BRITISH STANDARD

BS EN 1288-1:2000

Glass in building — Determination of the bending strength of glass —

Part 1: Fundamentals of testing glass

The European Standard EN 1288-1:2000 has the status of a British Standard

ICS 81.040.20

National foreword

This British Standard is the official English language version of EN 1288-1:2000.

The UK participation in its preparation was entrusted by Technical Committee B/520, Glass and glazing in building, to Subcommittee B/520/4, Properties and glazing methods, which has the responsibility to:

- — aid enquirers to understand the text;
- — present to the responsible European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
- — monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

Cross-references

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Summary of pages

This document comprises a front cover, an inside front cover, the EN title page, pages 2 to 24, an inside back cover and a back cover.

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English version

Glass in building - Determination of the bending strength of glass - Part 1: Fundamentals of testing glass

Verre dans la construction - Détermination de la résistance du verre à la flexion - Partie 1: Principes fondamentaux des essais sur le verre

Glas im Bauwesen - Bestimmung der Biegefestigkeit von Glas - Teil 1: Grundlagen

This European Standard was approved by CEN on 5 September 1999.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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EUROPÄISCHES KOMITEE FÜR NORMUNG

Central Secretariat: rue de Stassart, 36 B-1050 Brussels

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Contents

Foreword

This European Standard has been prepared by Technical Committee CEN/TC 129, Glass in building, the Secretariat of which is held by IBN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 2000, and conflicting national standards shall be withdrawn at the latest by December 2000.

CEN/TC 129/WG8, Mechanical Strength, prepared the draft, Glass in building – Determination of the bending strength of glass – Part 1: Fundamentals of testing glass.

There are four other parts to this standard:

- Part 2: Coaxial double ring test on flat specimens with large test surface areas;
- Part 3: Test with specimen supported at two points (four point bending);
- Part 4: Testing of channel shaped glass;
- Part 5: Coaxial double ring test on flat specimens with small test surface areas.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

This European Standard specifies the determination of the bending strength of monolithic glass for use in buildings. The testing of insulating units or laminated glass is excluded from this standard.

This standard describes:

- considerations to be taken into account when testing glass;
- explanations of the reasons for designing different test methods;
- limitations of the test methods;

and gives pointers to safety requirements for the personnel operating the test equipment.

EN 1288-2, EN 1288-3, EN 1288-4 and EN 1288-5 specify test methods in detail.

The test methods specified in this standard are intended to provide large numbers of bending strength values that can be used as the basis for statistical evaluation of glass strength.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references, the latest edition of the publication referred to applies.

EN 1288-2	Glass in building - Determination of the bending strength of glass – Part 2: Coaxial double ring test on flat specimens with large test surface areas.
EN 1288-3	Glass in building - Determination of the bending strength of glass – Part 3: Test with specimen supported at two points (four point bending).
EN 1288-4	Glass in building - Determination of the bending strength of glass – Part 4: Testing of channel shaped glass.
EN 1288-5	Glass in building - Determination of the bending strength of glass – Part 5: Coaxial double ring test on flat specimens with small test surface areas.
EN 572-1	Glass in building - Basic soda lime silicate glass products - Part 1: Definitions and general physical and mechanical properties.

EN 572-2	Glass in building - Basic soda lime silicate glass products - Part 2: Float glass.
EN 572-3	Glass in building - Basic soda lime silicate glass products - Part 3: Polished wired glass.
EN 572-4	Glass in building - Basic soda lime silicate glass products - Part 4: Drawn sheet glass.
EN 572-5	Glass in building - Basic soda lime silicate glass products - Part 5: Patterned glass.
EN 572-6	Glass in building - Basic soda lime silicate glass products - Part 6: Wired patterned glass.
EN 572-7	Glass in building - Basic soda lime silicate glass products - Part 7: Wired or unwired channel shaped glass.
EN 1748-1	Glass in building - Special basic products - Part 1: Borosilicate glasses.
EN 1748-2	Glass in building - Special basic products - Part 2: Glass ceramics.
EN 1863-1	Glass in building – Heat strengthened soda lime silicate glass – Part 1: Definition and description.
EN 12150-1	Glass in building – Thermally toughened soda lime silicate safety glass – Part 1: Definition and description.
EN 12337-1	Glass in building – Chemically strengthened soda lime silicate glass – Part 1: Definition and description.
EN ISO 12543-1	Glass in building - Laminated glass and laminated safety glass - Part 1: Definitions and description of component parts.
prEN 13024-1	Glass in building – Thermally toughened borosilicate safety glass – Part 1: Definition and description.

3 Definitions

For the purposes of this European Standard, the following definitions apply.

3.1 **flat glass**: any glass product conforming to EN 572-2, EN 572-3, EN 572-4, EN 572-5, EN 572-6, EN 1748-1, EN 1748-2, or any transformed glass made from these products without deliberately inducing profile or curvature

3.2 **bending stress**: the tensile bending stress induced in the surface of a specimen

NOTE: For testing purposes, the bending stress should be uniform over a specified part of the surface.

3.3 **effective bending stress**: a weighted average of the tensile bending stresses, calculated by applying a factor to take into account non-uniformity of the stress field

3.4 **bending strength**: the bending stress or effective bending stress which leads to breakage of the specimen

3.5 **equivalent bending strength**: the apparent bending strength of patterned glass, for which the irregularities in the thickness do not allow precise calculation of the bending stress

3.6 **profile bending strength**: the quotient of the maximum bending moment and the section modulus of a channel shaped glass (EN 572-7)

3.7 **stress intensity factor**: a measure of the stress at a crack tip

3.8 **prestressed glass**: any glass product conforming to EN 1863, EN 12150, EN 12337, and prEN 13024-1

4 Symbols

F	Applied load
h	Specimen thickness
L	Length of side of square test sample
k	Constant for calculation of bending stress in EN 1288-3
K_1,K_2	Constants for calculation of bending stress in EN 1288-5
M_{bB}	Maximum bending moment
p	Gas pressure applied within loading ring in EN 1288-2
P_{bB}	Profile bending strength (of channel shaped glass) = M_{bB}/Z
r_1	Radius of loading ring
r_2	Radius of supporting ring
r_3	Radius of circular specimen
$r_{3\mathrm{m}}$	Average specimen radius (for evaluation)
y_0	Central deflection of specimen
Z	Section modulus (of channel shaped glass)
μ	Poisson number of specimen

NOTE: For soda lime silicate glass (see EN 572-1) a value of 0,23 is used.

σ_b	Bending stress
σ_{beff}	Effective bending stress
σ_{bB}	Bending strength
σ_{beqB}	Equivalent bending strength
σ_{rad}	Radial stress
σ_T	Tangential stress
σ_L	Stress in a direction along the length of the specimen

5 Factors to be taken into account when testing glass

5.1 Glass as a material

5.1.1 General

Glass is a homogeneous isotropic material having almost perfect linear-elastic behaviour over its tensile strength range.

Glass has a very high compressive strength and theoretically a very high tensile strength, but the surface of the glass has many irregularities which act as weaknesses when glass is subjected to tensile stress. These irregularities are caused by attack from moisture and by contact with hard materials (e.g. grit) and are continually modified by moisture which is always present in the air.

Tensile strengths of around 10 000 N/mm^2 can be predicted from the molecular structure, but bulk glass normally fails at stresses considerably below 100 N/mm^2.

The presence of the irregularities and their modification by moisture contributes to the properties of glass which need consideration when performing tests of strength.

Because of the very high compressive strength, glass always fails under tensile stress. Since glass in buildings is very rarely used in direct tension, the most important property for load resistance is the tensile bending strength. All the tests described in this standard are intended to evaluate the tensile bending strength of glass.

The bending strength is influenced by the following factors:

a) surface condition (see 5.1.2);

b) rate and duration of loading (see 5.1.3);

c) area of surface stressed in tension (see 5.1.4);

d) ambient medium, through stress corrosion cracking as well as healing of surface damage in the glass (see 5.1.5 and [1] of annex A);

e) age, i.e. time elapsing since the last mechanical surface treatment or modification to simulate damage (see 5.1.6);

f) temperature (see 5.1.7).

The influence exerted by factors b) to f) on bending strength has been taken into account in this standard.

5.1.2 Effect of surface condition

For the purpose of bending strength tests according to this standard, glass behaves as an almost ideally linear-elastic material that fails in a brittle manner. This brittleness means that contact with any hard object can lead to surface damage in the form of ultra-fine, partly submicroscopic cracks and chips. Surface damage of this kind, which is practically unavoidable during normal handling of glass, exerts a notch action which is a major factor in reducing mechanical strength, whereas the chemical composition of the glass has only a minor and in some cases entirely negligible, significance.

Hence it follows that the bending strength determined by the methods referred to in this standard is related largely to the surface condition of the specimen to be tested.

This surface condition is characterized by the following main features.

a) The surface condition imparted by a particular method of treatment, which produces a specific damage spectrum and thus results in a strength which is specific to the finished surface condition;

b) Residual stress, e.g. in the form of thermal or chemical prestress intentionally imparted, as well as unintended residual stresses.

5.1.3 Effect of rate of loading

For the interpretation of the bending strength values determined as described in this standard, the rate of loading is of special importance.

Cracks propagate in glass over a wide range of values of tensile stress (see [2] of annex A). There is a lower limit to the stress intensity factor below which cracks do not propagate (see [1] of annex A). There is then some subcritical crack propagation at higher levels of stress intensity factor, which is influenced by humidity, temperature and chemical agents. Above a critical stress intensity factor crack propagation is very rapid and leads to (almost) instantaneous failure. The consequence of the subcritical crack propagation is, for example, that the rate of load increase and/or the duration of static loading influences the bending strength.

For prestressed glass, this time dependence does not manifest itself until the tensile stress induced in the surface exceeds the compressive stress permanently present there (see [3] of annex A).

5.1.4 Effect of test surface area

The decrease in bending strength of glass with increasing size of the test area exposed to high stress is also of importance (see [4] of annex A). This area effect is accounted for by the statistical distribution of surface defects varying in effectiveness; the larger the test area, the greater is the probability of its containing a large surface defect. Consequently, the influence of the area effect increases with decreasing incidence of defects in the surface, so that this influence is more pronounced in the case of undamaged, e.g. fire-finished glass surfaces (see [5] of annex A).

Differences are likely between the mean values of the bending strength as measured in accordance with EN 1288-2 (maximally stressed area: 240 000 mm^2), or by using devices R45 and R30 in accordance with EN 1288-5 (maximally stressed areas: 254 mm^2 and 113 mm^2), due to the size of the stressed area. Depending on surface damage, the results obtained from testing smaller surface areas may be significantly higher than those obtained from testing larger surface areas, as shown in Table 1.

Table 1: Approximate effects of test surface area on the mean measured bending strength

Test Method	Device	Relative bending strength
EN 1288-2	--	100 %
EN 1288-5	R45	140 % to 270 %
EN 1288-5	R30	145 % to 300 %

Since glass for use in buildings is often in large sizes, the test methods specified in EN 1288-2 and EN 1288-3 give values which are more appropriate as the basis for designing flat glass for use in buildings. The test method specified in EN 1288-5 can be useful as a method of evaluating the comparative bending strength of flat glass.

5.1.5 Effect of ambient medium

The surrounding medium in which the glass is tested has an influence on the strength of the glass, particularly if the moisture level is very low. When glass is used in buildings, the relative humidity typically ranges from 30 % to 100 %. Within this range, the effect on the bending strength, as tested according to this standard, is not great. However, tests on glass for use in buildings shall be undertaken in test conditions with relative humidity levels in the range of 40 % to 70 %, in order to eliminate this effect when comparing bending strength results.

5.1.6 Effect of aging

If the glass surface is modified (by abrasion, etching, edge working, etc.) before the testing, it is necessary to allow the fresh damage to heal before the test is undertaken. The continual surface modification by moisture affects the damage in a way that can reduce any weakening effect (see [1] of annex A). In practice, glass is highly unlikely to be stressed directly after it has been treated, so it shall be conditioned for at least 24 h before testing.

5.1.7 Effect of temperature

The bending strength of glass is affected by changes in temperature. Within the normal range of temperatures experienced by glass in buildings, this effect is not very significant, but, to avoid possible complications in the comparison of bending strength values, testing shall be undertaken in a restricted range of temperatures.

5.2 Bending stress and bending strength

5.2.1 General

The test methods described in EN 1288-2, EN 1288-3, EN 1288-4 and EN 1288-5 are designed to induce a uniform bending stress over an area (the test area) of the specimen. However, the tests are statically indeterminate, that is, the stresses induced by the applied loads depend on the nature of the material tested as well as the load distribution.

5.2.2 Effective stress

Where the stress varies significantly over the test area, as is the case in EN 1288-3 (see 6.2.2), it can be represented by a weighted average stress, called the effective bending stress, σ_{beff}. The weighting is obtained by statistically evaluating the probability of fracture at any point in the stressed area.

5.2.3 Equivalent bending strength

Variations in homogeneity or thickness of the specimen affect the stress distribution. Hence, the bending strength, σ_{bB}, is never entirely an accurate value and, in some instances, it is better termed the equivalent bending strength, σ_{beqB}.

For some of the glass types tested (for example float glass), such variations are very small and the bending strength determined by the tests is sufficiently close to the actual bending strength for the difference to be unimportant.

In the case of patterned glass, however, only the equivalent bending strength can be determined.

5.2.4 Profile bending strength

When channel shaped glass is tested according to EN 1288-4, most of the specimens fail from fractures originating at the corner of the profile, where the web and flange meet, and not at the extreme of the flange or surface of the web. This is due to secondary stresses generated by the spreading of the flanges when the channel section is bent. In this test the bending strength is better expressed as the profile bending strength, P_{bB}.

5.3 Types of glass

5.3.1 General

The tests specified in EN 1288-2, EN 1288-3 and EN 1288-5 are for testing flat glass. This includes float glass, drawn sheet glass, patterned glass, patterned wired glass, polished wired glass and prestressed glass, provided there has been no deliberately induced curvature or profile (other than the patterned surface of patterned glass).

5.3.2 Patterned glass

The coaxial double ring test for large test surface areas (EN 1288-2) can be used to determine the equivalent bending strength of patterned glass, provided the maximum and minimum thicknesses do not deviate by more than 30 % or 2 mm, whichever is the lower, from the average thickness. This is because of difficulties in sealing the pressure ring to a patterned surface.

There is no limitation on the depth of pattern if the four point bending test (EN 1288-3) is used.

5.3.3 Laminated glass

The testing of the bending strength of laminated glass (see EN ISO 12543-1) is excluded from this standard.

In a bending test, additional shear deformation arises in the elastic or plastic interlayers (sliding of the hard glass plies on the interlayer). This effect means that measuring the bending strength of laminated glass is likely to give a strength value less than the actual bending strength of a monolithic glass of the same thickness. This shear deformation is particularly sensitive to the effects of temperature and loading rate.

Laminated glass is manufactured from monolithic glass products that can be tested individually by the test methods described in EN 1288-2, EN 1288-3 and EN 1288-5.

The process of manufacture is unlikely to cause significant changes in the bending strength of the component glasses, so it is unnecessary to test laminated glass, which can be assumed to have bending strengths appropriate to their individual components.

The load resistance of laminated glass depends on the interactions between the component parts of the composite structure, which is beyond the scope of this standard.

5.4 Orientation of the specimens

Many glass products lack symmetry in their production. This may be immediately obvious, such as a patterned glass, which is likely to have one surface much more deeply patterned than the other and possibly in which the pattern is directional, or it may be less obvious, such as the side on which the wheel cut was made (see Figure 1 in EN 1288-3).

Where such asymmetry is present, it may be necessary to test the glass in several different orientations in order to determine the bending strength. Samples of glass to be tested shall have all the specimens nominally identical.

5.5 Number of specimens in a sample

The bending strength of glass displays a large variation between nominally identical specimens. Very little information can be obtained by testing only a few specimens, since there is considerable uncertainty about whether the results are representative.

In statistical terms, this uncertainty can be expressed as confidence limits, values between which there is a given probability that the target being sought will lie.

Where the target being sought is in the central part of the bending strength distribution (for instance the mean value), then the confidence limits can be fairly narrow even with just a few specimens.

An accurate determination of the tensile stress which leads to a low crack probability can require large numbers of specimens when, for example, a characteristic stress, or a permissible stress, or a design value of bending strength is to be determined.

6 Explanations of the test methods

6.1 Coaxial double ring test for large test surface areas

NOTE: This test is specified in EN 1288-2.

6.1.1 Elimination of edge effects

The special feature of the coaxial double ring bending test in accordance with EN 1288-2 lies in the fact that only a circular shaped limited area of the surface of the specimen - not, however, its edges - is subjected to maximum stressing. In contrast to other bending tests (for example see EN 1288-3), in which the edge of the specimen is subjected to the maximum stress, the procedure in accordance with EN 1288-2 is suitable for exclusively subjecting surfaces (or different surface conditions) to bending stress. The effect of the specimen edge condition is for the most part suppressed.

6.1.2 Analysis of the stress development

When the deflections are relatively small, the central surface area is subjected to uniform tensile stressing [see Figure 1a)], where the radial and tangential stresses are of equal size.

If the deflections become larger, i.e. if they exceed approximately half the thickness of the sheet (the precise limit is dependent on the ring ratio r_2/r_1), this leads to localized increases in stress below the edge of the loading ring, the extent of which increases as the load rises [see Figure 1b)]. At this stage of the loading, the tangential and radial stresses change differently and a simple calculation of the stresses is no longer possible. The stresses calculated from linear bending theory would be too high.

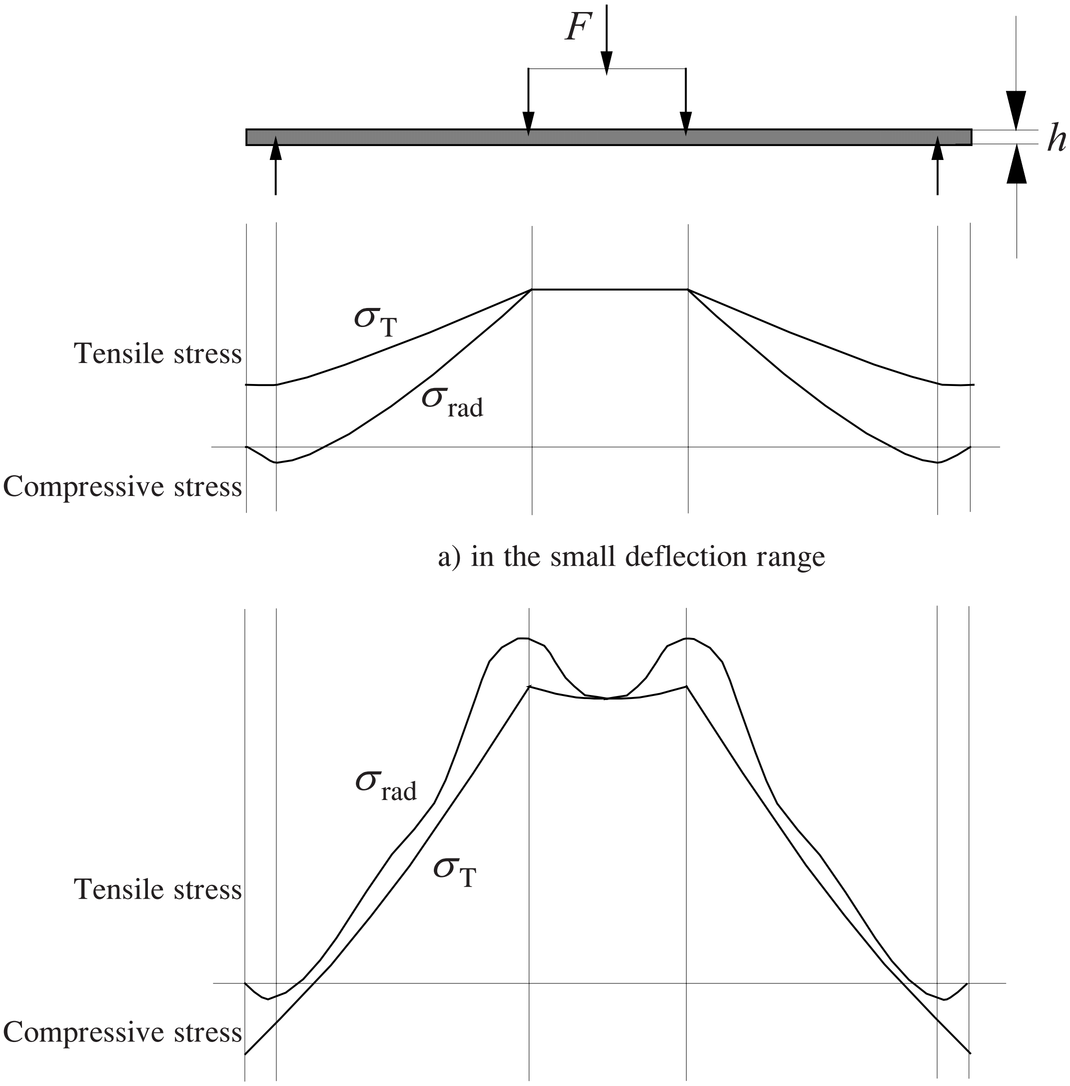


Figure 1: Schematic dependence of radial and tangential stresses upon the radius of the specimen, when loaded by a double ring device

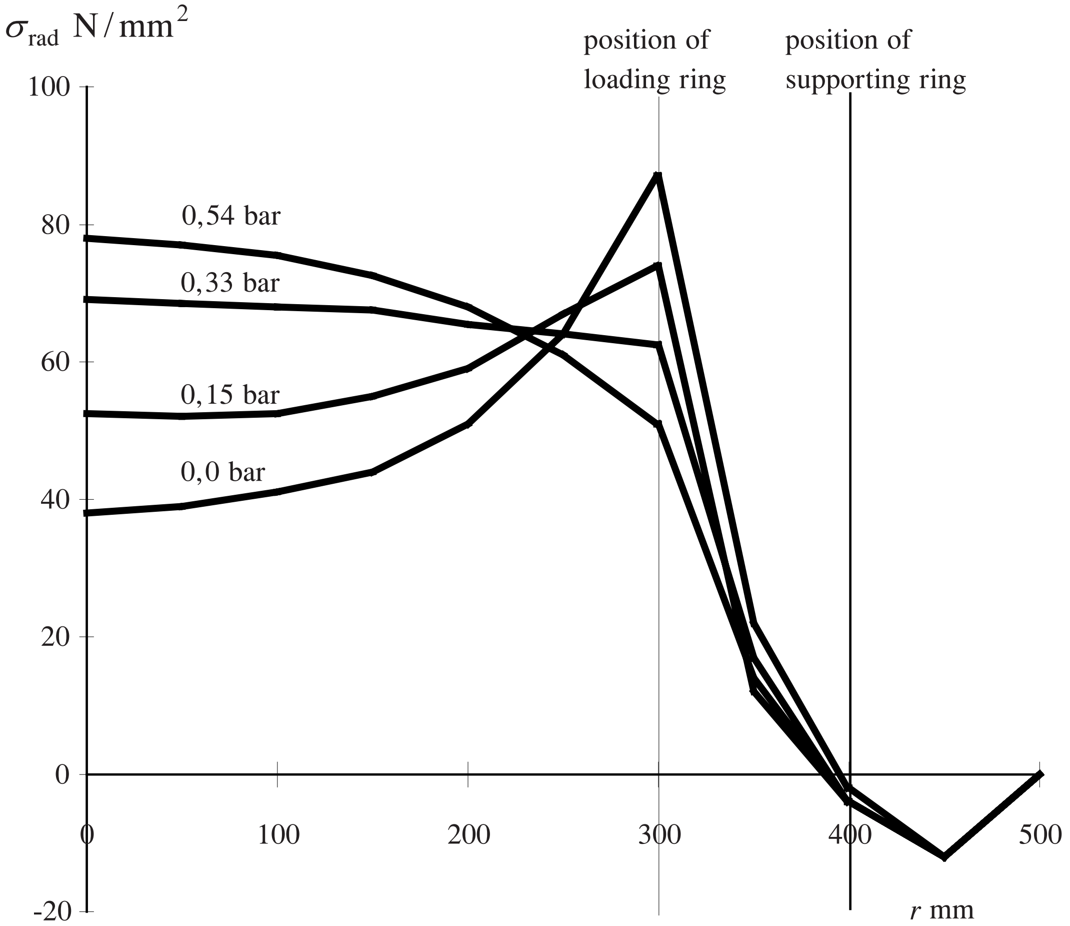
It has been demonstrated that, by means of a combined ring and surface load (see [6], [7] and [8] of annex A), this increase in stress below the edge of the loading ring can be avoided. With a constant piston force, *F*, the gas pressure, *p*, can be optimized in such a way that either the radial or tangential tensile stress develops almost uniformly within the loading ring (see Figures 2 and 3). It is, however, not possible to optimize the gas pressure, *p*, with regard both to the radial and tangential stress development at the same time.

If the gas pressure, *p*, is optimized with regard to the radial stress distribution (as given in Figure 2, curve *p* = 0,33 bars), then the tangential stress falls towards the loading ring (as given in Figure 3, curve *p* = 0,33 bars). If the gas pressure, p, is optimized with regard to the tangential stress distribution (as given in Figure 3, curve *p* = 0,15 bars) then the radial stress rises towards the loading ring (as given in Figure 2, curve *p* = 0,15 bars). Since, in the case of brittle materials, it is always the normal stresses which cause fractures to be triggered-off, the non-homogenous distribution of the radial stress is the decisive factor in the triggering of the fracture. For this reason the gas pressure, *p*, is always optimized with regard to the radial stress development for practical test purposes.

However, the advantage of the bi-axial stress condition, the two principal stresses of which are of equal size, as is apparent during the double ring bending process in the case of small deflections (see 6.3) is lost. This disadvantage is, however, more than offset by the large test surface area, unless the surface damage has a clear preferential direction (e.g. one or more parallel scratches).

In the case of square specimens, the stress distribution is slightly directional; the stresses along the medians and the diagonals differ slightly, within a range of about 5 %.

The curves in Figure 3 of EN 1288-2 and the values in Table 3 of EN 1288-2 have been determined from measurements. Deviations of individual measured values from the curves or table values are at most 5 %.

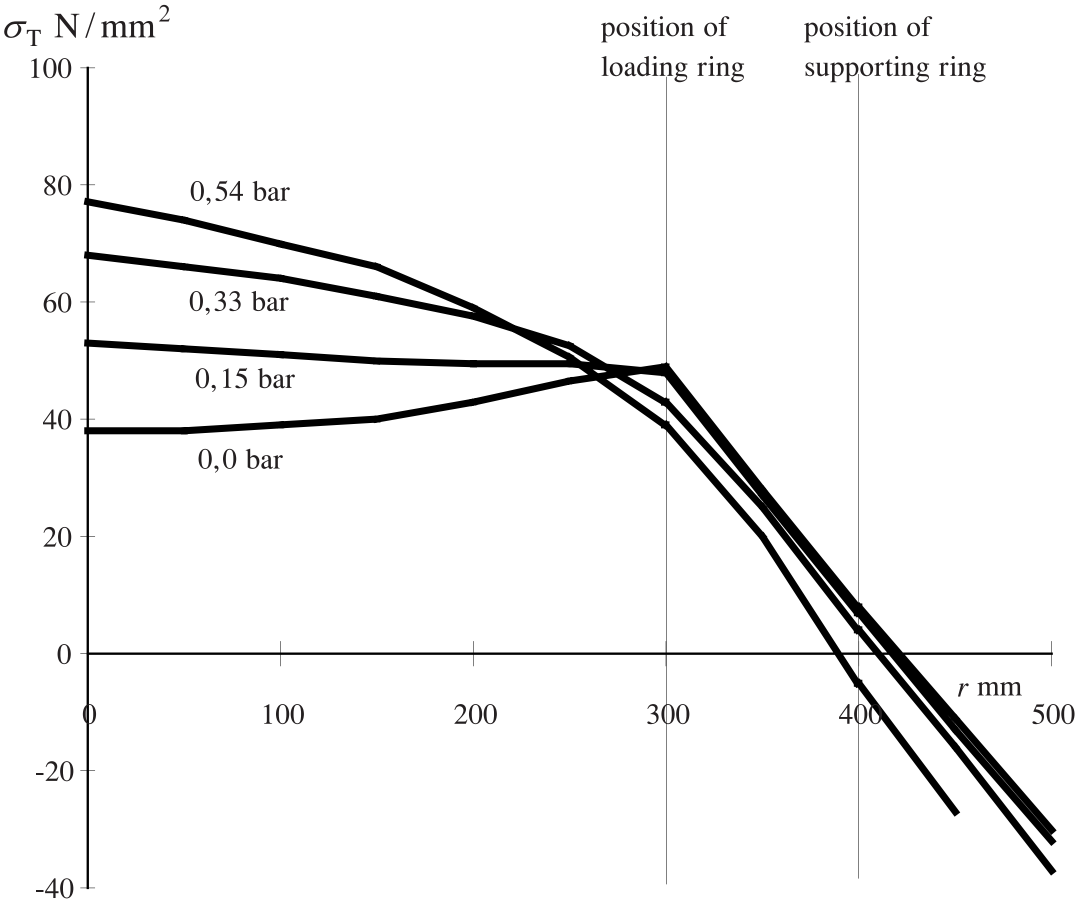


This graph has been measured using the following parameters:

Square specimen: 1 000 mm × 1 000 mm × 6 mm;
r_1 = 300 mm;
r_2 = 400 mm;
Piston force, F: 22 220 N;
Parameters: gas pressure, p

This determines that the optimized gas pressure, p, is 0,33 bars.

Figure 2: Radial stress development along the median of the convexly bent specimen surface



This graph has been measured using the following parameters:

Square specimen: 1 000 mm × 1 000 mm × 6 mm;
r_1 = 300 mm;
r_2 = 400 mm;
Piston force, *F*: 22 220 N;
Parameters: gas pressure, *p*

This determines that the optimized gas pressure, *p*, is 0,15 bars.

Figure 3: Tangential stress development along the median of the convexly bent surface

6.1.3 Testing of patterned glass

Specimens with one or two patterned surfaces cannot be tested by means of a small test area using the coaxial double ring bending test (see 6.3 and EN 1288-5), since the surface spread of the decorations are approximately the same size as the test surface area.

However, with a double ring bending test with a large test area in accordance with EN 1288-2, it is possible to test glass with patterned surfaces. The permissible structural depth given in 5.3.2 (local deviations from the average thickness a maximum of 30 % or 2 mm, whichever is the lower) is based upon experimental results.

Where there are one or two patterned surfaces, the condition of the line-shaped introduction of force by the edge of the loading ring is violated by the necessity to introduce a thicker intermediate layer on the loading ring side. The only effect, however, is to reduce somewhat in size the surface area of the virtually homogeneous radial stress distribution. Otherwise the stress values remain almost unaffected.

6.2 Test with specimen supported at two points (four point bending)

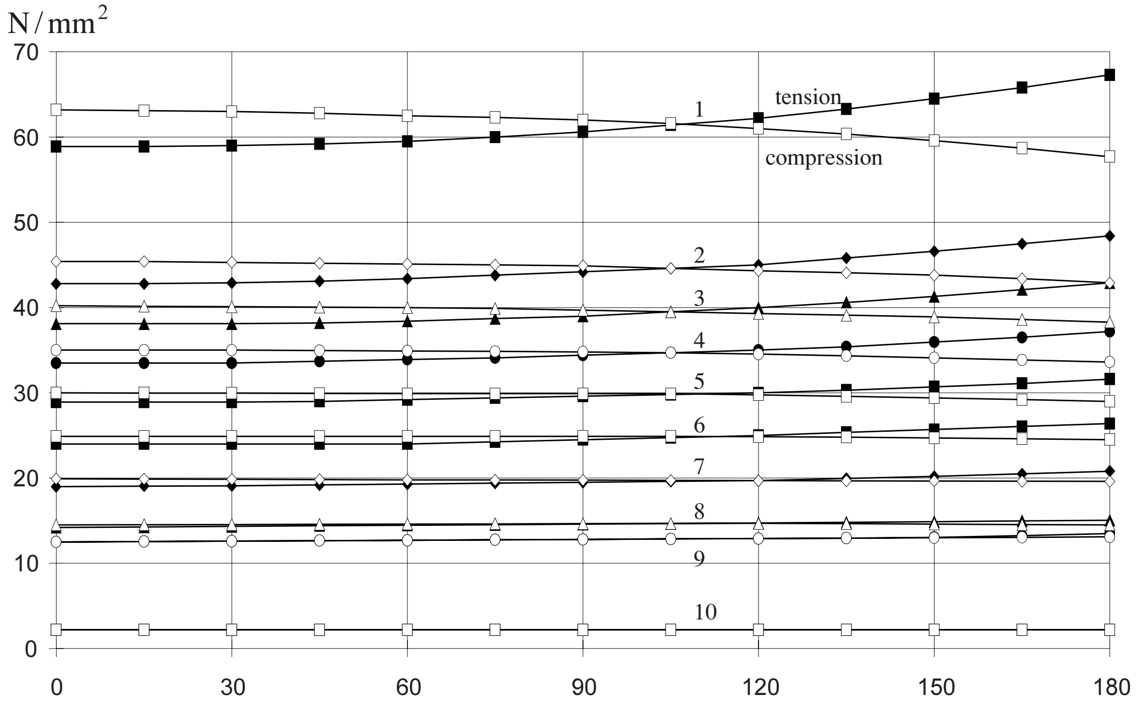
NOTE: This test is specified in EN 1288-3.

6.2.1 Inclusion of edge effects

This test is performed as a beam bending test using a wide beam. The edges of the specimen, over the central span of nominally uniform, unidirectional stress, are subjected to the maximum stress as well as the surface. If it is required to determine the bending strength of glass where the effects of the edge are important, this test should be used.

6.2.2 Analysis of the stress development

Simple theory assumes that there are no stresses developed across the width of a beam when it is subjected to bending along its length. However, while this may be a good approximation for narrow beams, the Poisson effect generates significant stresses across the width of wide beams. These stresses induce a contraflexion across the width of the beam, so that the longitudinal stress cannot be regarded as uniform across the width (see [9] of annex A). The effect is to increase the tensile bending stress developed at the edges of the beam and decrease the tensile bending stresses at the mid-line of the beam (as shown in Figure 4).



Distance from the middle axis of the specimen along the width (mm)

1 stress predicted from simple theory is 60,3 N/mm^2 tension or compression
2 stress predicted from simple theory is 43,5 N/mm^2 tension or compression
3 stress predicted from simple theory is 38,6 N/mm^2 tension or compression
4 stress predicted from simple theory is 33,7 N/mm^2 tension or compression
5 stress predicted from simple theory is 28,9 N/mm^2 tension or compression
6 stress predicted from simple theory is 24,0 N/mm^2 tension or compression
7 stress predicted from simple theory is 19,1 N/mm^2 tension or compression
8 stress predicted from simple theory is 14,2 N/mm^2 tension or compression
9 stress predicted from simple theory is 12,5 N/mm^2 tension or compression
10 stress predicted from simple theory is 2,2 N/mm^2 tension or compression

Figure 4: Variation in stress across the width of an 8,2 mm thick specimen of float glass at the middle of the span

If the exact origin of fracture is known, it is possible to obtain, by complex calculation, the precise local bending stress that has caused fracture of the specimen. If, however, the probability of flaws and the flaw distribution is considered, there is another approach which can be taken, depending upon whether the required bending strength is derived from all the bending test results (overall strength), or whether only those results from edge breaks are to be included (edge strength). It can be shown that the application of a factor, *k*, to the calculated bending stress can be used to modify the calculated bending stress to a “weighted average” of the bending stresses, called the effective bending strength, σ_{beff}. The factors are:

$k = k_s = 1{,}00$ when all the fractures are to be included
$k = k_e$ when only edge fractures are to be included.

The value of k_e depends on the deflection of the specimen at its centre, and values for this parameter are given in EN 1288-3.

6.3 Coaxial double ring test for small test surface areas

NOTE: This test is specified in EN 1288-5.

6.3.1 Elimination of edge effects

The special feature of the coaxial double ring bending test in accordance with EN 1288-5 lies in the fact that only a circular shaped limited area of the surface of the specimen - not, however, its edges - is subjected to maximum stressing. In contrast to other bending tests (for example EN 1288-3), in which the edge of the specimen is subjected to the maximum stress, the procedure in accordance with EN 1288-5 is suitable for exclusively subjecting surfaces (or different surface conditions) to bending stress. The effect of the specimen edge created by mechanical cold working is for the most part suppressed.

6.3.2 Analysis of the stress development

The advantages outlined in 6.1.1 and [10] of annex A prompted the choice of the coaxial double ring bending test as a test method for determining the bending strength of glass. One of these advantages is the uniform, and directionally independent loading of the specimen with the loading ring, which means that the direction of possible surface defects has no influence on the result. However, this only applies up to limited deflections, y_0, at the centre of the specimen.

Above this limit, excessive local stress may occur under the bearing edges of the loading ring, the magnitude of which increases as the load becomes greater. At the same time, tangential and radial stresses undergo variable modification, which is too complex for simple calculation. In this case, the stresses calculated from the linear bending theory are found to be excessively high (see 6.1).

For the ring size ratio $r_2/r_1 = 5$ chosen here, the permissible deflection range is given approximately by $y_0/h < 1{,}0$. The minimum values for the thickness of specimens specified in EN 1288-5 have been selected for bending stresses up to 600 N/mm^2 in such a way that, for elastic moduli of not less than 50 kN/mm^2, the relative deflections y_0/h in the centre of the specimen do not exceed 0,75. The stress differences in the loading ring region are then less than 2 %, according to [11] and [12] of annex A). For the purposes of EN 1288-5, the bending strength can be calculated from the test load using the equations given in EN 1288-5, provided that the ring and specimen dimensions and the values of minimum thickness of specimens are adhered to.

For this quasi-linear range of specimen loading, the following expression applies for the stresses in the surface of circular specimens bounded by the loading ring (see [5] of annex A):

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

Assuming a constant ratio between the values of r_1, r_2 and r_3 and a Poisson number, μ, for the specimen of 0,23, the formula used in EN 1288-5, for a circular specimen, may be derived from the following formula:

$$\sigma_{\mathrm{rad}} = \sigma_{\mathrm{T}} = K_1\frac{F}{h^2} \tag{2}$$

with K_1 = 1,09.

Table 2 shows the effect of Poisson number on K_1.

Table 2: Constant K_1, as a function of Poisson number, μ

Poisson Number μ	Constant K_1	Error on assuming μ = 0,23 %
0,18	1,059	2,7
0,19	1,065	2,1
0,20	1,071	1,6
0,21	1,076	1,1
0,22	1,082	0,5
0,23	1,088	0,0
0,24	1,094	0,5
0,25	1,100	1,1
0,26	1,106	1,6

The Poisson number for soda lime silicate glass (EN 572-1) is given as 0,23. For other types of glass, e.g. borosilicate (EN 1748-1) and glass ceramic (EN 1748-2), the value of K_1 should be selected to match the Poisson number of the glass.

For square specimens, equation (1) applies using the mean specimen radius, as follows:

$$r_{3\mathrm{m}} = \frac{(1+\sqrt{2})}{2}\cdot\frac{L}{2} = 0{,}60L \tag{3}$$

Here, $r_{3\mathrm{m}}$ corresponds to the mean of the radii of the circles circumscribing and inscribing the square. This leads to a constant K_2 = 1,04, in EN 1288-5, for square specimens of soda lime silicate glass.

When testing using loading devices R45 and R30 as specified in EN 1288-5, the tangential tensile stress at the edge of the sheet is about 30 % of the maximum tangential stress (= radial stress) within the loading ring. If this results in edge breaks, it is recommended to increase the specimen radius r_3 or side length L, and hence the projection of the specimen beyond the supporting ring. With a ratio $r_3/r_2 = 2$ or $L/2r_2 = 2$, the tangential stress at the edge of the sheet is definitely below 10 % of the maximum value (see [10] of annex A), so that the possibility of edge breaks can be virtually excluded. In this case, however, constants K_1 and K_2 need to be calculated again from equation (1).

In inter-laboratory tests the calculation principle given here for square and circular specimens has led to satisfactory agreement of the bending strength values determined for both forms of specimen.

7 Range of application of the test methods

7.1 General limitations

The test methods specified in this standard are not appropriate for the testing of laminated glass or insulating units.

7.2 Limitations to EN 1288-2

This test method is applicable only to flat glass (see 3.1).

Patterned glass can be tested provided the maximum and minimum thicknesses do not deviate by more than 30 %, but not more than 2 mm, from the mean thickness.

7.3 Limitations to EN 1288-3

This test method is applicable only to flat glass (see 3.1).

Patterned glass can be tested without limitations.

7.4 Limitations to EN 1288-4

This test method is applicable only to channel shaped glass.

7.5 Limitations to EN 1288-5

This test method is applicable only to flat glass (see 3.1).

Patterned glass shall not be tested by this method.

8 Calibration of the testing machines

The testing machines used according to EN 1288-2, EN 1288-3, EN 1288-4 and EN 1288-5 shall have been calibrated by the user within 3 months before a test.

For the purposes of calibration of a testing machine, the glass specimen can be replaced by a metal (e.g. steel) plate of appropriate thickness.

To perform the calibration of the force measuring instrument, an officially calibrated force gauge with independent instrument reading, accuracy ±1 %, shall be placed in series with the force measuring instrument of the testing machine.

To perform the calibration of the gas pressure measuring instrument, an officially calibrated pressure gauge with independent instrument reading, accuracy ±1 %, shall be placed in parallel to the pressure measuring instrument of the testing machine.

The force or pressure shall be increased in at least five approximately equidistant steps covering the ranges of measurement. At every step the instrument readings from the testing machine and that from the officially calibrated gauge shall be recorded. Both readings shall coincide within ±1 % over the whole measuring range. If the differences between the two readings exceed ±1 %, the measuring instrument of the testing machine shall be adjusted accordingly.

Only officially calibrated gauges shall be used for calibration. They shall be officially recalibrated every three years.

9 Recommendations for safe use of test equipment

Where material testing machines are in use, both the user and others may be exposed to hazards arising from the design of the machine and the behaviour of the specimen.

Material testing machines should be so designed that the user and others are protected, as far as possible, against hazards of all kinds, when the machine is used in the proper manner.

The tests methods specified in this standard are designed to break glass under high stresses, so there is an obvious hazard from the broken glass. Appropriate precautions shall be taken during the testing of glass specimens to avoid the particular hazards to both operators and observers from broken glass. These could include:

- providing appropriate protective clothing, e.g. safety spectacles and gloves, especially for the handling of glass specimens and broken glass fragments;

- applying an adhesive film to the surface of the glass, which is not being subjected to bending tension, to ensure that all the broken pieces are held together after breakage;

- using transparent safety screens between observers and/or operators and specimen.

If it is not possible, because of:

- the particular nature of the test process,

- different and unpredictable behaviour of the specimen during the test process,

to achieve safe handling of the testing machine by design measures or by additional safety features, the testing machine should be restricted to use by a limited group of persons who are able to assess the possible risks.

Annex A (informative)

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