Redundancy of composite glass beams at extreme conditions

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Abstract. To deal with the brittle failure of glass, researchers at Delft University of Technology have developed a composite glass beam concept which provides ductility for structural glass beams by adhesively bonding a reinforcement section at the edge of the glass beam. Crucial aspect in this concept is the adhesive bond between glass and reinforcement, which has to service under all conditions. The effects of elevated temperature and moisture exposure on the adhesive bond have been investigated through three series of bending tests on 1.5 m glass beam specimens. A first series has been tested at room temperature, a second series at 60°C and a third series after 8 weeks of moisture exposure. The results show that even at extreme temperature and moisture conditions the reinforced glass beam concept is a redundant system.

Introduction

Brittle glass failure is the most alarming aspect for the application of glass as a structural material in buildings. To deal with this brittle glass failure several research programs focus on the development of composite structural glass beams in which ductility is provided by a combined action of the glass and other materials like metals, carbon fibre, concrete or wood, see figure 1.

At Delft University of Technology the stainless steel reinforced glass beam concept is currently under investigation [1], see figure 1. In this concept a stainless steel reinforcement section is adhesively bonded at the edge of an annealed float glass beam. Upon glass failure this reinforcement section will act as a crack bridge and take up the tensile forces, see figure 2. Crucial aspect is that the glass-to-reinforcement adhesive bond has to service under all conditions. Two important conditions have been researched, namely: elevated temperature and moisture exposure. This has been tested through three series of bending tests on 1.5 m glass beam specimens. As a reference a first series has been tested at room temperature without any special exposure. A second series has been tested at 60°C and a third series after 8 weeks of salt-water-spraying. This paper is based on the results presented by Louter [2] at the Challenging Glass conference 2008 at the TU Delft.

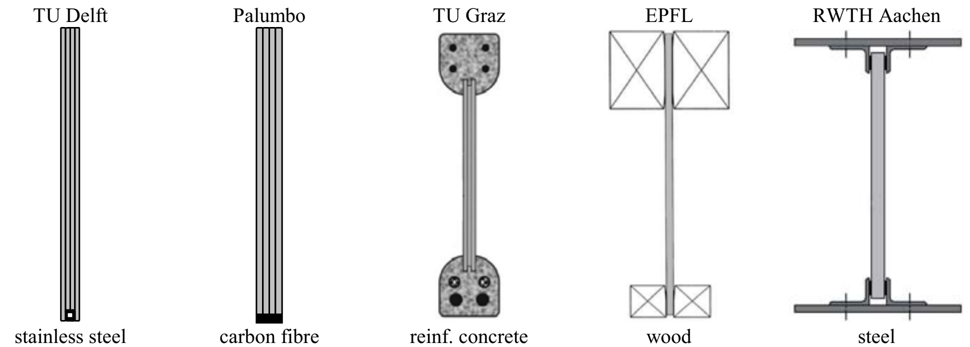


Figure 1: Different composite glass beam solutions aim for ductility at the post-failure stage.

Methodology

Beam specimens. For this research 1.5 m stainless steel reinforced glass beam specimens have been made according to the layout provided in figure 2. To simultaneously investigate the performance of different adhesives, each test series has been executed using a variety of adhesives [2]. This paper will focus on the results of a transparent UV-curing acrylate [3] and a grey two-component epoxy [4] adhesive.

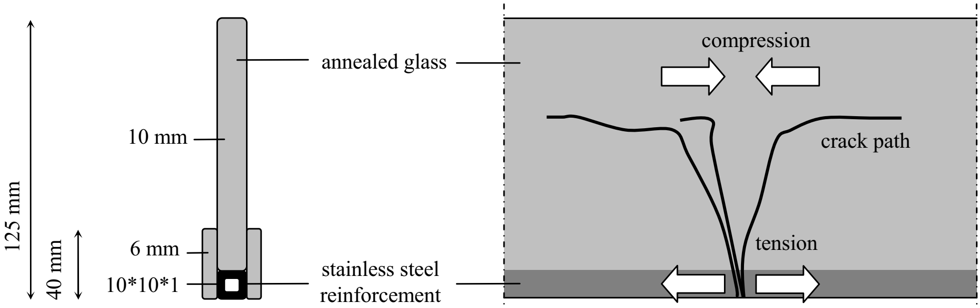
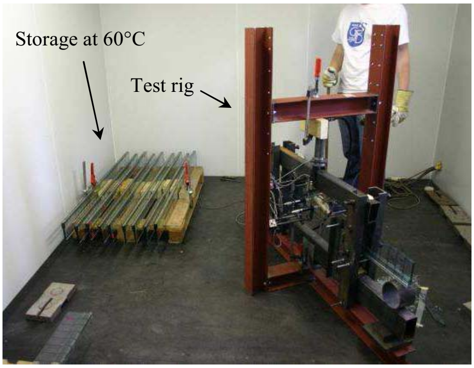


Figure 2: Left: cross-section of 1.5 m glass beam specimens; Right: post-breakage behaviour.

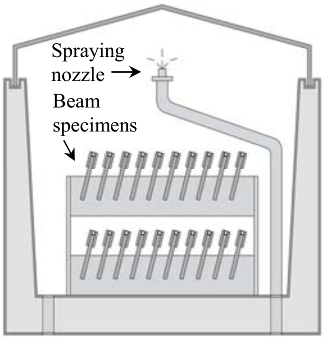
Bending tests at room temperature. As a reference a series of beam specimens has been tested at room temperature without any additional special exposure. The specimens were tested in four-point bending using a displacement-controlled Zwick Z100 Universal testing machine. The supports were 1400 mm apart and the loads were 400 mm apart. Lateral anti-buckling supports were provided 200 mm from mid-span. The load was applied at a rate of 1 mm/minute. Of each adhesive 5 specimens were tested.

Bending tests at 60°C. Since e.g. glass roofs are often exposed to direct sunlight radiation, an important condition is an increased serviceability temperature. Generally the strength of an adhesive bond will decrease at elevated temperatures, which might endanger the safety of reinforced glass beams. The effect of elevated temperatures on the adhesive bond has been investigated in cooperation with glass-researchers at Ghent University. Of both adhesives (epoxy and acrylate) 5 specimens have been stored for 24 hours at 60°C in a climatic room before being tested in four-point bending at this same temperature level, see figures 3 and 4. In the test setup the load was applied using a hydraulic jack, which was manually operated.

Figures 3 and 4: Beam specimens stored and tested at 60°C in a climatic room.

Bending tests after 8 weeks of moisture exposure. Moisture in the air or water from condensation – especially for roof beams – can affect the strength of the adhesive bond. To investigate the effect of moisture, 5 beam specimens of each adhesive were exposed to salt-water-spraying in a sealed container, see figures 5 and 6, for 8 weeks before being tested in four-point bending. The salt-water-spraying has been executed according to standard ASTM B-117-03 [5], which is used in aerospace engineering to test adhesive bonds. After removal from the spraying container the beam specimens have been cleaned with demineralised water and tested within the next 48 hours using a displacement-controlled Zwick Z100 Universal testing machine. The test setup was the same as was used for the specimens tested at room temperature.



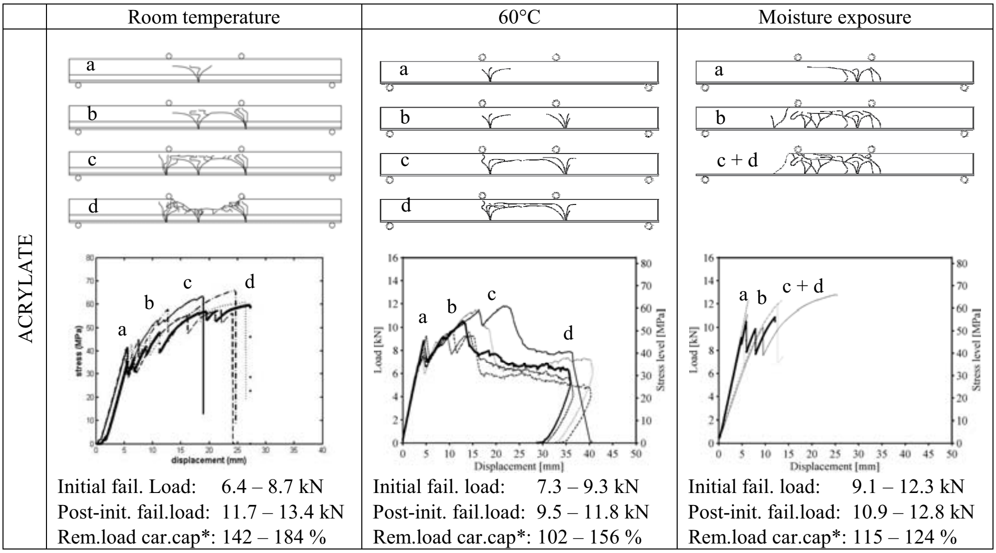
Figures 5 and 6: Beam specimens stored for 8 weeks in a salt-water-spraying container.

Results

The results of the three test series are presented in figures 7 and 8 and will be separately discussed in the following sections.

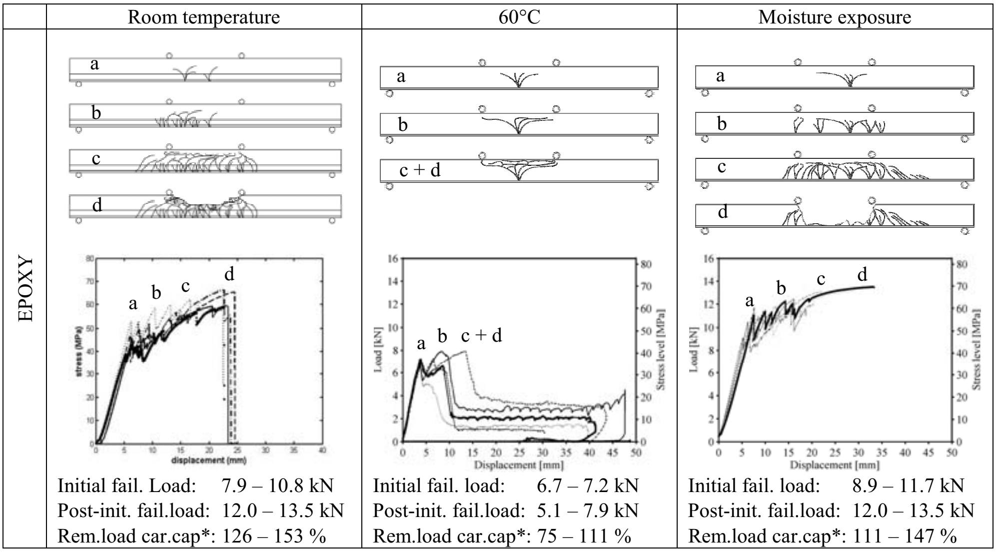
Results at room temperature. At the beginning of the loading procedure the beam specimens, tested at room temperature, showed a linear elastic response until initial failure occurred. As loading was continued additional cracking occurred, but the beam specimens were still capable of carrying the increasing load, see figures 7 and 8. The acrylate-specimens showed a significant remaining load carrying capacity of 142-184 % of the initial failure load. The epoxy-specimens showed a remaining load carrying capacity of 126 -153%. Eventually, all specimens failed rather explosively. The glass in the upper compression zone became excessively stressed and exploded. The glass-to-reinforcement adhesive bond was still intact and the reinforcement had not debonded.

The acrylate- and epoxy-specimens showed a similar structural response. However, their crack branching behaviour differed. The acrylate-specimens showed a more horizontally orientated crack pattern of widely extended V-shaped cracks, whereas the epoxy specimens showed a more dense fracture pattern of small un-extended cracks. This difference in crack branching behaviour is probably caused by a difference in toughness of both adhesives. For the acrylate-specimens local de-bonding of reinforcement was observed at the crack tips/origin. The shock load which occurred upon glass fracture caused the adhesive to fail for several centimetres on either side of the crack tip. This local de-bonding of reinforcement allowed for large crack opening displacements and extensive crack propagation. Due to the higher toughness of the epoxy adhesive local de-bonding occurred to a lesser extend for the epoxy-specimens.



failure stages; a = initial failure, b = additional cracking, c = horizontal crack propagation, d = ultimate failure
* Remaining load carrying capacity = (post-failure load / initial failure load) * 100%

Figure 7: Results of the three series of bending tests on acrylate specimens.



failure stages; a = initial failure, b = additional cracking, c = horizontal crack propagation, d = ultimate failure
* Remaining load carrying capacity = (post-failure load / initial failure load) * 100%

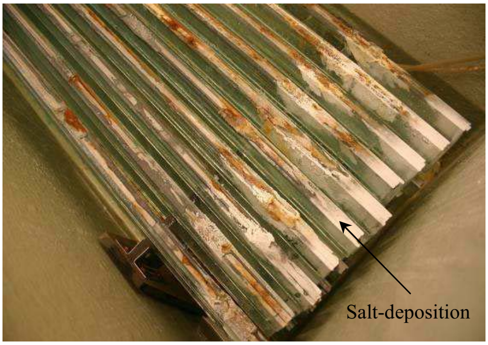
Figure 8: Results of the three series of bending tests on epoxy specimens.

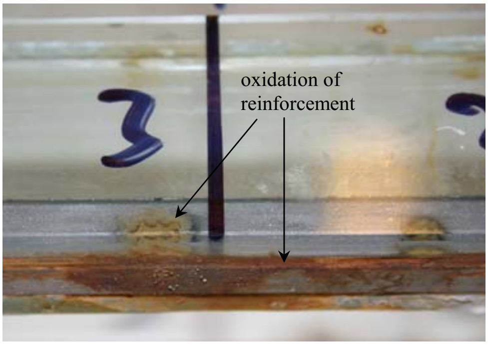
Results at 60°C. The beams tested at 60°C showed a similar response at the beginning of the loading procedure as the beams tested at room temperature. However, contrary to the specimens tested at room temperature, which eventually failed due to exploding glass, the specimens tested at 60°C finally failed due to slip of reinforcement, which was caused by adhesive failure. The strength of the adhesive was significantly decreased by the increased temperature level. However, despite of the decreased adhesive strength the beam specimens generally still showed a significant remaining load carrying capacity of >100% of the initial failure load, see figures 7 and 8.

The epoxy specimens performed significantly worse at 60°C than at room temperature. This difference was probably only partially caused by the increased temperature level and mainly caused by problems at the manufacturing process of the epoxy specimens for the 60°C-test. Since the glass-to-glass and glass-to-reinforcement bonding could not be executed simultaneously, due to the grey color of the epoxy adhesive, the reinforcement section had to be bonded afterwards. This caused an uneven distribution of adhesive over the bond area. Due to these errors at the bonding process the structural quality of the specimens was reduced.

Results after moisture exposure. After 8 weeks of salt-water-spraying the beam specimens were removed from the spraying container. The beams showed salt-deposition and severe oxidation of reinforcement, see figures 9 and 10. Oxidations spots occurred even between the glass and reinforcement, thereby affecting the adhesive bond.

The beam specimens tested after 8 weeks of salt-water-spraying showed a similar response as the beam specimens tested at room temperature without any special exposure, see figures 7 and 8. The 8 weeks of salt-water-spraying did not seem to have a significant negative effect on the adhesive bond. The beam specimens showed significant remaining load carrying capacities after initial failure. Finally, the beam specimens did not fail due to any slip of reinforcement caused by adhesive failure, but, like the beams tested at room temperature, due to an explosion of the glass compression zone.





Figures 9 and 10: Salt deposition and oxidation of reinforcement after 8 weeks of salt-water-spraying

Discussion

Out of the two investigated conditions ‘elevated temperature’ and ‘moisture exposure’ the first one was the most severe for the glass-to-reinforcement adhesive bond. Whereas the specimens tested at room temperature and after moisture exposure ultimately failed due to explosive glass failure without showing any debonding of reinforcement, the specimens tested at 60° ultimately failed due to slip of reinforcement caused by adhesive failure. However, the beams still showed significant post-initial failure strengths and slip of reinforcement occurred only at high loading levels. It can therefore be concluded that serviceability temperatures up to 60°C do decrease the strength of the glass-to-reinforcement adhesive bond, but do not necessarily endanger the redundancy and structural performance of reinforced glass beams. However, the exact response at 60°C is highly dependent on the applied glass-to-reinforcement adhesive bond and on the way this adhesive has been processed. Although the adhesive itself might be resistant for elevated temperature levels it still has be processed properly to prevent a reduction in strength due to manufacturing errors, as was illustrated by the results of the epoxy-specimens at 60°C.

The 8 weeks of salt-water-spraying did not have any significant negative effect on the redundancy of the reinforced glass beams. Although the salt-water-spraying is quite severe for the adhesive – far worse than conditions which will occur in building practice – the beam specimens still showed ductile failure behaviour and comparable post-initial-failure strengths as the beam specimens tested at room temperature without any special exposure. The tested adhesives seem to be inert for moisture exposure.

Conclusions

From the bending tests on 1.5 m reinforced glass beam specimens performed at room temperature, 60ºC and after moisture exposure, the following is concluded:

- An elevated temperature of 60ºC decreases the strength of the glass-to-reinforcement adhesive bond, but does not necessarily endanger the structural safety and redundancy of reinforced glass beams.
- Moisture exposure does not have a significant negative effect on the residual strength of reinforced glass beams prepared with the investigated adhesives.

Furthermore, it is concluded that the reinforced glass concept is a redundant system which is able to show a significant residual strength even at extreme temperature and moisture conditions.

References

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