Composites Part B 90 (2016) 97–106

Contents lists available at ScienceDirect

Composites Part B

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

Deformation and damage modeling of ceramic matrix composites under multiaxial stresses

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ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form
26 June 2015
Accepted 9 December 2015
Available online 7 January 2016

Keywords:
A. Ceramic–matrix composites (CMCs)
B. Mechanical properties
B. Progressive damage
C. Finite element analysis (FEA)
D. Mechanical testing

ABSTRACT

Ceramic matrix materials (CMCs) are candidates for several aerospace applications. There is a need for accurate design and life prediction of CMC components which would experience multiaxial stress states. The present paper propose a finite – element based method for deformation and damage modeling of CMCs under multiaxial stresses, including shear. Rules are developed to couple the normal and shear damage modes. The material properties and damage constants of the in-situ matrix are determined by analyzing tensile test data on cross-ply and $(\pm 45)_S$ specimens. The model is then used to predict the nonlinear load-displacement behavior of a $(\pm 45)_S$ tensile coupon containing a hole. Predictions are compared with experimental measurements.

1. Introduction

At high temperatures, CMCs offer higher stiffness and strength than metals and higher strain to failure and crack growth resistance than monolithic ceramics. These characteristics and their low density make CMCs attractive materials for several aerospace propulsion system components and for space vehicle structures. Over the past two decades, significant progress has been achieved in the development of CMC materials suitable for use up to different maximum temperatures and service environments and some have been incorporated in latest generation aircraft engines [1]. However, wider use of CMCs remains limited partly because of lack of sufficiently validated and reliable modeling methods for design and life prediction of components under anticipated service conditions, including multiaxial stress states and time dependent thermo-mechanical loading.

Currently, depending on the maximum use temperature, Oxide/Oxide (Ox/Ox) and Si-based (non-oxide) CMCs are of most interest for applications up to approximately 1000 C and 1200 C, respectively.

While there are differences in deformation and damage behaviors of Ox/Ox and Si-based CMCs, there are also similarities. For example, under monotonically increasing load along a fiber direction at any temperature, both CMC types exhibit a metal-like global (ply and laminate level) stress-strain response with a linear elastic region up to proportional limit, followed by a nonlinear region of decreasing tangent modulus culminating in failure. The similarity with metals has prompted attempts to model CMCs by methods similar to those used in modeling deformation of elastic–plastic materials [2]. Such models have limited usefulness because they require ad hoc criteria to be used in situations involving non-monotonic and/or multiaxial loading.

Based on extensive testing and observations by a number of researchers [3,4] it is now well established that the mechanism causing nonlinearity in the global stress-strain behavior of CMCs is progressive microcracking of the matrix and at or near fiber–matrix interfaces. A more detailed description of this progressive microcracking process can be found in Refs. [3] and [5]. Fiber pull-out and progressive fracture of fibers also contribute to nonlinearity, but fiber fractures occur at strain levels close to the strain of the composite at failure.

To address damage as the cause of nonlinearity of global stress-strain behavior, the various approaches proposed in the literature can be broadly classified as (a) Continuum Damage Models (CDM) and (b) Micromechanics based damage models (MBDM).

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http://dx.doi.org/10.1016/j.compositesb.2015.12.017
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In the CDM approach, CMC is represented as a homogeneous and anisotropic (usually orthotropic) continuum [6–9]. Damage, regardless of its form, is represented by a damage tensor.

In application, a major drawback of the CDM approach is that it doesn't distinguish between damage occurring in the fiber and that occurring in the matrix or at fiber–matrix interfaces. This delineation is important because in CMC applications significant amount of localized matrix and interface damage can be acceptable, but fiber damage is not. An advantage of the approach is that its application to multiaxial and non-monotonic loading has sound theoretical basis. However, establishment of the damage tensor requires extensive laboratory testing and specialized test techniques even if the stochastic nature of damage evolution in CMCs is ignored.

The MBDM approach does distinguish between matrix, interface and fiber damage and requires distinct criteria for the onset and growth for each. Typically, constituents (fiber and matrix) are modeled as distinct homogeneous materials. The differences between the several proposed models lie primarily in the formulation of “unit” representative “cells” and in the representations of the effects of constituent damage on global strain. For example, the Curtin model [10] assumes that in a unidirectional tensile test specimen with load applied in one of the fiber directions, all of the matrix cracks once stress in the matrix reaches “matrix cracking strength” and that there is no damage at matrix stress less than the matrix cracking strength. Thus, depending on the applied stress, the unit cell contains either no representation of damage, or the matrix is fully cracked. The two unit cell types are used sequentially – one before damage and one after matrix damage has occurred. In the latter case, a shear-lag model is used to estimate stress distribution in constituents based on an assumed “interfacial shear strength”. The onset and evolution of progressive fiber fracture is based on estimated fiber stress and Weibull distribution of fiber strength. Thus, the model acknowledges the stochastic nature of fiber fracture, but not of the matrix. The interface never actually becomes damaged in the sense that no stress-free crack surfaces develop along interfaces.

Some of the assumptions in the Curtin and other shear-lag based micromechanics models are in conflict with physical observations. For example, number of microcracks in the matrix have been observed to increase with increasing applied load in tensile tests [3] and cracks at or parallel to fiber–matrix interfaces have been observed [4]. Also, microcracks in the matrix do not all occur in the same plane. Furthermore, it is not clear how a shear-lag based micromechanics model can be used in situations involving multiaxial stress states.

Shear-lag models have been used in conjunction with the so called “crack-bridging” models [11] in which a dominant matrix crack is assumed normal to a fiber direction, with undamaged fibers across crack surfaces carrying load, thereby reducing the Stress Intensity Factor at the tip of the dominant crack. Such models have limited use in design and life prediction of components because, in many cases, the appearance of a dominant crack is considered the end of structural life.

There are also attempts to combine aspects of the CDM and MBDM approaches in multiscale modeling frameworks, e.g. Refs. [12,13], that allow explicit modeling of constituents, fiber architecture, and constituent damage. A drawback of such approaches is that they require extensive computational effort to establish values of damage parameters using global deformation measurements on laboratory test specimens, such as uniaxial tensile tests.

In the present work, attempt is made to extend an alternative MBDM approach [5] that was initially proposed for uniaxial stress in one of the fiber directions.

A mechanics based life-prediction model for brittle–matrix composites that builds on several concepts and ideas discussed above and also found in Refs. [10,11,14–16] has been described by Santhosh and Ahmad [5]. It considers the deformation due to dominant damage mechanisms such as matrix microcracking and fiber–matrix debonding that is characteristic of this material. In the interest of determining material characteristics at the ply level, details of the stress distribution, including the singularity at the tip of each microcrack in the brittle matrix is not considered. Instead, the model considers the average stress in the composite and the cumulative effect of the microcracks as determined from the experimentally observed ply-level stiffness response of the composite. The model also includes consideration of inelastic deformation of one of the constituents, such as creep of the fiber. This consideration is essential for life prediction of CMC components under high temperature thermomechanical loading. The deformation equations of the model are written in time-rate form and can be easily integrated to determine the load-history dependent composite response. The model has been used in Ref. [5] to characterize the deformation behavior under tension of several ceramic matrix composites. The range of problems that can be solved by the one-dimensional model was extended by Santhosh et al. [17] by incorporating it into a finite-element framework. Analysis of stress-concentration around open holes using this model shows that data from standard tensile tests can be used to predict both the global structural deformation and the local strain field around the hole with adequate accuracy. In Ref. [17], even though damage due to shear stress was not considered, predictions compared favorably with test data because the stress state was predominantly uniaxial.

Although it is preferable to ensure that the primary loads are in the direction of the fibers, CMC component designs do have to consider multidirectional loads and stress states, including shear. Even if the shear stresses are much smaller than the normal stresses, since these materials are weaker in shear than in tension, the consideration of shear in design very important. In the present paper we extend the matrix damage based life-prediction model described in Ref. [5] to include damage due to multiaxial normal and shear stress. In developing the model the emphasis is on modeling the relevant damage mechanisms without making the modeling procedure so complex that it becomes impractical to use in design of CMC components.

2. Matrix damage due to biaxial normal stress

Modeling of the effect of normal stress on damage and the resulting nonlinear load-deformation has been presented in Refs. [5] and [17]. To extend the modeling effort to more general multiaxial stresses one must include modeling of damage due to shear stress. The effect of shear on materials is understood most easily by studying data from pure shear tests such as the Iosipescu test [18]. In this specimen the pure shear region is very small and limited to the centerline between the notches. If the variation of strain over the gage area is sufficiently small, shear strain measurements can be obtained from this test. This test however poses limitations for the testing of woven CMC materials. Factors such as the profile of the tows, unevenness of the weaves, matrix porosity at the surface of the specimen, and presence of cracks in the matrix or at the fiber–matrix interface can all change the local stress state from one of pure shear to that of multiaxial stresses. Even if the initial stress state in the region of interest is that of pure shear, it can change as soon as the matrix in the shear region starts to crack. Therefore, in woven CMCs, shear stress-shear strain data from the Iosipescu test can be unreliable and difficult to unambiguously interpret. For CMCs such data are usually obtained from tensile