Composite Structures 111 (2014) 213–223

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

# Micromechanics modeling for fatigue damage analysis designed for fabric reinforced ceramic matrix composites

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ARTICLE INFO

*Article history:*
Available online 27 December 2013

*Keywords:*
Three-phase micromechanics
Shear-lag
Fracture mechanics
Damage progression
Fatigue failure
Fabric reinforced composite structures

ABSTRACT

A micromechanics analysis modeling method was developed to analyze the damage progression and fatigue failure of fabric reinforced composite structures, especially for the brittle ceramic matrix material composites. A repeating unit cell concept of fabric reinforced composites was used to represent the global composite structure. The thermal and mechanical properties of the repeating unit cell were considered as the same as those of the global composite structure. The three-phase micromechanics, the shear-lag, and the continuum fracture mechanics models were integrated with a statistical model in the repeating unit cell to predict the progressive damages and fatigue life of the composite structures. The global structure failure was defined as the loss of loading capability of the repeating unit cell, which depends on the stiffness reduction due to material slice failures and nonlinear material properties in the repeating unit cell. The present methodology is demonstrated with the analysis results evaluated through the experimental test performed with carbon fiber reinforced silicon carbide matrix plain weave composite specimens.

## 1. Introduction

Historically, advances in aerospace engine performance and durability have been linked to improvements in materials. Recent developments in high performance aerospace turbomachinery engines have led to increased interest in ceramic matrix composites (CMC) to achieve revolutionary gains in engine performance. The use of CMC promises many advantages in turbine development. The most beneficial aspects of CMC are the material's ability to maintain its strength to over 2400 °F, the internal material damping, and the relatively low density. While CMC reinforced with woven and braided fabric preforms are being considered for potential candidates in the NASA's next-generation aerospace turbomachinery engine applications [1,2], one of challenge areas in the development of highly efficient and lighter aircraft engines is that high performance rotating blades are subject to high cycle fatigue (HCF) limitations as a result of high vibratory stresses [3].

While fabric reinforced composites have considerable attention as alternative to conventional laminate composites consisting of stacked unidirectional plies, the architecture of a fabric reinforced composite is very complex and, therefore, the parameters controlling its strength properties are numerous. Considerable advancement has been developed in the analytical methods mainly for static properties of fabric reinforced composites [4–14], reliable analytical capability to analyze the component's fatigue strength and life prediction are still very limited and evolving. This necessitates the development of the effective approach with a feasible analysis procedure to design the fabric reinforced composite structures such as integrally bladed turbine disk (Fig. 1).

The present study has made an attempt to develop an analytical method especially with considering the applicable procedure that combines the analytical methods with limited testing for the fatigue life prediction analysis of fabric reinforced ceramic matrix composite structures.

The repeating unit cell (RUC) concept developed in the previous studies [4–9] has been considered as a reasonable approach to perform stress analysis and failure prediction of fabric reinforced composite structures without having difficulties normally encountered in the micro-structural level of finite element modeling used in predicting the mechanical properties of composites [15]. An analytical RUC concept approach demonstrated in our previous work was utilized in this study. By observing the periodicity of the repeating pattern in a woven (or braided) fabric, it was assumed that a small repeating unit cell can be isolated which is sufficient to describe the fabric architecture.

The geometry model of fabric composites assumed that the RUC (i.e. lamina) of a composite is a system consisting of matrix and yarn slices as depicted in Fig. 2. This micromechanics analytical technique was used to predict the global mechanical and thermal properties of fabric reinforced composites. The calculation of the

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0263-8223/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.compstruct.2013.12.025

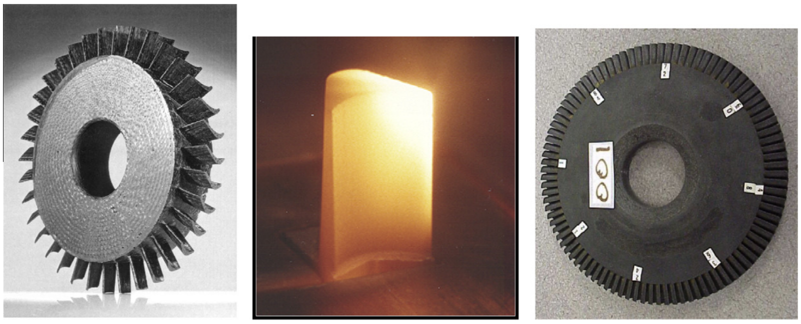

**Fig. 1.** Fabric reinforced ceramic matrix composite integrally bladed turbine disk specimens.

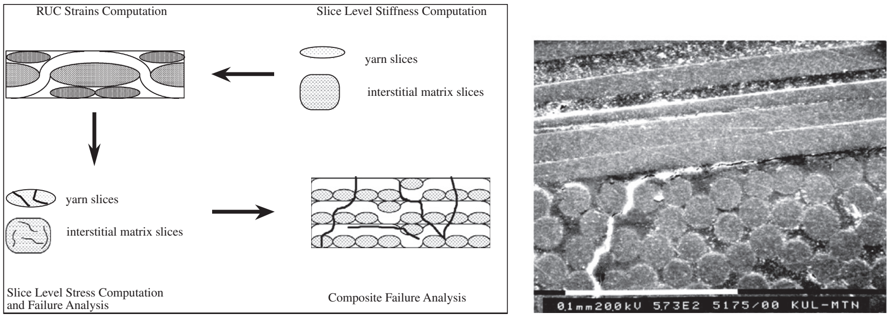

**Fig. 2.** Basic procedures of analysis techniques and micrographic image of failure of plain weave bundle yarn.

mechanical properties was based on a simple geometry analysis which transforms the RUC of a composite into a typical microstructure under uniform global strains. The RUC of a composite was used to represent the global composite structure, and thermal and mechanical properties of the RUC were considered as the same as those of the global composite. The statistical failure criterion and maximum stress strength or maximum strain strength criteria were taken together to predict the failure of individual material slice in the RUC and overall composite structure.

For the progressive failure analysis, the composite failure was defined as the loss of loading capability of the RUC, which depends on the stiffness reduction due to material slice (matrix slice and yarn slice) failures and nonlinear material properties. Fiber failure and matrix cracking reduce the composite global stiffness and number of intact fibers to the point of failure.

The failure mechanism of the yarn slice in the RUC is quite similar to that of a laminated composite, which involves fiber/matrix debonding, fiber-bridged matrix cracking, and statistical fiber failure. In the present study, a progressive failure analysis modeling technique based on the three-phase fiber–matrix micromechanics, fracture mechanics, and statistical models was developed at the yarn and matrix slice level for fiber–matrix yarn slice failures. While the main assumptions and procedures were used from the previous studies [4–9], the present model included the fiber-bridged matrix crack model idealized by a continuum model in which the effect of the bridging fibers can be modeled by an equivalent closure pressure on the crack surface as illustrated in Fig. 3.

The present paper describes the analysis procedure to compute the damage progression and fatigue failure of multilayer fabric reinforced composites. Experimental test results showed that inelastic strain can occur when the applied stress exceeds a “yielding stress”, accordingly a parameter related to the RUC (lamina) stress ratio was engaged to reduce the fiber and matrix stiffness after the “yielding”. Matrix stiffness reduction due to the cracking in the direction normal to the fibers was estimated according to the tensile stress in this direction. A stepwise loading procedure was required since the stress–strain curve is nonlinear due to the material degradation caused by fiber breakage, matrix cracking and inelastic yielding. The analysis steps are summarized in Fig. 4.

## 2. Calculation of effective composite material properties utilizing RUC concept

Real fabric reinforced composites have very complicated geometry structures. As an example, Fig. 5 shows a two-dimensional (2-D) carbon fiber reinforced silicon carbide matrix (C/SiC) plain weave composite laminate which is one of the simplest fiber architectures in fabric composites. It consists of stacked, pre-impregnated layers of woven fabric which are cured and consolidated by a process similar to tape laminates. Each yarn is a bundle of filaments (or fibers) and the yarn size is measured by the number of filaments in the yarn. To model this geometry is very difficult without certain simplifications.

A general geometry model was developed [4] in details for fabric reinforced composites based on several assumptions to describe the fabric architectures and then calculate the mechanical and thermal properties of the fabric composites. Individual yarn architecture was discretely modeled using sinusoidal undulations at yarn crossovers and a straight portion. The iso-strain assumption was used to calculate the overall thermal and mechanical properties and average strains over the RUC. This section describes a brief derivation of geometry model for 2-D plain weave composites, and the calculation for overall thermal and mechanical properties of RUCs.

### 2.1. Geometric model for 2-D plain weave composites

The RUC for the 2-D plain weave composite is described as Fig. 6. The sectional view (section *A*–*A*) shows the undulation of a warp yarn as it crosses over and under the fill yarns. Only one layer of the plain weave is shown in the sectional view.