Durability of SG-laminated reinforced glass beams

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Keywords

1 = reinforced glass 2 = beam 3 = interlayer 4 = laminate 5 = redundancy 6 = durability

Abstract

This paper investigates the effects of temperature, thermal cycling and humidity on the structural response of SG-laminated reinforced glass beams (SG = SentryGlas®). To do so, a series of pull-out test (to investigate the bond strength of the SG interlayer) and a series of bending tests (to investigate the structural response of the beams) have been performed at -20, +23, +60 and +80°C (the latter temperature only for the pull-out tests), after thermal cycling between -20 and +30°C, and after humidity exposure. From the test results it is concluded that the SG-laminated reinforced glass beams provide high redundancy and durability.

1. Introduction

In preceding research, SG-laminated stainless steel reinforced annealed float glass beams have been developed and tested. For these beams a significant post-breakage strength is obtained through the stainless steel reinforcement, which bridges the cracks upon glass failure thereby transferring the tensile forces over the cracks. The reinforcement is laminated to the glass by means of the SG interlayer. All forces between the glass and the reinforcement are thus transferred by this interlayer.

The current paper investigates the effects of temperature, thermal cycling and humidity on the structural response of SG-laminated stainless steel reinforced annealed float glass beams. This is done by means of pull-out tests to investigate the bond strength of the SG interlayer, and by means of bending tests to investigate the structural response of the beams.

The temperature pull-out tests have been performed at -20, +23, +60 and +80°C and the temperature bending tests at -20, +23 and +60°C. For the thermal cycling investigations the specimens have been exposed to 150 cycles between -20 and +30°C before they were tested. For the humidity investigations the specimens have been exposed to 100% rH at 50°C for 4 weeks before they were tested.

The followings sections describe the specimens and the test methods. Subsequently, the test results are given. Finally, conclusions from the research are provided. A more extensive discussion on the durability of SG-laminated reinforced glass beams is provided in associated publications [1, 2, 3].

2. Specimens

2.1 Pull-out specimens

The pull-out specimens consisted of 3 layers of SG-laminated annealed float glass with a metal insert laminated in the middle, see Figure 1. This metal insert – a 10*10*1 mm stainless steel hollow section – was identical to the reinforcement applied in the beam specimens. The middle glass layer of the specimens was split in two parts to host the metal insert. Furthermore, a gap was provided between the metal insert and the middle glass parts to avoid any bonding between the metal and the inner glass parts. In other words, the metal insert was only laminated to both outer glass layers. Standard SG interlayer sheets with a thickness of t = 1.52 mm were applied.

2.2 Beam specimens

The beam specimens consisted of 3 layers of SG-laminated annealed float glass with a 10*10*1 mm stainless steel hollow section reinforcement laminated at the inner recessed edge, see Figure 2. The beams were 1.5 m long and layered in 6, 10 and 6 mm thick glass panes respectively. The SG interlayer sheets were provided only between the glass layers and not at the short edge between the inner glass layer and the

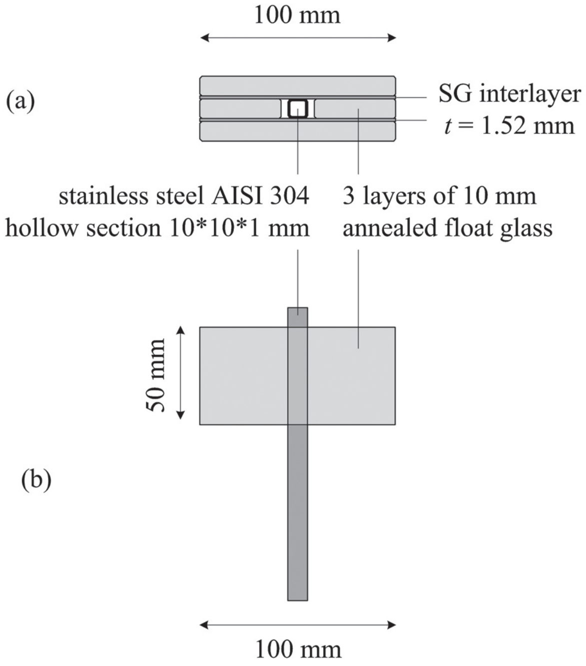


Figure 1: (a) cross-section and (b) front view, of the SG-laminated pull-out specimens.

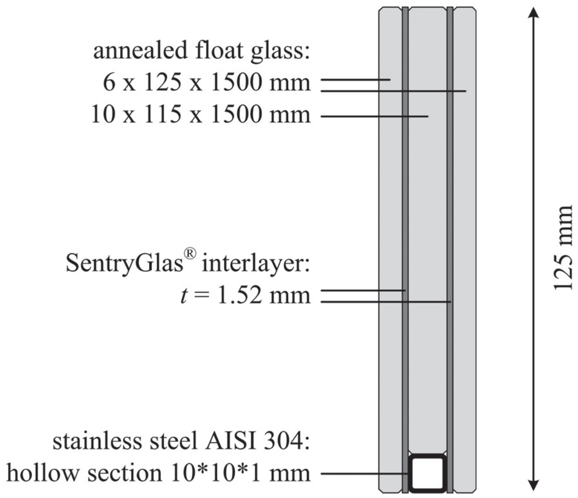


Figure 2: Cross-section of the SG-laminated reinforced glass beam specimens.

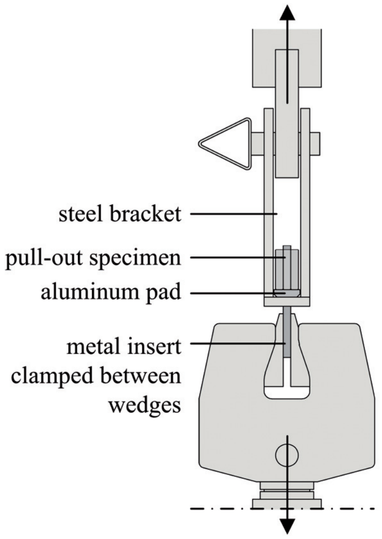


Figure 3: Schematic representation of the pull-out test setup.

reinforcement. However, due to the low viscosity of the SG interlayer during the lamination process and due to the vacuum created in the vacuum bag, the SG interlayer also seeped between the inner glass layer and the reinforcement thereby creating an additional bond at that position. In other words, the reinforcement was bonded with three faces to the glass. Standard SG interlayer sheets with a thickness of t = 1.52 mm were applied.

3. Methods

3.1 Temperature tests and pre-conditioning

The effects of temperature were investigated by means of pull-out tests performed at -20, +23, +60 and +80°C and by means of bending tests performed at -20, +23 and +60°C. This temperature range was selected based on the temperature range provided in ETAG 002 [4], which suggests adhesion tests at -20, +23 and +80°C. However, the high test temperature of +80°C could not be reached for the beam tests due to practical limitations of the test setup. Therefore the temperature was lowered to +60°C and also the pull-out test series was extended with this temperature level.

The following subsections briefly discuss the methods applied for the tests and for the specimen pre-conditioning. The methods are more extensively described in [1, 2, 3].

3.1.1 Temperature pull-out tests

The -20, +23, +60 and +80°C pull-out tests were performed on a Zwick Z100 test machine which was provided with a custom-made steel bracket to host the pull-out specimens. The pull-out specimens were positioned in the upper steel bracket and the metal inserts were clamped in the lower clamping wedges, see Figure 3. Subsequently, the upper bracket was moved upwards at a constant displacement rate of 2 mm/minute, thereby pulling the metal insert out of the glass laminate. The +23°C pull-out tests were performed in the 'open air', whereas for the -20, +60 and +80°C pull-out tests a climate box was put around the test setup. The box was either cooled with vaporized liquid nitrogen or heated with an electric heating element to obtain the required test temperature.

Prior to the temperature pull-out tests the specimens were conditioned for 5 days at -23, +23, +63 and +83°C for the different test temperatures respectively. This was done in an ordinary refrigerator or oven, respectively. The additional 3 degrees was selected to compensate for the increase or decrease in temperature during the mounting of the specimens in the test setup.

3.1.2 Temperature bending tests

The -20 and +23°C four-point bending tests were performed at a universal test machine which was provided with a custom-made support frame to host the beam specimens. In this test setup the load, support and lateral support span corresponded to the distances presented in Figure 4. The load was applied at a constant displacement rate of 2 mm/minute. For the -20°C bending tests, a climate box was placed around the beam specimens and was cooled with vaporized liquid nitrogen.

The +60°C four-point bending tests were performed in a climate chamber in which a custom-made test setup was placed. The load, support and lateral support span were identical to the -20 and +23°C bending tests. For the +60°C bending tests the load was applied by means of a manually operated hydraulic jack.

Prior to the bending tests the beam specimens were conditioned for 7 days at -30, +23 and +60°C for the different test temperatures respectively. For the -20°C bending tests an additional 10 degrees were used for the conditioning of the specimens to compensate for the increase in specimen temperature during the mounting of the specimens in the test setup. For the +60°C bending tests this was not necessary as the pre-conditioning and the testing both took place in the climate chamber, so that there was no loss in specimen temperature during the mounting.

3.2 Thermal cycling procedure

To investigate the effects of thermal cycling, a series of pull-out specimens and a series of beam specimens was subjected to a thermal cycling procedure before being tested at room temperature (+23°C). The specimens were subjected to 150 cycles between -20 and +30°C. Each full cycle spanned over 8 hours. The temperature range was selected based on the ultimate capacity of the applied thermal cycling cabinet. After the thermal cycling procedure the specimens were kept at room temperature for 24 hours, before being tested at room temperature (+23°C). The same pull-out and bending test setups as described for the +23°C tests in section 3.1 were applied.

3.3 Humidity exposure procedure

To investigate the effects of humidity, a series of pull-out specimens and a series of beam specimens was subjected to a humidity exposure procedure before being tested at room temperature (+23°C). The specimens were stored for 4 weeks over water in a closed container. The water was heated to 55°C which resulted in an air temperature of 52°C (±2 °C) and a relative humidity of 100% (condensation) inside the container. This procedure largely follows the humidity exposure procedure described in EN 12543-4 [5] which is intended for the investigation of the durability of laminated glass.

4. Results

The results of the temperature, thermal cycling and humidity pull-out and bending tests are provided in Tables 1 and 2 and in Figure 5. Furthermore, Figure 6 shows bargraphs of the experimental results. Additionally, Figure 7 provides a schematic representation and interpretation of the temperature, thermal cycling and humidity bending test results.

5. Discussion

The effects of temperature, thermal cycling and humidity are separately discussed in the following subsections. For a more extensive discussion than could be provided in the current paper, is referred to previous contributions [1, 2, 3].

5.1 Effect of temperature

From the temperature pull-out tests it is observed that temperature has a significant effect on the bond strength and shear stiffness of the SG interlayer. At increased temperatures (+60 and +80°C) the bond strength and shear stiffness of the SG interlayer reduced, see Figure 5 and Figure 6(a). This reduction in bond strength and shear stiffness is related to the reduction in polymer stiffness of the SG interlayer at and above its glass transition temperature of about 55-60°C [6]. At decreased temperature (-20°C) the bond strength of the SG interlayer increased, see Figure 6(a). This increase in bond strength is related to an increased polymer stiffness of the SG interlayer at decreased temperature. However, it should be noted that the dispersion in the -20°C pull-out tests results is rather large, which hinders a strong conclusion about the observed tendency for increased bond strength at decreased temperature.

From the temperature bending tests it is observed that temperature has a significant effect on the structural response of the reinforced glass beams. Both at increased temperature (+60°C) and decreased temperature (-20°C) the post-breakage strength is reduced compared to room temperature (+23°C), see Figure 6(b) and 7(a). At room temperature the SG-laminated reinforced glass beams profit from a crack blocking mechanism of the SG interlayer. Due to this crack blocking mechanism the cracks in the glass remain localized to one glass layer and do not run through the full width of the glass beam. A crack in one glass layer is thus often bridged by glass (fragments) in the other layers. These glass fragments are able to transfer forces over the crack through shear in the SG interlayer, thereby generating an additional load-carrying mechanism [1, 7]. At increased temperature this additional load-carrying mechanism is not present, which results in a lower post-breakage strength. Due to decreased bond strength at increased temperature, the beams tested at +60°C showed more extensive (local) debonding of reinforcement than was observed at room temperature. As a result of this more extensive local debonding, which occurred along some centimeters on either side of the crack origin in the glass, the cracks in the glass could open up further thereby stimulating plastic hinges to occur in the beam. These plastic hinges nullified the positive effect of the additional load-carrying mechanism, thereby causing a reduction in post-breakage strength. At decreased temperature a similar effect of debonding of reinforcement and subsequent development of plastic hinges occurred. Assumedly, the more extensive debonding was in this case caused by a decreased fracture toughness of the SG interlayer at decreased temperature. As earlier described, this more extensive debonding caused plastic hinges to occur in the beam, which was even further stimulated by rupture of the SG interlayer at these plastic hinges.

5.2 Effect of thermal cycling

From the pull-out tests performed after thermal cycling it is observed that thermal cycling has a negative effect on the bond strength of the SG interlayer. The specimens that have been pre-exposed to a thermal cycling procedure showed significantly lower pull-out strength levels than non-exposed specimens, see Figure 6(a). Whether or not this decrease in bond strength of the SG interlayer was fully caused by the thermal cycling procedure is not fully clear. Possibly, humidity may have played a crucial role. During the thermal cycling procedure the specimens have –

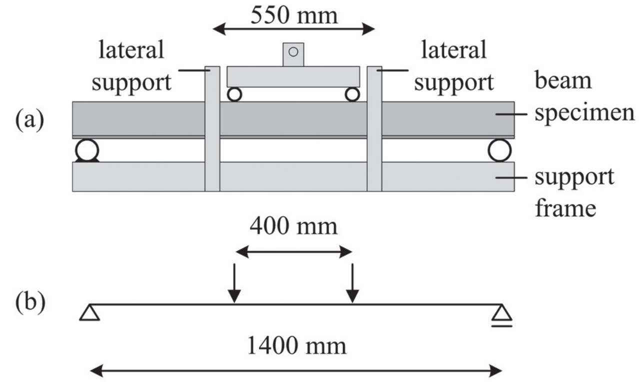


Figure 4: Schematic representation of the bending test setup.

Table 1: Pull-out test results for the -20, +23, +60 and +80°C tests, the thermal cycling (TC) and humidity exposure (HE) tests.

		pull-out test results					
		-20°C	+23°C	+60°C	+80°C	TC	HE
Number of specimens	-	3	3	3	3	3	3
Maximum load:							
mean	kN	24.2	21.8	11.1	3.2	6.2	12.1
st.dev.	kN	4.3	1.2	0.9	0.2	0.3	1.8
rel.st.dev.	%	17.8	5.3	8.1	4.9	5.1	15.2

Table 2: Bending test results for the -20, +23 and +60°C tests, the thermal cycling (TC) and humidity exposure (HE) tests.

		bending test results				
		-20˚C	+23˚C	+60˚C	TC	HE
Number of specimens	-	5	5	5	3	3
Initial failure load:						
mean	kN	16.1	11.7	9.1	10.1	13.0
st.dev	kN	1.8	1.1	1.3	1.7	1.8
rel.st.dev.	%	11.2	9.5	14.4	16.5	13.7
Post-breakage load:						
mean	kN	15.4	17.5	14.3	16.5	16.7
st.dev.	kN	0.9	0.5	0.5	0.5	1.0
rel.st.dev.	%	5.6	2.8	3.7	3.2	6.1
Post-breakage/initial failure load:						
mean	%	96.4	150.0	159.1	166.6	129.5
st.dev.	%	7.7	12.0	22.7	21.0	9.2
rel.st.dev.	%	7.9	7.7	14.2	12.6	7.1

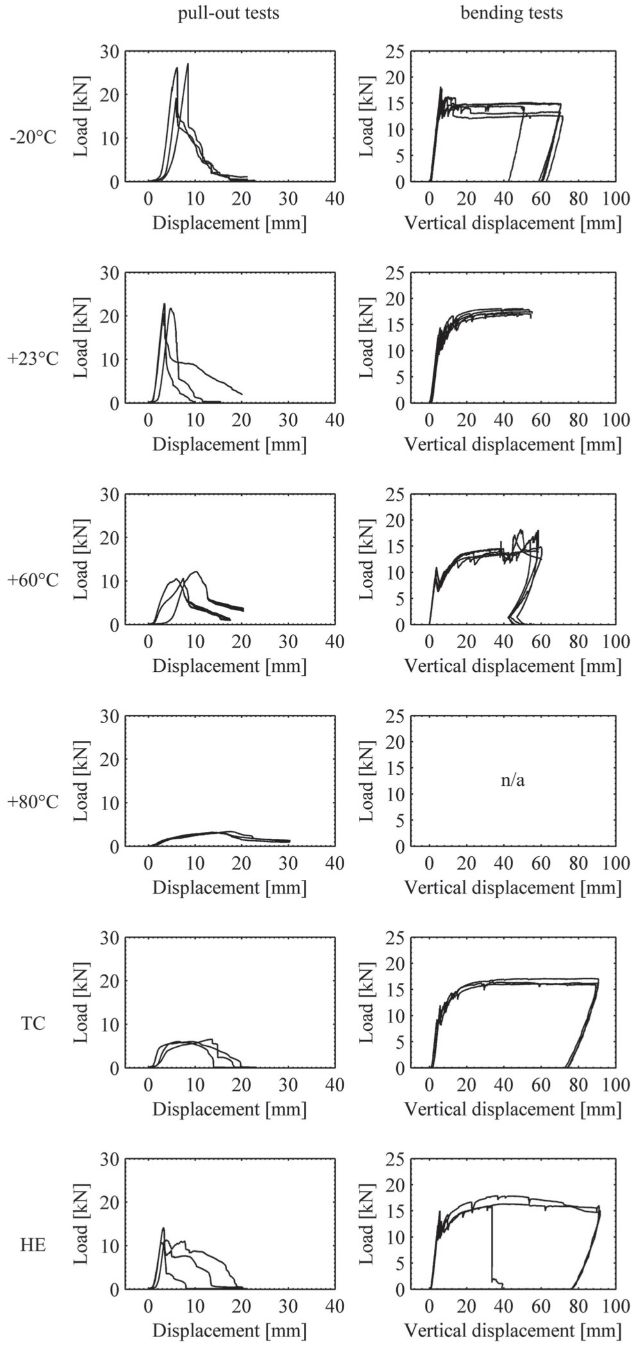
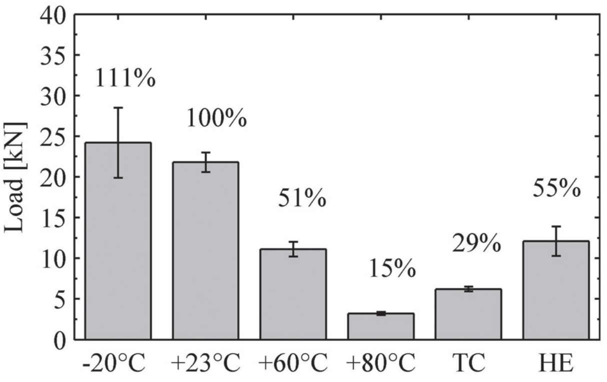


Figure 5: Experimental results of the pull-out and bending tests.



(a) pull-out tests

(b) bending tests

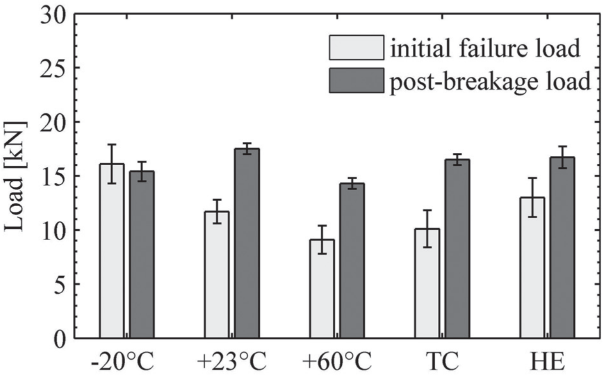


Figure 6: Bargraph of the (a) pull-out and (b) bending test results, including an indicator of the standard deviation.

as a result of the changing temperature level – repetitively been exposed to high relative humidity and possibly to water condensation. This highly humid environment may have had a significant effect on the bond strength of the SG interlayer, as can be seen from the humidity tests discussed in the following section.

From the bending tests performed after thermal cycling it is observed that thermal cycling has only a limited effect on the structural response of the SG-laminated reinforced glass beams, see Figure 6(b) and Figure 7(b). Apart from a small reduction in post-breakage strength, due to somewhat more excessive debonding of reinforcement, the thermal cycling exposed beam specimens showed similar structural response as the non-exposed beam specimens. The SG interlayer was, assumedly due to its rather large thickness of t = 1.52 mm, sufficiently able to compensate for the difference in thermal expansion between the glass and the reinforcement. However, it should be noted that the absolute difference in thermal expansion between the glass and reinforcement was relatively small, due to the limited size of the beam specimens, and amounted to about 0,3 mm for the investigated thermal cycling temperature range.

As can be observed from the before mentioned, thermal cycling had a significant negative effect on the pull-out specimens, whereas it had only a limited effect on the beam specimens. This difference in thermal cycling effect is probably related to a difference in size and geometry of the pull-out and beam specimens. This is explained in more detail in the following section.

5.3 Effect of humidity

The humidity pull-out tests demonstrate a significant reduction in bond-strength of the humidity pre-exposed specimens compared to the non-exposed specimens, see Figure 6(a). It is assumed

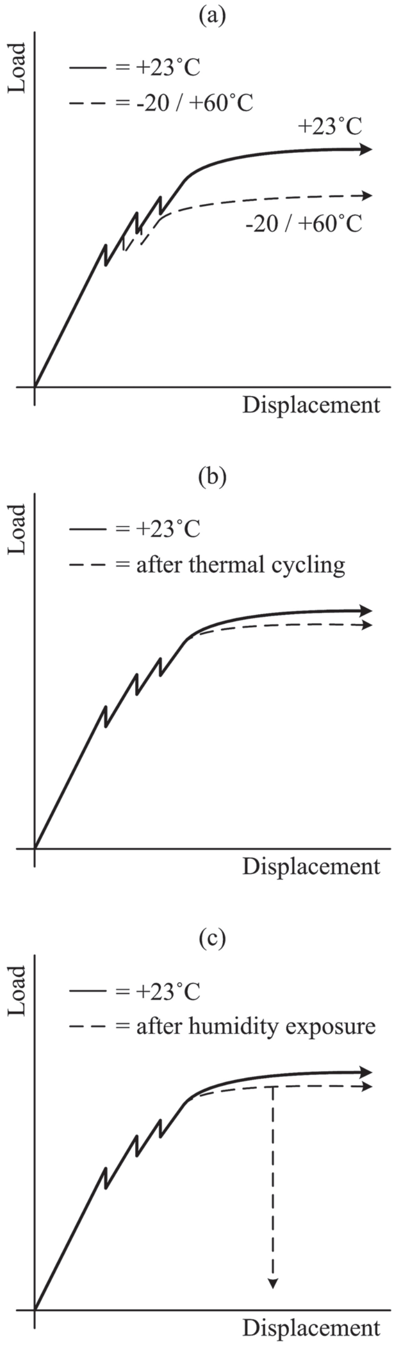


Figure 7: Schematic representation of (a) temperature, (b) thermal cycling and (c) humidity, on the structural response of SG-laminated reinforced glass beams.

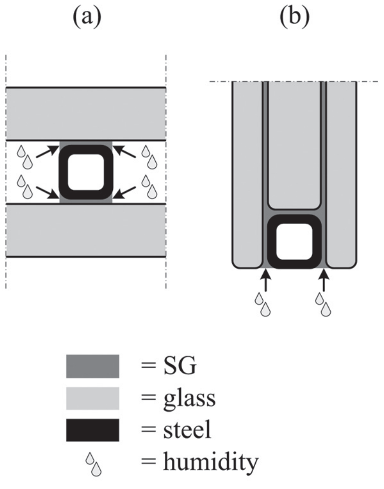


Figure 8: Perimeter effect of humidity; (a) cross-section of the pull-out specimens; (b) cross-section of the beam specimens.

that this reduction in bond strength results from water penetrating between the SG interlayer and the glass, thereby breaking the physical bond between them. Furthermore, water absorption by the SG interlayer itself may also have influenced its bond strength.

For the bending tests the negative effect of humidity, as it has been observed at the pull-out tests, seemed initially largely absent. The beams that had been pre-exposed to humidity reached similar post-breakage levels as the non-exposed beams, see Figure 6(b) and Figure 7(c). However, one beam demonstrated delamination during the bending tests, which caused the beam to collapse. Assumedly, the bond strength of the SG interlayer had significantly reduced due to the humidity pre-exposure. However, since it only occurred for one (out of three) specimens, it remains unclear whether the delamination was fully caused by the humidity pre-exposure or possibly due to unnoticed manufacturing errors.

Overall, the effect of humidity was, apart from the delamination of one beam, smaller for the beam specimens than for the pull-out specimens. It is assumed that this difference in humidity effect is caused by a difference in specimen geometry. In the pull-out specimens the bond area is smaller and the perimeter of the bond is more exposed than in the beam specimens, see Figure 8. The perimeter effect of humidity penetration and absorption is therefore assumedly more significant for the pull-out specimens than for the beam specimens.

Conclusions

From the temperature tests it is concluded that both increased and decreased temperatures have a negative effect on the post-breakage strength of the SG-laminated reinforced glass beams. Compared to room temperature, the beams show both at -20 and +60ºC more excessive local debonding of reinforcement due to a reduction in fracture toughness and bond strength of the SG interlayer at -20 and +60ºC respectively. However, from the temperature tests it is also concluded that temperature levels in the range of -20 to +60ºC do not endanger the safety performance of the beams. The beams reached significant post-breakage strength levels at all test temperatures.

From the thermal cycling tests it is concluded that thermal cycling has only a limited effect on the performance of the SG-laminated reinforced glass beams. The beams demonstrate only a minor reduction in post-breakage strength after the thermal cycling procedure. However, it should be noted that thermal cycling effects may become more significant for beam sizes larger than have been tested in this research, due to a larger absolute difference in thermal expansion between the glass and the reinforcement.

From the humidity tests it is concluded that humidity has an inconsistent though predominantly negative effect on the structural response of the SG-laminated reinforced glass beams. One out of the three humidity pre-exposed beams demonstrated delamination during the bending test. Although it could not be traced whether this delamination was fully caused by humidity or possibly the result of an incidental manufacturing error, the observed delamination urges for caution in the application of the beams in highly humid environments.

Overall, it is concluded that the SG-laminated reinforced glass beams provide a high redundancy and durability. The beams perform well at a rather wide temperature range and after thermal cycling. However, the effects of humidity on the structural response of the beams are not yet sufficiently understood and should be further investigated.

Acknowledgements

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References

[1] Louter PC, 'Fragile yet Ductile – Structural Aspects of Reinforced Glass Beams', Dissertation, TU Delft, Delft, The Netherlands, April 2011.

[2] Louter PC, Belis J, Veer FA, Lebet J-P, 'Durability of SG-laminated reinforced glass beams: effects of temperature, thermal cycling, humidity and load-duration', submitted for publication in Construction and Building Materials.

[3] Louter PC, Belis J, Bos FP, Callewaert D, Veer FA, 'Experimental investigation of the temperature effect on the structural response of SG-laminated reinforced glass beams', Engineering Structures, Volume 32, Issue 6, June 2010, Pages 1590-1599, doi:10.1016/j.engstruct.2010.02.007

[4] European Organization for Technical Approvals (EOTA), 'ETAG 002, Edition November 1999, Guideline for European technical approval for structural sealant glazing systems (SSGS), Part 1: Supported and unsupported systems', Brussels, 1999.

[5] EN ISO 12543-4: 1998. 'Glass in building - Laminated glass and laminated safety glass - Part 4: Test methods for durability', CEN; 1998

[6] Callewaert D, Delincé D, Belis J, Van Impe R. 'Temperature-dependent behaviour of glass/ionomer laminates: preliminary test results'. In the proceedings of the Challenging Glass conference, Amsterdam: IOS Press; 2008, p. 431-7.

[7] Bos FP, 'Safety Concepts in Structural Glass Engineering – Towards an Integrated Approach', Dissertation, TU Delft, Delft, The Netherlands; December 2009