MICROMECHANICS OF FIBER-CRACK INTERACTION: BRIDGING FIBER

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Summary Micromechanics of bridging fiber/ crack interaction were investigated by micro-Raman spectroscopy. The stress distribution on a bridging fiber was measured point-by-point using micro-Raman spectroscopy. The interaction between the crack and bridging fiber was discussed and a bridging fiber stress transfer model was established. A reverse sliding of the bridging fiber within the debonded zone was gradually converted to a forward sliding during reloading and at last the bridging fiber was wholly reloaded. It is noted that the stress on the bridging fiber distributed uniformly and a fiber bridging zone is isolated from the fiber debonded zone in the new model. The interfacial friction does't works within the bridging fiber length so that the bridging fiber stress remains a constant.

INTRODUCTION

Mechanical behavior of fiber reinforced composites depends on structure properties of fiber, matrix and their interface. Appropriate interfacial bonding can effectively transfer the load from matrix to fiber. Matrix crack propagation can be blocked by the high-performance fiber with different damage forms, such as debonding, bridging, broken and pull-out. All kinds of fiber damage ways can consume more fracture energy, thereby the overall toughening in fiber reinforced composite can be enhanced [1-2].
Bridging fiber, namely unbroken fiber bridging on both sides of a crack under loading, is one of toughening mechanisms in fiber-reinforced composites. Fracture mechanics numerical methods are common way to study the bridging mechanism, but it is hard to deal with mechanical properties of each phases and the interface in composites at micro-scale. So the direct measurements at micro-scale are expected to observe the phenomenon of bridging [3]. In the article, a new specimen preparation method was developed to study the interaction between bridging fiber and crack. MRS is utilized to investigate the fiber bridging phenomenon in Kevlar49 aramid fiber and epoxy matrix composite system. Reliable experimental data is provided to explain the fiber bridging phenomenon in the composites.

MICRO-RAMAN TESTING

A relationship between Raman shift and strain can be obtained from a Kevlar49 single fiber under axial tension at room temperature, and then converted to a relationship between Raman shift and stress, After a linear fitting, the stress sensitivity to Raman shift of -285.22 MPa/cm-1 can be obtained. Nearly linear relationship for aramid fiber can be used to measure stress in the fiber composites, and further monitor the crack opening and failure of the fiber/ matrix interface. The specimen was fixed on a loading mini-device, as shown in Fig. 1(a). The fiber direction must be consistent with the tensile loading direction as the specimen was fixed. Raman measurements for a bridging fiber were carried out step by step after loading the debonding and friction mechanisms on the bridging fiber can be observed. Fig. 1(b) shows a photo of fiber bridging to a crack.

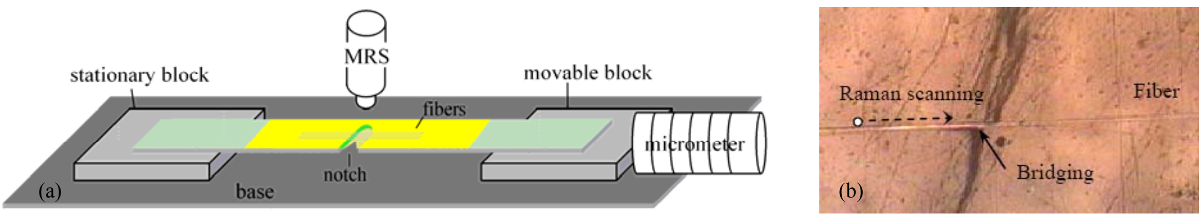

Fig. 1 (a) Schematic of micro-Raman spectra test and (b)a crack propogating across a bridging fiber

RESULTS AND DISCUSSION

Fiber axis stress under reloading

Fig. 2 shows the symmetric axial stress distribution on the bridging fiber without the residual stress. The fiber stress along the good adhesion parts reveal a gradient-increased tendency and reach the maximum at the bonded/ debonded transition points. Especially, a stress platform zone appears in the middle of the curves and increases with the load. The stress platform zone exists in a fiber bridging part and remains a constant stress. The fiber debonded part would slide with the load to overcome an interfacial friction.

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When the displacement between the specimen ends elongated to 100 μm, the fiber stress at the bonded / debonded transitions achieved its maximum. Then the fiber stress decrease to overcome the interfacial friction as entering into the fiber debonded zone until the fiber stress reached a stress plateau zone. When the displacement between the specimen ends elongated to 200 μm, the forward sliding appeared to overcome the interfacial friction such that the fiber stress gradually increased and the length of the stress plateau zone reduced. When the displacement between the specimen ends elongated to 350 μm, the length of the stress plateau zone is equal to the length of the bridging fiber.

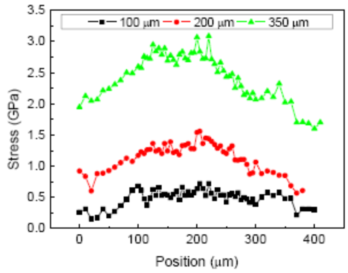

Fig. 2 Stress distributions on the bridging fiber

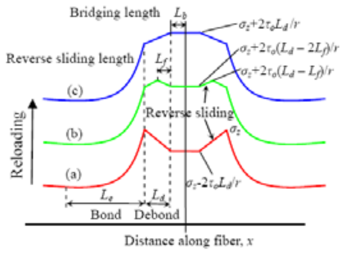

Fig. 3 Stress transfer model for a bridging fiber

Stress transfer model

At initial loading (Fig. 3a), the fiber stress reaches the maximum stress of σ_z at fiber bonded/ debonded transition point. After the transition the fiber stress began to decrease because the fully-debonded fiber belongs to the reverse sliding zone, where the reverse interfacial friction must be overcome. The minimum stress appears at the debonded/ bridging transition, which is equal to the difference of the fiber stress of σ_z at the bonded/ debonded transition and the friction stress within the entire debond length of L_d, i.e., σ_z-$2\tau_o L_d/r$. Finally, the fiber enters into the fiber bridging zone after the debonded/ bridging transition. The interface friction does not work so that the bridging fiber stress remains a constant, which is equal to the minimum stress at the debonded/ bridging transition.

Further loading (Fig. 3b), the length of reverse sliding zone is reduced from the fiber debonded length of L_d to L_f. The debonded fiber gradually begins to overcome the interfacial friction due to the forward sliding. The fiber stress continues to increase after the bonded/ debonded transition and reaches the maximum at the forward sliding/ reverse sliding transition. The maximum is equal to the sum of the stress σ_z at the bonded/ debonded transition and the friction stress within the forward sliding length (L_d-L_f), i.e., $\sigma_z+2\tau_o(L_d-L_f)/r$. Next, the fiber stress will overcome the reverse interfacial friction within the reverse sliding zone, and reaches the minimum at the debonded/ bridging transition. The minimum is equal to the sum of the maximum stress at the forward sliding/ reverse sliding transition and the friction stress within the reverse sliding length of L_f, i.e., $\sigma_z+2\tau_o(L_d-2L_f)/r$. Finally, the fiber enters into the bridging zone after debonded/ bridging transition, and the bridging fiber stress remains a constant due to the interfacial friction does not work. The fiber stress is equal to the minimum stress at the debonded/ bridging transition.

Until the last loading (Fig. 3c), the fiber in the debond zone is completely loaded. There is no reverse sliding zone. At the debonded/ bridging transition, the fiber stress reaches the maximum, $\sigma_z+2\tau_o L_d/r$, due to the fiber stress overcomes the forward interfacial friction within the debonded fiber length of L_d. After the debonded/ bridging transition, the interfacial friction disappears. The fiber stress remains a constant so that a maximum stress plateau forms within the bridging zone. It can be expected that the interfacial debonding will continue to expand if the shear stress at the bonded/ debonded transition reaches the fiber/ matrix interfacial shear strength. If the tensile load is further increased, the maximum stress of the bridging fiber in the plateau zone will reaches the fiber tensile strength and the bridging fiber will fracture.

CONCLUSIONS

Micro-Raman spectroscopy was utilized to study the interaction of crack and bridging fiber. A stress transfer model for the bridging fiber was built to explore the debonding and friction sliding mechanisms in the fiber/ matrix interface. The new model has two distinct features. First, the fiber debonded zone is divided into the forward sliding and the reverse sliding zones. Second, the new model takes into account the fact that there is no friction effect happened at the fiber bridging zone. The fiber bridging zone is isolated from the fiber debonded zone and there is a constant stress within the fiber bridging zone.

References

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