Designation: ~~C158 – 02 (Reapproved 2017)~~ C158 – 23

Standard Test Methods for Strength of Glass by Flexure (Determination of Modulus of Rupture)[1]

This standard is issued under the fixed designation C158; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 These test methods cover the determination of the flexural strength (the modulus of rupture in ~~bending~~bending) of glass and glass-ceramics.

1.2 These test methods are applicable to annealed and prestressed glasses and glass-ceramics available in varied forms. Alternative test methods are described; the test method used shall be determined by the purpose of the test and geometric characteristics of specimens representative of the material.

1.2.1 Test Method A is a test for ~~modulus of rupture~~ flexural strength of flat glass.

1.2.2 Test Method B is a comparative test for ~~modulus of rupture~~ flexural strength of glass and glass-ceramics.

1.3 The test methods appear in the following order:

	Sections
~~Test Method A~~	~~6 to 9~~
Test Method A	7 to 10
~~Test Method B~~	~~10 to 15~~
Test Method B	11 to 16

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* ~~*Specific hazard statements are given in Section 10 and A1.5, A2.3.3, A2.4.3 and A2.5.3.*~~

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C148 Test Methods for Polariscopic Examination of Glass Containers

E4 Practices for Force Calibration and Verification of Testing Machines

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[1] These test methods are under the jurisdiction of ASTM Committee C14 on Glass and Glass Products and are the direct responsibility of Subcommittee C14.04 on Physical and Mechanical Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

SI10-02 IEEE/ASTM SI 10 American National Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions:*

3.1.1 *glass-ceramics*—solid materials, predominantly crystalline in nature, formed by the controlled crystallization of glasses.

3.1.2 ~~*modulus of rupture in bending*—~~*flexural strength*—the value of maximum tensile ~~or compressive stress (whichever causes failure)~~ stress in the extreme fiber of a beam loaded to failure in ~~bending computed from the flexure formula:~~ bending.

$$S_b = \frac{M\,c}{I} \tag{1}$$

~~where:~~

~~M = maximum bending moment, computed from the maximum load and the original moment arm,~~
~~c = initial distance from the neutral axis to the extreme fiber where failure occurs, and~~
~~I = initial moment of inertia of the cross section about the neutral axis.~~

3.1.3 *prestressed*—material in which a significant and controlled degree of compressive stress has been deliberately produced in the surfaces.

3.1.4 *standard laboratory atmosphere*—an atmosphere having a temperature of ~~23 ± 2°C~~23 °C ± 2 °C and a relative humidity of ~~40~~40 % ± 10 %.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *abraded*—describes a test specimen that has at least a portion of the area of maximum surface tensile stress during testing subjected to an operationally defined procedure for mechanical abrasion. The severity and uniformity of abrasion should be sufficient to ensure origin of failure substantially in the region of maximum stress.

3.2.2 *annealed glass*—describes a specimen that shall not have a temper or degree of residual stress resulting from prior thermal treatment in excess of the following limits when measured polarimetrically (see Annex A1):

3.2.2.1 Specimens of rectangular section shall not have a tensile stress at the midplane of more than ~~1.38-MPa (200-psi)~~1.4 MPa (200 psi) nor more than ~~2.76-MPa (400-psi)~~2.8 MPa (400 psi) compression at the surface.

3.2.2.2 Specimens in rod form may be examined by viewing through a diameter at least four diameters from an end. The *apparent* central axial tension shall not exceed ~~0.92 MPa (133 psi).~~0.90 MPa (130 psi). Surface compression, if measured on sections cut from the rods, shall not exceed ~~2.76~~2.8 MPa (400 psi) when viewed axially.

4. Significance and Use

4.1 For the purpose of this test, glasses and glass-ceramics are considered brittle (perfectly elastic) and to have the property that fracture normally occurs at the surface of the test specimen from the principal tensile stress. The ~~modulus of rupture~~ flexural strength is considered a valid measure of the tensile strength subject to the considerations ~~discussed below.~~that follow.

~~4.2 It is recognized that the modulus of rupture for a group of test specimens is influenced by variables associated with the test procedure. These include the rate of stressing, test environment, and the area of the specimen subjected to stress. Such factors are specified in the test procedure or required to be stated in the report.~~

~~4.3 It is also recognized that the variables having the greatest effect on the modulus of rupture value for a group of test specimens are the condition of the surfaces and glass quality near the surfaces in regard to the number and severity of stress-concentrating discontinuities or flaws, and the degree of prestress existing in the specimens. Each of these can represent an inherent part of the strength characteristic being determined or can be a random interfering factor in the measurement.~~

~~4.4 Test Method A is designed to include the condition of the surface of the specimen as a factor in the measured strength. It is,~~

~~therefore, desirable to subject a fixed and significant area of the surface to the maximum tensile stress. Since the number and severity of surface flaws in glass are primarily determined by manufacturing and handling processes, this test method is limited to products from which specimens of suitable size can be obtained with minimal dependence of measured strength upon specimen preparation techniques. This test method is therefore designated as a test for modulus of rupture of flat glass.~~

4.2 ~~Test Method B describes a general procedure for test, applicable to specimens of rectangular or elliptical cross section. This test method is based on the assumption that a comparative measurement of strength on groups of specimens is of significance for many purposes, such as determining the effect of environment or stress duration, or the effectiveness of varied prestressing techniques or strengths characteristic of glass-ceramics of differing composition or heat treatment. In this test method the surfaces of the specimens are not assumed to be characteristic of a product or material, but are considered to be determined by the procedures used to prepare the specimens. Though the stated procedure permits a wide variation in both specimen size and test geometry, it is necessary to use identical test conditions and equivalent procedures for specimen preparation to obtain comparable strength values. The use of a controlled abrasion of the specimen as a final normalizing procedure is recommended for such comparative tests.~~The flexural strength for a group of test specimens is influenced by variables associated with the test procedure. Such factors are specified in the test procedure or required to be stated in the report. These include but are not limited to the rate of stressing, the test environment, and the area of the specimen subjected to stress.

4.2.1 In addition, the variables having the greatest effect on the flexural strength value for a group of test specimens are the condition of the surfaces and glass quality near the surfaces in regard to the number and severity of stress-concentrating discontinuities or flaws, and the degree of prestress existing in the specimens. Each of these can represent an inherent part of the strength characteristic being determined or can be a random interfering factor in the measurement.

4.2.2 Test Method A is designed to include the condition of the surface of the specimen as a factor in the measured strength. Therefore, subjecting a fixed and significant area of the surface to the maximum tensile stress is desirable. Since the number and severity of surface flaws in glass are primarily determined by manufacturing and handling processes, this test method is limited to products from which specimens of suitable size can be obtained with minimal dependence of measured strength upon specimen preparation techniques. This test method is therefore designated as a test for flexural strength of flat glass.

4.2.3 Test Method B describes a general procedure for test, applicable to specimens of rectangular or elliptical cross section. This test method is based on the assumption that a comparative measurement of strength on groups of specimens is of significance for many purposes such as: determining the effect of environment or stress duration, the effectiveness of varied prestressing techniques, and strengths characteristic of glass-ceramics of differing composition or heat treatment. In this test method, the surfaces of the specimens are not assumed to be characteristic of a product or material, but are considered to be determined by the procedures used to prepare the specimens. Though the stated procedure permits a wide variation in both specimen size and test geometry, use of identical test conditions and equivalent procedures for specimen preparation is necessary to obtain comparable strength values. The use of a controlled abrasion of the specimen as a final normalizing procedure is recommended for such comparative tests.

4.2.4 A comparative abraded strength, determined as suggested in Test Method B, is not to be considered as a minimum value characteristic of the material tested nor as directly related to a maximum attainable strength value through test of specimens with identical flaws. The operationally defined abrasion procedure undoubtedly produces flaws of differing severity when applied to varied materials, and the measured comparative strengths describe the relative ability to withstand externally induced stress as affected by the specific abrasion procedure.

4.2.5 Test environment (ambient air, inert gas, vacuum, etc.) including moisture content (for example, relative humidity) may have an influence on the flexural strength. Testing to evaluate the maximum strength potential of a glass can be conducted in inert environments and/or at sufficiently rapid testing rates to minimize any environmental effects. Conversely, testing can be conducted in environments, test modes, and test rates representative of service conditions to evaluate flexural performance under use conditions.

~~4.6 A comparative abraded strength, determined as suggested in Test Method B, is not to be considered as a minimum value characteristic of the material tested nor as directly related to a maximum attainable strength value through test of specimens with identical flaws. The operationally defined abrasion procedure undoubtedly produces flaws of differing severity when applied to varied materials, and the measured comparative strengths describe the relative ability to withstand externally induced stress as affected by the specific abrasion procedure.~~

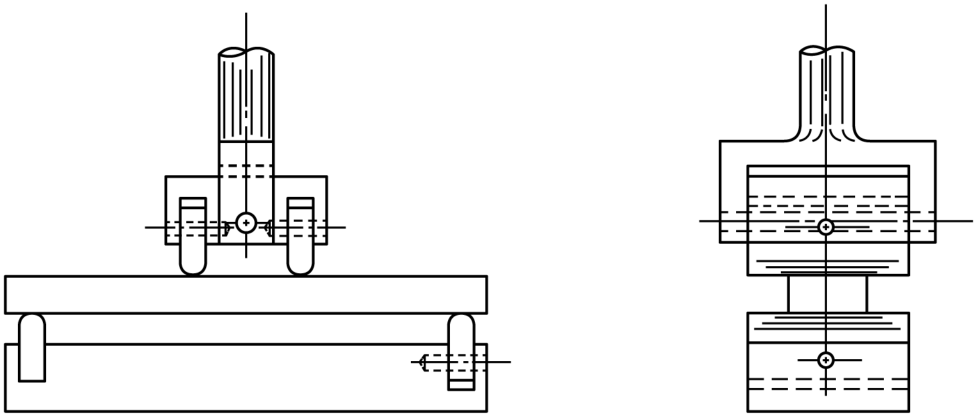

FIG. 1 Pinned Bearing Edges

5. Interferences

5.1 Additional experimental errors which may arise during testing should be minimized (**1-3**).[3]

5.2 Calculation of the flexural strength using equations derived based on linear bending theory will lead to an overestimate of the flexural strength when large beam deflections are present.

5.3 Wedging stress effects along the tensile surface in the vicinity of the contact load line may lead to failure when the ratio of thickness to moment or distance between adjacent support and loading edges is large.

5.4 Eccentric loading, improper choice of span dimensions, non-parallel rollers, friction, contact stresses, wedging stresses caused by non-rotating rollers, beam overhang, and contact point tangency shifting can introduce localized failure not representative of the flexural strength under ideal loading conditions.

5.5 Fabrication of test specimens can introduce dimensional variations that may have pronounced effects on the measured flexural mechanical properties and behavior (for example, flexural strength, failure location, etc.).

5.5.1 Initial beam curvature and nonflat and nonparallel thickness along the length of the specimen may lead to errors (for example, beam twisting).

5.5.2 Rounded or chamfered corners should be used to reduce edge failures in specimens of rectangular cross section. Corner radii and chamfers should be kept small such that the change in moment of inertia is small.

6. Apparatus

6.1 *Testing Machine*—The loading mechanism shall be sufficiently adjustable to give the required uniform rate of increase of stress. The load-measuring system shall be essentially free of inertial lag at the loading rates used and shall be equipped with means for retaining indication of the maximum load applied to the specimen. The accuracy of the testing machine shall conform to the requirements of Practice E4.

6.2 *Bearing Edges*—Cylindrical bearing edges of approximately ~~3-mm~~3 mm (1⁄8~~-in.)~~ in.) radius shall be used for the support of the test specimen and the application of the load. The bearing edges shall be of steel and sufficiently hardened to prevent excessive deformation under load. ~~Two-point~~Four-point loading tests shall be performed with the loading member pivoted about a central transverse axis to ensure equal distribution of load between the two bearing edges. For the testing of specimens of rectangular section, both loading bearing edges and one support bearing edge also shall be provided laterally to compensate for irregularities of the test specimen. Fig. 1 shows a suitable arrangement using pinned bearing edges. In test of specimens of a circular or elliptical section, the fixed cylindrical support edges may have a curvature of approximately 76 mm (3 in.) in the plane of the bearing edge to stabilize the alignment of the specimens. Such support edges are shown in Fig. 2.

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[3] The boldface numbers in parentheses refer to a list of references located at the end of this standard.

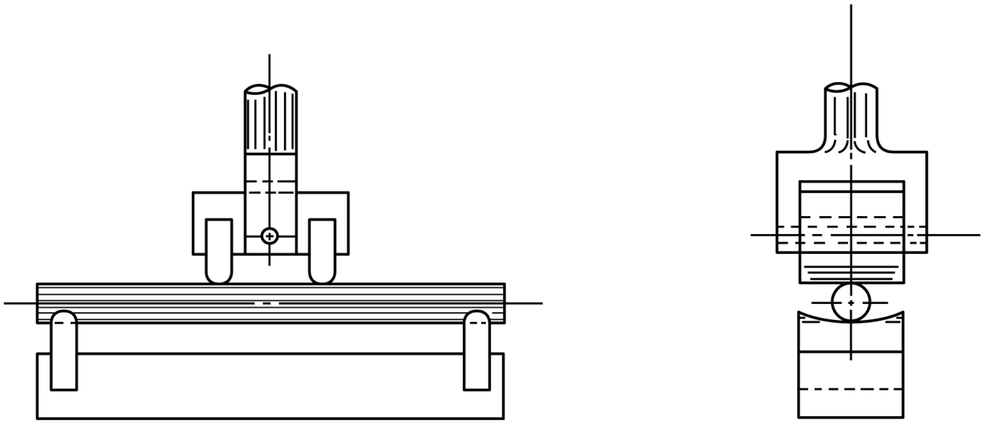

FIG. 2 Fixed Cylindrical Support Edges

TEST METHOD A—TEST FOR ~~MODULUS OF RUPTURE~~ FLEXURAL STRENGTH OF FLAT GLASS

7. Test Specimens

7.1 *Preparation of Specimens*—Test specimens shall be cut from the sheet stock with a diamond or a cutting wheel. Both longitudinal cuts shall be on the same original surface and none of the original edge of the sheet shall be used as a longitudinal side of the specimen. End cuts may be on either surface. The direction of cutting of half of the total number of specimens shall be perpendicular to the direction of cutting of the remainder. Specimens that must be cut from sheet stock prior to the use of a prestressing treatment shall have the corners of the longitudinal edges rounded to minimize damage to the edges in the prestressing process. All operations shall be performed with the direction of grind or polish parallel to the longitudinal axis. The radius of the corner shall not exceed 1.6 mm (1⁄16 in.).

7.2 *Size of Specimens*—The specimens shall be approximately 250 mm (10 in.) in length and ~~38.1 ± 3.2~~38 mm ± 3 mm (1½ in. ± 1⁄8 in.) in width. The specimens should be at least 4 mm and not more than 10 mm in thickness. The variation in width or thickness shall not exceed 5 % from one end to the other.

7.3 *Number of Specimens*—At least 30 specimens shall be used for one test and shall preferably be taken from several sheets, or regions of a single sheet.

7.4 *Examination of Specimens*—Any specimen may be rejected prior to test for observable defects considered likely to affect the ~~modulus of rupture.~~ flexural strength. To be considered representative of annealed glass the specimens must meet the requirement of 3.2.2. At least 30 % of the specimens shall be examined for residual stress. If any of these fail to meet the requirement, the remainder of the specimens shall be examined and those exceeding the stated limit shall be rejected.

7.5 *Float Glass*—The surface of float glass in contact with tin has been found to be lower in strength (~~1~~4) as compared to the "air" surface. For comparative tests, therefore, surface orientation should be kept constant.

8. Procedure

8.1 Space the supporting edges of the test fixture approximately 200 mm ~~(8.00~~(8 in.) apart and centrally position the loading edges with a separation of approximately 100 mm ~~(4.00~~(4 in.). Break specimens having cut edges with the cutter marks on the face under compression. Carefully place each specimen in the test fixture to minimize possible damage and to ensure alignment of specimen in the fixture. The permissible maximum fiber stress due to initial load on the specimen shall not exceed 25 % of the mean ~~modulus of rupture.~~ flexural strength. Load the specimen at a constant rate to failure. For annealed glass the rate of loading shall correspond to a rate of increase of maximum stress of ~~1.1~~1.1 MPa⁄s ± 0.2 MPa/s ~~(10 000~~(10 000 psi⁄min ± 2000 psi/min). Test prestressed glasses with the increase of maximum stress per minute between ~~80~~80 % and 120 % of the ~~modulus of rupture.~~ flexural strength. The first six specimens of the group may be tested at a loading rate based on an estimate of the ~~modulus of rupture~~ flexural strength and the average value for these specimens used to correct this estimate. If range of width and thickness variation in the specimens is less than 5 %, the mean values may be used to represent all specimens for the purpose of calculation of rate of loading.

8.2 Determine the thickness and width of each specimen to an accuracy of ±1 %. To avoid damage from gaging in the critical area, take measurements prior to testing near each end with a separation equal to the support span, and average the values. Measurements following test shall be in the uniformly stressed region of the specimen.

8.3 Determine the location of point of failure and note it as edge or face origin. Plastic or other tape of low elastic modulus may be used on the compressive surface to contain the fragmentation and allow observation of point of failure for highly prestressed specimens. Report all values, although segregation of edge break values is permitted.

9. Calculation

9.1 Calculate the ~~modulus of rupture,~~ flexural strength, initial maximum fiber stress, and rate of increase of stress as follows:

9.1.1 ~~Modulus of rupture:~~ Flexural strength:

~~$S = \frac{3\,La}{bd^2}$~~ (1)

$$\sigma = \frac{3Pa}{bd^2} \tag{1}$$

9.1.2 Maximum stress due to initial load if present:

~~$S_0 = \frac{3\,L_0 a}{bd^2}$~~ (2)

$$\sigma_0 = \frac{3P_0 a}{bd^2} \tag{2}$$

9.1.3 Rate of increase of maximum stress:

~~$R = \frac{3a}{bd^2} \times \frac{\Delta L}{\Delta t}$~~ (3)

~~$R = S - \frac{S_0}{t}$~~

$$R = \frac{3a}{bd^2} \times \frac{\Delta P}{\Delta t}$$

$$R = \frac{\sigma - \sigma_0}{t} \tag{3}$$

where:

~~S = modulus of rupture, MPa (psi),~~
σ = flexural strength, MPa (psi),
~~S_0 = maximum fiber stress due to initial load if present, MPa (psi),~~
σ_0 = maximum fiber stress due to initial load if present, MPa (psi),
R = rate of increase of maximum fiber stress, MPa/s (psi/min),
~~L = breaking load including initial load, N (lbf),~~
P = breaking load including initial load, N (lbf),
~~L_0 = initial load, N (lbf),~~
P_0 = initial load, N (lbf),
a = moment arm or distance between adjacent support and loading edges, mm (in.),
b = width of specimen, mm (in.),
d = thickness of specimen, mm (in.),
t = time from start of continuous loading to rupture, s (min), and
~~$\Delta L/\Delta t$ = rate of increase of load, N/s (lbf/min).~~
$\Delta P/\Delta t$ = rate of increase of load, N/s (lbf/min).