Post-Fracture Performance of Laminated Glass

Introduction

Unlike traditional building materials, glass is inherently brittle and has no ability to redistribute stress concentrations though plastic deformation. It shows no warning signs of failure, and failure can be sudden and catastrophic. Laminated glass elements (two or more layers of glass bonded together with a polymer interlayer) are becoming increasingly utilised in response to this. When one or more layers of glass break, the glass fragments adhere to the polymer. The advantages of this are twofold: firstly the risk of falling glass shards is significantly reduced, and secondly the remaining glass element has a degree of residual load bearing capacity. After fracture of one or more glass plies, the ability to carry load - including self weight, is known as *'post-fracture performance'*.

As with other engineering materials, there are two limit states associated with the post-fracture performance of laminated glass elements:

1) serviceability limit state – the load deformation characteristics of a fractured laminated glass element
2) ultimate limit state – the load bearing capacity of a fractured laminated glass element

which can be referred to as *'post-fracture behaviour'* (PFB) and *'post-fracture capacity'* (PFC) respectively.

Currently there is no method of predicting post-fracture performance in terms of either PFB or PFC, other than by means of full scale destructive testing on a project-by-project basis. The consequence of this is designs are often very expensive, and frequently overestimate required dimensions in an attempt to minimise the number of destructive tests to be performed.

In response to this, a method is sought which would significantly reduce, or even eliminate, the need for full-scale destructive testing during the design of glass elements for post-fracture performance. A PhD research project is underway at the University of Cambridge, the aim of which is to develop a method of determining the post-fracture performance of laminated glass analytically, implementing data acquired from a series of easily repeatable small-scale tests.

Methodology

The ultimate aim of the research project is to develop an analytical technique for determining the post-fracture performance for any given loading condition, boundary condition, and fracture pattern. It has previously been suggested [1] that the behaviour of any given laminated glass plate, with a generic fracture pattern can be described as the superposition of the behaviours of each individual fracture in that plate. This separates the problem of determining post-fracture performance into two distinct phases: firstly the problem of determining the post-fracture performance of a single fracture, and secondly superimposing the performance of individual fractures to determine the post-fracture performance of the whole element.

Focussing on a single fracture in the laminated glass plate, as shown in figure 1, it can clearly be seen that there are several distinct post-fracture phases. An analytical model must be capable of describing any and all of these simultaneously, or most importantly, predicting which of these will occur, and when.

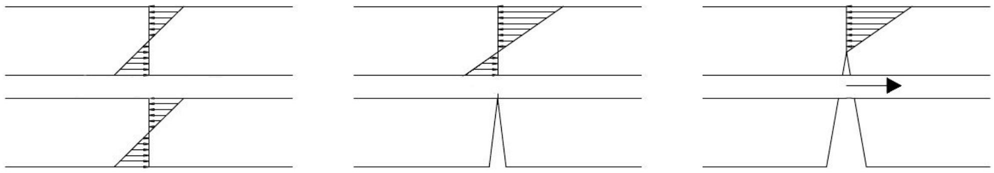

Figure 1: Different Phases of Post-Fracture Performance

Looking at a single fracture within a fractured laminated element it becomes clear that there are a number of separate processes occurring, each of which are highlighted in figure 2. This research approaches the problem using an energy balance technique: the energy dissipated across the single fracture can be described as the sum of the energies dissipated in each process that occurs at that fracture.

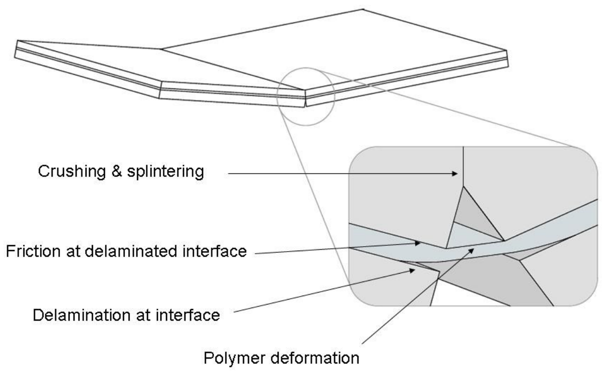

Figure 2: Processes contributing to post-fracture energy dissipation

The problem of determining post-fracture performance then becomes a problem of determining the energy dissipation in each of these processes under a range of suitable loading and boundary conditions. This research project will investigate each of these processes separately, before combining their individual characteristics in order to predict the more complex problems of the single fracture, and ultimately the whole fractured element.

Any information found regarding the behaviour of each of these processes must be independent from all other processes, and from any geometry or loading conditions. Without ensuring this, any data gathered will be geometry specific, and only applicable to the boundary and loading conditions under which the data was gathered.

An additional problem when considering post-fracture performance is whether the characteristics of laminated glass plates vary from one manufacturer to another and even from one laminator to another. For this reason, the research must not simply quantify the post-fracture performance but also describe a method for others to quantify the post-fracture performance of their product. It is envisaged that after each batch of laminated glass is produced, the post-fracture performance of that batch would be determined by the laminator, following a pre-described process, and the product would be sold with a specified post-fracture performance *'grade'*.

Polymer Deformation

The first process to be considered is deformation in the polymer interlayer. The majority of polymers used to produce laminated glass behave in a viscoelastic way; that is, their behaviour is dependent on temperature and the duration of loading. The first stage of the research project is to determine the viscoelastic material properties of the polymer interlayer, and to ensure that the method used to determine these properties is suitable for the prediction of post-fracture performance. Additionally, tests must be performed to ensure that (as is currently assumed) the polymer does behave in a linear viscoelastic way, and that there is no non-linear viscoelastic or viscoplastic behaviour present.

The first stage of this research involved performing indentation tests on small samples of Polyvinyl Butryal (PVB). The shear modulus was determined and expressed as a function of time using a Prony series. Through crack-tensile tests were then performed on samples of glass laminated with the same PVB interlayer [2]. A dotted grid was printed on the interlayer prior to lamination so that during the test polymer deformation could be observed. The deformation of the interlayer predicted using the shear modulus was compared to that found using digital image correlation, which tracked the movement of the dotted grid throughout the test.

Interlayer Delamination

The second process to be investigated is delamination at the glass-polymer interface. Delamination can be described in terms of interfacial adhesion - the energy required to separate two surfaces per unit area. Previous studies show that interfacial adhesion is a function of both loading rate, and angle at which the two surfaces separate. As can be seen in figure 2, the angle of separation of glass and interlayer will depend on the fracture pattern and support conditions, additionally the rate of separation will be strongly dependent on the applied loading. In order to determine interfacial adhesion as a function of both angle and rate, peel tests will be performed at a range of peel rates, and a range of peel angles.

Friction

Under certain conditions, the delaminated interlayer will be in contact with glass. There is evidence to suggest that small amounts of the polymer interlayer remain adhered to the glass plies after delamination. For this reason the frictional properties between the delaminated glass and polymer interlayer must be determined. It is envisaged that the amount of energy dissipated through friction will be negligible in comparison with other energy dissipation processes such as deformation and delamination.

Crushing

When two glass fragments are in contact there will be energy dissipated in several ways:

1) crushing and splintering
2) strain in the glass fragment
3) Movement/ rotation of the glass fragment.

It is expected that all of these mechanisms will take place, but that crushing and splintering will be responsible for the majority of energy dissipation in this category. Four point bending tests are to be carried out on glass plies with a pre-defined fracture, in order to determine the level of energy dissipated above that expected of strain energy alone.

Aging

It is expected that the age of the laminated glass element or the conditions to which it has been subjected will have an impact on the post-fracture performance. For example, the presence of contaminants is expected to affect adhesion, and weathered glass will likely have different fractured characteristics to ‘new’ glass. Samples of laminated glass will be tested under varying conditions in order to determine whether or not the conditions affect post-fracture performance.

Superposition

Once all processes are understood fully and independently from one another, they can be superposed in order to predict the post-fracture performance of a single fracture. An analytical method will be developed which uses data gathered from tests investigating each of the processes described above in order to predict both the PFB and PFC of a single fracture in a laminated glass element. This analytical technique will be validated by means of four-point bending tests on laminated glass plates with a single fracture induced in the plate prior to testing.

An extension of the analytical method for the single fracture will be found for the more general case of an unspecified fracture pattern in a laminated glass plate. This extension will be verified by full-scale tests on a range of fracture patterns

Conclusion

Research is underway to develop a method for determining the post fracture performance of laminated glass. The research will present a standardised method for determining the key properties of laminated glass from a series of small scale tests. It will then go on to describe a method for analysing the data analytically or numerically in order to determine the post-fracture load bearing capacity, and the post-fracture load-deformation characteristics of laminated glass. Finally the research will summarise the data gathered in charts, with the aim of simplifying the determination of post-fracture performance for everyday use.

[1] S. J. Bennison, A. Jagota, and C. A. Smith, “Fracture of Glass/Poly(vinyl butyral) (Butacite) Laminates in Biaxial Flexure,” *Journal of the American Ceramic Society*, vol. 82, no. 7, pp. 1761–1770, 1999.

[2] C. Butchart and M. Overend, “Delamination in Fractured Laminated Glass,” in *Proceedings of the 3rd international conference Engineered Transparency*, 2012.