Interfacial mechanics of fiber push-out test: nano-indention technique and cohesive element modeling

Xi Li, Qingsheng Yang *, Zhiyuan Liu

Department of Engineering Mechanics, Beijing University of Technology, Beijing 100124, China
* Qingsheng Yang: qsyang@bjut.edu.cn

Abstract The fiber push-out test is a basic method to probe the mechanical properties of the fiber/matrix interface of a fiber-reinforced composite. In this paper, the interfacial mechanical properties of carbon fiber/epoxy composites are analyzed effectively combing nano-indention technique with cohesive element modeling. Based on the load-displacement curve obtained from the nano-indention experiments, the interfacial shear strength is calculated about 13.7MPa. Furthermore, the finite element method (FEM) model of a fiber-reinforced composite is built in software ABAQUS, in which cohesive zone model is chosen to represent of carbon fiber/epoxy composites interface. The computed results are consistent with experiment data.

Keywords Nano-indentation, Cohesive element, Fiber push-out test, Interfacial shear strength

1. Introduction

Due to the superb properties of high stiffness, high modules, high strength and low thermal, carbon fiber-reinforced composites material are widely used in many fields such as aerospace, electronic and medical engineering [1]. The carbon fiber-reinforced composite is consisting of three components, ie. fiber, matrix and interface. A good interfacial bonding is important to the effective load transfer from matrix to fiber, which helps reducing stress concentrations. Besides, fracture toughness and fatigue life of fiber-reinforced composites also rely on their interfacial properties. Therefore, research on the interface between fiber and matrix can help designing fiber-reinforced composites material with improvement of the above properties [2].

In recent decades, three main methods are used to analysis interfacial bonding strength, namely, single fiber pull-out, single fiber push-out and fiber fragmentation (Figures1-3). The fiber push-out test is the most effective measure method to quantify the in situ characterization of interfacial properties of the fiber-reinforced composite. Nowadays, most experimental investigations of the fiber push-out debonding are based on universal testing machine (UTM), in which the fiber diameter is chosen larger than the one used in actual composites. However, compare to UTM, nano-indentation push-out test has higher precision, in which mechanical properties of interface is investigated under micro-nanoscale, A.Urena[3]studied the interfacial mechanical properties of AA6061(aluminum alloy) reinforced by short carbon fibers coated with different metallic films using the nano-indentation technique and presented the load-displacement curve. In order to obtain accurate interfacial parameter, combined experimental and numerical studies of carbon fiber/polymer composites are more used in this paper. Cohesive zone in finite element analysis (FEA) is a common method to build the interfacial model, which was proposed by Barenblatt[4]and Dugdale[5]. Afterwards, many studies pay attention to mode Ⅰ fracture failure by using cohesive zone simulation. For example, cohesive finite element method (CFEM) is employed by X. Guo [6] to investigate the paradox of a brittle nano-structured interface (nano-grained interface layer) and a ductile layered stainless steel. However, less attention has been paid to cohesive modeling of fiber push-out test. In our work, the interface is built by zero thickness cohesive elements in ABAQUS software.

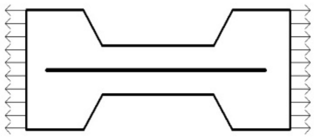

Figure 1. Fiber fragmentation

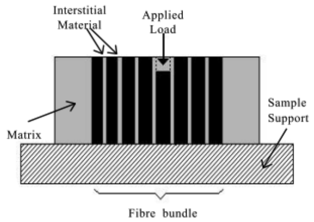

Figure 2. Fiber push-out

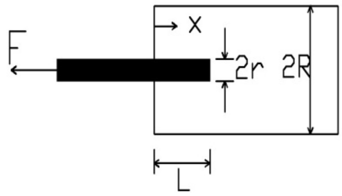

Figure 3. Fiber pull-out

2. Experiment details

Push-out tests were performed on carbon fiber-reinforced epoxy composite material where the fiber volume fraction is about 0.6. The specimens were cut from the original composite by wire cutting machine and the uniform size is 20mm in length, 18mm in width and 10mm in thickness. Afterwards, the specimens are polished by using Sic abrasive paper with 2500 grain size, a thickness 100μm can be obtained. In order to make sure that fiber has enough space to be pushed out, we designed a sample table (as shown in Figure4). There is a circle hole in the centre of sample table; the specimens cut-well were glued on the top face. Besides, the direction of fiber layer should be perpendicular to the sample table.

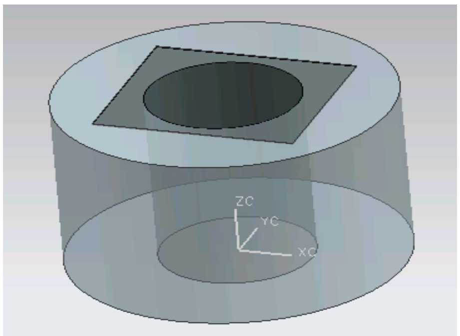

Figure 4. Sample for fiber push-out

The load-displacement curve of a single fiber push-out process is measured by nano-indention instrument and illustrated in Figure 5. It is shown that the whole process can be divided into three stages. In the first stage, fiber displacement is increased linearly with the applied load; and in the second stage, fiber begins to slide from the matrix and crack start to propagate in the interface, until interfacial failure, both the maximum load of fiber debonding and maximum displacement can be achieved in this stage. At last stage, because of indenter contact the matrix, the load continues to grow with the growth of the displacement, this stage means the end of push-out test.

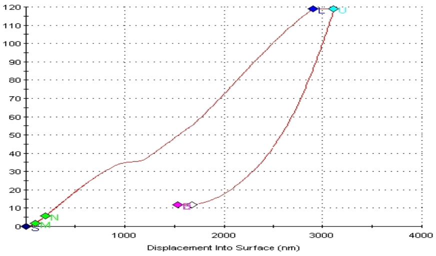

Figure 5. Load-displacement curve of fiber push-out test

In this paper, single fiber nano-indentation push-out tests were performed by using a spherical indenter with a contact diameter of 10μm.The applied load on the fiber was increased at a constant rate of 0.05μm/s. The load-displacement curve was obtained in which the maximum load is 32-35mN and the related displacement is about 1μm.It is assumed that the shear stress was uniform distribution at the interface, so the interface shear strength can be calculated as equation (1).

$$\tau_{max} = \frac{p_{max}}{2\pi RL} \quad (1)$$

where P_{max} indicates the maximum load, R represents fibre radius, L denotes the thickness of the sample, the calculated shear strength is about 13.7MPa.

3. Numerical simulation

3.1 FEM model and material parameters

Currently there are three main kinds of interface element: represented-line spring element [7], represented-Contact element [8] and CFEM. Particularly in CFEM, the damage variable can be specified by an initiation criterion and evolution law, thus the CFEM has been widely used for interface failure and debonding study [9-11].

In this paper, the FEM model is built by commercial software ABAQUS, which consists of carbon fiber, epoxy matrix, and interface (Figure6). Four-node axi-symmetric plane element (CAX4R) is used for both fiber and matrix and four-node axi-symmetric plane cohesive element (COHAX4) is used for interface between them. In total, there are 4097 CAX4R elements and 250 COHAX4 elements. Moreover, the material properties of fiber and matrix are listed in tables 1 and 2.

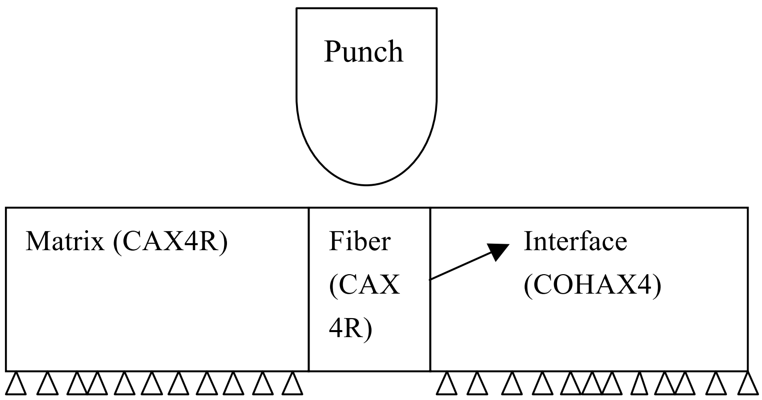

Figure 6 . FEM model

Table 1. Mechanical properties of carbon fiber [1]

Parameter	Carbon fiber(T300)
Transverse modulus (GPa)	15
Axial modulus (GPa)	230
Axial shear modulus (GPa)	27
Transverse shear modulus (GPa)	7
Axial Poisson’s ratio	0.013
Fiber radius (μm)	3.5

Table 2. Mechanical properties of epoxy [1]

Parameter	Epoxy 3501
Modulus (GPa)	4.3
Poisson ratio	0.3

3.2 Cohesive zone traction-separation law

In addition, a traction-separation law is implemented to describe the interface cohesive elements between the fiber and the matrix for FEM simulation as shown in Figure 7. The debonding in push-out process is a pure mode II fracture problem. At first, the stress of crack tip in cohesive zone increases linearly with the separation displacement until the displacement reaches the initiation point of damage δ_{init} at where the crack begins to propagate. Afterwards, the tensile stress of crack will be decreased linearly with the displacement. When the stress is reduced to zero at the point of δ_{fail}, the crack is extended along the whole interface surface which leads to the interface failure of the material.

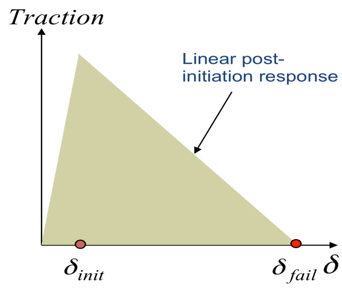

Figure 7. Traction-separation law proposed for interface fracture modeling

The interfacial shear stress τ_{is} can be expressed as equation (2) where τ_{max} is the interfacial crack initiation stress under shear loading condition

$$\tau_{is} = \begin{cases} \frac{\tau_{max}}{\delta_{init}}\delta & 0 \le \delta \le \delta_{init} \\ \frac{\tau_{max}}{\delta_{fail}-\delta_{init}}(\delta_{fail} - \delta) & \delta_{init} \le \delta \le \delta_{fail} \end{cases} \tag{2}$$

Correlating to energy-based fracture toughness and load-displacement curve, the fracture energy can be calculated as equation (3):

$$G_{II\,C} = \frac{1}{2}\tau_{max}\delta_f \tag{3}$$

The cohesive element stiffness equal to the material stiffness .The uncoupled elastic constitutive relation is written as equation (4):

$$T = \begin{pmatrix} T_n \\ T_s \end{pmatrix} = \begin{bmatrix} K_{nn} & K_{ns} \\ K_{ns} & K_{ss} \end{bmatrix} \begin{pmatrix} \varepsilon_n \\ \varepsilon_s \end{pmatrix} = \begin{pmatrix} \delta_n \\ \delta_s \end{pmatrix} \tag{4}$$

The damage and fail law of the cohesive elements is according to the traction-separation relation, while the traction-separation relation was defined by the initiation and evolution. Damage initiations rely on the beginning of stiffness degradation. In our work, the linear maximum nominal stress criterion was used. Damage is initiated when the maximum nominal stress ratio reaches unity [10]:

$$\max\left[\frac{T_n}{T_n^0}, \frac{T_S}{T_S^0}\right] = 1 \tag{5}$$

where T_n^0, T_S^0 represent the peak nominal and shear stress, the damage evolution law describes the rate at which the effective material stiffness degrades after damage initiation.

4. Numerical results

By numerical simulation, a typical fiber push-out load-displacement curve can be obtained. The whole process a divided into three stages that can be shown in Figure 8, the first stage of curve is mainly fiber elastic deformation occurs. The second stage of curve is a nonlinear relationship, due to the punch increase load on interface characterized by cohesive element damaged and failure, Led to the separation between fibers and matrix. The third stage, the fiber and matrix lose bonding; there is only friction between them.

Compared with previous experimental curve, the reason why the experimental curve different with Simulation curve was attributed to that our work was not consider the contact between punch and fiber, the effect of contact with matrix is meaningless. While debonding force and failure displacement from the simulation and experimental are the same value.

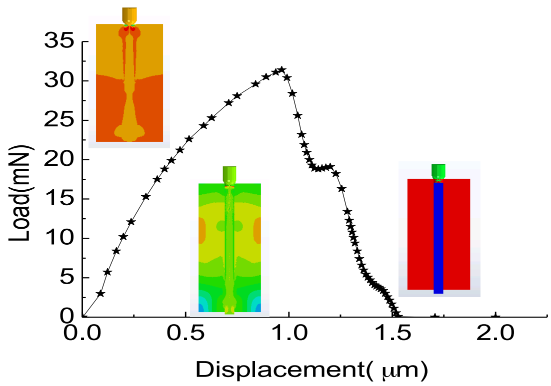

Figure 8. Load-displacement curve of numerical simulation

As the lateral friction will be produced when punch contact fiber, the numerical simulation which fully considered. The coefficient of friction in simulation are 0、0.3、0.6、0.9. The results are shown in Figure 9.

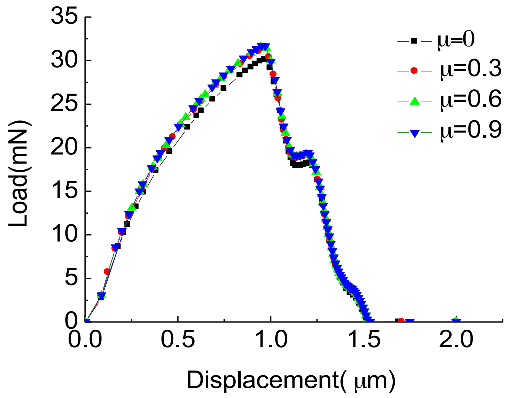

Figure 9. Variation of load with push-out displacement of carbon fibers with different fiction coefficients

Because the interface characterized by cohesive element, wherein the relationship exists between modulus, strength and fracture energy release, therefore, fracture energy release rate is important parameters, its impact is shown in Figure 10.

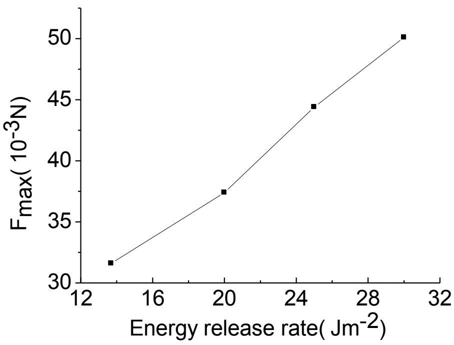

Figure 10. Relation of fracture energy release and maximum debonding force

5. Conclusions

In this paper, the interfacial shear strength of carbon fiber-reinforced composite was investigated by nano-indentation experiment. The interface was also simulated by cohesive element in software ABAQUS. The conclusions are as follows.

(1) The load-displacement curve of carbon fiber push-out derived from experiments is different with the one obtained from the simulation. However, the debonding force and failure displacement are the same from the simulation and experiment as the contact between punch and fiber is ignored.

(2) The effect of lateral friction between punch and fiber can be ignored due to its slight effect on the experimental results.

(3) The maximum debonding force is related to the fracture energy release of cohesive elements and increases with the interfacial strength.

Acknowledegement
The financial support form the from the NSFC under grant #11172012 is gratefully acknowledged

References

[1]Y.Y.Jia,W.Y.Yan.Carbon fiber pull out under the influence of residual thermal stresses in polymer matrix composites. Computational Materials Science. 62(2012)79–86

[2]A.Godara, L.Gorbatikh, G.Kalinka. Interfacial shear strength of a glass fiber/epoxy bonding in composites modified with carbon nanotubes. Composites Science and Technology. 70 (2010)1346–1352

[3]A.Urena,J.Rams,M.D.Escalera, M.Sanchez. Characterization of interfacial mechanical properties in carbon fiber/aluminium matrix composites by the nanoindentation technique. Composites Science and Technology. 65(2005)2025–2038

[4]G.Barenblatt. The mathematical theory of equilibrium cracks in brittle fracture [J]. Advances in Applied Mechanics. 7(1962) 55–129.

[5]D.Dugdale. Yielding of steel sheets containing slits. Journal of the Mechanics and Physics of Solids .8(1960)100–104

[6]X.Guo, G.J.Weng, A.K.Soh. Ducility enhancement of layered stainless steel with nanograined interface layers. Computational Materials Science. 55(2012)350-350

[7]N.Chandra,C.R.Ananth. Analysis of interfacial behavior in MMCS and IMCS by the use of thin slice push-out tests. Composites Science and Technology. 54(1995)87-92

[8]V.T.Bechel, N.R.Sottos, A comparison of calculated and measured debond length from fiber push-out tests. Composites Science and Technology. 58(1998)1727-1739.

[9]G.Lin, G.Geubelle, P.H. Sottos, N.R. Simulation of fiber debonding with frictionin a model composite push-out test. International Journal of Solids and Structures. 38(2001)8547–8562.

[10]J.H.You, W. Lutz. Fiber push-out study of a copper matrix composite with an engineered interface: Experiments and cohesive element simulation. International Journal of Solids and Structures. 46 (2009)4277–4286

[11]R. Sharma, P. Mahajan. Fiber bundle push-out test and image-based finite element simulation for 3D carbon/carbon composites. Carbon. 50(2012)2717–2725