IFF) takes place. It can be addressed by incorporating appropriate artificial viscous effects in post-failure loading phase by introducing the viscous regularization coefficient usually denoted by (η) [6–8,11,17]. The influence of the viscous regularization coefficient has been highlighted in [11], therefore, it must be selected carefully so that the results are not significantly affected.

The commonly used failure criteria predict the meso-damage which is the consequence of the micro-damages (matrix micro-cracking, debonding, etc.). As a result, the non-linearity caused by the micro-damage prior to the meso-damage is overlooked in this manner and are assumed to be attributed solely to the plasticity of the matrix. One possible approach exists to define a sub-failure surface depicting the initiation of the micro-damage/diffused damage inside the meso-damage failure surface. Böhm et al. [20] applied Cuntze failure theory [21] with sub-failure surface and, Scheucker et al. [2,10,22] employed Puck's failure theory [23,24]: sub-failure surface defines the diffused damage threshold whilst the outer surface defines the loci of the meso-damage initiation. Nevertheless, this sub-surface inclusion in the model increases the requirement of the additional diffused damage initiation thresholds to be determined experimentally for the material modeling.

Failure criterion shall be simpler enough to be used in the engineering and industrial applications but, in parallel, it shall be equipped to capture effectively the corresponding physics of the failure phenomenon [23,24]. There are about twenty failure theories in total which are available as a conclusion from the World-Wide Failure Exercises (WWFEs) after testing and thoroughly comparison of the combined loading cases [25,26]. It is pertinent to describe that no failure criterion is ideal but the accuracy varies depending on the laminate stacking sequence and type of loading. Hashin's failure theory [16] is widely used in the models though it may not predict the matrix damage with high precision as highlighted in [11]. The motivation behind the present research work is to apply Puck's theory in the same context as the Hashin's theory has been used [6,8]. The accuracy of the matrix meso-damage initiation of Puck's theory has been demonstrated [27] in which the authors predicted the matrix damage with 95.8% accuracy for different combined experimental load cases. Similar conclusions were also made in number of scientific studies [28,29]. Perillo et al. [28] have predicted the ultimate breaking load capacity of OHT composite coupon having relative less error with the experiments by using Puck's theory as compared to Hashin's theory. It was recommended by the authors [28] that Puck's theory shall be used in conjunction with gradual damage evolution rather than sudden degradation in order to minimize the deviation from the experimental values. Hence, Puck's theory seems to be a better candidate to be used for the damage initiation based on the prediction accuracy with the elastoplastic constitutive law.

Puck's theory has been used earlier with the progressive damage evolution by number of researchers. In fact this theory has its own damage degradation as well [30,31]. However, the range of the parameters is very broad and the secant elastic properties are used rather than the initial elastic properties of the lamina in order to capture the pre-IFF non-linearity caused by the plasticity and micro-damage in the matrix material. Zhong et al. [32] proposed the damage evolution in woven composites by considering the 3D Puck's theory for the damage onset in the fiber yarn because of the capability to predict the damage as well as the orientation of the damage. In addition, Lee et al. [27] used the plane stress case of Puck's theory in CFRP OHT where an instantaneous unloading of the corresponding finite element has been accomplished, a sudden death concept, when one of any five Puck's failure indices turns into unity in that particular finite element. A series of publications has been presented by Schuecker et al. [2,10,22] in which the physically based Puck's theory has been efficiently exploited to its best to develop a robust CDM model. The model [2,10,22] stems on the Puck's theory and the determination of the damaged compliance tensor on Mori-Tanaka method [33]. The crack induced by the external loading was termed as inclusion whose shapes were assumed as oblated spheroidized, having a known aspect ratio as a priori, and then the Eshelby tensor for each inclusion was determined in the fracture plane coordinate system using Puck's theory in a transversely isotropic host continuum. Knowing the Eshelby tensor, the damage compliance tensor for a ply was computed. This model [2,10,22] is attributed with some aided unique features over the other models as it defines a sub-surface inside the Puck's envelope which captures the initiation of the micro-damages (point A in Fig. 1-a), the predecessors of the meso-damage or in other words the IFFs, as shown in Fig. 1-a [2] and Fig. 1-b[31].

The model [2,10,22] exhibited its capability in uni-axial as well as multi-axial loading along with the load reversals, but the implementation possesses the difficulty. More recently, the 3D form of Puck's theory has been used for triggering the intra-laminar damage by coupling the elastic constitutive law with CDM [9].

In present work, the anisotropic elastoplastic damage law has been derived in detail with isotropic hardening plasticity. The intra-ply meso-damage initiation, the FFs and IFFs, are predicted with the help of 2D Puck's theory based on the plane stress assumption. Firstly, the non-linear prediction capability of the rate-independent constitutive law is validated by making comparison of the experimental results for the bi-angle CFRP laminates: $[\pm 30^\circ]_{2s}$, $[\pm 45^\circ]_{2s}$ [15]. Then the ultimate breaking load of the OHT made of T300/1034-C FRPs has been predicted for some of the laminates chosen from the published literature [6,8,27,34]. Furthermore, perfect bonding is assumed amongst the plies and no delamination is considered in the upcoming Finite Element Method (FEM) analysis.

2. Anisotropic damage/plasticity coupled material modeling

This section pertains to the detailed discussion of the anisotropic damage modeling on the basis of irreversible thermodynamics and the CDM theory. The damage initiation and the evolution are formulated keeping in view the 2D version of Puck's theory. At the end, the plasticity/damage coupled model is presented.