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# Micromechanics-based progressive failure analysis of carbon fiber/epoxy composite vessel under combined internal pressure and thermomechanical loading

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ABSTRACT

A progressive failure analysis algorithm based on micromechanics of failure (MMF) theory and material property degradation method (MPDM) is developed, wherein the MMF is used to predict the failure initiation at constituent level and the MPDM is employed to account for the post failure behavior of the damaged materials. The progress of damage is controlled by a linear damage evolution law, which is based on the fracture energy dissipating during the process. This micromechanics-based approach is implemented by a user-material subroutine (UMAT) in ABAQUS, which is sufficiently general to predict the ultimate strength and complex failure behaviors of the composite vessel subject to both high pressure and thermal loading. In addition, the predictions of the model are also compared with those by experiment and traditional finite element analysis.



## 1. Introduction

Fiber-reinforced polymer composites are finding increasing application in aerospace, marine and many other industries due to the advantages they provide in performance, structural efficiency and cost. The carbon fiber/epoxy composite pressure vessel is an important application of composites in the field of hydrogen storage and transportation, which contributes to safety, economy and high efficiency [1,2]. In general, the composite vessel can be taken as aluminum-carbon fiber/epoxy composite laminated structures. The laminate layers are stacked by placing the composite layers with different thickness and different ply orientations, such to achieve high stiffness and strength of the vessel structure. The design flexibility of the composite vessel enables it to be applicable to various working conditions by adapting the ply stacking patterns and the vessel geometry parameters [3].

The optimal design of composite vessel as a fundamental research highly depends on the failure properties and ultimate strength of the composite structure. However, the fast filling of hydrogen leads to a significant temperature rise within the vessel due to the Joule Thomson effect and the released heat of gas compression [4,5]. The composite vessels are directly subjected to the cyclic loading of both high pressure and temperature, which contribute to the complicated failure mechanisms of the vessel structure, such as fiber breakage, matrix cracking and fiber/matrix interface debonding, from the point view of composite micromechanics [6–8]. There is now a need for reliable failure theories and damage evolution methodologies which will accurately and effectively predict the complex failure mechanisms of the composite vessel structure.

Since the failure of composite materials exhibit significant heterogeneity and anisotropy, various approaches have been proposed to characterize the onset and progression of damage during the past decades [9–13]. However, most of the failure theories among them are macroscopic or ply-level failure criterions which need empirical determination of the different failure modes and the predicted results are not always precise and reliable. By contrast, the micromechanics-based failure theory determine material failure at the constituent level, which show more accuracy in predicting the complicated failure behaviors especially for the composite vessel subjected to coupled thermal-mechanical loadings. Typical examples of the micromechanics-based failure theories are the strain invariant failure theory (SIFT) by Gosse et al. [14] and the multicontinuum theory (MCT) by Garnich and Hansen [15].

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Recently, Ha et al. [16] proposed a micromechanics of failure (MMF) criterion based on comprehensive failure theory of homogeneous isotropic constituents. Essentially, it is the application of a quadratic-type failure criterion at the local points of micromechanics-unite cell model, in which the fibers and matrix are modeled explicitly. The micromechanics of failure theory is usually performed with a micromechanical calculation in order to obtain the interaction information between the micro- and macro-level of composites.

For modeling the post-initial failure behaviors of the composite laminated structure, progressive failure analysis of composites are mainly performed based on continuum damage mechanics (CDM), in which the loss of stiffness can be physically considered as a consequence of distributed microcracks and microvoids and these material defects are phenomenologically represented by introducing a set of internal state variables [17–21]. Within the framework of CDM, the material property degradation method can be successfully applied to approach stiffness reduction in the MMF based progressive failure analysis. Since the MMF approach is developed in homogeneous constituent level, the degradation scheme is much simpler requiring a single degradation parameter for the matrix and fiber respectively [22]. Once the damage is detected in the fiber or matrix, the corresponding damage variable will degrade to some extent based on the prescribed damage evolution strategy.

The objective of this study is to propose a micromechanics-based progressive damage analysis strategy, which is sufficiently general to predict the coupled thermal-mechanical responses and complex failure behaviors of the composite vessel structure. An effective finite element model is developed based on the integration of micromechanics of failure (MMF) theory and material property degradation method (MPDM), where the MMF is used to predict the failure initiation at each constituent and the MPDM is employed to account for the post failure behavior of the damaged materials. In addition, the micromechanics analysis of a typical unit cell model is performed in order to obtain the interaction information which bridge the micro- and macro-level analysis. The predicted results show good consistency with those of traditional finite element analysis and experiments. This micromechanics-based progressive failure analysis provides a deeper insight into the multiple failure mechanism and complex thermal-mechanical behaviors of the composite vessel structure.

## 2. Damage progression model

As the mismatched material properties of fiber and matrix, any external mechanical and thermal loading will result in a non-uniform micro-stress distribution at the constituent level of composite materials. The damage initiation and propagation can have different mechanisms depending on where the failure exists, i.e., in the fiber or in the matrix. In this study, a micromechanics of failure (MMF) criterion for each constituent is adopted to determine where the failure initiates. The constituent properties of the failed layer or element are then degraded with the given degradation factors, i.e. $d_m$ for the matrix damage and $d_f$ for the fiber damage, to model the post-initial failure behavior of the material. This approach for modeling micromechanics-based progressive failure analysis of composites is implemented by a user-defined material subroutine (UMAT) in ABAQUS [23]. Details of these modeling strategies are presented in the following sections.

### *2.1. Micromechanics-based failure criterion*

The micromechanics of failure (MMF) criterion was developed by Ha et al. [16] for failure prediction of composites at the constituent level. In the MMF criterion, fibre is considered to be longitudinally continuous and has a higher modulus and strength than those of matrix, which suggests that fiber supports almost the entire load for both longitudinal tension and compression. Thus, fiber dominated damage initiation is determined using a simple non-interacting Max-stress criterion:

(1) Fiber failure criteria

$$-C_f < \sigma_{f1} < T_f, \tag{1}$$

where $T_f$ and $C_f$ are fiber tensile and compressive strengths, and $\sigma_{f1}$ is the fiber micro stress in the longitudinal direction.

The matrix is assumed as isotropic material, and has different tensile and compressive strengths. A modified von Mises failure criterion is adopted to determine the initiation of matrix damage:

(2) Matrix failure criteria

$$\frac{\sigma_{vm}^2}{T_m C_m} + \left(\frac{1}{T_m} - \frac{1}{C_m}\right) I_1 = 1, \tag{2}$$

where $T_m$ and $C_\mathrm{m}$ are matrix tensile and compressive strengths respectively, $I_1$ and $\sigma_{vm}$ are the first stress invariant and von Mises stress at micro level.

Note that, the micro stress caused by the macro mechanical and thermal stress is due to the material and geometric inhomogeneity of composites. The relationships between macro and micro stress at constituent level, i.e. in the fiber or matrix, can be described by introducing a set of stress amplification factors, $\boldsymbol{M}$ and $\boldsymbol{A}$:

$$\boldsymbol{\sigma} = \boldsymbol{M}_\sigma \overline{\sigma} + \boldsymbol{A}_\sigma \Delta T \tag{3}$$

$$\boldsymbol{M}_\sigma = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & 0 & 0 \\ M_{21} & M_{22} & M_{23} & M_{24} & 0 & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} & 0 & 0 \\ M_{41} & M_{42} & M_{43} & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & M_{56} \\ 0 & 0 & 0 & 0 & M_{65} & M_{65} \end{bmatrix} \tag{4}$$

$$\boldsymbol{A}_\sigma = [A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \quad A_6]_\sigma^T \tag{5}$$

where $\boldsymbol{M}$ and $\boldsymbol{A}$ are mechanical and thermal-mechanical stress amplification factors, respectively. Generally, these stress amplification factors can be calculated with a unit cell model either analytically or numerically. Details about the typical unit cell model and the calculation of stress amplification factors for the given composite structure are illustrated in Section 3.

### *2.2. Damage evolution and constitutive model*

Once the above failure criterions are satisfied, the material stiffness of the damaged element will degrade gradually based on the linear softening law [24,25], which the strength of the ply decreases linearly with strain. The energy-based linear softening law is defined by effective stress and displacement as shown in Fig. 1, wherein the fracture energy dissipating during the damage process is assumed to be equal to the area under the effective stress–displacement curve:

$$\int_0^\infty \sigma_{eq} d(\delta_{eq}) = G_c \tag{6}$$