MICROSCOPIC ANALYTICAL AND NUMERICAL INVESTIGATION OF ORTHOGONAL CUTTING CFRP

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Keywords: Carbon Fiber Reinforced Polymer, Machining, Micro-mechanical model, Finite element method

ABSTRACT

Carbon Fiber Reinforced Polymer (CFRP) is non-homogeneous and anisotropic, which results in that the machining process of CFRP is quite different with that of metal. In fact, the machining of CFRP includes the damage of fiber fracture, matrix fracture and debonding between the fibers and matrix. The three kinds of damage lead to complex stress evolution patterns and material removal mechanisms.

It has been observed that the constraint effects of the surrounding composite on the fiber to be cut have quite significant influences on the fracture of the fibers and interface damage. In this paper, in order to consider the normal and transverse constraint effects on the fracture of fibers, the elastic foundation beam theory is applied to establish a micro-mechanical model with explicitly modelling the carbon fiber, matrix and the interface. The quasi-static solution of cutting fiber is obtained analytically from the present micro-mechanical model. As a comparison, a micro-mechanical finite element model considering the fiber, matrix and interface is established and solved to reveal the dynamic process of cutting CFRP. The fiber phase, matrix phase, interfacial phase and equivalent homogeneous phase are explicitly established with their respective constitutive relation, as well as the initiation and evolution criteria in the finite element model. The theoretical model for the quasi-static case and finite element simulation for the dynamic case are compared to investigate the normal and transverse supporting effects on the material removal and interface debonding. Particularly, the geometry of the cutting tool such as the tool edge radii on the fracture mode of fibers and the effects of depths of cut are studied based on the finite element model.

1 INTRODUCTION

Because of composite material's excellent mechanical and physical properties [1, 2], it is widely used in aerospace, vehicle manufacturing and other fields [3]. The carbon fiber reinforced polymer (CFRP) composite material includes carbon fiber as the reinforcing material and resin as the matrix [4]. CFRP shows a mixture of fiber, matrix and interface [5]. In fact, the material removal mechanism can be illustrated by the removal behaviour of the fiber, the matrix and the interface during machining. In the actual engineering of machining CFRP, such as drilling or milling CFRP process, it is usually simplified as a two-dimensional orthogonal cutting to reveal the removal mechanism of the material [6]. Due to anisotropy and heterogeneity, the action of cutting force is prone to cause material damages in the machining CFRP.

The book [7] mentioned an approach to predict the cutting force, through the orthogonal cutting experiments to obtain the data of the cutting force, and then according to the empirical formula to establish cutting force Model. The process of cutting CFRP is studied a lot in literature by theoretical, numerical and experimental method. The static analytical approach can analyze the fiber fracture and predict cutting force by introducing the elastic foundation beam model [8]. The static foundation beam model is established on the basis of the Winkler model to predict the cutting force of single fiber. Many scholars have used the static analysis method to simplify the complex model [9, 10]. The fiber is surrounded by the matrix in the micro-model. In order to study the fracture mechanism of single fiber, the single fiber is constrained by the surrounding material during the cutting process. However, the machining CFRP is a dynamic process. Numerous studies of micro/macro approach using FEM for modelling of machining CFRP have been done. In the macro approach of machining CFRP, the finite element method is used to simulate the process of the chip formation and the variation of the sub-surface damage under different fiber angles [11-13]. The micro model of machining CFRP is used to simulate the removal of the microscopic phase and the crack of inter-phase [2]. Rao [14] established a microscopic finite element model, which considered the fiber phase, matrix phase and interface phase. The failure criterion of the fiber was defined by the maximum stress failure criterion, and the failure form of the fiber was analyzed. Calzada [15] established microscopic models of four typical fiber angles (0 °, 45 °, 90 ° and 135 °). The interface phase was defined by continuum elements. The chip formation and the fracture of material in the micro model were analyzed for the different fiber orientation angles. Abena [16] et al. defined the interface element by a bespoke user material subroutine, which is described by cohesive element, under tension and shear behaviour. The fiber phase is defined with the failure form of the maximum stress failure criterion. The resulting cutting force is similar to that of the literature [15]. Mkaddem [17] studied the two-dimensional orthogonal cutting composite by the finite element method, and discussed the variation of cutting forces under the different fiber orientation angles, depths of cut and tool rake angles. Zenia [18] studied the effect of cutting parameters on cutting forces and sub-surface damage. In the process of machining composite materials, the cutting force will change with different cutting parameters, tool geometry, material parameters and other factors.

In this paper, we consider the influence of normal and tangential restraints on the fracture of fiber, and establish the micro-mechanics model based on the elastic foundation beam theory, and then perform the quasi-static analysis. Furthermore, a FE simulation model of single fiber considering various failure modes is established. The model includes single carbon fiber phase, matrix phase, interfacial phase and equivalent homogeneous phase. The carbon fiber is assumed to be transversely anisotropic, and the Young's modulus in the longitudinal direction (along the fiber) and the transverse direction (perpendicular to the fiber), shear modulus in the cross-section and Poisson's ratio are defined. The damage model of the carbon fiber is established by using the maximum stress criterion. The material of the matrix is resin, which is considered to be isotropic and elasto-plastic. The failure initiation model of the matrix is established by shear failure, and the damage initiation and evolution of the resin material depend on the yield strain and fracture energy respectively. Continuum elements are used to describe the interface region. The interface is assumed to be isotropic, and the failure mode of the continuum element is defined by the shear failure. The EHM phase plays the role of supporting constraints without failure definition, because it is not cut during the machining process. The static theoretical model, the quasi – static finite element model (FEM) and dynamic finite element model are used to reveal the failure mechanism of cutting a single fiber. The variation of the cutting force for cutting a single fiber under different process parameters is obtained. In addition, the effects of the tool geometry (such as the tool edge radii) and the depths of cut on the fracture mode of the fiber are investigated by taking into account the local contact of the fiber and the tool.

2 THEORETICAL MODEL

The constraint of the surrounding composite material has a significant effect on the fiber breakage. In the literature [8], the influence of the normal and tangential restraints on the fiber is discussed. The micro-mechanics model based on the theory of elastic foundation beam is established. The model considers carbon fiber, matrix and interface as shown in Fig.1. In the case of changing the cutting depths, the fracture modes of the fiber will have different effects on the material removal mechanism. The static analytical expressions are established for predicting the cutting force.

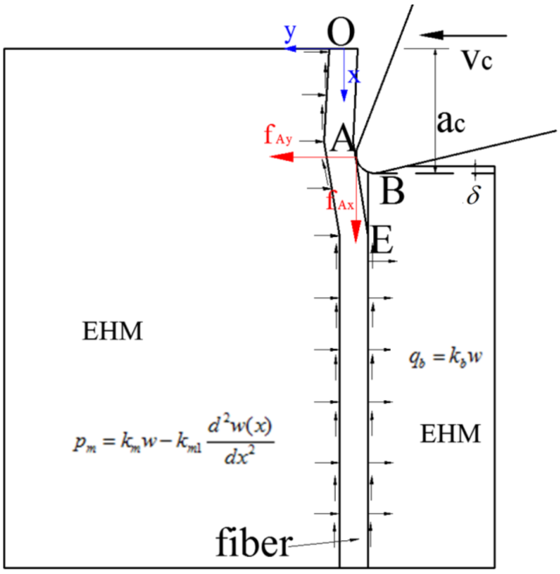


Figure 1: The elastic foundation beam model.

In the model, the reaction force from the supporting composite material per unit length is expressed as

$$p_m = k_m w - k_{m1}\frac{d^2w(x)}{dx^2} \tag{1}$$

The bonding force between the fiber and the matrix per unit length is expressed as

$$q_b = k_b w \tag{2}$$

The equilibrium equation of an infinitesimal element of a length dx of fiber can be obtained:

$$E_f I_f \frac{d^4w(x)}{dx^4} - k_{m1}\frac{d^2w(x)}{dx^2} + (k_m + k_b)w(x) = 0 \tag{3}$$

Where k_m is the modulus of the supporting composite, which is the role of normal, k_{m1} is the second parameter of the supporting composite, which is attributed to the tangential effect.

The maximum stress of the beam is expressed as

$$\sigma = E_f r \frac{d^2w}{dx^2} \tag{4}$$

Where r refers to the fiber radius. When the fiber and the matrix appear to be separated, until $\max\left(E_f r \frac{d^2w(h, f_{Ay})}{dx^2}\right) = \sigma^{tensile}$ is satisfied, and $k_b w_E(h, f_{Ay}) \le \sigma_b$, the force of the single fiber cut off is obtained, which is expressed as $\min\limits_{h, f_{Ay}}\left\{\left(\max\left(E_f r \frac{d^2w\left(h, f_{Ay}\right)}{dx^2}\right) - \sigma^{tensile}\right)^2\right\}$. The Solving procedure of the critical cutting force using the theoretical model is shown in Fig.2.

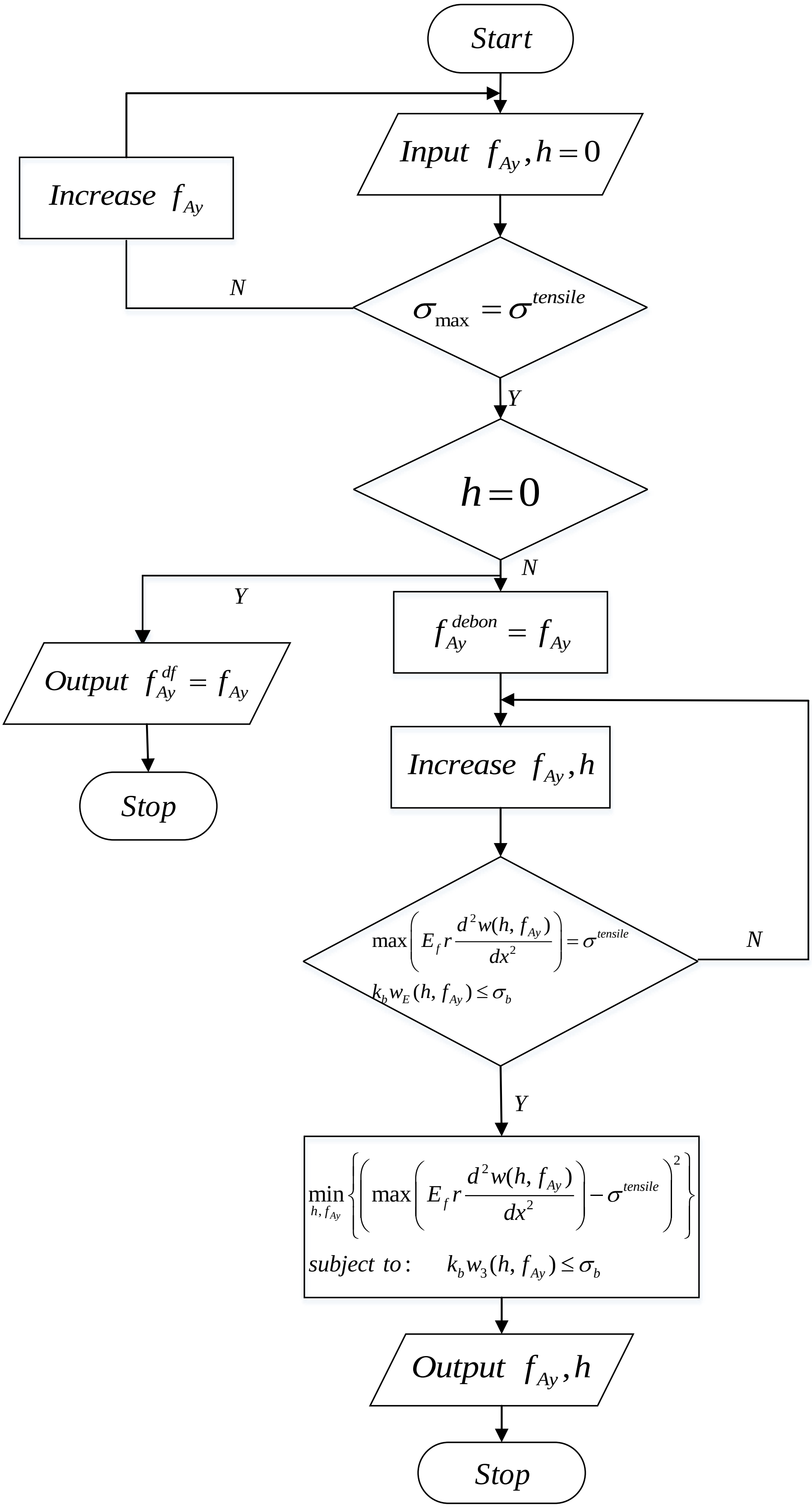


Figure 2: Solving procedure of the critical cutting force using the theoretical model

3 DYNAMIC SOLVING ALGORITHM AND MATERIAL MODELS

In this section, the explicit dynamic solving algorithm and the material models in the numerical analysis of the cutting process are presented.

3.1 Iteration algorithm

In this paper, the finite element method is used to analyze the cutting process of the single fiber, which belongs to the nonlinear dynamic solution problem and is calculated by explicit dynamic analysis. The explicit integral algorithm is based on the explicit integration principle and the diagonal element mass matrix [19]. The equation of motion is established using the central difference integration rule, expressed as follows:

$$\begin{aligned} \dot{\mathbf{u}}^N_{(i+\frac{1}{2})} &= \dot{\mathbf{u}}^N_{(i-\frac{1}{2})} + \frac{\Delta t_{(i+1)} + \Delta t_{(i)}}{2}\ddot{\mathbf{u}}^N_{(i)}, \\ \mathbf{u}^N_{(i+1)} &= \mathbf{u}^N_{(i)} + \Delta t_{(i+1)}\dot{\mathbf{u}}^N_{(i+\frac{1}{2})}, \end{aligned} \tag{5}$$

Here, $\mathbf{u}^N$ is the displacement, i represents the number of increments in the explicit dynamic analysis step. The central difference integration operation is explicit in the sense that the kinematic state is advanced using known values of $\dot{\mathbf{u}}^N_{(i-1/2)}$ and $\ddot{\mathbf{u}}^N_{(i)}$ from the previous increment. The key to improve the computational efficiency is to introduce the diagonal element mass matrix, and the acceleration is calculated from the following equation

$$\ddot{\mathbf{u}}^N_i = (\mathbf{M}^{NJ})^{-1}(\mathbf{P}^J_{(i)} - \mathbf{I}^J_{(i)}) \tag{6}$$

where, $\mathbf{M}^{NJ}$ is the mass matrix, $\mathbf{P}^J$ is the applied load vector and $\mathbf{I}^J$ is the internal force vector.

The mesh division technology is the key of FEM analysis. Firstly, the coarse mesh is used to test the model, and then the mesh is refined by the mesh convergence analysis to select the exact analysis results. The mesh of processed region is refined locally, and the other part is divided by the coarse mesh.

3.2 Material Models

CFRP is formed by curing carbon fibers and resins, consisting of fiber, matrix and interface essentially. The material failure criterion is defined by the material stiffness degradation, when the damage factor reaches one, the material begins to failure. The different material properties are given for different composition phases. In this paper, the material stiffness degradation is used to simulate the damage in the actual processing of the material. During the calculation, when the stress field satisfies the failure criterion, the corresponding stiffness is reduced.

The property of carbon fiber is different in the fiber direction and perpendicular to the fiber direction, and the fiber is modelled as an elastic-brittle and anisotropic material. The maximum stress is used to predict the failure of carbon fiber material. When the stress reaches to the strength limit, the material will begin to failure. The material of matrix is resin, which is regarded as an isotropic hardened plastic material. The implicit integral algorithm is used to calculate the matrix material. In this paper, the shear failure criterion is defined as the starting failure criterion, and the damage evolution is defined by the fracture energy. The interface is the connection between the fiber and the matrix, and plays a transfer role. The interfacial phase is described as a continuum element, which is considered to be an isotropic material. The failure model is defined by shear failure. The equivalent homogeneous phase plays a supporting role in the model, and the deformation of machining process is unconsidered. Therefore, the material's anisotropy is considered only. The two-dimensional microscopic model of cutting CFRP is shown in Fig. 3.

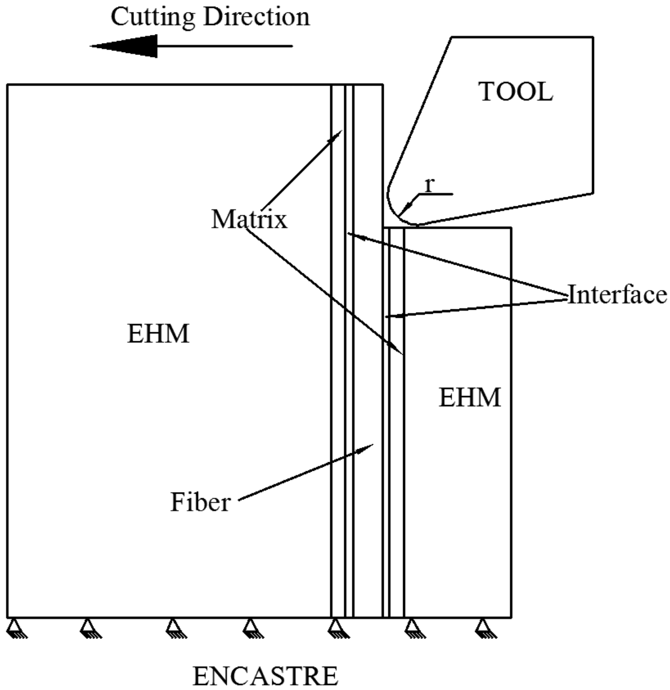


Figure 3: Model of cutting single fiber.

4 NUMERICAL RESULTS

The numerical analysis of cutting a single fiber is conducted by a microscopic finite element (FE) model, which includes the fiber phase, matrix phase, interfacial phase and equivalent homogeneous material. The quasi – static FE and the dynamic FE analysis of the cutting process are performed in the finite element analysis software ABAQUS, and the numerical results are compared with the theoretical results obtained in Section 2. In the dynamic model of cutting CFRP, the variation of the cutting force under different depths of cut and tool edge radii, as well the failure mechanism of a single fiber is studied.

4.1 The establishment of the geometric model

The material is a unidirectional CFRP with 90 ° fiber orientation angle, in which the carbon fiber has a diameter of 6.5μm and a volume fraction of 65%. The model in Fig.4 shows the fiber phase, the matrix phase, the interface phase, and EHM phase. The above four-phase model is established by two-dimensional modeling method. The size of the workpiece is specified as: a single fiber with the diameter 6.5μm, the interface phase thickness 1μm, and the matrix thickness 2μm. Because the single fiber fracture is concerned in the present study, the fiber phase, the interface phase and the matrix phase are assigned the structured mesh. The mesh size is finely meshed about 1μm according to the mesh convergence analysis. The EHM phase is used the free mesh, and the mesh size of EHM is meshed finely next to the matrix, and meshed coarsely away from matrix. The element type used a 4-node bilinear plane stress quadrilateral with reduced integration (CPS4R). The tool is defined as the analytical rigid, with the rake angle 25 ° and the clearance angle 5 °.

The bottom of the CFRP workpiece is fully constrained. A reference point RP is defined at the tool, and the cutting speed is defined at the point RP. The contact type is the surface-node contact between the surface of the tool and the nodes of the cutting region. The tie constraint is defined at neighboring nodes of each phase, in order to avoid the phenomenon of invasion.

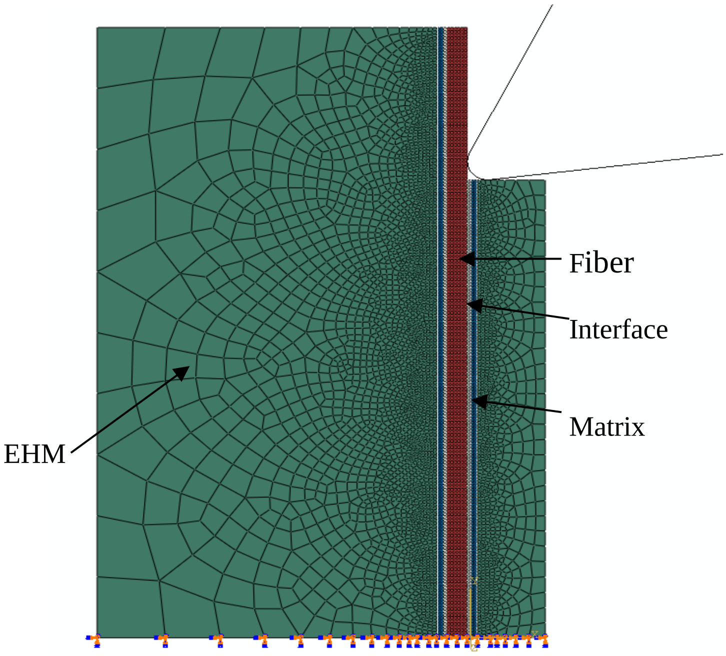


Figure 4: Meshing model of cutting single fiber.

4.2 Numerical analysis of cutting a single fiber

The normal and the transverse effects are considered in the static theoretical model and the FE simulation for the quasi-static and the dynamic case respectively. The comparison between the theoretical and the numerical results is conducted in this section. In the dynamic model, the influence of four different tool edge radii and the effect of different depths of cut on the removal of CFRP are studied. The stress distribution in the CFRP and the variation of the cutting force are analyzed in this section. Material properties used are shown in Table 2.

Items	**Symbol**	**Value**
Young's modulus of fiber	E_f	295 GPa
Shear modulus of fiber	G_f	103 Gpa
Poisson's ratio of fiber	v_f	0.3
Tensile strength of fiber	σ_t	4.0 Gpa
Compressive strength of fiber	σ_c	4.0 Gpa
Shear strength of fiber	σ_s	0.38 Gpa
Young's modulus of matrix	E_m	3.45 Gpa
Poisson's ratio of matrix	v_m	0.3
Yield strength of matrix	σ_y	85 MPa
Equivalent modulus of the interface	E_i	115 GPa
Transverse effective elastic modulus of EHM	E_m^*	9.65 GPa
Shear modulus of EHM	G_s	6.21 GPa
Poisson's ratio of EHM	v	0.3

Table 2: The material properties.

In the numerical analysis, the static and dynamic finite element analyses of cutting CFRP are accomplished, respectively. The quasi-static analysis is conducted using the general static analysis step, and the load condition of the static analysis is applied by prescribing the displacement of the cutting tool. The numerical models consider the effect of normal and transverse. In the theoretical analysis, the effect of normal only, as well as both the normal and transverse effects are considered respectively. From the comparison in Fig.5, the cutting forces obtained from the numerical and the theoretical models agree well. When the depth of cut is relatively larger, the cutting force predicted from theoretical model is quite close to the result from the numerical model. In numerical analysis, the Hashin failure criteria consider the effect of the longitudinal, the transverse and the shear failure, and any one of the failure occurs, the material will fracture. In theory, the fiber material is only defined the tensile failure. Therefore, the theoretical result is a bit larger than that of the numerical simulation.

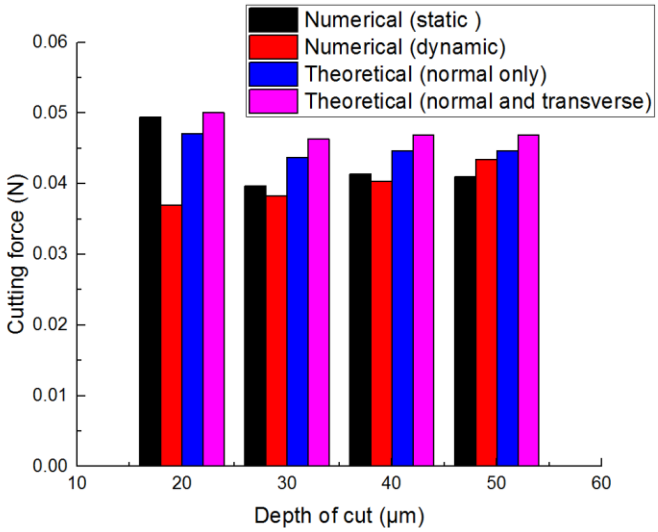
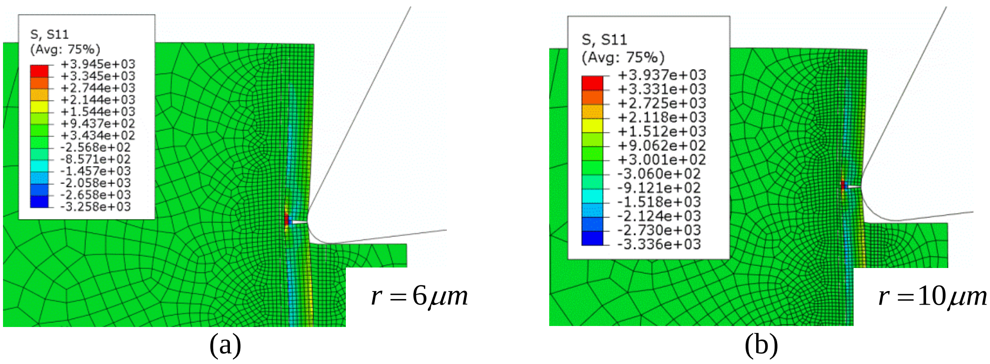
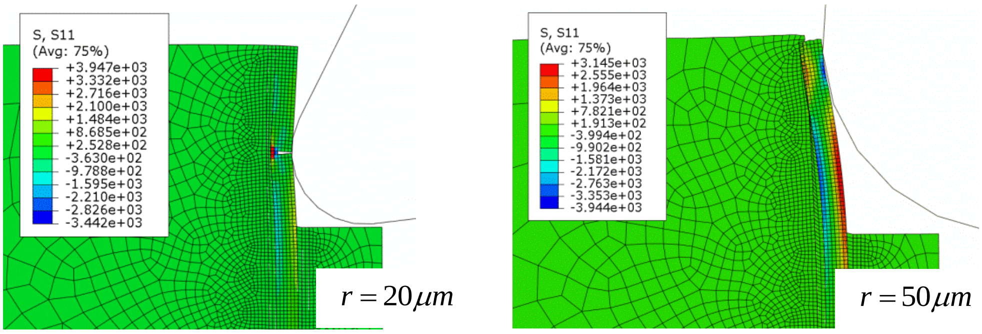


Figure 5: Comparison of the cutting forces obtained from the numerical (static and dynamic) and the theoretical models (considering normal only, and both the normal and transverse effects) for different depths of cut.

In fact, the process of machining CFRP is a dynamic process, and it is significant to reveal the fracture process of the fiber through the dynamic simulation. In the dynamic process of cutting CFRP, the normal and transverse supports are considered. Therefore, the results of dynamic simulation of machining CFRP is summarized as follow.





(c) (d)

Figure 6: Failure mode of fiber under different tool edge radii (depth of cut is 50 μm)

As shown in Fig.6, the fracture position of the fiber is in the contact position between the tool and the fiber, with the stress concentration occurring. With the movement of the tool, the fiber and the matrix and the EHM deform significantly in the local contact area. The fibers are cut off gradually, the rear matrix is crushed, and the interface is stretched. In the cutting process, due to the different tool edge radii, the stress distribution in the fiber is different. When the depth of cut is the same, i.e. 50 μm shown in Fig. 6, the fracture of the fiber occurs in the contact position for a relatively small tool edge radius. For the same depth of cut, when the tool edge radius is larger, the fiber deforms with the bending effect, then the fracture of the fiber occurs. The cutting force is obtained as in Fig.7, where it is observed that as the radii of the cutting edge increasing, the cutting force is gradually increased.

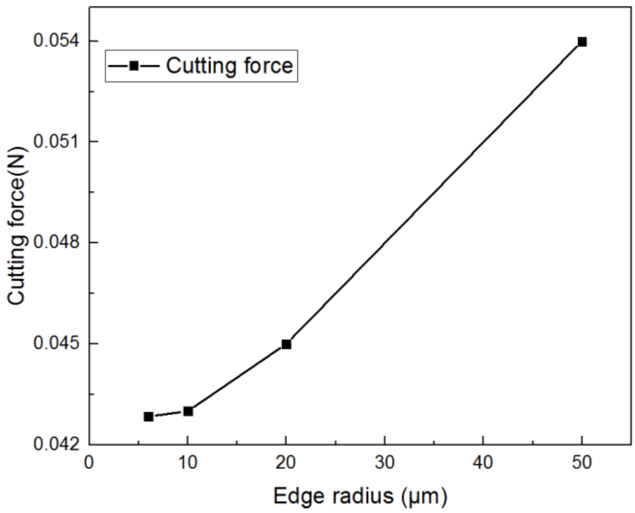
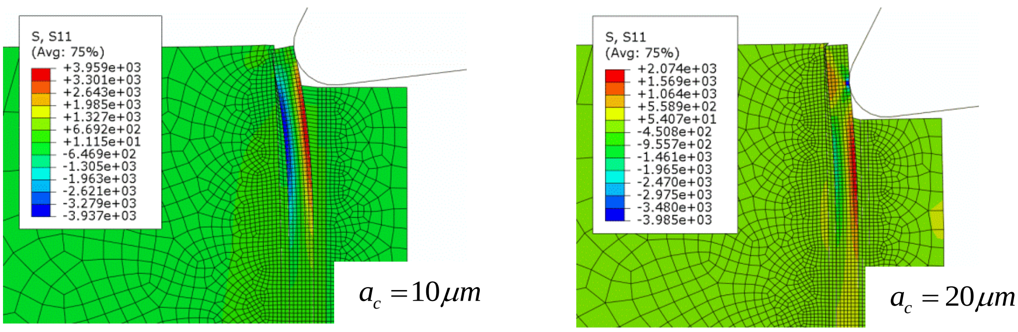


Figure 7: Curve of single fiber cutting force under different cutting edge radii.



(a) (b)

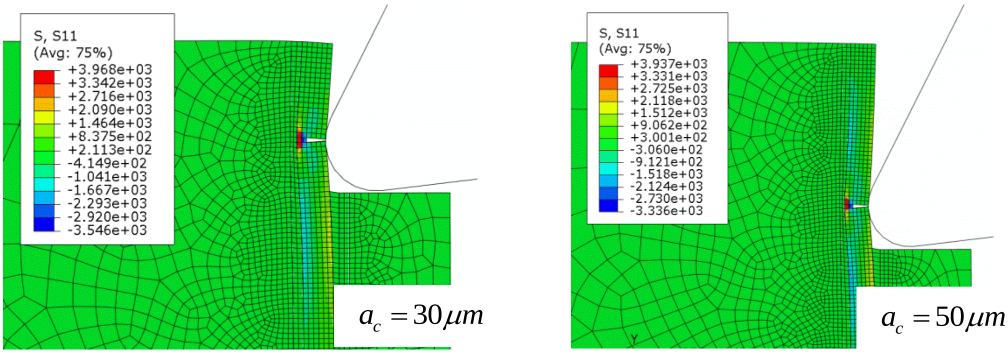


Figure 8: Failure mode of fiber under different depths of cut (tool edge radius is 10 μm)

As shown in Fig.8, the stress concentration occurs in the contact position. With the movement of the tool, the interface is stretched by the stretching action, the fiber is cut off and the rear matrix is crushed. When the tool edge radius is 10 μm, and the depth of cut is larger than the tool edge radius, the fracture position of the fiber occurs in the locally contact region between the fiber and the tool. When the depth of cut is smaller than the tool edge radius, the fiber is directly pressed by the tool edge, and then the fiber cracks. The cutting force is obtained as in Fig.9, it can be seen that the cutting force gradually increases with the increase of cutting depth.

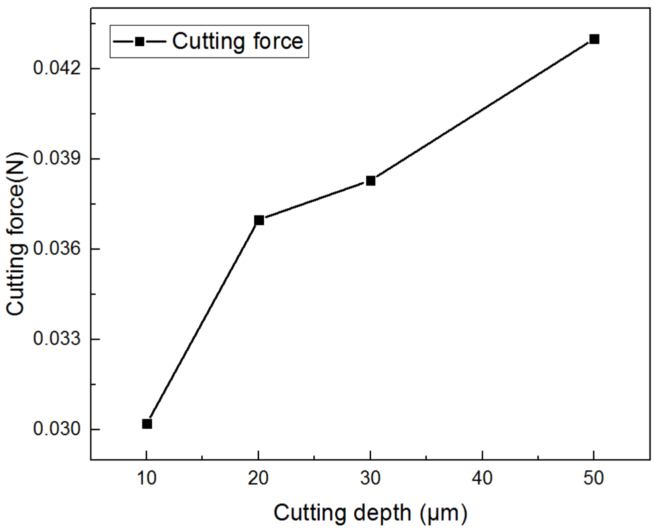


Figure 9: Curve of single fiber cutting force under different depths of cut.

5 CONCLUSION

The elastic foundation beam theory is applied to establish a micro-mechanical model, with considering the normal and transverse constraint effects on the fracture of fiber. The static solution of cutting fiber is obtained analytically from the present micro-mechanical model. In the numerical analysis, due to the Hashin failure criteria considering the effect of the longitudinal, the transverse and the shear strength, the fiber may fracture when any one of failures occurs. In theoretical model, the fiber material is only defined the tensile failure. The theoretical values considering the normal supporting effect only, as well as both the normal and the transverse supporting effects are larger than the numerical results a little. When the depth of cut is relatively larger, the cutting forces obtained from the numerical and the theoretical models agree well.

The removal of a single fiber is solved from the two-dimension microscopic model. Fiber fracture occurs in the contact position between the fiber and the tool from the numerical analysis of the FE model. For the relatively small tool edge radius, the fiber deforms at the locally contact position between the fiber and the tool, and then fractures. For the relatively small depth of cut, i.e. comparable with the tool edge radius, the fiber is bent by the tool and then fractures. The cutting force increases with the increase of tool edge radius or the increasing the depth of cut.

ACKNOWLEDGEMENTS

This work is partly supported by the National Natural Science Foundation of China (no.51505064, 51621064), and 973 Project of China (2014CB046503). These supports are gratefully appreciated.

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