Performance of Sentry-Glas-laminated metal-reinforced glass beams at 23, -20, and 60 ºC

Citation for published version (APA):
Louter, P. C., Bos, F. P., Callewaert, D. D., & Veer, F. A. (2009). Performance of Sentry-Glas-laminated metal-reinforced glass beams at 23, -20, and 60 ºC. In *Proceedings of the Glass Performance Days 2009* (pp. 334-339)

Document status and date:
Published: 01/06/2009

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 28. Oct. 2021

Performance of SentryGlas-laminated metal-reinforced glass beams at 23, -20 and 60°C.

Christian Louter [a], Freek Bos [a], Dieter Callewaert [b], Fred Veer[a]
[a] Delft University of Technology, Faculty of Architecture www.glass.bk.tudelft.nl, p.c.louter@tudelft.nl,
[b] Ghent University, Laboratory for Research on Structural Models (LMO)

Keywords:
1=reinforced 2=beam 3=SentryGlas 4=interlayer 5=temperature 6=redundancy.

Abstract

To validate the novel concept of laminating a metal reinforcement to a glass beam using a SentryGlas (SG) interlayer, a series of bending tests has been performed at 23, -20 and 60°C on 1.5 m SG-laminated metal-reinforced glass beams. The beams consisted of three glass layers with a stainless steel box section laminated in between the glass at the lower edge. The test results showed high redundancy of the beam specimens at all tested temperature levels. However, the specific response of the beam specimens varied at different temperature levels. At 23°C the beam specimens showed the highest residual strength, whereas the residual strength was reduced at both -20 and 60°C. This difference in response was caused by a difference in glass cracking behaviour and the occurrence of plastic hinges in the beams. These plastic hinges limited the residual strength of the beam and probably originated from a more brittle response of the SG at -20°C and a lower metal-to-glass bond strength of the SG at 60°C. Since the SG-laminated metal-reinforced glass beams showed promising results, future research at TU Delft will further explore the possibilities of this concept.

Introduction

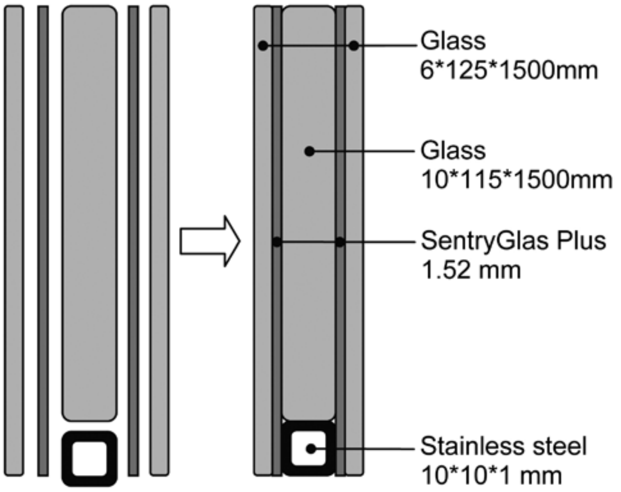
Within the ongoing research at Delft University of Technology (TU Delft) on reinforced glass beams [1], research has now focused on the possibilities of bonding a metal reinforcement to a glass beam using a SentryGlas (SG) interlayer. This ionoplast interlayer, which has originally been developed by Dupont for hurricane, vandalism and burglary resistant glazing, offers the possibility of laminating metal to glass with significant bond strength. The potential of this high metal-to-glass bond strength has been exploited in various projects, amongst which the Apple Store stairs [2] and the Seele staircase at Glastec 2007.

To validate the concept of laminating a metal reinforcement to a glass beam, a series of bending tests has been performed on small scale (1.5 m) SG-laminated metal-reinforced glass beams. Since SG is a visco-elastic material, which strength and stiffness is besides load duration dependent on temperature level, the bending tests have been performed at 23°C (room temperature), -20°C and 60°C. As can be seen in table 1, which lists the material properties of SG at room temperature, SG has a glass transition temperature of ~55-60°C. At higher temperature levels the strength and stiffness of the SG will decrease and at lower temperature levels its stiffness increases and the SG might become more brittle. The bending tests will show whether these changing material properties affect the structural response of the SG-laminated metal-reinforced glass beams.

Parallel to the bending tests, a series of pull-out tests has been performed on small SG laminates with a metal insertion. These pull-out tests, which have also been performed at 23, -20 and 60°C, show a clear reduction in bond strength of 60% at 60°C compared to 23°C. However, no significant change in bond strength at -20°C could be determined, since the failure of the SG bond was probably dominated by unfavourable stresses caused by contraction of the metal insertion, which reached its maximum tensile strength. The full results are presented by Louter at this conference in [3].

Figure 1:

Exploded and assembled view of the cross section of the SentryGlas-laminated metal-reinforced glass beam specimens.



The current paper on the bending tests on SG-laminated metal-reinforced glass beams forms an extension to the preliminary results published by Louter et al. in [4].

Property	Unit	SentryGlas
Tensile strength	N/mm^2	34.5
Elastic modulus	N/mm^2	300
Glass aluminum shear strength	N/mm^2	unknown
Glass transition temperature	°C	~55-60
Elongation at tear	%	400
Density	kg/m^3	950
Coefficient of thermal expansion	x 10^{-3} K^{-1}	10-15

Table 1:

Material properties of SentryGlas at room temperature derived from [5].

Manufacturing of the SentryGlas-laminated metal-reinforced glass beam specimens

Three series of five SG-laminated metal-reinforced glass beam specimens have been manufactured for this research. All beam specimens were manufactured according to the layout provided in figure 1. The 1.5 m beam specimens consisted of two outer glass layers of 6*125*1500 mm and an inner glass layer of 10*115*1500 mm. A 10*10*1 mm stainless steel reinforcement section has been positioned at the edge of the inner layer between both outer layers. The specimens have been laminated using a single sheet of 1.52 mm SG between the glass layers. The metal reinforcement has only been laminated to both outer glass layers and not to the inner glass layer. The beam specimens have been manufactured using a conventional vacuum bag lamination technique, see figure 2.

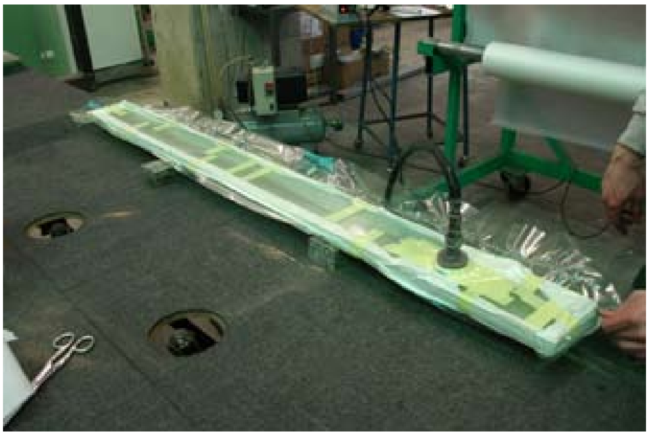


Figure 2:

Manufacturing of the SentryGlas specimens using a vacuum bag technique.

Bending test setup at 23, -20 and 60°C

The three series of beam specimens have been tested in four-point bending at either 23, -20 or 60°C. For each temperature level the test equipment differed, but in all test setups the spans were the same; namely a support span of 1400 mm, a load span of 400 mm and a lateral support span of 550 mm, see figure 3.

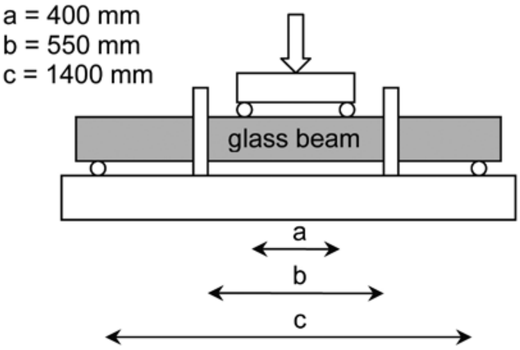


Figure 3:

Bending test setup

The bending tests at room temperature (23°C) were performed at a Zwick Universal 100 kN test machine which was provided with an additional support frame for the beam specimens. The beam specimens were loaded in a first test run at a rate of 2 mm/minute until initial failure occurred. Upon initial failure the load was removed in order to investigate the fracture pattern. Afterwards the specimens were loaded in a second test run at a rate of 5 mm/minute. During the tests the inflicted force and the displacement of the crosshead have been measured.

The bending tests at -20°C have been performed at an Instron 1195 test machine, which has been provided with a custom made insulated wooden climatic chamber, see figure 4. The wooden chamber has been cooled with vaporized liquid nitrogen. The test temperature, which was controlled by opening or closing a valve, was manually targeted at -20°C (±5°C). During the bending tests the load was applied at a rate of 2 mm/minute. During the tests the inflicted force and the displacement of the crosshead has been measured. Prior to the bending tests the beam specimens were conditioned for 1 week in a fridge at -30°C (±3°C). The conditioning temperature has been selected 10 degrees lower than the test temperature to compensate for any heat gain during transport and mounting of the specimen in the test setup, which took about 5 minutes per specimen.

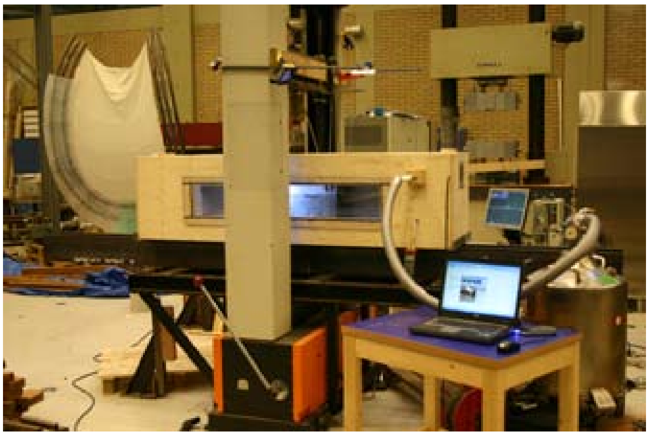


Figure 4:

Bending test setup with a wooden climatic chamber, which has been cooled with vaporized liquid nitrogen to -20°C.

The bending tests at 60°C were performed in a climatic chamber at Ghent University. Prior to the bending tests the beam specimens were stored for at least 36 hours at 60°C in the same climatic chamber, see figure 5. Since both conditioning and testing took place in the same chamber no temperature difference occurred in transporting and mounting the specimens in the test setup. In the test setup the load was applied manually

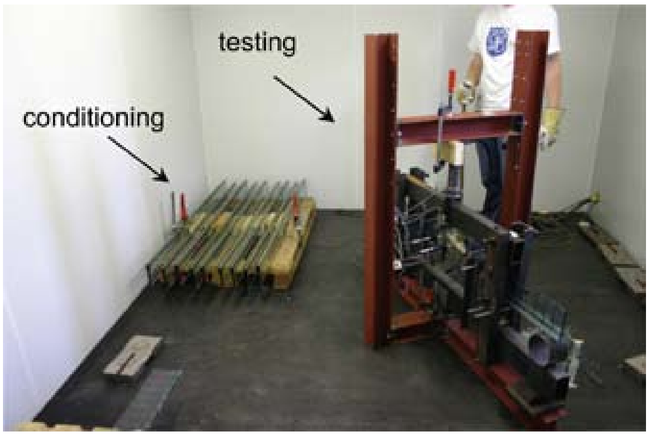


Figure 5:

Climatic room at Ghent University. Conditioning and testing at 60°C within the same space.

	unit	23°C	-20°C	60°C
Initial failure load	kN	11.7	16.1	9.1
st. dev.	kN	1.1	1.8	1.3
rel st. dev.	%	9.5	11.2	14.4
Initial failure stress*	N/mm²	50.0	68.8	38.9
st. dev.	N/mm²	4.8	7.7	5.6
rel. st. dev.	%	9.5	11.2	14.4
Crack height**	% / height	73	62.4	80
st. dev.	% / height	1.8	10.0	4.9
rel. st. dev.	%	2.5	16.1	6.1
Residual strength	kN	17.5	15.4	14.3
st. dev.	kN	0.5	0.9	0.5
rel. st. dev.	%	2.8	5.6	3.7
Rel. res. strength ***	% / initial	150	96.4	159.1
st. dev.	% / initial	12.0	7.7	22.7
rel. st. dev.	%	7.7	7.9	14.2

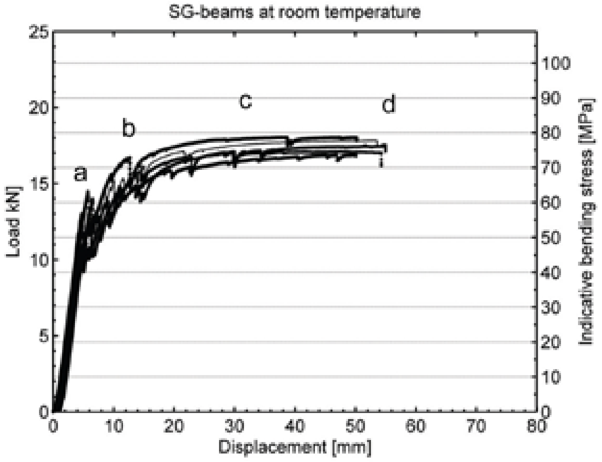
Table 2:

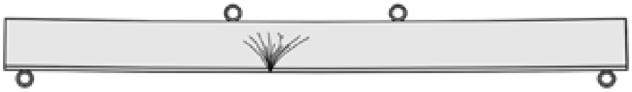
Average results of three series of 5 bending tests at 23, -20 and 60°C.

** calculated at the lower edge of the glass; **(crack height / beam height) * 100%; *** (residual strength / initial strength) * 100%*

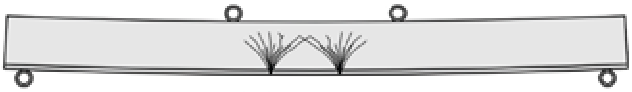
Figure 6:

Load-displacement diagram and cracking sequence of the beams tested at 23°C.

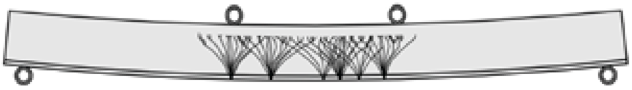




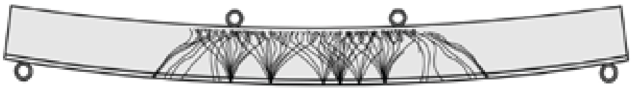
a. Initial glass failure at 11.7 kN (50.0 MPa);
A dense V-shaped crack occurs.



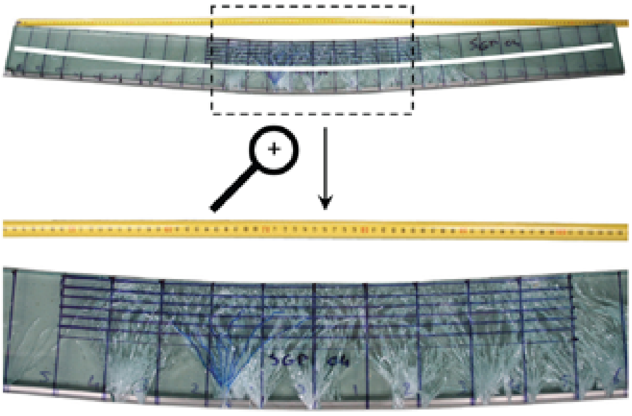
b. Additional cracking;
The compression zone remains uncracked.



c. Additional cracking and crack propagation;
compression zone height reduces.



d. Final stage; test stopped, limit of test rig reached;
The beam shows an evenly distributed crack pattern.



Overview and close up of a beam tested at 23°C.

using a hydraulic jag. The inflicted force and the displacement, which was measured at mid-span using an extensometer (LVDT), have been recorded.

Bending test results

The results of the bending tests are presented in figures 6, 7 and 8, which show both the load-displacement diagrams and an indicative cracking sequence marked as “a) initial failure” to “d) final stage.” This cracking sequence is also referred to in the load-displacement diagrams. Table 2, shows the average numerical test results. The following sections will discuss the results by temperature level.

Results at 23°C

The beam specimens tested at room temperature showed linear elastic response until initial glass failure (stage a) occurred at an average load of 11.7 kN, see figure 6, which corresponds with a global tensile bending stress of 50.0 N/mm². A rather dense V-shaped crack occurred in the glass, which on average travelled 73% of the beam height leaving a compression zone of about 35 mm uncracked. The initial crack generally occurred in only one glass layer leaving the other glass layers undamaged.

As the specimens were reloaded during the second test run additional cracking occurred (stage b), repetitively causing a drop in load. Furthermore, the cracks started to extend towards the compression zone, thereby gradually causing a reduction in height of the compression zone. The combination of this reduction of the compression zone and plastic deformation of the reinforcement section caused a gradual reduction of beam stiffness (stage c), as is shown by the load-displacement diagram.

Although the beam specimens were severely cracked they were still able to carry increasing loads up to an average value of 17.5 kN, which is about 150% of the initial failure load. Although the beam specimens had not collapsed at a displacement of 50-55 mm, the tests were stopped since at this point the deformation limit of the test setup was reached (stage d).

After removing the specimens from the test setup the specimens were visually inspected. The specimens were extensively cracked, but the cracks were more or less evenly divided along the length of the beam. No significant debonding or delamination at the metal reinforcement was observed.

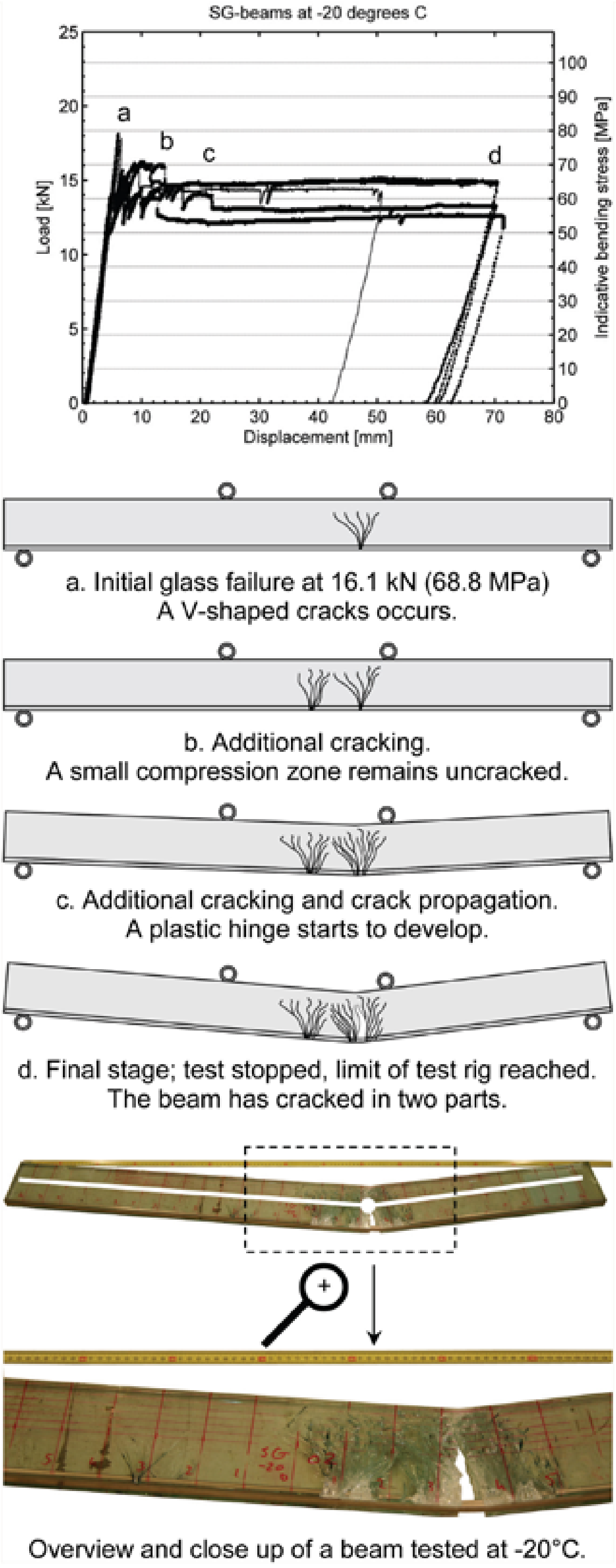
Results at -20°C

The beam specimens tested at -20°C showed an average initial failure load of 16.1 kN, see figure 7, which corresponds with a global tensile bending stress of 68.8 N/mm^2. Similar to the room temperature tests an initial V-shaped crack occurred which on average travelled 62% of the beam height (stage a). The crack generally occurred in only one glass layer leaving the other glass layers uncracked. As loading was continued the residual strength remained limited to 96% of the initial failure strength. Some additional cracks occurred (stage b), which often ran through multiple glass layers. The cracks gradually started to extend towards the compression zone and at a displacement of about 20 mm one of the more severe cracks started to open up (stage c). This specific crack ran through all glass and SG layers. The SG showed brittle failure without any plastic deformation capacity. Due to the large crack opening displacement the beam started to develop a plastic hinge. The metal reinforcement started to yield and the applied load stabilized at an average of about 14 kN, see figure 7. Although the beam specimens had not collapsed at a displacement of 70 mm, the tests were stopped, since at this point the deformation limit of the test setup was reached (stage d).

After removing the specimens from the test setup the specimens were visually inspected. In general the beams showed less cracks than the beams tested at room temperature. Furthermore, they were clearly cracked up in two parts, see figure 7. The beams showed debonding of the metal reinforcement along 10-15 cm on either side of the major crack.

Figure 7:

Load-displacement diagram and cracking sequence of the beams tested at -20°C.



Results at 60°C

At 60°C the beam specimens showed an average initial failure load of 9.1 kN, see figure 8, which corresponds with a global tensile bending stress of 38.9 N/mm^2. Upon initial failure a V-shaped cracked occurred (stage a), which on average travelled 80% of the beam height. After a drop in load the load increased again and briefly exceeded the initial failure load by 60%. Some additional cracks occurred (stage b). The cracks started to extend towards the compression zone and the beam stiffness gradually decreased. The applied load stabilized at an upper loading level of about 14 kN, see figure 8 (stage c). At a displacement of 70 mm the tests were stopped since the deformation limit of the test setup was reached (stage d). At the end of the loading procedure the load-displacement diagram shows some sudden increases in load (see figure 8), caused by a rapid increase of the applied displacement rate. These load peaks, however, should be disregarded in the further analysis of the test results.

Visual inspecting of the beam specimens showed debonding or delamination of the metal reinforcement along several centimetres on either side of the crack origins, see figure 9. Furthermore, the specimens showed less cracks than the beams tested at room

Figure 8:

Load-displacement diagram and cracking sequence of the beams tested at 60°C

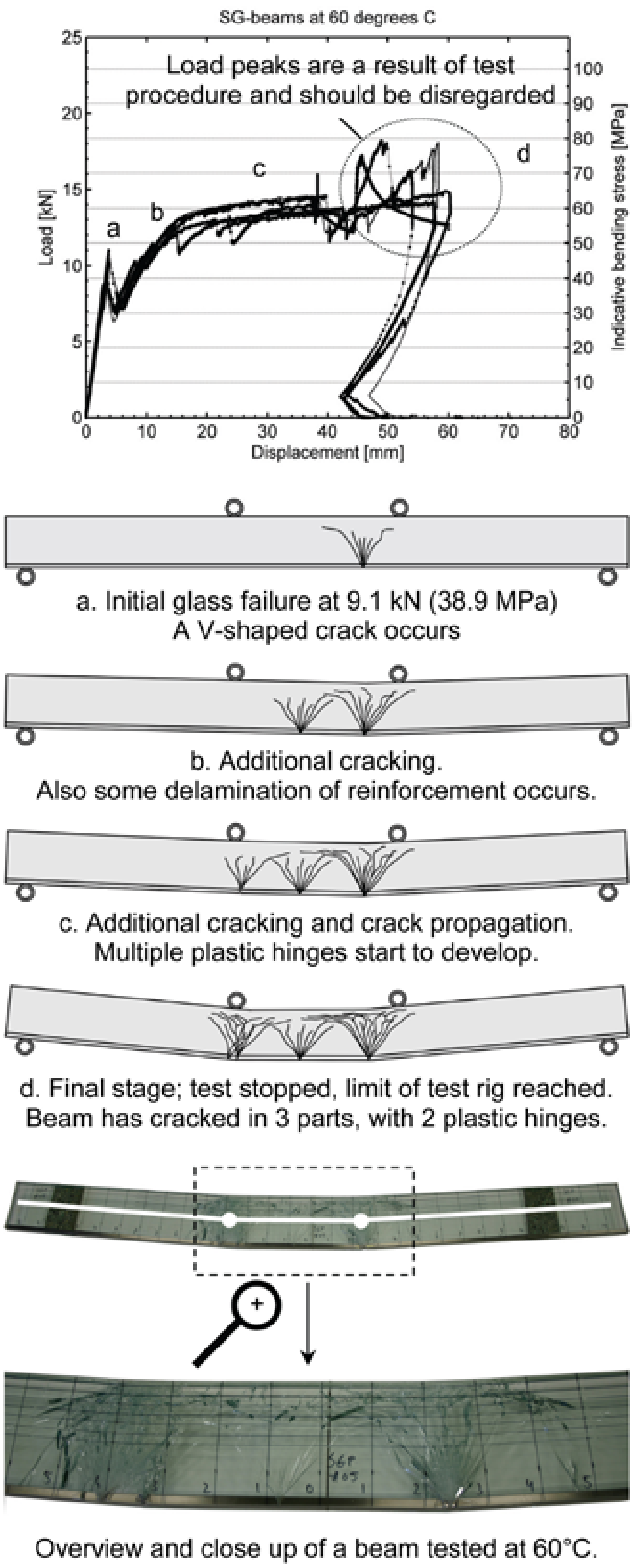


Figure 9:

Delamination of the metal reinforcement at 60°C.

temperature and were cracked up in three parts, see figure 8.

Discussion

The results of the bending tests performed at 23, -20 and 60°C on SG laminated metal-reinforced glass beams showed that laminating a metal reinforcement to a structural glass beam using SG is a feasible and promising concept, which generates a high level of redundancy even at extreme temperature conditions. The metal-to-glass bond, generated by the SG interlayer, is strong enough to transfer the forces between glass and reinforcement once the glass has cracked and the reinforcement is activated. However, significant differences in the structural response at 23, -20 and 60°C have been observed.

At 23°C the beam specimens performed best. They showed a residual strength of 150% of the initial failure strength and reached an average ultimate loading level of 17.5 kN. This loading level even exceeds the theoretical post-failure strength of the beam specimens, which is assumed to be mainly generated by a tensile force in the reinforcement and a compression force in the uncracked upper glass compression zone, see figure 10. When we consider a maximum tensile strength of 31.6 kN of the metal reinforcement, adopted from figure 11, and a theoretical maximum internal lever arm between tensile and compression force of 0.12 m (see figure 10), the theoretical maximum moment capacity of the beam specimens amounts 31.6*0.12 = 3.8 kNm, which equals a load of 15.2 kN within the used test setup. The difference between the theoretical maximum residual strength of 15.2 kN and the determined strength of 17.5 kN must have been generated by an additional load carrying mechanism. As suggested by Bos in [6], an additional load carrying mechanism is generated by glass fragments overlapping local cracks in the glass. Since the SG interlayer acts as a crack barrier, a crack will only affect one glass layer of the beam laminate. The other layers will remain (locally) uncracked and will bridge the crack, thereby transferring tensile forces through shear in the SG interlayer. As long as cracks do not coincide, which is initially prevented by the crack stopping properties of the SG interlayer, the overlapping glass segments provide a significant additional load carrying capacity. Furthermore, due to the high bond strength of the SG at room temperature, the beam specimens did not show any debonding of reinforcement. This enabled the reinforcement to effectively arrest cracks and to limit crack growth in the glass, which enhanced the residual strength of the beams.

At -20°C the residual load carrying capacity was significantly less than at room temperature. At room temperature the beams showed a residual strength up to 17,5 kN,

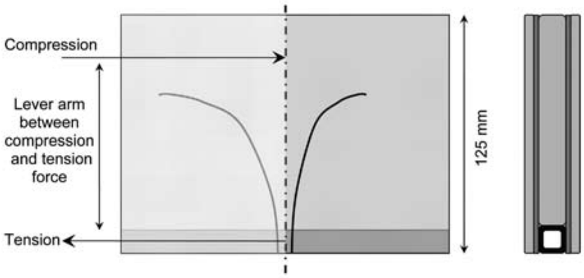


Figure 10:

Schematic representation of the main post-failure load carrying mechanism.

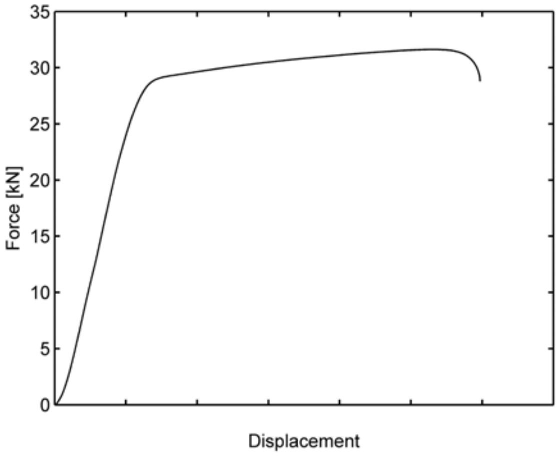


Figure 11:

Force-displacement diagram of a tensile test on the metal reinforcement.

whereas at -20°C the residual strength stabilized at a load of about 14 kN. This difference is caused by a difference in cracking behaviour. Whereas the beam specimens tested at 23°C showed an evenly distributed crack pattern along the length of the beam, the beams at -20°C clearly showed concentrated crack growth and the development of a plastic hinge, see figure 7. The capacity of this hinge was limited by the tensile capacity of the metal reinforcement, which started to yield and caused the applied load to stabilize around a value of 14 kN. At this loading level the applied bending moment amounts 3.5 kNm. If we assume an internal lever arm, see figure 10, of 0.115 m, which has been observed during the tests, this bending moment generates a tensile force in the reinforcement of 3.5/0.115 = 30,4 kN, see figure 10. As can be seen in figure 11 this loading level is well within the yielding stage of the reinforcement and approaches its maximum tensile strength.

The occurrence of the concentrated crack growth and the plastic hinge might have been caused by the increased brittleness of the SG at -20°C. Due to its increased brittleness the SG could less effectively function as a crack barrier, thereby enabling cracks to growth through the full width of the beam laminate. This effect might have been further enlarged by a high energy release upon glass failure, due to a relatively high initial failure strength of the -20°C beam specimens, see table 2.

Also at 60°C the residual strength of the beams is less than at room temperature. Again this is probably caused by a change in properties of the SG. At 60°C the bond strength of the SG decreased [3], which caused local debonding of the reinforcement section along several centimetres on either side of a crack origin. Due to this local debonding of reinforcement the cracks could not be arrested as effectively as at room temperature. Furthermore, the cracks in the glass could open up further than at room temperature and, although not as severe as at -20°C, multiple glass hinges started to develop. As can be seen in figure 8, the beams cracked up in three parts due to the presence of two plastic hinges. The plastic hinges limited the load carrying capacity of the beams, which stabilized at a load of 14.3 kN.

Besides a difference in post-failure response, the beam specimens also showed a significant difference in initial failure strength. The room temperature beams showed average initial failure strength of 11.7 kN, whereas the -20 and 60°C specimens showed an initial failure strength of 16.1 kN and 9.1 kN respectively. Although this difference is theoretically in line with an increased stiffness of the SG at low temperature levels and a decreased stiffness at increased temperature levels, its seems unlikely that the SG has contributed this significantly to the difference in initial load carrying capacity. Since the elastic modulus of SG, which is 300 N/mm^2 at room temperature (see table 1), is relatively low compared to the Young's modulus of glass, which is 70000 N/mm^2, the SG contributes to the initial load carrying capacity only to a limited extent. It seems more likely that the difference in initial strength originates from a difference in sub-critical crack growth in the glass which is dependent on temperature level [7].

Conclusions

The bending tests performed at 23, -20 and 60°C on SentryGlas-laminated metal-reinforced glass showed that laminating a metal reinforcement to a structural glass beam using SentryGlas (SG) is a feasible and promising concept. Even at extreme temperature conditions the beams showed a high level of redundancy. However, the structural response of the beam specimens varied at different temperature levels. At 23°C the beam specimens showed the highest residual strength, whereas the residual strength was reduced at both -20 and 60°C. This difference in response was caused by a difference in glass cracking behaviour and the occurrence of plastic hinges in the beams. These plastic hinges limited the residual strength of the beam and probably originated from a more brittle response of the SG at -20°C and a lower metal-to-glass bond strength of the SG at 60°C. Since the SG-laminated metal-reinforced glass beams showed promising results, future research at TU Delft will further explore the possibilities of this concept.

Acknowledgements

The authors gratefully acknowledge the support of glass supplier 'Van Noordenne Groep' and Dupont for this research.

References

[1] LOUTER, P.C., "Adhesively Bonded Reinforced Glass Beams", Heron, Vol. 52, Issue 1/2, 2007, http://heron.tudelft.nl

[2] O'CALLAGHAN J., "Glass Structures from Stairs to Cubes", Proceedings of the Challenging Glass conference, Delft, May 2008, www.bk.tudelft.nl/challengingglass

[3] LOUTER P.C., "Metal-to-glass bonding properties of an acrylate adhesive and SentryGlas at 23, -20 and 60°C", Proceedings of the Glass Processing Days 2009 (this conference), Tampere, Finland, June 2009, www.glassfiles.com

[4] LOUTER P.C., BOS F.P., VEER, F.A., "Performance of SGP and adhesively bonded metal-reinforced glass beams", Proceedings of the ISAAG 2008 conference, Munich, Germany, 2008, www.isaag.com

[5] DELINCÉ D., CALLEWAERT D., BELIS J., IMPE R. Van, "Post-breakage Behaviour of Laminated Glass in Structural Applications", Proceedings of the Challenging Glass conference, Delft, May 2008, www.bk.tudelft.nl/challengingglass

[6] BOS F.P., "Appendix K: 'Comparison between Failure Behaviour of SGP and GB368 Laminated Reinforced Glass Beams' of dissertation", to be published in 2009, Delft, www.glass.bk.tudelft.nl

[7] HALDIMANN, M., Fracture Strength of Structural Glass Elements – Analytical and numerical modeling, testing and design, Thèse No 3671, Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland, 2006.