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Determination of Bending Tensile Strength of Thin Glass

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Glass with a thickness of 0.55 up to 2.0 mm can be defined as a thin glass or even as ultra-light. On the market there are several suppliers, which offer such thin glass. On the one hand there are e.g. Gorilla Glass produced by Corning Incorporated or Leoflex by AGC, which are pre-stress by chemical treatment and on the other hand there are soda lime silicate glass products, which are pre-stress by thermal or chemical treatment. Not only the design with thin glass causes a totally new kind of thinking, also possible test scenarios for determination of the ultimate bending strength are currently not distinctly regulated in standards. Some existing test set-ups described in standards e.g. EN 1288 (four-point bending test or large ring on ring test) cannot be used for the determination of the ultimate bending tensile strength of thin glass. Different test set-ups published in several papers show possibilities for alternative determination of ultimate bending strength. These different configurations were investigated and analyzed for their applicability for determination of bending strength of thin glass. This paper gives a summary of theoretical investigation and shows results of experimental testing.

Keywords: Thin Glass, Bending Tensile Strength, Ring on Ring Test, Four Point Bending Test

1. Introduction

Everybody knows thin glass in application as a screen for laptops, tablets or mobile phones, but an application of such a glass in building is relatively new and an interesting topic for the future. Glass with a thickness of 0.55 up to 2.0 mm can be defined as a thin glass or even as ultra-light. On the market there are several suppliers, which offer such a thin glass. On the one hand there are e.g. “GORILLA GLASS” by Corning Incorporated or “LEOFLEX” by AGC, which are pre-stress by chemical treatment and on the other hand there are soda lime silicate glass, which is pre-stress thermally or chemically.

The design with thin glass causes a totally new kind of thinking. This thin glass is very weak against local bending stresses and has a large capacity against membrane stresses. For this reason structures with less portion of local bending stresses and large part of membrane stresses had to be found. Such structures are more or less curved structures. For example cylindrically or conically shaped geometries of glass are favorable for such transfer mainly by membrane forces (Neugebauer, 2015).

A nice example for an application made from thin glass is the movable canopy, which was presented on Glasstec in Düsseldorf 2014.

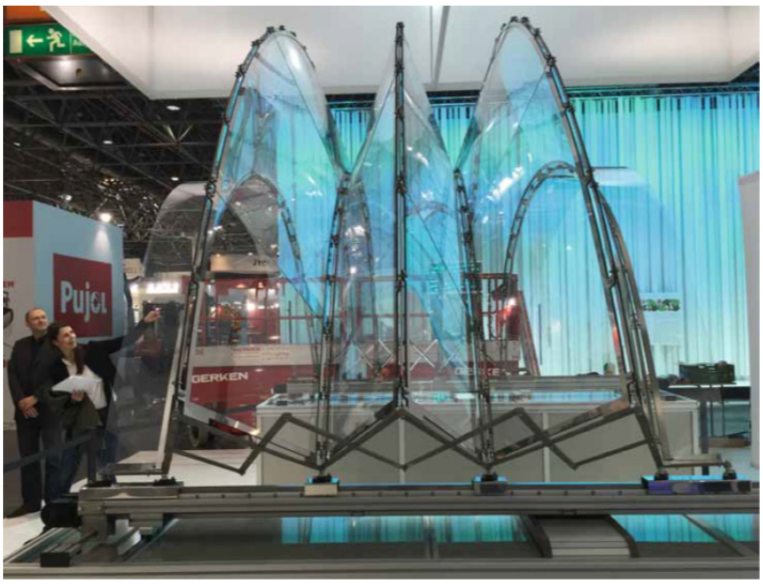


Fig. 1 Movable canopy at Glasstec in Düsseldorf.

The question for a structural designer is how to get values of the ultimate bending strength, which can be used for a structural design.

2. Production of thin glass

2.1. Float glass process

Float glass is a sheet of glass made by floating molten glass on a bed of molten tin. After a controlled down cooling process the glass is cut into certain sizes, as typically known as jumbo size. This method gives the sheet a uniform thickness and very plane-parallel surfaces.

2.2. Dawn draw process

The molten glass flows through a small gap at the bottom of the melting tank down and is down cooled by annealing furnaces. After this controlled down cooling process the glass is cut into certain sizes [Neugebauer].

2.3. Overflow fusing process

The molten glass is poured into an overflow gutter. From this gutter the molten glass flows on both sides down and fuses at the bottom point of the gutter. After a down cooling phase the glass is cut into panels with certain sizes [Neugebauer].

3. Pre-stressing of glass

To increase the ultimate bending strength, the glass can be pre-stressed. With a thermal or chemical treatment are mainly two different possibilities available for the pre-stressing of glass.

3.1. Thermal treatment

In figure 2 below two different possibilities for a thermal treatment are shown. The left sketch illustrates the typical process in which the glass is moved on rollers forwards into the heating zone and is heated up above the transition point. After this heating process the glass is blown up with air. During this down cooling process the glass is permanently moved forwards and backwards. The thinner the glass the more so called roller waves can occur.

For this reason the Austrian company LISEC has investigated a new process in which the glass is transported on air cushion, as shown in figure 2 right. With this technique it is possible to pre-stress a thinner glass by thermal treatment without roller waves.

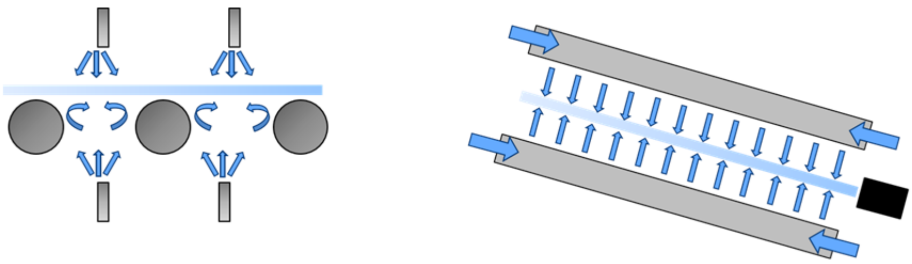


Fig. 2 Thermal treatment.

3.2. Chemical treatment - Ionic Exchange

Another possibility to pre-stress the glass is the chemical treatment. The glass is immerged into molten potassium nitrate. At a temperature of approx. 370 - 400°C the effect of ionic exchange takes place. The smaller sodium ions diffuse from the glass into the liquid potassium nitrate and the larger potassium ions penetrate into the glass matrix, as shown in figure 3. Due to the larger ionic diameter of potassium ions a compressive stress in the close up range of the surface results. The depth of penetration is around 50 - 100 μm.

Different suppliers give numbers for ultimate bending strength. Corning Incorporated shows in their data sheet for the "GORILLA GLASS" a compressive stress (pre-stress) of 600 MPa and AGC for the "LEOFLEX" a compressive stress 800 MPa (Neugebauer, 2015).

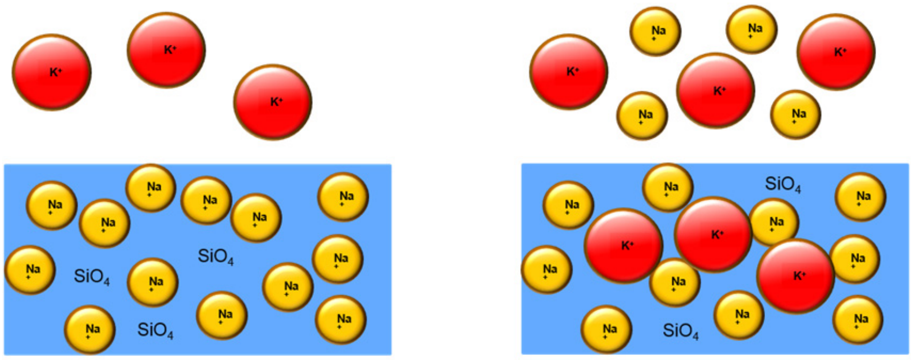


Fig. 3 Chemical treatment – Ionic Exchange.

The values for ultimate bending strength, which are the basis for a structural design, are still missing. Therefore a couple of different test scenarios were investigated for their applicability for determination of ultimate bending strength of thin glass.

Due to the application one has to differ between test scenarios with and without the influence of the edge strength (edge quality) – the so called edge effect. In the following a couple of possible test scenarios are described.

4. Determination of ultimate bending strength without influence of edge strength

All sides simply supported glass elements e.g. window glass, are good examples for application where the edge effect has not be taken into account. Because the maximum stress arises in the middle of the glass pane. At the edges tiny stresses arises and therefore the influence of the edge strength has not be taken into account.

4.1. Ring on ring test

The test set-up is performed by placing the glass sample on a circular steel reaction ring and applying on its upper surface a load transmitted through a steel loading ring, until the glass breaks, as shown in figure 4 left below. The purpose of this test is to achieve a uniform tensile stress field inside of the loading ring that is independent of edge effects. The area with a uniform stress can easily be described with the area inside the loading ring.

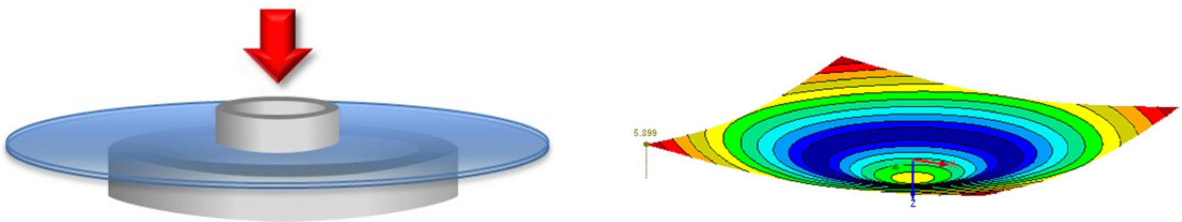


Fig. 4 Ring on ring test set-up, deformation of glass sample.

Such test set-ups are defined e.g. in EN ISO 1288-2 for large surfaces [EN ISO 1288-2] and EN ISO 1288-5 for [EN ISO 1288-5] for small glass samples.

The test set-up for large surfaces defined in part 2 is not usable, because the deflection of the glass is much too high. The test scenarios (R 30, R 45, R 60 and R 105) defined in part 5 of EN ISO 1288 are more or less applicable for determination of bending strength of thin glass. But effects like as size effect, geometrical non-linearity or imperfections influences the results very much and have to be considered. Due to the thinness of the glass the geometrical non-linear effect becomes dominant in the this test scenario, this is also mention in [Wilcox]

Pressure pat on ring test

As a possible improvement of the ring on ring test a pressure pat on ring test was investigated. The test set-up is performed by placing the glass sample on a circular steel reaction ring and applying on its upper surface a load transmitted through pressure pat instead of the loading ring, until the glass breaks, as shown in figure 5 left below.

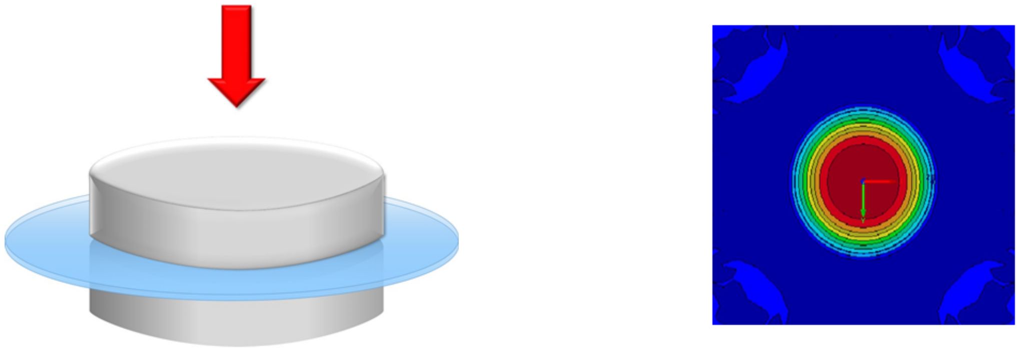


Fig. 5 Pressure pat on ring test set-up, distribution of principle stress.

The benefit of this scenario is that stability and buckling effects (described later in chapter 10) are minimized and the area in which the stress can be assumed as uniform can be increased in comparison to a ring on ring test. A disadvantage is that the stress inside the supporting ring, as shown in figure 5 right, cannot be assumed as uniformly, therefore an effective area A_{eff} has to be determined according equation (6) in chapter 9.

5. Determination of ultimate bending strength with influence of edge strength

On two opposite sides simply supported glass elements e.g. room-high façade elements are good examples for application where the edge effect has be taken into account. The reason for this is that in such cases edges are bended and get bending stress at these edges.

5.1. Four-point bending test

Figure 6 shows the principle test set-up for a four point bending test according EN ISO 1288-3 [EN ISO 1288-3]. The test specimen with a length of 1100 mm and a width of 360 mm is supported on two supporting rollers with a distance of 1000 mm. On its upper surface a load transmitted through two additional rollers is applied until the glass breaks.

As it can be seen easily in figure 6 right, large deflections result and the bearing forces are no longer vertical but inclined. The glass pane distributes its bearing force only by contact and eventually by friction between glass and rubber (EPDM). A simple resolution (breakdown) of the force to vertical and horizontal force shows that with increasing deflection also horizontal components is increasing. And this has a growing influence on bending moment and therefore on the bending tensile stress.

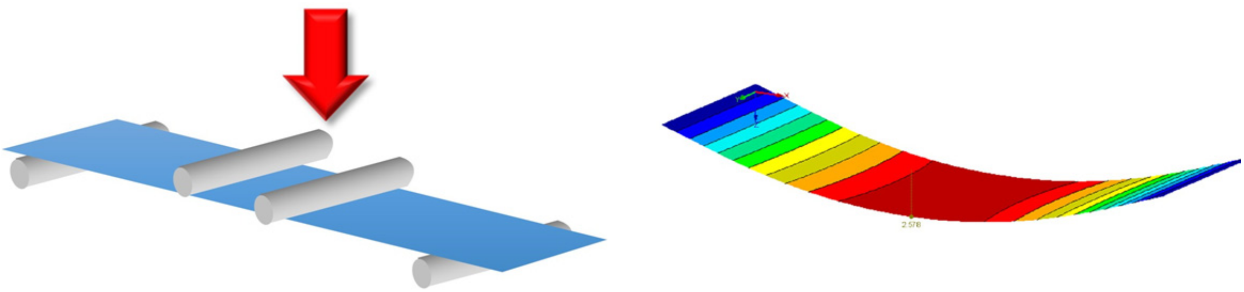


Fig. 6 Four-point bending principle test set-up, deflection of test specimen.

Due to the thinness no breakage of these thin glass panels can eventually be reached, because of slip from bearing rollers due to bowstring effect (distance of rollers is constant but end of panes move towards) or on some testing machines reach of maximum piston stroke. For evaluating testing results simple formulas are given, derived from simple linear theory, but are not applicable for thin glass, because of the geometric non-linear effect of large deformations.

5.2. Multiple point bending

To be able to use the well-known format of 1100 x 360 mm for bending test also for thin glass two possibilities for modifications given for the four point bending test are possible. On the one hand modify the distance of bearing and eventually loading rollers and on the other hand introducing additional rollers for bearing as well as for loading.

Figure 7 left shows a possible set-up with 4 pairs of loading rollers on the top and appropriate bearing rollers on the bottom of the test specimen. The number of rollers is evaluated in a way, that an area in total with a uniform tensile stress like with standard four point bending test set-up is achieved. Figure 7 right gives an impression of the distribution of bending stress. Due to disadvantages of tensile stress arises on both surfaces - top and bottom, with the meaning the tensile stress arises in the zone below the pairs of loading rollers on the bottom surface and over the bearing rollers on the top surface. This set-up induces alternative tensile stress on lower and upper surface (Siebert, 2013).

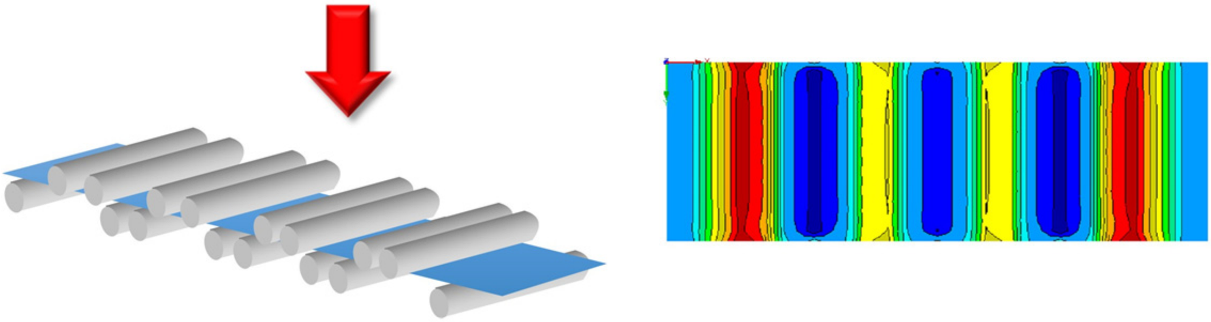


Fig. 7 Multi-point bending test set-up, stress distribution.

Due to the alternative tensile stress distribution (top and bottom surface of the specimen) the determination of the effective area A_{eff} (according equation (6) in chapter 9), which represents a homogeneous stress has to be validated by experimental testing.

6. Bending by in-plane force

The value for the ultimate bending strength can for example be determined with a kind of a stability test, as shown in figure 8 below. With the force *F* and eccentricity *e* the maximum stress can be determined according the theory of large deformations. Instead of inducing bending by loading perpendicular to test specimen an alternative concept applies the load in plane of the test pane with bending due to deflection. Figure 8 shows the principle of the test set-up and gives an impression of stress distribution and deflection. The determination of bending moment and bending stress can be derived e.g. by using theory of large deformations, implemented in FE programs (Siebert).

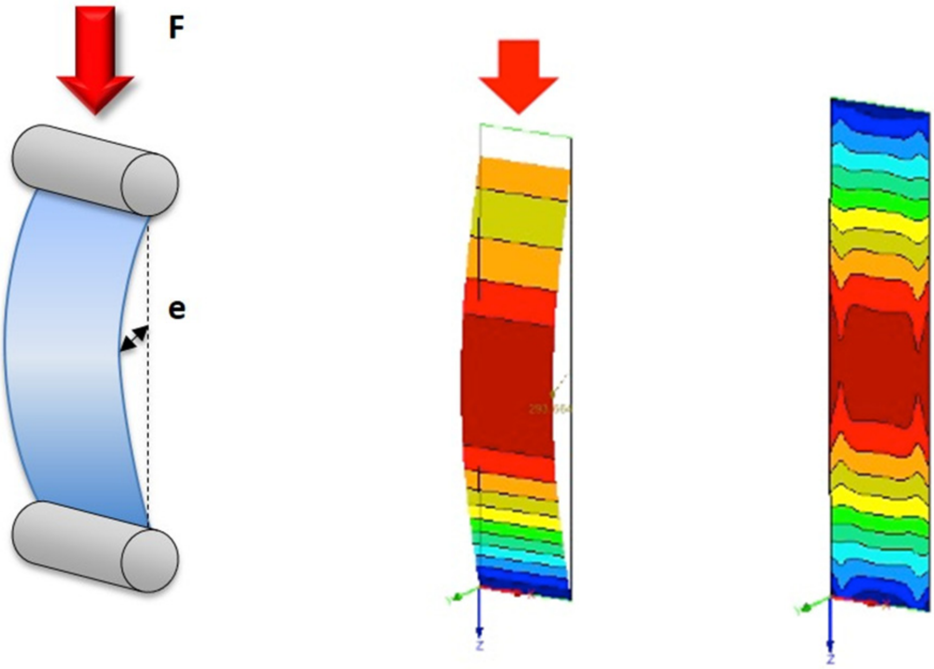


Fig. 8 Principle test set-up for bending in-plane force, defection and stress distribution.

Figure 8 right above shows the distribution tensile stress on the test sample therefore the effective area A_{eff} which represents the area with a homogeneous stress distribution has to be determined according equation (6) in chapter 9.

7. Bending with constant radius

Instead of introducing the load in plane as described in the previous chapter 6 it is also possible to apply the load with a bending moment on the straight opposite edges, as shown in figure 9 left below. With an accurate adjustment of the length of bowstring (distance between the supporting hinges) of the arched bent glass sample and the applied bending moment a constant stress distribution on nearly the whole surface (excluding a small zone at the straight edges where the bending moment is introduced) arises.

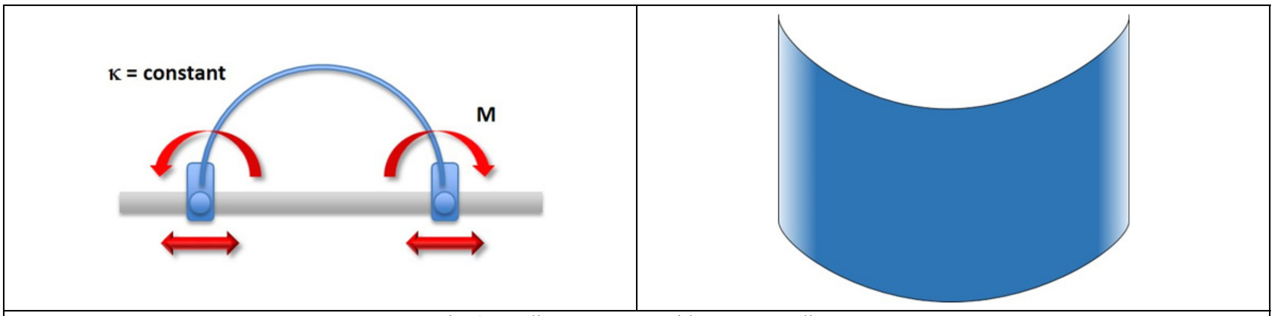


Fig. 9 Bending test set-up with constant radius.

With this set-up the effective area A_{eff} which represents the area with a homogeneous stress can be increased enormously in comparison to other test scenarios.

As an approach the stress can be determined with the following equations (1) and (2). The bending moment can be calculated with equation (1) based on the differential equation of bending theory and with the section modulus the stress can be computed easily with equation (2). This approach neglects the influence of the poisson´s ratio.

$$EIw'' = M\,;\, EI\kappa = M \tag{1}$$

$$\sigma = \frac{M}{W} \tag{2}$$

E	young´s modulus
I	modulus of inertia
w''	curvature κ
M	bending moment
W	section modulus

In the further investigation following effects or influences have been taken into account for the determination of the ultimate bending strength, which can be used for a structural design of specific application. These effects and influences are described in the following chapters.

8. Nonlinearity of test set-up

The effect of geometrical non-linearity e.g. the so-called membrane effect was investigated and published many times [Wilcox]. For the testing of thin glass it is of interest whether the determination of the stress in the glass can be determined according the linear theory of small deformations or the non-linear theory of large deformations.

For the ring on ring test according EN ISO 1288-5 (small test samples) this effect was investigated and the results are shown in figure 10 and 11. Figure 10 shows a comparison of deflections of the glass sample according theory of small deformations and theory of large deformations and figure 11 shows a comparison of maximum stresses at the glass sample according theory of small deformations and theory of large deformations.

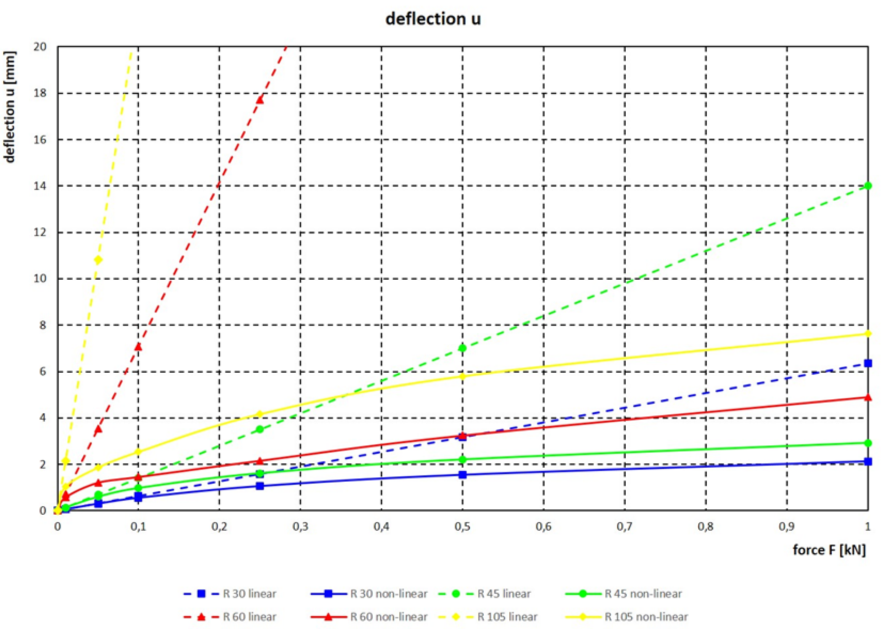


Fig. 10 Diagram - deflection u / force F.

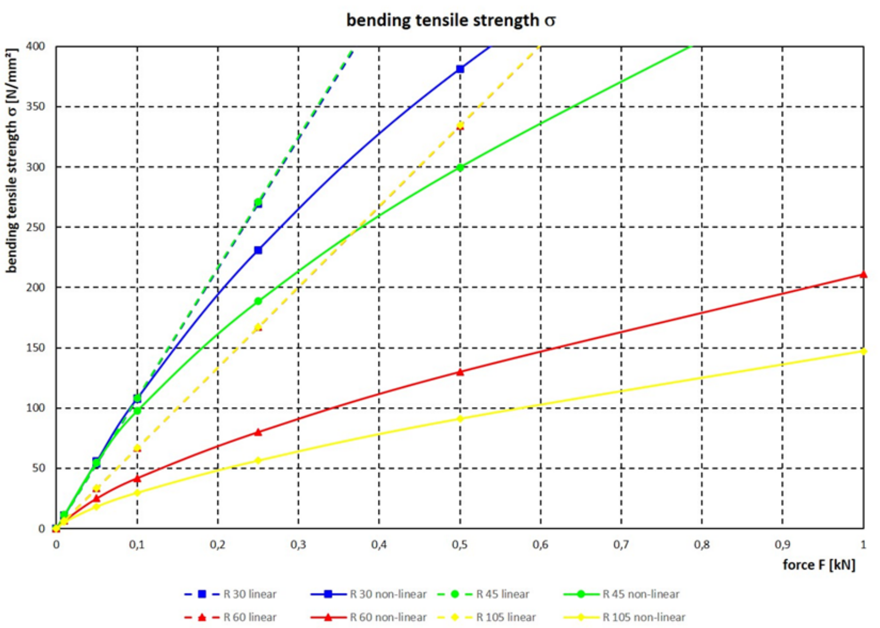


Fig. 11 Diagram - bending tensile strength σ /force F .

The main result and furthermore consequence of this investigation is that the given equation (3) for the determination of bending strength, which is based on theory of small deformation, cannot be used for thin glass.

$$\sigma_{rad} = \sigma_T = \frac{3(1+\mu)}{2\pi}\left[\frac{(1-\mu)}{(1+\mu)} \cdot \frac{r_2^2 - r_1^2}{2r_3^2} + \ln\frac{r_2}{r_1}\right] \cdot \frac{F}{h^2} \tag{3}$$

For quadratic glass sample an average radius r_{3m} has to be used instead of r_3 in equation (3) above. This average radius r_{3m} can be calculated with the following equation (4) below [EN ISO 1288-1].

$$r_{3m} = \frac{\left(1+\sqrt{2}\right)}{2} \cdot \frac{L}{2} = 0{,}6 \cdot L \tag{4}$$

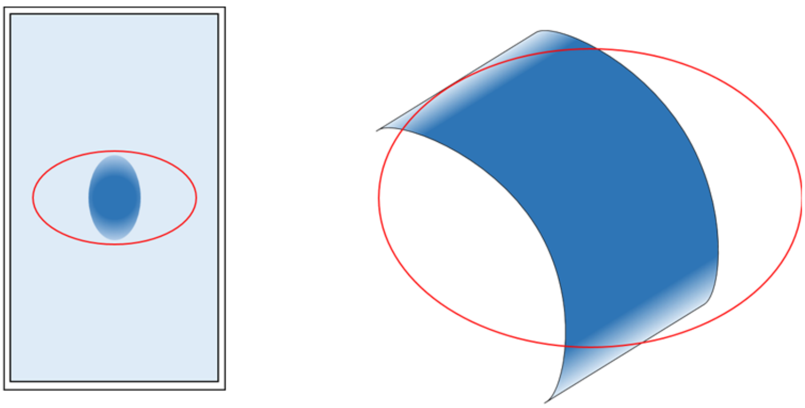
σ_{rad}	radial stress
σ_T	tangential stress
μ	poisson´s ratio
r_1	radius of supporting ring
r_2	radius of loading ring
r_3	radius glass of round specimen
F	measured force in test set-up
h	thickness of glass specimen
r_{3m}	radius of quadratic glass test specimen according equation (4)
L	length of quadratic glass test specimen

9. Effect of sample size

For the ultimate bending tensile strength the so-called size effect has to be taken into account. This effect describes the relationship between a measured and statistically evaluated bending strength with a certain size according the test set-up and the size of the area of a glass application in which the maximum stress can be assumed as homogeneous.

For a better understanding two examples were investigated and presented in the following. Example A is a glass with a length of 1500 mm and a width of 1000 mm which is simply supported on all sides. Example B has the same size and is simply supported too, but this glass is cold bent to a semicircle. Both glass panes are uniformly loaded with 1.0 kN/m². In addition to the uniform load stress results from cold bending process of the glass element too. This stress is a uniform stress and influences the total stress distribution of example B.

The specific glass was tested by ring on ring test series. It can be assumed for these examples that a bending strength $\sigma = 80$ MPa was measured with a probability of failure $\lambda = 8.7$ according Weibull distribution.



a.) b.)

Fig. 12 Area of homogeneous maximum principle stress of simply supported a.) flat glass, b.) cold bent cylindrical glass (semicircle).

The distribution of principle stresses σ_I for example A and B are calculated with help of FE-element program. To take into account the influence of the stress distribution on the surface of the glass based on the probability of failure a weighted average value for the principle stress σ_I is determined. This effective stress σ_{eff} can be calculated according equation (5).

$$\sigma_{eff} = \left[\frac{1}{A} \iint \sigma_1^{\beta}(x, y) dxdy \right]^{\frac{1}{\beta}} \tag{5}$$

Based on this equation (5) the effective area A_{eff} in which the stress can be assumed as homogeneous can be determined by the following equation (6)

$$A_{eff} = \left[\frac{1}{\sigma_{\max}^{\beta}} \iint \sigma_1^{\beta}(x, y) dxdy \right] \tag{6}$$

The size effect can be calculated according equation (7). The results of the influence of the size effect is shown in table 1. [Fink]

$$\sigma_L = \sigma_0 \cdot \left(\frac{A_0}{A_L} \right)^{\frac{1}{\beta}} \tag{7}$$

σ_L	stress with size effect
σ_O	determined stress of glass sample
A_L	area with homogeneous stress of loaded glass
A_0	area with homogeneous stress of glass sample
β	probability of failure (form function according Weibull distribution)

Table 1: Expected ultimate stress for example A and B

Test set-up according EN 1288-5	Diameter of load ring d_L[mm]	Area with homogeneous stress A_0[mm²]	Expected ultimate stress for example A σ_L[N/mm²]	Expected ultimate stress for example B σ_L[N/mm²]
R 30	6	113	34,7	26,9
R 45	9	254	38,1	29,6
R 60	20	1257	45,8	35,5
R 105	35	3848	52,1	40,4

In the extreme case of test set-up R 30 according EN ISO 1288-5 with a small area in which the stress was determined with σ = 80 MPa the expected ultimate bending strength for example B is σ_L= 26,9 MPa, which can be taken for the structural design. That is roughly 33% of the measured strength.

10. Imperfections

Thin glass is much more sensitive related to imperfections in test set-up in comparison to thicker glass and needs more awareness of such effects. An experimental ring on ring test, as shown in figure 13 below, demonstrates these issues very well.

In this ring on ring test R 105 according EN ISO 1288-5 a couple of such effects occurred. Due to the large deformation in the middle of the glass sample non-linear effects like a stability effect at the edges arose. This effect can be described with the membrane effect, which describes compression stresses at the edges. At a certain level of loading, a stability effect with large asymmetric deformations of edges was observed, as shown in figure 13.

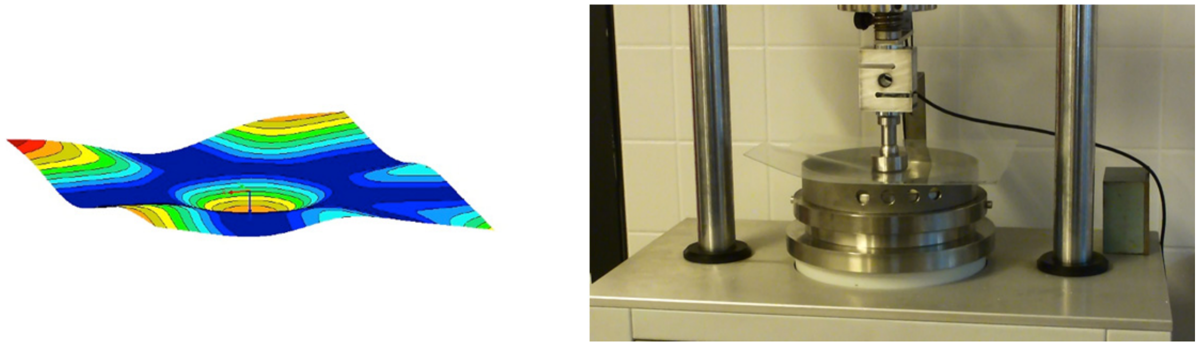


Fig. 13 Imperfection of glass sample and set-up.

This effect was also evaluated with the help of a FE-program. A result is shown in figure 13 left.

In addition to this stability effect a snap through effect at the corners of the sample was observed too. Due to the dead weight of the glass the corners had at the beginning of the test a displacement in direction downward. At a certain level of loading a prompt snap through effect (without breakage of the glass) in direction upwards was observed.

Such imperfections can occur for example due to following reasons.

- imperfections in test set-up
- imperfections in glass samples (e.g. thickness)

- not exact centered load ring

Of course, all these effects of imperfection have to be avoided during determination of the ultimate bending tensile strength of thin glass.

11. Effect of load duration

The load history during the lifetime of the glass element has an influence on the ultimate bending strength too, but was not investigated in detail and is therefore no part of this paper.

12. Summary

For the determination it is needed to find an accurate balance between size of the effective area, in which the measured stress can be assumed as homogeneous, and sensitivity related to imperfections and non-linear effects. This area has to be increased as much as possible, because in e.g. cold bent glass elements a large area of maximum stress in which the measured stress can be assumed as homogeneous arises, to minimize the size effect. For ring on ring tests the in EN 1288-5 given test set-ups have to be improved to minimize the probability of stability effects. The most promising test scenario of bending with constant radius with influence of edge strength shall be investigated much more relating to the applicability of this test scenario.

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