Fracture mechanics of delamination in ballistic glass laminates

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Introduction

Ballistic glass systems, typically designed as multi-material composites optimized for impact resistance [1, 2], are known to fail in service via interlayer delamination, creating visibility hazards [3]. In this work, we apply a fracture mechanics approach to investigate the delamination of a simplified ballistic glass coupon consisting of thermoplastic polyurethane (TPU) and polycarbonate (PC) layers. Using wedge-loaded double cantilever beam (DCB) test specimens, we compare crack growth for dry and high-humidity (50% RH) environments at 65°C. Results suggest that high humidity significantly accelerates initial crack velocity in this material system, but has no statistically significant effect on the ultimate (arrested) crack length for a given wedge size. As a result, we predict a common interface fracture toughness (K_{IC} = 0.125 ± 0.010 MPa√m) valid for both dry and humid environments at 65°C.

Analytical

The wedge-loaded DCB is well suited to testing in non-ambient environments because of its self-loading feature. A wedge inserted at one end of the specimen advances the interfacial crack, as shown in Figure 1.

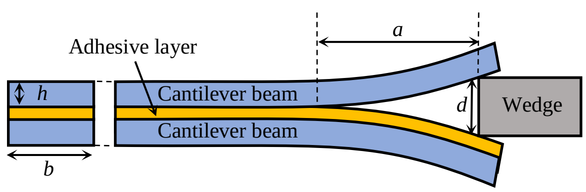

Figure 1. Schematic of the wedge-loaded double cantilever beam (DCB) specimen.

We adopt the so-called "Boeing" wedge test, in which the wedge remains stationary and fracture is imposed at a set opening displacement *d* (maintained by the wedge). Based on simple beam theory, the mode I energy release rate (G_I) in this case can be calculated as a function of crack length *a* as [4]:

Simple beam theory:

$$G_I = \frac{3Eh^3d^2}{16a^4}, \tag{1}$$

where *E* is the Young's modulus of the beam material and *h* is the beam thickness. Accuracy can be improved by correcting for the contributions of transfer shear and root rotation, as presented in Gowrishankar *et al.* [4]:

Corrected for shear and root rotation:

$$G_I = \frac{3Eh^3d^2}{16a^4}\left(1 - 2.691\frac{h}{a} + 4.485\frac{h^2}{a^2}\right). \tag{2}$$

This corrected form for G_I was used in the calculations of this study; and assuming plane strain, the stress intensity factor K_I can be related to the energy release rate G_I by [5]:

$$K_I = \left(\frac{E}{1-\nu^2}\right)\mathrm{G}, \tag{3}$$

where ν is Poisson's ratio for the beam material. Application of equations (2) and (3) can be used to generate time-dependent plots of G_I and K_I. Provided that the crack arrests, the critical energy release rate (G_{IC}) and interface fracture toughness (K_{IC}) can be assessed based on final values of crack length *a*. Note that while wedge thickness controls the initial crack loading, wedge size should not affect the *critical* values. Therefore, G_{IC} and K_{IC} results for different wedge sizes, in otherwise identical specimens, would be expected to converge.

Experimental

In a typical glass/TPU/PC ballistic glass system, delamination most commonly occurs at a characteristic interface between PC and TPU. To isolate this interface for study, DCB specimens were fabricated by sandwiching a layer of Krystalflex® PE399 TPU adhesive (1.3 mm thick) between two identical layers of PC (3.2 mm thick). Coupons of this sandwich material was assembled and bonded using manufacturing processes and an autoclave cycle similar to those used in the processing of ballistic glass parts. The coupons were then cut into 1-inch by 7-inch (25 mm by 178 mm) beams using a bandsaw, and a hot wire was used to remove a few centimeters of TPU at the end of each beam, generating an initial separation between the two adherends. The layers were then separated mechanically (after firmly pressing a knife into one PC/TPU interface to initiate an interface crack), and the wedge was inserted. Figure 2 shows a representative DCB specimen from the study, photographed in two orientations. Wedges consisted of un-tapered aluminum bars in several thicknesses (in some cases, two bars were stacked to achieve the desired wedge thickness) and ranged in thickness from 2.5 mm to 6.4 mm. Wedge sizes are specified in results plot legends.

Humidity conditions tested included a dry condition (achieved by placing specimens in a sealed jar together with a small beaker of 5Å molecular sieve dessicant) and a 50% RH humidity condition (achieved using an Espec SH-241 benchtop environmental chamber). The 65°C test temperature, used for all experiments, is in line with upper temperature extremes experienced by ballistic glass products under heavy solar loads. For specimens subjected to the dry environment, a self-adhesive ruler was attached to each DCB specimen prior to the start of testing to enable measurement of crack length by inspection without opening the sealed jar. DCB specimens were stored in a room ambient environment from initial fabrication until the beginning of testing. Wedges were inserted 1-7 days prior to the beginning of testing, and cracks did not advance measurably in the room ambient environment during that period.

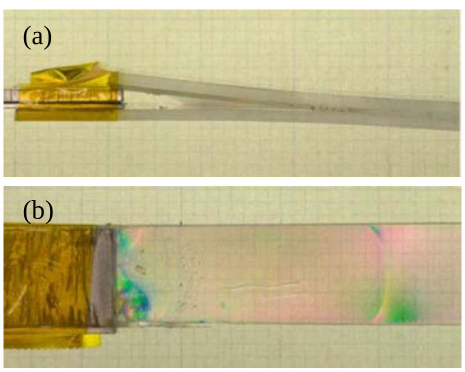

Figure 2. Ballistic glass DCB with wedge inserted, imaged between crossed polarizers to increase visibility of the advancing crack front, in (a) side and (b) top views.

During each test, crack length was recorded regularly (from the wedge tip to the peak of the parabolic advancing crack front) and energy release rates and stress intensity factors were calculated as functions of time using equations (2) and (3). The geometrical and mechanical parameters used in the analysis are shown in Table 1.

Table 1. Assumed geometrical and mechanical parameters

Parameter (for polycarbonate beam)	**Value**	**Reference**
Thickness h	3.2 mm	Measured
Width b	25.4 mm	Measured
Young's modulus E	2.38 GPa	[6]
Poisson's ratio v	0.38	[7]

Results and Discussion

Crack length a and stress intensity factor K_I are plotted as functions of time in Figure 3 and Figure 4 respectively. Solid red markers correspond to the humid environment, and open black markers correspond to the dry environment. From Figure 3, initial crack growth was clearly more rapid in the high-humidity case. This led to a relatively rapid drop in stress intensity factor K_I over time for the high-humidity tests, as compared to the dry tests (Figure 4). However, as crack growth slowed and finally arrested (after 60 to 90 days), values for K_I converged.

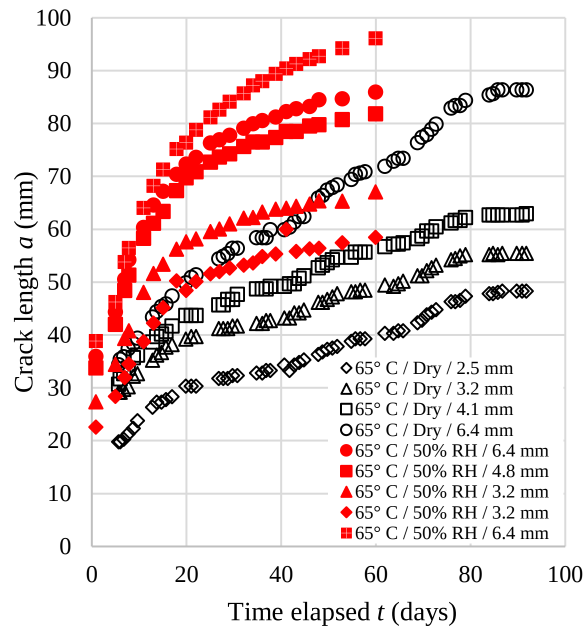

Figure 3. Crack length versus time elapsed

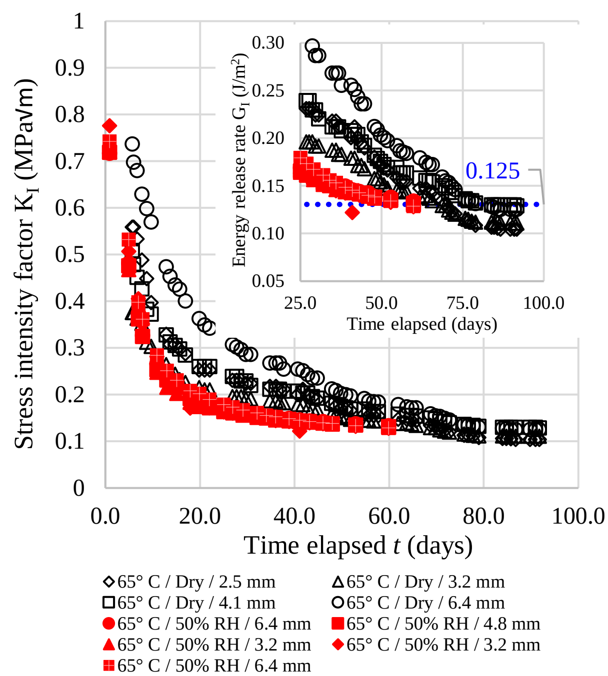

Figure 4. Stress intensity factor versus time elapsed

Figure 5 shows the final value of K_I plotted against the final crack length for each test. Convergence of final K_I values across wedge sizes suggests that a critical value K_{IC} can be reasonably assessed from this work, while convergence of K_I across humidity conditions suggests that humidity had no effect on the interface fracture toughness K_{IC}. Indeed, a Student's t-test (assuming unequal variances, based on results of an F-test) failed to demonstrate a statistically significant humidity effect at the $\alpha = 0.05$ level. We therefore predict a single fracture toughness of $K_{IC} = 0.125 \pm 0.010$ MPa√m (valid across both humidity cases) for this material system at 65°C. The corresponding interface fracture energy is estimated at $G_{IC} = 5.63 \pm 0.86$ J/m^2 for this system.

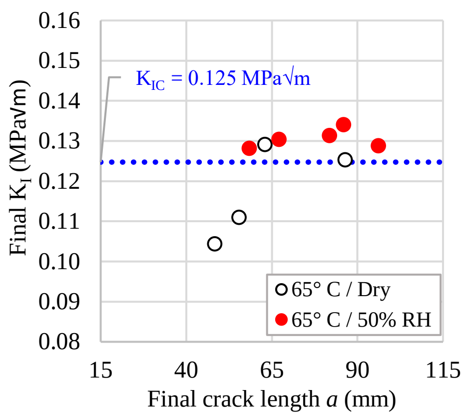

Figure 5. Final stress intensity factor K_I versus final crack length a for each DCB sample

Conclusions

Using the Boeing wedge test, we investigated humidity effects on the fracture mechanics of delamination between TPU and PC layers similar to those in ballistic glass products. We estimated an interfacial fracture energy of G_{IC} = 5.63 ± 0.86 kJ/m^2 and an interfacial fracture toughness of $K_{IC} = 0.125 \pm 0.01$ MPa√m for this material system at 65°C, and found no significant difference in these values across the two humidity conditions (dry and 50% RH). While results did not show a measurable effect of humidity on critical values G_{IC} or K_{IC}, early crack growth behavior for the two sample sets suggested that high humidity accelerated the initial rate of crack propagation. Further experiments are underway now to evaluate effects of other relevant environmental parameters, including temperature and chemical exposures from potting (sealant) materials.

Acknowledgments

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