engineered transparency. International Conference at glasstec, Düsseldorf, Germany
25 and 26 October 2012

Delamination in fractured laminated glass

Caroline BUTCHART*,
Mauro OVEREND[a]

* Department of Engineering, University of Cambridge
Trumpington Street, Cambridge, CB2 1PZ, UK
cvb25@cam.ac.uk

[a] Department of Engineering, University of Cambridge

Abstract

In order to simulate the post-fracture behaviour of laminated glass, the interfacial adhesion must be fully understood. This work proposes a method to determine the interfacial adhesion independent of testing rate. Through-crack tension tests were performed at two loading rates, from which the interfacial adhesion was calculated. The values of interfacial adhesion determined varied with testing rate, indicating that the adhesion itself may also be dependent on loading rate.

Keywords: laminated glass, PVB, viscoelasticity, interfacial adhesion

1 Introduction

The deformation response of a fractured laminated plate can be described by the superposition of a number of micro-mechanisms. Each of these mechanisms must be understood, and characterised independently of one another before the global behaviour can be accurately described. This paper isolates two of these mechanisms: delamination at the glass-polymer interface; and deformation in the polymer interlayer, and investigates both, analytically and experimentally through the use of '*through-crack tensile* (TCT) *tests'*. This work describes the behaviour of these mechanisms, and provides a method for determining the interfacial adhesion independent of interlayer rate-dependencies

1.1 Previous work.

Deformation and delamination in fractured laminated glass has been investigated a number of times, predominantly using TCT tests: examples include work by Seshadri [1], Bati [2], Delincé *et al* [3], and Ferretti *et al.* [4]. Other test methods include the double lap shear test and the compression shear test (CST), as performed by Jagota *et al*. [5]. The majority of these works use an energy balance approach, equating the external work done to the energy dissipated during delamination *(W_{delam})*, that stored as strain energy in the interlayer *(W_{strain})*, and that dissipated in the interlayer by viscous deformation *(W_{visco})*

$$F.\delta = W_{delam} + W_{strain} + W_{visco} \tag{1}$$

where F and δ are the applied load and corresponding displacement. The approach of these works is to describe the energy utilised during deformation of the interlayer analytically, and use this to determine W_{delam}. One common assumption to date is that the behaviour of the polymer interlayer can be modelled by a rate-independent hyperelastic material law. The most commonly used interlayers for laminated glass: polyvinyl butyral (PVB) and SentryGlas Plus® (SGP), exhibit highly rate-dependent viscoelastic behaviour. The consequence of this is, the viscous dissipation term W_{visco} in equation (1) is 'absorbed' by the other terms. Accordingly the validity of the interfacial adhesion obtained from this approach is applicable only to the loading rate used in the experiment. In order to describe the deformation behaviour of fractured laminated glass for a wide variety boundary conditions the interfacial adhesion must be quantified independent of any interlayer rate dependencies.

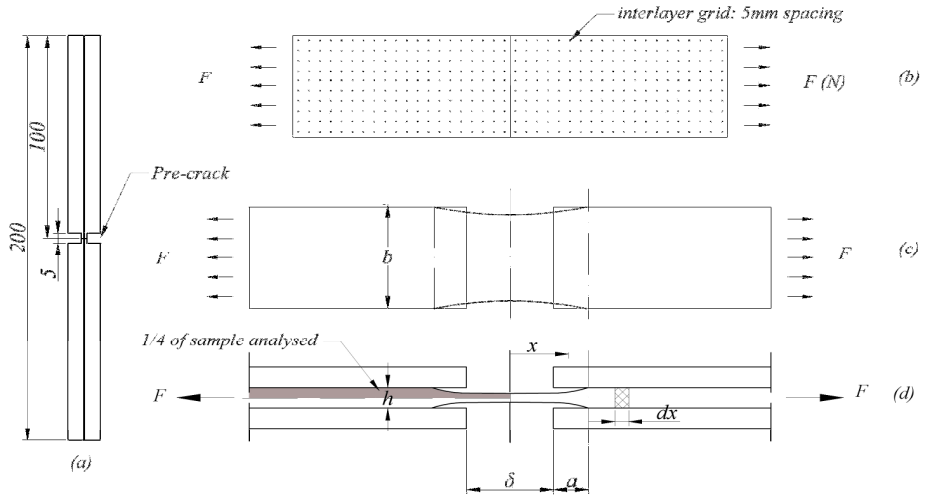

Figure 1: TCT sample parameter definitions

The interfacial adhesion Γ (J/m^2) can be defined as the energy per unit area required to separate two surfaces (W_{delam}/A), where A is the total area of separated interface. Values of interfacial adhesion published to date are summarised for glass-PVB laminates in figure 2.

1.2 Theory.

By combining a viscoelastic material law for the interlayer deformation, with the existing energy balance theory, a value of interfacial adhesion independent of loading rate can be found. The energy utilised in deformation of the polymer interlayer is defined as

$$W_{def} = W_{strain} + W_{visco} = \int_0^V \sigma.\varepsilon(x)dV \tag{2}$$

Where σ is the stress in the interlayer $\varepsilon(x)$ is the strain in the interlayer at location x, and V is the initial interlayer volume.

Source	Value [J.m^{-2}]	Experimental method	Interlayer material law
Seshadri [1]	280 – 930	TCT	Hyperelastic
Jagota [5]	400	CST	Viscoelastic
Bati [2]	600	TCT	Elastic (rate specific)
Iwasaki [6]	400 – 800	TCT	Elastic (rate specific)
Ferretti [4]	700 - 1400	TCT	Elastic (rate specific)

Figure 2: Published glass-PVB interfacial adhesion values

By assuming symmetry (see figure 1), one quarter of the sample can be considered, with $V=ab(h/2)$. It has been shown previously by Sheshadri [1] that the stress in the interlayer is approximately constant during the steady state phase of the TCT test, at which point delamination is occurring at a constant rate. For a viscoelastic material under constant stress, σ, the strain in the interlayer is defined as

$$\varepsilon(t) = \sigma \cdot D(t - \tau) \tag{3}$$

where $D(t)$ is the rate-dependent material compliance, and τ is the time at which the stress was applied . Ignoring edge effects, the delamination is assumed to begin at the pre-crack in figure 1 and travel evenly along all four glass faces. The rate at which the delamination occurs, ξ, can be defined as

$$\xi = da/dt \tag{4}$$

where a, is the average delamination length along one of the four glass faces. It is assumed that any segment of interlayer at location $x \geq (\delta/2 + a)$, remains unstressed until delaminated, at which point it is subjected to a stress $\sigma = F/bh$, where F, b, and h are defined in figure 1. The point in time at which delamination occurs at a given location x, therefore corresponds to τ, in equation (3): $\tau = x/\xi$

By substitution of equation (4) into equation (3) the strain profile along the interlayer can be described by:

$$d\varepsilon(x) = \frac{F}{bh} D\left(t - x/\xi\right) \tag{5}$$

An assumption of elasticity would result in constant strain along the interlayer length $\varepsilon_0=\sigma.E$. By substituting viscoelastic material properties of PVB published by Duser *et al.* [7] into equation (5) a prediction of the actual strain variation along the interlayer can be made. This can be seen in figure 3.

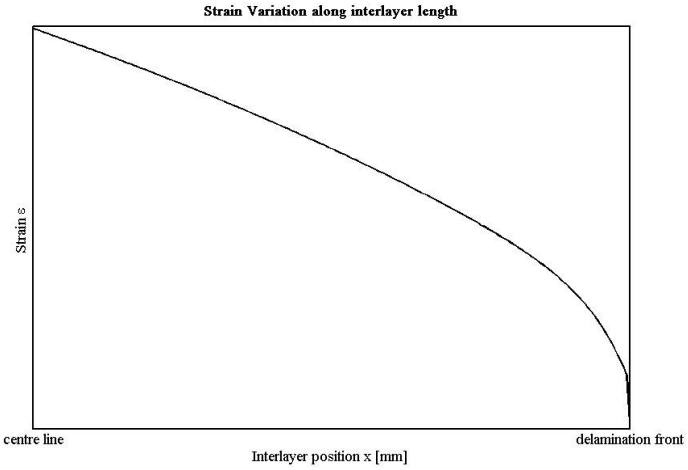

Figure 3: Variation in strain along interlayer length

The work done during deformation of one quarter of the interlayer can be found by integrating equation (2) along the length of the un-deformed, delaminated interlayer:

$$W_{def} = \frac{F^2}{2bh}\int_0^a D\left(t - x/\xi\right)dx \tag{6}$$

A viscoelastic material can be described using a Prony series, as outlined by Ferry [8]:

$$D\left(t - x/\xi\right) = D_g + \sum_{j=1}^{m} D_j\left[1 - \exp\left(\frac{x/\xi - t}{\tau_j}\right)\right] \tag{7}$$

where D_g is the glassy compliance (i.e. $D(t)$ as t tends to 0). D_j and τ_j are the retardation strengths and times respectively, and t is a constant equal to the test duration. The Prony series representation (7) can be substituted into equation (6) to enable integration. The resulting expression for W_{def}, along with $W_{delam}= \Gamma ab$ can be substituted into equation (1) to give an expression for the interfacial adhesion, Γ.

$$\Gamma = \frac{F}{4ab}\left[\delta - \frac{2F}{bh}\left[D_g a + \sum_{j=1}^{m} D_j\left(a - \tau_j\xi\left(\exp\left(\frac{a - t\xi}{\tau_j\xi}\right) - \exp\left(-t/\tau_j\right)\right)\right)\right]\right] \tag{8}$$

2 Experimental Procedure

2.1 TCT Tests

TCT tests were carried out on 10 samples (*200x50x[6AN + 0.36PVB + 6AN]mm*) of glass, laminated with Solutia's RB41 PVB, at two displacement rates: 0.0264mm/s (slow) and 0.264mm/s (fast). The pre-crack was induced using a glass grinding disk, to form a *5mm* wide by *5mm* deep groove along the centre line of both glass plies . The remaining width of glass was then fractured manually prior to testing. The purpose of this was to minimize damage to the interlayer during formation of the pre-crack. Displacement was applied to the sample using an electromechanical testing machine (INSTRON 5500 series). The sample was held using self-tightening jaws. Aluminium plates were bonded to the glass surface to minimize slip between the jaws and the sample, and to reduce the risk of stress concentrations causing fracture of the glass. The TCT samples were produced with a dotted grid at 5mm spacing, printed on the polymer interlayer. Images captured in the plane of the interlayer every 2 seconds, were used to measure the varying strain along the interlayer using digital image correlation (DIC). Simultaneously, images were captured of the delamination zone during the course of the test by means of a portable optical microscope. The images of the delamination zone provided information about alignment, friction, and angle of separation at the delamination front.

3 Results and discussion

Typical force-displacement responses are shown in figure 4 for both fast and slow rates. As found by Ferretti *et al*. [4] the response between samples was fairly inconsistent. Several samples failed early through tearing of the interlayer, usually initiating from the centre of the sample rather than the free edges. Early failure was much more common during the fast rate tests, whilst the slow rate tests performed much more consistently. All tests responded with an initial linear phase until a peak load was reached. This occurred between 230 and 350N for all fast-rate tests, and between 140 and 180N for all slow rate tests. This was preceded by a short 'steady-state' phase during which delamination and deformation are occurring at a constant rate. This continued until tearing occurred, beyond which point the behaviour varied widely.

The strain profiles produced using DIC can be seen in figure 5 at various stages of the test, alongside the corresponding test image. As expected, the strain profile varies significantly throughout the length of the interlayer, with a peak along the centre line. Force displacement data from the TCT tests, along with PVB viscoelastic material properties published by Duser *et al*. [7] were substituted into equation (8). This was then solved to determine the interfacial adhesion independent of PVB deformation-rate dependencies (Γ). This was done for both the fast and slow rate tests, the findings of which are summarised

below in figure 6. It can be seen that the value for the fast loading rate agrees well with the data highlighted in figure 2. It is expected that the value of interfacial adhesion independent of viscous deformation would be lower than that found using an elastic material law, due to the subtraction of viscous dissipation from the delamination term. It was expected that the interfacial adhesion would be independent of loading rate, but this was not reflected in the results. There has been some debate about whether interfacial adhesion itself is rate-dependent, and further work is required to investigate this.

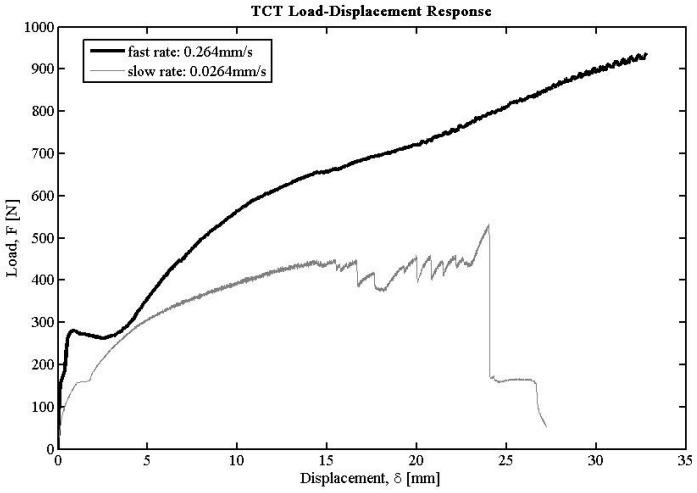

Figure 4: Typical load displacement response: fast displacement rate

3.1 Experimental inaccuracies

Although at test initiation, images captured by the portable microscope showed no horizontal misalignment of the two halves of the samples, as the tests progressed, interlayer deformation was always accompanied by frictional sliding along the delaminated glass face. It is believed that this is one of the reasons for the variation in delamination along different glass faces of the same sample. In the slow rate tests in particular, deformation of the interlayer was extremely localised, resulting in large deformation of just one row on the interlayer grid. Consequently DIC was limited by the detail available to capture. The value of interfacial adhesion found using equation (8) was extremely sensitive to delaminated length a. Variations in a of even 0.1mm caused a significant variation in Γ. In addition it is expected that the material properties of PVB are dependent on PVB manufacturer and even lamination process. Further improvements in the accuracy of the predicted interfacial adhesion could be made by using material properties specific to the PVB used to laminate the TCT samples.

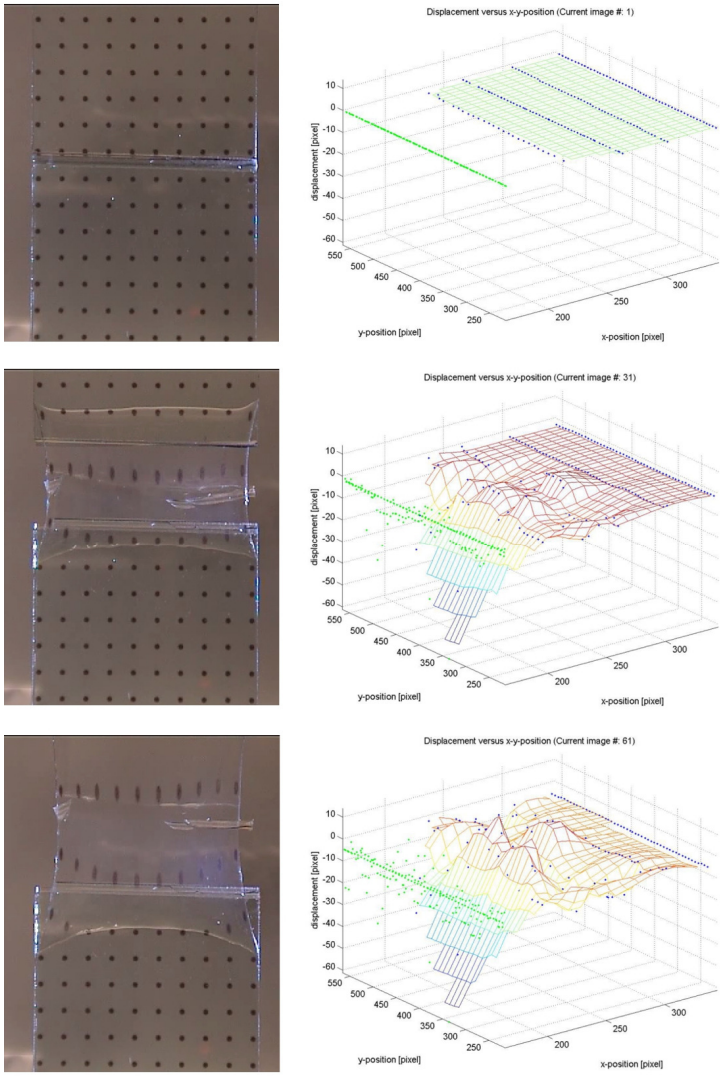

Figure 5: Strain profile at various stages during testing

Test Rate [*mm/s*]	a [*mm*]	ξ [*mm/s*]	Γ [J/m^2]
Fast	2.5	0.208	258
Slow	0.81	0.0118	660

Figure 6: Predicted interfacial adhesion

4 Conclusions

The tests confirmed the expected strain variation along the interlayer length. It was found that friction plays a significant role in the test response, as well as early onset of interlayer tearing. Values of interfacial adhesion found here varied with rate. Further investigation to determine whether this dependency is caused by a rate-dependence of adhesion itself must be performed.

4.1 Acknowledgements

The authors would like to thank Interpane, and Saint Gobain for the samples provided.

5 References

[1] Muralidhar, S.; Jagota, A.; Bennison, S.J.; Saigal, S.: Mechanical behaviour in tension of cracked glass bridged by an elastomeric ligament. In: *Acta Materiala.* Vol. 48, 2000, pp 4577-4588.

[2] Bati, S.B.; Fagone, M.; Ranocchiai, G.: Analysis of the post-crack behaviour of a laminated glass beam. In: *Glass Performance Days 2009,* Tampere, 2009, 349-352

[3] Delincé, D.; Sonck, D.; Belis, J.; Callewaert, D.; Van Impe, R.: Experimental investigation of the local bridging behaviour of the interlayer in broken laminated glass. In: *International Symposium on the Application of Architectural Glass*, Munich, 2008, 41-49.

[4] Ferretti, D,; Rossi, M.; Royer-Carfagni, G.: Through-cracked-tensile delamination tests with photoelastic measurements. In: *Challenging Glass 3,* Delft, 2012, 641-652

[5] Jagota, A.; Bennison, S.J.; Smith, C.A.: Analysis of a compressive shear test for adhesion between elastomeric polymers and rigid substrates. In: *International Journal of Fracture*. Vol. 104, 2000, pp 105–130.

[6] Iwasaki R.; Sato, C.: The influence of strain rate on the interfacial fracture toughness between PVB and laminated glass. In: *Journal de Physique IV*, vol. 134, 2006, pp 1153–1158.

[7] Duser, A.V.; Jagota, A.; Bennison, S.J.: Analysis of Glass/ Polyvinyl Butyral Laminates Subjected to Uniform Pressure. In: *Journal of engineering Mechanics*, vol. 125, 1999, pp. 435–442.

[8] Ferry, J.D.: *Viscoelastic properties of polymers. N*ew York: Wiley, 1980