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# Micro-mechanics of failure for fatigue strength prediction of bolted joint structures of carbon fiber reinforced polymer composite

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ABSTRACT

In this paper, the application of theory of micro-mechanics of failure (MMF) is extended to analyze the fatigue progressive failure and predict the strength for the bolted joint structures of carbon fiber reinforced polymer (CFRP) composites. The MMF approach includes the methods of material strength characterization and structure strength prediction for the CFRP structures. The structure strength prediction is realized by developing the user defined material (UMAT) subroutine with Fortran scripts on the ABAQUS platform. The failure mechanism evolution from initial failure to final failure of the bolted joint structures of the UTS50/E51 laminate under the static loading and the fatigue loading are investigated, respectively, in details by using the MMF approach. The experiments under both static and fatigue loading are performed for the bolted joint structures. The predicted strength accuracy of the MMF approach as well as the classical Tsai–Wu and Hashin theories is compared with the experimental results, which shows the MMF approach has the best accuracy. The predicted macro-scale failure appearances of the bolted joint structures under the static tensile loading and the fatigue tensile loading behave as shearing modes. The validation of predicted macro-scale failure appearances is studied by comparing with the tested results.



## 1. Introduction

The carbon fiber reinforced polymer (CFRP) have many excellent features, such as higher strength and specific stiffness, strong design ability, good fatigue properties, corrosion resistance and so on, so it is widely used in aviation, aerospace and other advanced fields. The mechanical joint structure is the key factor for applying the CFRP materials to the model industries because the joints are the potential weaknesses of the composite structures. In recent years, the composite bolted structures are widely investigated in many aspects [1–9], such as the failure analysis, load distribution, fatigue lifespan and joint strength. In order to guarantee the security of the CFRP composite structure in use, it is necessary to develop the accurate strength theories.

Currently, the traditional macro strength theory is still the widely used theory for composite structures, like the Tsai–Wu [10], Hashin [11] and Puck [12] theory. These theories are mainly based on the mathematic approximation formulas and the error will be relatively big in practical situations. Where, the Tsai–Wu theory fails to specify the failure mechanism of damage. Hashin and Park considered the constituent failure mechanism, but those failure criteria are not calculated in micro-level. In essence, they also belong to the macro analysis. In order to overcome the deficiencies of the macro theories, it is imperative to build a real physically strength theory for composite materials, which will have great importance in the design and application of the CFRP composites.

The micro-mechanics of failure (MMF) proposed by Ha et al.[13] is a real physics-based strength theory for strength prediction of the structures made of carbon fiber reinforced polymer (CFRP) laminates, in which the initial failure of constituents is analyzed in micro-level with the interactive failure criteria. In their research, the square or hexagonal unit cell model applied with the loads, corresponding to the stress states in macro-level, at the boundaries were used to look insight into the stresses in the fiber and matrix in micro-level. Based on the interactive MMF, both transverse tensile and compressive failure of the Graphite/Epoxy were analyzed in that paper. In this way, the strength and failure modes of laminate with multidirectional stacking sequence have been predicted. These predictions are compared with predictions from other widely used failure criteria as well as experimental data, good agreement was confirmed. However, the large amount of iterative

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calculation for the extraction of the MMF critical parameters using the interactive failure criteria lowers the computational efficiency and has a poor convergence performance. Therefore, a simple and reliable MMF failure criterion that can increase computational efficiency and improve the convergence is necessary.

This paper establishes the MMF approach which extends MMF theory to analyze the fatigue progressive failure and conduct the strength prediction for the bolted joint structures of the UTS50/E51 CFRP composites. The MMF approach includes the material strength characterization and structure strength prediction for the CFRP structures. The material strength characterization includes macro-mechanics experiments, micro-mechanics analysis and MMF critical parameters extraction. The structure strength design includes modeling of a specific structure, macroscopic stress analysis, microscopic stress amplification, constituents' failure judgments, material properties degradation and crack propagation in the structures. The structure strength prediction is realized by developing the user defined material (UMAT) subroutine with Fortran scripts on the ABAQUS platform. Micro-scale stress of the constituents is visualized for detailed analysis. The progressive failure and the strengths of the single-bolt double shear lap joint of the UTS50/E51 laminate under the static loading and the fatigue loading, respectively, are analyzed in details by using the MMF approach. Finally, the analysis accuracy of the MMF approach is compared with that of the classical Tsai–Wu and Hashin theories.

## 2. The micromechanics-based strength theory for composites

### 2.1. Micro-mechanics of failure criteria

In the MMF theory, the constituent strength is characterized by four MMF critical parameters, including the fiber tensile strength $T_f$, the fiber compressive strength $C_f$, the matrix tensile strength $T_m$, and the matrix compressive strength $C_m$. $T_f$ and $C_f$ are used to judge the failure of fiber under tensile and compressive loading, respectively. $T_m$ and $C_m$ are used to judge the failure of matrix under tensile and compressive loading, respectively. The calculations of the four characteristic values are shown as formula (1).

$$\begin{cases} T_f = \sigma_1^f, & (\sigma_1^f > 0) \\ C_f = \sigma_{eq}^f, & (\sigma_1^f < 0) \\ T_m = I_1^m \\ C_m = \sigma_{eq}^m \end{cases} \tag{1}$$

where the material axes 123 are used as coordinate direction. $\sigma_1$ is the stress of fiber direction, $I_1$ is the first stress invariant and $\sigma_{eq}$ is the equivalent stress. The superscript/subscript f and m represent the fiber and matrix respectively.

It is necessary to point out that, this paper uses the none-interactive MMF failure criteria. The fiber tensile strength is extracted by using the maximum stress along the fiber length direction because fibers only present high rigidity in the longitudinal direction and the rigidities in other directions are very low. So it can be described as the maximum strength of fiber direction. The fiber compressive strength is described by the equivalent stress on the fiber. As to the failure of the matrix, Gosse and Christensen [14] proposed the strain invariant failure theory to describe the strength of matrix, the first invariant of strain $J_1$ and the equivalent strain $\varepsilon_{eq}$ are used to characterize the tensile strength and compressive strength of matrix respectively, because $J_1$ is suitable to judge the failure due to the volume increase while $\varepsilon_{eq}$ is suitable to judge matrix failure due to the shearing deformation. This paper uses the first stress invariant $I_1$ and the equivalent stress $\sigma_{eq}$ which correspond to $J_1$ and $\varepsilon_{eq}$, to describe the tensile strength and compressive strength of matrix, respectively.

As it can be seen from formula (2), once the value of $k$ reaches to 1, the material is suffered to the corresponding mode of damage. Therefore, in the MMF theory, the MMF critical parameters of the constituents are the key indexes for analyzing the structure strength of the laminates. Hence, to accurately predict the strengths of the laminate structures, it is necessary to accurately calculate the values of the four MMF critical parameters of $T_f$, $C_f$, $T_m$ and $C_m$.

$$\begin{aligned} k &= \max\left[k_{T,f}, k_{C,f}, k_{T,m}, k_{C,m}\right] \\ k_{T,f} &= \max\left(\sigma_1^{f,1}/T_f, \ldots, \sigma_1^{f,i}/T_f, \ldots, \sigma_1^{f,n_1}/T_f\right) \\ k_{C,f} &= \max\left(\sigma_{eq}^{f,1}/C_f, \ldots, \sigma_{eq}^{f,i}/C_f, \ldots, \sigma_{eq}^{f,n_1}/C_f\right) \\ k_{T,m} &= \max\left(I_1^{m,1}/T_m, \ldots, I_1^{m,j}/T_m, \ldots, I_1^{m,n_2}/T_m\right) \\ k_{C,m} &= \max\left(\sigma_{eq}^{m,1}/C_m, \ldots, \sigma_{eq}^{m,j}/C_m, \ldots, \sigma_{eq}^{m,n_2}/C_m\right) \end{aligned} \tag{2}$$

where $k$ without subscript means the failure index of the element, $k_{T,f}$ and $k_{C,f}$ are the fiber tensile failure index and fiber compressive failure index, respectively; $k_{T,m}$ and $k_{C,m}$ are the matrix tensile failure index and matrix compressive failure index, respectively; $i = 1 \ldots n_1$, $j = 1 \ldots n_2$, $n_1$, $n_2$ represent the total numbers of the key points in the fiber and the matrix, respectively.

When the element within the structure fails, an action against the material property degradation should be performed according to the failure mechanism, which needs to introduce the constituent damage factors. The definitions of the constituent damage factors are shown in formula (3) to formula (6).

Tensile fiber failure ($\sigma_1^f > 0$)

$$\text{If} \quad k_{T,f} \geq 1, \quad \text{then } d_f = 0.99 \tag{3}$$

Compressive fiber failure ($\sigma_1^f < 0$)

$$\text{If} \quad k_{C,f} \geq 1, \text{then } d_f = 0.99 \tag{4}$$

Tensile matrix failure

$$\text{If} \quad k_{T,m} \geq 1, \text{then } d_m = 0.99 \tag{5}$$

Compressive matrix failure

$$\text{If} \quad k_{C,m} \geq 1, \text{then } d_m = 0.99 \tag{6}$$

where $d_f$ is the fiber damage parameter; $d_m$ is the matrix damage parameter.

The laminate gradual failure analysis is conducted by calculating the constituent failure indexes of each element to adjust the values of its constituent damage factors, thus a material reasonable performance degradation scheme can be applied to each element of the structure. With the loads increasing, the failure indexes, damage factors and the distribution of stresses are updating constantly until the laminates fails completely. The specific implementation method is described in Chapter 4.1.

### 2.2. Macro–micro mechanics analysis method of the composite materials

The unit cell model with the face-centered array distribution of carbon fibers is constructed, shown in Fig. 1, to analyze the stresses of fiber and matrix in micro-level by FEM using ANSYS code. This unit cell model is applied with prescribed loads of average unit stress in one of three normal stresses and one of three shear stresses as well as one case with thermal load of unit temperature in the unit cell model, as shown in Fig. 2. The boundary constraint conditions set for the model are the same as it described in the literature by Cai et al. [15]. For example, to obtain stress amplification factors for the prescribed load in the fiber (or 1-) direction for one of the faces, the prescribed load with average unit stress is applied to