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A New Approach to Simulate Interface Damage in Brittle Matrix Composites

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Abstract

Under mechanical loading, brittle matrix composites develop various damage processes which include cracking of matrix and fiber/matrix interface. Cohesive zone models (CZM) are widely used to model interfacial damage. The aim of this paper is to propose an alternative approach based on a damage model associated to a diffuse meshing method. In this study, the deflection of a matrix crack at the fiber/matrix interface in a single fiber composite is simulated using CZM and the results are compared with those obtained with the new approach. The simulation of a tensile test (in the fiber direction) on a brittle single fiber composite is performed by using the damage model and the result show a good agreement with the reference one obtained with CZM. On this basis, it is shown that the damage model is able to reproduce complex phenomenon as periodic matrix crack deflections at the fiber/matrix interface.

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Keywords: damage, crack deflection, fiber/matrix interface, brittle matrix composites.

1. Introduction

The deflection mechanism at an interface in brittle matrix composites plays an important role in the composite fracture mechanisms. With weak enough interfaces, a matrix crack can be stopped by a deflection mechanism which improves the composite toughness (Evans et al. (1991)). Thus, the analysis of crack deflection in ceramic composites has been widely investigated.

In order to simulate the interface behavior, a finite element analysis has been proposed by Alfano and Crisfield (2001) using a damage law for interface elements. Cohesive zone models are extensively used to simulate interfacial damage and will then be considered as references.

Different criteria have been proposed to predict a crack behavior at an interface between two materials under monotonic loading: the competition between deflection and penetration at the interface is analyzed. A criterion has

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been presented by Martin et al. (2001). The criterion is based on an energetic analysis without any assumption on the ratio of the crack extensions in the deflected and penetrated directions. The crack path selected is the path maximizing the additional energy released by the fracture process. An other crack deflection criterion has been proposed by Pompidou and Lamon (2007). This criterion is based on a stress condition applied to the Cook and Gordon mechanism which considers the initiation of an interfacial crack induced by the stress concentration of the matrix crack.

In this paper, a new approach to simulate the interaction of a matrix crack with an interface is presented. The new approach, called as Fichant-La Borderie model, consists in an isotropic damage model acting at the mesoscopic scale of the material and combined with a diffuse meshing method.

For the rest of the paper, a matrix crack deflection is simulated by modeling the single fiber composite presented by Coradi (2014).

Nomenclature

$\epsilon, \sigma, \tilde{\sigma}$	strain, stress and effective stress tensors
E, ν	material's elastic properties: Young's modulus and Poisson's ratio
$\epsilon^R, \sigma^R, \delta^R, G_f$	material's fracture properties: fracture strain, stress, displacement and energy
D	damage variable
h	finite element size
K	penalty stiffness parameter
δ^f	final displacement

2. Fichant-La Borderie model

The Fichant-La Borderie (FLB) model consists in an isotropic damage law (Fichant et al. (1997)) implemented in the finite element code modeling software Cast3M, used with a diffuse meshing method. The FLB model was originally developed to simulate concrete materials behavior at mesoscopic scale (i.e., at the scale of the meso-components of concrete such as aggregates and cement matrix). Hence, FLB model can describe the failure of heterogeneous or composite materials insofar as this failure is expected to be quasibrittle at the mesoscopic scale which is the case of concrete and various composite materials and especially SiC/SiC composites.

2.1. Damage law

The FLB damage law controls the fracture energy G_f and is regularized by a Hillerborg's method. This model is able to consider the preferential orientation of the damage caused by extensions as well as the crack closure effects and hence describes unilateral effects (i.e., anisotropy induced by damage). In its original version, the FLB model couples damage and plasticity. For brittle matrix composites, only elastic damage in traction is considered without plastic behavior.

The effective stress $\tilde{\sigma}$ is obtained from strain ϵ and mechanical characteristics of materials E and ν :

$$\tilde{\sigma}_{ij} = \frac{E}{(1+\nu)}\epsilon_{ij} + \frac{E\nu}{(1+\nu)(1-2\nu)}\epsilon_{kk}\delta_{ij}. \quad (1)$$

Then the stresses σ_{ij} are derived from the damage variable D :

$$\sigma_{ij} = (1-D)\tilde{\sigma}_{ij}^+ + \tilde{\sigma}_{ij}^-, \quad (2)$$

where $\tilde{\sigma}_{ij}^+$ and $\tilde{\sigma}_{ij}^-$ are respectively the positive and negative components of the effective stress tensor.

The damage variable D is calculated from the maximal positive principal strain ϵ_I ($\epsilon_I > \epsilon_{II} > \epsilon_{III}$) and the fracture strain ϵ^R :

$$D = 1 - \frac{\epsilon^R}{\epsilon_I} \exp \left[A \left(1 - \frac{\epsilon_I}{\epsilon^R} \right) \right] \quad \text{when } \epsilon_I > \epsilon^R > 0, \quad \text{with } A = \frac{E(\epsilon^R)^2 h}{G_f}. \quad (3)$$

The damage variable D ranges from 0 to 1: 0 when the material is undamaged, 1 when the material is fractured.

The FLB damage law, represented in Fig. 1, has the advantage to need only four parameters (E , ν , ϵ^R , G_f) to simulate the damage of a material.

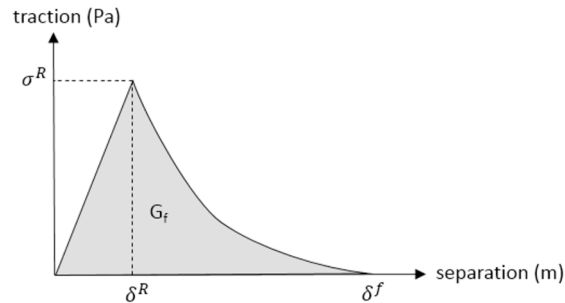


Fig. 1. Damage law for FLB model.

2.2. Meshing method

In addition to this damage law, a special meshing method, presented by Daoud et al. (2013), is used. It consists in projecting material properties on the shape functions of a finite element mesh. This method, called diffuse meshing method, allows the user to override the geometry of heterogeneities and therefore to use a regular mesh. Clearly, some finite element are of “mixed” type with different materials in this element. For the SiC/SiC single fiber composite, at each integration point, the properties of the fiber, matrix or interface are assigned based on the integration point position as illustrated in Fig. 2.

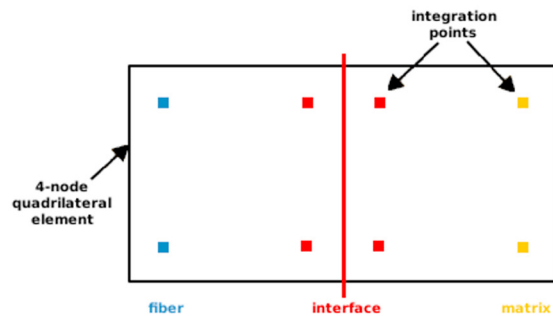


Fig. 2. Diffuse meshing method principle.

3. Simulation of a matrix crack deflection at the fiber/matrix interface

In order to validate the FLB model, a numerical sample is tested and the results are compared with the results provided by another model using a cohesive zone model (CZM).

The material simulated is a single fiber composite with a SiC fiber surrounded by a SiC matrix cylinder (Fig. 3 (a)). The micro-composite’s geometry and properties are extracted from Coradi (2014).

A tensile test is simulated in the fiber direction. This tensile test is used to model a matrix crack propagation (mode I crack) followed by a deflection of the matrix crack at the fiber/matrix interface (mode II crack). The test is driven by equal imposed displacements \bar{U} on both upper and lower specimen surfaces. The loading and boundary conditions are illustrated in Fig. 3 (b).

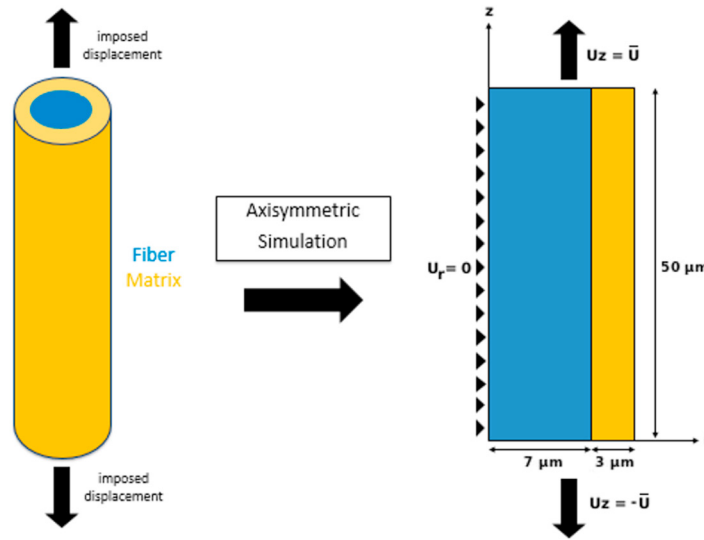


Fig. 3. (a) Geometry of the single fiber composite; (b) Axisymmetric model with boundary conditions.

The CZM and FLB model simulations are illustrated in Fig. 4 and detailed in the following sections.

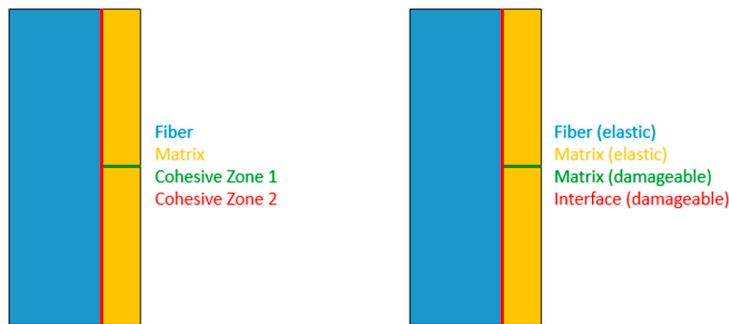


Fig. 4. (a) Simulation with the CZM; (b) Simulation with the FLB model.

3.1. Simulation with cohesive zone model

The simulation with the cohesive zone model (CZM) is performed with the finite element modeling software Abaqus using the surface-based cohesive method implemented. To mesh the specimen, 12500 CAX8 (8-node bi-quadratic axisymmetric quadrilateral) elements and 38101 nodes are used.

The damage initiation criterion used is defined in Eq. 4. The damage initiates when a quadratic interaction function, involving the nominal stress ratios, reaches a value of one:

$$\left\{ \frac{\langle \sigma_n \rangle}{\sigma_n^R} \right\}^2 + \left\{ \frac{\sigma_s}{\sigma_s^R} \right\}^2 + \left\{ \frac{\sigma_t}{\sigma_t^R} \right\}^2 = 1, \tag{4}$$

where \vec{n} , \vec{s} and \vec{t} are respectively the normal, first shear and second shear directions as described in Fig. 5 (a). For the specimen simulated, fracture properties are assumed to be equal in all directions:

$$\sigma_n^R = \sigma_s^R = \sigma_t^R \quad \text{and} \quad K_{nn} = K_{ss} = K_{tt}. \tag{5}$$

The traction-separation law used has a linear shape and introduces the fracture energy $G_f = \frac{1}{2} \delta^R \sigma^R$ as shown in Fig. 5 (b).

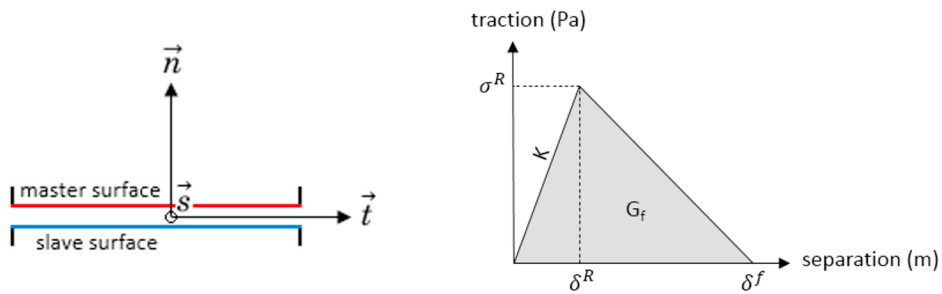


Fig. 5. (a) Surface-based cohesive method principle; (b) Traction-separation law for CZM.

In order to simulate the matrix crack deflection at the interface, two cohesive zones were created: one (CZ1) to simulate the matrix crack propagation with the matrix fracture properties, the other (CZ2) to simulate the fiber/matrix decohesion with the interface fracture properties. The cohesive zones properties are summarized in Table 1.

Table 1. Cohesive zone properties.

Cohesive Zone	K (N/m^3)	σ^R (MPa)	G_f (N/m)
CZ1	10^{19}	500	3
CZ2	10^{19}	300	4

The penalty stiffness parameter K is chosen the higher possible without jeopardizing the simulation stability. Indeed, too high values of K lead to numerical errors while too small values can lead to wrong solutions.

An isotropic elastic law is used to model fiber and matrix behaviors with $E_{fiber} = 200$ GPa, $E_{matrix} = 400$ GPa and $\nu_{fiber} = \nu_{matrix} = 0,2$.

3.2. Simulation with Fichant-La Borderie model

Cohesive zones are replaced by a continuous approach using FLB isotropic damage law with diffuse meshing method. In order to make the comparison with the CZM possible, the crack path is also predefined in the FLB model simulation by setting only one horizontal line of elements in the matrix which can be damaged (Fig. 4 (b)). To simulate the interface behavior, the diffuse meshing method already presented in Fig. 2 is used.

Materials properties are summarized in Table 2. Fracture properties of the matrix, which can be damaged, and interface are identical to those applied to respectively CZ1 and CZ2. To mesh the single fiber composite, 12500 QUA4 (4-node linear quadrilateral) elements and 12801 nodes are used.

Table 2. Material properties.

Material	Material behavior	E (GPa)	ν	σ^R (MPa)	G_f (N/m)
Fiber	Elastic	200	0.2		
Matrix	Elastic	400	0.2		
Matrix	Damageable	400	0.2	500	3
Interface	Damageable	200	0.2	300	4

3.3. Cohesive zone model vs. Fichant-La Borderie model

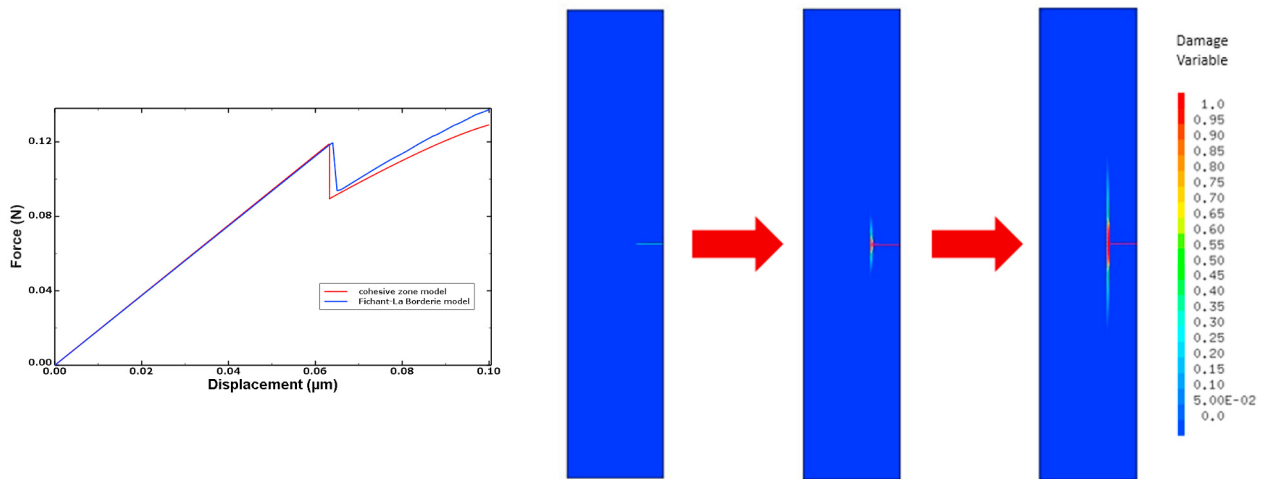


Fig. 6. (a) Matrix crack deflection at the interface: CZM vs. FLB model response; (b) Damage propagation with the FLB model.

The CZM and FLB model are now compared and both, global and local, behaviors are analyzed in order to validate the new approach.

For the global behavior, force versus displacement curves are confronted in Fig. 6 (a) and the FLB response shows a good agreement with the CZM used as a reference. For the local behavior, the FLB model accurately describes the crack path propagation in the specimen in Fig. 6 (b). The matrix crack pattern is perpendicular to the axis of tensile loading until reaching the fiber. Then, a deflection along the fiber/matrix interface is observed and is related to the sudden decrease of the load observed on the Load-Deflection response plotted in Fig. 6 (a). The simulation allows to show that the deflection mechanism can be satisfactorily reproduced with the FLB model.

4. Simulation of periodic matrix crack deflections at the fiber/matrix interface

Once the FLB model validated, a simulation without a predefined crack path is performed. In this case, all materials can be damaged as shown in Table 3. A default is created which consists in lowering the fracture stress of the selected elements. The default allows the damage to localize in the middle of the specimen.

Table 3. Material properties.

Material	Material behavior	E (GPa)	ν	σ^R (MPa)	G_f (N/m)
Fiber	Damage	200	0.2	3000	3
Matrix	Damage	400	0.2	500	3
Default	Damage	400	0.2	250	3
Interface	Damage	200	0.2	300	4

The results are illustrated in Fig. 7. As the entire matrix can be damaged, a multi-cracking phenomenon can be simulated. The first crack develops at the default level and once this crack deflects at the interface, other matrix cracks appear and deflect until the full debonding between fiber and matrix is reached. Then, as shown in Fig. 7 (a), the specimen rigidity becomes equal to the fiber rigidity. This simulation demonstrates the possibility, with the FLB model, to simulate periodic crack deflections without pre-defining cracks paths.

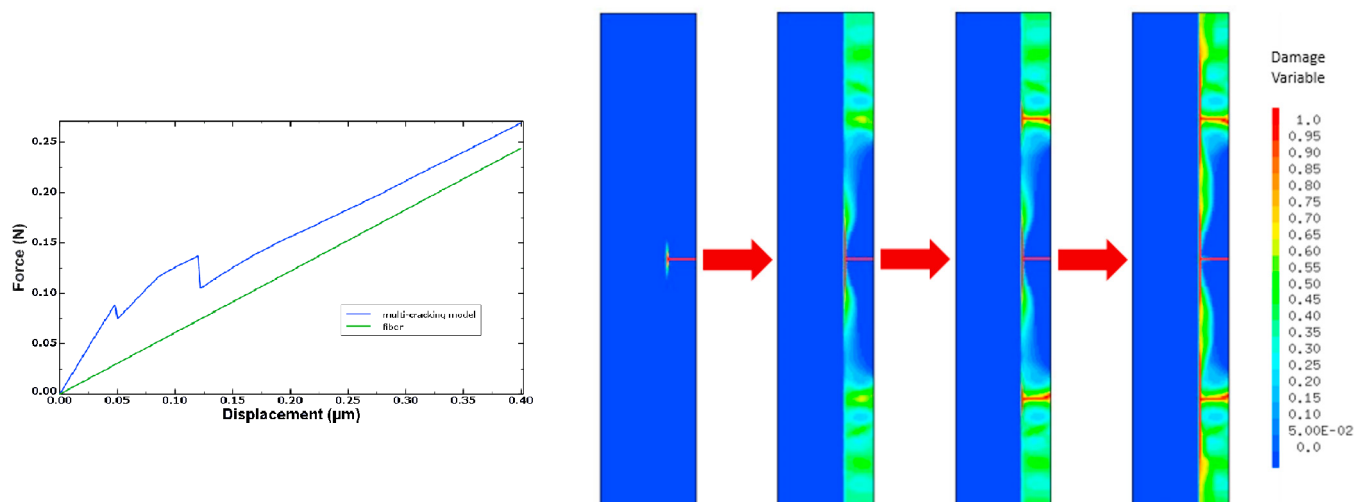


Fig. 7. (a) Periodic matrix crack deflection response; (b) Damage propagation of periodic matrix crack deflection.

With longer specimens, the influence of the model parameters on the number of cracks and the distance between cracks can be studied.

5. Conclusion

The FLB model, consisting in an isotropic damage model acting at the mesoscopic scale of materials described from diffuse meshing, has been successfully applied to simulate the matrix crack deflection at the fiber/matrix interface of a SiC/SiC micro-composite. In order to validate the FLB model, the results have been compared with a cohesive zone model used as reference. The possibility to simulate a crack deflection and periodic cracks deflections with the FLB model without forcing crack path has been shown. The influence of the model parameters on the crack path and the periodic crack phenomenon will be investigated.

Acknowledgements

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