Designation: C1279 − 13

Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass[1]

This standard is issued under the fixed designation C1279; 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.

1. Scope

1.1 This test method covers the determination of edge stresses and surface stresses in annealed, heat-strengthened, and fully tempered flat glass products.

1.2 This test method is non-destructive.

1.3 This test method uses transmitted light and is, therefore, applicable to light-transmitting glasses.

1.4 The test method is not applicable to chemically-tempered glass.

1.5 Using the procedure described, surface stresses can be measured only on the "tin" side of float glass.

1.6 Surface-stress measuring instruments are designed for a specific range of surface index of refraction.

1.7 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.8 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C158 Test Methods for Strength of Glass by Flexure (Determination of Modulus of Rupture)
C162 Terminology of Glass and Glass Products
C770 Test Method for Measurement of Glass Stress—Optical Coefficient
C1048 Specification for Heat-Strengthened and Fully Tempered Flat Glass
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

2.2 *Other Documents:*

Engineering Standards Manual[3]
"Surface and Edge Stress in Tempered Glass"[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *analyzer*—a polarizing element, typically positioned between the specimen being evaluated and the viewer.

3.1.2 *polarizer*—an optical assembly that transmits light vibrating in a single planar direction, typically positioned between a light source and the specimen being evaluated.

3.1.3 *retardation compensator*—an optical device, variants of which are used to quantify the optical retardation produced in transparent birefringent materials: typically positioned between the specimen being evaluated and the analyzer.

3.2 For definition of terms used in this test method, refer to Terminology C162.

4. Summary of Test Methods

4.1 Two test methods are described in this standard:

4.1.1 *Procedure A*—describes a test method for measuring surface stress using light propagating nearly parallel to the surface.

4.1.2 *Procedure B*—describes a test method for measuring edge-stress using light propagating in the direction perpendicular to the surface.

4.2 In both methods, the fundamental photoelastic concept is used. As a result of stresses, the material becomes optically anisotropic or birefringent. When polarized light propagates through such anisotropic materials, the differences in the speed of light rays vibrating along the maximum and minimum

[1] This test method is under the jurisdiction of ASTM Committee C14 on Glass and Glass Products and is the direct responsibility of Subcommittee C14.08 on Flat Glass.

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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.

[3] Available from Glass Association of North America (GANA), 800 SW Jackson Street, Ste 1500, Topeka, Kansas 66612–1200. http://www.glasswebsite.com

[4] Redner, A. S. and Voloshin, A. S., Proceedings of the Ninth International Conference on Experimental Mechanics, Denmark, 1990.

principal stress introduce a relative retardation between these rays. This relative retardation is proportional to the measured stresses, and can be accurately determined using compensators. For additional background see "Surface and Edge Stress in Tempered Glass"[4].

5. Significance and Use

5.1 The strength and performance of heat-strengthened and fully-tempered glass is greatly affected by the surface and edge stress induced during the heat-treating process.

5.2 The edge and surface stress levels are specified in Specification C1048, in the Engineering Standards Manual[3] of GANA Tempering Division and in foreign specifications.

5.3 This test method offers a direct and convenient way to non-destructively determine the residual state of stress on the surface and at the edge of annealed and heat-treated glass.

6. Principles of Operation

6.1 *Procedure A: Measuring Surface Stress:*

6.1.1 Measurement of surface stresses requires an optical apparatus that permits the injection of polarized light rays propagating in a thin layer adjacent to the surface (see Note 1). A prism is usually used for this purpose. The rays emerge at critical angle i_c. The photoelastic retardation due to the surface stresses, (see Fig. 1), is measured using a wedge-compensator.

6.1.2 The incident light beam should be arriving at the critical angle i_c and polarized at 45° to the entrance of the prism edge. A quartz wedge-compensator, W_c, placed in the path of emerging light adds a retardation, R_c, to the retardation R_s induced by stresses in the surface of the specimen. The analyzer, A, placed between the eyepiece, E, and the wedge-compensator, W_c, generates a visible set of fringes or lines of constant retardation R where

$$R = R_s + R_c \quad (1)$$

Since the specimen-induced retardation is proportional to the surface stress, S, and the path, t, we have:

$$R_s = C \cdot S \cdot t = C \cdot S \cdot ax \quad (2)$$

where:

R = is the relative retardation,
C = stress-optical constant (see Note 2),
S = surface stress in the direction perpendicular to the path, t
t = path of light traveling between the entrance and exit points 1, 2 (Fig. 1),
a = Geometrical factor, (depending upon the prism design) $a = t/x$. This constant is determined by the manufacturer.

6.1.3 The compensator adds its own retardation. It is linearly variable along its length y and is calculated as

$$R_c = b \cdot y \quad (3)$$

Where b is a constant, determined by the manufacturer of the compensator. The observer sees in the compensator plane a total retardation R.

$$R = R_s + R_c = a \cdot C \cdot S \cdot x + b \cdot y \quad (4)$$

6.1.4 The fringes (lines of R = Constant) are, therefore, tilted lines. (See Fig. 2). The angle θ is the tilt of these fringes relative to a plane containing the light path of Figs. 1 and 2. The measured stress is proportional to the tangent of the tilt angle θ, measured using a goniometer, and to an instrument calibration constant, K MPa, determined by the manufacturer.

$$\tan\theta = \frac{a \cdot C \cdot S}{b} \text{ and} \quad (5)$$

$$\text{Stress} = \frac{b}{Ca} \cdot \tan\theta = K \cdot \tan\theta$$

In the actual procedure (see 15.1 below) the operator measures the tilt angle θ of the observed set of fringes.

NOTE 1—The surface-stress measuring apparatus described in this section is manufactured by Strainoptic Technologies, Inc. in North Wales, Pennsylvania.

NOTE 2—The stress constant of float glass is typically 2.55 to 2.65 Brewsters. Calibration can be performed using one of the test methods described in Test Methods C770.

6.2 *Procedure B: Measuring Edge Stress:*

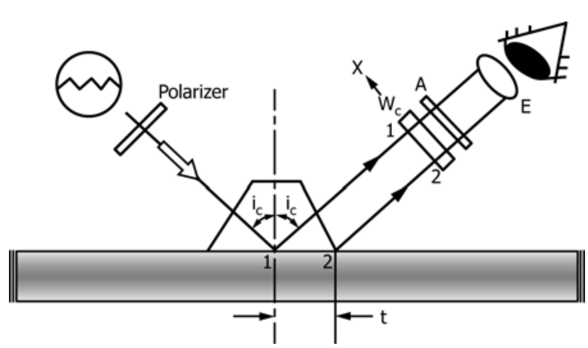

FIG. 1 Apparatus For Measuring Surface Stress

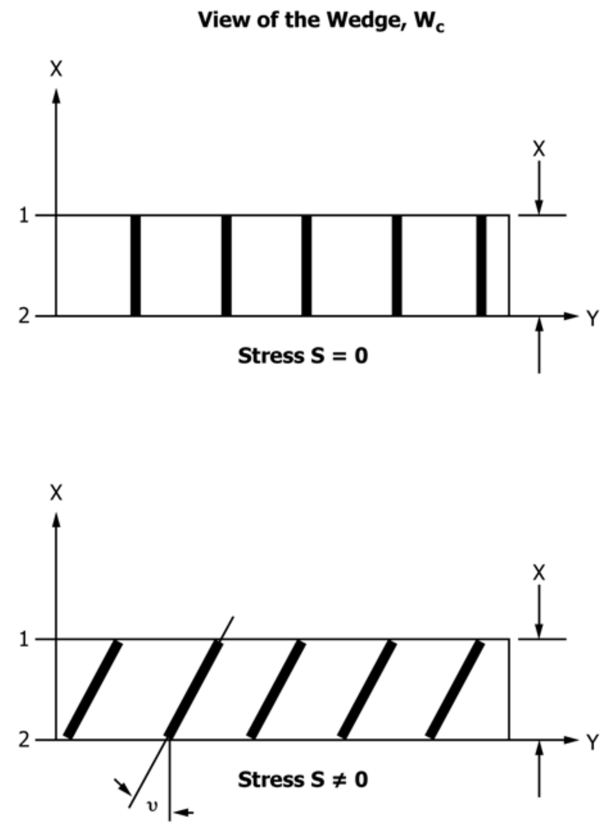

FIG. 1 Apparatus For Measuring Surface Stress *(continued)*

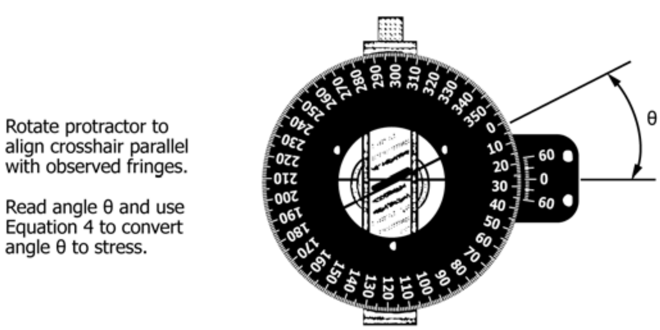

FIG. 2 Fringes Observed in the Plane of the Compensator

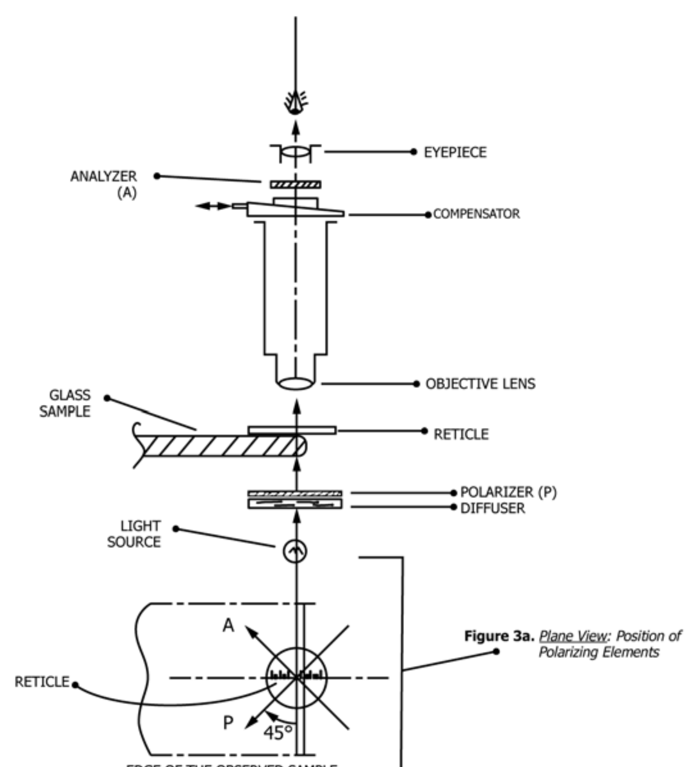

FIG. 3 Schematic of the Instrument for Measuring Edge Stress

6.2.1 Measurement of edge stress is accomplished using a polarimeter equipped with a wedge-compensator, as shown schematically in Fig. 3.

6.2.2 The angle between the polarizer and the edge of the specimen must be 45° (see Fig. 3a), and the analyzer must be perpendicular to the polarizer. The overall magnification should be at least 20× to permit clear visibility of the reticle, and of photoelastic fringes near the edge. The reticle placed adjacent to the specimen must have graduations of 0.1 mm (0.004 in.) or smaller. The resolution of the compensator should be at least 5 nm, and the compensator should be calibrated by the manufacturer at 565 nm wavelength with results of calibration expressed in nm/div.

6.2.3 The compensator used could be of linear wedge type (Babinet) or uniform-field type (Babinet-Soleil). The linear-wedge type requires a reticle placed adjacent to the compensator wedge and a linear-motion scale, or lead screw, locating the wedge position with reference to the reticle.

6.2.4 The uniform field does not require a reticle, and must be equipped with a lead screw measuring the relative motion of its wedges.

7. Sampling

7.1 *Procedure A: Measuring Surface Stress*—The number of points to be measured are determined by either the product specification or by the following protocol described in Specification C1048.

7.2 *Procedure B: Measuring Edge Stress*—Readings must be obtained at the mid-span point of every edge.

8. Calibration and Standardization

8.1 A test bar is subjected to bending using traceably certified deadweights or calibrated load-cells to introduce surface stresses that can be calculated from the specimen geometry and forces applied. At a point in which the stresses are calculated, those same stresses also are measured using the instrument to be calibrated or verified. Since both the specimen dimension and the applied forces can be established accurately using traceable (primary) standards, the method permits a fully traceable calibration of the stress-measuring instrument.

8.2 The instrument to be calibrated is placed on the surface of the calibration specimen. Stresses at a point where the instrument is placed are calculated using expressions shown in Section 11. To increase the precision of measurement, several levels of stress are produced by applying forces incrementally. Measurement of stress using the instrument to be calibrated is repeated for each stress level and these measurements are used to calibrate the instrument.

9. Test Specimens and Loading Schemes

9.1 Two loading geometries can be practiced: cantilever and four-point bending.

9.2 *Cantilever-Beam Specimen (Fig. 4)*—the dimensions of the specimen used for cantilever loading should be selected within limits shown below:

Thickness (t): 6 mm (0.22 in.) minimum,
Width (W): 8t ≤ W ≤ 12t,
Length (L): 6W minimum,
Distance to the point of measurement (L_O): 4W, and
Clamped length: 1.5W

9.2.1 A heat-strengthened or tempered specimen, with polished edges is preferred, but annealed specimens can be used if the range of stress is less than 24.13 MPa (3500 psi).

9.3 *Four-Point Bending Specimen (Fig. 5)*—The four-point bending specimen should be preferred since it has uniform stress in the central loading zone. The dimensions of the specimen should be selected within the following limits:

Thickness (t): minimum 2 mm (0.079 in.),
Width (W): 8t ≤ W ≤ 12t (see Note 3),
Length L_O: 6W minimum,
Gage length L_C sction: 3W,
Minimum overall length L: 12W, and
Edges: Polished, no chips in the gage section, bevel less than 0.1t.

NOTE 3—When the thickness *t* is less than 6 mm, and width of the beam exceeds 12*t*, instead of the beam bending, plate bending equations should be used to calculate surface stress, or suitable corrections are required in the equations in 11.1. Barata[5] and Ashwell[6] show the correction procedures.

9.4 *Application of Forces*—Forces required must be calculated to eliminate possible breakage. Stresses must be estimated first using the equations in 9.1. A tempered specimen

[5] Barata, F. I., "When Is a Beam a Plate?" American Ceramic Society Communications, May 1981.

[6] Ashwell, D. G., "The Anticlastic Curvature of Rectangular Beams and Plates," Journal of Aeronautics, Vol 54, 1950, pp. 708-715.

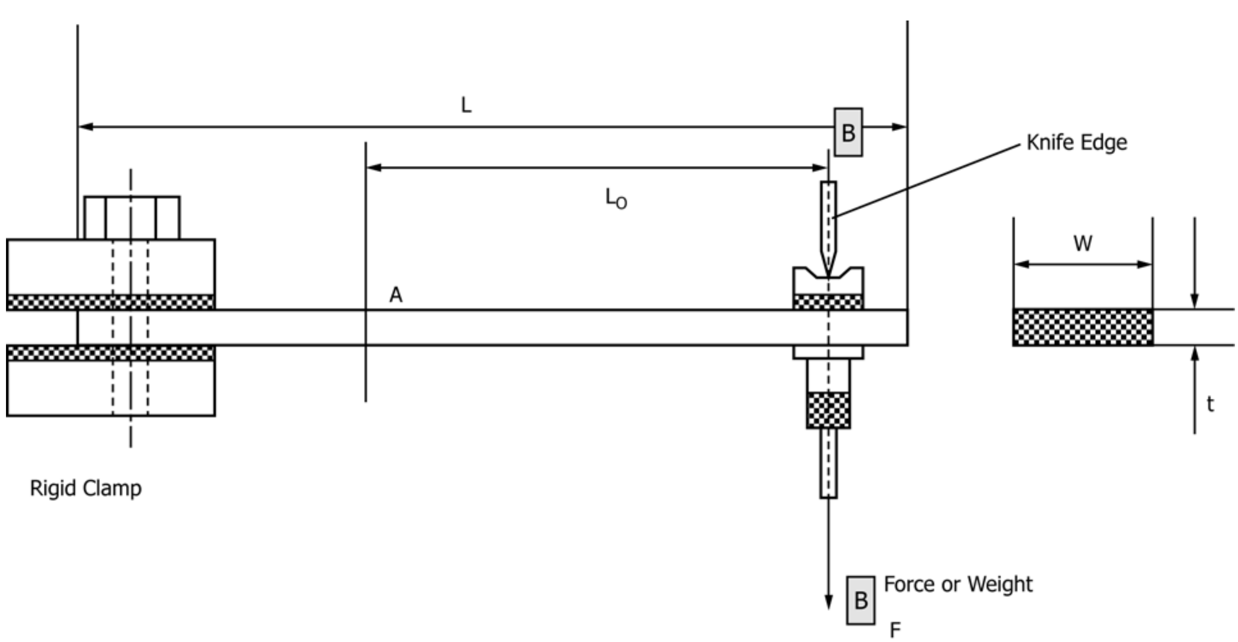

FIG. 4 Cantilever Beam Loading

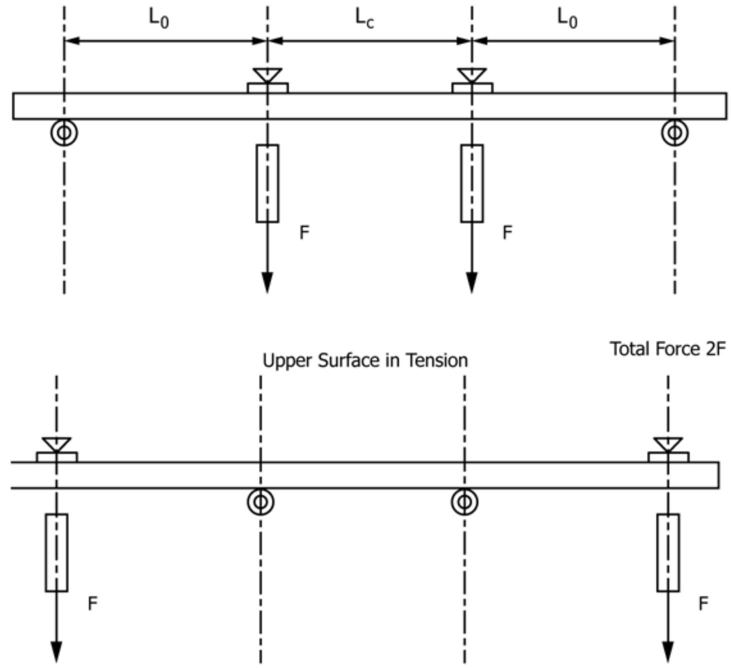

FIG. 5 Calibration Using Four-Point Bending

may be subjected to stress levels up to 10 000 psi (69 MPa). Using annealed specimens, the stress should remain at a safe level, typically below 3500 psi (24 MPa).

9.4.1 *Cantilever Specimen*—The specimen must be clamped securely using wood, plastic, or rubber-lined metal clamping surfaces, with rounded edges, as shown in Fig. 6. The forces can be applied using a calibrated testing machine or dead weights, by means of knife edges, to insure exact positioning of the line-of-loading B-B. The pad used for load application can be secured from slipping using high-friction materials. To eliminate possible twisting action, the knife edge should be narrow, or a steel ball used to center the point of application of force.

9.4.2 *Four-Point Bending Specimen*—In the case of four-point bending, the force must be applied equally at two points, and two articulated knives or roller supports are required to ascertain accurately the length L_0 and L_c. Particular precautions are required to insure that the end supports do not introduce a twist in the specimen, as a result of nonparallel support surfaces or nonflatness of the specimen itself. Fig. 5

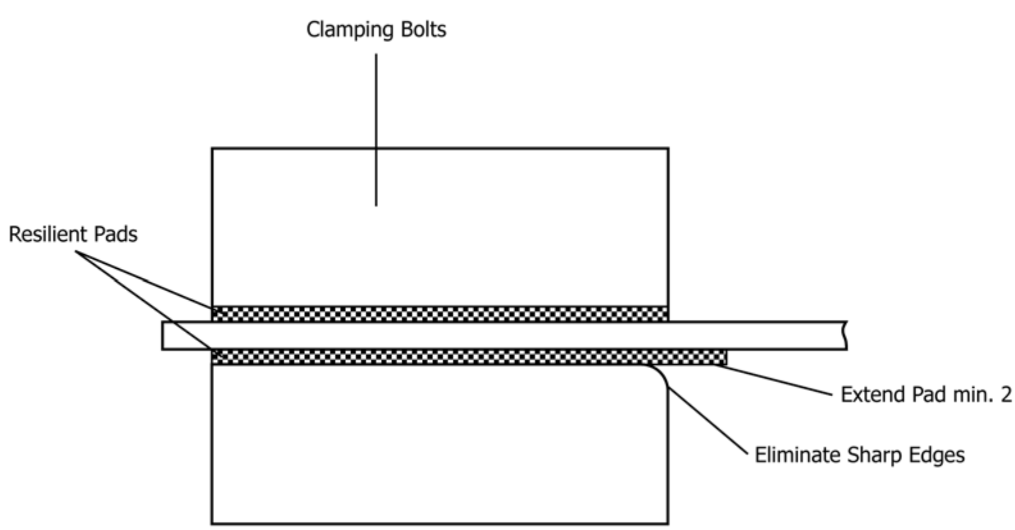

FIG. 6 Clamping of a Cantilever Beam

illustrates the setup for application of forces to obtain tension and compression on the upper face. Test Methods C158 provides a description of support design.

10. Calibration Procedure

10.1 When calibrating a surface polarimeter, apply forces in five equal increments, using a testing machine or dead weight. When calibrating a critical angle measuring instrument, at least ten increments are needed, and a tempered specimen must be used.

10.2 For each incremental loading, including zero, obtain the instrument reading. Repeat the reading at least three times, and average the readings. When calibrating a surface polarimeter, measure the fringe tilt θ. When calibrating a differential refractometer, measure the differential angle using a micrometer reticle, and read the distance between the borders of illuminated zones at mutually perpendicular polarization in accordance with instrument manual.

10.3 Prepare a table of results, and plot these data, with applied stress as the ordinant (*x* axis) and tan θ (using surface Polarimeter or angular distance between emerging light beams (using refractometer) versus applied stress (see Fig. 7).

11. Calculation

11.1 For each force increment, calculate the stress at Point A where measurements are obtained using the following formula:

$$\text{Stress}_{(psi)} = \text{FORCE}_{(lbs)} \times \frac{6L_{0(in.)}}{W_{(in.)}t^2_{(in.)}} \tag{6}$$

or

$$\text{Stress}_{(MPa)} = \text{FORCE}_{(N)} \times \frac{6L_{0(mm)}}{W_{(mm)}t^2_{(mm)}} \tag{7}$$

11.2 Construct a graph as described in 10.3 showing tan θ versus stress, when using surface polarimeter, or division versus stress, using critical angle measurement (see Fig. 7).

11.3 Trace "best fit" straight line, to establish the instrument constant *K* for the surface polarimeter:

$$K = \frac{\Delta \text{Stress}}{\Delta \tan\theta} \tag{8}$$

11.4 Since the relation between the measured distance and the stress in the refractometry is nonlinear, the calibration of this instrument requires an annealed specimen or a specimen exhibiting known surface stress in the unloaded state. For each increment, add the unloaded-specimen stress to the calculated stress and verify calibration of the critical-angle measuring instrument provided by the manufacturer.

12. Report

12.1 Report the following information:

12.1.1 Date of calibration,

12.1.2 Type and dimension of the specimen,

12.1.3 Instrument constant *K* established (surface polarimeter), and

12.1.4 Table of data and initial specimen surface stress (critical angle measuring instrument).

13. Alternative Procedure for End Users

13.1 End users of surface stress measurement instruments generally will not have access to the calibration apparatus described in Section 9 and their instruments must be returned to the manufacturer or sent to a third-party laboratory to

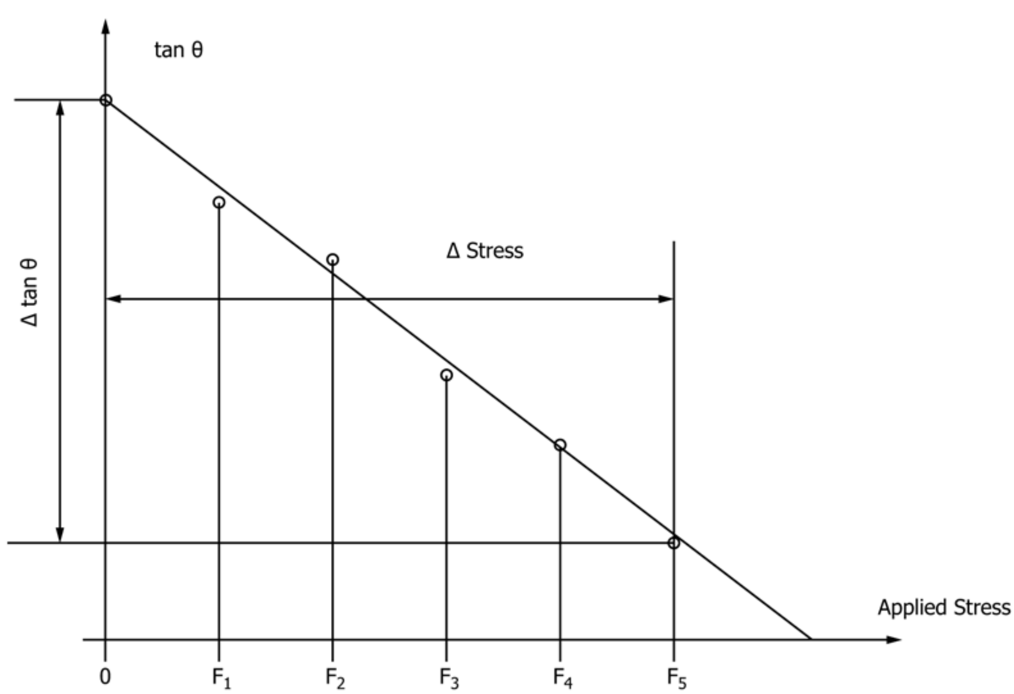

FIG. 7 Graphical Plot of Results

perform the primary calibration procedures. However, secondary calibration (verification) of the instruments may be carried out using a traceably calibrated reference standard (cal-plate). This reference standard is a heat-strengthened or fully tempered glass plate that has been certified by the instrument manufacturer as to its surface compression at a specific area (Fig. 8).[7] By measuring this reference standard, end users can verify that their instrument is measuring accurately within the stated tolerance and desired measurement range. This alternative procedure may or may not satisfy a company's Quality Control System requirements. If acceptable; however, the cal-plate itself may be sent periodically to the manufacturer for recertification, instead of having the instrument out of service for the time it takes for its recommended annual recalibration.

14. Conditioning

14.1 In order to avoid thermal stresses, the specimen should be allowed to reach ambient temperature throughout its entire mass prior to testing.

15. Procedure

15.1 *Procedure A—Measuring Surface Stress:*

15.1.1 Clean the surface of any trace of oil or other chemical deposits.

15.1.2 Place a few drops of index liquid on the tin side surface of the specimen at the point of interest. The index of refraction of the liquid should be higher than the index of the examined glass and lower or equal to the index of the prism.

15.1.3 Perform the adjustments of the optical path in accordance with manufacturer's specifications to obtain a clear image of an equally-spaced set of fringes in the compensator plane.

15.1.4 Using the goniometer, measure the angle θ (in degrees) of these fringes to the plane of symmetry (see Fig. 2).

15.1.5 Where surface stress at the point to be measured is known to be uniform (within 1° in the three directions α_1, α_2, α_3) or it is specifically prescribed to be measured at a certain direction, take a measurement at each location(s) prescribed in 7.1.

15.1.5.1 In those instances where uniformity at a point to be measured is not present or uncertain (that is, as a result of irregular geometry, proximity of edges, or non-uniformity of process), maximum and minimum surface stress can be determined by orienting the instrument in three directions and measuring the fringe pattern angle in degrees at each direction as follows:

α_1 parallel to the nearest edge,

α_2 45° to the nearest edge, and

α_3 perpendicular to the nearest edge. (See Fig. 9)

15.2 *Procedure B—Measuring Edge Stress:*

15.2.1 Using a micrometer, measure the thickness of the specimen at the location where the stress is measured.

15.2.2 Place the instrument in position, with a measuring reticle placed adjacent to instrument, and in close contact with the edge of glass.

15.2.3 Using the reticle graduation, measure the depth, *d*, in mm (in.), of the seamed or beveled region, which is non-transmitting. If the depth of the beveled region, *d* (see Fig. 10), is less than 0.25 mm (0.010 in.), use visual extrapolation of the observed fringe pattern (see 15.2.4). When the depth is equal to or greater than 0.25 mm (0.010 in.), use the extrapolation equation (see 15.2.6).

15.2.4 *Measurement Using Visual Extrapolation*—Observe the pattern of photoelastic fringes near the edge of the specimen (see Fig. 11a and Fig. 11b). Adjust the wedge (or double wedge) until the black fringe arrives to the edge (double wedge, Fig. 11b), or crosses the edge at the crosshair (single wedge, Fig. 11a).

[7] Photo courtesy of Strainoptics, Inc.

FIG. 8 Reference Standard (Cal-Plate) for Verifying Surface Polarimeters

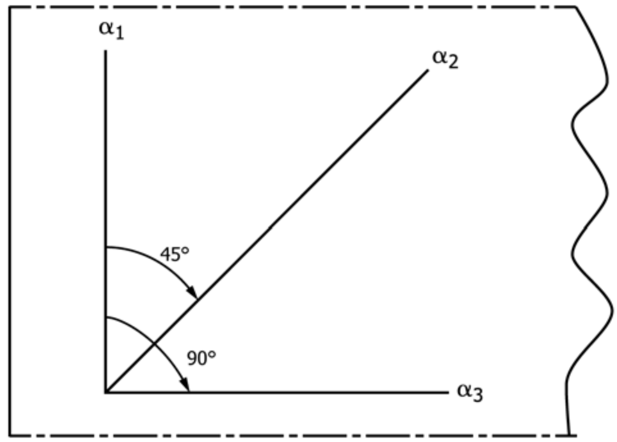

FIG. 9 Orientation of the Instrument for Measuring Surface Stress

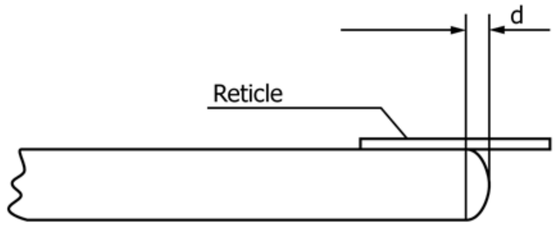

FIG. 10 Depth Measurement of Beveled Region

15.2.4.1 When using a double wedge, adjust the lead-screw driving the double wedge until the black fringe arrives to the edge (Fig. 11b) and obtain the drum reading D_e of the wedge position.

15.2.4.2 When using a single wedge compensator, adjust the wedge position until the black fringe crosses the edge a the crosshair. (Fig. 11a) and obtain the scale reading D_e on the scale of the compressoror on the lead screw drive drum.

15.2.5 Obtain a a retardation reading (R_e) using a single or double wedge, at the center of each edge of the glass, multipilying the scale or drum reading by the calibration factor b:

$$R_e = D_e * b \tag{9}$$

Where:

R_e	=	is the retardation (nm)
D_e	=	is the scale or drum reading (number)
b	=	is the compensator calibration, nm/division

15.2.6 *Measurement Using an Extrapolation Equation*—In case the seamed edge makes the reading at the edge difficult [d > 0.25 mm (0.01 in.)], measurement of retardation R_1 and R_2 at two points, x_1 and x_2 (Fig. 11a and Fig. 11b), of the reticle scale must be made. These points are to be selected per Table 1. The retardations R_1 and R_2 (nm) are retardation values measured using the compensator scale at the points x_1 and x_2. The edge retardation R_e (nm) is obtained from the equation:

$$R_e = 3.8 \cdot R_1 - 2.8 \cdot R_2 \tag{10}$$

15.2.7 Using a micrometer, measure the thickness of the specimen at the location where the stress is measured.

16. Calculation and Interpretation

16.1 *Procedure A: Measuring Surface Stress*—When the measured angle is obtained using procedure 15.1.5, calculate the surface stress, S, using:

$$S = K \tan\theta \tag{11}$$

where K is the instrument calibration constant determined by the manufacturer, in MPa (psi).

16.1.1 In those instances where the surface stress is directional, assess the state of stress by comparing the reading S in three directions α_1, α_2, α_3. If all three directions yield the same measured angles θ_1, θ_2, θ_3 within 1°, calculate the average angle, then obtain the surface stress from Eq 12 and Eq 13.

$$\theta_{\text{average}} = \frac{\theta_1 + \theta_2 + \theta_3}{3} \tag{12}$$

$$S = K \cdot \tan\theta_{\text{average}} \tag{13}$$

If the measured angles θ_1, θ_2, and θ_3 differ by more than 1°, then using Eq 11, obtain the three stresses S_1, S_2, and S_3 in directions α_1, α_2, and α_3, and then calculate the principal stresses S_{max}, and S_{min}, from Eq 14 and Eq 15.

$$S_{\max} = \frac{S_1 + S_3}{2} + \frac{\sqrt{2}}{2}\sqrt{(S_1 - S_2)^2 + (S_2 - S_3)^2} \tag{14}$$

$$S_{\min} = \frac{S_1 + S_3}{2} - \frac{\sqrt{2}}{2}\sqrt{(S_1 - S_2)^2 + (S_2 - S_3)^2} \tag{15}$$

16.2 *Procedure B: Measuring Edge Stress*— From the measured retardation R_e calculate the edge stress in MPa:

$$\textit{Edge Stress } S_e = \frac{R_e}{T * C_B} \tag{16}$$

where:

D	=	Compensator scale reading, indicated by a scale or a lead screw drum
$R_e = D*b$	=	the compensator reading (nm),
T	=	the thickness of the glass sample mm,
C_B	=	stress-optical constant, Brewsters or 10^{-12}/Pa,
S_e	=	stress MPa, and

NOTE 4—To convert MPa to psi units, multiply value of S_e in MPa by 145.

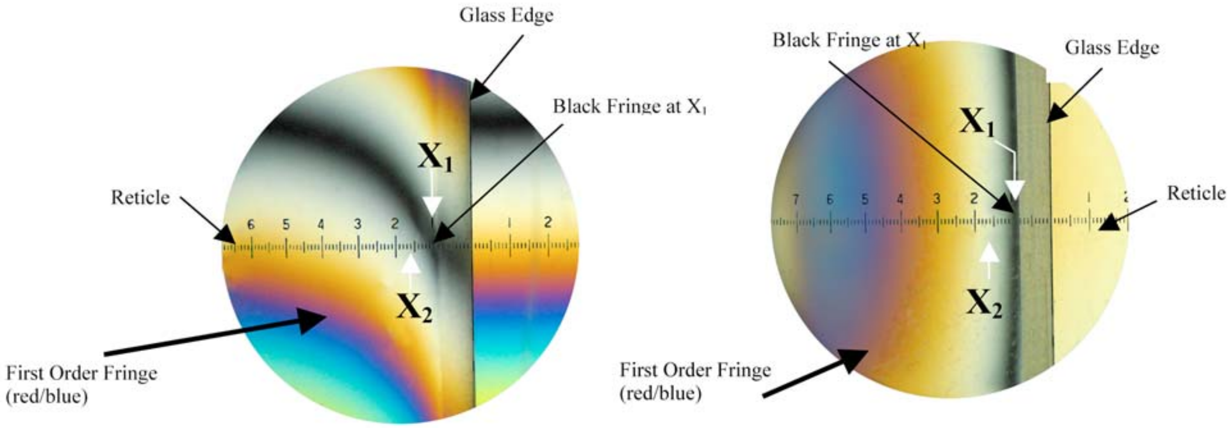

FIG. 11 a) Fringes observed on 6 mm Glass Using Single Wedge Compensator (Babinet), b) Fringes Observed Using Double Wedge Compensator (Babinet-Soleil).
The readings at points X_1 and X_2 from Table 1 are used for the values of R_1 and R_2 in the Extrapolation Equation Procedure 15.2.6.

TABLE 1 Location of Points x_1 and x_2

	Thickness of Glass		
	⅛ to ³⁄₁₆ inch (3 to 5 mm)	¼ to ⅜ inch (6 to 10 mm)	½ to 1 inch (12 to 24.5 mm)
x_1^A	0.6 or 0.8 mm	1.0 mm	2.0 mm
x_2^A	1.0 or 1.3 mm	1.6 mm	3.0 mm

^{A}Select X_1 = 0.6mm X_2 = 1.0mm when the edge is not ground deeply. Select X_1 =0.8mm, X_2= 1.3mm when the first choice is not practical, for example, when X_1 falls within the area of the ground edge.

17. Report

17.1 At a minimum, the report must contain:
17.1.1 Date of specimen manufacture, if known
17.1.2 Identification of specimen (material)
17.1.3 Selected procedure
17.1.4 Glass thickness
17.1.5 For surface measurement:
17.1.5.1 Location(s) of measurement(s)
17.1.5.2 Direction of measurement(s)
17.1.5.3 Values of θ_1, θ_2, θ_3 at each location and the calculated stress
17.1.6 For edge measurements:
17.1.6.1 Location of measurement(s)
17.1.6.2 Chamfer size
17.1.6.3 Thickness of specimen at point of measurement
17.1.6.4 Extrapolation method used— *visual* (15.2.4) or *calculated* (15.2.6)
17.1.6.5 Average edge stress

18. Precision and Bias[8,9]

Procedure A

18.1 An interlaboratory round robin test was conducted in accordance with Practice E691 to establish the precision and bias of surface stress measurements. Table 2 summarizes the result of this study. In this test, seven laboratories measured surface stress on six samples using Procedure A. Each test result was an average of 3 replicates. The samples used exhibited a broad range of stress levels. A thorough analysis of raw data and intermediate calculation was filed in a Research Report format with ASTM.

18.1.1 The results shown in Table 2 summarize the statistical analysis using data collected at the same location (point "A") of all samples, and lists both the measured fringe angle (in degrees) and the calculated stress. Test data were collected at 5 points of each sample. A considerable variation of surface stress was measured within each sample, yielding a substantial data scatter. The variability of stress in each sample was substantially higher than the reproducibility of measurements at an individual point

18.1.2 In Table 2, the repeatability standard deviation S_r expresses an average of "within laboratory" reproducibility and the standard deviation S_x expresses interlaboratory deviation. The stress was calculated from the measured angle using Eq 4. There is no assurance that all instruments used in the round robin were calibrated to verify their conformance to factory specification.

18.1.3 *Bias*—The calibration and instrument constant K used to convert measured fringe angle θ to stress is affected by the material stress-optical constant C and the index of refraction of the measured sample. Disregarding these changes will result in a systematic error that can be only eliminated when the calibration of the instrument is performed on the same batch of material as the measured sample.

Procedure B

18.2 An inter-laboratory Round Robin test was conducted in accordance with Practice E691 to establish the precision and bias of edge stress measurement. Table 3 summarizes the results of this study. Each test result was an average of three replicates. Eight samples were used, including heat strengthened and tempered glass, ranging in thickness from 2 to 12 mm. A thorough analysis of data and intermediate calculations are in the Research Report now on file with ASTM International.

[8] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:C14-1002.
[9] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:C14-1004.

TABLE 2 Procedure A – Result of Statistical Data Analysis
(Measuring Stresses in direction X and Y at a point "A" in all samples.)

Sample #	14		13		17		16		18		15	
Stress direction	x	y	x	y	x	y	x	y	x	y	x	y
Average measured angle (degrees)	23.6	29.6	53.4	54.1	55.4	55.4	61.5	64	68.4	68.4	70.6	71.9
Average stress, psi	2657	3454	8188	8401	8815	8815	11200	12468	15359	15359	17268	18605
Average stress, MPa	18.3	23.8	56.5	57.7	60.8	60.8	77.2	86.0	105.9	105.9	119.1	128.3
Between laboratories std dev. Sx (degrees)	2.04	23.8	1.7	57.9	1.82	60.8	2.01	86.0	1.63	...	1.98	...
Repeatability Std Dev. (degrees)	0.49	...	0.48	...	0.41	...	0.61	...	0.33	...	0.46	...
Standard deviation, psi	258	...	507	...	598	...	936	...	1274	...	1901	...
Standard deviation, MPa	1.78	...	3.50	...	4.12	...	6.46	...	8.79	...	13.11	...

TABLE 3 Procedure B-Results of Statistical Data Analysis

Sample #	Units	6	11	8	0	15	13	14	3
thickness	mm	2.36	2.36	3.15	3.18	5.64	5.69	5.69	12.4
Edge Compression	MPa	67.55	83.61	60.04	74.11	88.53	97.33	104.6	80.49
	psi	9 800	12 120	8 700	10 750	12 840	14 100	15 160	11 670
Between MPaLaboratory std. deviation S_x	MPa	5.35	4.59	3.26	3.95	2.77	3.82	4.22	3.65
Repeatability std., S_r	MPa	1.22	1.95	2.21	1.76	2.00	1.44	1.40	0.53
Reproducibility Std.	MPa	5.44	4.86	3.73	4.2	3.22	3.99	4.37	3.67
Deviation SR	psi	790	704	540	610	470	580	630	530

18.2.1 The results shown in Table 3 summarize the statistical analysis using data collected by participating laboratories using Procedure B. Each test result was obtained as an average of stress measured at the mid-point of all four edges. In all instances where the depth of the ground finish was greater than 0.25 mm, an extrapolation procedure was used. All results are expressed as MPa.

18.2.2 In Table 3, the repeatability standard deviation Sr expresses an average of "within laboratory" reproducibility and the standard deviation S_x expresses interlaboratory deviation. The stress was calculated from the retardation using a stress-optical constant C_B = 2.65 for all samples using Eq 16.

18.2.3 Compensators used in Procedure B require calibration. There is no assurance that all laboratories calibrated their compensators recently.

19. Keywords

19.1 annealed glass; heat-strengthened glass; polariscopic examination; stress measurement; tempered glass