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Glass-Steel Beams as Structural Members of Façades

Bernhard Weller, Anja Meier, Thorsten Weimar
Technische Universität Dresden, Institute of Building Construction, Germany, www.bauko.bau.tu-dresden.de

Glass used in structural applications enables a higher level of transparency in façades. However, attention should be paid to the material specific properties, such as brittleness and its incapability of plastic deformation. Laminated glass beams may improve several properties due to the elastic behaviour of the interlayer material. Contrary to laminated panes, which are subject to plate bending, laminated beams lose all their bearing capacity in case all individual plies are broken. The presented hybrid beams that are composed of glass and steel and bonded together with a transparent acrylate adhesive are developed to improve the post-breakage performance of transparent beams. Hybrid beams, therefore, offer a variety of potential applications in façades and glass structures. Within this research, a number of hybrid beams with different cross sections and combinations of glass and steel were tested. The results confirm a better structural behaviour of hybrid beams in comparison with conventional laminated glass beams.

Keywords: glass beams, hybrid structures, bending stiffness, numerical simulation

1. Introduction

The structural members of contemporary curtain wall systems are usually made of steel or aluminium. Even for large glazing areas, this conventional system is not always satisfactory for a modern transparent architecture. Therefore, glass is no longer exclusively used for enclosing functions, but also increasingly for load-bearing and stiffening elements, such as beams, columns, fins or frames.

2. Motivation

The execution of bonded glass façades with glass acting as a load-bearing, linear element will always result in special constructions since there are currently no regulations for the structural design. The brittleness of glass often results in unprofitable oversizing when glass is intended to be used as a linear element in façades. The reason for this is not only the ultimate limit state of bearing capacity and serviceability, but also the post-breakage behaviour after glass breakage must be taken into account. Recent researches show that - independently of the type of glass used - the post-breakage performance of glass beams that are made of laminated glass and subject to bending stress is not ensured after all glass panes are broken [5], [6], [8].

3. Subject of Research

Therefore, the research project HybridGlasSt studies the use of hybrid glass beams in façades. The glass beams consist of laminated glass and stainless steel elements [7]. A transparent acrylate adhesive is used for linear bonding of the steel elements with the glass. Since this adhesive has a shorter curing time than many other adhesives, production times in the manufacturing process chain can be reduced.

The linearly bonded joint enables continuous load distribution between the steel elements and the glass thus avoiding local stress concentrations. Therefore, the leading requirements that are made to the adhesive are high strength to distribute loads and sufficient elasticity to compensate elongations due to temperature variations. With regard to the compensation of manufacturing tolerances, for example, the minimum thickness of the adhesive joints shall be 1.5 mm.

In general, the mechanical properties of acrylate adhesives depend on temperature, medium, duration and amount of load [9]. Therefore, this research concentrates on vertical façade systems for interior areas at the moment. A major point of research is the development of suitable cross section geometries of the hybrid glass beams to ensure durable mechanical functioning of the adhesive bond and to guarantee exposure to sufficient light for the curing process during production.

4. Testing Procedure

The main load that acts on hybrid glass beams, which are designed to be used in façades, is bending about the strong axis. The four-point bending test according to DIN EN 1288-3 [3] is therefore a suitable method to test the load-bearing and post-breakage behaviour of the specimens developed. However, the experimental setup specified in the standard describes bending about the weak axis. Hence the setup has to be modified to test the loading relevant in the application (Figure 1).

The bearing distance of the modified experimental setup in the four-point bending test is 1,000 mm. The specimen dimensions were determined as: length 1,100 mm and height 100 mm. This results in a slenderness ratio between bearing distance and beam height of 1 to 10, which reflects the possible ratio for real applications of laminated glass beams. The specimens have a fixed bearing and an expansion bearing. Fork supports prevent the specimens from lateral torsional buckling.

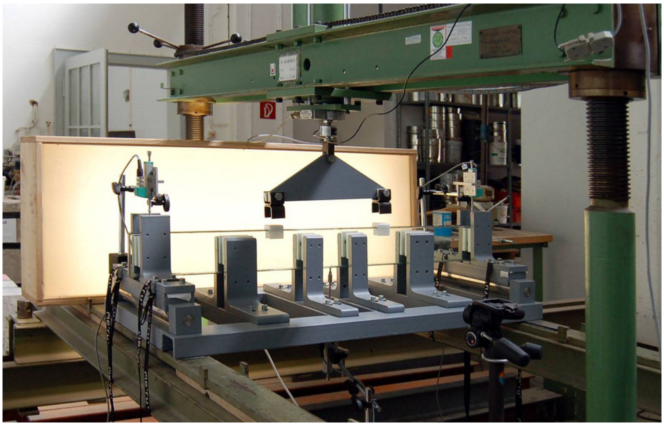

Figure 1: Experimental setup of four-point bending test.

Two load application points are designed to ensure that the region of constant tensile stresses along the bottom edge of the hybrid beam is as large as possible. They are positioned at the tripart points along the bearing distance. The ratio between the distance of the two points of load application and the height of the specimens was set to be three. This avoids the overlapping of the two load distribution areas. Hence the breakage does not occur as a result of superposition of stress during force application. The force application is force-controlled during the four-point bending tests. The loading rate was 10 N/s. Three displacement transducers, one in the centre of the beam and the other above the two supports, recorded deformations.

During the test, loading was stopped when the first crack appeared. Afterwards, new loads were applied until all of the three panes of the laminated safety glass showed at least one crack. In all four variants, 10 specimens were tested. Linear strain gauges were applied to the bottom glass edge of all three glass panes of five specimens of each composition in the centre of the beam to measure the elongations. After all three glass panes were broken, further load was applied until increased cracking resulted in a stress drop of 1 %.

5. Testing Specimen

The hybrid glass beams tested are made of laminated safety glass. It consists of 3 x 6 mm float glass according to DIN EN 572-2 [2] and a PVB interlayer with a nominal thickness of 0.76 mm. The edges were ground in accordance with DIN 1249-11 [1]. Experimental tests showed that the characteristic values of the bending tensile strength were less dispersed than the values for broken, seamed or polished edges [8]. The steel elements of the hybrid beams were made of stainless steel 1.4401. This material was chosen based on the results obtained in previous tests in which small specimens of glass and steel were examined. These tests examined the adhesive strength and wettability of stainless steel, mild, galvanised and chrome-plated steel. The adhesive bonding between glass and steel was realised with the UV and light-curing acrylate adhesive that was developed within this research project [10].

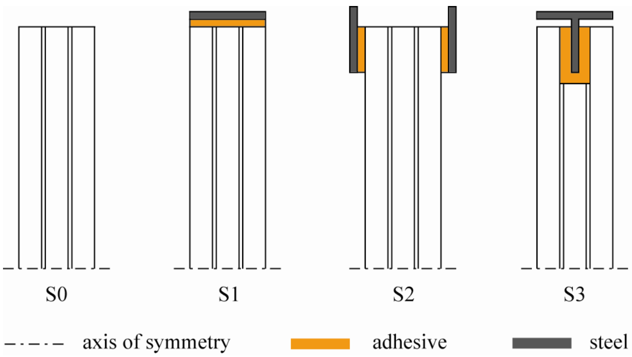

Figure 2: Half cross sections of the tested specimens.

Figure 2 demonstrates the three cross sections of the hybrid beams tested (S1, S2 and S3). Cross section S0 is a laminated safety glass beam without steel elements and was used for reference. In specimen S1, a steel sheet of 20 mm x 2 mm is attached to the upper and lower glass edges of the laminated safety glass. Two lateral steel sheets of the size 13 mm x 2 mm are attached to the upper and lower edges of cross section S2. In cross section S3, the central glass pane of the laminated safety glass is set back by 12 mm. Thus, a T-section can be inserted into the resulting slot. The T-section has a flange of 20 x 1.5 mm and a web of 12 mm x 3 mm. The nominal thickness of the adhesive is 2 mm for all cross sections. The steel elements are designed such that they can be adapted to standard façade systems.

6. Test Results

6.1. Crack pattern

The crack behaviour of the test specimens was documented during experimentation. Figure 3 shows the test procedure for an S1 specimen.

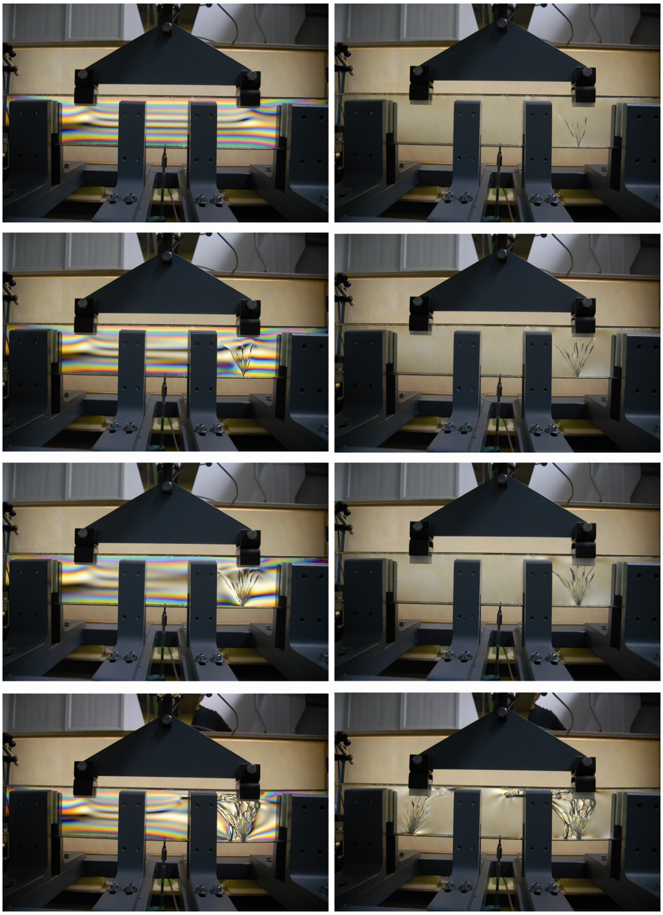

Figure 3: Changes of stress during loading.

A camera with a polarising filter attached to the lens documented the qualitative changes of stress in the glass. The curve of compression stress between the two points of load application becomes clearly obvious.

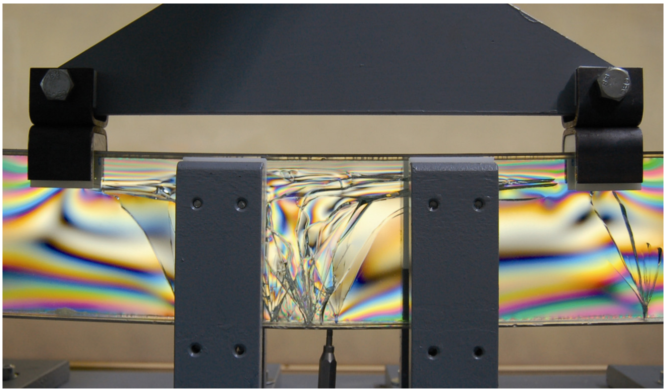

Figure 4: Crack pattern of a hybrid beam after breakage of all panes.

This effect can also be observed in the crack patterns (Figure 4). The cracks often run parallel to the edge and very close to the upper edge of the glass panes.

6.2. Ultimate loads

The summary of measured ultimate loads in figure 5 shows that the ultimate loads of hybrid glass beams are significantly higher than those of the glass beams without steel elements. The maximum ultimate load before the first crack had appeared was obtained with cross section S1. The ultimate loads of the post-breakage capacity were a bit higher than the ultimate loads before the first crack of a glass pane because of the higher threshold set in detection of breakage during experimentation. Cross section S2 displayed the lowest bending stiffness of the hybrid glass beams. The hybrid cross sections S1 and S3 had similar bending stiffness.

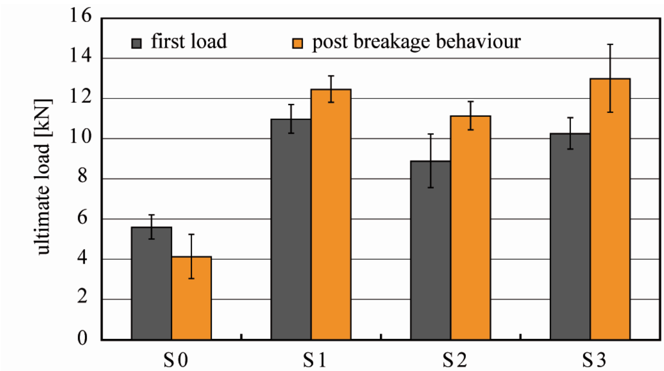

Figure 5: Ultimate load of the hybrid beams.

6.3. Bending stiffness according to the load-bearing behaviour

The recorded values of force and deformation were used to calculate the bending stiffness for the individual specimens depending on the static system. Figure 6 gives the bending stiffness of all cross sections for the first loading. Because of the steel elements, the bending stiffness of the hybrid glass beams before the first crack is principally higher than that of the glass beams without steel elements. The hybrid glass beams with cross section S1 have the maximum value of bending stiffness. The bending stiffness of cross sections S2 and S3 is slightly lower.

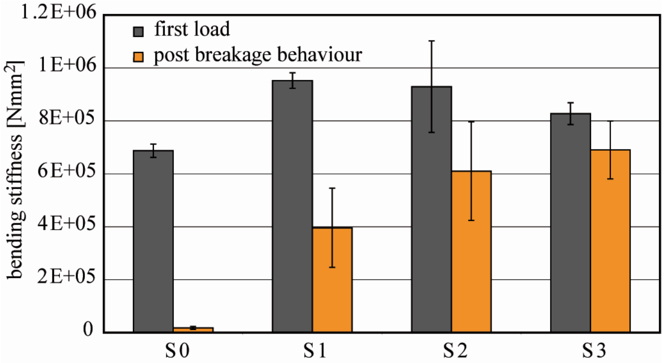

Figure 6: Bending stiffness of the tested beams.

6.4. Bending stiffness according to the post-breakage behaviour

The graph in figure 6 also shows the bending stiffness of the different cross sections during loading in relation to the post-breakage behaviour. After all three glass panes are broken, the glass beam S0 without steel elements has lost almost all of its total load-bearing capacity. The post breakage behaviour is very poor compared with the hybrid cross sections. The broken glass panes of the hybrid glass beams are strengthened by the additional steel elements. It is possible to increase loading after all glass panes are broken. The hybrid cross section S3 has the maximum bending stiffness in terms of the post-breakage capacity and is approximately 80 % of the bending stiffness before the first crack appeared. The hybrid glass beam with section S1 has the least bending stiffness in terms of the post-breakage capacity. However, it is still many times higher than the bending stiffness of the glass beams S0 without steel elements.

7. Numerical Analysis

It is essential to take into account the individual material components and the type of joining for numerical analysis of hybrid components. Since failure of the adhesive can considerably affect the overall load-bearing capacity, it is necessary to simulate the material behaviour of the adhesive as close to reality as possible. The material characteristics of the acrylate adhesive used were determined using shouldered test bars according to [4] and purpose-built, small specimens made of glass and stainless steel [10].

The experimental ultimate loads of specimens S1 and S3 amount to an average of 80 % of the numerically simulated ultimate loads that were assumed to have a positive principal stress of 45 MPa in the glass beam. The ultimate loads obtained for the hybrid glass beams S2 are between 60 % and 85 % of the calculated ultimate load owing to the larger variability of the measurements. The experimental ultimate load of the glass beams S0 without steel elements is approximately 60 % of the calculated ultimate load. According to [5] and [8], the characteristic edge strength of float glass is approximately 75 % of the characteristic bending tensile strength in plane.

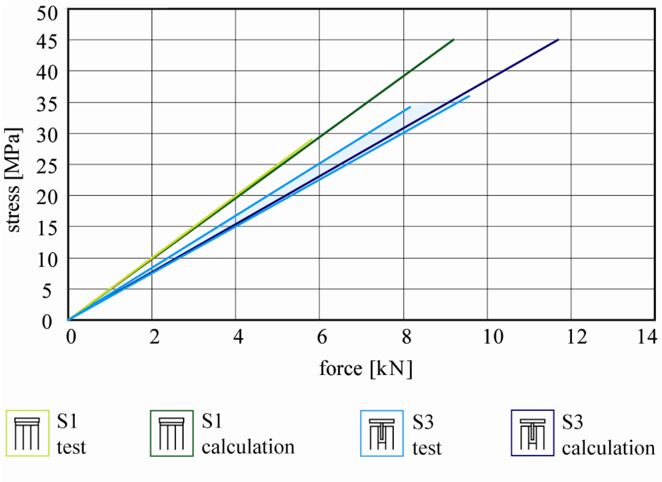

Figure 7. Comparison of the experimental force-stress diagram with the results of the numerical simulation.

The force-stress diagram (Figure 7) uses the beams S0 and S3 as examples to compare the experimental and numerical results. The numerically determined maximum stress in the glass of beam S3 is ranged between the limit values measured in the tests. The results obtained for beam S0 are almost identical. The results obtained by numerical analysis are in good compliance with the values measured in the four-point bending test.

8. Summary and Conclusions

As observed in experimental studies, the load-bearing capacity of the presented hybrid glass beams, which are manufactured from laminated safety glass with additional stainless steel elements, is higher than the load-bearing capacity of glass beams without steel elements. The steel elements, which are linearly connected with the glass using a transparent acrylate adhesive, increase the residual strength of the hybrid glass beams after breakage of all glass beams. The experimental results confirm the numerical calculations and can be used for further optimisation of the cross sections.

9. Acknowledgements

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