# Redundancy of reinforced glass beams; temperature, moisture and time dependent behaviour of the adhesive bond

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The most important aspect of the reinforced glass beam concept, which provides ductility and redundancy for structural glass beams, is the adhesive bond between glass and reinforcement. To guarantee structural safety, this adhesive bond has to service under all conditions. The effects of elevated temperature, moisture exposure and load duration on the adhesive bond, have separately been investigated through three series of bending tests on 1.5 m reinforced glass beam specimens. A first series has been tested at 60ºC; a second series has been tested after 8 weeks of salt-water-spraying; and a third series has been loaded until initial failure whereupon it has been left statically loaded for at least 72 hours. The results show that the reinforced glass beam concept is a redundant system which shows, dependent on the applied adhesive, a significant residual strength even at extreme temperature and moisture conditions, and for a significant period of time.

**Keywords:** Reinforced glass, adhesive, redundancy, temperature, moisture, time

## 1. Introduction

The main problem of the application of glass as a structural material is its unpredictable and brittle failure behaviour. However, ductile instead of brittle failure behaviour, can be obtained through the combination of glass with other materials, such as plastics or metals [1] or even wood [2]. Research at the Faculty of Architecture, Delft University of Technology focuses on the development of such glass-composite structures and components with safe and ductile failure behaviour. One of the concepts currently under investigation is the reinforced glass beam concept, which aims at ductility and redundancy by adhesively bonding a small stainless steel reinforcement section at the edge of an annealed float glass beam [3]. Upon glass failure the reinforcement will act as a crack bridge and carry the tensile forces. Together with a compression force in the uncracked compression zone the beam will still be able to carry load, see figure 4.

An important aspect of the reinforced glass beam concept is the adherence of the reinforcement to the glass. Once the glass has cracked due to whatever cause, the glass-to-reinforcement adhesive bond has to transfer the tensile forces. To prevent collapse of the beam, the adhesive has to service under all conditions and for a significant period of time. Three important conditions which affect the strength of the adhesive bond – namely: elevated temperature; moisture exposure; and load duration – have therefore been investigated through three series of bending tests on 1.5 m beam specimens.

## 2. Test procedures

### *2.1. Temperature: Bending tests at 60ºC*

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 [4]. A total of 30 reinforced glass beam specimens have been stored for 24 hours at 60°C before being tested in four-point bending at this same temperature level (see figure 1). In the test setup the load was applied using a hydraulic jack, which was manually operated.

### *2.2. Moisture: Bending tests after 8 weeks of salt-water-spraying*

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, a total of 20 beam specimens were exposed to salt-water-spraying in a sealed container (see figure 2) 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.

### *2.3. Time: Statically loaded bending tests*

Once a reinforced glass beam – applied in e.g. a roof structure – has cracked due to whatever cause, it has to provide redundancy for a certain period of time [6] to allow bystanders to flee or to take measures. To prevent premature collapse of the beam, the glass-to-reinforcement adhesive bond has to be able to transfer forces for a significant period of time without showing severe creep or progressive bond failure. To investigate the post-breakage behaviour of reinforced glass beams in time, a total of 8 reinforced beam specimens have been tested in a load-controlled test rig (see figure 3), in which the load was manually increased by adding weights at the counterpart of a cantilever every 30 seconds, until initial failure occurred. Subsequently, the beam specimens were left statically loaded for at least 72 hours. During this time period the displacement and crack propagation have been monitored.

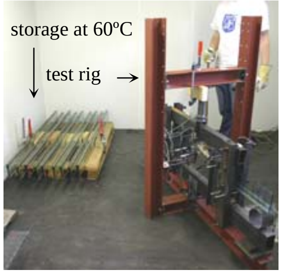


Figure 1: Storage and testing at 60ºC in climatic room

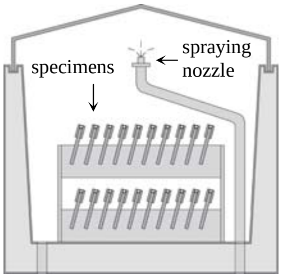


Figure 2: Specimens subjected to salt-water –spraying.

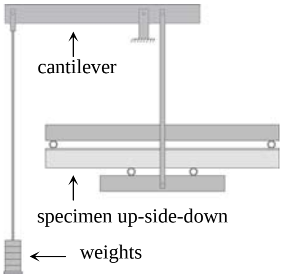


Figure 3: Load-controlled test rig with cantilever.

### *2.4. Specimen preparation with different adhesive types*

To simultaneously investigate the performance of different adhesives, each test series has been executed using 4 or 6 different adhesives to prepare the specimens. The specimens for each test series have been prepared according to the geometry provided in figure 4. Each specimen consists of a 1500*115*10 mm inner glass layer, two 1500*40*6 mm outer glass layers and a 10*10*1 mm stainless steel box section. The reinforcement is encapsulated by both outer layers which enlarge the bond area between glass and reinforcement thus enhance the transfer of forces. Different adhesives – 1*epoxy, 3*acrylates, 1*polyurethane and 1*silicone – have been used to bond the reinforcement to the glass (see table 1). The adhesives vary in curing time, color, strength and gap-filling properties. The glass-to-glass bonding has been executed with the same adhesive as applied for the glass-to-reinforcement bonding, except for the non-transparent and/or slow-curing adhesives. In those cases the glass-to-glass bonding has been executed with the transparent and UV-curing acrylate-1 adhesive. For the specimens tested at 60°C and after salt-water-spraying the reinforcement has been sandblasted prior to the bonding process.

Table 1: Overview of properties of the tested adhesives

| Adhesive type a) | Shear strength [MPa] | Curing time | Color | Gap-filling capacity [mm] | Number of specimens | | |
|---|---|---|---|---|---|---|---|
| | | | | | at 60°C | salt-water | static load |
| Epoxy | 18 b) | > 10 hours d) | grey | up to 5 | 5 g) | 5 g) | 2 |
| Acrylate-1 | 23 b) | 30-60 sec. e) | transp. | < 0.1 | 5 g) | 5 g) | 2 |
| Acrylate-2 | 19 b) | 30-60 sec. e) | transp. | < 0.1 | 5 g) | 5 g) | 2 |
| Acrylate-3 | 24 b) | 30-60 sec. e) | transp. | < 0.1 | 5 g) | 5 g) | 2 |
| Polyurethane | 7 b) | > 8 hours d) | transp. | 0.05 – 0.1 | 5 g) | 0 | 0 |
| Silicone | 1.06 c) | > 7 days f) | black | 6 - 15 | 5 g) | 0 | 0 |

a) epoxy = Araldite 2013, two-component; Acrylate-1 = DELO GB368, one-component; Acrylate-2 = DELO GB485, one-component; Acrylate-3 = DELO GB4468, one-component; polyurethane = Araldite 2026, two-component; silicone = Dow Corning 895, one-component;
b) glass-aluminum, by datasheets; c) tensile strength, H-piece testing, by datasheet; d) at 23ºC e) cured by UV-light; f) at 25ºC; g) the reinforcement has been sandblasted prior to the bonding process

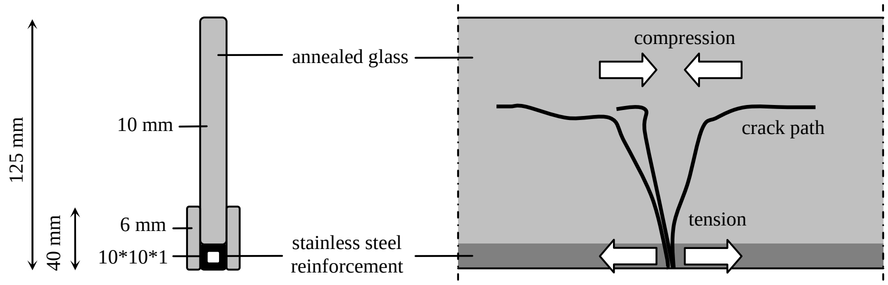


Figure 4: Schematic cross section and side view (at cracked stage) of reinforced glass beam specimen

## 3. Test results

The results of the bending tests will be presented in detail in sections 3.1, 3.2 and 3.3. Table 2 shows a summary of the results of the bending tests performed at 60ºC and after 8 weeks of salt-water-spraying. As a reference the results of bending tests executed at room temperature without any special exposure, which have been performed in preceding research [7] for epoxy and acrylate-1 specimens, have also been included in this table.

Table 2: Summary of the results of bending tests performed at 20ºC, 60ºC and after water-spraying (= WS)

| Adhesive type | Test type | Initial failure load [a] | | Initial crack height [a] | Post initial-failure load [a] | Remaining load carrying capacity [a,b] | Final failure cause |
|---|---|---|---|---|---|---|---|
| | | [kN] | [MPa] | [%] | [kN] | [%] | |
| Epoxy | 20 ºC | 7.9 – 10.8 | 40.9 – 55.6 | 64 – 76 | 12.0 – 13.5 | 126 – 153 | glass |
| | 60 ºC | 6.7 – 7.2 | 34.6 – 37.3 | 72 – 80 | 5.1 – 7.9 | 75 – 111 [c] | adh. |
| | WS | 8.9 – 11.7 | 46.1 – 60.6 | 72 – 80 | 12.0 – 13.5 | 111 – 147 | glass |
| Acrylate 1 | 20 ºC | 6.4 – 8.7 | 32.9 – 45.0 | 64 – 76 | 11.7 – 13.4 | 142 – 184 | glass |
| | 60 ºC | 7.3 – 9.3 | 37.9 – 47.9 | 72 – 80 | 9.5 – 11.8 | 102 – 156 | adh. |
| | WS | 9.1 – 12.3 | 46.9 – 63.5 | 68 – 80 | 10.9 – 12.8 | 115 – 124 [d] | glass |
| Acrylate 2 | 60 ºC | 6.9 – 9.5 | 35.7 – 48.8 | 72 – 80 | 6.7 – 12.4 | 74 – 163 | adh. |
| | WS | 8.3 – 11.4 | 42.7 – 58.8 | 60 – 72 | 13.0 – 13.5 | 119 – 158 | glass |
| Acrylate 3 | 60 ºC | 5.8 – 8.5 | 29.9 – 43.8 | 64 – 80 | 8.1 – 12.0 | 96 – 174 | adh. |
| | WS | 9.9 – 12.7 | 51.3 – 65.3 | 68 – 80 | 12.7 – 13.5 | 103 – 136 | glass |
| Polyurethane | 60 ºC | 6.6 – 8.4 | 34.0 – 43.6 | 80 | 4.5 – 5.5 | 59 – 83 | adh. |
| Silicone | 60 ºC | 5.2 – 9.0 | 27.0 – 46.3 | 100 | 0 | 0 [c] | adh. |

[a] The results are presented in a range, which represents the results of 5 specimens; [b] (initial failure load / post failure load) x 100%; [c] the remaining load carrying capacity might have been limited due to manufacturing errors. [d] One specimen did not show any remaining load carrying capacity.

For a better understanding of the test results, four general failure stages, which occurred during the tests, are distinguished, namely:

I. Initial failure; the specimens showed linear elastic response until initial failure occurred. Cracks originated from the lower edge of the beam and ran up to the compression zone before being arrested. The initial crack height is indicated in table 2.
II. Additional cracking; as the loading procedure is continued new cracks occurred along the lower edge of the beam or existing cracks extended.
III. Horizontal crack propagation; the existing cracks gradually propagated horizontally, which reduced the stiffness of the beam specimens.
IV. Final failure; final failure occurred due to either debonding of reinforcement, which was initiated by progressive adhesive failure or due to (explosive) glass failure. The main final failure cause is indicated per test in table 2.

These four failure stages are indicated in all figures (5 – 19) showing the test results.

### *3.1. Results at 60°C*

The results of the bending tests performed at 60°C are presented in figures 5 – 10, which show the load-displacement diagram and crack propagation of all specimens.

For all specimens tested at 60ºC final failure occurred due to slip of the reinforcement, caused by adhesive failure. However, although the strength of the adhesives had decreased at 60ºC, most specimens – mainly the acrylate specimens – still showed significant residual strengths at the post-breakage state.

#### *Epoxy*

The epoxy-specimens did not perform very well. Slip of reinforcement, due to adhesive failure, occurred rapidly after initial failure and only two epoxy specimens showed a remaining load-carrying capacity of more than 100%, see table 2. However, for the epoxy specimens probably not the adhesive, but the manufacturing process of the specimens was the weakest link. At the manufacturing of the epoxy specimens some difficulties were encountered: 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.

#### *Acrylate*

The acrylate-specimens performed best. They showed high remaining load-carrying capacities and consistent results. Only two acrylate specimens showed a remaining load-carrying capacity of only a bit less than 100% (one acrylate-2 and one acrylate-3 specimen, see table 2). Specifically the acrylate-1 specimens performed well, since they consistently showed remaining load-carrying capacities of more than 100%.

#### *Polyurethane*

The polyurethane-specimens performed worse than the epoxy and acrylate specimens, but better than the silicone specimens. However, their remaining load-carrying capacity was still limited. Upon glass failure the reinforcement instantly slipped due to adhesive failure, and the remaining load-carrying capacity was only generated by a limited residual friction between glass and reinforcement, see figure 10.

#### *Silicone*

The silicone-specimens did not show any significant remaining load-carrying capacity. The silicone bond was not able to transfer the shear forces between glass and reinforcement upon glass failure, which caused slip of the reinforcement. Crack branching could therefore not be limited by any elongation of the reinforcement section. This resulted in severe cracking of the beam specimens upon initial glass failure and an almost instant collapse of the beam specimens.

The strength of the silicone bond, however, might have been limited due to the limited applied curing times. The specimens have been tested within a week after production. Although the thickness of the silicone bond was limited (< 1 mm) it might not have been fully cured before the specimens were tested. Furthermore, the applied thickness of less than 1 mm is significantly less than the advised thickness of 6–15 mm, as stated by the manufacturer’s datasheet (see also table 1).

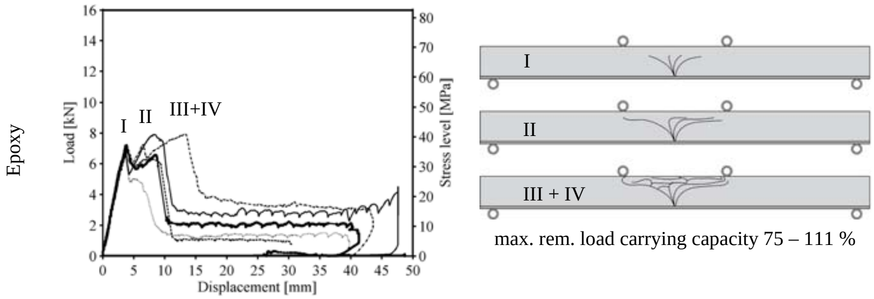


Figure 5: Load-displacement diagram and cracking sequence* of epoxy specimens tested at 60ºC.

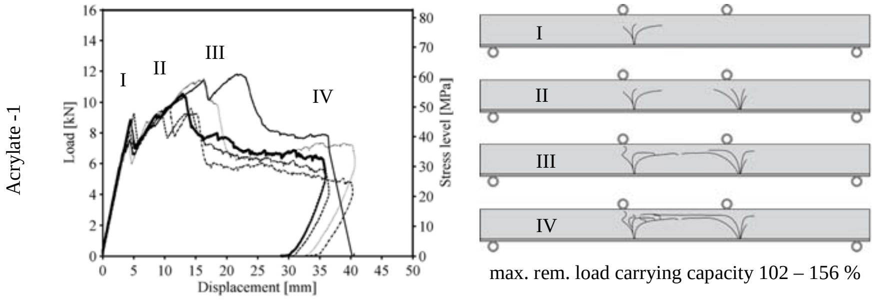


Figure 6: Load-displacement diagram and cracking sequence* of acrylate-1-specimens tested at 60ºC.

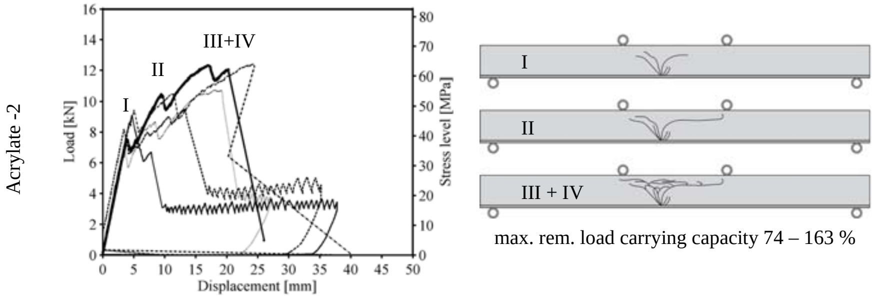


Figure 7: Load-displacement diagram and cracking sequence* of acrylate-2-specimens tested at 60ºC.

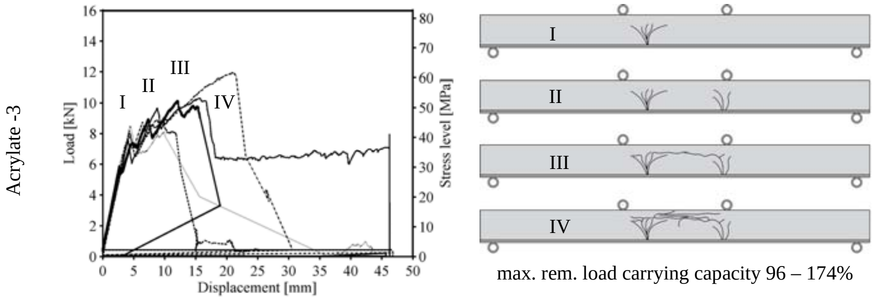


Figure 8: Load-displacement diagram and cracking sequence* of acrylate-3-specimens tested at 60ºC.

* I = initial failure, II = additional cracking, III = horizontal crack propagation, IV = final failure

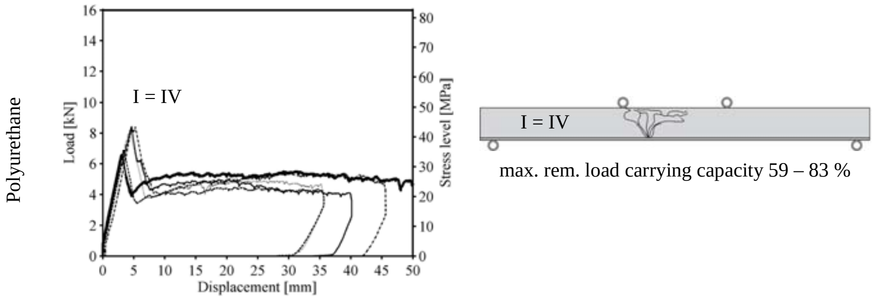


Figure 9: Load-displacement diagram and cracking sequence* of polyurethane-specimens tested at 60ºC.

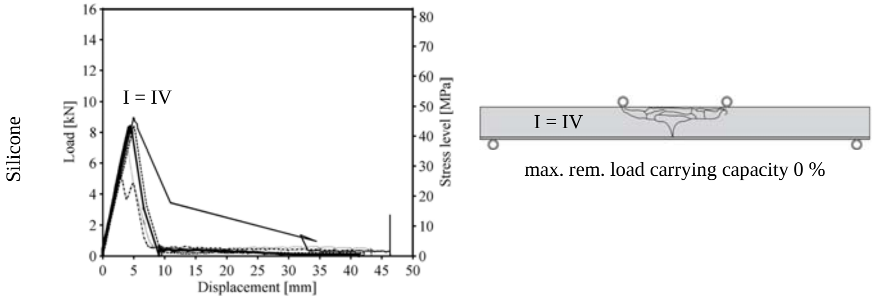


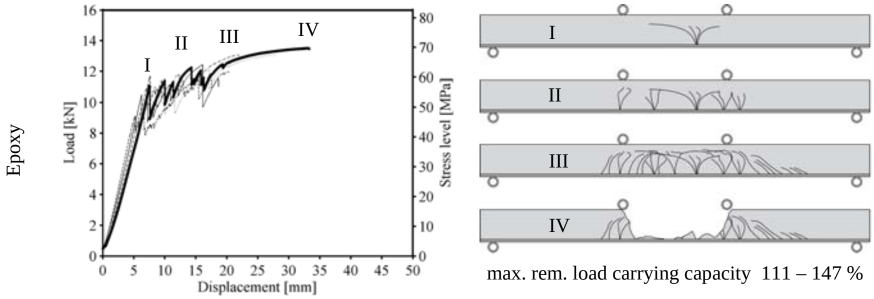
Figure 10: Load-displacement diagram and cracking sequence* of silicone-specimens tested at 60ºC.

* I = initial failure, II = additional cracking, III = horizontal crack propagation, IV = final failure

### *3.2. Results after salt-water-spraying*

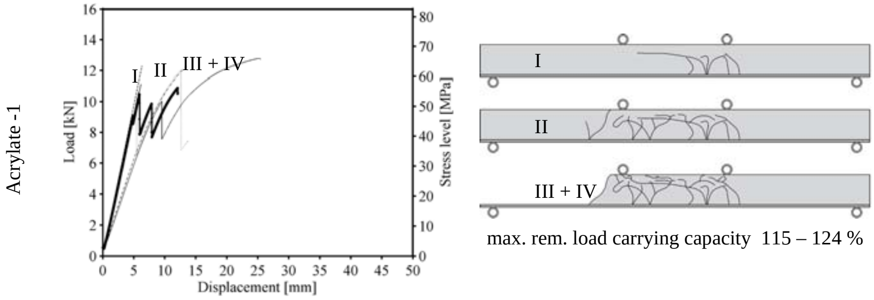
After 8 weeks of salt-water-spraying the beam specimens showed severe oxidation of the reinforcement section. This oxidation, which was most severe at the lower edge of the reinforcement, had at some spots penetrated between glass and reinforcement, by that affecting the adhesive bond. The results of the bending tests performed after salt-water-spraying are presented in figures 11 – 14, which show the load-displacement diagram and crack propagation of all specimens.

In general the salt-water-sprayed specimens showed a similar response as the specimens tested at 60ºC; after initial failure the cracks started to propagate horizontally and the bending stiffness gradually decreased. However, their final failure mechanism differed. Contrary to the specimens tested at 60°C, the reinforcement generally did not slip. This time the weakest link was not the adherence of the reinforcement, but the compression strength of the glass. Due to the increasing applied load, the glass in the upper compression zone became excessively stressed and, in most cases, exploded (see stage IV in figures 11, 13 and 14). Except for one acrylate-1 specimen, the beam specimens showed significant remaining load-carrying capacities and the final failure load generally exceeded the initial failure load.



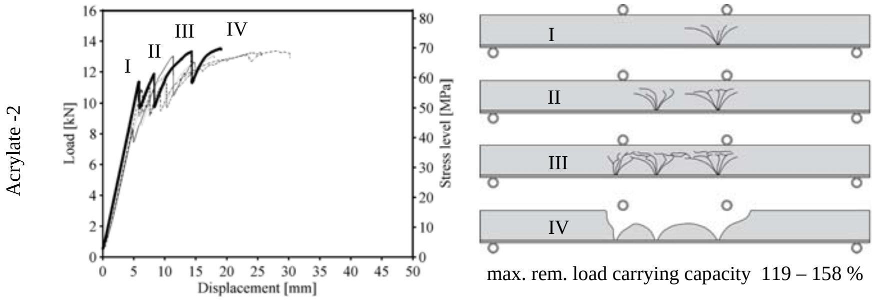
max. rem. load carrying capacity 111 – 147 %

Figure 11: Load-displacement diagram and cracking sequence* of water-sprayed epoxy specimens.



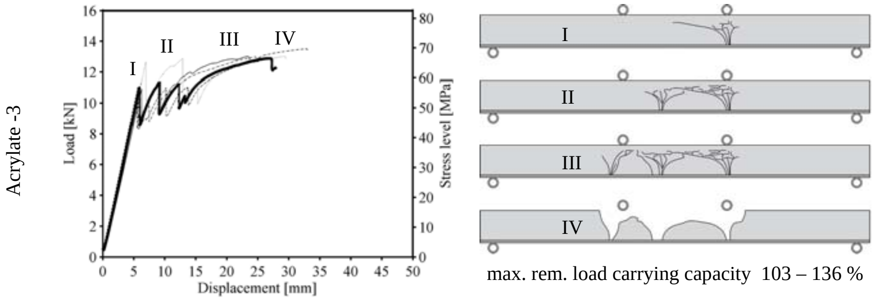
max. rem. load carrying capacity 115 – 124 %

Figure 12: Load-displacement diagram and cracking sequence* of water-sprayed acrylate-1-specimens.



max. rem. load carrying capacity 119 – 158 %

Figure 13: Load-displacement diagram and cracking sequence* of water-sprayed acrylate-2-specimens.



max. rem. load carrying capacity 103 – 136 %

Figure 14: Load-displacement diagram and cracking sequence* of water-sprayed acrylate-3-specimens.

* I = initial failure, II = additional cracking, III = horizontal crack propagation, IV = final failure

*Epoxy*

The epoxy-specimens performed well, and showed significant remaining load-carrying capacities. They typically showed a dense fracture pattern with seemingly unrelated cracks and many un-branched diagonal cracks (see stage III+IV in figure 11).

*Acrylate*

The acrylate-1-specimens generally showed quite severe cracking upon initial failure, which limited their remaining load-carrying capacity. One specimen did not even show any remaining load-carrying capacity and instantly collapsed upon initial failure. Upon final failure often large shards of glass were catapulted from the beam specimens (see stage III + IV in figure 12), which is not desirable since it can cause severe injuries.

The acrylate-2-specimens showed the most controlled crack branching behaviour. Of the tested adhesives these specimens showed the lowest initial crack height, which indicates controlled initial failure behaviour, and the highest remaining load carrying capacity (see table 2).

The acrylate-3-specimens showed similar failure behaviour as the acrylate-2-specimens. However, their remaining load-carrying capacity was less.

### 3.3. Results time / load duration

The results of the load controlled tests are plotted in figures 15 –18, which show the vertical deformation of the specimens and the applied load in time. Only one graph per adhesive type has been plotted. It should be noted that a total of only 8 specimens has been tested so far. This research should therefore be regarded as preliminary. Additional testing will provide more data.

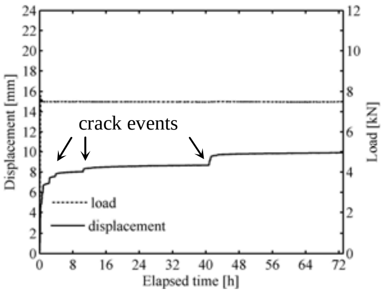


Figure 15: Response in time of epoxy specimen

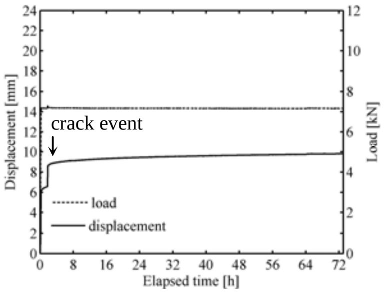


Figure 16: Response in time of acrylate-1 specimen

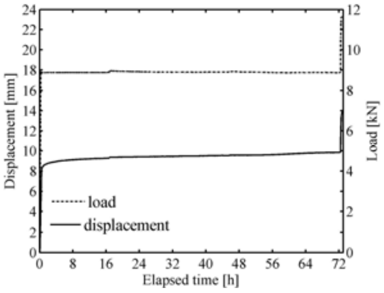


Figure 17: Response in time of acrylate-2 specimen

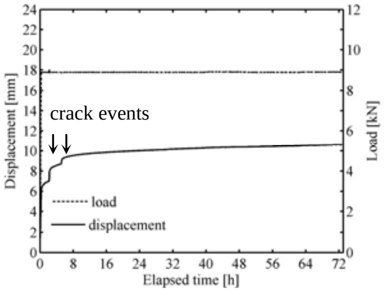


Figure 18: Response in time of acrylate-3 specimen

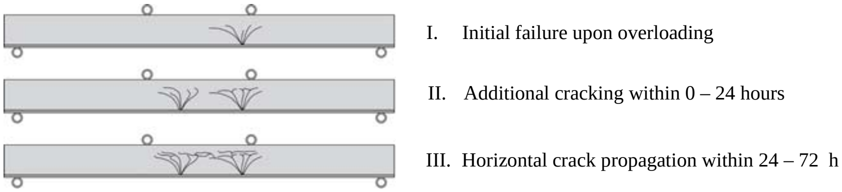


Figure 19: Crack development in acrylate-2 beam specimens under static load.

The specimens which have been statically loaded for 72 hours, showed a similar response and cracking sequence as was observed at the previous tests at 60ºC and after salt-water-spraying. The cracking process, however, was stretched over a longer period of time. This is illustrated by figure 19, which shows the cracking sequence of an acrylate-2 specimen. After initial failure (stage I) the specimens were left statically loaded. Additional cracking (stage II) generally occurred within the next 24 hours. These crack events are indicated by a sudden increase in vertical deformation of the beam specimens, see figures 15 – 18. Besides these crack events, the vertical deformation was gradually further increased due to gradual horizontal crack propagation (stage III) in the glass. None of the specimens collapsed within the first 72 hours. Some specimens did not even collapse after 5 weeks of being statically loaded. This time span, however, is not indicated in the figures.

## 4. Discussion

The results of the bending tests performed at 60ºC and after 8 weeks of salt-water-spraying show that the reinforced glass beam concept is, depending on the applied adhesive type, able to provide ductility and redundancy even at these extreme conditions. Furthermore, the results of the load-controlled bending tests show that the reinforced glass concept is capable of guarantying structural safety at the post-breakage state for a significant period of time (>72 hours). The test results will be discussed in more detail in the next sections.

### *4.1. Discussion tests performed at 60ºC*

The results of the tests performed at 60ºC show that the increased temperature level significantly decreased the strength of the glass-to-reinforcement adhesive bond. Whereas the specimens tested at room temperature ultimately exploded due to glass failure without showing any adhesive failure (see table 2), all specimens tested at 60ºC ultimately failed due to adhesive failure causing slip of the reinforcement and collapse of the beam. However, most specimens tested at 60ºC – mainly the acrylate specimens – still showed a significant residual strength, and were still able to provide safe failure behaviour.

### *4.2. Discussion tests performed after salt-water-spraying*

Although the adhesive had locally been affected due to oxidation of reinforcement, the 8 weeks of salt-water-spraying did not have a significant negative effect on the strength of the tested adhesives. All beam specimens ultimately failed quite explosively due to glass failure, without showing any slip of reinforcement.

The salt-water-sprayed beam specimens showed comparable post-initial failure loads, as the beam specimens tested at room temperature (see table 2). The lower percentage of remaining load carrying capacity – as stated in table 2 – is a bit misleading, since this percentage is decreased for the salt-water-sprayed specimens due to their high initial failure load, which is mainly dependent on the edge quality of the glass.

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 a significant residual strength.

### *4.3. Discussion time / load duration tests*

Since only a limited amount of beam specimens has been tested, the results of the statically loaded tests have to be regarded as preliminary. Additional tests have to be performed. However, the specimens tested so far clearly showed significant residual strengths (> initial failure strength) for a significant period of time (>72 hours). Some beam specimens did not even collapse within 5 weeks time. The glass-to-reinforcement adhesive showed no severe creep or progressive failure, even when additional cracks in the glass occurred.

During the tests a gradual increase in vertical deformation of the beam specimens has been observed. This deformation was not caused by any slip of reinforcement, but was caused by slow propagation of cracks in the glass. This crack propagation was probably caused by stress corrosion, which is a reaction of water and glass accelerated by high tensile stresses at the crack tip [8]. Ultimately the slow propagation of cracks leads to extensive crack lengths, which might endanger the stability of the glass beam. It might be that in the end not the adhesive, but the glass itself becomes the critical component.

### *4.4. Discussion adhesive types*

The applied glass-to-reinforcement adhesive bond type plays a crucial role in limiting the crack branching upon initial failure. The adhesive has to transfer the forces properly between glass and reinforcement to enable the reinforcement to limit the crack growth in the glass. Some of the tested adhesives, however, locally failed upon initial glass failure, causing extensive crack branching in the glass; as was the case for e.g. the salt-water-sprayed acrylate-1 and -3 specimens. Some adhesives even fully failed upon initial glass failure causing an almost instant collapse of the beam specimens; as was the case for e.g. the polyurethane and silicone specimens tested at 60ºC. Important is that the applied adhesive has to be able to absorb the shock which occurs upon initial glass failure without failing, in order to limit crack branching in the glass.

The tests did not clearly bring forward an overall ‘best-performing’ adhesive. For instance at the tests performed at 60ºC the acrylate-1-specimens performed best, but after 8 weeks of salt-water-spraying they did not perform very well. Furthermore, the results of the epoxy specimens tested at 60ºC (see section 3.1) showed that not only the properties of the adhesive itself – like strength, temperature and moisture resistance – are crucial, but also the way the adhesives have to be processed. Especially for the slow curing or non-transparent adhesives, errors occurred at the manufacturing process. Since these adhesives can not be applied for simultaneous glass-to-glass and glass-to-reinforcement bonding, the reinforcement had to be bonded to the glass afterwards, which – especially for encapsulated reinforcements (see figure 4) – causes difficulties in creating an even adhesive thickness. Uneven adhesive thicknesses might limit the strength of an adhesive bond due to an uneven stress distribution. In this respect the tested transparent UV-cured acrylates provide an advantage, since due to their applicability for rapid and simultaneous glass-to-glass and glass-to-reinforcement bonding, the bonding process is easier to control, which enhance the realization of even adhesive thicknesses.

Ideally, the adhesive used to bond the reinforcement to the glass combines all structural and manufacturing advantages. However, this probably requires a modification of the existing adhesives to ideally suit the reinforced glass concept. Furthermore, the key aspect in structural bonding is not only selecting the proper adhesive, but also controlling the bonding process to be able to repetitively ensure a high quality bond. All aspects which affect the strength of an adhesive bond should be carefully monitored during the bonding process, since it currently is impossible to determine the actual strength of an adhesive bond, after the bonding process, in a non-destructive manner.

## 5. Conclusions

From the bending tests on 1.5 m reinforced glass beam specimens performed at 60ºC, after salt-water-spraying and for significant load durations, the following is concluded:

- Temperature levels up to 60ºC do not endanger the structural safety of reinforced glass beams, provided that the proper adhesive has been selected to bond the reinforcement to the glass.
- Moisture exposure does not have a significant negative effect on the residual strength of reinforced glass beams.
- Reinforced glass beams are able to carry the initial failure load at the post-breakage state for at least 72 hours.
- Ideally, the reinforcement is bonded to the glass using a modified adhesive in which all structural and manufacturing advantages are combined.

Furthermore, it is concluded that the reinforced glass concept is a redundant system which shows a significant residual strength even at extreme temperature and moisture conditions and for a significant period of time.

## 6. Acknowledgements

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## 7. References

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