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Intra and damage analysis of laminated composites using coupled continuum damage mechanics with cohesive interface layer

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ABSTRACT

In the present article a model based on coupling of continuum damage mechanics with cohesive interface layer is proposed in order to predict the progressive damages including the large delamination growth in composite laminates. A new interface cohesive constitutive law is developed which is compatible with 3D continuum damage mechanics (CDM). To avoid the difficulties of 3D mesh generation and 3D interface modeling between the layers, the cohesive interface layer is implemented in the Reddy's full layer-wise plate theory. An angle-ply laminate is analyzed to evaluate the developed CDM+cohesive layer in edge delamination initiation and evolution during uniaxial tension loading. The proposed approach is demonstrated to predict progressive damage and final failure load of angle-ply laminated composites both accurately and effectively.

1. Introduction

Composite materials have been largely used due to their higher strength to weight ratio comparing to traditional metallic materials. Many industries have been taking advantage of excellent properties of this material such as flexibility, easy to manufacture, and lower cost. Although composites exhibit very good mechanical behavior under various loading condition, in many cases there are many unknown factors such as their mechanical properties and failure mechanisms affecting on their behavior. In micro-scale many damage mechanisms contributes to the failure such as fiber fracture, fiber pullout, matrix cracking, delamination, fiber kinking etc. Experimentally, it has been proven that the mentioned mechanisms begin to deteriorate composite in the loads far below than ultimate strength of composite. The first result of this event is the decreasing of stiffness [1–3]. The decreased stiffness maybe leads to deterioration near the damaged area, causing new damage mechanism evolution through composite. This means investigation about how damage initiates and propagates is of high importance and needs to be noted in any damage mechanisms. Nonetheless, in composite materials there are five major damage mechanisms: 1-lamina diffused damage, 2-matrix cracking, 3-interlayer diffused damage, 4-delamination, and 5-fiber breakage.

The first type of observable damage at failure initiation of laminate is intra-layer damage which is in the form of matrix cracking parallel and perpendicular to fiber direction in non-adjacent layers. Matrix cracking occurs before the laminates lose considerably its final strength and consequently leads to stiffness and strength degradation [4]. Matrix cracking may cause leaking in high pressure vessels made of composite laminates, therefore they are very important. Additionally, matrix cracking can be the initiation of other failures such as delamination and matrix cracking in adjacent layers or the combination of both [5–8]. Delamination might cause loading durability degradation on other associated laminas which results in loading durability degradation of laminate composites [7]. Matrix cracking investigation is classified to two categories: 1-crack initiation caused by matrix failure and 2-crack initiation caused by fiber/matrix debonding. Joffe [9] observed when fiber/matrix debonding happens; this discontinuity emerges and forms a transverse crack.

In the three past decades, there have been intensive research activities in damage analysis of composite materials, and different damage models have been proposed such as various kinds of shear lag models [10,11], variational approaches [12], stress transfer models [13], and continuum damage mechanics [14] in the framework of irreversible thermodynamics. Transverse matrix cracking has been investigated extensively in the literature especially in cross-ply laminates. One of the key issues in these studies is stiffness reduction of laminate due to the existence of matrix cracks in the laminate. Most of the research has, however, been focused on cross-ply laminates which are excellent for academic investigations

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but are limited in practical applications. Laminates with a general layup configuration containing multiple matrix cracks in layers with various directions are, therefore, a challenge for any constitutive model.

A two-dimensional shear-lag analysis is a simplest way to describe a doubly periodic matrix cracking in cross-ply laminates. At shear-lag theory as pointed firstly by Hedgepeth and Van Dyke [15], the elastic 0-degree layers carry only simple axial load and cracked 90-degree layers deforms only in simply shear by considering a resin rich thin layer between 0/90 layers. This model has seen many variations.

The variational model was proposed by Hashin [12]. An approximate state of stress in the vicinity of a transverse crack was obtained by minimizing stress perturbations using the principle of minimum complementary energy. Hashin's variational method was developed by Nairn [16], Varna and Berglund [17,18]. Despite of shear lag method in which it needs some empirical data to obtain mechanical parameters of resin rich layer, in variational method there is no additional data. However, this method is just applicable for cross ply laminate due to difficulty in solving complex governing equations of stress or displacement fields.

The most accurate local stress state comparable with a very fine FE solution and, therefore, also accurate stiffness prediction can be obtained using semi-analytical model of McCartney [13,19–21] which is known Stress transfer method. Using proposed method, analysis of multiple matrix cracks in symmetric general laminates is possible under three dimensions axial and shear loading. In the McCartney's model, each layer in the laminate is divided into a certain number of thin sub-layers. All displacement and stress continuity conditions at sub-layer interfaces are satisfied as are the stress–strain relationships, except one, which is satisfied in an average sense. However, the calculation routines in these models are extremely complex which limits the application.

Neither of above mentioned unit cell based models can be directly used for laminates with general layups including matrix cracked layers. However, some of models have capability of considering these cracked layers as non-interacting, one can first introduce crack system in 90-layer only and back calculate the effective stiffness of the cracked layer from the damaged laminate stiffness. Then the matrix cracks are introduced in the q-layer only and similar problems as described above are solved in a system of coordinates rotated by 90. Finally the equivalent mechanical properties of all damaged layers could be used in laminate theory to calculate the overall stiffness of laminate with multiple matrix cracks in different layers. Each unit cell based models have some limitations in loading and stacking sequence. In addition, these methods are highly based on either functions of matrix cracks density or delamination surface venues applied load must be obtained from experiments. In most methods of micromechanics, interactions of the various damages are not considered.

Continuum damage mechanics (CDM) considers a damage tensor in which all damage interactions are presumed. Additionally, composite material is supposed a continuous media that damage tensor is contributed with mechanical properties. The progression of distributed microscopic damage in a structure is the main effort of continuum damage mechanics (CDM). It was first introduced by Kachanov [22] in creep analysis and afterward developed by Lemaitre [23,24], Chaboche [25,26], and Krajcinovic [27,28] in the field of the isotropic materials especially in metals. They used CDM to predict damage in various types of brittle or ductile material by defining a continuous damage variable. It is worth noting that CDM has been firstly used for damage analysis of transversely isotropic composites by Talreja [14]. Also there has been an enormous effort to develop CDM in composite materials by Voyiadjis [29], Talreja [30,31], Ladevèze [32,33], and Barbero [34–36], Talreja [14,37], Lene [38], and Allen [39,40], and [41]. Talreja [14] proposed a second-order tensorial damage parameter, representing the damage effects in each density of matrix cracks. Lene [38] used a scalar variable of damage in order to describe matrix/fiber debonding for the homogenized composite material at the ply level. Allen et al. [39–41] proposed a progressive damage model in composite laminates in the framework of damage mechanics. A plane model in meso scale was developed by Ladevèze et al. [42] in which damage was homogenized in a lamina. Philips et al. [43] suggested a damage model in meso scale which they could investigate damage evolution in carbon polymer composite with severe stress gradient. In another work, Allix and Ladevèze [44] studied delamination in a laminate with a central hole. They used an interlaminar element like a very thin plane whose elastic properties was evaluated by thickness and elasticity of interlayer. Allix and Corigliano [45] presumed a classical interface element to simulate numerical delamination using FEM which was developed based on damage mechanics. Additionally Corigliano in [46] developed a common type of interlaminar element for elastic and plastic delamination damage modeling. A 3D model of continuum damage coupling with plasticity in metal matrix composites was proposed by Voyiadjis and Kattan [47–50], Voyiadjis and Park [51]. Williams et al. [52] developed a constitutive law for laminate composites using CDM principals. Their model was established based on the combination of physical behavior of damage with the thermo-mechanical foundation of CDM. Barbero et al. [35] developed a 2D plane stress model for progressive damage based on the use of a symmetric second order damage tensor. Damage evolution and stiffness reduction were computed for the pre-homogenized composite material simplifying the formulation. In 2002 Barbero and Lonetti [36] extended their previous model [35] to include plasticity. This model was developed further by Lonetti et al. [53] containing the modification to include tri axial orthotropic damage in terms of three damage eigenvalues.

It is worth to mention that consideration of macroscopic damages such as delamination is a noticeable weakness of the currently available CDM approaches.

Free edges of laminates can provoke both intra- and inter-layer damages due to arising high stress gradients. The interlaminar stresses at free edges may lead to the edge delamination and final failure of laminates. Experimental results indicate that, the free edge failure caused by interlaminar shear stresses often results in immediate laminate final failure [54]. The progressive damage of different angle-ply composite laminates under quasi-static loading that exhibit the free edge effects were investigated by Mohammadi et al. [55] using developed 3D continuum damage mechanics formulation. The predicted results of stress–strain response and failure load of angle-ply laminates, prone to edge delamination, lead to significant differences with respect to experimental results [55].

Considering the above mentioned CDM challenges and drawbacks, the main goal of this paper is developing an interface layer with cohesive law, which is compatible with CDM concept. To simplify the 3D mesh generation and comfortable insertion of interface medium at any interface between layers, developed interface layer was implemented in the layer-wise finite element plate theory. To evaluate the proposed model, the [10/−10]2s and [30/−30]2s angle ply laminate are analyzed and the obtained results are compared with the existed experimental results.

2. CDM in composite laminate

In order to describe the effects of damage and its microscopic growth on the macro-mechanical properties of the materials, damage variables can be presented through the internal state variables. A symmetric 2nd order damage tensor φ whose principal