TUDelft

Challenging Glass 2 – Conference on Architectural and Structural Applications of Glass,
Bos, Louter, Veer (Eds.), TU Delft, May 2010.

Experimental Research on Glass-Polycarbonate Beams

Bernhard Weller, Kristina Härth
Technische Universität Dresden, Institute of Building Construction, Germany,
www.bauko.bau.tu-dresden.de

A research project at the Institute of Building Construction explores composite beams made of glass and transparent polycarbonate. These beams consist of one inner polycarbonate sheet and two outer panes of glass and are bonded by a transparent adhesive. Several experimental tests demonstrated that the glass-polycarbonate beams can behave in a ductile manner when the load-bearing capacity is exceeded. Furthermore, a high residual load-bearing capacity after complete glass-breakage exists. On the contrary, typical laminated glass beams fail in cases of complete glass breakage despite the PVB-foil used. Tests with the composite beams made of glass and polycarbonate were carried out with varying cross-sections, glass types and loadings. Moreover, the different elongations due to temperature were investigated in climate tests.

Keywords: glass, polycarbonate, structural elements, post-breakage performance

1. Motivation

In architecture, there is a growing demand for structural load-bearing elements made of glass. Especially for the support of glass roofs, beams made of glass are used. These beams consist of several glass panes that are laminated with PVB-foil. As a rule, the number of glass panes in one beam is greater and their thickness is stronger than statically required. The reason for this oversizing is the fear of complete glass failure which can be put on a level with the failure of the whole beam. This fact was observed in research studies [1] and could be confirmed by own studies [2].

In these own tests, a series of laminated glass beams, each made of three panes of annealed glass with 4 mm thickness each, was tested in a four point bending test. The experimental set-up is comparable with that described in [3]. Contrary to [3], the specimens with a height of 150 mm were tested vertically. In this setup, the load generated a bending moment about the strong axis of the tested beams. This is consistent with the actual loading of beams in buildings. The specimens were loaded until glass breakage which occurred in most beams nearly simultaneously in all glass panes. After complete glass breakage, a reloading was hardly possible – the beams had lost practically all load-bearing capacity (Figure 1). This is due to the completely broken glass panes and the PVB interlayer that is torn by the tensile force. These results show that it is necessary to either use more and thicker glass panes in laminated glass beams or to find ways to give a residual load-bearing capacity to these structural glass elements.

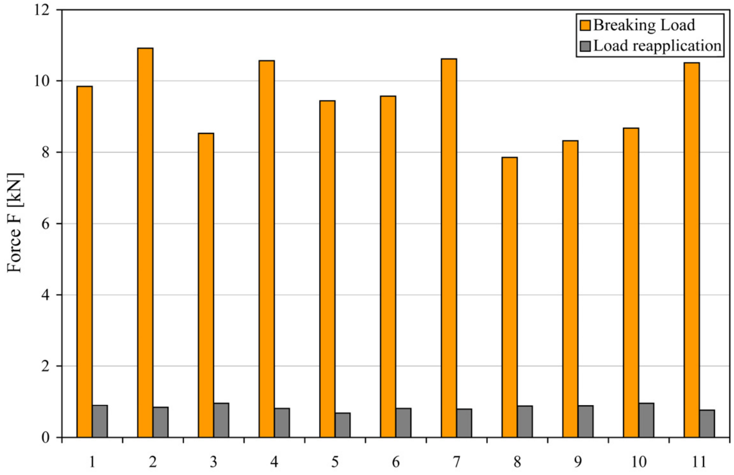

Figure 1: Breaking load and load reapplication of laminated glass beams.

2. Concept and Preliminary Tests of Glass-Polycarbonate Beams

The special appeal of building with glass is the transparency of this building material. Therefore, the method for increasing the residual load-bearing capacity should not affect this outstanding attribute. The PVB-foil that is used in laminated glass meets this requirement but is not able to carry the tensile stress in a glass beam when the glass breaks. Another transparent material has to be used. Thus, polycarbonate plates have been chosen to manufacture a transparent composite beam. This material is characterised by high impact strength, high elongation at break, low weight and has a tensile strength that is sufficient for this purpose.

Like laminated glass beams, the composite beams have a rectangular cross-section but consist of only two outer glass panes and one inner pane of polycarbonate (Figure 2). To join glass and polycarbonate, a transparent adhesive is required that can compensate the different elongations caused by temperature in the relevant temperature range. In this case, a light-curing acrylate has been chosen after several preliminary material tests. In normal condition, i.e. with unbroken glass, the polycarbonate plate should carry hardly any forces because of the significantly lower elastic modulus. Until glass breakage, the composite beam should display ideal elastic without any plastic material behaviour. After glass breakage, the polycarbonate should start carrying loads in combination with the broken glass and allow for removal and substitution of the beam.

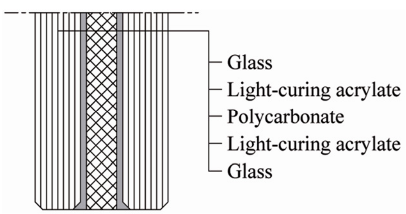

Figure 2: Cross-section of glass-polycarbonate beams.

A series of ten composite beams was manufactured to check the residual load-bearing capacity of glass-polycarbonate beams in principal. These beams consist of two outer panes of annealed glass with a thickness of 6 mm each and one inner sheet of polycarbonate with a thickness of 4 mm. As with the laminated glass beams, the specimens with a height of 150 mm were loaded in a four point bending test until glass breakage which occurred again nearly simultaneously in both glass panes. Unlike the laminated glass beams, the beams made of annealed glass and polycarbonate had an excellent post-breakage behaviour. The residual load-bearing capacity was in all beams almost as high as the breaking load or even more (Figure 3). The positive results of those preliminary tests were the base for further tests with varying parameters.

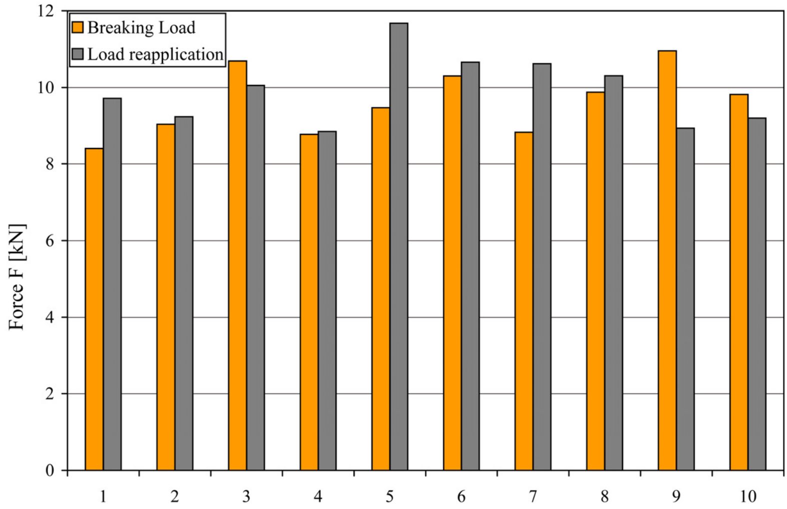

Figure 3: Breaking load and load reapplication of glass-polycarbonate beams.

3. Load-bearing Behaviour and Post-Breakage Performance of Glass-Polycarbonate Beams

3.1. Short-term tests

The short-term tests were executed under the same conditions as the preliminary tests with laminated glass beams and glass-polycarbonate beams (Figure 4). The panes of annealed glass were of the same thickness as in the preliminary tests (6 mm), but the thickness of the polycarbonate plate, the height of the beams and the points of load application varied. All tests were carried out with a loading rate of 100 N/s and stopped when breakage occurred in one or both glass panes. Beside the deflections in the middle of the beams, the tensile stresses at the bottom edges of the glass panes were measured by linear strain gauges. These measurements showed that in all executed tests the polycarbonate pane in the middle of the composite carried almost no load as long as the glass panes were intact, which can be ascribed to the much lower stiffness of the polycarbonate (E_{PC} = 2400 MPa) compared with that of glass (E_{Glass} = 70000 MPa). Furthermore, it became apparent that stress varies even between the glass panes. This applies to glass-polycarbonate beams as well as to laminated glass beams and results from different load applications in the glass panes. The hybrid beams were manufactured manually, which caused an edge offset. But even the laminated glass beams, which are manufactured in an industrial process, have this characteristic. This can be considered as a further safety risk because the exact tensile stress in the glass edge cannot be determined and it has to be assumed that one glass edge carries more tensile stress than others, which increases the risk of failure. Therefore, the residual load-bearing capacity plays an important role.

Figure 4: Experimental set-up of short-term tests.

Firstly, the dimensions of the beams and the points of load application were the same as with the preliminary tests (Figure 4), however, the thickness of the polycarbonate plate varied. The polycarbonate thicknesses tested were 4, 3 and 2 mm. The thickness of the glass panes remained 6 mm. Thus the glass thickness of all beams, composite as well as laminated beams, was 12 mm. In the load-bearing tests with intact beams, the deflections in the middle of all composite beams were comparable regardless of the thickness of the polycarbonate plate. Furthermore, the deflections could be compared with those in the formerly tested, conventional laminated glass beams. Hence, at least under short-term loading, the polycarbonate does not influence the load-bearing behaviour of the glass beams. The beams were loaded until complete glass breakage. In cases where only one glass pane broke in the first test run, a second test run was executed.

After complete glass breakage, the glass-polycarbonate beams were reloaded to check the post-breakage behaviour. These tests showed that, on the one hand, the residual load-bearing capacity decreases with decreasing polycarbonate thickness, but, on the other, the participation of the broken glass in the load transfer and therefore, the fracture origins and the fracture pattern of the two glass panes play an important role. When the two glass panes broke independently of each other in two test runs and, furthermore, the fracture origins were distant from each other, the residual load-bearing capacity increased even more. Figure 5 shows load-deflection curves of completely broken composite beams with 4, 3 and 2 mm polycarbonate thicknesses. One beam with a polycarbonate thickness of 3 mm had very distant fracture origins in the two glass panes. This increased the residual load-bearing capacity considerably.

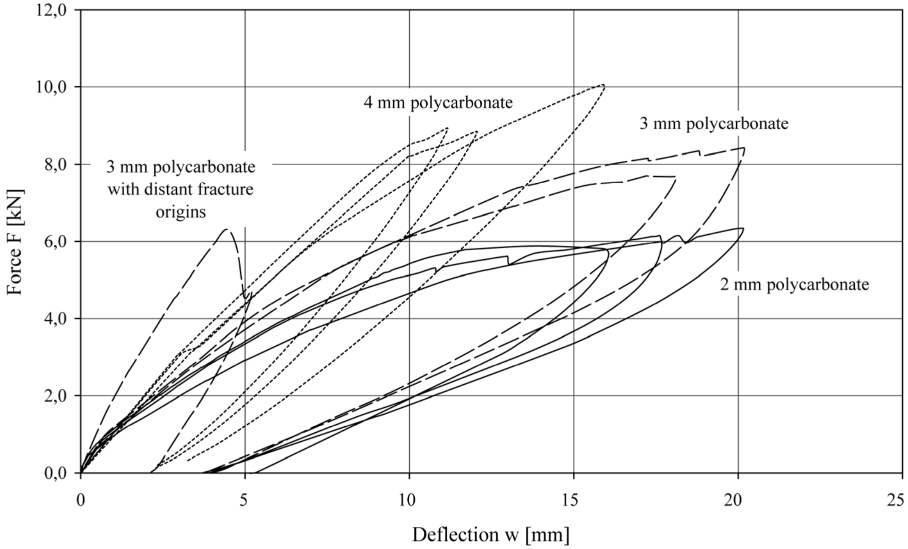

Figure 5: Load-deflection curves of composite beams with polycarbonate thicknesses of 4, 3 and 2 mm.

The post-breakage behaviour of the glass-polycarbonate beams with its excellent residual load-bearing capacity can be ascribed to the capability of the polycarbonate to take the tensile stresses in the moment of glass breakage and the participation of the glass in the load transfer in the upper part of the beam. The fracture pattern in the glass is characterised by the fact that the cracks do not run to the top edge of the glass panes but grow towards each other in the upper part of the beam (Figure 6). This shows clearly that the polycarbonate pane in the moment of glass breakage takes the tensile stress. Because of this, the glass pane can still carry the compression stress in the upper part of the beam, and the cracks cannot run until the top of the glass pane because of the existing compression stress.

Figure 6: Typical glass fracture pattern in a composite beam.

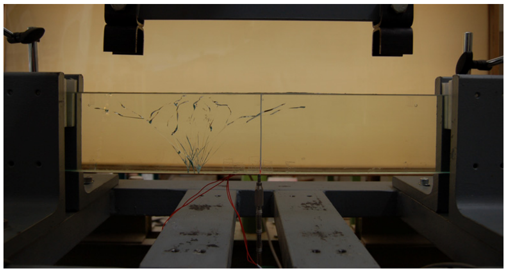

Figure 7: Fracture pattern in a more slender composite beam with a height of 100 mm and loading points in the one-third and two-thirds point of length.

In another test series, the height of the beams was reduced to 100 mm and the load was applied at the one-third point and the two-thirds point of the length. The length remained the same as with the former tests. These more slender beams were again loaded until glass breakage and reloaded after complete glass breakage. The tests should demonstrate if the distinguishing fracture pattern could also develop with modified load application and less height. Figure 7 shows the fracture pattern that developed in those tests and is comparable with that of the beams with a height of 150 mm (Figure 6). The residual load-bearing capacity was again very high and reached the breaking load of the beams in most cases.

The short-term tests were furthermore executed with composite beams manufactured with pre-stressed glass panes. These tests demonstrated clearly the necessity of the participation of the broken glass panes in the load transfer for a sufficient residual load-bearing capacity. This participation of the broken glass depends on a beneficial fracture pattern as could be noticed in the tests of the beams made of polycarbonate and annealed glass. Fully toughened glass and even heat-strengthened glass do not develop this fracture pattern in a composite beam and therefore these types of beams had hardly any residual load-bearing capacity (Figure 8).

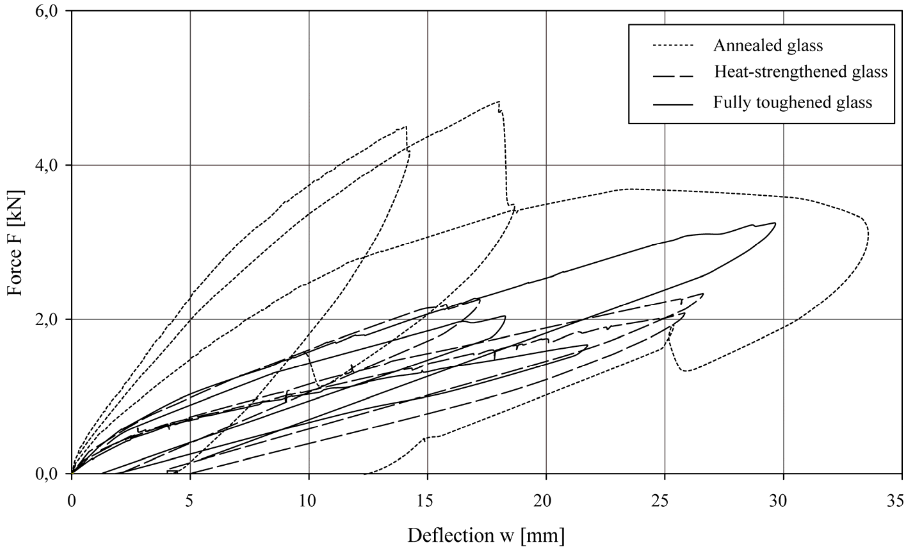

Figure 8: Load-deflection curves of composite beams manufactured with annealed glass, heat-strengthened glass and fully toughened glass.

3.2. Long-term tests

As the load-bearing behaviour of the composite beams in the short-term tests was comparable with that of typical laminated glass beams, long-term tests should demonstrate if the polycarbonate influences this behaviour under constant load, because polycarbonate as a plastic material has a tendency to creep. For this purpose, composite beams were manufactured to the dimensions of the beams in the short-term tests. Again, thickness of the polycarbonate, height and load application varied, but the thickness of the panes of annealed glass remained constant at 6 mm.

The load applied in the long-term tests was chosen according to former tests in which the strength of the glass edges had been examined [4]. For the constant load, the strength of the glass edge was assumed to be about one third of the strength observed in short-term tests. This corresponds to 12 to 13 MPa in the glass edge, which is furthermore approximately the design stress for annealed glass in overhead application in Germany. After at least 1000 hours under this loading, one glass pane was destroyed manually. After a time of 24 hours, the second glass pane was destroyed as well. It was necessary that the completely destroyed composite beam remained under full loading for another 24 hours.

The tests demonstrated that creep did not occur under this loading. Linear strain gauges again showed that most of the load is carried by the glass panes. Because of their high stiffness they do not allow the polycarbonate to creep under loading. The polycarbonate begins to deform highly only after the glass is broken. However, this is only valid for two broken glass panes: with one broken pane the deformations are still relatively small.

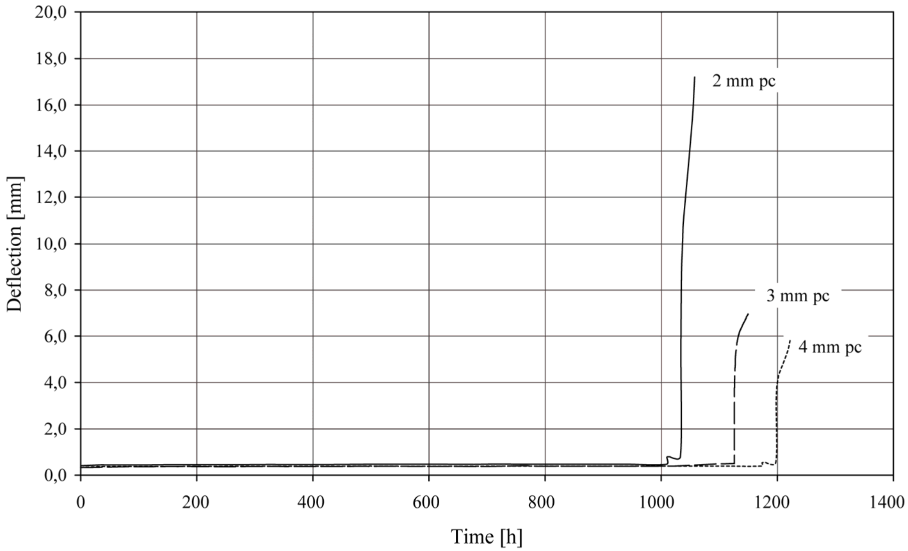

Figure 9: Deformations of composite beams with 2, 3 and 4 mm polycarbonate under constant load. With the fraction of the first glass pane the deformations increase only slightly, with the breakage of the second, they increase strongly.

After 24 hours with two broken glass panes, the cracks in the glass had spread and increased. The delaminating of the adhesive interlayer was very intense. All beams, however, even those with only 2 mm polycarbonate, had a sufficient residual load-bearing capacity and passed the post-breakage test.

4. Climate tests

Beside the mechanical tests, the behaviour of the adhesive interlayer under large deformations was examined. Because of the difference of the linear thermal expansion coefficient between glass and polycarbonate, different elongations in glass and polycarbonate occur due to temperature (Table 1).

Table 1: Thermal characteristics of glass and polycarbonate.

Material	Linear thermal expansion coefficient [1/K]
Annealed Glass [5]	9×10^{-6}
Polycarbonate (Makrolon) [6]	65×10^{-6}

Small specimens with dimensions of 500 x 50 mm were manufactured to examine the suitability of different transparent acrylates. These specimens had the same build-up as the beams (glass-polycarbonate-glass). The adhesive layer between the panes had a thickness of 0.5 and 0.8 mm, respectively. In a first test series, a climate test according to [7] had been chosen in which the temperature was varied from -20 °C to +80 °C. None of the chosen acrylates passed the climate test because the elongation difference of the two materials was too large (Figure 10). Furthermore, the change from minimum to maximum temperature happened in only one hour, which was also too fast for the acrylates.

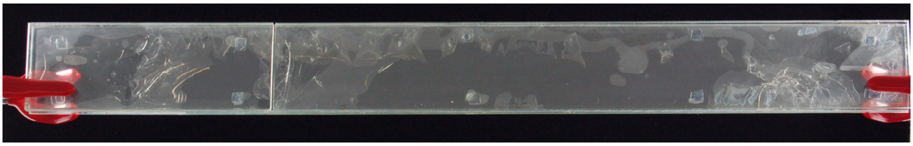

Figure 10: Specimen after climate test according to [7].

Another climate test series was run with the acrylate that showed good results in the mechanical tests. This climate test originates from the engineering standards for building with glass [8]. However, it is limited from -18 °C to +53 °C. The specimens with the chosen acrylate passed this climate test, which shows that compensating different material elongations is possible but limited (Figure 11).

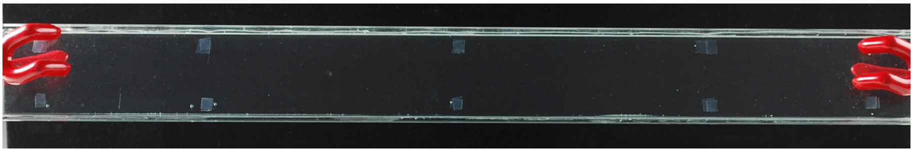

Figure 11: Specimen after climate test according to [8].

5. Conclusion and summary

A structural load-bearing element made of glass and polycarbonate has been tested under different conditions. The mechanical tests performed show that the composite beams have an excellent post-breakage performance in case of complete glass failure, when annealed glass is used. Long-term tests demonstrated that the beams do not have a tendency to creep as long as the glass panes are intact. The compensation of different elongations due to temperature is more problematic because the acrylate adhesives, which have good strength, do not enable large deformations. An interior application under controlled climatic conditions could be a solution.

6. Acknowledgements

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for supporting the research project as well as the project partners. Special thanks go to DELO Industrial Adhesives, Germany, for sponsoring parts of the test specimens.

7. References

[1] Hess, Rudolf, *Glasträger,* Forschungsbericht, vdf Hochschulverlag, Zürich, Switzerland, 2000.
[2] Weller, Bernhard; Weimar, Thorsten; Härth, Kristina, *Hybrid Components of Glass and Polycarbonate,* Proceedings of the 11th International Conference on Architectural and Automotive Glass (Glass Performance Days), Tampere, Finland, 2009.
[3] DIN EN 1288-3, *Glass in building. Determination of the bending strength of glass. Part 3: Test with specimen supported at two points (four point bending),* Beuth, Berlin, Germany, 2000.
[4] Weller, Bernhard; Härth, Kristina; Werner, Frank; Hildebrand, Jörg, *Hybridbauteile im Konstruktiven Glasbau,* Stahlbau Spezial – Konstruktiver Glasbau, 2009, pp. 29-35
[5] DIN EN 572-1, *Glass in building. Basic soda lime silicate glass products. Part 1: Definitions and general physical and mechanical properties,* Beuth, Berlin, Germany, 2004.
[6] Bayer Sheet Europe, *Makrolon UV,* Datasheet, Bayer Sheet Europe GmbH, Darmstadt, Germany, 2004.
[7] DIN EN ISO 9142, *Adhesives. Guide to the selection of standard laboratory ageing conditions for testing bonded joints,* Beuth, Berlin, Germany 2003.
[8] DIN EN 1279-2, *Glass in building. Insulating glass units. Part 2: Long term test method and requirements for moisture penetration,* Beuth, Berlin, Germany, 2003.