Energy absorption in glass-polycarbonate laminates

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ABSTRACT

Recently advanced laminated glass structures have been developed that are designed for structural use. These advanced laminates fail progressively, losing some of their stiffness in exchange for a quasi-plastic deformation and thus have a failure behaviour comparable to metals and thermoplastic polymers in that they yield before failing. Beam specimens of several different types of configuration have been manufactured and tested in bending. It is shown that the configuration has a significant effect on the energy absorption. In certain configurations near metallic ductility and failure behaviour is possible while maintaining the transparency of glass. The relevancy of the results for the design of transparent laminate systems are discussed

INTRODUCTION

In modern constructions that require a high degree of safety laminated glass is used for the windows. This ranges from the simple Glass-PVB laminates in windows to advanced glass-polycarbonate laminates in bullet-proof glass. In practice little is known about the structural safety of these laminates. Generally it is accepted that these materials have no real structural function. Traditional laminates are composed in such a way that once one pane of glass fractures, the polymer interlayer holds the pieces together while a second pane of glass keeps everything in position.
More advanced laminates fail progressively, losing some of their stiffness in exchange for a quasi-plastic deformation as shown by Veer et al. [1]. These advanced laminates thus have a failure behaviour comparable to metals and thermoplastic polymers in that they yield before failing. This should allow these advanced laminates to be used as a structural material as it has

sufficient safety without the need for grossly overdimensioning the structure.
To determine the safety of this type of laminate, beam specimens of several different types of configuration have been manufactured. These have been tested in 3-point bending.

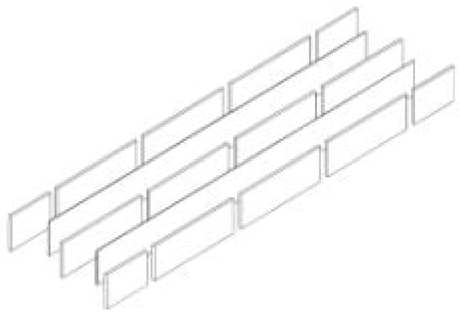
EXPERIMENTAL PROCEDURE

Glass strips of size 400 mm long and 40 mm wide were cut from glass plates with a thicknesses of 3 mm. These were cut using a standard oil-lubricated glass cutter by an experienced glazier. Where the glass for the layered, laminated and segmented laminated specimens was strengthened by ion-exchanging it in molten KNO_3 for 72 hours at 380°C. The glass of the reinforced laminated glass was not strengthened.
The glass strips were bonded together into four configurations :

1 Layered glass	3 strips of glass bonded together directly
2 Laminated glass	3 strips of glass bonded together with a 1 mm polycarbonate strip as intermediary
3 Laminated segmented glass	3 strips of glass bonded together with a 1 mm polycarbonate strip as intermediary. The glass being cut into segments to simulate a large beam build up from small component. This is illustrated in figure 1.
4 Laminated reinforced glass	3 strips of glass bonded together with a 1 mm polycarbonate strip as intermediary, with the centre strip being reinforced at the bottom by a stainless steel L profile of 1 mm thickness and sides of 3 mm. A cross-section is shown in figure 2.

For the layered glass DELO photobond 4302 adhesive was used. For the glass-polycarbonate specimens DELO photobond 4455 adhesive was used. The stainless steel profile was bonded to the glass centre strip using a transparent 2 component epoxy manufactured by Bison. This adhesive was chosen because of it’s high glass/metal shear strength of 30 MPa, and it’s ability to produce high strength bonds on rough surfaces.
All beams were wrapped in plastic safety foil to prevent shards flying around after failure.

The resulting beams were tested in 3 point bending on a Zwick Z 100 universal testing machine. The specimens were tested until the load dropped by 20%. After this they were tested for a second and third time except for the layered glass which lost all cohesion at maximum load.



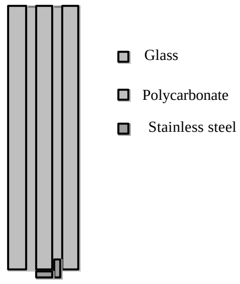


Figure 1: Configuration of segmented laminated specimen

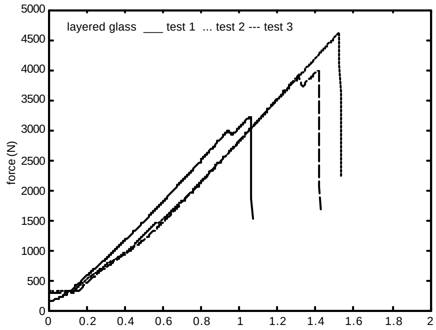
Figure 2: Cross section of reinforced laminated glass

RESULTS FOR LAYERED GLASS

The layered glass failed in two ways :

- first one pane with the second and third failing simultaneously at a slightly higher load.
- all panes failing simultaneously at maximum load.

Failure was usually by the occurrence of multiple branched cracks resulting from a single origin. The load displacement curves are given in figure 3. Figure 4 shows the fracture pattern in the layered glass.



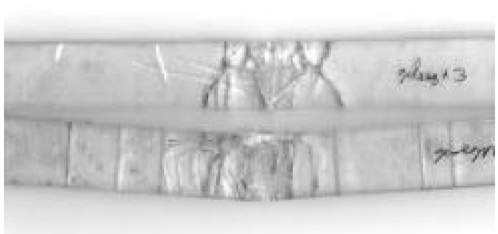


Figure 3 : Load displacement data for layered glass

Figure 4 : Photo of layered glass (top) and segmented specimen after testing

After failure is no load carrying capacity left. The part of the curve after maximum load is due to the plastic safety foil wrapped around the specimen to prevent shards of glass flying around after final failure.

RESULTS FOR LAMINATED GLASS

The laminated glass fails at lower loads than the layered glass. There is however a significant load carrying capacity left. In the second loading the specimens could carry upto 40% of their initial load while deforming for several millimetres. The load displacement curves are given in figure 5. This deformation is permanent and is the result of increased cracking of the glass in combination with visco-elastic deformation of the polycarbonate.

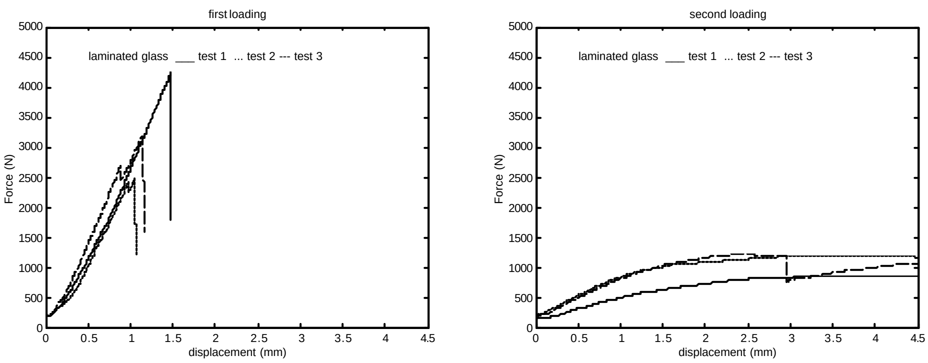


Figure 5 : Load displacement data for laminated glass

RESULTS FOR SEGMENTED LAMINATED GLASS

The segmented glass has lower maximum loads than the laminated glass. The load displacement curves are given in figure 6. Figure 2 shows the fracture pattern in the (bent) segmented laminated glass.
However the lower maximum load also mean there is less elastic energy. This means that when cracking starts the polycarbonate layers can better absorb the energy. The result is that more total deformation is possible at higher stresses increasing the total energy absorption.

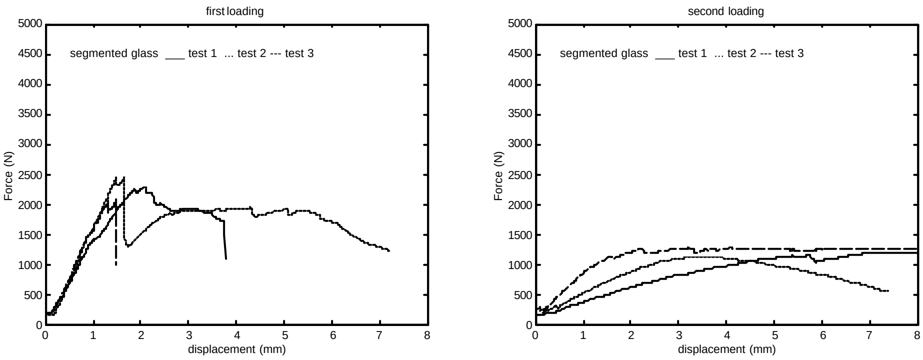


Figure 6 : Load displacement data for segmented laminated glass

RESULTS FOR REINFORCED LAMINATED GLASS

The reinforced laminated glass started to crack at stresses intermediate between the segmented and the laminated glass. As the glass in these specimens was not strengthened the crack resistance of the glass in these specimens is higher than would be expected for non strengthened glass as given by Veer et al [2]. The load displacement curves are given in figure 7.

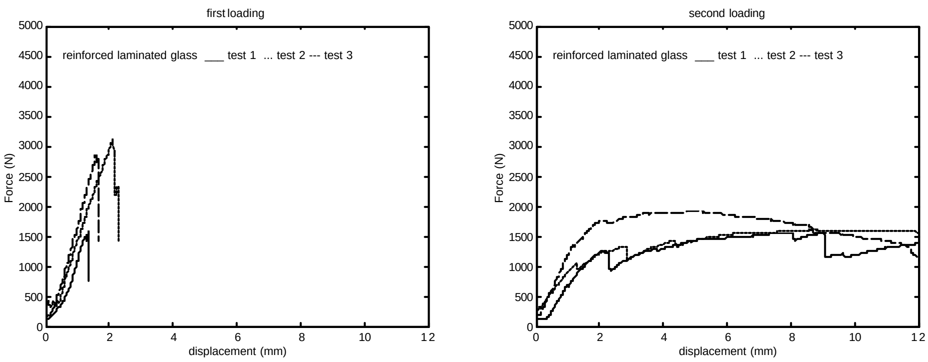


Figure 7 : Load displacement data for reinforced laminated glass

As the glass was not segmented the elastic energy release after first cracking causes a significant drop in load carrying capacity. The maximum stresses in the second loading tests were higher than with the laminated and segmented specimens. In addition the displacements carrying a given stress are greater thus indicating that the energy absorption is significantly higher.
The E-modulus of the specimens in the first and second loading was higher than for the laminated or segmented specimens.

FINITE ELEMENT MODELLING

The reinforced laminated specimen was modelled using the ANSYS 5.7 finite element package using SOLID65 elements with plasticity option for the stainless steel and the polycarbonate and cracking crushing option for the glass. The results shown in figure 9 show that under elastic conditions the highest tensile stresses are carried by the stainless steel reinforcement. The glass is thus stressed less than normal, which explains the apparently higher strength of the glass in the reinforced laminated specimens.
The calculations further showed that due to the cracking/crushing of the glass the stiffness of the specimen decreases as it is bent. Simulations of first, second and third loading sequences as experimentally conducted showed the same pattern as observed in the reinforced laminated glass.
Additional Finite Element Studies will be conducted to see if the damage development can be adequately modelled using the cracking/crushing model for the glass and the plasticity models for the stainless steel and the polycarbonate.

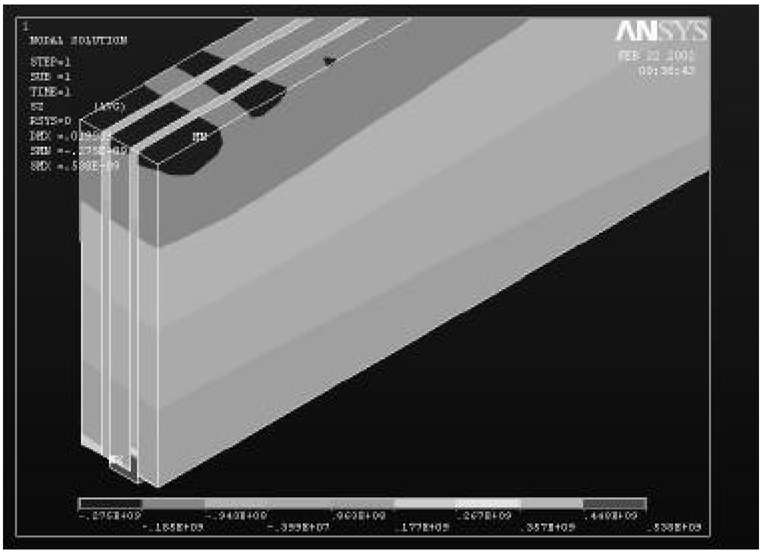


Figure 9: Longitudinal stresses in reinforced beam

DISCUSSION

The results of the experiments are summarised in table 1 and illustrated in figure 10. The results indicate that layered glass is unsuitable as a structural

material. Although in some cases one pane fails before the others this is not always present and some specimens show simultaneous cracking of all panes. After this there is no reserve as once the glass is cracked there is no material left that can carry load. Thus layered glass can only be used with a very high safety factor as failure has to be avoided at all cost.
Glass laminated using the method in this research is more suitable as a structural material. It still requires a large safety factor as the material has a lot of stored elastic energy at maximum load. The release of this elastic energy causes extensive cracking at maximum load considerably reducing the integrity of the glass and thus the E-modulus and strength of the laminate.
The segmented laminate has less strength but because the elastic energy release at maximum load is smaller, less damage is inflicted on the segmented laminate at maximum load. The load carrying capacity after maximum is thus higher. The segmented laminate is thus safer and can be used with a smaller safety factor.
The reinforced laminate has the best performance. This is due to the fact that after cracking occurs the stainless steel strip can carry most of the tensile loads. The cracked glass is quite capable of taking the compressive loads as shown by Hobbelman et al.(3), if the tensile stresses are taken by another material. The polycarbonate in the laminated and segmented specimens has a limited load carrying capacity. The stainless steel however has a considerably higher load carrying capacity and in this configuration is almost invisible.
A reinforced segmented laminate using strengthened glass will in all probability have even better performance. This will be tested in the near future.

CONCLUSIONS

- Layered and laminated glass can only be used as a structural material using a high safety factor.
- Segmented laminated glass has less strength but is safer as the failure is more predictable.
- Reinforced laminated glass is more safe as a structural material.
- The configuration of a laminate determines the mechanical behaviour and thus the safety inherent in the material.

Table 1 : Summary of test results

Configuration	σ_{max} first loading (MPa)	σ_{max} second loading (MPa)	E first loading (MPa)	E second loading (MPa)
Layered	144	0	65.000	0
Laminated	121	41	55.000	19.000
Segmented	84	45	35.000	12.000
Reinforced	93	62	58.000	20.000

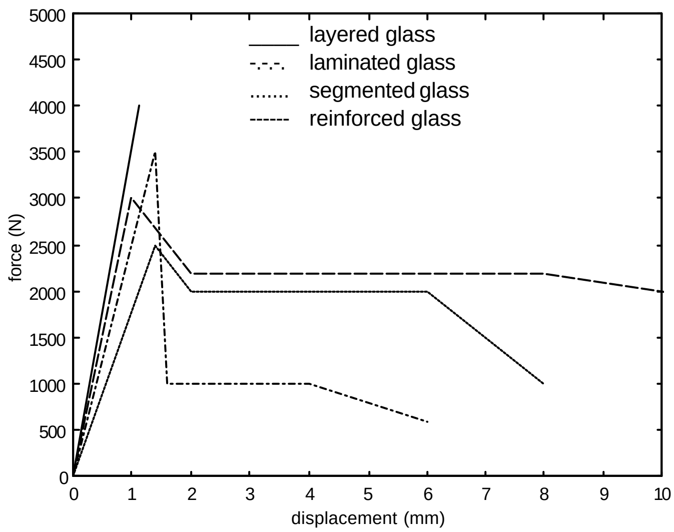


Figure 10 : Test results for the four configurations tested

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