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A tapered bondline thickness double cantilever beam (DCB) specimen geometry for combinatorial fracture studies of adhesive bonds

Shantanu R. Ranade [a], Youliang Guan [b], Donatus C. Ohanehi [b], John G. Dillard [c], Romesh C. Batra [b], David A. Dillard [b,*]

[a] Macromolecules and Interfaces Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States
[b] Department of Biomedical Engineering and Mechanics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States
[c] Department of Chemistry, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States

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ABSTRACT

The characterization of fracture energy (G_{Ic}) of an adhesive joint as a function of bondline thickness requires multiple specimens covering a range of bondline thicknesses. In this work, DCB specimens with linearly increasing or decreasing bondline thickness were studied for their feasibility to determine fracture energy as a function of bondline thickness. In a combinatorial characterization sense, this approach explores the possibility to characterize the effect of bondline thickness on fracture energy through fewer tests than those required for a "one at a time" characterization approach, thus offering a significant reduction in characterization times. Fracture energies were characterized under mode I loading conditions using corrected beam theory. The results obtained from linearly increasing or decreasing bondline thickness specimens showed good agreement with those obtained from specimens with a range of constant bondline thicknesses.

1. Introduction

The effect of bondline thickness (t), on adhesive joint performance has been the subject of considerable research, with many studies showing quite significant differences in resistance to failure as a function of the adhesive bondline thickness[1–13]. It has been observed, as shown schematically in Fig. 1 for toughened epoxy adhesive systems, that the fracture energy of an adhesive joint shows complex dependence upon the bondline thickness, with fracture energy values passing through a maximum at a certain bondline thickness t_m [1–3,10].

It has been suggested that such behavior, for a toughened adhesive system, is due to varying amounts of plastic deformation that develop ahead of the crack tip. In the fracture of monolithic materials, the radius of the plastic zone (r_p) developing at the crack tip often affects the resulting fracture energy. For small adhesive bondline thickness, $t < t_m$, the development of the plastic zone at the crack tip is restricted due to the presence of stiff, high yield strength adherends. Thus the adhesive fracture energy decreases with a decrease in the bondline thickness for $t < t_m$. As shown in Fig. 2(a), at $t = t_m$, the plastic zone ahead of the crack tip is fully developed with the diameter of the plastic zone ($2r_p$) normal to the plane of the crack being nearly equal to the bondline thickness, which results in a maximum fracture energy value for a double cantilever beam (DCB) specimen bonded with a given adhesive.

It has been reported that due to constraints imposed by stiff adherends, local tensile stresses ahead of the crack tip act over longer distances, thus leading to plastic zone size being significantly longer in length in joints than those in bulk adhesive specimens [3,14,15]. In Fig. 1 at bondline thicknesses $t > t_m$, the constraint due to the presence of stiff adherends decreases, thus decreasing the length of the plastic zone and resulting in lower fracture energy values compared to the fracture energy at $t = t_m$. Similar observations have been reported based on studies using finite element methods [7,8]. Cooper et al. conducted finite element analysis of tapered double cantilever beam (TDCB) joints with several bondline thicknesses, using a Dugdale-type cohesive zone model (CZM) to simulate mode I fracture in an adhesive joint [9]. Martiny et al. used a model based on a critical maximum principal stress at a critical distance ahead of a crack tip as a failure criterion to study the variation of the fracture energy with the bondline thickness [10,16]. It has been observed for toughened epoxy adhesive systems that the fracture energy vs. bondline thickness trends and the maximum in the fracture energy value also depend upon test variables such as the loading rate and

* Corresponding author. Tel.: +1 5 4 0 231 4714.
E-mail address: dillard@vt.edu (D.A. Dillard).

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the test temperature. It was also observed that at a given loading rate, test temperature changes in joint width altered trends for the fracture energy as a function of the bondline thickness [1].

In light of the dependence of the fracture energy on the bondline thickness and to maintain high quality of joints, the aircraft industry has long used techniques that tightly control the bondline thickness for critical structural joints. The use of supporting scrim cloth layers, for example, resists the flow of viscous adhesives and can result in good bondline thickness control [17]. However, in some applications, tolerances over bondline thickness are less strict, such as in the mass-produced automotive industry. The very large size and complex shapes involved in wind turbine blade assembly lead to an even wider range of bondline thicknesses, which may be many millimeters thick, much thicker than what has typically been used or recommended for structural joints. For these and other similar applications, an understanding of adhesive joint performance as a function of bondline thickness is critical. This typically requires characterizing the fracture energy using multiple DCB specimens, with each specimen having a constant bondline thickness. This “one at a time” characterization approach requires many specimens and significant preparation, testing, and analysis effort.

In a combinatorial characterization sense, the approach outlined in this study aims to explore the possibility of characterizing the effect of the bondline thickness on the fracture energy through fewer tests and in less time than those required for “one at a time” bondline thickness characterization approach. In this study the feasibility of using double cantilever beam (DCB) specimens with either increasing or decreasing bondline thickness (Fig. 3) has been assessed to determine the fracture energy as a function of the bondline thickness. An estimate of the plastic zone size in mode I plane strain conditions for bulk adhesive specimens was obtained through single edge notch bend (SENB) tests and the plastic zone size was then compared to t_m measured (Fig. 1) in DCB tests.

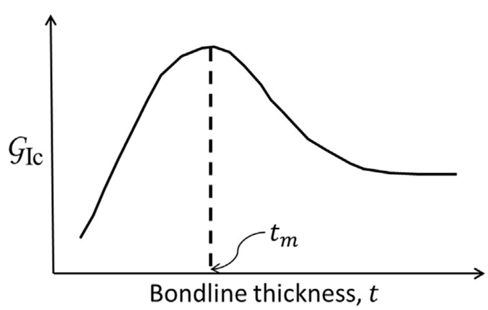

Fig. 1. Schematic representation of the effect of bondline thickness on mode I fracture energy of a toughened epoxy adhesive DCB specimen.

2. Experimental work

2.1. DCB tests

DCB test specimens were prepared using 6061-T6511 aluminum adherends, having dimensions of 305 mm × 25.4 mm × 12.7 mm (length × width × thickness). Circular holes were drilled at one end of each aluminum bar to accommodate 6.4 mm diameter loading pins. The adherends were then abraded with #220 sandpaper and exposed to a base-acid surface treatment, which consisted of placing aluminum bars in 10% (wt/wt) NaOH solution for 10 min, rinsing with deionized (DI) water and placing them in HNO_3:H_2O = 1:1 (vol/vol) for 2 to 3 min or until the surfaces regained a white metallic appearance. The adherends were then rinsed again with DI water, and placed in an oven heated to 110 °C for about 2 h to remove moisture absorbed on the surface. Two types of specimens were prepared. The first type of specimens had several constant adhesive bondline thicknesses (six specimens with bondline thicknesses of 0.02 mm, 0.77 mm, 1.7 mm, 1.87 mm, 2.26 mm, and 4.52 mm); the second type of specimens consisted of 10 either linearly increasing or linearly decreasing

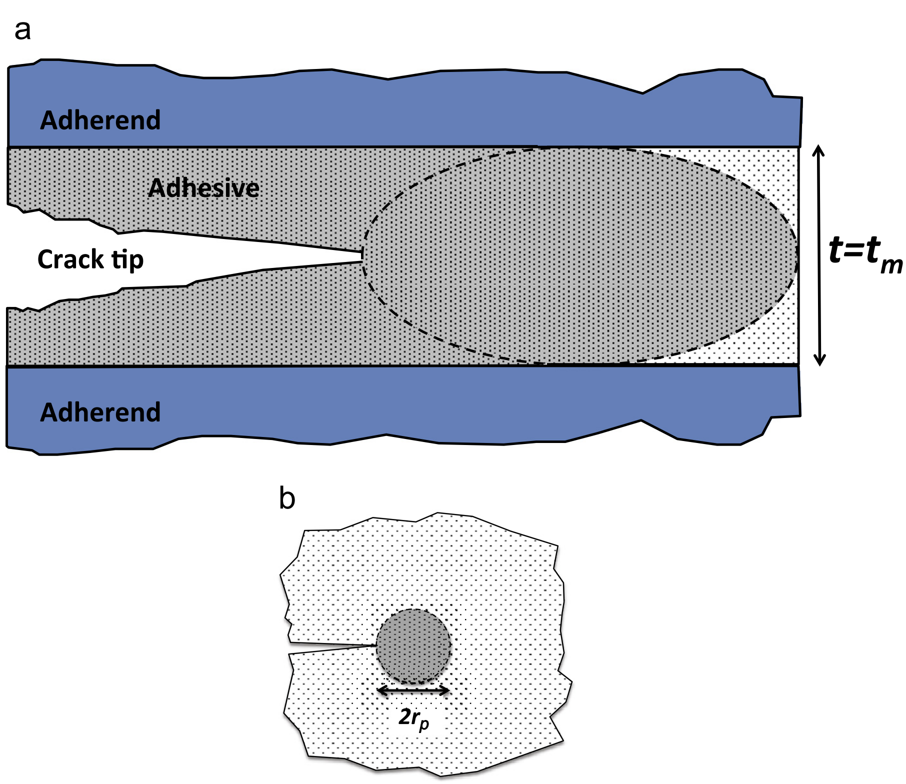

Fig. 2. Schematic sketch of the plastic zone developed at a crack tip in (a) an adhesive joint at bondline thickness $t = t_m$ [1], and (b) in a monolithic elastic–plastic material.