Chapter 6

# FUTURE WORK

## INTRODUCTION

This dissertation investigated various aspects of crack path selection in adhesively bonded joints, including direction of cracking, and the effect of the T-stress, specimen geometry, loading conditions, fracture mode mixity, surface preparation, and thermal-mechanical properties of bonding materials. An overall picture has been obtained through the study about crack propagation behavior in layered bi-material systems. This study also provided some important insights into the selection and designing of material testing methods, especially the double cantilever beam (DCB) test.

As a beam type of specimen, a DCB specimen can be loaded in different fixtures to achieve different modes of fracture. For instance, when a DCB specimen is loaded under opening mode, mode I fracture is achieved whereas when the specimen is loaded under three-point bending, pure mode II fracture is achieved. A DCB specimen can also be loaded in different testing frames such as screw-driven universal test machines or impact drop towers to achieve various rates of testing. On the other hand, since the preparation of DCB specimens is relatively simple, the geometry of the specimens such as adherend and adhesive thicknesses can be varied rather easily. Consequently, asymmetric DCB specimens with different adherend thickness ratios can be made without extra effort. When an asymmetric DCB specimen is loaded under opening mode, mixed mode fracture is achieved, and the global mode mixity depends on the adherend thickness ratio of the specimen.

As indicated by the post-failure analyses results in Chapter 4, failures in DCB specimens were cohesive when they were loaded under mode I conditions whereas failures in asymmetric DCB specimens tended to be more and more interfacial as the mode II fracture components increased. Especially, when the mode II fracture components were greater than 14% in the asymmetric DCB tests, the locus of failure were very similar to that observed in pure mode II end-notched flex (ENF) tests. This mode mixity dependence of the locus of failure observed in DCB tests suggests that: a) since failures are cohesive, mode I DCB tests more or less measure the fracture toughness of adhesive materials instead of bonding interfaces; to measure the fracture toughness of the adhesive bonds, asymmetric DCB or ENF tests should be used. b) since the locus of failure in asymmetric DCB tests approaches that in ENF tests, the ENF test can be substituted by the asymmetric DCB test. The major disadvantage of ENF tests is that the crack length is very difficult to measure because the tests are conducted under three-point bending loading. Due to this disadvantage, the data scatter in the ENF tests is relatively large, which limits the accuracy of this testing method. On the other hand, asymmetric DCB tests are conducted in opening mode and the measurement of the crack length can be achieved with relatively high accuracy. Therefore, replacing ENF tests with asymmetric DCB tests with sufficient mode mixity can reduce the difficulty of measuring a crack length and may enhance the accuracy of the measurement.

In the following sections, the future work of this study is proposed. The proposal is based on the problems that we do not have direct answers at this point of time and possible applications of this study.

**FUNDAMENTAL PHYSICS FOR THE RATE DEPENDENCE OF LOCUS OF FAILURE**

As discussed in Chapter 4, the locus of failure is closely related to the rate of crack propagation. In quasi-static DCB tests, failures tend to be interfacial when cracks propagate slowly whereas tend to be cohesive when the rate of crack propagation is high. Although the fundamental physics of this rate dependence phenomenon is still unclear, important insights have been obtained through this study. As shown in Chapter 5, when a more advanced surface preparation technique was used in preparing specimens, the rate dependence of the locus of failure was not as pronounced, which suggests that this rate dependence phenomenon is closely related to the material properties near the interfaces. One possible mechanism is that the concentration of low-molecular polymers near the interfaces is higher than elsewhere in the adhesive layer. As a result, the material near the interfaces is more viscoelastic and its response is therefore more rate sensitive. Supportive information of this hypothesis can be found in the earlier results from the Adhesion Lab at Virginia Tech obtained during testing steel/epoxy bonded DCB specimens. When the failure was interfacial, the fracture toughness was found to increase with the rate of crack propagation, whereas when the failure was cohesive, the fracture toughness decreased with the rate of crack propagation. This result indicates that the material in the vicinity of the interface is more viscoelastic and therefore supports the molecular weight variation hypothesis.

To further support the hypothesis, preliminary post-failure analyses using 2990 Micro-Thermal Analyzer (TA Instrument, Inc.) was conducted on both fast and slow crack propagation regions on the failure surfaces of a high T-stress DCB specimens tested quasi-statically. The 2990 Micro-Thermal Analyzer has the capacities to conduct atomic force microscopy and measure thermal responses providing information similar to that of modulated differential scanning calorimetry (DSC) at the same time. Due to the limitations of sample size required by the instrument, the analyses were carried out on representative areas on the adhesive side of the specimen surfaces. Although the results at this stage are still preliminary and no conclusive statement can be made, they do show that the glass transition temperature measured at slow crack propagation regions is slightly lower than that measured in fast crack propagation regions. This finding supported the molecular weight variation argument, and further study in this area is therefore recommeded.

## INTERACTIONS OF MULTIPLE CRACKS

In the analysis of this dissertation, only one crack was present in an adhesively bonded joint, and elsewhere the bonding was assumed to be perfect and the materials were assumed to be flawless. This idealization greatly simplified the mathematical model and the analyses provided useful insights into the failure mechanism and behavior of the adhesively bonded joints in practical application. However, cracks and flaws are inevitable in materials, and their interactions with each other will greatly influence the crack propagation behavior and shorten the service life of materials. Therefore, investigations of crack path selections in bi-material or multiple material systems with the present of multiple cracks are essential and necessary. Direct applications of this research can be found in automotive tire industries. Every year, tire companies receive complaints and lawsuits of unexpected failures of tires. Examinations of these failed tire cross-sections showed that 95% of the failures occurred at the interfaces between steel belts and rubber. More interestingly, analyses of the failure surfaces revealed that there were multiple cracks existed at the interfaces, which may be initiated during the service, and the failures of the tires are most likely due to the propagation of these cracks. The knowledge of interactions of multiple cracks in bi-material or multiple material systems will certainly help to solve this tire problem.