Adhesively bonded reinforced glass beams

P.C. (Christian) Louter

Faculty of Architecture, Delft University of Technology, the Netherlands

www.glass.bk.tudelft.nl

Researchers at the faculty of Architecture at Delft University of Technology have developed an unconventional construction method for large span structural glass beams based on two concepts: 1) glass beams are reinforced with a small stainless steel section bonded at the tensile zone, 2) large spans are created by adhesively bonding overlapping glass segments. The effect of cross-section geometry, reinforcement geometry and glass-reinforcement bond on the structural behaviour of the beams has been investigated experimentally by bend tests on several small and large scale specimens. The knowledge gained from these experiments will be implemented in the design of an 18 m adhesively bonded reinforced glass beam, which is planned to be constructed to validate the concepts for large span glass beams.

Key words: Structural glass, glass beam, reinforcement, ductility, adhesive bond, composite, safety

1 Introduction

In contemporary architecture there is an increasing demand for transparent buildings and structures. Glass is desired as a load-bearing material for structural components like columns and beams. However, due to the brittleness and unpredictable failure behaviour, glass is considered a structurally unsafe material. At the faculty of Architecture at Delft University of Technology, a research group focuses on the development of transparent structures and components with *safe* failure behaviour. The research group has developed a construction method for structural glass beams which differs from that of 'ordinary' glass beams and is based on two innovative concepts:

- *Reinforced glass*

A small stainless steel section which is adhesively bonded at the tensile zone of the glass beam acts as reinforcement. This way safe failure behaviour, comparable to reinforced concrete, is obtained.

- *Adhesively bonded glass segments*

Overlapping glass segments are adhesively bonded to create beams with a span exceeding the standard maximum size of a glass pane, being 6 x 3.21 m.

These concepts enable the realization of large span glass beams with higher structural safety than common glass beams. For several years now the research group has been working on these concepts [Veer, 2005] and has successfully produced and tested beams up to a length of 7.2 meters [Louter, 2005].
To validate the concepts of *reinforced glass* and *adhesively bonded glass segments* for large span beams the research group is now planning to construct an 18 meter reinforced glass beam. If the concepts are valid, all architecturally relevant beam sizes ranging from 6 to 18 meters can be realized according to these concepts.
To reach this challenging goal, several aspects of the 'adhesively bonded reinforced glass beams' have to be investigated. Therefore a series of 1:8, 1:4 and 1:2 scale models of the 18 m beam will be constructed and tested prior to the construction of the 18 m beam. Furthermore, specific aspects will be investigated by additional experiments on small scale specimens. Knowledge gained from these experiments and from preceding beam designs will be implemented in the design of the 18 m beam.

Recently, the experimental research on the scale 1:8 models has been completed and the results have been published by Louter et al. [Louter, 2006]. Parallel to the tests on the scale 1:8 models, additional research has focused on the effect of different reinforcement geometries and different adhesive types on the failure behaviour of reinforced glass beams [Louter, 2007]. Based on the results of these experiments and on the knowledge gained from previous beam designs, the following aspects, which are essential for the further development of the 18 m beam, will be discussed in this article:

- Cross-section geometry
    - Alternative cross-section geometries.
    - Effect of the cross-section geometry on the structural behaviour of the beam.
- Reinforcement geometry
    - Effect of different reinforcement geometries on the structural behaviour of the beam.
- Glass-reinforcement bond
    - Effect of the applied glass-reinforcement adhesive bond on the structural behaviour of the beam.

Firstly, the underlying concepts and the general failure behaviour of the 'adhesively bonded reinforced glass beams' will be described, followed by the results of experimental research into the aspects mentioned above.

2 Reinforced glass

2.1 General concept

To design a safe glass beam one has to overcome the fundamental problem of the brittle failure of glass. Unlike a steel beam that will visually deform upon overloading, glass has no built-in warning mechanism; it can only deform elastically or fracture. To deal with the problem of brittle failure, in current building practices glass beams are generally composed of multiple glass layers, which are laminated using a foil or resin interlayer. The safety concept is based on overdimensioning. Sacrificial outer layers are added to the laminated beam to protect the inner layers. If one of the outer layers might fail due to an impact, the remaining layers will still be able to carry the load. Furthermore, large safety factors and often tempered glass types are applied. All these measures minimize the probability of total glass failure. However, the chances of a total collapse of the beam laminate cannot be eliminated since failure of all glass layers might still occur due to repeating impacts, nickel sulphide inclusions (for tempered glass) [Kasper, 2003], or unforeseen stress concentrations caused by assembly errors at the joints or supports.

The reinforced glass concept has been developed from a totally different perspective. Rather than minimizing the probability of a total glass failure, it focuses on the consequences of any glass failure and aims at controlled and *ductile* failure behaviour. This ductile failure behaviour is obtained by bonding a small stainless steel reinforcement in the tensile zone along the edge of the glass beam. Since the edges of a glass pane are always distinct, bonding a stainless steel section at the edge hardly compromises the transparency of the beam. Upon overloading, the glass will crack, but crack propagation will be limited due to dissipation of fracture energy by deformation of the reinforcement. The reinforcement will act as a crack bridge taking up the tensile forces. Together with a compression force in the (uncracked) compression zone, an internal couple will be generated (see Figure 1), and the beam will still be able to carry load. This way, safe failure behaviour, comparable to reinforced concrete, is obtained. The cracks which will occur in the beam upon overloading will alarm bystanders and the redundancy of the system will provide time to flee or to take measures.

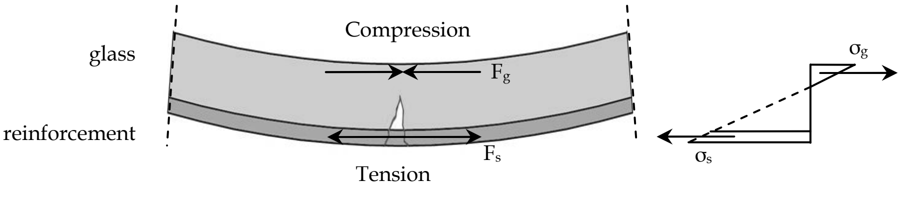


Figure 1: Schematic overview of distribution of forces after glass failure

2.2 *Glass type*

Like concrete, glass is strong in compression, but weak in tension. Although glass has a theoretical strength in the range of 1-100 GPa [Shelby, 2005], the actual (tensile bending) strength of annealed float glass is limited to 20-110 MPa [Veer, 2006] due to small defects at the glass surface. The strength at the edge of a glass pane is at the low end of this range, because of defects caused by the cutting and grinding process [Veer, 2003]. A common method to increase the strength of glass is pre-stressing the glass through thermal treatments. A residual surface compressive stress is introduced by heating the glass followed by a rapid cooling of the glass. Depending on the level of pre-stress, these glass types can be divided into heat-strengthened or fully tempered glass. Although the application of stronger glass may seem advantageous, it is has a negative effect on the structural behaviour of a reinforced glass beam. Due to the increased energy release upon glass failure these glass types show more extensive crack branching than annealed float glass (without internal pre-stress) [Veer, 2005] (see Figure 2).

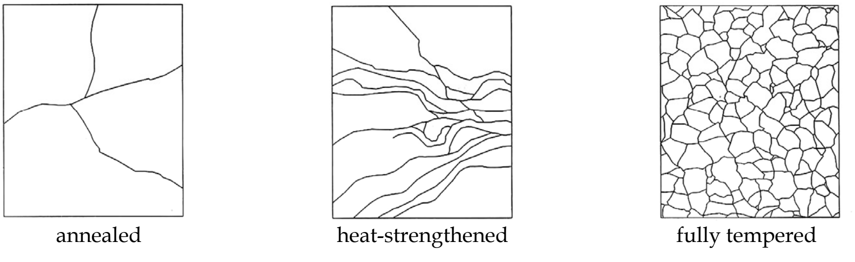
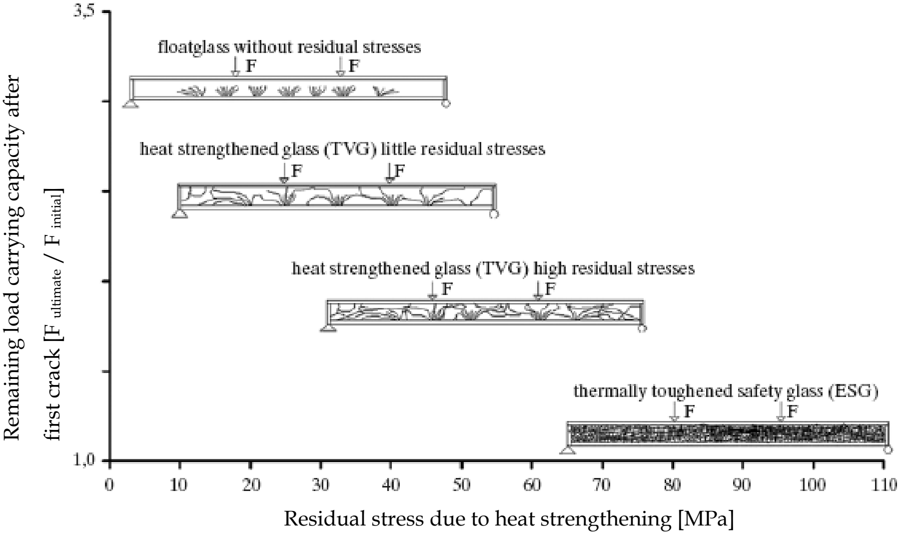


Figure 2: Fracture pattern of annealed, heat-strengthened and fully tempered float glass [Schittich, 1999]

To prevent total disintegration upon glass failure, the reinforced glass beam concept requires the use of ordinary annealed float glass, which fails at relatively low stresses and in large shards. Unlike the small fragments which occur upon failure of fully tempered glass, large shards offer the highest remaining load carrying potential since these shards can still transfer compression forces due to an interlocking effect. This theory is supported by the experimental research of Kreher [Kreher, 2004]. The remaining load carrying capacity of timber-glass-composite girders, which show some similarities with the reinforced glass concept, has been examined for different glass types. Glass beams are reinforced with wooden flanges which are adhesively bonded to the web of the beam. Timber-reinforced *annealed* float glass beams showed a remaining load carrying capacity three times larger than *fully tempered* timber-reinforced glass beams (see Figure 3). The research of Kreher showed that timber-reinforced beams with an internal residual stress below 50 MPa are considered to fail in a ductile manner, while residual stresses larger than 50 MPa cause brittle failure.



(toughened glass = fully tempered glass)

Figure 3: Relation of residual (internal) pre-stress and remaining load-carrying capacity for timber-reinforced glass beams [Kreher, 2004]

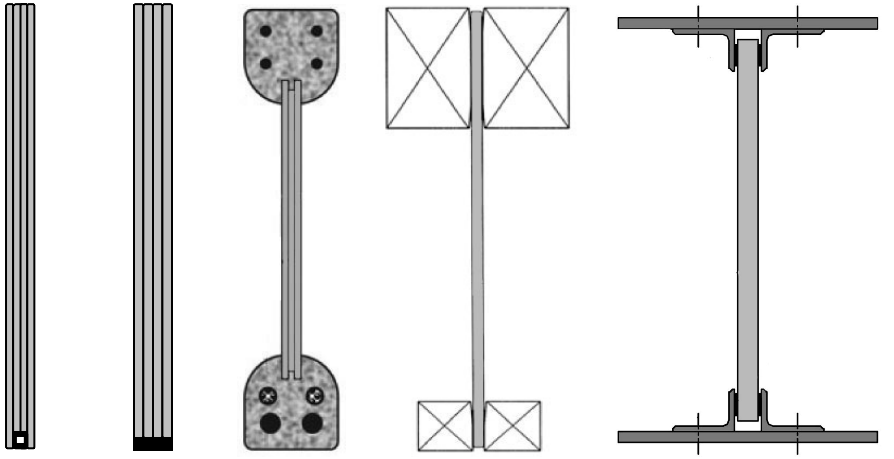
2.3 ***Similar research projects by others***

Several other (research) projects focus on glass composite beam concepts. These beam concepts show some similarities with the reinforced glass concept and all focus on obtaining ductile failure behaviour through the combination of glass with other materials. Some beam concepts even include a lengthening scheme to exceed the standard limit glass size of 6 m, which is similar to the 'overlapping glass segments concept' described in section 3. A short description of these beam concepts is provided below:

- Carbon fibre reinforced annealed float glass beams are researched by Palumbo [Palumbo, 2005]. A carbon fibre reinforcement, which is commonly applied for masonry or concrete repair, is bonded in the tensile zone of the glass beam (see Figure 4). This concept is demonstrably safe for 1.1 m glass beam specimens and has been applied for 6 m beams in a saddle roof structure.
- Glass-concrete composite beams are researched at Graz University of Technology [Freytag, 2004]. Two ultra-high-performance reinforced concrete flanges are joint with a fully tempered glass web (see Figure 4). The connection is realized by covering the glass with liquid concrete. This concept has been successfully tested for a 7.8 m span

beam, which was composed of multiple overlapping resin laminated glass panes. However, the visco-elastic interlayer has only limited shear strength and shear forces will probably mainly be transferred via the concrete flanges. In addition, there are some questions about the long-term stability, as the highly alkaline concrete can corrode the glass [Veer, 2003].

- Timber-glass composite beams are researched at École Polytechnique Fédérale de Lausanne [Kreher, 2004; Hamm, 2000]. Wooden flanges are adhesively bonded to a single layer glass beam web (see Figure 4). This concept is demonstrably safe and 6 m beams have been applied in a roof structure [Kreher, 2004].
- Hybrid steel-glass beams are researched at the Institute of Steel Construction at RWTH Aachen and the University of Dortmund [Wellershof, 2003; Flinterhoff, 2003; Grotepaß, 2006]. Steel flanges are bolted to steel L-sections which are adhesively bonded to a laminated glass beam web. This concept has been tested on a 12 m span beam, which was composed of 6 laminated glass panes.



Stainless steel reinforced (TU Delft)	Carbon fibre reinforced (Palumbo)	Concrete-glass composite (TU Graz)	Timber-glass composite (EPFL)	Steel-glass composite (RWTH Aachen + University of Dortmund)

Figure 4: Similar structural glass composite beam concepts. The figures are schematic and not to the same scale

These projects show there is a tendency in structural glass engineering to seek ductility and focus on the consequences of glass failure, rather than adding material to the beam laminate to minimize the probability of total glass failure.

3 Adhesively bonded glass segments

3.1 General concept

The spans of structural glass beams – applied in contemporary architecture – tend to increase. Although large spans (>12 m) are still quite exceptional, several large span glass beams have been applied in practice. For instance for a 14 m span courtyard roof covering in Munich [Betsch, 2004] and a triangular atrium roof structure in Glasgow, with a maximum span of 15.5 m (see Figures 5 and 6).

Figure 5: (left) 14.5 m span courtyard roof covering IHK Munich, Ludwig und Weiler [Betsch, 2004]
Figure 6: (right) Maximum 15.5 m span triangular atrium roof structure, Glasgow, Arup

Although glass is manufactured in a continuous ribbon of approximately 3.5 m wide, it is cut to a standard final size of 6x3.21 m. The glass industry is fully equipped for the production, handling and transport of this standard maximum size. Larger sizes have occasionally been manufactured, but are quite extraordinary and extremely expensive. Large span glass beams are therefore generally composed of multiple standard sized glass panes which are connected using steel joints or clamping plates (see Figures 5 and 6). This solution, however, has two main drawbacks:

- the applied steel joints affect the transparency of the glass beam
- the application of steel joints often implies the drilling of holes in glass, which affects the strength of the glass and introduces high local stresses [Siebert, 2003].

The developed 'adhesively bonded glass segments' concept enables the realization of continuous and fully transparent glass beams without using metal joints or drilled holes. Overlapping annealed float glass segments are adhesively bonded using an acrylic-based photo-initiated curing adhesive (DELO-Photobond Glassbond [DELO]). Forces are transferred between the glass segments through shear in the adhesive bond. Stresses are distributed over a large bond area thus shear-stresses are low and local peak stresses are avoided. Applied in a thickness of < 0.1 mm, this specific adhesive bond results in a strong and stiff connection, with a shear strength >10 MPa. Strength, creep and aging of this particular adhesive are examined in related research [Veer, 2006].

3.2 Segmentation scheme

The adhesively bonded glass beams are composed of multiple overlapping glass segments which have to be laid out according to a specific segmentation scheme (see Figure 7). The dimensions of the individual glass segments are dependent on the applied segmentation scheme, which itself is dependent on beam length and load distribution. Important aspects for the development of an appropriate segmentation scheme are as follows:

- Beam height to span ratio

Preceding research has shown that the beam height should not exceed 1/10 of the span. Increasing the height of the beam will result in a stiff beam and consequently high elastic energy release upon glass failure. To avoid too much crack branching due to an excessive energy release upon glass failure (as discussed in section 2.2), the beam height has to be limited.

- Number of glass layers

The number of glass layers should preferably be limited. Increasing the number of glass layers increases the number of bond layers, thus increasing production time and costs. To reduce the number of bond layers 'ordinary' foil laminated glass sheets can be applied. However, transfer of shear stresses via this foil interlayer should be avoided, since the shear-modulus of this visco-elastic interlayer is strongly dependent on temperature and load duration [Belis, 2006; Weller, 2005].

- Number of glass segments

To optimize the transparency of the beam, the number of glass segments should preferably be small and the length of glass segments large. Although hardly visible, a seam between two glass segments causes a small vertical line due to exposure of the edges of the glass segments.

- Overlap length

To avoid high shear stresses in the glass-glass adhesive bond, a certain minimum overlap length of the glass segments is required. The exact minimum overlap to length ratio has not been researched yet, but has temporarily been set at 1/3. Future research at Delft University of Technology will focus on this aspect.

- Position of the seam

At the seams between the glass segments (see Figure 7) the local bending stresses are increased due to a reduced cross-section. A seam is therefore preferably not placed at the zone of maximum bending moments.

Optimising all these aspects will result in an appropriate segmentation scheme. Preceding research has mainly focused on symmetric segmentation schemes. A-symmetric segmentation schemes (see Figure 7) have been researched for glass-polycarbonate composite beams [Veer, 2001], but not yet for stainless steel reinforced glass beams. A-symmetric segmentation schemes offer a favourable minimal reduction of the cross-section at the seams. Future research at Delft University of Technology will focus on the possibilities for adhesively bonded reinforced glass beams of a-symmetric segmentation schemes and their lateral torsional stability.

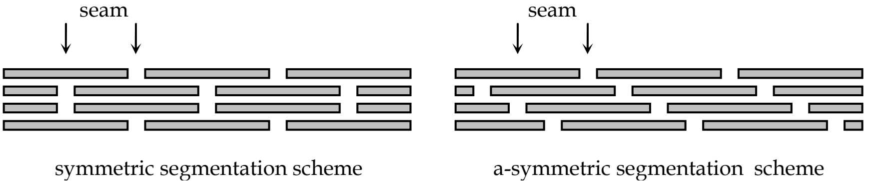


Figure 7: Examples of symmetric and a-symmetric segmentation scheme for a four-layer beam. (top view, figures are schematic and dimensions are without proportion)

4 Failure behaviour

In this section the general structural (failure) behaviour of stainless steel reinforced glass beams will be discussed by means of a schematic stress-displacement diagram, which is provided in Figure 8. This diagram is based on experimental data obtained by displacement controlled bend tests on several small and large scale specimens. Four general (crack) events are distinguished (see also Figures 8 and 9):

a. Small cracks (initial failure)

The beam specimens show linear elastic behaviour until the global tensile bending stress at the lower edge exceeds the local tensile strength of the glass. One or several small cracks occur, which originate at the lower edge of the glass beam and run over 2/3 of the total beam height before being stopped in the upper compression zone. The cracks generally only run in one glass layer and do not affect the other glass layers in the beam laminate. Depending on the applied adhesive, the cracks are V-shaped or consist of a single line of fracture (see section 7). Although the *local* bending stress at the seams between the glass segments is a multitude of the *global* bending stress (see section 3.2) the first cracks do not necessarily occur at these seams.

b. Large cracks at the seams

As loading is continued, bending stiffness is slightly decreased. Load starts to rise again until, at a certain point, large vertical cracks appear. These cracks are generally located at the seams and run in all glass layers present at this seam. These cracks might occur at once or in segments at small time intervals (total crack growth within a second).

Depending on the applied adhesive (see section 7) the reinforcement might be torn from the glass locally on either side of the crack origin due to the shock load upon glass failure. A sudden increase in vertical displacement of the specimen causes a drop in load (*displacement* controlled tests). As loading is continued the load starts to rise again until, at a second peak-load, similar cracks occur at a different position along the edge of the beam and existing small cracks start to propagate. Depending on the applied reinforcement geometry (see section 6) and applied adhesive (see section 7), progressive detachment of reinforcement might occur.
This process might repeat itself one or several times (see b1, b2, etc. in Figure 8). The stress-displacement diagram clearly shows a decrease in bending stiffness after each peak-load.

c. Horizontal crack propagation

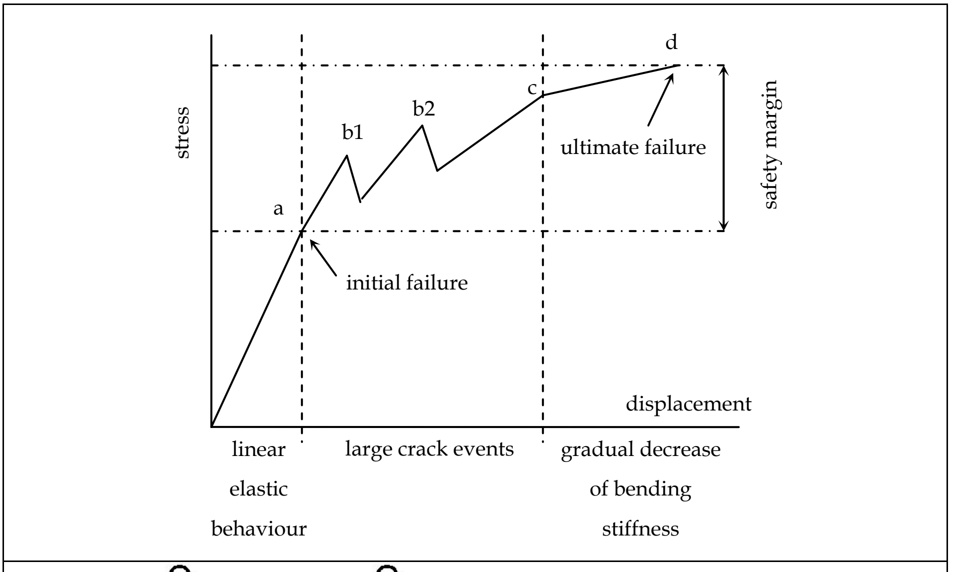
The existing large (vertical) cracks start to propagate horizontally and start to grow towards each other. Bending stiffness gradually decreases until final failure occurs.

d. Collapse (ultimate failure)

At the final failure stage the beam has largely lost its bending stiffness and collapses. Two different failure mechanisms have been observed:

- Detachment of reinforcement; the reinforcement has been torn from the glass. Tensile forces cannot be transferred anymore and the beam collapses.
- Buckling; lateral instability due to decreased cohesion of the glass by excessive cracking causes the beam to buckle (see section 5.2).

Which final failure mechanism occurs is dependent on the beam cross-section geometry, the geometry of reinforcement and the type of glass-reinforcement adhesive bond.
The stress-displacement diagram shows gradual failure behaviour of the reinforced glass beams. As the ultimate failure load exceeds the initial failure load a safety margin (redundancy) has been built in the system. Whether and to what extend the ultimate failure load exceeds the initial failure load depends on the cross-section geometry (see section 5), reinforcement geometry (see section 6) and applied glass-reinforcement bond (see section 7). These aspects will be discussed in the following sections.



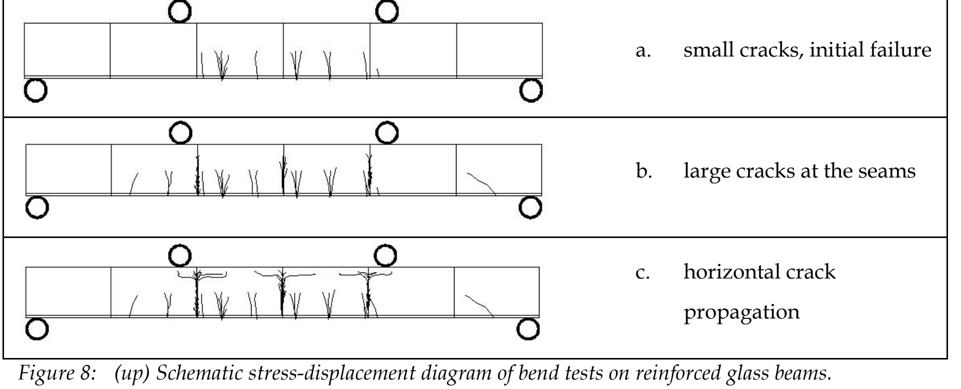


Figure 8: (up) Schematic stress-displacement diagram of bend tests on reinforced glass beams.

Figure 9: (below; a, b, c) Schematic crack branching behaviour; see also the stress-displacement diagram.

5 Cross-section geometry

Current glass bonding technology enables the realization of various glass section geometries. Besides bonding glass in overlap glass panes can be bonded perpendicularly, which enables the realization of hollow section glass beams. For the adhesively bonded reinforced glass beams, several section geometries have been designed and tested in beam prototypes. A schematic overview is provided in Figure 10. These cross-section designs will be discussed in the following section.

5.1 *Cross-section designs*

5.1.1 U-section

In 2003 Veer [Veer, 2003], designed and built an 8 m stainless steel reinforced glass aquarium, which was designed as a U-shaped channel (see Figure 10). The side and bottom parts were constructed by adhesively bonding overlapping glass segments. These parts were subsequently bonded in a perpendicular way to create the U-shape. To obtain stability, 0.5 m long glass segments were bonded on top of the U-shape to connect the upper edges of the side panes. These glass segments were bonded only every 0.5 m to allow for air entering the aquarium.

5.1.2 Box section

Based on the layout of the 8m aquarium Louter designed a 12 m stainless steel reinforced glass box section beam (see Figure 10) in 2003 [Bos et al., 2004]. Similar to the aquarium, this box section beam was composed of perpendicularly bonded glass webs and flanges, which themselves were composed of adhesively bonded overlapping glass segments. Two stainless steel box sections were integrated at the tensile zone and bonded to the side and bottom panes. A 3 m prototype of the box-section beam was built and subjected to a four-point bend test to validate its structural behaviour.

5.1.3 T-section

In 2004, Louter designed a 12 m reinforced and post-tensioned glass T- section beam (see Figure 10) [Bos et al., 2004]. Web and flange, which were adhesively bonded, were both composed of overlapping glass segments. A stainless steel box section was integrated in the web of the beam. A 3 m prototype of the T-section beam was built and subjected to a four-point bend test to validate its structural behaviour. Research into the buckling behaviour of this post-tensioned glass T-beam has been executed by Belis [Belis, 2006].

5.1.4 Full-section

For a temporary All Transparent Pavilion [Bos, 2005], which was constructed at the faculty of Architecture at Delft University of Technology, 7.2 m reinforced glass beams were designed and built by Louter et al. [Louter et al., 2005]. The beams spanned 4.8 m and cantilevered 1.2 m on either side. Lateral torsional buckling was prevented by purlins which were placed between the glass beams and supported the beam sideways. The beams were composed of four 15 mm thick overlapping glass layers which were adhesively bonded. Due to the cantilever parts, tensile stresses occurred at both edges of the glass beam, requiring stainless steel reinforcement on either side (see Figure 10). Similar to the T-section beam, these box sections were placed between the outer glass layers.

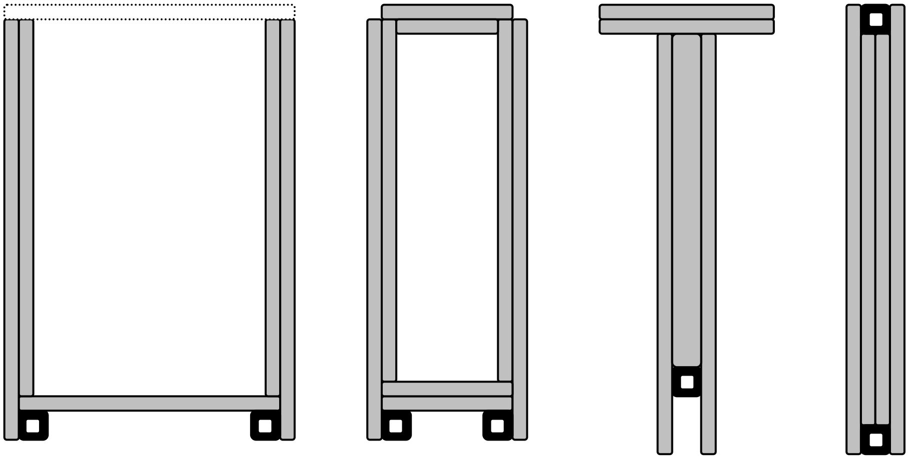


Figure 10: Alternative cross-section designs, developed at Delft University of Technology

5.2 ***Lateral stability***

An important aspect of the beam cross-section geometry is its lateral stability. High stresses at the (upper) compression zone might cause a beam to collapse due to lateral torsional buckling. For a box- and T-section beam lateral stability is provided by the flange(s). Slender full section beams, however, might become laterally instable as these flanges are absent [Belis, 2006]. Lateral stability turned out to be a critical aspect at the experimental research on the scale 1:8 models of the 18 m beam. Two alternative full section beam designs, which are given in Figure 11, were tested [Louter, 2006].

Beam layout A consisted of 5 glass layers. Two separate stainless steel sections were bonded from the inside out to both outer layers. The developed segmentation scheme for this beam (see Figure 11) guarantees a minimal amount of three out of five glass layers at each seam. This way, the local moment of inertia (at the seam) is never less than 3/5 times the global moment of inertia (at full section).

To reduce the amount of bonded area and to increase the ease of manufacture beam layout B consisted of only 4 glass layers of which both inner layers were foil laminated. Two reinforcement sections were bonded from the outside to both inner glass layers. The developed segmentation scheme for this beam layout (see Figure 11) guarantees a minimal amount of 2 out of 4 glass layers at the seams, thus the local moment of inertia amounts to half the global moment of inertia.

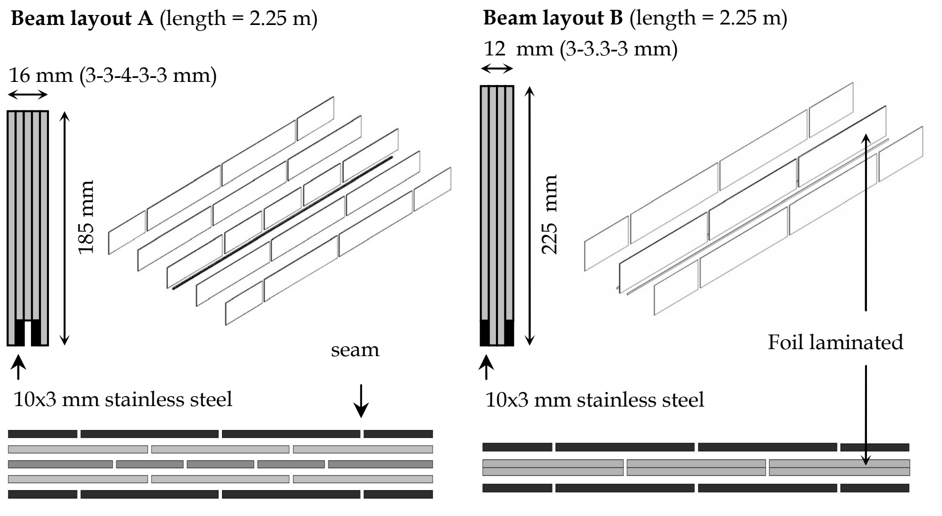


Figure 11: Schematic cross-section geometry and segmentation scheme of alternative beam designs.

The amount of reinforcement in the section was equal for both layouts. However, cross section dimensions differed. Beam layout B had a more slender cross-section (width to height ratio ≈ 1 : 18) than beam layout A (width to height ratio ≈ 1 : 11).
Of both beam layouts a series of 3 specimens was built and subjected to four-point bend tests to validate their structural behaviour. In the test setup, supports were 2.15 m apart and loads were 0.9 m apart. Lateral (anti-buckling) supports were provided at 0.3 m from mid-span (see Figure 13). The specimens were loaded at a rate of 1 mm/minute and loading was continued until total destruction occurred.

The stress-displacement diagrams of the specimens of both beam layouts are given in Figure 12. At first instance, all specimens responded according to the general failure behaviour as described in section 4 and all specimens showed gradual failure behaviour.
However, two differences in failure behaviour were observed. The first difference concerns the final failure mechanism of both beam layouts. Whereas beam layout A -specimens failed due to progressive detachment of reinforcement caused by adhesive failure, beam layout B -specimens failed due to lateral torsional buckling (see Figure 14). At first instance, the layout B -specimens were not prone to buckling, but during the tests the lateral stiffness of the beams gradually decreased due to increasing crack growth. Despite the presence of lateral anti-buckling supports, this reduced lateral stiffness in combination with a rather slender section caused the beam to buckle. Although buckling only occurred at a combination of extreme loading and expansive crack growth, it still requires specific attention in future beam designs.

The lateral stability of this beam layout might be improved by enlarging the compression zone. This can, for instance, be done by adding material to the compression zone or creating a T-section beam. Altering the segmentation scheme, however, might also improve the lateral stability of this beam design since the applied segmentation scheme contained an unfavourable seam at mid span, which might have strongly affected the lateral stability (see Figure 11).

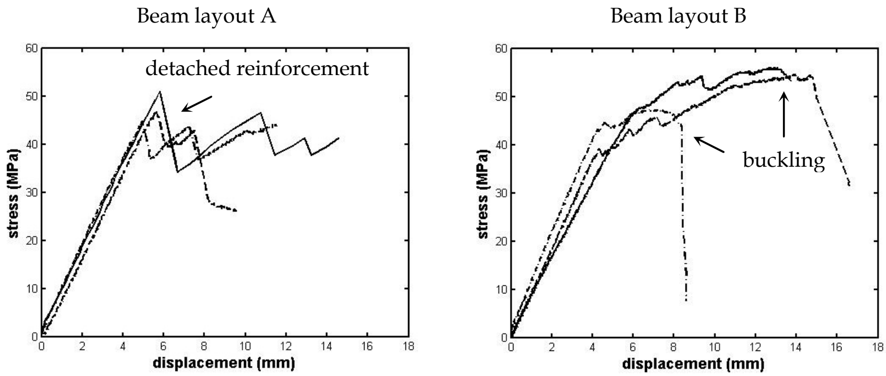
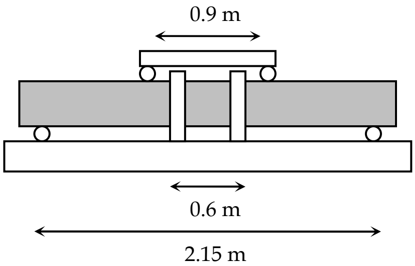


Figure 12: Stress-displacement diagrams of beam layout A-specimens and beam layout B-specimens.



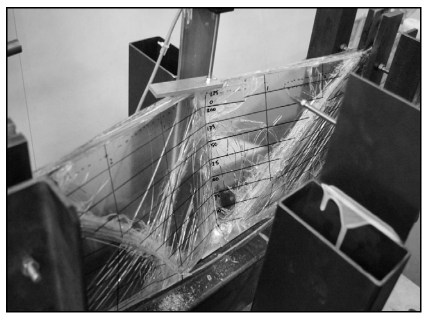


Figure 13: (left) Schematic overview of test setup for 1:8 scale models of 18 m beam
Figure 14: (right)Buckling at mid-span of beam layout B-specimen.

The second difference in structural behaviour concerns the residual strength. Contrary to layout B –specimens, the residual strength for layout A -specimens did not exceed the initial failure load (see Figure 12). This difference was caused by the relatively small beam height and consequently small lever arm between compressive and tensile zone upon glass failure. Due to this small lever arm, compression forces in the glass were high and the glass started to crush and crumble in an early failure stage, which affected the remaining load carrying capacity. Enlarging the compression zone or increasing the beam height (to a limited extend) might enhance the failure behaviour for this beam layout. Since the failure behaviour of both beam layouts might be improved by enlarging the compression zone, subsequent research into the scale models of the 18 m beam will focus on cross-sections with enlarged compression zones.

The results of the scale 1:8 models of the 18 m beam showed that, although a reinforced glass beam is not prone to buckle at first instance, it might become laterally instable once cracks occur. Due to increased (horizontal) crack growth, the upper compression zone will separate from the lower tensile zone and might become laterally instable. At the design and calculation of the cross-section geometry, it is therefore important to consider the lateral stability of the uncracked as well as the cracked cross-section geometry.

6 Reinforcement geometry

The stainless steel reinforcement can be integrated in the design of a reinforced glass beam in several ways. The reinforcement can, for instance, be bonded to the edge or side panes of the beam, or be integrated in the web of the beam. Furthermore, different reinforcement sections like box- or full-sections can be applied. All these alternative reinforcement possibilities have an effect on the assembly method [Louter, 2006], quality of the structural bond [Louter, 2007] and on the structural behaviour of the reinforced glass beam.
The effect of different reinforcement geometries on the structural behaviour of a reinforced glass beam has been experimentally examined by four-point bend tests on small specimens. The results of these experiments will be discussed in the following sections.

6.1 Experimental research

Three different reinforcement geometries, which are displayed in Figure 15, were tested. For each geometry a single layer annealed float glass beam of 1500*115*10 mm was applied.

- Geometry 1F (1-face bond) consists of a stainless steel box section (10*10*1 mm), which is bonded to the edge of the glass beam.
- Geometry 2F (2-face bond) consists of two stainless steel sections (each 2*9 mm), which are bonded to the side panes of the glass beam.
- Geometry 3F (3-face bond) consists of a stainless steel box section (10*10*1 mm), which is bonded to the edge of the glass beam and encapsulated by two additional outer layers (each 40*6 mm). These outer layers are bonded to the side panes of the glass beam (using an acrylic-based photo-initiated curing adhesive).

The amount of steel in the section is equal for each geometry; the area of the box section (36 mm^2) is equal to the area of both full sections (2* 2*9 mm = 36 mm^2).
However, the glass-reinforcement bond area (1-, 2- or 3-face bond, see Figure 15) differs for each reinforcement geometry. The structural performance of the stainless steel reinforcement is fully

dependent on the glass-reinforcement adhesive bond. Failure of this adhesive bond will lead to complete collapse of the glass beam, since tensile (bending) forces cannot be transferred anymore. Enlarging the bond area between glass and reinforcement seems advantageous, since this will reduce shear stresses in the adhesive bond and will postpone or prevent adhesive failure. Geometry 3F has the largest bond area (3-face bond) and is expected to perform best.
A series of 10 specimens has been made of each reinforcement geometry and subsequently tested. To simultaneously investigate the effect of different glass-reinforcement adhesive bonds on the structural behaviour of the beam, each series consists of 5 specimens executed with an acrylic-based adhesive and 5 specimens executed with a two-component epoxy adhesive. The differences in structural behaviour between the three alternative *geometries* will be discussed in the next section (6.2). The differences in structural performance of both applied *adhesives* will be discussed in section 7.

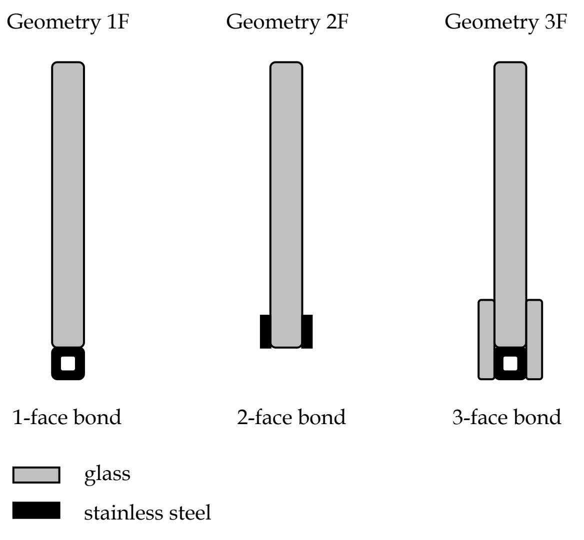
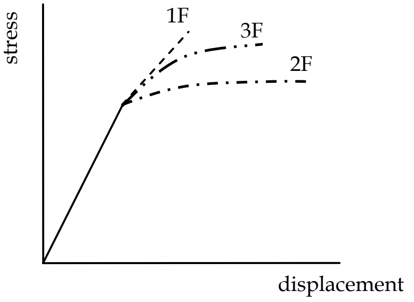


Figure 15: Alternative reinforcement geometries, which differ in 1-, 2- or 3-face bond.

*6.2 **Test results***

The specimens were subjected to a displacement controlled 4-point bend test. In this test setup supports were 1.4 m apart, loads were 0.4 m apart and lateral supports were provided at a distance of 0.5 m around mid-span (see Figure 17). The specimens were loaded at a rate of 1 mm/minute and loading was continued until total destruction. All specimens responded according to the general failure behaviour as described in section 4. The final failure mechanism, however, differed for each geometry. A schematic stress-displacement diagram of all three reinforcement geometries is given in Figure 16. The deformation capacity and remaining load carrying capacity after initial failure of each geometry is listed in table 1. A schematic overview of the crack propagation at different time steps is provided in Figure 21 and will be discussed in section 7.



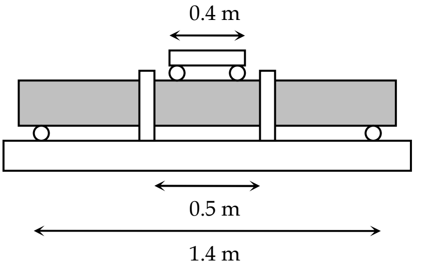


Figure 16: (left) Schematic stress-displacement diagram of the reinforcement geometries 1F, 2F and 3F.
Figure 17: (right) Schematic overview of 4-point bend test setup.

Table 1: Deformation capacity and remaining load carrying capacity after initial failure for all reinforcement geometries.

	Deformation capacity [$displacement_{ultimate}$ / $displacement_{initial\ failure}$ x 100%]	Remaining load carrying capacity [load $_{maximum}$ / load $_{initital\ failure}$ x 100%]
Geometry 1F	127 – 325%	75 - 194%
Geometry 2F	314 –775 %	85 - 164%
Geometry 3F	340 – 510%	126 - 184%

6.2.1 Geometry 1F

The stress-displacement diagrams of the geometry 1F – specimens for both adhesives are provided in Figure 18. Of the three tested geometries this geometry shows the most brittle behaviour. After initial failure a limited decrease in bending stiffness was observed and the beams were still able to carry increasing loads (maximum load was 75 – 194 % of initial failure load). The specimens showed a relatively small increase in vertical displacement of (127 – 325% of deformation at initial failure). For this geometry, all specimens failed due to detachment of reinforcement (adhesive failure). This can be explained by the limited bond area between glass and reinforcement, which leads to high shear stresses in the bond line. Unlike reinforcement geometry 2F, geometry 1F has no built-in redundancy, since it is fully dependent on one reinforcement section and one single bond line.

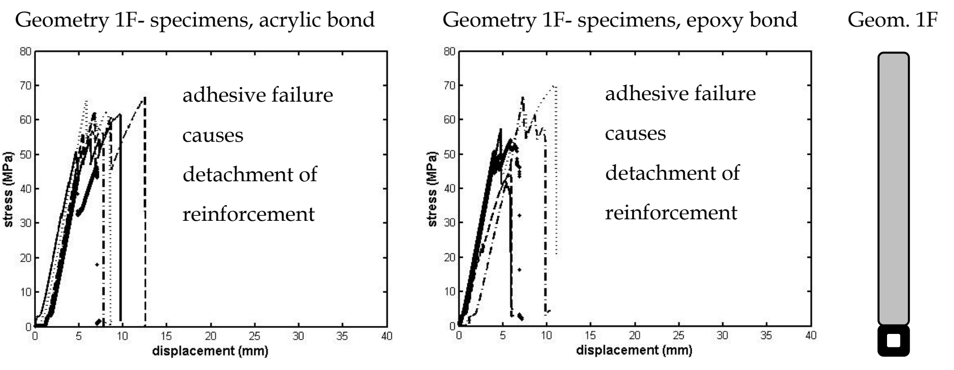


Figure 18: Stress-displacement diagrams of geometry 1F -specimens (for both adhesives).

6.2.2 Geometry 2F

The stress-displacement diagrams of the geometry 2F – specimens for both adhesives are provided in Figure 19. The geometry 2F – specimens showed an elastic ideal plastic behaviour. After initial failure bending stiffness was strongly reduced. The specimens showed a large deformation capacity (ultimate deformation was 314 – 775 % of deformation at initial failure), but only a small capability of carrying increasing loads (maximum load was 85 – 164 % of initial failure load). Final failure occurred due to either detachment of both reinforcement sections caused by adhesive failure or due to lateral torsional buckling caused by lateral instability of the compression zone.

An advantage of the application of two separate reinforcement sections is its built-in redundancy. For some specimens, one of the reinforcement sections detached at one beam end, causing a 50% drop in load. Total collapse of the beam, however, was prevented by the second reinforcement section, which was still attached to the beam.

A disadvantage of bonding the reinforcement sections to the side panes are the large deformations upon local glass-reinforcement debonding. Once the reinforcement started to detach at mid-span, the glass started to slide past the reinforcement, allowing for large deformations and large crack opening displacements. This limited the remaining load carrying capacity and not all specimens were able to carry loads exceeding the initial failure load.

6.2.3 Geometry 3F

The stress-displacement diagrams of the geometry 3F – specimens for both adhesives are provided in Figure 20. Geometry 3F – specimens showed elastic - strain hardening behaviour. After initial failure bending stiffness gradually decreased. The specimens showed a large deformation capacity (ultimate deformation was 340 –510% of deformation at initial failure) and a rather large capacity of carrying increasing loads (maximum load was 126-184% of initial failure load).

Small cracks, which occurred at initial failure, started to propagate horizontally and the upper compression zone started to separate from the lower tensile zone, causing a decrease in lateral stability of the compression zone. All specimens failed rather explosively due to buckling of the compression zone (see Figures 20 and 21).

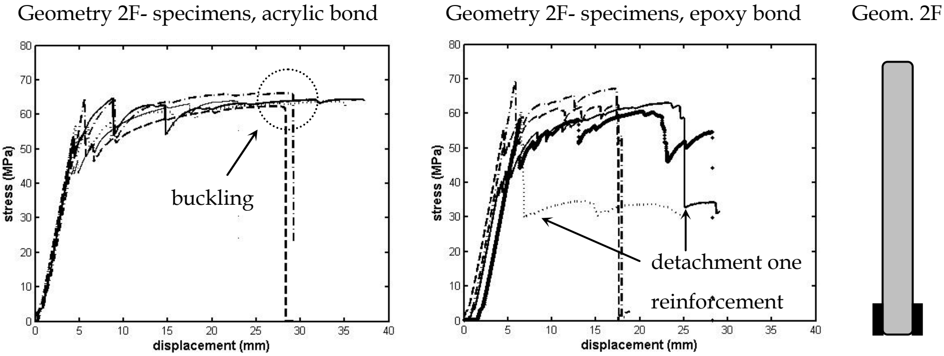


Figure 19: Stress-displacement diagrams of geometry 2F -specimens (for both adhesives).

Geometry 3F -specimens provided the most consistent test results. All specimens failed due to lateral instability and no detachment of reinforcement has been observed. Disregarding possible difficulties at the assembly process [Louter, 2006], this geometry seems to be the most favourable for the reinforced glass concept.

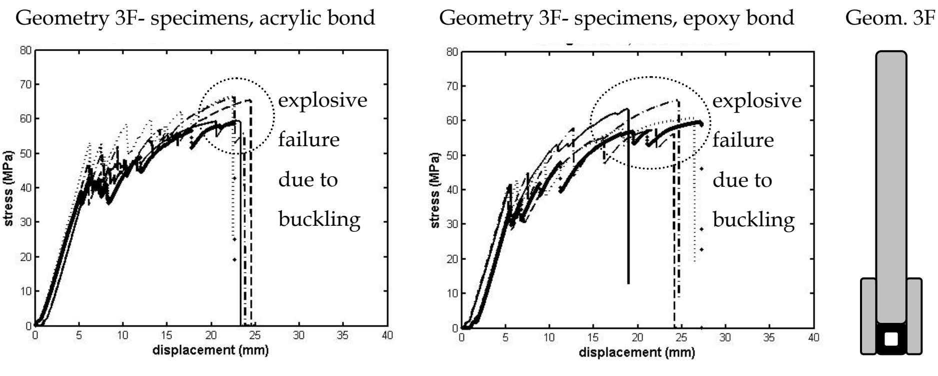


Figure 20: Stress-displacement diagrams of geometry 3F -specimens (for both adhesives).

7 Glass-reinforcement adhesive bond

To investigate the effect of different adhesive types on the post-initial failure behaviour of reinforced glass beams, the three alternative reinforcement geometries, as described in section 6.1, were tested for two different adhesives:

- An acrylic-based transparent photo-initiated curing adhesive DELO Photobond GB 368 [DELO], which shows brittle failure. Specimens manufactured with this adhesive are referred to as acrylic-bond specimens.
- A two-component epoxy Araldite 2013 [Huntsman], which is a rather tough and shock resistant adhesive. Specimens manufactured with this adhesive are referred to as epoxy-bond specimens.

The test results will be discussed in the following sections.

*7.1 **Test results***

Of each reinforcement geometry a separate stress-displacement diagram of the acrylic-bond and the epoxy-bond specimens is provided in Figures 18, 19 and 20. These stress-displacement diagrams do not show significant differences in initial and ultimate failure stress between the adhesive-bond and the epoxy-bond specimens of each reinforcement geometry. However, a difference in crack propagation and crack branching was observed during the tests. A general and schematic overview of the crack propagation at different time steps (1=initial failure, to 4=ultimate failure) per geometry for both adhesives is provided in Figure 21. Two different fracture patterns can be distinguished:

- Horizontally orientated crack branching
  The acrylic-bond specimens show a rather horizontally orientated and widely extended fracture pattern of *few* but *large* V-shaped cracks.
- Dense fracture pattern
  The epoxy-bond specimens show a rather dense fracture pattern of *many* but *small* un-extended cracks, which are more or less unrelated.

This difference in crack branching was caused by a difference in toughness and shock resistance of both adhesives. For the acrylic-bond specimens, local debonding of reinforcement was observed at the crack tips. Shock loads, which occurred upon glass failure, caused the adhesive to fail along several centimeters on either side of the crack tip. This local debonding of reinforcement allowed for large crack opening displacements and consequently extensive horizontal crack propagation.

Due to the higher toughness of the epoxy bond local debonding occurred to a much lesser extend, allowing for only limited crack opening displacements and limited crack propagation.

Stresses are more evenly (re)distributed, which allows for the occurrence of many small cracks along the lower edge of the beam.

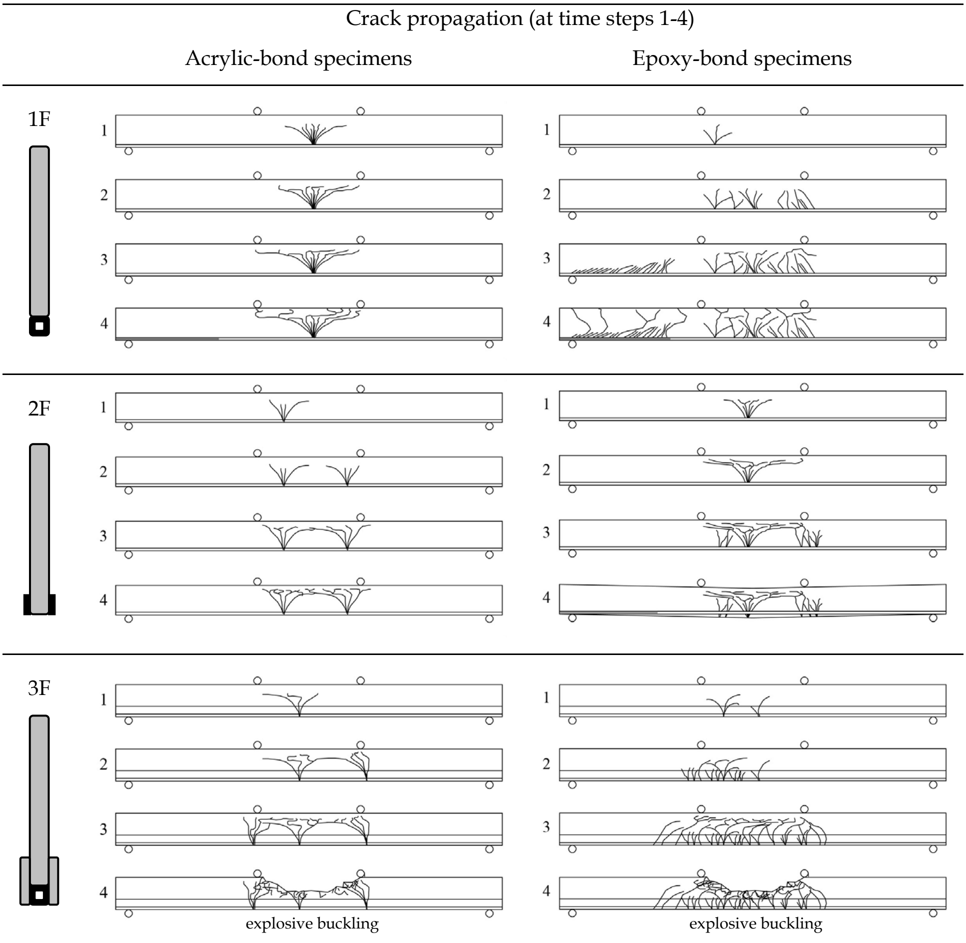


Figure 21: Schematic overview of crack propagation at different time steps (1-4) for both adhesives and all reinforcement geometries. (1 = initial failure 4 = ultimate failure)

This research into the effect of different adhesives on the failure behaviour of reinforced glass beams has only been executed for *single* layer glass beams. A large span reinforced glass beam, however, will consist of *multiple* overlapping glass layers (see section 3). For a multilayer glass beam, the occurrence of many small cracks, as has been observed for the epoxy-bond specimens, might be more advantageous since this will affect the lateral stability to only a limited extend. Horizontal crack branching (as has been observed for the acrylic-bond specimens), however, causes the upper compression zone to separate from the lower tensile zone. This will strongly reduce the lateral stability of the compression zone and might cause a collapse of the beam in an early failure stage. Future research at Delft University of Technology will focus on this aspect for multilayer glass beams.

8 Summary

Since glass can only deform elastically or fracture, it has no built-in redundancy. Safety concepts and redundancy are therefore key aspects in structural glass engineering. Glass failure should never lead to complete collapse of the structure.

The 'adhesively bonded reinforced glass beam' concept offers a demonstrably safe construction method for large span structural glass components with built-in redundancy and high structural safety. Rather than minimizing the *probability* of any glass failure by adding protective outer layers to the beam laminate, it focuses on the *consequences* of any glass failure and seeks ductile and controlled failure behaviour.

Safe large span glass beam are composed of multiple adhesively bonded overlapping annealed float glass segments and a stainless steel reinforcement section. The structural behaviour of these adhesively bonded reinforced glass beams is influenced by the following aspects:

- Cross-section geometry

  Several cross-section geometries can be realized by bonding glass panes perpendicular or in overlap, for instance box-, T- or full sections can be realized. An important aspect is the lateral stability of the cross-section. For an appropriate design of the cross-section geometry, the lateral stability of both uncracked and cracked cross-sections has to be considered. Although the cross-section is not prone to buckling in the uncracked stage, it might become laterally instable due to decreased cohesion of the glass by excessive (horizontal) crack growth. Whether the lateral stability of the beam can effectively be improved by enlarging the compression zone will be examined in future research at Delft University of Technology.

- Reinforcement geometry

  The reinforcement section can be integrated in the beam cross-section geometry in several manners. It can, for instance, be bonded at the edge or to the side panes of the glass beam or it can be integrated in the beam web. Integrating the reinforcement in the web of the beam is the most advantageous option from a structural point of view. The reinforcement is encapsulated by glass panes and its structural performance depends on a favourable 3-face bond. Research into this specific geometry (geometry 3F) showed the most consistent results without any detachment of reinforcement. However, this reinforcement geometry might cause manufacturing difficulties due to dimensional inaccuracies. A consistent structural quality of the adhesive bond is hard to ensure since the thickness of the adhesive bond is fully dependent on a dimensional match between the reinforcement and the inner glass layer(s) [Louter, 2006]. Future research will focus on this aspect.

- Glass-reinforcement adhesive bond

  The interaction between glass and reinforcement is fully dependent on the adhesive bond. Failure of this adhesive bond will lead to collapse of a cracked beam, since the tensile forces cannot be transferred anymore.

  The research into the effect of two different adhesives (acrylic and epoxy bond) on the structural failure behaviour of a reinforced glass beam showed that the toughness and shock-resistance of the applied adhesive are of great importance. An adhesive which is limited resistant to shock load and less tough will fail, due to the shock load upon glass failure, along several centimeters on either side of the crack origin allowing for large crack opening displacements and extensive (horizontal) crack growth. Due to extensive horizontal crack branching, the upper compression zone will separate from the lower tensile zone. This will strongly reduce the lateral stability of the compression zone and might cause a collapse of the beam in an early failure stage.

  In this respect, the application of the researched tough and shock-resistant epoxy-bond seems more favourable, since the epoxy-bond specimens showed many small cracks instead of widely extended horizontal branches.

The results of the researches into the aspects mentioned above will be implemented in the further development of an 18 m beam reinforced glass beam, which will be constructed and tested to validate the 'adhesively bonded reinforced glass beam' concept for large span beams. Furthermore, these results will be implemented in design and calculation methods for adhesively bonded reinforced glass beam. Based on these methods, which will be developed in following research, an appropriate cross-section geometry, reinforcement geometry, glass-reinforcement bond and segmentation scheme can be determined for adhesively bonded reinforced glass beams applied in specific structures.

9 Conclusions

General concept

- The 'adhesively bonded reinforced glass beam' concept offers a demonstrably safe construction method for large span structural glass components with built-in redundancy and ductile failure behaviour.

Cross-section geometry

- Several cross-section geometries can be realized by bonding glass panes perpendicularly or in overlap.
- Lateral torsional buckling is an important aspect in the cross-section design. Although not decisive at first instance, lateral torsional buckling might become critical for slender full section beams, as extensive (horizontal) crack growth occurs.

Reinforcement geometry

- Integration of the reinforcement in the web of the beam is advantageous from a structural point of view, since its structural performance depends on a favourable multi-face bond.
- The application of multiple reinforcement sections provides extra redundancy, since a single reinforcement section can still transfer tensile force in case the others detach from the glass.

Glass-reinforcement bond

- A glass-reinforcement bond which is limited resistant to shock loads and shows low toughness, will locally detach upon glass failure, causing large crack opening displacements and large horizontal crack branching .
- Large horizontal crack branching will cause separation of the compression and tensile zone and will lead to collapse of the beam due to lateral instability of the compression zone.

Acknowledgement

The author wishes to acknowledge the support of the Van Noordenne groep in providing the glass needed for the research projects.

References

Belis, J. (2006) *Kipsterkte van monolithische en gelamineerde glazen liggers*' Dissertation Ghent University: Laboratory for Research on Structural Models ,

Belis, J, Louter, PC, Verfaille, K, Impe, R, & Callewaert, D, (2006). 'The effect of post-tensioning on the buckling behaviour of a glass T-beam' In G Siebert (Ed.), *International symposium on the application of architectural glass ISAAG 2006 : conference proceedings* (pp. 129-136). Munich: Universität der Bundeswehr.

Betsch, 'Courtyard Roof Covering in Munich', journal *DETAIL Review of Architecture*, series 2004-10, pp. 1145-1148

Bos, FP,Veer, FA,Hobbelman, GJ, & Louter, PC (2004) 'Stainless steel reinforced and post-tensioned glass beams' in C Pappalettere (Ed.), *International conference on experimental mechanics / icem12 / advances in experimental mechanics* (pp. #1-#9). Bari: Politecnico di Bari.

Bos, FP,Veer, FA,Hobbelman, GJ, Romein, T, Nijsse, R, Belis, J, Louter, PC, & Nieuwenhuijzen, EJ van (2005) 'Designing and planning the world's biggest experimental glass structure' In J Vitkala (Ed.), *Glass processing days* (pp. 401-405). Tampere: GPD.

Delo Industrial Adhesives 'Technical Information DELO-PHOTOBOND GB368' Landsberg www.delo.de

European Standard EN 572-2 (2004) 'Glass in Building –Basic Soda lime silicate glass products – part 2: Float glass'

Flinterhoff, A. (2003) 'Load carrying behaviour of hybrid steel-glass beams in bending' Master Thesis. University of Dortmund. Institute of Steel Construction.

Freytag, B. (2004) 'Glass-Concrete Composite Technology', in *Structural Engineering International 2/2004*, pp. 111-117

Grotepaß, B. (2006) 'Application of hybrid steel-glass beams in modern architecture' Master Thesis. University of Dortmund. Institute of Steel Construction

Hamm, J. (2000) *Tragverhalten von Holz und Holzwerkstoffen im statischen Verbund mit Glas*, PhD Thesis Nr. 2065, IBOIS/EPFL

Huntsman 'Araldite 2013 AV144-2/HV997 Two-component epoxy paste adhesive' Cambridge, www.araldite.com

Kasper, A (2003) 'Fundamentals of Spontaneous Breakage Mechanism Caused by Nickel Sulfide', In J Vitkala (Ed.), *Glass processing days* (pp. 696-698). Tampere: GPD

Kreher, K. (2004) *Tragverhalten und Bemessung von Holz-Glass-Verbundträgern unter Berücksichtigung der Eigenspannungen im Glas*, PhD Thesis Nr. 2999, IBIOS/EPFL 2004

Kreher, K, Natterer Jul., Natterer, Joh. (2004) '*Timber-Glass-Composite Girders for a Hotel in Switzerland*', in *Structural Engineering International 2/2004*, pp. 149-151

Louter, P.C., Veer, F.A., Hobbelman, G.J. (2007) 'Reinforcing glass, effects of reinforcement geometry and bonding technology', *Glass Performance Days 2007*, www.glassfiles.com Tampere, Finland

Louter, PC, Herwijnen, F van, Schetters, L, Romein, T, & Veer, FA (2006) 'Experimental research on scale 1:8 models of an 18 m reinforced glass beam' In G Siebert (Ed.), *International symposium on the application of architectural glass ISAAG 2006 : conference proceedings* (pp. 215-222). Munich: Universität der Bundeswehr.

Louter, PC, Belis, J, Bos, FP, Veer, FA, & Hobbelman, GJ (2005) 'Reinforced glass cantilever beams'. In J Vitkala (Ed.), *Glass processing days* (pp. 429-433). Tampere: GPD.

Palumbo, M. (2005) ‘A New Roof for the XIIIth Century “Loggia de Vicari” (Arquà Petrarca -PD – Italy) Based on Structural Glass Trusses: a Case Study’, In J Vitkala (Ed.), *Proceedings Glass processing days*. Tampere: GPD

Schittich, C., Staib, G., Balkow, D., Schuler, M., Sobek, W. (1999) *Glass Construction Manual*, Basel: Birkhäuser.

Shelby, J.E., (2005) *Introduction to Glass Science and Technology*, Cambridge: The Royal Society of Chemistry

Siebert, B. (2003) ‘Calculation of Point Bearings for Glass as Load-Bearing Element in Structural Engineering, In J Vitkala (Ed.), *Glass processing days* (pp. 758-761). Tampere: GPD

Veer, FA, Riemslag, AC, & Ting, CN (2001). ‘Structurally efficient glass laminated composite beams’ In J Vitkala (Ed.), *Glass Processing Days* (pp. 363-367). Tampere, Finland: Glass Processing Days/Tamglass Ltd.Oy. (TUD)

Veer, FA, Gross, S,Hobbelman, GJ, Vredeling, M, Janssen, MJHC, Berg, R van den, & Rijgersberg, HA (2003) ‘Spanning stuctures in glass’ In J Vitkala (Ed.), *Glass processing days / educational glass conference* (pp. 78-81). Tampere, Finland: Glass processing days / tamglass ltd.Oy.

Veer, FA, Sluis, MMA van der, Hobbelman, GJ, & Zuidema, J (2003) ‘The use of glass in concrete as reinforcement and aggregate’ In SR Bodner (Ed.), *9th Int. Conf. on the Mechanical Behaviour of Materials (ICM9), Geneva, Switzerland, May 25-29, 2003.* (pp. 1-6). ICM9.

Veer, FA, & Zuidema, J (2003) ‘The strenght of glass, effect of edge quality’ In J Vitkala (Ed.), *Glass processing days / educational glass conference* (pp. 106-109). Tampere, Finland: GPD.

Veer, FA, Bos, FP,Zuidema, J, & Romein, T (2005). ‘Strength and fracture behaviour of annealed and tempered float glass’ In A Carpinteri (Ed.), *11th International conference on fracture Turin (Italy)* (pp. 1-6). Torino: Politecnico di Torino.

Veer, FA (2005) ‘10 years of zappi research’ In J Vitkala (Ed.), *Glass processing days* (pp. 424-428). Tampere: GPD.

Veer, FA, Richemont, S de, Kranenburg, C van, & Zuidema, J (2006) ‘Fatigue of photo catalytic adhesives in direct tension and shear’ In SN (Ed.), *Proc. 9th International Fatigue Congress, Atlanta, USA* (pp. 1-10). S.l.: Elsevier.

Veer, FA (2006) ‘The strength of glass, a non-transparent value’ Heron this issue.

Weller, B., Wünsch, J., Härth, K. (2005) ‘Experimental Study on Different Interlayer Materials for Laminated Glass’, In J Vitkala (Ed.), *Glass processing days* (pp. 120-123). Tampere: GPD.

Wellershoff F., Sedlacek G., (2003) ‘Structural Use of Glass in Hybrid Elements, Steel-Glass-Beams, Glass-GFRP-Plates’, In J Vitkala (Ed.), *Glass processing days* (pp. 268-270). Tampere: GPD