Influence of Moisture on the Post-fracture Performance of Laminated Glass

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Keywords

1 =Laminated Glass
2 = Post-fracture
3 = Adhesion
4 = Peel
5 = Polyvinyl Butyral
6 = Durability

Abstract

In laminated glass, adhesion between the glass and interlayer has a significant effect on the post-fracture load-bearing capacity. Peel tests have been performed in order to investigate adhesion under different moisture levels, simulating sheltered conditions (e.g. internal glazing), exposed - drained conditions (e.g. vertical external glazing exposed to rainwater) and exposed - subject to ponding conditions (e.g. horizontal external glazing subject to snow load or ponding of rainwater). The investigations show that in the presence of water the adhesion between the glass and interlayer was less than half that observed in dry conditions.

1. Introduction

Residual load bearing capacity beyond initial glass fracture is required in a variety of design scenarios, in particular overhead glazing. This residual, or post-fracture, capacity is provided through adhesion of glass fragments to a polymer interlayer, such as Polyvinyl Butyral (PVB). This increases safety by reducing the risk of falling glass shards, and applied bending moments are carried through a combination of compressive stresses in interlocking glass fragments, and tensile stresses in the interlayer. The level of interfacial adhesion is crucial: too low means glass shards cannot be secured, too high can result in tearing of the interlayer. Currently there is no method of determining post-fracture load bearing capacity other than by full scale destructive testing, such as that outlined by Smith [1] and Beer [2].

Work is ongoing by both academic and industry based bodies, to develop a method of predicting post-fracture performance. It is widely agreed that post-fracture load-bearing capacity is a function of several factors: interlayer material properties; interfacial adhesion between the interlayer and glass; and glass fragmentation pattern. Work has focussed on describing each of these analytically [3,4] before using these properties to describe the behaviour of a single fracture [5] or a plate with a simple fracture pattern [6].

As yet, little work has been done to investigate how environmental conditions affect post-fracture performance. The long term effects of humidity, high temperature and radiation are already taken into consideration by European Standards [7] for un-fractured laminated glass. Before glass fracture, the interlayer is protected from environmental contaminants by the outer glass plies. Upon fracture, the interlayer is exposed, therefore the approach used for un-fractured laminated glass is no longer suitable.

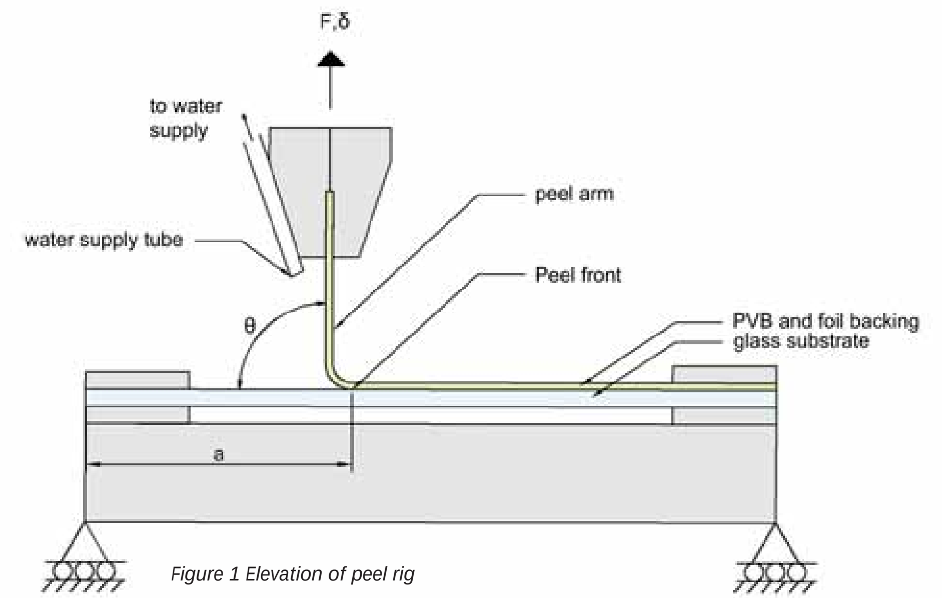

Figure 1 Elevation of peel rig

Unsheltered, external glazing can be exposed to rainwater, snow, sea spray etc. This work investigates the influence of water presence on post-fracture performance through investigation of the influence of water presence on interfacial adhesion.

There are several methods currently used to measure adhesion between glass and interlayer materials, the most noteworthy being the pummel, compressive shear [8], and peel tests [9]. Peel tests are particularly suitable for determining adhesion for post-fracture performance since the geometry of peel, seen in figure 1, closely resembles that observed during post-fracture delamination.

Peel tests are currently used by interlayer manufacturers as a quality control method to ensure adequate adhesion between the interlayer and glass. This paper presents the results of peel tests performed under different levels of exposure to water.

2. Method

Peel tests have been performed on specimens of PVB laminated between a layer of glass and a layer of foil backing, as shown in figure 2.

The specimens were manufactured from Saflex RB41 PVB under the same conditions as used to laminate full scale glass panels. All specimens were manufactured with a 30mm pre-peel length (ap), which was formed by taping a strip of PET to one end of the glass surface. The thickness of the tape is only 100µm, however this created a step on what would normally be a perfectly flat surface. Along the edge of this step, bubbles formed in some samples. Prior to the start of the test the interlayer was peeled manually from the glass surface until there were no bubbles remaining in the laminated area. This resulted in different initial delaminated lengths a0 between samples.

Peel tests were performed as outlined in BS EN 28510-1:1993 (ISO 8510-1:1990) [9] with the exception of specimen width, (b=30mm in figure 2).

All tests were carried out at 21±10C and 50±5% RH. Five specimens were tested at each of three different exposure levels:

Group A) Sheltered conditions (simulating internal / sheltered glazing not exposed to rain): Specimens tested at internal ambient conditions, but no further water applied to the test specimen.

Group B) Exposed - drained conditions (simulating external vertical glazing exposed to rain): Specimens tested at internal ambient conditions and in addition water is applied to the specimen at a constant rate in a manner that ensures water is present at the point of contact between the interlayer and glass throughout the entire test duration. The water is supplied at a constant rate, through a tube as shown in figure 1. Water lands on the glass surface at which point it spreads until it reaches the peel front.

Group C) Exposed - subject to ponding conditions (simulating horizontal glazing subject to ponding / snow): specimens were immersed in water held at a temperature of 21±2°C for a period of five days (deemed the longest time period before a fractured panel could be replaced/ supported). The peel tests were then carried out under the same conditions as group B.

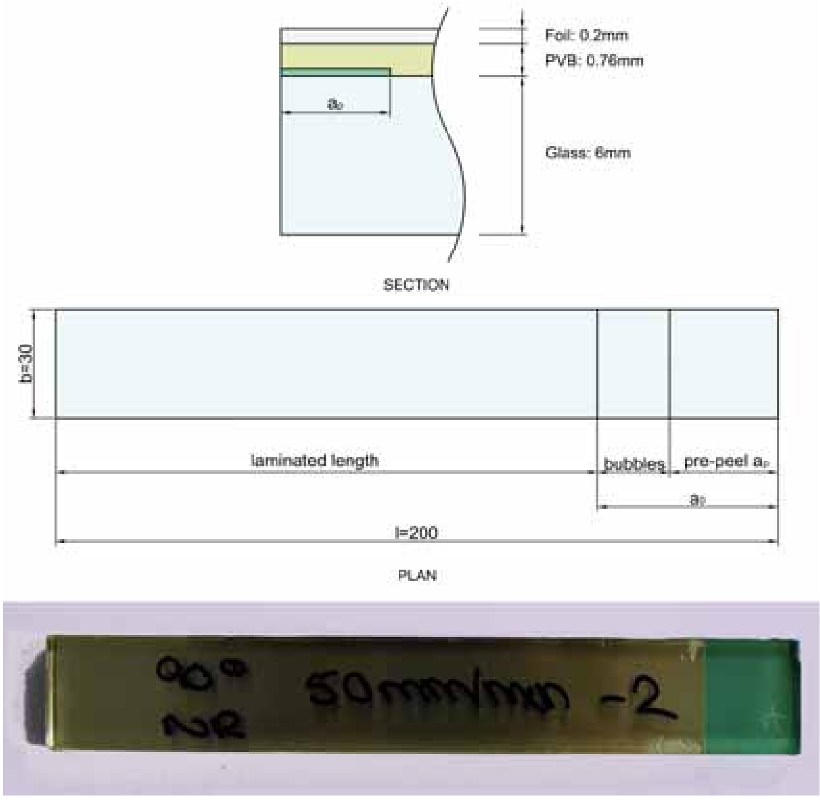

Figure 2 Peel test specimens - plan and section,

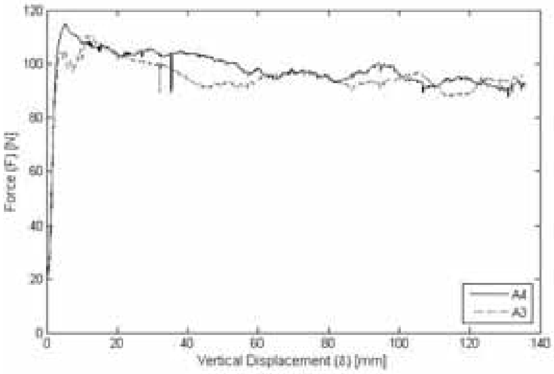

Figure 3 Force-displacement response - sheltered conditions

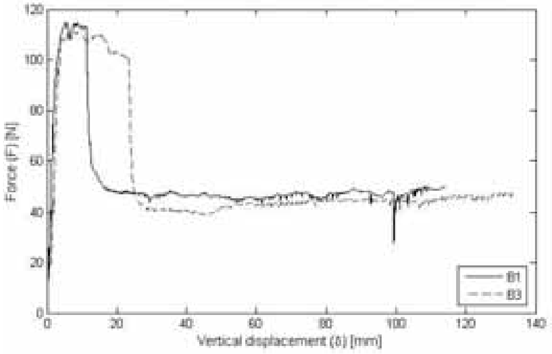

Figure 4 Force displacement response - exposed - drained conditions

The test rig, shown schematically in figure 1, was mounted on horizontal rollers which ensured the angle between peel arm and glass substrate (θ in figure 1) was maintained at a constant 90o. Displacement was applied to the peel arm at a speed of 50mm/minute. The force (F) required to maintain this displacement, and the delamination (a) were measured as a function of displacement (δ). Additionally the peel front was observed locally using a portable microscope in order to investigate the contact angle between the interlayer and glass.

3. Results

3.1 Group A: Sheltered conditions

When tested without additional water, all peel test specimens showed a response similar to that of specimens A3 and A4 in figure 3.

There was an initial linear phase where force increased steadily to approximately 110N. This phase was accompanied by stretching and straightening of the peel arm. Beyond this point was a quasi- steady-state phase during which delamination occurred at a roughly constant rate and the force gradually decreased to approximately 95N. This decrease in force can be attributed to the stress-relaxation of the viscoelastic interlayer. Delamination occurred in a stick-slip manner, which was attributed to friction in the horizontal rollers of the test rig. This stick-slip process, is responsible for the noise in the data.

3.2 Group B: Exposed - drained conditions

Specimens in group B were tested under the same conditions as group A with the addition of a continuous supply of water to the peel front. Water was supplied through a tube aimed at the exposed glass surface. Water spread along the glass making contact with the peel front (figure 1).

The peel force recorded is shown in figure 4 for two specimens. The response was consistent across all five tests.

There are several distinct stages to the test. Initially the response is similar to that of group A, increasing linearly to approximately 110N. The force then drops significantly to approximately 44N - less than half the steady-state force recorded in the sheltered conditions. This force is maintained throughout the remainder of the test, during which time delamination occurs in the same stick-slip manner observed during the conditions of group A.

During the initial phase of the test, the exposed area of glass is small. During this time the tube supplying water is not directed at the sample, rather over the edge of the test rig. After some time, the supply tube moves to a position over the glass surface and water comes into contact with the peel front. The point at which the load drops coincides exactly with the point in time when water reaches the peel front. This highlights the immediate and dramatic change in adhesive properties in the presence of water.

Additionally, the supply of water in specimen B3 was interrupted. No new water reached the glass surface beyond a vertical displacement of 95mm. Instead of returning to the peel forces observed during the sheltered test conditions, the peel force remained constant at 43N. An explanation for this was found when observing the peel front during this stage of the test. A small pocket of water, seen in figure 5a, which is smaller than that seen earlier in the test (figure 5b), travelled with the peel front. This can be attributed to the surface tension of water. Even though the volume of water supplied is significantly reduced there is sufficient water at the peel front for the peel force to remain constant.

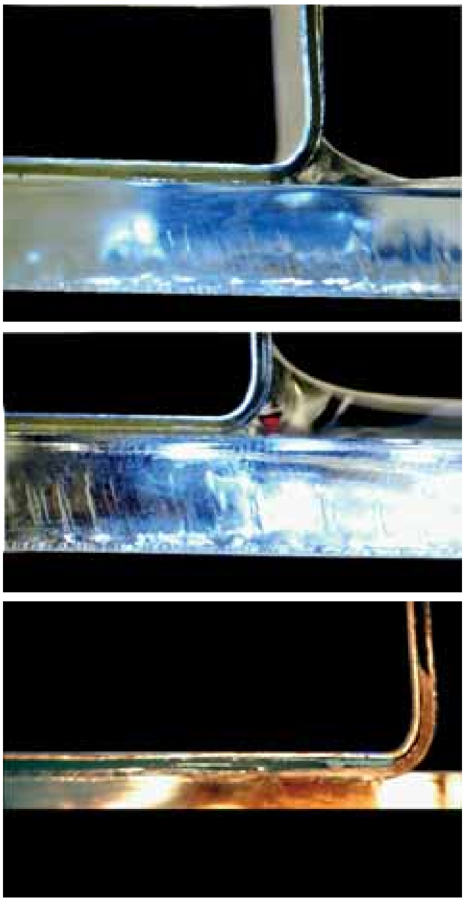

Figure 5 elevation of peel front a) low water volume b) normal water volume c) no supplied water

3.3 Group C) Exposed - subject to ponding

The specimens tested in this category were immersed in water for a period of five days before being tested under the same conditions as group B. The response, shown in figure 6, can still be divided into two stages, however these are less distinct than those observed in group B. Initially there was a linear increase in force, during which time the peel arm straightened and stretched. An average peak force of 55N was observed, beyond which the peel force steadily decreased to an average of 44N in 4 out of 5 samples. The steady state phase of the test was identical to that seen in group B.

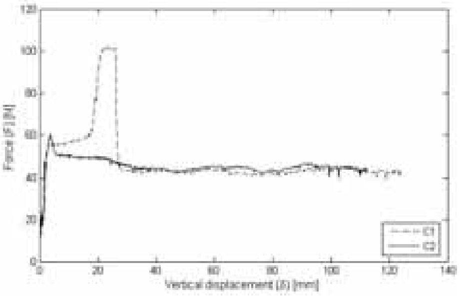

Figure 6 Force displacement response - exposed - subject to ponding conditions

Specimen C1 responded in a different manner to the others in this group. As explained earlier, the initial length of delaminated interlayer varied from sample to sample, depending on the presence, and extent of bubbles. Specimen C1 had no bubbles, and as such had the shortest initial length. As with group B, there is a period of time during which there is no water applied to the peel front. The shorter the initial delaminated length ao, the longer the time taken for the moisture to reach the peel front. After an initial response similar to those seen in the remaining group C specimens, the peel force then increased to values similar to those seen under dry conditions (figure 3). An explanation for this is during the soaking period water was absorbed into the interlayer. This absorption only occurred to a certain depth, beyond which there was no change in moisture content of the PVB. Once delamination had passed this point, the sample is effectively under sheltered conditions until the supplied water reaches the peel front. Beyond this point the specimen behaved in exactly the same way as all other samples in group C.

4. Discussion

The results of these tests can be summarised simply: if there was water present at the peel front, the adhesion strength was found to be less than 50% of that observed during sheltered conditions.

In all practical applications, fractured laminated glass that is subject to ponding would also have water present at the peel front during delamination. As such, the intermediate peel force observed in the initial stages of group C would have little relevance in a design scenario. Ponding was not found to decrease the steady state peel force further.

The results from specimen B3 indicate that there is no change in peel force with change in water volume. As such it is reasonable to conclude that the influence of water at the peel front is analogue. This would lead to the development of two sets of criteria for the design of laminated glass in the post-fracture stage: sheltered or exposed.

There are several implications of these results. Firstly it is clear that the current method of using full scale destructive testing to determine the post-fracture performance should be altered to testing under wet conditions for external glazing. Secondly, methods under development to predict post-fracture performance need to account for the reduced adhesion in the presence of water. Thirdly laminated glass compositions where the interlayer remained protected during the post-fracture stage would have significant advantages over those where the interlayer is exposed to water. Laminated glass elements constructed of three or more layers of glass are common in applications outside ‘normal’ glass usage, for example for the construction of floors, staircases, and beams. If the internal layers of glass are designed to fail before the outer layers, for example through the use of an annealed core, the interlayer would remain protected from water ingress. However this may be difficult to achieve when designing for impact or other surface damage which normally results in fracture of the outer glass layers before the core.

5. Conclusion

Peel tests have been performed on specimens of PVB laminated between a layer of glass and a layer of flexible foil backing. The tests were performed under three different moisture levels, simulating sheltered conditions (e.g. internal glazing), exposed - drained conditions (e.g. vertical external glazing exposed to rain) and exposed - ponded conditions (e.g. horizontal external glazing subject to snow load or ponding of rainwater).

The results show that in the presence of water the force required to peel the interlayer from the glass was less than half of that recorded under dry conditions. Post-fracture performance of laminated glass is strongly dependent on adhesion between the interlayer and glass. The reduced adhesion due to the presence of moisture would have a negative effect on the post-fracture performance. As a consequence of this, full-scale destructive testing should be performed under wet rather than ambient conditions for exposed glazing. Future methods developed to determine the post-fracture performance of laminated glass should distinguish between internal and external laminated glass. Alternatively, laminated glass constructed of three or more layers of glass could be used to protect the interlayer from water ingress.

This research programme is at an early stage and it is as yet unconfirmed whether similar results will be found for other interlayer materials, such as Ionomers and Ethylene Vinyl Acetates. Additionally, further work should investigate whether this result is dependent on rate of peel. Finally a threshold volume of water below which the reduction in adhesion is suppressed may exist. This threshold volume, or even relative humidity, should be investigated further.

Acknowledgements

The authors would like to thank Eastman for both providing materials for this study and taking the time to help produce the samples. Their guidance has been invaluable to this research.

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