Post-fracture behaviour of laminated glass

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Background

Project relevance

With the increasing use of glass as a structural material, this project investigated the ties between practical design cases and fundamental fracture mechanics of laminated glass.

Architects love the clean aesthetic of glass, but it is a difficult material to use as it is brittle. As a result, current design practice is overly-conservative and expensive. Laminated glass has some useful structural properties and so is becoming a popular choice. Also, injuries from falling glass shards are of great concern to designers. Laminated glass, if fractured, retains the shards in the frame, eliminating such hazards.

Project purpose

This project aimed, through modelling and experimentation, to investigate the post-fracture structural capacity of laminated glass, and to establish some new design principles.

Glass facts

Glass is a ceramic, and is very brittle. New glass typically has a tensile strength of 40-80MPa, but its vulnerability to flaws leads to a design strength of 8-16MPa . If sheets of glass experience bending moments, flaws on the tension surface open, and cracks swiftly propagate, leading to catastrophic failure.

Laminated glass

Laminated glass has a better post-fracture performance than common glass. The poor tensile behaviour of glass is partially mitigated by the laminating polymer, resulting in a material which takes advantage of the compressive strength of glass and the tensile strength of a polymer—often PVB (PolyVinyl Butyrol). The PVB also acts to hold together the framgments of glass after fracture.

Analytical model

This model describes the mechanics of a single crack forming at the central point of a laminated glass sheet, perpendicular to the edge of the sheet:

Equation 1 relates the width of the interlayer as the crack opens to the vertical deflection of the glass at the midpoint:

Equation 1

$$x = 2\left(T + \frac{t}{2}\right)\sin\theta$$

Equation 2 relates the work done by the applied load to the strain energy stored in the interlayer:

Equation 2

$$F\delta = 2k\left(T + \frac{t}{2}\right)^2\left(\frac{\delta}{L}\right)^2$$

Experimental work

I decided to investigate the effects of interlayer thickness and glass thickness, and designed experiments to test the validity of my analytical post-fracture model. I tested 150x350mm specimens in four-point bending to large deformations, measuring load and deflection. The tests are detailed in Table 1:

Table 1

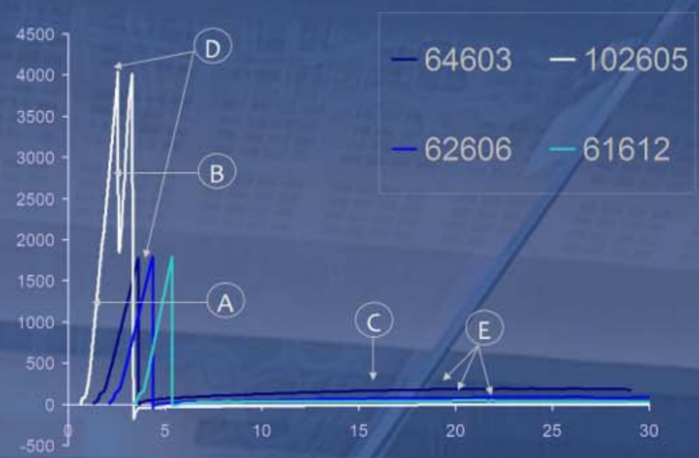
Variable	Glass lite 1 (mm)	IL layers / thickness	Glass lite 2 (mm)	No. of tests
Control	6	2 / 0.76mm	6	11
Lite thickness	4	2 / 0.76mm	6	10
	10	2 / 0.76mm	6	10
IL thickness	6	1 / 0.38mm	6	12
	6	4 / 1.52mm	6	10

NB Each specimen had a number abcd where a = top lite thickness, b = layers of interlayer, c = bottom lite thickness and d = no. of specimen in the batch.

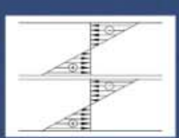
Eg. Control tests are 62601—62611

Mechanics of fracture

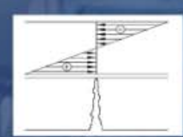
This graph shows the test data from four specimens.



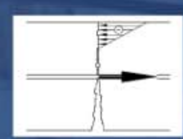
A. The two lites of glass behave as two layers of glass with some shear transfer through the interlayer. The load increases up to the point when the first lite breaks.



B. The first lite breaks, and the load capacity drops significantly. The load is taken by the top lite of glass up to the point when it fractures.



C. The second lite of glass breaks and the load capacity decreases again. The load is now carried by the interlayer in tension and compression through a small section of glass at the top of the section.



D. Increasing glass thickness increases initial breakage load: 102605 breaks at a higher load than the other specimens.

E. Increasing interlayer thickness increases post-fracture capacity: 64603 > 62606 > 61612

Initial results

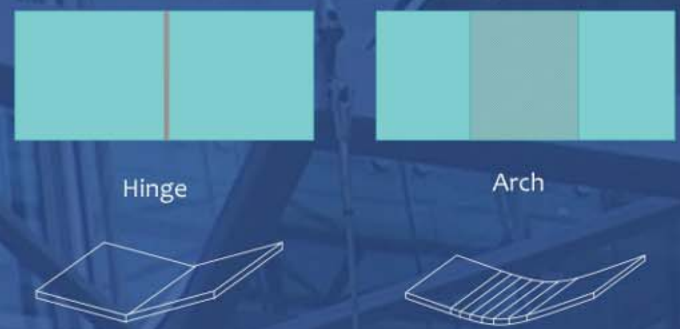
I induced a single crack in some specimens in the 4mm batch prior to loading in order to investigate a simple mechanism.

Table 2

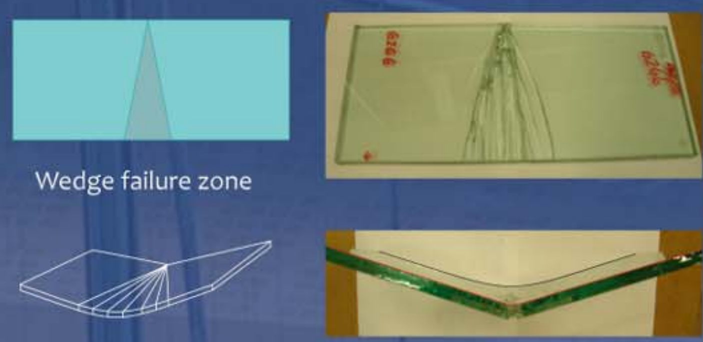
Specimen	k (N/mm)
42605	95.8
42606	173
42607	124
mean	131

These results show consistent k values for hinge failures. However, results were less conclusive for other failures.

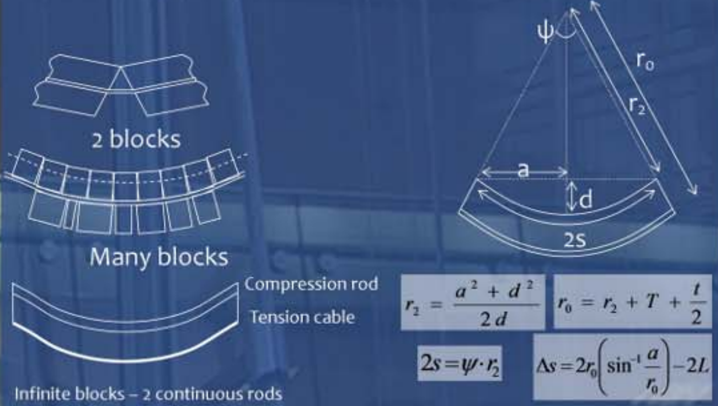
Modes of failure



Two fundamental modes of failure were observed: hinge and arch. Hinge specimens failed with one perpendicular crack. Others failed with several roughly-parallel cracks, and so deformed in a more arch-like way. However, most specimens failed somewhere between the two in a more wedge-shaped failure:



Specimens that failed in an arch or wedge mechanism did not fit my initial model well. I therefore expanded my analytical model to include arch behaviour:



$$r_2 = \frac{a^2 + d^2}{2d} \qquad r_0 = r_2 + T + \frac{t}{2}$$

$$2s = \psi \cdot r_2 \qquad \Delta s = 2r_0\left(\sin^{-1}\frac{a}{r_0}\right) - 2L$$

However, the results from the arch model were inconsistent. I concluded that an additional term was required, describing the work done crushing the glass in the compression rod:

Equation 3

$$F\delta = \frac{1}{2}k(\Delta s)^2 + \sigma\varepsilon \cdot \Delta V$$

Unfortunately, even with the extra term the results were still very inconsistent. Most of the problems were associated with determining the length of the IL section strained by the bending moment, and quantifying the work done by crushing glass.

Conclusions & the future

1. Laminated glass can be modelled in terms of fracture mechanics and energy, but this approach currently is only effective in simple, hinge cases.
2. The initial fracture strength of glass is determined by the glass thickness.
3. The post-fracture strength of laminated glass is determined by the interlayer thickness.
4. Future work could further investigate the arch failure mode by examining and quantifying of the work done by the crushing glass