FRACTURE CONTROL OF GLASS THROUGH LAMINATION

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ABSTRACT

The mechanism of fracture in glass has been studied extensively. Through it's brittle nature it is an ideal model material. This suitability as a model material unfortunately also makes it a poor engineering material. The unique characteristics of transparency and chemical durability of glass forces the large scale use of this material in architecture and many other engineering branches. The limitations of glass as an engineering material however are a problem creating a requirement for a transparent material with mechanical properties comparable to metals.

Research into novel laminated glass based composites has resulted in a concept material that combines the transparency of glass with the structural safety of metals. This material is based on the concept of controlling the crack behaviour of the glass and arresting the cracks using crack bridging by the polymer interlayer in the crack wake.

KEYWORDS

Glass, Laminates, Fracture control, Crack bridging

INTRODUCTION

In many design's glass is used because it is the only transparent material available with a sufficiently high E-modulus to achieve adequate rigidity of the structure. Glass is however an extremely brittle material. The fracture mechanics of glass is well known, as the material was used by Griffith to develop the discipline of fracture mechanics. Although the mechanism of fracture in glass has been well understood for decades the only improvement that has been made is laminating the glass to increase the safety by avoiding spalling of glass fragments after failure has started. From the mechanical point of view no safety is obtained because, after failure of a glass pane in a laminated sheet has started, it effectively has no residual strength. Current tendencies in architecture are for increased usage of glass to the point where it is used as a structural material. The lack of residual strength after failure has been initiated requires the use of very high quantities of glass to provide for adequate structural safety by introducing redundancy through overdimensioning the structure. To avoid the extreme overdimensioning of the structure a material that combines the transparency of glass with the ductility of metals is required. This paper will show some of the steps in developing the resulting composite.

THEORETICAL FORMULATION

To develop a transparent structural material it has to be realised that transparency imposes unique restrictions. A material that is transparent must not disperse light. Thus all phase boundaries must be in the plane of the material to assure that all light is refracted in the same way. The requirement of high E-modulus requires the use of glass sheets as a base material. The question thus resolves itself to how to control the fracture behaviour of glass. A pane of glass normally fails by cracks developing from defects on the edges of the material. These edges are the result of processing. The inherent brittleness of glass means that even defects with sizes of 10 µm can lead to cracks developing at low stresses. Pre-stressing the glass can reduce the stress concentrations at these defects by introducing a permanent compressive stress in the surface. The normal thermal pre-stressing methods however stores so much energy in the material that once failure is induced the material disintegrates. Using ion-exchange techniques for pre-stressing allow for exact control of the residual stress. This means that fracture initiation can be delayed but total disintegration can be avoided (1). This means that the problem resolves itself to arresting the cracks and bridging the cracks that are initiated. Successful crack bridging and crack arrest means that the material has potentially enough residual strength to allow it carry loads after accidental overloading has introduced some cracks.

This problems is similar to that faced in concrete. In concrete fibre or rod reinforcements can bridge cracks arresting and bridging the cracks by deformation of the reinforcement in the crack wake (2). Unfortunately these fibres would scatter the light passing through the glass making the material translucent. Crack wake effects must thus be introduced not into the sheet of glass but in a adjacent sheet of a transparent polymer bonded to the glass. If an edge crack starts in a glass pane, the crack will grow until the energy released by crack propagation is equalled by the energy absorbed by deformation of the polymer in the crack wake.
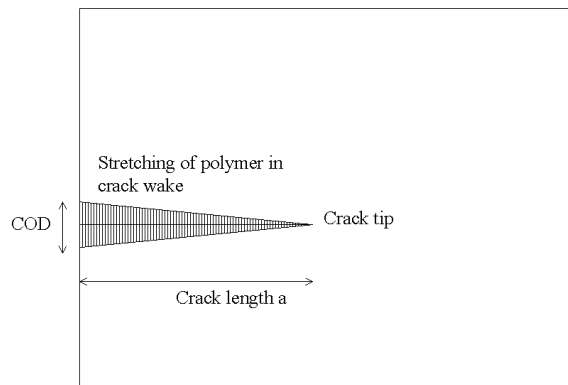

Figure 1: Schematic diagram of crack wake activity in laminated glass

The problem lies in the adhesive layer. If the adhesive is too strong all the energy will be focussed on a small region of polymer adjacent to the actual crack. In theory this means that an almost infinite strain will be placed on a small area of the polymer adjacent to the actual crack. If the adhesive fails locally, local debonding becomes possible allowing for distribution of the strain across a greater volume.
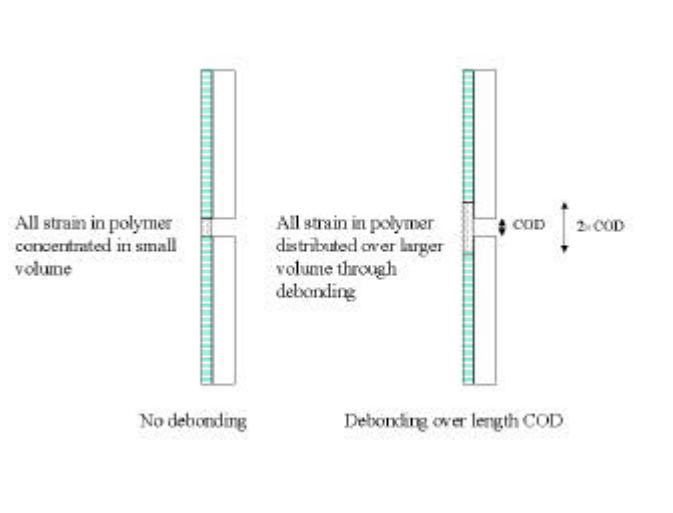
Figure 2: Effect of debonding on strain distribution in the polymer

Assuming that the length of the debonding region is X×COD, at any point in the crack wake a length of 2X×COD is being stretched to (2X+1)×COD. If X is too small the strain in the polymer will exceed the fracture strain and the polymer will fail leading to total failure of the element. If X is too big the composite will delaminate and fail. Achieving a critical value of X allows the possibility of successful crack arrest and crack bridging. This can be solved analytically for a single crack in glass with two sheets of polymer on either side. In a realistic component multiple layers of glass will be used with polymer interlayers. The interaction will be too complex for effective analytical formulation. In addition the possibility of building up large components from smaller plates by an overlapping arrangement complicates the modelling.
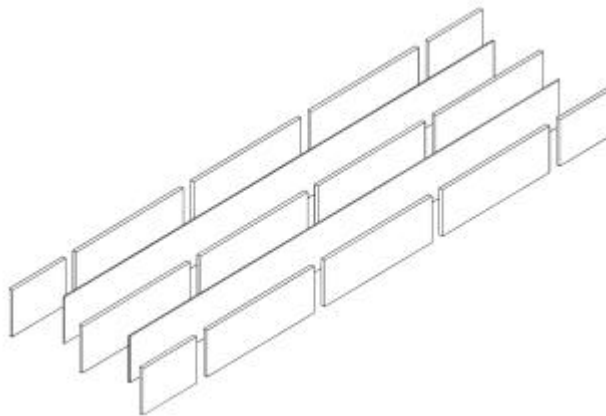

Figure 3 : Beam build up from smaller components

Numerical studies of the concept using the finite element technique are possible. Some studies were conducted using the ANSYS FEM programme. Initial studies suggested the following :

- the theoretical concept should work in real life
- the polymer plies should be much thinner than the glass plies
- the polymer should have a large fracture strain (>50%) for the mechanism to work efficient, polymers with small fracture strains require large debonding lengths, which reduces the properties of the composite to an unacceptable level.
- the individual glass plates should be as large as possible in relation to the thickness to prevent hinges forming in the component

The results of these calculations were interesting and showed that the concept was workable but also showed that very complicated models are required to take account of the following :

-        debonding of the adhesive layer
-        transfer of compressive and shear loading across the crack face

 From these initial results it was decided to use polycarbonate as the polymer due to it's large fracture strain and easy availability. As a result an experimental programme was formulated to test the concept and to determine :

-        the required strength of the adhesive to give adequate debonding
-        the optimum thicknesses of glass and polymer

RESEARCH INTO THE ADHESIVES

 As sufficient is known about the effect of ion-exchange on the residual stress in glass and the fracture properties, the primary problem was to investigate which adhesives are suitable for this requirement. Although several types of transparent adhesive exist, they are not all able to bond polycarbonate which has a low surface energy. Testing different types of polyurethane and acrylic adhesives showed that the polyurethane adhesives were not suitable because they only formed thick adhesive layers. The thickness of the adhesive did allow for quick redistribution of the stresses from the glass to the polycarbonate. In addition the adhesive was too tough to effect delamination. Acrylic adhesives formed thin layers ($\tilde{}$10µm) with a shear strength of 5 MPa and sufficient brittleness to delaminate close to the crack.
 Further research used photo-catalytic acrylic adhesives which are easier to use as they only start to cure when illuminated by light of the right frequency. These photo-catalytic adhesive have a shear strength of 5 MPa, can wetten the polycarbonate. They have sufficient bond strength to bond the glass and polycarbonate together and sufficient brittleness to allow for easy local debonding near cracks.

RESEARCH INTO COMPOSITE BEAMS

 Prototype beams were made using several configurations based on the general design shown in figure 3. These were tested in 4 point bending. In the test the following phases could be distinguished :

(a)   an initial elastic part
(b)   a part where cracks start to form in the tensile region, these cracks propagate at angles of about 20º to the loading axis, E-modulus falls but strength remains constant
(c)   a part where cracking intensifies and significant displacement of the specimen occurs, the E-modulus falls but the strength remains constant
(d)   the final stages where crushing of the glass takes place in the compression zone, strength falls slowly until final failure occurs
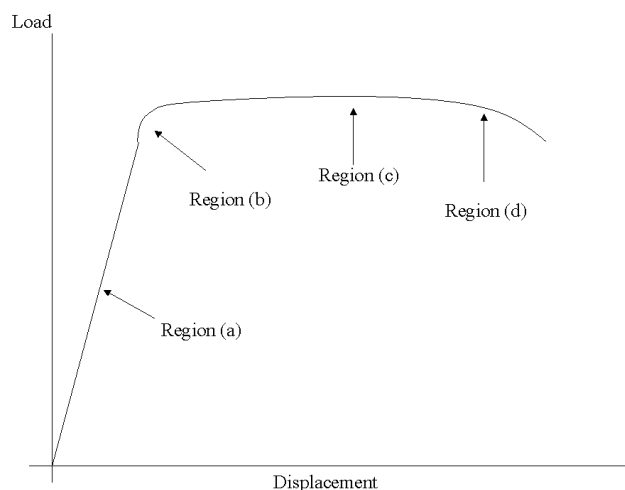

Figure 4: Generalised load-displacement curve of composite beams

The actual strength is dependent on the level of pre-stressing of the glass and the configuration. Ultimate strengths in bending of 80 MPa with a Young's modulus of 50 GPa and a fracture strain of 25% can be achieved reliably. This is similar to the mechanical properties of some aluminium alloys.
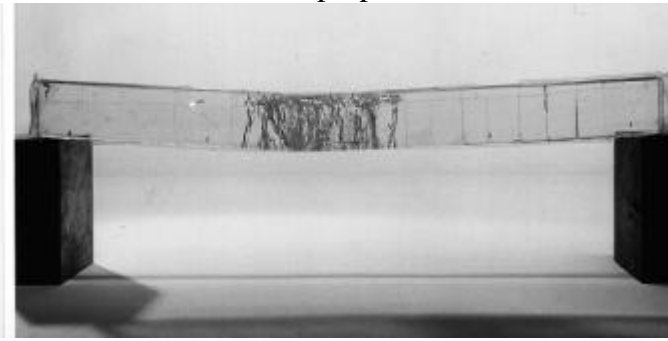

Figure 5: Beam specimen after testing

RESEARCH INTO COMPOSITE PLATES

 In a similar way composite plates were produced. The number of layers, number segments in a glass ply and method of overlapping is a design variable that allows for tailoring of the properties. The plates were tested by supporting them at the four corners and loading them in the centre until cracks started to form.
 Cracks were always started at the edges of the glass segments in the tensile bottom layer. At a given stress level the cracks were arrested after several mm of growth. Increasing the stress resulted in limited crack growth followed by crack arrest. Study of the arrested cracks under load with microscopes showed that debonding took place over a length of approximately 2× COD at any point in the crack length with variations between 1 and 3× COD depending on bonding quality. Properties are again dependent on the configuration but similar to those found for beams. In addition the plates have a significant anti-penetration capability.
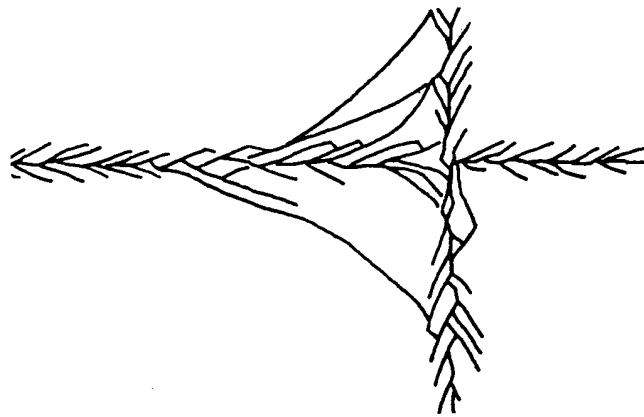

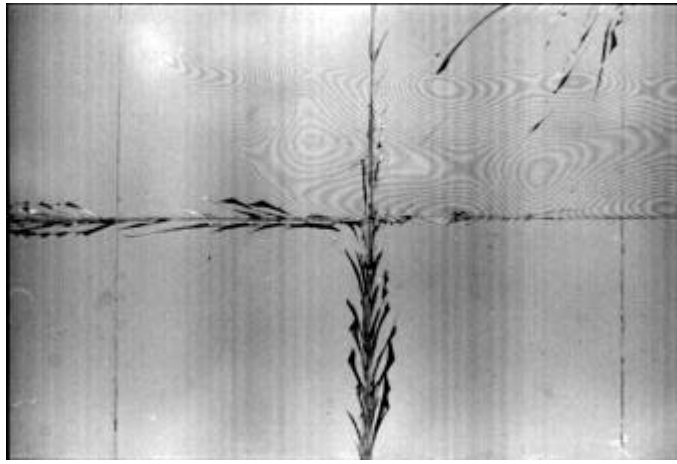Figure 6: Drawing of arrested cracks at edges of segments in composite plates

Figure 7: Foto of arrested cracks at edges of segments in composite plates

CONCLUSIONS

  Although the brittle nature of glass cannot be changed some toughness can be build into laminated composite glass structures by new methods of lamination. Using a thin ductile polymer interlayer bonded to the glass cracks in the glass can be arrested by stretching of the polymer interlayer in the crack wake. In addition this provides crack bridging.
  This stretching can only occur if the adhesive delaminates locally, distributing the strain in the polymer over a greater volume. A brittle and strong adhesive that can be applied in a thin layer is required for this. If the adhesive is too strong or the layer is too thick the mechanism does not work because the strains are not properly distributed to the polymer interlayer resulting in failure of the interlayer of failure of the laminate.
  Using this method of obtaining crack arrest and crack bridging transparent composite beams and plates can be made with mechanical properties similar to some aluminium alloys. Although considerable work is yet required to produce a real engineering material the concept provides the basis for an unique material combining transparency with the ability to safely carry loads. Patent for the various developments is being applied for.

ACKNOWLEDGEMENTS

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