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Curved Glass – Quality and Application

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The desire of modern architecture for free form structures opens a large market for curved glass. Compared to flat glass, the production of curved glass is much more difficult because of additional parameters through the bending process. Since there is no standard available for curved glass in construction so far, at present the rules for flat glass are being considered. However, several cases of damage show that the application of curved glass needs own regulations to avoid glass breakage on the construction site. Therefore, the Munich University of Applied Sciences and the RWTH Aachen University have performed a research program [1] concerning the quality control and criteria of curved glass.

Keywords: Glass, heat strengthened glass, thermally toughened glass, curved glass, tempering, material strength, breakage pattern, thermal pre-stress

1. Problem

So far no standards are available for the product "curved glass" and there are no regulation standards for glass facades or glass roofs containing curved glass elements. As no other rules are available the quality criteria like geometrical tolerance, optical distortion, material strength or breakage pattern of flat glass panels are generally assumed. However, during the last years several damages of curved glass constructions occurred. This shows that curved glass needs own regulations and a quality control is necessary for a product which manufacturing process is far more challenging than the flat glass one.

2. Examples

Curved glass panels are used for glass facades, glass roofs and balustrades. Besides hot bending, cold bending may be an option when strength is subordinated optical appearance. Elements consisting of monolithic glass, laminated glass panels or insulated glass units can be produced. Hot bent curved glass is available in qualities comparable to plane annealed glass, heat strengthened glass and thermally toughened glass. Furthermore the refining possibility of chemically tempering through surface ion exchange also exists. Simple cylindrical forms as well as spherical geometries or sinusoidal shapes can be produced.

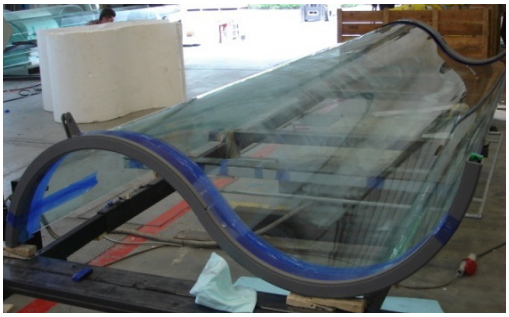
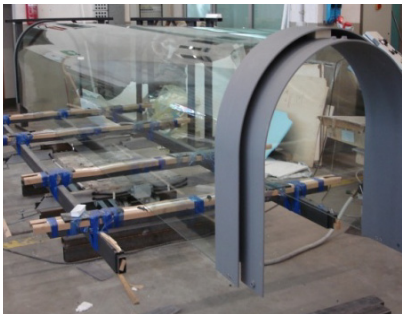



Figure 1a and b: possible shapes of hot bent glass.

3. Cases of damages and disagreement concerning the quality

Occurring Problems with curved glass in use can mainly be related to two major reasons:

- Discussion about the geometrical tolerances and the optical quality and
- Glass breakage on the construction site.

The first mentioned discussions can be avoided by fixing the demanded accuracy in the contract and producing samples to define e.g. the reachable optical quality.

Glass breakage on the construction site is commonly caused by large imperfections of glass panes and steel structures. For example railings of curved glass balustrades may induce inadmissible restraints in the glass due to forced edge aligning.

Restraint problems often induced glass failure occurs in conjunction with non-uniform pre-stress distributions. As explained below, the thermal pre-stress distribution can be visualized with polarization filters. Figure 2 shows the non-uniform stress distribution of a laminated glass unit made of heat-strengthened glass and the associated breakage pattern. This kind of breakage pattern is typical for curved laminated glass made of heat strengthened glass panels. The number of fracture lines is higher than expected from flat glass experiences. Until now, it has not been satisfactory evaluated if this phenomenon is caused by the non-uniform tempering or unintentionally induced stresses through the lamination process.

Non-uniform pre-stress distribution is the result of non-uniform tempering. Until 1960, non-uniform tempering was scheduled used to produce thermally tempered glass (name of the product VISURIT) with a breakage pattern shown in figure 3a. VISURIT was used for car windshields. The well known parabolic pre-stress distribution over the glass thickness is superposed with a constant membrane stress (figure 3b). In the area Z the membrane stress causes pressure, outside this area the membrane stress evokes tension. In the case of a glass breakage the rupture lines are concentrating at the border of the area Z. If the membrane stresses are high enough compared to the parabolic stresses, there will be no rupture line in the area Z.

Until now, the quantity of the membrane stresses is unknown. The relation between polarization colors and the quantity of the non-uniformity of the pre-stress is not known yet. The acceptable non-uniformity has to be part of further investigations because of non-uniform tempered glass seemed to be more sensible concerning unintentionally restraints.

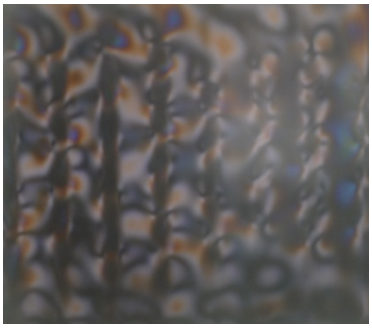
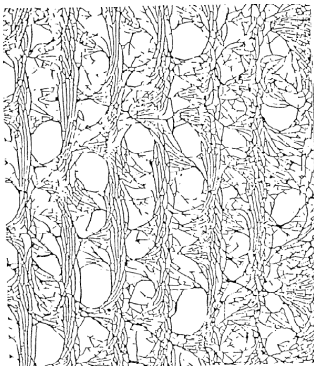


Figure 2a and b: Laminated glass unit made of 2 panels heat strengthened curved glass – Visualization of the non-uniform stress distribution and associated fracture lines after breakage.



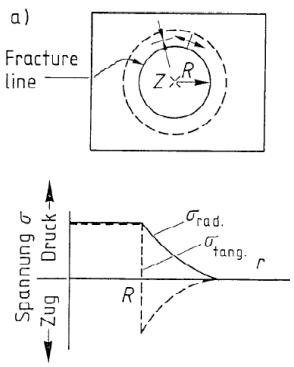


Figure 3a and b: Typical fracture lines of the product "VISURIT" [2] and simplified model to explain the thermal membrane stresses.

4. Production of curved glass panels

The production of curved glass panels is much more difficult than the production of flat glass.

For curved glass with annealed glass properties, annealed glass panels are heated up to the transformation temperature (circ 600°C). With the aid of gravity loading, the panels fall into the mould. Afterwards, a slow and controlled cooling down is necessary to avoid internal stresses. For insulating glass units or laminated glass panels, two glass panes can be formed pairwise. Hence, a good parallelism of the surfaces can be reached.

The tempering of curved glass needs a lot of experience. A glass panel is heated up to the transformation temperature of about 600°C and formed by pressing in the desired

shape. Afterwards the tempering stresses are induced by fast cooling. Depending on the process parameters, curved glass with properties of heat strengthened glass or thermally toughened glass can be produced. A pairwise forming is not possible, so the surface parallelism of tempered curved glass pairs is worse compared to curved annealed ones.

In discussions with several manufacturers it was clarified that the quality of curved glass is not comparable with the quality of flat glass. This means that heat strengthened glass with good optical properties, compliance with the regarded tolerances, bending strength of f_{ck}= 70 N/mm² and a typical heat strengthened breakage pattern is not yet economical producible. That applies for curved thermally toughened glass with a bending strength of f_{ck}= 120 N/mm² in the same manner.

5. Material strength tests

5.1. Testing of curved glass panels

Today no standardized test procedure to determine the bending strength of curved glass exists. Based on the existing test procedure for bending strength of flat glass [3] (Four-Point-bending test and coaxial double ring test), a new test set-up has been developed [1,4,5]. The test specimens are cylindrically formed and have dimensions of 1100 mm x 360 mm. The material strength has been determined for the two directions: “n” and “u” (compare figure 4). For the evaluation of the test results, the geometrical non-linearity of the system has to be taken into account. By using the modified Four-Point-Bending-Test, only the glass strength parallel to the curved line can be tested. Additional large scale tests (dimension of the test specimens 2000 mm x 800 mm) have been carried out by using a new vacuum test set-up (figure 5).

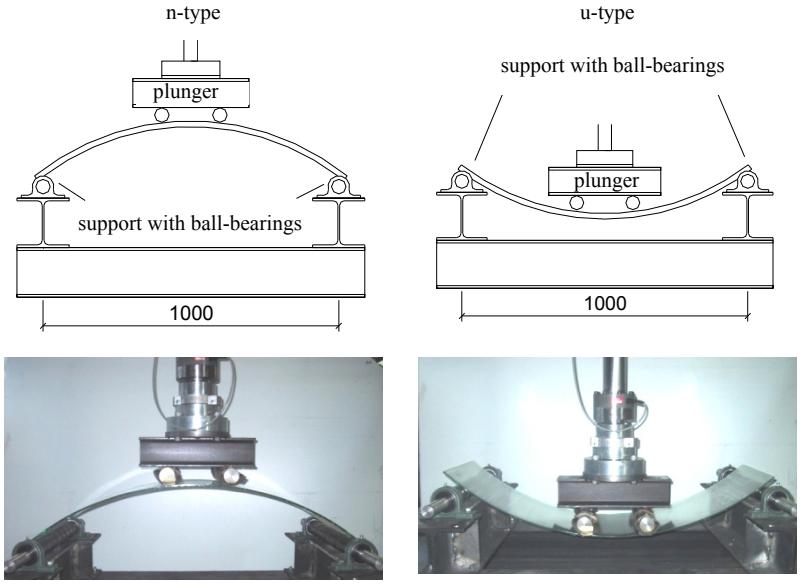


Figure 4a and b: Modified Four-Point-Bending test set-up for curved glass panels (“n”- and “u”-direction).

Figure 5: Vacuum test set-up.

5.2. Results

The following results of the tests can be evaluated:

- The material strength determined in the “u”-direction is lower compared to the strength values determined in the “n”-direction. Finally, all tests have been carried out in the “u”-direction.
- The test results are depending on the edge processing. Polished edges lead to high test values, but also to a large scatter. Grinded edges are preferable for material strength tests due to the small scatter in the strength results
- The evaluated and recommended bending strengths of curved glass in the qualities of annealed glass, heat strengthened glass and thermally toughened glass are given in Chapter 8.1.

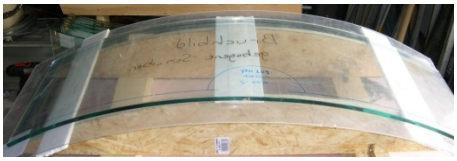
6. Breakage pattern

The breakage pattern of small test specimens (360 mm x 1100 mm) is a quality criteria of heat strengthened and thermally toughened flat glass panels [6] [7]. According to the European Product Standards, the breakage pattern of tempered curved glass panels has to be determined.

Within this research project the specimens were laid on a mockup form or in case of lager dimensions on air bags (figure 6), to avoid any external stress in the glass panels which is influencing the breakage pattern.

The breakage pattern tests of bent heat strengthened and bent toughened glass led to different results when they were compared to flat glass. It could be determined, that the breakage pattern of bent toughened, uniform pre-stressed glass is comparable to the known breakage pattern of flat toughened glass (figure 8). Therefore the requirements according to [7] could also defined for bent glass. Unlike toughened glass, the breakage pattern of bent heat strengthened glass is not comparable to the flat ones. In most cases the bent specimens showed more fragments as it is common by flat glass (figure 7).

In accordance with the manufacturers, one can say that bent heat strengthened glass with a breakage pattern as expected from flat glass, high bending strength and low geometric tolerances at the same time are not economic producible.



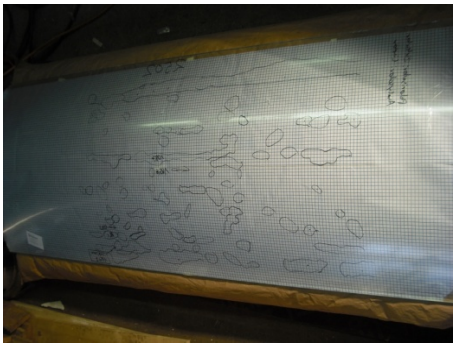


Figure 6a and b: breakage pattern tests a) small specimen with mockup form b) lager specimen with air bag support.

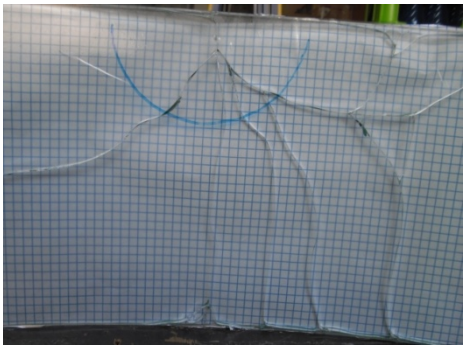
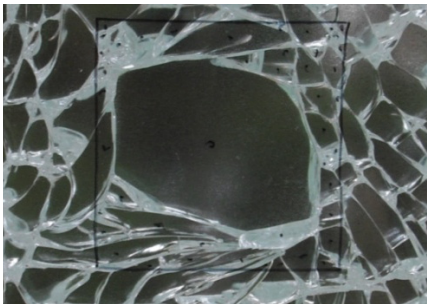


Figure 7a and b: Breakage pattern of curved heat strengthened glass panels (7a: not conform, 7b: conform to DIN EN 1863).



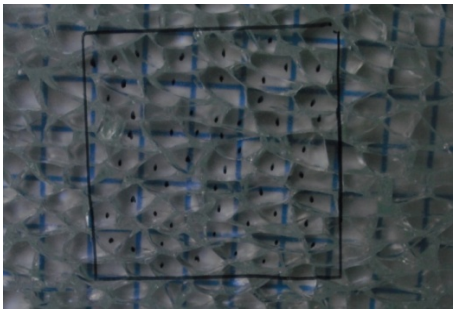


Figure 8a and b: Breakage pattern of curved thermally toughened glass panels (8a: not conform, 8b: conform to DIN EN 12150).

7. Distribution of thermal pre-stress

An important quality characteristic is the distribution of the thermal pre-stress. In many cases of damage a non-uniform pre-stress distribution over the glass panel can be qualitatively shown with polarizations filters, as mentioned above.

Quantitative pre-stress values can be determined with measurement devices like Scalp-03 [8] and LaserGASP [9]. Here, only a local value can be determined.

Because of the high thermal pre-stress variation of tempered curved glass panels both methods (global visualization and local measurements) have been used. Within the research project several polarization filter photographs of toughened and heat strengthened glass specimens were taken. In consideration with the breakage pattern tests and the local stress measurements typical interference fringes which lead to an abnormal breakage pattern (Figure 8b) could be determined.

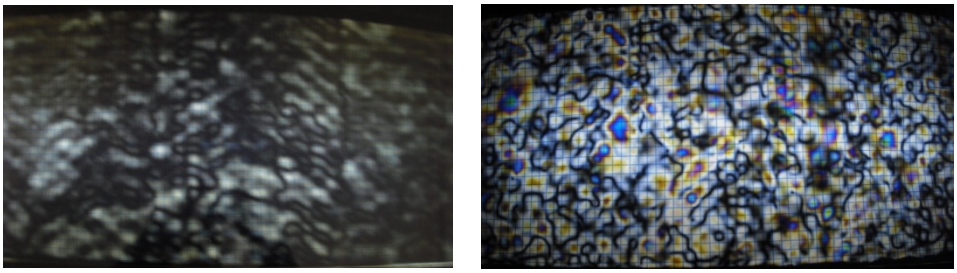


Figure 8a and b: polarization filter pictures of toughened bent glass specimens with a) uniform and b) non-uniform pre-stress distribution.

8. Recommendations for the production and use of curved glass panels

Regarding the gathered perceptions of this research project the following issues should be considered.

8.1. Material strength criteria

Based on the tests results the following strength values are recommended for the application of curved glass panes. For heat strengthened glass and thermally toughened glass the material strength should be tested object- and manufacturer-related.

- Annealed glass
  Characteristic bending strength f_{ck} = 45 N/mm^2 in the plane
  Characteristic bending strength f_{ck} = 36 N/mm^2 at the edges (reduction to 80%)
- Heat strengthened glass
  Characteristic bending strength f_{ck} = 55 N/mm^2
- Toughened glass
  Characteristic bending strength f_{ck} = 105 N/mm^2

8.2. Breakage pattern criteria

Heat strengthened glass:
Based on the research results a final breakage pattern quality criterion for heat strengthened glass cannot be determined. Here further experimental investigations based on existing flat glass accreditations for flat heat strengthened glass are necessary to gain an authoritative result.

Toughened glass:
Toughened glass can fulfill the demands to the breakage pattern according to DIN EN 12150-1:2000

8.3. Design of curved glass panels

Beside common load situations like own weight, wind and snow, additional load cases should be taken into account. Depending on load direction and geometrical shape of the curved glass pane, higher bending stiffnesses compared to flat panels may occur. So deformations of substructures and climate loading of curved insulated glazing units have to be considered separately and superposed with common loads.

8.4. Quality control and delivery arrangements

To control the uniformity of the thermal pre-stress distribution polarization filters should be used. Furthermore, the optical quality of the curved glass panes should be stipulated with samples. Also the geometrical tolerances ought to be declared in advance.

8.5. Further advices

For laminated curved glass units the interlayer thickness should be high enough to compensate geometrical variations. Residual resistance should be tested for overhead glazings made of laminated glass consisting of 2 x heat strengthened glass panels. Generally it should be avoided to induce constructional restraints into the glass panels.

9. Summary

The research project “Curved glass” analyzed the material strength of curved glass panels and figured out possible procedures to ensure a certain product quality.

The application of curved glass panels requires own design rules and benchmark criteria. The well known product properties of flat glass should not be assigned to curved glass one to one.

The presented approach shall aid the quality control of the manufacturers as well as assist the engineer in his design tasks. Moreover, the results of this project can be taken as a foundation for future product accreditations.

10. Acknowledgements

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We wish to thank them all for their contribution to our work.

11. References

[1] Forschungsbericht, AiF Nr. 1703X06: *Tragverhalten von gebogenen Glasscheiben im Bauwesen*, 2009.

[2] DIN EN 1288:2000 – *Glas im Bauwesen – Bestimmung der Biegefestigkeit von Glas.*

[3] Blank, Kurt, *Verfahren zur Festigkeitssteigerung*, In: Fortbildungskurs „Festigkeit von Glas“ HVG, 1987.

[4] Bucak, Ömer; Feldmann, Markus; Kasper, Ruth; Bues, Martin; Illguth, Marcus, *Das Bauprodukt "warm gebogenes Glas" – Prüfverfahren, Festigkeiten und Qualitätssicherung*, In: Stahlbau Spezial Ernst & Sohn, 3/2009, pp.23-28.

[5] Bucak, Ömer; Feldmann, Markus; Kasper, Ruth; Bues, Martin; Illguth, Marcus, *Tragverhalten von gebogenen Gläser in Bauwesen*, Glas in Konstruktiven Ingenieurbau 7, 2009.

[6] DIN EN 1863:2000 – *Glas im Bauwesen – teilvorgespanntes Glas*.

[7] DIN EN 12150:2000– *Glas im Bauwesen – thermisch vorgespanntes Einscheibensicherheitsglas*.

[8] *Instruction Manual Grazing Angle Surface Polarimeter.* s.l.: Strainoptic Technologies Inc.

[9] *Scattered Light Polariscope SCAPL-03.* s.l.: Instruction Manual, Glass Stress Ltd.