Bundesverband Flachglas

Guidelines for thermally-curved glass in the building industry

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1.0 Introduction

The use of glass in the building envelope is a practice increasingly popular among both planners and persons commissioning building projects. The development that glass as a building material has seen in recent decades has shown that limits can hardly any longer be set to the material's application in this way. It makes available to the planner and the commissioning party a broad spectrum of different design possibilities. There thus arise multifunctional, geometrically complex façades, the execution of which requires not only flat but also curved types of glazing.

The earliest glass façades were erected using almost exclusively flat glass. Research as well, in recent decades, has focused primarily on these types of glazing. Curved glass tended to be used only seldom. Thanks to the further development of production processes and other techniques of processing, like the use of coatings with special functions such as heat-insulation and solar control, the fields of application of both flat and curved glass became larger.

These guidelines are intended to provide the user (architect, planner, or builder executing the project) with some orientation in the use of curved glass, both in the planning and design phase and in the phase of actual execution, and also to give him some necessary pointers in respect of important emerging questions. Descriptions are provided of the basic construction regulations applying and pointers given regarding dimensioning of glass and regarding glazing itself. In addition, the basic principles for the assessment of the visible quality of curved glass are explained and statements made as to permissible tolerances. Pointers regarding transport and installation are also given.

In the case of questions arising which go beyond the limits of these general guidelines, or relate specifically to individual cases, the manufacturers or planning offices concerned should be contacted directly.

2.0 Area of application

These guidelines are valid for thermally-curved glass intended for use in the building industry (use in the building envelope and in the extension of existing buildings to form annexes and other structures).

As regards special applications – e.g. in ship- and boat-building, as yacht glass, or in furniture-making – questions as to the products that might be used, their tolerances, their visual quality etc. should be directed to the manufacturers of said products.

3.0 Manufacture and geometry

Since the beginning of the modern history of the bending of glass for use as an architectural material – in the middle of the 19th Century in England – the basic principle of manufacture of thermally-curved glass units has not substantially altered. As a rule, the principle applied is the principle of "gravity bending" illustrated in Fig. 1. This method involves laying the flat float glass blank on a bending mould and heating it, in a bending furnace, to temperatures of between 550 and 620 °C. Once the softening range has been reached, the blank will, by force of gravity, sink into the mould or, where the mould is convex, lay itself over this latter. It is the subsequent cooling-off phase that determines the properties of the end-product.

For the manufacture of curved float glass a very slow cooling-off must be conducted. The process goes on, as a rule, for several hours, so as to achieve an end product almost devoid of intrinsic stress and easily cut and shaped.

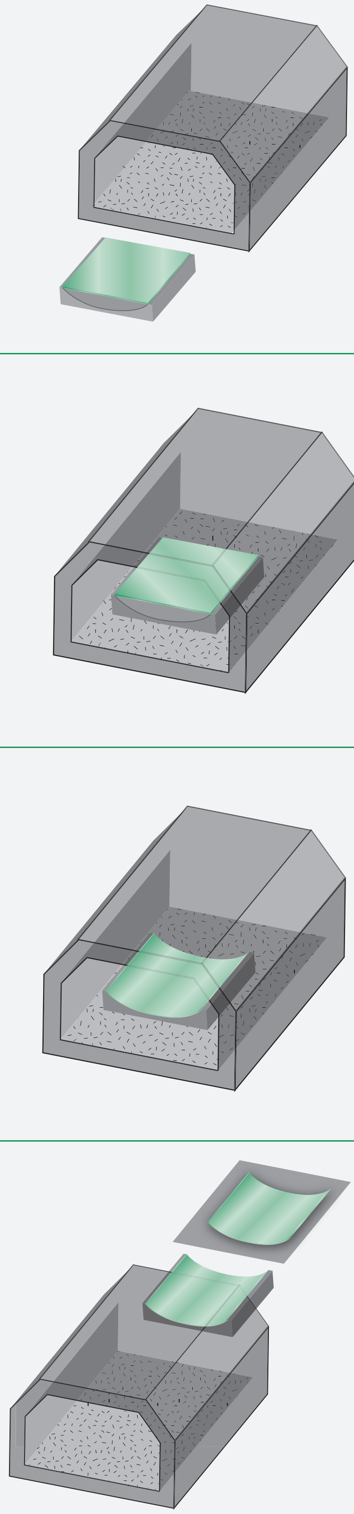
A rapid cooling-off process, on the other hand, produces a curved glass that is either of the heat-strengthened or of the toughened type. The manufacturing process of heat-strenthened and thermally toughened curved glass units has, however, altered as a result of the continuing development of machine technology. Modern bending furnaces for manufacturing heat-strenthened and thermally toughened glass units work with movable bending moulds which bring the heated-up blank, from both sides, into the desired form and also hold it in this form during the whole process of heat strengthening and toughening. The bending and cooling-off take place here within the same furnace unit.

Simple, however, as the principle of glass-bending may be in itself, its actual putting into practice is a difficult and demanding matter. Whether or not a bending process is successful depends on a whole series of parameters. Besides the determining geometrical conditions, coatings and the particular basic glass used (e.g. low-iron-oxide-content glass, or so-called "white glass") also exert a significant influence on the decisive production phases of heating-up and cooling-off. Also decisively important for the quality of the end-product, of course, are such factors as the amount of experience possessed by the enterprise performing the bending and the technical characteristics of the bending furnaces used.

Whether it will be possible, therefore, in any given case, to realize the desired bending geometry in combination with the chosen glass construction – possibly also with coating – is a matter that depends also on the particular manufacturer(s) involved, so that the making of general statements about possible bend radii and glass constructions is only possible to a limited degree.

As a matter of general principle, however, it can be said that more elaborate geometries, such as spherical bends and bows, are generally only possible in the form of annealed float glass. In cases where curved laminated glass (CL) or curved laminated safety glass (CLS) are required, the individual panes can be laid together on the bending mould during the float glass bending process. For this reason the tolerances of the individual panes are, for the most part, significantly lower than in the case of laminated safety glass manufactured from heat-strengthened and thermally toughened curved glass, since in this case the panes can only be manufactured pane-by-pane.

When manufacturing curved panes a fundamental distinction is made between slightly curved glazing units, with a radius of curvature of over two metres, and strongly curved glazing units, with smaller radii of curvature. Moreover, a distinction is also made between glass curved on a single axis (i.e. cylindrically) and glass curved on a double axis (i.e. spherically). The thermal-bending process allows the realization of very small bend radii. The exact values depend on the individual manufacturer, but radii as small as 100 mm are possible where glass-thicknesses lie above 10 mm up to about 300 mm.



Step 1:
Building of a bending mould and laying of the flat glass-blank on the mould

Step 2:
Heating-up of the glass to between 550 and 620 °C

Step 3:
The blank sinks into the bending mould

Step 4:
- In the case of float glass, slow cooling-off (several hours)
- In the case of heat-strengthened and thermally toughened glass units, fast cooling-off.

Fig. 1: Principal Steps in Manufacture

4.0 Construction regulations

4.1 General remarks

A fundamental distinction is to be made between regulations, or standards, bearing on the products (i.e. their inherent properties) and regulations or standards bearing on the use or application. Whereas product standards contain regulations bearing on manufacture and specifications regarding the technical properties of the products in question, standards and directives relating to use and application deal rather with requirements specifically in building terms, and describe the required proofs of the load-bearing capacity and fitness for use of a particular building product or particular building type within the context of a built construction.

Product standards are taken up uniformly all over Germany into Construction Products Lists A, B and C, published by the Deutsches Institut für Bautechnik in agreement with the Senior Building Supervisory Authorities (SBSA) in all the individual German federal states.

Standards and directives relating to use and application, on the other hand, are published by separately in each of these German federal states as part of the state's respective List of Technical Construction Specifications. Here, therefore, it cannot be assumed that the same rules and stipulations apply all across the territory of the Federal Republic of Germany. Rather, there must always be enquired and investigated, in each federal state, which regulations currently apply there.

4.2 Thermally curved glass

Thermally curved glass is not listed in the Construction Products Lists A, B, or C. This means that, from the point of view of construction law, we are dealing here with a non-regulated building product. In this case, fitness for use can only be proven via a National Technical Approval (Allgemeine bauaufsichtliche Zulassung, or AbZ) or via a European Technical Approval (ETA). In the case where neither of the just-named proofs of fitness for use is extant, it will be necessary to make an application to the competent Senior Building Supervisory Authority of the German federal state concerned – or, where appropriate, to some other office authorized by the latter – for an Exceptional Approval (Zustimmung im Einzelfall, or ZiE).

The “Technical Regulations for the Use of Glazing with Linear Supports” (hereinafter referred to by the German acronym: TRLV) [1] and the “Technical Regulations for the Use of Fall-Proof Glazing” (hereinafter referred to by the German acronym: TRAV) [2], which have currently been introduced into all the Federal German states, govern construction regulations and required proofs of load-bearing safety and fitness for use in principle also for curved vertical glazing. Containing as they do stipulations regarding glass-types that may be used, official requirements in terms of construction, and instructions as to glass-design and -dimensioning, etc. the TRLV constitute a foundation for the TRAV.

For curved glass a National Technical Approval is required in which the properties of the product and the area of its application are explicitly stated. Curved vertical glazing units (without fall-proof functions) may then without further ado be designed and dimensioned according to the terms of the TRLV. In the case where the area of application specified in the National Technical Approval comprehends the TRLV, it is permissible that the curved glass also be used for the manufacture of fall-proof glazing in the meaning of the TRAV. In respect of proofs of fitness for use and of applicability there then additionally apply the stipulations of the Construction Products List A Part 2 or Part 3. These stipulations require in such cases a General Building Inspection Test Certificate (Allgemeines bauaufsichtliches Prüfzeugnis, or AbP).

In the DIN standard which will in future regulate the design and dimensioning of glazing units in Germany, DIN 18008, constructions with curved glass are not included in the ambit of the regulation. Likewise, no description is included in this new general standard of that application of curved vertical glazing with linear supports which is presently regulated by the TRLV. This means that the application of the building product “curved glass” will henceforth only be possible via an official general approval – be it a National Technical Approval for Germany (AbZ) or a European Technical Approval (ETA) – or an Exceptional Approval (ZiE).

Neither the permissble bending strength stated in the TRLV nor the designing and dimensioning procedures prescribed there for the taking into account of climatic pressures may be used for the design and dimensioning of curved glazing units. Here, there apply essentially rather the determinations of the National Technical Approval (AbZ) bearing on the specific product(s).

The proofs of impact-resistance stipulated in Table 2 of the TRAV likewise do not apply to curved glass.

5.0 Building products

5.1 General remarks
In the following sections there are listed the various different curved building products, in accordance with the European product standards for flat glass units. By way of supplement to this, there are pointed up the relevant differences here between flat glass and curved glass, or the special characteristics of the latter.

In order to distinguish flat from curved glass, and to set the products off from one another as regards their inherent properties, we introduce here the abbreviation "c" (for "curved") as a supplement to the already-current abbreviations for glass building products.

5.2 Curved float glass (curved annealed glass, CA)
The starting product for curved float glass (CA) is described in EN 572-2. This European Standard defines float glass as a flat, transparent, clear or coloured soda lime silicate glass with parallel and fire-polished surfaces, manufactured by continuous pouring and flowing over a molten metal bath.

In addition, EN 572 also sees other basic-glass products, such as ornamental glass, wired glass, wired plate glass and profiled glass, as capable of being manufactured as curved-glass products. Here, however, the manufacturers should be consulted. The product standards for these products likewise refer only to flat glass.

5.3 Curved thermally toughened safety glass (CTS)
The European Product Standard EN 12150-1 describes only flat fully-toughened glass. However the "informative" section of this Standard (Annex B) says:

> *"Curved thermally-toughened soda lime silicate safety glass is a glass to which a fixed shape has been given in the course of the production process. It does not form part of the object of the present Product Standard, since the available data are not sufficient for standardization. Notwithstanding this fact, the information contained in the present Product Standard relative to thicknesses, edgework and fracture patterns can also be applied to curved thermally-toughened soda lime silicate safety glass."*

5.4 Curved heat-strengthened glass (CHS)
The European Product Standard EN 1863-1 describes only flat heat-strengthened glass. However the "informative" section of this Standard (Annex B) says:

> *"Curved heat-strengthened soda lime glass is a glass to which a fixed shape has been given in the course of the production process. It does not form part of the object of the present Product Standard, since the available data are not sufficient for standardization. Notwithstanding this fact, the information contained in the present Product Standard relative to thicknesses, edgework and fracture patterns can also be applied to curved heat-strengthened soda lime glass."*

It is especially to be noted that above all the fracture-pattern behaviour typical of flat heat-strengthened glass is not transferrable with exactitude to curved heat-strengthened glass. In Germany, a National Technical Approval is required for heat-strengthened glass and for laminated safety glass made from heat-strengthened glass.

5.5 Curved laminated glass and laminated safety glass (CL, CLS)
The European Product Standard EN 14449 describes only flat laminated glass and laminated safety glass.

For use in Germany, however, LSG must, in addition, comply with the requirements set by the Construction Products List A, Part 1, Item 11.14. That list defines LSG as a building product with interlayers made from polyvinyl butyral (PVB) or made from other interlayer materials the fitness for use of which has already been proven. To discover which interlayer other than a PVB interlayer it is permissible to use in curved LSG, the relevant National Technical Approval should be consulted.
Simple laminated glass, on the other hand, is a building product making use of interlayers or interstrata of a different type, the properties of which are not proven on the basis either of the Construction Products List or of a National Technical Approval.

5.6 Curved insulating glass units (CIG)
The European Product Standard EN 1279 is applicable to curved IGU with certain limitations. In Part 1 of EN 1279 (Section 4.6) we find the following formulation:

> *"Units with a bend radius of > 1000 mm are in compliance with the present Product Standard without having undergone the additional tests for curved test specimens. Units with a bend radius of 1000 mm or less are in compli-*

ance with this Product Standard where the further condition is fulfilled that curved test specimens with the same or with a smaller bend radius satisfy the requirements in respect of water-vapour diffusion set by EN 1279-2. The test specimens should be curved with the bending axis parallel to their longest side."

In principle, it is also possible to execute triple-glazed insulating glass units in the form of curved glazing. Here, however, the manufacturers should always be consulted first about feasibilities (i.e. in terms of size and scale, glass composition, glass types, technical indices etc.) and tolerances.

5.7 Designing with curved glass

In principle, the working of designs into curved glass – by means, for example, of enamelling, screen- or digital printing, printed films, sandblasting, fusing, or partial coating – is possible.
The resulting properties are to be determined individually, case by case, and the feasibilities and tolerances are to be clarified with the respective manufacturers.

6.0 Building Physics

6.1 General remarks

The Energy Performance of Buildings Directive (EPBD) formulates targets and guidelines aimed at reducing the energy consumption of buildings and increasing the use of renewable energy-forms. With this aim in view, the EPBD states, on a pan-European level, a series of minimum requirements, which can then be correspondingly altered or adapted within the individual EU member states. This means that, among other requirements, requirements are stated regarding the permissible primary energy consumption of a building. Germany's specific national implementation of this pan-European EU Directive, the Federal German Energy-Saving Ordinance (Energieeinsparverordnung, or EnEV), involves placing statutory requirements on, among other things, heat insulation, and heat-absorption in summer, for such building components as windows and façades.

6.2 Thermal insulation and solar control

Both curved and flat glazing units must satisfy the statutory requirements just referred to. It is possible that there may be applied here heat-insulation and solar-control coatings. Important particularly in the case of solar-control coatings are, besides the functional requirements, also the aesthetic ones (e.g. the reflectance of the coated glass, the specific colouring lent to the glazing unit by the coating or by the glass substrate).

When establishing required visual properties, use should be made right from the start, particularly in the case of larger-scale buildings and constructions, of samples prepared on the same scale as the actual building component, so as to come to an understanding with the manufacturer about the specific optical quality to be expected. An initial determination of the specific type of product required can, however, be carried out using so-called "hand samples", which have, as a rule, dimensions of 200 x 300 mm.

Just what possibilities exist as regards coatings is something which depends on the geometry of the glazing unit, the glass composition, its size etc. and will need to be clarified on a case-by-case basis with the manufacturer of the curved glass. Given the large number of the just-named parameters, no prior general determination of attainable Ug values, g values etc. is possible. The statement given of Ug values and of light and solar radiant heat factors is, as a rule, that for flat glazing units with the same glass structure. The procedure by which these values are arrived at is that stipulated in EN 673 and EN 410.

6.3 Sound insulation

The measurement of the sound insulation rating is carried out in accordance with EN ISO 140 and the establishment of the evaluated sound reduction index is carried out according to EN ISO 717. The measurement is effected on flat glazing units of the size: 1.23 x 1.48 m.

The transferral of these specifications to curved glazing is only limitedly possible, since the emitting surface is larger than in flat planes of a comparable size. Here, a test conducted by some appropriate testing institute is to be recommended.

7.0 Safety with glass

7.1 Special safety glazing

Flat as well as curved glass must fulfil requirements as regards resistance to manual attack, projectile attack, bullet attack and explosive impact. Whether every one of the just-named requirements – taking into account the window- and façade-construction – can actually be fulfilled, and whether testing procedures for flat glazing can be carried over and applied to curved glazing are questions that must be clarified on a case-by-case basis with the respective manufacturer, or a testing institute.

7.2 Proof against danger to the visiting public

For a glazing unit to be proof against danger to the visiting public means that, assuming a normal and proper use of said glazing unit, the risk of accident has been assessed and adapted to by means of appropriate construction measures.

Intended here is the safety of glazing units which are situated adjacent to areas where people regularly pass and assemble. That is to say, it may indeed be permitted that the building component glass shatter under the effect of some force, but the fragments of it which, in such a case, fall down into these areas may not be such as to lead to dangerous injuries among the passing and assembling public.

Responsibility for reducing the risk of accident to a minimum lies with the party commissioning the building or other work. The requirements relative to safety are to be set, or to be examined beforehand, by the planner, and are to be agreed and coordinated with the competent authorities. These safety requirements must also be fulfilled by curved glazing units, in the case where the latter are applied in a manner corresponding to that just described.

7.2.1 Appropriate glass products

The requirement that constructions be proof against danger to the visiting public can be fulfilled, as regards the area of glass, by means of a properly functioning glazing system and the application of safety glass. The Federal German Workplaces Ordinance (Arbeitsstättenverordnung, or Arb- StättV) and the rules and regulations of the Accident Prevention & Insurance Association must be complied with.

A generally important point of reference here is the document BGI/GUV–I 669 of the Federal German Statutory Accident Insurance. According to this document, the following types of glass fulfil the safety requirements and can be used as safety glass:

- thermally toughened safety glass and heat soaked thermally tougehened safety glass (in Germany ESG-H)
- Laminated safety glass, and
- Translucent plastics with comparable safety properties.

The glass referred to here is flat glass. Curved glass may, where conditions are right, be used as safety glass, provided that proof is provided of its possession of the properties required.
In the case of TG the properties concerned would be, among others, those relating to its behaviour during breakage; in the case of LSG they would be the properties of the interlayer, as stipulated by the Construction Products List, and, where required, residual load-bearing capacity. These properties must be confirmed to by a National Technical Approval or within the framework of an Exceptional Approval (ZiE).
In the case of statutory accident-prevention and statutory accident-insurance regulations, the insuring body may, in certain individual cases, need to be consulted regarding the use of the products.
That is to say, it must be ensured that the glass construction in question is appropriate for the intended application. Each separate area and aspect of its use must fulfil the requirements in terms of safety.

8.0 Visual quality

Basically the “Guideline to Assess the Visible Quality of Glass in Buildings” [3] is valid. In addition, however, to the allowable discrepancies named in Section 3 of this Guideline there are also allowable, in the case of curved glass: burn marks, coating defects, surface marks and impressions.

Tests of visual quality are conducted by diffuse daylight (e.g. during times of overcast sky), without direct solar radiation or artificial lighting, and from a distance of at least 3 m, looking from the inward side to the outward, and adopting an angle of observation which corresponds to the normal use of the room or space in question.

The transparency and the colour-impression are influenced by the curvature of the glass because the reflectance of curved glazing units is always, on account of optical laws, a different reflectance from that found in flat glass. Behaviour in terms of reflectance is influenced by the following criteria:

- The inherent reflectance of the basic glass
- Coatings
- Bend radius
- Bend-angles of large magnitude (e. g. more than 90°)
- Tangential transitions (see Fig. 7)
- Glass thickness

It is recommended that sample panes be made, so as to get an initial impression of the visual quality and optical effect.

9.0 Tolerances

The following tolerances apply to cylindrically curved glass. The tolerances listed in Table 1 have been established for a maximum edge-length of 4000 mm and a maximum bend-angle of 90°.

In the case of dimensions which exceed these, the manufacturer should be consulted. The tolerances cited are to be applied to all types of edgework. The quality of the edgework is, at a minimum, arrissed. All other types of edgework are to be agreed in writing before the awarding of the contract.

For special applications, e. g. in ship- and boat-building, as yacht glass or in furniture-making, the tolerances are to be agreed with the manufacturer.

All indicated tolerances refer to the glass edges.

	Glass thickness (T)	CA	CT/CHS	CL/CLS*	Double CIG	
Arc (A) / Height (L) ≤ 2000 mm	≤ 12 mm	+/- 2	+/- 2	+/- 2	+/- 2	mm
Arc (A) / Height (L) ≤ 2000 mm	> 12mm	+/- 3	+/- 3	+/- 3	+/- 3	mm
Arc (A) / Height (L) > 2000 mm	≤ 12 mm	+/- 3	+/- 3	+/- 3	+/- 3	mm
Arc (A) / Height (L) > 2000 mm	> 12mm	+/- 4	+/- 4	+/- 4	+/- 4	mm
Shape Accuracy (PC)**	-	+/- 3 mm/m Absolute value: min. 2 mm, max. 4 mm		+/- 3 mm/m Absolute value: min. 2 mm, max. 5 mm		
Straightness of upper edge (RB)	≤ 12 mm	+/- 2	+/- 2	+/- 2	+/- 2	mm per rm.
Edge straightness deviation (RB)	> 12 mm	+/- 3	+/- 3	+/- 3	+/- 3	mm per rm.
Twist deviation (V) ***	-	+/- 3	+/- 3	+/- 3	+/- 3	mm per rm.
Displacement (d)**** ≤ 5 m^2	-	-	-	+/- 2	+/- 3	mm
Displacement (d)**** > 5 m^2	-	-	-	+/- 3	+/- 4	mm
Position of drill-hole	-	-	EN 12150	EN 12150	-	mm
Glass thickness tolerance	-	EN 572	EN 572	-	-	mm

* In the case of CL/CLS the glass thickness is the sum of the individual glass thicknesses, not counting the interlayer.
The tolerances are valid for CL/CLS made from annealed float glass, thermally toughened glass (TG) or heat-strengthened glass (HSG).

** Curved glass must always be expected to display tangential transitions, along with bulges of the arc-shaped edges.

*** By reference to the longest edges of the glazing unit.

**** By reference to the upper edge and arc-shaped edge; the values stated here are valid for all types of edgework; the proper offset for drill-holes in CL and CLS is worked out with reference to this tolerance.

Table 1: Tolerances

Local bow

It is not necessarily possible to carry over the values cited in the product standards for flat fully-toughened glass and flat heat-strengthened glass and make them apply to curved glass, since said values depend on, among other factors, glass size, geometry, and glass thicknesses. In individual cases, these tolerances are to be discussed and agreed with the manufacturer.

Shape accuracy (PC)

The term “trueness to contour” designates the degree of precision of a bend. All the edges of the contour are subject to a 3 mm inward or outward offset. The actual bend-contour must not deviate in any greater measure than this from the ideal contour. (see Fig. 2). When testing trueness to contour, it is permissible to average out the glass within this ideal contour

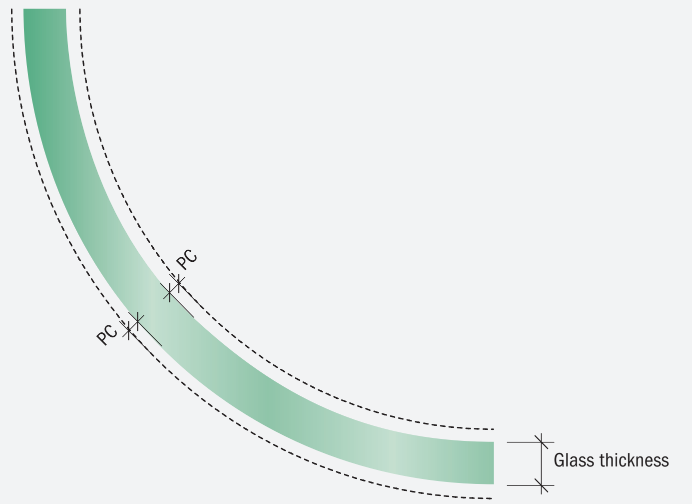


Fig. 2: Schematic representation of shape accuracy (PC)

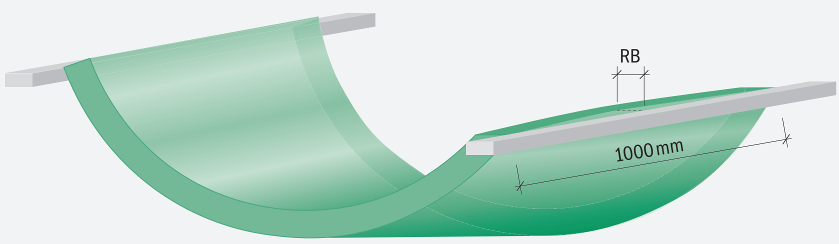


Fig. 3: Straightness of Upper Edge (RB)

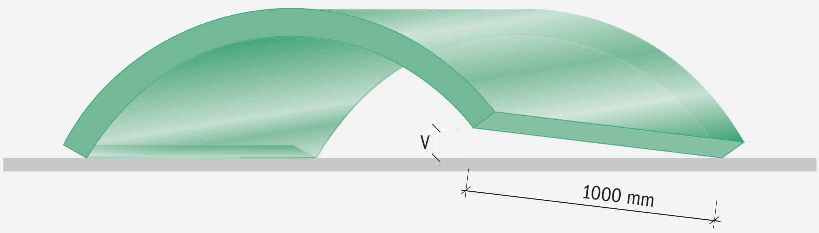


Fig. 4: Schematic representation of twist deviation (V)

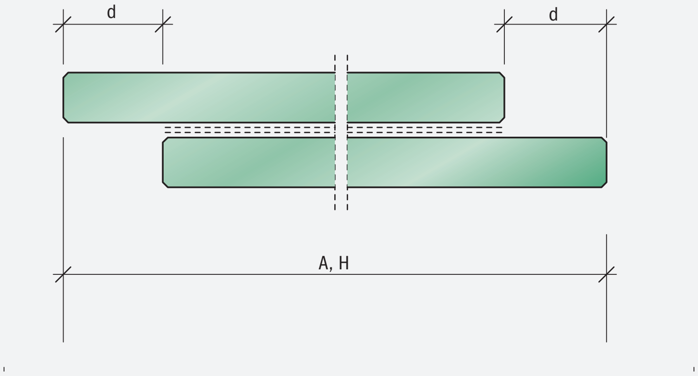


Fig. 5: Displacement in CL/CLS (d)

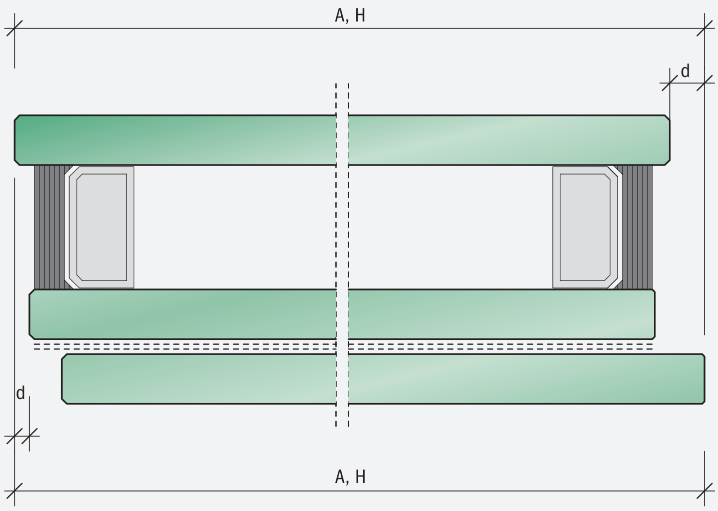


Fig. 6: Displacement in CIG (d)

Twist deviation (V)

The term “torsion” describes the exactness of the parallelity of the upper edges in the glass’s bent condition. In curved glass, torsion must not exceed +/- 3 mm per running metre (straight edge) (see Fig. 4). To this end, the glass must be laid with its upper edges on a flat surface and tested (convex position or N position).

Tangential transitions

A tangent is a straight line which touches a given curve at one particular point. A tangent is perpendicular to that radius with which it is associated.

If there were not a tangential transition the glass would have a kink in it! This is, indeed, technically possible, but not to be recommended. At the point of the kink there emerge higher tolerances than at a point of tangential transition.

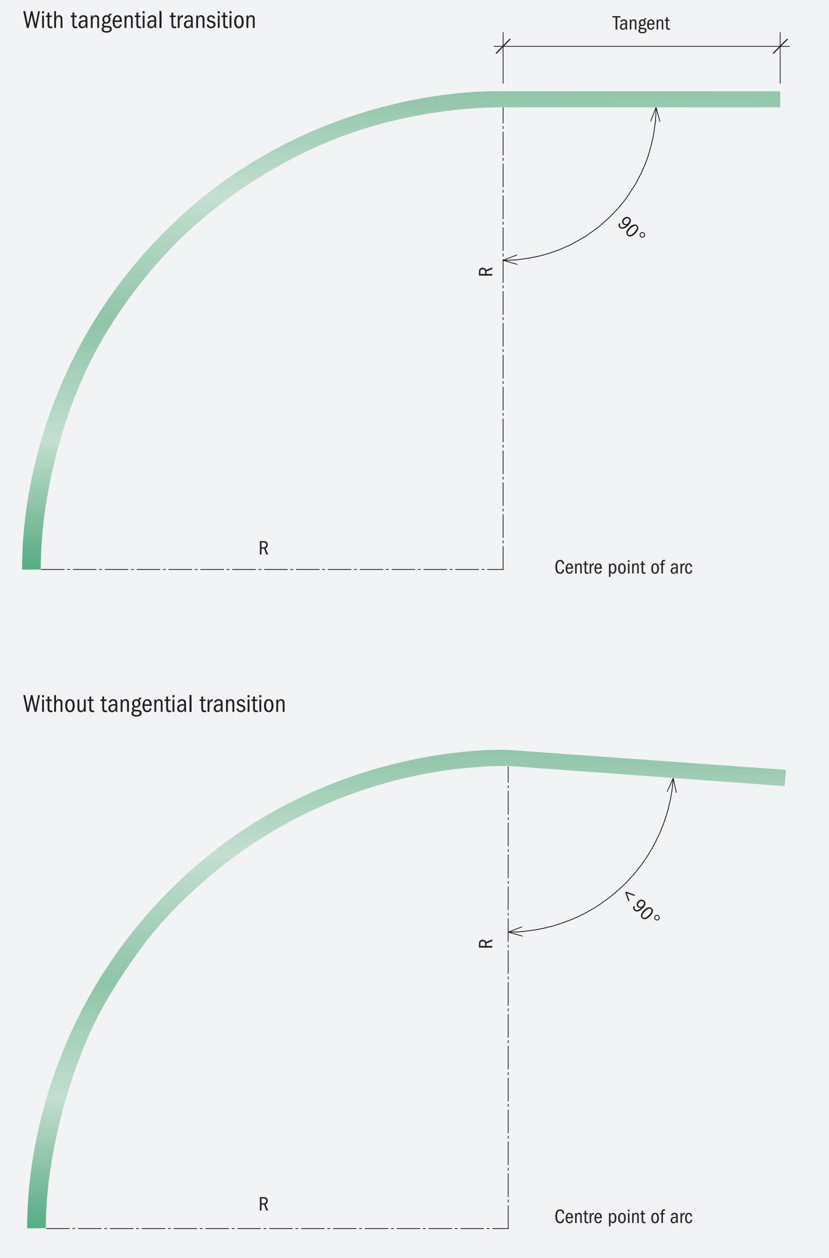


Fig. 7: Tangential transitions

10.0 Dimensioning

10.1 Peculiarities in structural physics as compared to flat glass panes

Shell load-bearing capacity of curved glass
The calculation of stress and deformation phenomena in curved glass panels is to be conducted by means of an appropriate finite element model according to the "theory of shells" in structural mechanics. This model must be capable of representing the geometry of the pane, in particular its curvature.

A simplified calculation of the curved glass panels as if it were a matter of flat glass panels will lead necessarily to false stress and deformation values.

When establishing the necessary glass thickness, the curvature can sometimes, depending on the positioning conditions in the case of single-glazing units (monolithic glass, LG, and LSG), prove advantageous, since the shell load-bearing capacity can be taken into account.

10.2 Climatic pressures applying to curved insulating glass

In the case of insulating glass units it is compulsorily necessary to take the curvature of the glass into account, since insulating glass's higher resistance to bending can result in extremely heavy climatic pressures (inner load). The advantage gained in terms of the shell load-bearing capacity of curved single glazing units is not so great when they are constructed in the form of insulating glass units as it is in their application as single glazing.

A proof in terms of structural engineering of these high levels of pressure and stress is only possible where a value for the glass curvature has been arrived at and can be used in the calculation. The climatic pressures in question may not be determined on the basis of the "Technical Regulations for the Use of Glazing with Linear Supports" ("TRLV") [1], since these climatic loads are derived from plate theory as this applies to flat panes of glass.

Particularly close attention is to be paid to the dimensioning of bent insulating glass units with flat extension pieces, since the flat area of the whole is significantly more flexible than the bent area.

Due to the greater climatic pressures affecting curved insulating glass units , the load that is placed on the edge seal of this glass is greater, as compared to flat insulating glass. The edge seal is to be constructed in a way that takes account of this fact. This in turn can affect the width of the edge seal or the requisite glass bite. All this is to be taken into account already at the stage of planning and design.

10.3 Bases of calculation

Characteristic bending tensile strengths
For flat glass panes, the characteristic bending tensile strengths are established in the product standards or National Technical Approvals (e.g. for HSG). At the present time, the use of curved glass panes is only possible where an Exceptional Approval has been granted or where the product used is the subject of a National Technical Approval. If tolerances in respect of permissible stress levels are already defined in a National Technical Approval, these can be used directly in working out dimensioning. If the values listed are characteristic values, then the manner of proceeding should be the same as when using values derived from experiments.

Where a curved glass without National Technical Approval is used, there should be confirmed, in consultation and coordination with the competent Senior Building Supervisory Authority of the German federal state concerned, those characteristic bending tensile strengths which are cited by the respective manufacturer and which form the basis of the dimensioning. These bending tensile strengths should have been established beforehand by a testing institute.

The basis for this is a well-founded statistical evaluation of experiments with a correspondingly sufficiently large number of test objects (e.g. 20 objects).
A description of how the experiments were conducted is given in [4] and [5] .

The experiments should be conducted with test pieces constituted in such a way that the results they yield can be transferred to the construction in question.

Account should be taken, already during the phase of planning of time and calculation of costs, of the effort and expenditure required to plan and conduct these experiments. For a provisional dimensioning there can be used the characteristic bending tensile strengths fk given in Table 2. On the basis of the general safety concept outlined in the "Technical Regulations for the Use of Glazing with Linear Supports" (TRLV) [1] the permissible bending tensile strengths can be established, with a certain safety factor, in reliance on the TRLV, provided that coordination with and adaptation of the latter are conducted in accordance with professional engineering standards.

In individual cases, this procedure is to be coordinated with the competent Senior Building Supervisory Authority of the German federal state concerned.

Glass Type	f_k (N/mm^2)	
	Glass surface	Glass edge
Curved float glass (CA)	40	32
Curved heat-strengthened glass (CHS)	55	55
Curved thermally toughened safety glass (CT)	105	105

Table 2: Typical Bending Tensile Strengths, Cited from (4)

10.4 Fitness for use

10.4.1 Limitation of the degree of deflection of the glazing

Deflection in the curved glazing is to be restricted in such a manner as to ensure that any slipping of the glass out of its sill boards is safely prevented and that the criteria for fitness-for-use are fulfilled.

10.4.2 Limitation of the degree of deflection in the substructure

Standards and specifications applicable to flat glazing units are not to be carried over and applied to curved glazing units, since minimal deformations of the substructure tend to exert significantly greater effects upon curved panes than they do upon comparable flat-glass panes. For this reason, the behaviour of the substructure must, when carrying out dimensioning work from a structural-engineering perspective, quite definitely be taken into account.

11.0 Storage and transport

The glazing units must, in accordance with their geometry, be stored and transported in an upright position which will result in the least amount of stress and strain being placed on them. The manufacturer's specifications are to be complied with.

The materials that they are placed on, or that are used to support them and keep them from tipping over, must always be such as not to cause any damage to the edge seal of the CIGs or to the glass itself.

The glazing units must also never, not even for a short period, be set down on a hard surface, such as for example a concrete or stone floor.

During handling and setting in place, care must be taken to ensure that the edge seal and the glass edges are not damaged, since even very slight damage to the edges of the panes, which might not be immediately noticeable, can nonetheless be the cause of pane breakage at some later point in time.

As a general principle, glass units must be protected against damaging chemical or physical effects on site. All glass units must be protected against prolonged exposure to moisture or solar radiation by means of a suitable full-size cover.

The transporting of heavy glazing units must be conducted in such a manner that all the individual panes are held steadily and evenly in place. The lifting, for a short time, of the glazing unit by just a single one of its constituent panes, in order to handle it or set it in its place, is possible, but should be effected with the aid of appropriate equipment.

When transporting CIGs to, or through, high altitudes above sea level the use of a pressure compensation valve may be necessary. This is because of the possible pressure difference between the cavity of the CIG and that of the ambient environment (this depends on the height above sea level of the place where the IGU was manufactured). This is to be stated at the time of placing the order with the glass manufacturer.

12.0 Glazing

12.1 General remarks

The glazing guidelines formulated for flat glazing units are, in principle, also applicable to curved glazing units. However, given the special behaviour characteristic of curved glass, the supplementary instructions and indications provided by the manufacturer are also to be complied with.

12.2 Instructions in respect of design and construction matters

On account of its high degree of stiffness the tolerances of curved glass (see Ch. 9) must definitely be taken into account already at the time of its design and construction, so as to ensure that the glass can be positioned and set in place without any forcing or straining.
It is also necessary that the glass be stored in a manner which is likewise free of all forcing or straining, so as to avoid glass breakage or, in the case where the glass being used is a curved IGUs, overstraining of the edge seal. In addition, storage which does not take care to avoid forcing and straining may lead to impairment of the glass's visual qualitiy.
The substructure must satisfy the special requirements bearing on curved glazing units. Necessary here are sufficiently well-dimensioned rebates in frame constructions and façade constructions.

12.3 Necessary rebate width

The minimum required rebate width = (total glass thickness + tolerance derived from trueness to contour) + 6 mm.
Glass thicknesses are to be taken into account in the form of nominal dimensions. In addition to this, the specifications stated in DIN 18545 [6] are also to be complied with.
Furthermore, the tolerances relative to the substructure are also to be taken into account.

It is recommended that the window and façade systems be executed using the wet-sealing method.

The manufacturers of curved glass should be drawn into the planning process early on, so as to allow the special features and properties of curved glass units to be taken into consideration from the design and construction viewpoint. This is especially necessary also for the application of curved glass in the area of structural glass engineering.

13.0 Blocking

The basic principles involved in the placing of glazing blocks are described in [7]. The system of glazing blocks must conduct the dead load of the glazing unit safely into the substructure. The glazing units do not, as a rule, themselves take on the task of bearing loads originating within the structure. In the case where it is intended that the glazing units should indeed take on the function of bearing loads or weights originating in the structure, this must be taken into account already at the stage of planning out the basic structural-engineering principles that will apply in the given project. The glass manufacturer or system provider should also be contacted and consulted here.

In all systems using curved glass units both a circulating water vapour pressure equalization and a permanent drainage must be ensured. Glazing block placement is itself a task which belongs already to the planning stage and should be carried out before the execution of the assembly work.

The location block placed in the middle (see Fig. 8) serves to stabilize the glazing unit and to prevent its tipping over during the process of assembly. Once the glazing unit has been fixed in place, this location block must be removed again.

Curved single glazing or insulating glazing units installed in a vertical position must have their glazing blocks placed in the same manner as these are placed in the case of flat panes. In System 1 the weight of the glass is conducted away onto the lower curved glass edge, via the setting blocks, into the frame structure and then on into the retaining structure (see Fig. 8).

In the case where installation positions deviate from the one just described – for example, in the case of glazing installed at a sloped or inclined angle – the manufacturer or planner should be contacted.
In System 2 the effects of glass-weight and wind-load are exerted in a manner that is spread out along the glass edge (see Fig. 9).

This must be taken especially into account when setting up the system of supports and bearings. The constructions described above represent only a selection from among a series of possible situations. In cases where other profiles or section are set into the insulating glass edge seal – as, for example, in the case of spherical bending – or where the glass is applied as part of structural glazing, the manufacturer must in every case be contacted and consulted.

For curved glazing units, the following recommendations in respect of glazing block placement are also made:
The placing of setting blocks must be carried out in such a manner that the glazing unit is in a state of equilibrium and cannot tip over. This means that the setting blocks must be arranged in such a way that a line connecting the central points of the two glazing blocks cuts across the line of the centre of gravity of the glazing. At this point of maximum load the dead load of the glazing unit is conducted away into the surrounding structure.

Positioning is dependent on geometry, size, and glass construction. The position of the setting blocks must be taken into account in the dimensioning of the substructure.

13.1 Definitions

T = Setting block, conducts away the weight of the glazing unit. Blocks consisting of elastic material of approx. 60-80 Shore A hardness and a load-capable substrate.

D = Location block, ensures that a distance is maintained between glass-edge and rebate base. Blocks likewise consisting of elastic material with approx. 60-80 Shore A hardness. The weight is taken over by the setting blocks alone. The distance maintained from the corner of the glass should correspond to the regular distance of 100 mm.

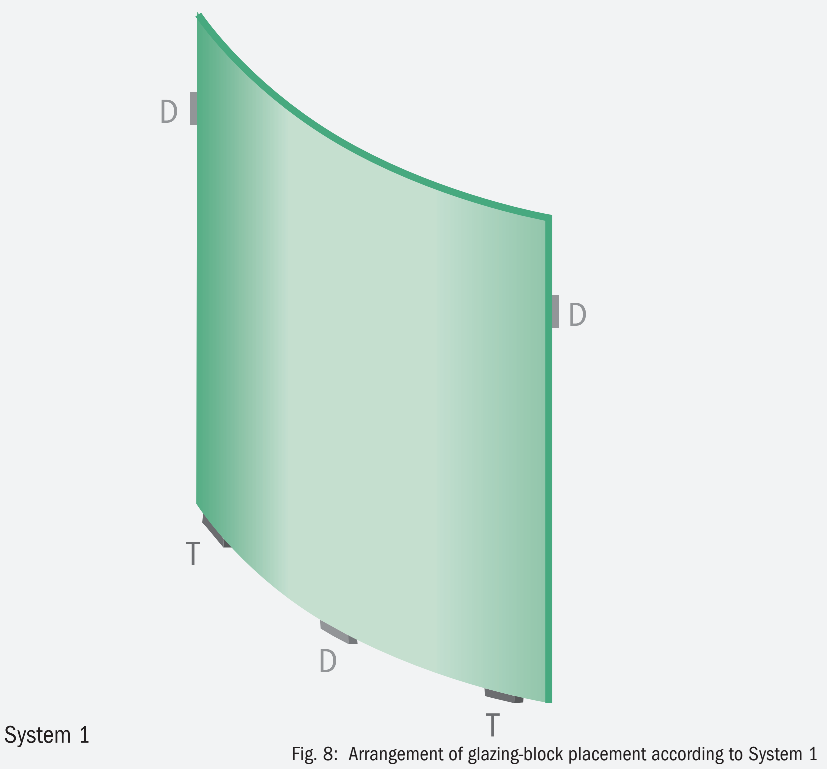


Fig. 8: Arrangement of glazing-block placement according to System 1

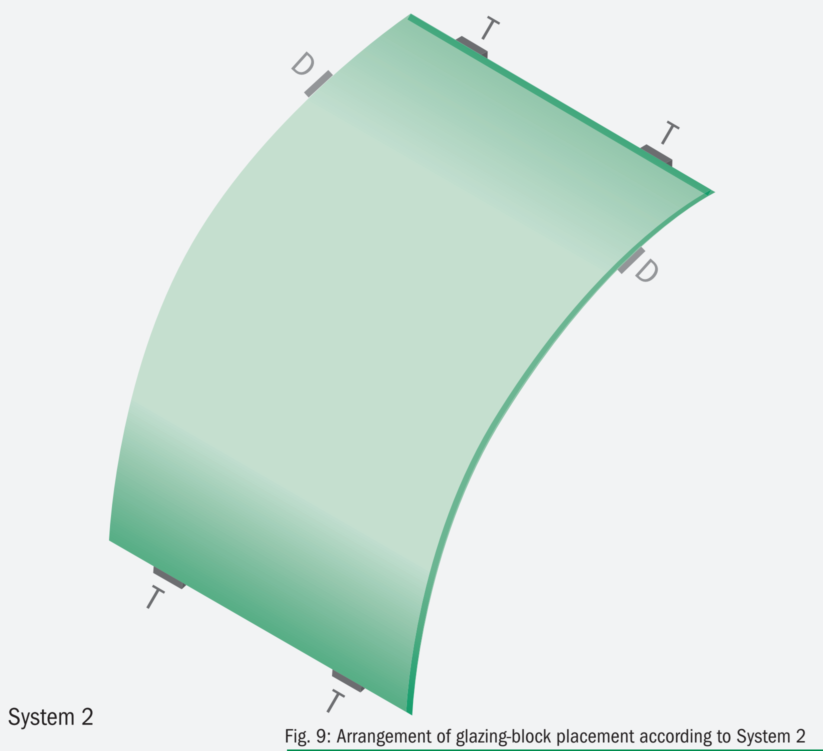


Fig. 9: Arrangement of glazing-block placement according to System 2

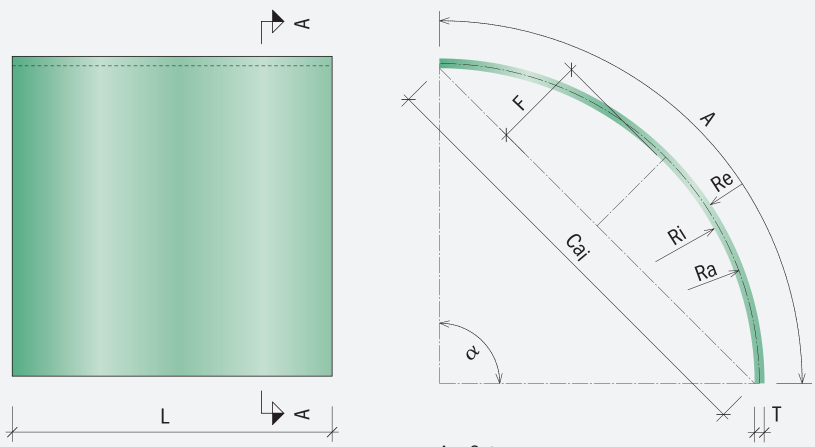
14.0 Measurement

So as to manufacture the end-product wished for, it is very important in the case of curved glass that a very precise measurement be carried out and that there be stated information of various sorts bearing on dimensions etc. In the case of cylindrically curved glass units, regardless of the type of glass planned for, the parameters listed below must necessarily be stated, so as to allow the determination of a technically feasible and economically advantageous solution.

This involves the stating of at least two of the values listed below:

- Arc
- Bend radius
- Rise (inner or outer)
- Angle.

In addition, there should be stated the length of the straight edge as well as the number of panes.



A = Outer arc
Ra = Radius to middle of pane (= neutral arc)
Ri = Inner radius
Re = Pitch
F = Rise
Cai = Chord (internal)
α = Angle
T = Glass thickness

Fig. 10: Measurement

15.0 Literature

[1] TRLV:2006-08 - Technical Regulations for the Use of Glazing with Linear Supports. Deutsches Institut für Bautechnik, Berlin

[2] TRAV:2003-01 - Technical Regulations for the Use of Fall-Proof Glazing. Deutsches Institut für Bautechnik, Berlin

[3] Guideline to Assess the Visible Quality of Glass in Buildings. Bundesverband Flachglas e.V., Troisdorf, 05/2009

[4] Bucak, Ö., Feldmann, M., Kasper, R., Bues, M.Illguth, M.: Das Bauprodukt "warm gebogenes Glas" – Prüfverfahren, Festigkeiten und Qualitätssicherung. (The building product "Thermally curved glass": testing procedures, consistencies, and quality assurance) Stahlbau Spezial (2009) – (Special Edition on Steel Constructions (2009), pps. 23 - 28

[5] Ensslen, F., Schneider, J., Schula, S.: Produktion, Eigenschaften und Tragverhalten von thermisch gebogenen Floatgläsern für das Bauwesen – Erstprüfung und werkseigene Produktionskontrolle im Rahmen des Zulassungsverfahrens (Production, properties, and load-bearing behaviour of thermally curved float glass for the building industry – Initial testing and production-site self-supervision in the context of Official Approval Procedures). Stahlbau Spezial (2010) – (Special Edition on Steel Constructions (2009)), pps. 46 - 51

[6] DIN 18545: Sealing of glazing units with sealants – Part 1: Requirements with respect to glass rebates. Beuth-Verlag, Berlin, 02/1992

[7] Technical Directive No. 3 of the Institute of Glazing: Blocking of Glazing Units. Verlagsanstalt Handwerk GmbH, Düsseldorf, 7th Edition, 2009

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17.0 Standards, regulations and directives

EN ISO 140- 3: Acoustics – Measurement of sound insulation in buildings and in building components – Part 3: laboratory measurements of airborne sound insulation of building components

EN 356: Glass in building – security glazing – testing and classification of resistance against manual attack

EN 357: Glass in building – Fire resistant glazed elements with transparent or translucent glass products – Classification of fire resistance.

EN 410: Glass in building – Determination of luminous and solar characteristics of glazing

EN 572: Glass in building – Basic soda lime silicate glass products

EN 673: Glass in building – Determination of thermal transmittance (U value) – Calculation method.

EN ISO 717-1: Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation

DIN 1055: Actions on structures

EN 1063: Glass in building – Security glazing – bullet-resistant glazing – classification and test method

EN 1096: Glass in building – coated glass, high-rise construction – sealants for joints – classification and requirements for sealant masses

EN 12150: Glass in building – thermally toughened soda lime silicate safety glass

EN 1863: Glass in buildings – heat strengthened soda lime silicate glass

EN ISO 12543: Glass in building – laminated glass and laminated safety glass

EN 14179: Glass in buildings – heat soaked thermally toughened soda lime silicate safety glass

EN 14449: Glass in building – Laminated glass and laminated safety glass

DIN 18008: Glass in building – design and construction rules

DIN 18032: Sport halls – halls for gymnastics and games

DIN 18361: Glazing works

EN 20140: Acoustics – measurement of sound insulation in buildings and in building components

BF (Bundesverband Flachglas) guidelines

- Guideline to assess the visible quality of glass in buildings
- Guideline to asses the visible quality of enameled and screen printed glasses
- Compatibility of materials as relating to insulating glass and associated topics
- Compass for sealant-bonded windows
- Guidelines for the handling of multipane insulating glass units

Fact-sheets from the association: Fenster und Fassade e.V.

- Uniformity of colour in transparent glass units in the building industry
- Installation recommendations for safety and security glass in the building industry
- Glass joints and all-glass corners in windows and facades

Technical Guidelines of the Federal Association of German Glazing Guilds, Hadamar

Pamphlet 1 Sealants for glazing units and adjacent joints
Pamphlet 3 Glazing-block placement in glazing units
Pamphlet 8 Making glass proof against danger to the visiting public
Pamphlet 9 Principles for the visual testing and evaluation of glazing in buildings
Pamphlet 10 Technical concepts from the area of glass handicraft
Pamphlet 14 Glass in building – classification of glass products
Pamphlet 17 Glazing with insulating glass
Pamphlet 18 Fall-proof glazing according to the stipulations of the TRAV
Pamphlet 19 Glazing with linear supports and secured at individual points
Pamphlet 20 Guidelines for the assembly of windows and house doors

Fact-Sheets from the Federal German Statutory Accident Insurance

- GUV-SI 8027 More safety in cases of glass breakage
- GUV-VS 2 Nurseries and day-care centres
- BGI/GUV-I 669 Glass doors, glass walls
- GUV-VS 1 School buildings
- GUV-VC 9 Cash offices

18.0 Further reading

- Runkel, H.-W., Scheideler, E.: Gebogenes Glas – Herstellung und Statik. (Curved glass – Manufacture and structural-engineering properties). Sonderdruck aus Glaswelt 6 und 8/2000 (Special Edition reprinted from Glaswelt 6 und 8/2000), Gentner-Verlag, Stuttgart
- Feldmeier, F.: Klimabelastung und Lastverteilung bei Isolierglas (Climatic Stress and load distribution in insulating glass). Stahlbau 75 (2006), Vol. 6, Ernst & Sohn, Berlin
- Bucak, Ö., Schuler C.: Curved glass. Ch. 6, Glas im konstruktiven Ingenieurbau (Glass in civil-engineering construction) Stahlbau Yearbook (2008), Beuth-Verlag, Berlin
- Elstner, M., Schäfer, S.: Herausforderung gebogene Gläser (The challenge of curved glass units). Glas + Rahmen, Verlagsanstalt Handwerk GmbH, Düsseldorf, 09/2010
- Ensslen, F.: Gebogenes Glas – Herausforderungen für Anwender (Curved glass – challenges for the user) Glaswelt, Genter-Verlag, Stuttgart, 10/2010

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