NUMERICAL STUDY ON RESIDUAL THERMAL STRESSES IN CARBON FIBRE PULLOUT

Y. -Y. Jia*, W.-Y. Yan*, H.-Y. Liu**
***Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800 Australia,**
****School of Aerospace, Mechanical and Mechatronic Engineering J07, The University of Sydney, Sydney, Australia**
yuan.jia@monash.edu;wenyi.yan@monash.edu

Keywords: *carbon fibre, pullout, residual stress, cohesive zone model*

Abstract

This paper investigated the effect of residual thermal stresses on carbon fibre pullout by using cohesive zone modelling. The finite element method was applied to analyse the residual thermal stress components along the interface between the fibre and matrix due to curing. A comparison study on the anisotropic and isotropic material properties are considered using four typical carbon fibres, T300, AS4, T800HB-40B and IM7. The results show that the simplified isotropic fibres model would overestimate the compressive residual axial and interfacial radial stress. The anisotropic material properties of the fibres should be considered in the theoretical study of carbon fibre pullout. The results also show that the influence of the residual thermal stresses is significant at the stage of frictional sliding after interfacial debonding.

1 Introduction

Carbon fibre used in advanced composites contains at least 92% carbon [1]. This type of material has generated a great scientific and industrial interest due to its remarkable characteristics and properties, such as small size, high stiffness, low thermal expansion and high strength.

The properties of interface between the fibre and matrix often influence significantly the composite performance in all types of composites, such as failure mode and the fracture toughness of composites. Interfacial debonding is considered as an important mechanism of energy absorption during the failure of a composite. Interfacial shear strength, which controls the occurrence and evolution of fibre/matrix debonding, is one of the main properties used to characterise the interface. The single fibre pullout test is one of the most widely used techniques to quantify the interfacial strength. There are three stages during a single fibre pullout, which include elastic deformation stage before debonding, debonding stage and sliding stage. In the first stage, the fibre and the matrix are well bonded. As the pullout force increases, a crack propagates along the interface between the fibre and the matrix, leading to a complete debonding, which is the debonding stage. In the last stage, the fibre slides out from the matrix, with friction acting between the two newly formed surfaces. Several analytical and numerical models have been developed for the single fibre pullout test [2-5].

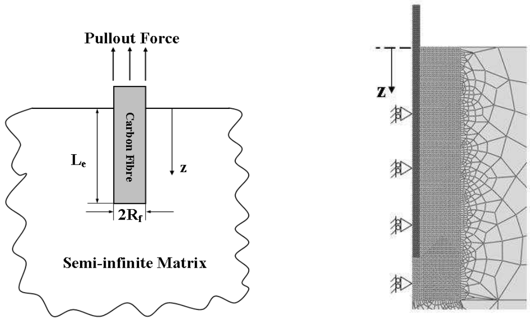
Residual thermal stresses are caused by the mismatch in the coefficient of thermal expansion between the fibre and matrix during the curing process. Residual thermal stresses play an important role in a mechanical performance of a composite structure [6], which can have significant effects on the fibre-matrix interfacial properties such as interfacial debonding. The residual stresses developed at the fibre/matrix interface provide large frictional resistance in the pullout process, which increase the fracture energy consumption [7]. Several studies have been carried out on the distribution of residual thermal stresses in a single fibre composite [8-10]. To authors' knowledge, the study on the effect of residual thermal stresses on fibre pullout is still insufficient.

The purpose of this paper is to investigate the single carbon fibre pullout test under the influence of residual thermal stresses by using cohesive zone modelling. Four typical commercial carbon fibres T300, AS4, T800HB-40B and IM7 with anisotropic elastic and thermal properties embedded in epoxy matrix HY6010 are considered in this study.

In this paper, a numerical model is firstly established, followed by the analysis of distribution of the residual thermal stresses along the interface between the fibre and matrix. Secondly, the results obtained from the anisotropic material properties of fibre model with simplified isotropic fibre model are compared. Finally, the effects of the residual thermal stresses on the fibre pullout test are examined.

2 Numerical Model

The physical problem of a typical fibre pullout test can be treated as a cylindrical fibre embedded in a semi-infinite matrix, as shown in Fig. 1(a). The radius of the fibre is denoted as R_f and L_e is the total embedded fibre length. In a fibre pullout test, a pullout force with low pullout rate is applied uniformly on the top surface of the fibre in the axial direction. The commercial finite element package Abaqus was used to investigate the fibre pullout problem. Due to the symmetry of this problem, a two-dimensional axisymmetric model was constructed in this finite element analysis. The radius and depth of the matrix are much larger than the dimensions of the fibre in the numerical models so as to simulate a semi-infinite matrix body. The bottom of the model is constrained in both the radial and axial directions. The vertical side along the axisymmetric axis is constrained only in the radial direction. A very fine mesh (element size: 1μm ×1μm) is used in the area around the interface between the fibre and the matrix to ensure the accuracy of the numerical results, which is shown in Fig. 1(b).



(a) (b)

Fig. 1. (a) A schematic diagram of the fibre pullout model; (b) Axisymmetric finite element model with a fine mesh around the interface.

Cohesive zone (CZ) modelling [11] is a commonly used technique for investigating the fracture failure governed by crack or debonding propagation. It bridges the gap between the stress- and energy-based approaches. Cohesive zone model establishes the traction-separation relation for the interface. The traction across the interface increases and reaches to a peak value, then decreases and eventually vanishes, permitting a complete decohesion [12]. In this research, a bilinear cohesive law was implemented, which reduces the artificial compliance inherent in the intrinsic cohesive zone model [13]. A small number of four-node, axisymmetric cohesive elements (COHAX4) were used to define the cohesive zone.

3 Results and Discussion

3.1 Distribution of Residual Thermal Stresses

In the thermal stress analysis, there is no mechanical pullout force. The loading is from the change of the temperature during a curing process. A temperature change of $\Delta T =$ -95°C was chosen in the finite element simulations, which corresponds to a typical curing process from 120°C cooling down to the ambient temperature of 25°C. In the first case study, carbon fibre T300 ($R_f =$ 3.5μm) embedded in epoxy matrix HY6010 with fibre embedded length $L_e =$ 100μm was considered. The mechanical and physical properties of the fibre and matrix are summarized in Table 1 and 2.

Table 1 Material properties of carbon fibres. [8, 15]

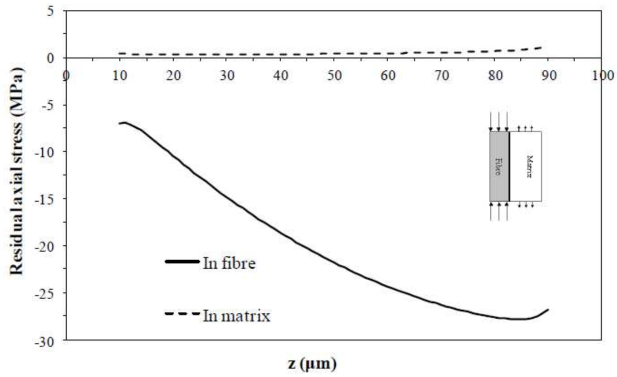
Parameter		T300	AS4	T800HB-40B	IM7
Transverse Young's modulus (GPa)	E_1^f	15	15	23	21
Axial Young's modulus (GPa)	E_2^f	230	235	294	290
Axial shear modulus (GPa)	G_{12}^f	27	27	25	14
Transverse shear modulus (GPa)	G_{13}^f	7	7	9	8
Axial Poisson's ratio	v_{12}^f	0.013	0.013	0.0203	0.0144
Fibre radius (μm)	R_f	3.5	3.5	2.6	2
Transverse coefficient of thermal expansion (/°C)	α_1^f	12 x10^{-6}	15 x10^{-6}	18 x10^{-6}	10 x10^{-6}
Longitudinal coefficient of thermal expansion (/°C)	α_2^f	-0.7x10^{-6}	-0.5 x10^{-6}	-0.9 x10^{-6}	-0.2 x10^{-6}

Table 2 Material properties of epoxy. [15]

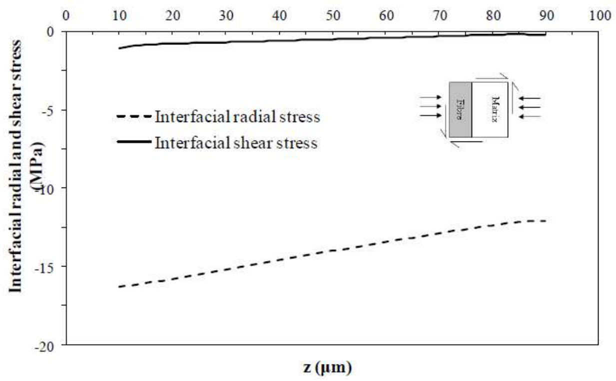
Parameter		Epoxy HY6010
Young's modulus (GPa)	E_m	3.4
Poisson's ratio	v_m	0.36
Coefficient of thermal expansion (/°C)	α_m	62 x10^{-6}

The residual stresses fields at the interface from the numerical simulation are plotted in Fig. 2, which presents the distribution of axial stresses and interfacial radial and shear stresses along the interface between fibre and matrix. These plots only show the distribution of residual stresses along the interface from z = 10μm to z = 90μm, which excludes the results around the singularity points. The singularity points, where the fibre intersects the matrix at the two ends (z = 0 and z = 100μm), can be identified by mesh sensitivity study.

As shown in Fig. 2(a), the axial stress in the fibre near the interface is significantly different from that in the matrix. The axial stress in the fibre is compressive and its value increases towards the fibre bottom end, while the axial stress in the matrix is tensile and small. A large matrix radius (here it's theoretically infinite) leads to small values of all the residual thermal stress components [9]. Fig. 2(b) shows that the interfacial radial stress is also compressive and varies almost linearly from -16.3MPa near the top end to -12MPa near the bottom end of the fibre. As discussed by Parlevliet et al. [14], the fibre always experiences compressive residual stresses in most polymer composite laminates. In contrast, the magnitude of interfacial shear stress is very small. The distribution of residual thermal stresses obtained in this study exhibits similar trends as those reported in previous work [8, 9]. As the fibres loaded in compression along the interface, this may lead to interfacial debonding and fibre microbuckling [15]. To improve the fibre-matrix bond strength, fibre treatment, such as fibre coating (sizing) are commonly used.



(a) Residual axial stresses in fibre and matrix



(b) Interfacial radial and shear stress

Fig. 2. Residual thermal stresses along fibre-matrix interface (T300).

3.2 Effect of Carbon Fibre's Anisotropy on Residual Thermal Stresses

To apply this study to practical problems, four typical commercial carbon fibres, T300, AS4, T800HB-40B and IM7 embedded in epoxy matrix HY6010 were considered in this investigation. The material properties of the four carbon fibres and matrix are listed in Table 1 and 2. As shown in Fig. 2, the residual axial stress in matrix and interfacial shear stress are very small, therefore, only the residual axial stress in the fibre and the interfacial radial stress will be presented and discussed in the following section.

As listed in Table 1, carbon fibres are transversely isotropic materials, whose elastic properties and thermal extension coefficient in fibre axial direction are significantly different from those in transverse directions. Zhou and Mai [16] indicated that fibre anisotropy is an important factor to influence the stress transfer and the interfacial debonding in both fibre pullout and pushout. In this study, it is hypothesized that the anisotropic behaviour of carbon fibres should affect the residual stresses due to curing. Due to the limitation of analytical solutions, carbon fibres were simplified as isotropic materials in previous analytical studies [17-19]. To validate the hypothesis on the anisotropy effect, an additional set of simulations with simplified isotropic carbon fibres were carried out. The real material data in the fibre axial direction were used in the isotropic study.

The maximum residual thermal stresses in the four typical commercial carbon fibres are presented in Fig. 3, which compared with the results from simplified isotropic fibres. In the case of anisotropic real carbon fibres, the residual axial stresses in four fibres are compressive with a magnitude between -28MPa to -49MPa (Fig. 3(a)). Carbon fibre IM7 has the highest magnitude, followed by the fibre T800HB-40B. The magnitude of the residual axial stresses in the composites with fibre T300 and AS4 are similar. The difference of the axial stress in these fibres is due to the smaller fibre radius and higher Young's modulus of the fibre IM7 and T800HB-40B, as listed in Table 1. It can also be seen clearly that the magnitude of the axial stress for anisotropic real carbon fibres are higher than that for their corresponding simplified isotropic carbon fibres. The difference in percentage varies from 18% to 30%, which should not be ignored in composite design.

Fig. 3(b) shows the difference of the maximum interfacial radial stress among these four real fibres is small. The averaged magnitude is around -16MPa in the case of anisotropic real carbon fibres, which may be due to the small differences of coefficient of thermal expansion in these fibres. The magnitude of radial stress for anisotropic real carbon fibres is lower than the simplified isotropic carbon fibres. The maximum difference is 14%. Both Figs 3(a) and 3(b) indicate that the effect of anisotropic material property is significant on the residual thermal stresses. The simplified isotropic fibres would overestimate both the interfacial compressive axial and radial stress by up to 30%. The anisotropic material property of the fibres, instead of their simplified isotropic material properties, should be used in the study of residual thermal stresses in composite and the consequent pullout test.

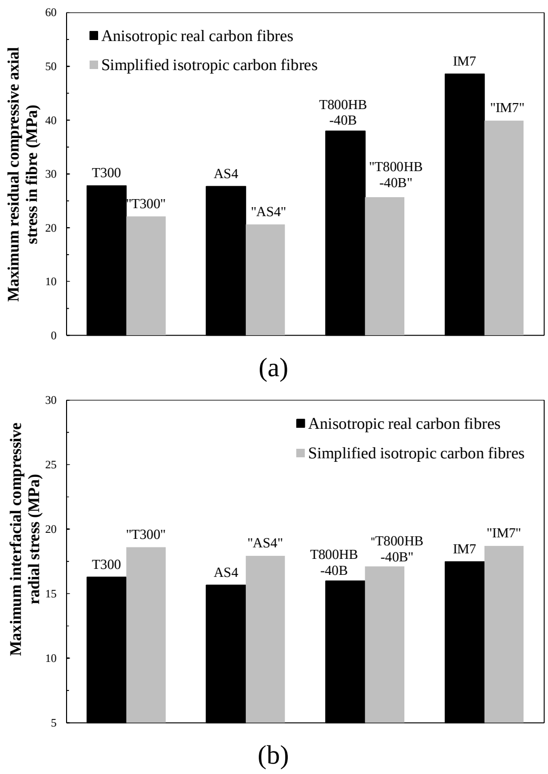


Fig. 3. (a) Maximum residual compressive axial stress in fibre and (b) maximum interfacial compressive radial stress for four carbon fibres compared with their corresponding simplified isotropic fibres.

4 Effect of Residual Thermal Stresses on Fibre Pullout

4.1 Effect on Pullout Curve

The maximum pullout force (F_{max}), the so called debonding force, is one of the most important parameters recorded from a pullout test, which is used to calculate the average interfacial strength. In this study, the residual thermal stresses are introduced in the finite element simulation of fibre pullout. A carbon fibre T300 embedded in epoxy matrix HY6010 with an embedded length L_e = 100μm is used. Comparison between the results from the models with and without residual stresses is presented in Fig. 4. It can be seen that the influence of the residual thermal stresses on the debonding force (F_{max}) is very small. But it is clear that the effect of residual thermal stress is significant after initial debonding. In the debonded region, the frictional shear stress is governed by the radial compression, which provides a large resistance to further debonding. Therefore, a larger applied force is required to pull out the fibre even though the interface is debonded.

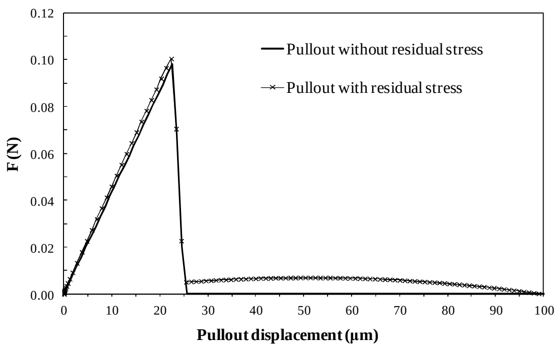


Fig. 4. Fibre pullout curve with and without residual stress.

4.2 Cases Studies on Pullout Force

As shown in Fig. 5, the magnitude of the debonding force for carbon fibre T300 and AS4 are highest, followed by T800HB-40B and IM7. This is due to the larger fibre radius for T300 and AS4, see Table 1. As observed in previous work [20, 21], the effect of the fibre radius on the pullout force was significant. The debonding force F_{max} increases linearly with fibre radius. The four cases presented in Fig. 5 further confirm that the influence of the residual thermal stress is insignificant on the debonding force.

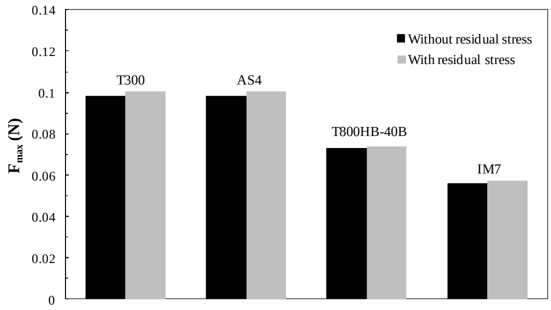


Fig. 5. Debonding force for four carbon fibres with epoxy HY6010.

5 Conclusions

In this paper, a single carbon fibre pullout under the influence of residual thermal stresses due to curing process was numerically studied. The result showed that the residual thermal stresses depend on the material properties of fibre and matrix. The difference of the residual stresses obtained from the models considering carbon fibre's anisotropic material property and those simplifying carbon fibre as simplified isotropic material is significant, which could affect the fibre pullout. Thus, the anisotropic material property of the fibres, instead of their simplified isotropic material properties, should be used in the study of residual thermal stresses in composite. The case studies of fibre pullout show that the residual thermal stresses have negligible effect on the debonding force, but they increase the resistance during the stage of fibre sliding after interfacial debonding.

6 References

[1] Fitzer E. *Carbon fibres filaments and composites*. Kluwer Academic, Dordrecht, 1990.

[2] Hsueh C-H. Interfacial debonding and fiber pull-out stresses of fiber-reinforced composites. *Materials Science and Engineering A*, Vol. A123, No. 1, pp 1-11, 1990.

[3] Liu H-Y, Zhou L-M and Mai Y-W. On fibre pull-out with a rough interface. *Philosophical Magazine A*, Vol. 72, No. 2, pp 359-372, 1994.

[4] Zhong W, Pan N. A computer simulation of single fiber pull out process in a composite. *Journal of Composite Materials*, Vol. 37, No. 21, pp 1951-1969, 2003.
[5] Tsai JH, Patra A and Wetherhold R. Finite element simulation of shaped ductile fiber pullout using a mixed cohesive zone/friction interface model. *Composites Part A: Applied Science and Manufacturing*, Vol. 36, No. 6, pp 827-838, 2005.
[6] Favre JP. Residual thermal stresses in fibre reinforced composite materials—a review. *Journal of the Mechanical Behavior of Materials*, Vol. 1, No. 1-4, pp 37-53, 1988.
[7] Suzuki T, Sato M and Sakai M. Fiber pullout processes and mechanisms of a carbon fiber reinforced silicon nitride ceramic composite. *Journal of Materials Research*, Vol. 7, No. 10, pp 2869-2875, 1992.
[8] Leroy FH, Auvray MH and Lesne PM. Residual thermal stresses in the pull-out specimen: a finite element calculation. *Journal of Materials Science*, Vol. 30, No. 18, pp 4651-4658, 1995.
[9] Quek MY. Analysis of residual stresses in a single fibre-matrix composite. *International Journal of Adhesion and Adhesives*, Vol. 24, No. 5, pp 379-388, 2004.
[10] Metehri A, Serier B, Bachir Bouiadjra B, Belhouari M and Mecirdi MA. Numerical analysis of the residual stresses in polymer matrix composites. *Materials and Design*, Vol. 30, No. 7, pp 2332-2338, 2009.
[11] Anderson TL. *Fracture mechanics*. 3rd edition, Taylor and Francis, 2005.
[12] Chandra N, Li H, Shet C and Ghonem H. Some issues in the application of cohesive zone models for metal-ceramic interfaces. *International Journal of Solids and Structures*, Vol. 39, No. 10, pp 2827-2855, 2002.
[13] Paulino GH, Seong HS and Buttlar WG. A bilinear cohesive zone model tailored for fracture of asphalt concrete considering viscoelastic bulk material. *Engineering Fracture Mechanics*, Vol. 73, No. 18, pp 2829-2848, 2006.
[14] Parlevliet PP, Bersee HEN and Beukers A. Residual stresses in thermoplastic composites-A study of the literature-Part I: Formation of residual stresses. *Composites Part A: Applied Science and Manufacturing*, Vol. 37, No. 11, pp 1847-1857, 2006.
[15] Daniel IM and Ishai O. *Engineering Mechanics of Composite Materials*. 2nd edition, New York: Oxford University Press, 2006.
[16] Zhou LM and Mai Y-W. On the single fibre pullout and pushout problem: Effect of fibre anisotropy. *Zeitschrift für Angewandte Mathematik und Physik (ZAMP)*, Vol. 44, No. 4, pp 769-775, 1993.
[17] Zhang X, Liu H-Y, Mai Y-W and Diao X-X. On steady-state fibre pull-out I The stress field. *Composites Science and Technology*, Vol. 59, No. 15, pp 2179-2189, 1999.
[18] Tan X and Kin L. A nonlinear pullout model for unidirectional carbon nanotube-reinforcedcomposites. *Composites Part B*, Vol. 35B, No. 3, pp 211-217.
[19] Ohno N, Ando T, Miyake T and Biwa S. A variational method for unidirectional fiber-reinforced composites with matrix creep. *International Journal of Solids and Structures*, Vol. 39, No. 1, pp 159-174, 2002.
[20] Alwan JM, Naaman AE and Hansen W. Pull-out work of steel fibers from cementitious composites: Analytical investigation. *Cement and Concrete Composites*, Vol. 13, No. 4, pp 247-255, 1991.
[21] Jia Y-Y, Yan W-Y, Liu H-Y. Numerical study on carbon fibre pullout using a cohesive zone model. *Proceeding of 18th International Conference on Composite Materials*. Jeju Island, Korea, pp 21-26 2011.

Copyright Statement