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Impact damage and residual strength predictions of 2D woven SiC/SiC composites

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A B S T R A C T

Lightweight, Ceramic Matrix Composites (CMC) are very attractive alternatives to superalloys for applications in hot turbine sections. However, debris, such as dirt, ice and metallic particles may be ingested by aero-engines and impact from them may cause serious damage and/or degradation to CMC components of the engines. It is important to develop predictive models and computational tools that would address this problem. The objective of this paper is to develop a progressive damage model for Ceramic Matrix Composite and implement it into ABAQUS Explicit to numerically predict impact damage and residual strength of a CMC component. To achieve this objective, experimental data on 2D woven SiC/SiC beams subjected to high velocity impact and subsequent four-point-bending tests were used. Modified Hashin–Rotem criteria were assumed for damage initiation and specialized cohesive traction-separation laws were developed to address the fiber toughening mechanism experienced by the CMC in tension and shear modes. Impact damage and four-point-bending of the SiC/SiC specimens were simulated in ABAQUS Explicit, and relatively good agreement was found between FEA predictions and test results, including the impact zone shape and size, as well as the load-deflection response and residual bending strength from the four-point-bending tests.

1. Introduction

Ceramic Matrix Composite (CMC) consists of ceramic fibers embedded in a ceramic matrix. Compared to pure ceramic materials such as Silicon Carbide, Alumina and Silicon Nitride, CMCs have much higher fracture toughness so that they become attractive alternatives to superalloys in hot turbine applications. Not only can the CMC resist higher temperatures, but it is more lightweight than a superalloy. However, there are serious concerns to the damage resistance and tolerance of a CMC from impacting debris, such as dirt, ice and metallic particles ingested by aero-engines. A means of using finite element analysis (FEA) to quantify damage associated with the so-called Foreign Object Damage (FOD) will help engineers to better design CMC components in aero-engines. Furthermore, knowledge of the damage extent and material degradation of the CMC provide valuable information on the remaining life of a CMC component, which is critical for the aerospace industry. The objective of this paper is to use FEA to simulate impact damage and predict the residual flexural strength after impact of a SiC/SiC composite beam.

The concept of Cohesive Zone Model (CZM) is a relatively new method to describe crack growth, and some research has been done to simulate the fracture of CMC by using the CZM. Chandra et al. [1] proposed a specific form of traction-separation equations in a CZM during fracture of a brittle composite material. Walter et al. [2] used cohesive elements to simulate crack propagation in matrix, matrix-fiber interface and fibers in unidirectional fiber-reinforced ceramic matrix composites. Brost et al. [3] applied a CZM to simulate the entire crack initiation, growth and breaking of brittle material under dynamic loading. They also investigated the problem of mesh-dependency and provided a proper mesh representation for the CZM. However, the cohesive zone models used in the above-mentioned studies are all based on cohesive elements or cohesive interfaces, which required a pre-defined crack path during the FEA simulation. In this paper, specialized CZMs are developed and embedded in progressive damage criteria to predict the deformation and fracture behavior of a 2D woven SiC/SiC material. Because the CZM is embedded in the material properties and constitutive equations of the SiC/SiC, it can be used to predict crack initiation and growth regardless of the geometry of the components. It does not require a pre-defined crack path. The CZMs for a 2D woven SiC/SiC material is used to numerically simulate experiments by Choi [4], who conducted high velocity impact and subsequent four-point-bending tests on plain weave, 5 harness satin woven SiC/SiC beams specimens.

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Unlike Polymer Matrix Composites (PMCs), weak interfaces between the fiber and matrix of the CMC allow them to achieve their high toughness from a fiber-bridging mechanism [5,6]. Such fiber-toughening is only apparent when the CMC is in tension and/or shear, and results in non-linear, strain-hardening response after damage initiates and before material instability or the load drop. A three-dimensional progressive damage approach is taken in order to address damage in the through-thickness direction of the CMC. Material deformation, damage initiation and damage evolution for the SiC/SiC are developed and programmed into ABAQUS user-defined material subroutine (VUMAT). The ABAQUS software has a built-in progressive damage model for composite materials [7], but it is two-dimensional and limited to PMCs, which do not undergo the same fiber-toughening mechanism of a CMC.

Recently three-dimensional progressive damage models for FEA predictions of projectile impact damage of PMCs have been proposed [8,9]. However, three-dimensional progressive damage models are lacking for CMCs. Three-dimensional progressive damage criteria are needed to capture through-thickness damage, including cratering, delamination and spalling of a CMC structure. While such local damage may not cause total failure, it weakens or degrades a CMC component. Furthermore, degraded material properties are stored as material state variables in the VUMAT subroutine. The proposed user-material subroutine should therefore be able to address residual strength of the CMC after impact. The following section describes impact and residual bend tests conducted by Choi [4]. A constitutive or progressive damage model that can be used to describe the impact damage is then proposed and implemented in a user-defined material subroutine. The user-subroutine is used in ABAQUS Explicit to numerically simulate high velocity impact damage of a SiC/SiC beam with a steel ball followed by four-point-bending test of the impacted beam to determine the beam's residual bending stiffness and strength after impact.

2. Impact of SiC/SiC beams

In Ref. [4], CMC beams were made from five harness-satin weave SiC preforms, and then manufactured with BN-based interface and SiC matrix by chemical vapor infiltration (CVI). The composite was 0/90°, 8 ply-stacked, and composed of about 34 vol% SiC fibers, 5 vol% BN interface coating, 58 vol% SiC matrix and about 2–3% porosity. Panels were cut into beam specimens with 8 mm in width, 45 mm in length and 2.2 mm in thickness. Material axes and dimensions of the 2D woven SiC/SiC composite are shown in Fig. 1.

Foreign Objective Damage (FOD) test was conducted with a steel ball projectile. The hardened ($HRC > 60$) chrome steel ball had a diameter of 1.59 mm. The target or beam specimen was either partially or fully supported as shown in Fig. 2(a) and (b), respectively. Each specimen was aligned such that the projectile impacted at the center of the beam with a normal incidence angle. Impact damage on the target specimens was then examined by optical and scanning electron microscopy after the impact test. Results from these impact tests will be presented and compared to FEA predictions in later section.

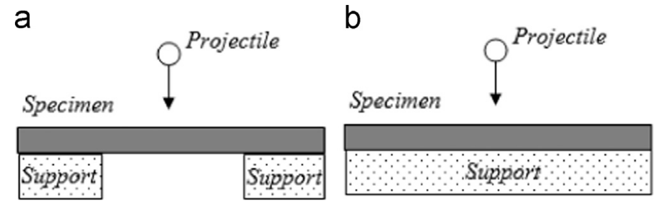

Fig. 2. SiC/SiC beam specimens with (a) partial support and (b) full support.

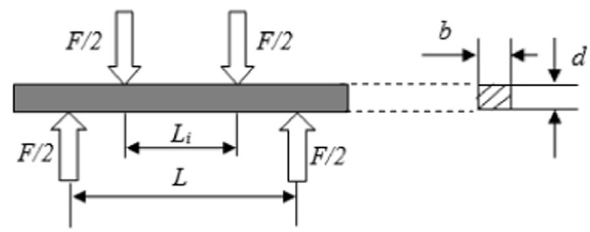

Fig. 3. Four-point-bending test setup.

After the impact tests, four-point-bending tests were performed on the damaged beams to evaluate their residual stiffness and strength. The setup of the four-point-bending test is shown in Fig. 3. Displacement loading was applied evenly in the middle of beam, while force was measured by load cells at the ends of beam. Deflections were measured at center of beam on the opposite side of the impact crater with a linear variable displacement transformer (LVDT).

The maximum bending stress σ at the back side of the beam center is given by

$$\sigma = \frac{3FL}{4bd^2} \tag{1}$$

where F is total loading force, $b = 8$ mm is the width of the beam, $d = 2.2$ mm is the thickness of the beam, $L = 40$ mm is length between pin supports, and $L_i = \frac{L}{2} = 20$ mm is the length between displacement loading, as defined in Fig. 3. The residual flexural strength is calculated from Eq. (1) at the load drop when the CMC beam can no longer sustain increasing force with increasing displacement. Results from the four-point-bending test will be also presented and compared to FEA predictions in a later section.

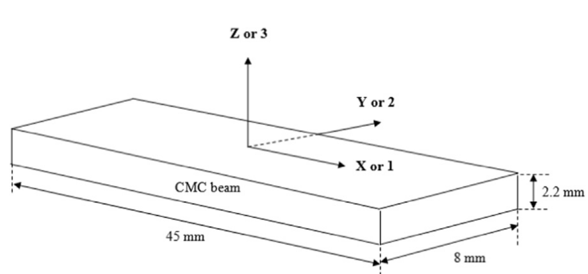

Fig. 1. Material axes and dimensions of SiC/SiC beam in Ref. [4].

3. Constitutive damage model of CMC

A general stress–strain curve of the CMC is characterized by three events as shown in Fig. 4: (1) linear elastic behavior before damage *OA*, (2) damage initiation at *A*, and (3) nonlinear elastic behavior after damage *ABC*. The load drop after Point *B* may occur earlier to coincide with Point A if ideal brittle behavior is to occur after damage initiation. As mentioned earlier, CMCs experience fiber-toughening when they are loaded in-plane tension and/or shear. This is represented as nonlinear strain-hardening response before the load drop (*AB*). The strain-hardening event does not occur in compression or out-of-plane shear because CMCs are ideally linear elastic and brittle in these modes. The following sections describe specific constitutive equations for 2D woven SiC/SiC in Regions *OA*, *AB* and *BC* of Fig. 4.

3.1. Linear elastic behavior before damage (OA)

The 2D woven SiC/SiC composite behaves as an orthotropic, linear elastic material in which the material properties vary