Chapter

Finite Element Analysis of Fiber Pull-Out of Ceramic Matrix Composites

Wang Hong

Abstract

Ceramic matrix composites (CMCs) are widely used in aerospace, defense industry, and other fields because of their high strength, high toughness, and high temperature resistance. The interface phase with matching performance and structural coordination is the key element to improve the brittleness of CMCs and improve their strength and toughness. In this chapter, based on the fiber pull-out experiment, using the cohesive zone model as the interface element model, a two-dimensional axisymmetric fiber pull-out finite element model was established and simulated. The results show that within a certain range, higher interface bonding strength and interface fracture energy increase the maximum debonding load during fiber pull-out and enhance the material bearing capacity.

Keywords: ceramic matrix composites (CMCs), interface mechanics, fiber pull-out, finite element method (FEM), cohesive zone model

1. Introduction

Ceramic matrix composite (CMC) is a third-generation composite material composed of ceramic as the matrix and various reinforcing phase fibers [1]. It has excellent properties such as high strength, high toughness, high temperature resistance, and oxidation resistance, which overcome traditional ceramic materials that have large brittle performance defects and are widely used in components such as nose cones and wing leading edges of space vehicles, rocket engine nozzles, rocket head radar radomes, etc. [2, 3]. The interfacial phase is the medium and transition zone between the matrix and the reinforced phase material of the ceramic matrix composite material [4], which mainly plays the role of transferring load and blocking crack propagation. Its structure and composition play a vital role in the performance of the interface, in turn, affects the mechanical properties of ceramic matrix composites. There are methods for studying interface problems such as fiber pull-out and fiber push-out. The most typical one is the fiber pull-out experiment. This method was introduced several decades ago [5] and has now become the basic experimental method for related research. However, the experimental investigation can only reflect a certain phenomenon intuitively. It is difficult to prepare the specimen for the fiber pull-out experiment. At the same time, the debonding process between the fiber and the matrix is also affected by factors such as interface strength and interface fracture energy.

The numerical simulation method can obtain data that is difficult to obtain in the experiment, which provides a powerful tool for studying interface problems.

In this chapter, the cohesive zone model [6, 7] is used to simulate the interface of ceramic matrix composites, the maximum nominal stress damage criterion is used to determine the initial damage of the interface element, and the energy-based linear attenuation damage evolution criterion is used to determine the damage evolution law of the interface element. At the same time, considering the influence of interface bonding strength and interface fracture energy, the debonding process of fiber pull-out of ceramic matrix composites are analyzed.

2. Fiber pull-out model

In this chapter, the commercial software ABAQUS is used to perform finite element simulation analysis on the fiber-out process of ceramic matrix composites. In the calculation process of the finite element method, it is necessary to first establish a geometric model for single fiber extraction. According to the geometric and mechanical characteristics of the single fiber extraction experiment, a two-dimensional axisymmetric cylindrical model is used to simulate and analyze it. The geometric model of the fiber pull-out is shown in **Figure 1**. Its structure contains fiber, interface layer, and matrix. The fiber has a certain embedding depth in the matrix.

In the fiber pull-out model, the fiber and the matrix are its main structures. Considering the calculation efficiency, the CAX4R element is selected for the fiber and the matrix. The interface layer is the most deformed part of the fiber pull-out model, which requires higher accuracy. The COHAX4 element is selected for the interface. The meshing result of the fiber pull-out model is shown in **Figure 2**.

The cohesive element [8, 9] is a special element constructed based on the cohesive zone model. In the two-dimensional model, the debonding of the interface is divided into two directions, tangential and normal. The stress $\boldsymbol{\sigma}$ in the crack area is a function of the crack opening displacement $\boldsymbol{\delta}$.

$$\boldsymbol{\sigma} = f(\boldsymbol{\delta}) \tag{1}$$

As the crack opening displacement $\boldsymbol{\delta}$ increases, the stress $\boldsymbol{\sigma}$ increases. When the stress reaches the initial damage criterion, the initial damage of the cohesive element in the interface occurs. The initial damage criterion uses the maximum nominal stress criterion.

$$\max\left\{\frac{\sigma}{\sigma_s}, \frac{\tau}{\sigma_t}\right\} = 1 \tag{2}$$

where σ and τ represent the tangential and normal stress at the interface and σ_s and σ_t represent the bonding strength of the interface.

The energy released during cracking is called fracture energy or energy release rate G, and its calculation formula is

$$G = \int \boldsymbol{\sigma} d\boldsymbol{\delta} = \int f(\boldsymbol{\delta}) d\boldsymbol{\delta} \tag{3}$$

In order to characterize the damage evolution law after the initial damage of the cohesive element at the interface, the damage factor d needs to be defined. When the cohesive element just occurred at the initial damage, the damage factor $d = 0$, and no damage evolution of the cohesive element occurred at this time. When the stress of the cohesive element in the interface continues to increase and the damage evolution conditions are met, the damage factor will increase according to its evolution

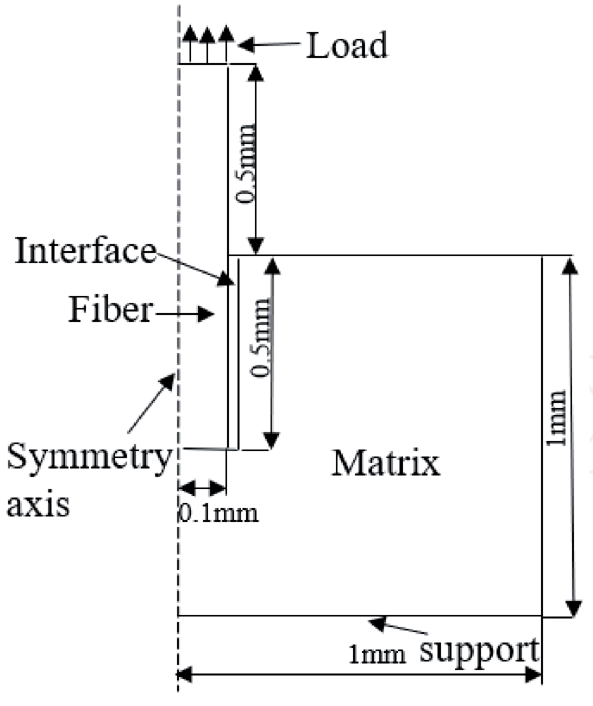

Figure 1.
Geometric model of fiber pull-out.

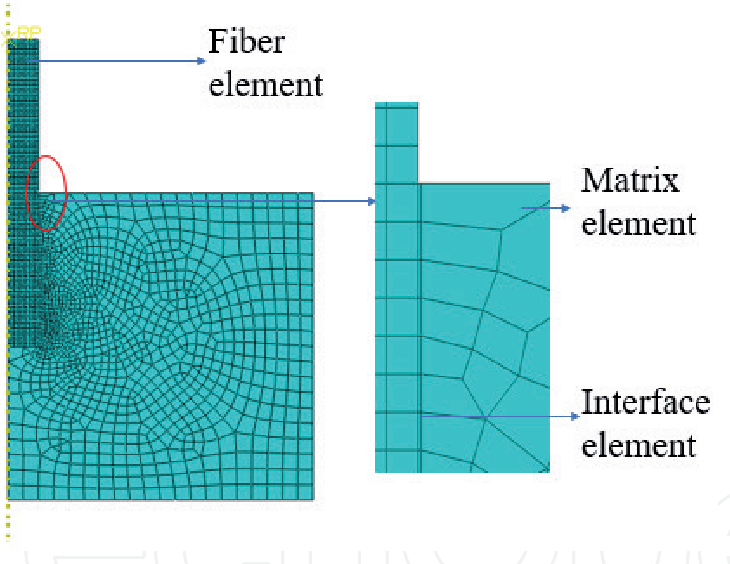

Figure 2.
Finite element meshing results.

rule until the damage factor d = 1, and at this time the cohesive element fails and is deleted. Damage evolution criterion adopts energy-based damage evolution form.

$$d = \int_{\delta_m^{fail}}^{\delta_m^{init}} \frac{\boldsymbol{\sigma}_m}{G - G_{init}} d\boldsymbol{\delta} \tag{4}$$

where $\boldsymbol{\delta}_m$ represents the equivalent displacement, $\boldsymbol{\delta}_m^{init}$ represents the equivalent displacement when the cohesive element is initially damaged, and $\boldsymbol{\delta}_m^{fail}$ represents the equivalent displacement when the cohesive element fails completely. G is the fracture energy and G_{init} is the energy at the initial damage of the cohesive element.

In the following research, T300 fiber, SiC matrix, and PyC interface layers are taken as the research objects, and the material properties are shown in **Tables 1** and **2**.

Material	Transverse Young's modulus (GPa)	Axial Young's modulus (GPa)	Transverse shear modulus (GPa)
Fiber (T300)	15	230	7
Material	**Axial shear modulus (GPa)**	**Transverse Poisson's ratio**	**Axial Poisson's ratio**
Fiber (T300)	27	0.3	0.013

Table 1.
Material properties for T300 fiber.

Material	Modulus (GPa)	Poisson's ratio (GPa)	Fracture energy (J/m^2)
Matrix (SiC)	450	0.17	—
Interface (T300)	35	—	4–10

Table 2.
Material properties for SiC matrix and PyC interface.

3. Results and discussion

Figure 3 shows the load–displacement curve of the simulation results of fiber pull-out. The fiber pull-out process is mainly divided into four stages: elastic deformation, partial debonding, complete debonding, and fiber friction slip. It can be seen from the figure that during the stage of elastic deformation (O–A), there is a linear relationship between load and displacement, and no damage occurs at the interface. During the stage of partial debonding (A–B), the load–displacement curve exhibits nonlinearity, at which time some interface elements are damaged and enter the damage evolution phase. During the stage of complete debonding (B–C), the load drops suddenly, and all interface elements are damaged. When the damage factor *d* of all units is zero, the interface is completely debonded. During the stage of fiber friction slip (C–D), the load is kept at a low level to resist friction.

The load–displacement curve of fiber pull-out under different interface bonding strength is shown in **Figure 4**. With the increase of the interface bonding strength,

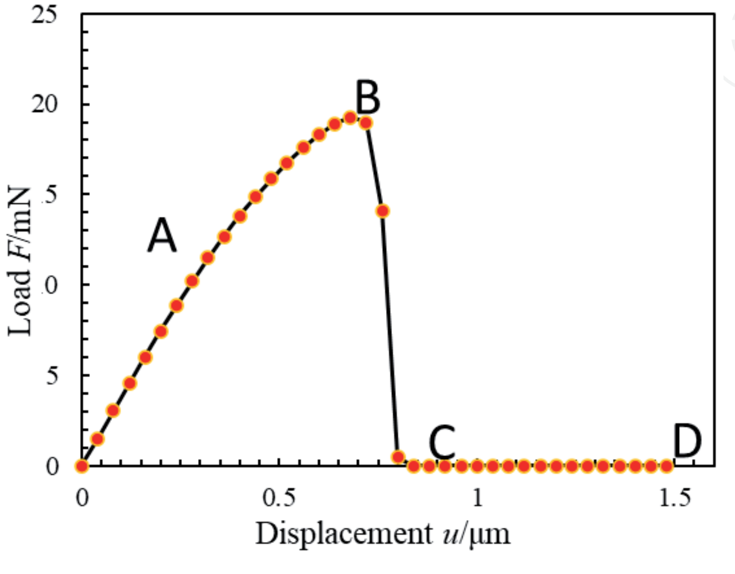

Figure 3.
Load vs. displacement curve of fiber pull-out.

the initial damage of the interface unit needs to be carried out under a higher load, thereby increasing the maximum debonding load and improving the bearing capacity of the material. The maximum debonding load at the interface bonding strength of $\sigma_s = \sigma_t = 30$ MPa is increased by nearly 28.34% compared to the interface strength of $\sigma_s = \sigma_t = 15$ MPa. At the same time, the stiffness of the load–displacement curve also increases as the interface bonding strength increases.

The load–displacement curve of fiber pull-out under different interface fracture energy is shown in **Figure 5**. Due to the increase of the interface fracture energy, more energy need to be released during the damage evolution of the interface element to completely damage the interface, thereby increasing the maximum debonding load, expanding the debonding area of the interface, and improving the bearing capacity of the material. At the same time, at a higher interface fracture energy level, its influence on the fiber pull-out process becomes smaller, possibly because the failure of the cohesive element at this time is mainly controlled by the interface bonding strength.

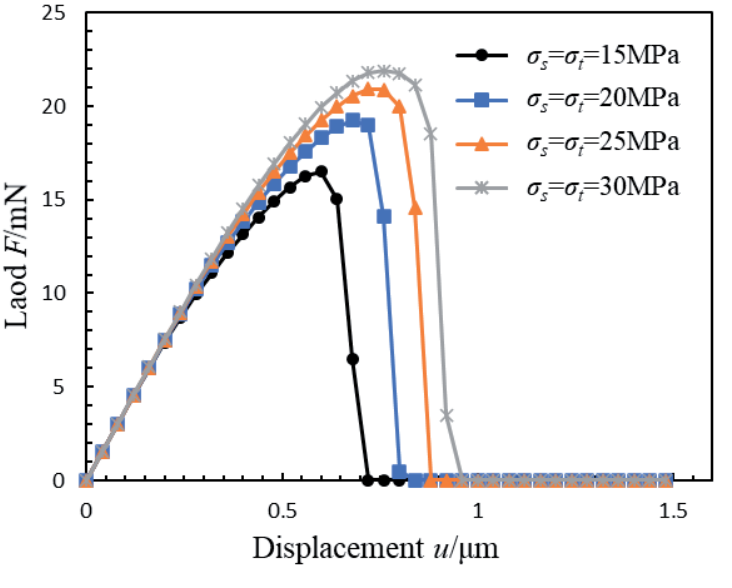

Figure 4.
Load vs. displacement curve of fiber pull-out under different interface bonding strength.

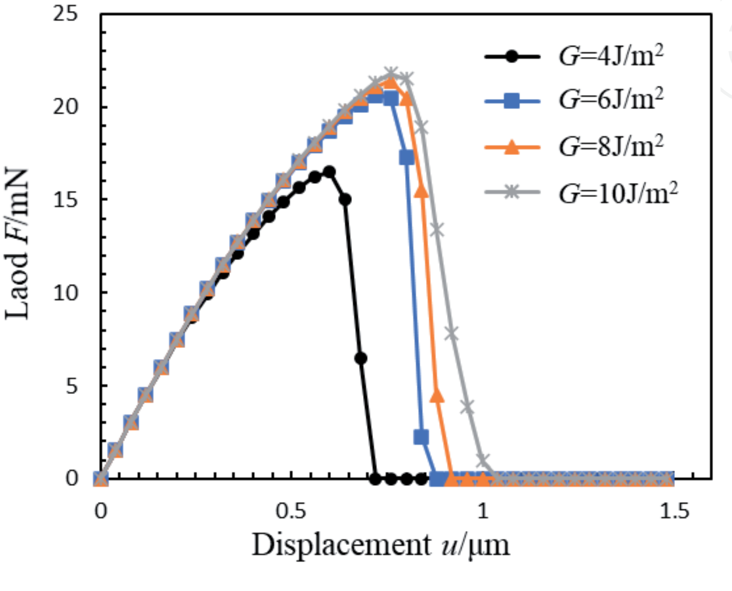

Figure 5.
Load vs. displacement curve of fiber pull-out under different interface fracture energy.

4. Conclusion

Fiber pull-out has experienced four stages, elastic deformation, partial debonding, complete debonding, and fiber friction slip. The maximum debonding load and the bearing capacity of the material increase with the increase of the interface bonding strength and interface fracture energy. However, when the interface bonding strength is too large, the fibers will first undergo brittle fracture, and its impact on the load-bearing capacity of ceramic matrix composites needs further study.

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