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# Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials[1]

This standard is issued under the fixed designation D790; 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 are used to determine the flexural properties of unreinforced and reinforced plastics, including high modulus composites and electrical insulating materials utilizing a three-point loading system to apply a load to a simply supported beam (specimen). The method is generally applicable to both rigid and semi-rigid materials, but flexural strength cannot be determined for those materials that do not break or yield in the outer surface of the test specimen within the 5.0 % strain limit.

1.2 Test specimens of rectangular cross section are injection molded or, cut from molded or extruded sheets or plates, or cut from molded or extruded shapes. Specimens must be solid and uniformly rectangular. The specimen rests on two supports and is loaded by means of a loading nose midway between the supports.

1.3 Measure deflection in one of two ways; using crosshead position or a deflectometer. Please note that studies have shown that deflection data obtained with a deflectometer will differ from data obtained using crosshead position. The method of deflection measurement shall be reported.

NOTE 1—Requirements for quality control in production environments are usually met by measuring deflection using crosshead position. However, more accurate measurement may be obtained by using an deflection indicator such as a deflectometer.

NOTE 2—Materials that do not rupture by the maximum strain allowed under this test method may be more suited to a 4-point bend test. The basic difference between the two test methods is in the location of the maximum bending moment and maximum axial fiber stresses. The maximum axial fiber stresses occur on a line under the loading nose in 3-point bending and over the area between the loading noses in 4-point bending. A four-point loading system method can be found in Test Method D6272.

1.4 The values stated in SI units are to be regarded as the standard. The values provided in parentheses are for information only.

1.5 *The text of this standard references notes and footnotes that provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.*

1.6 *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.*

NOTE 3—This standard and ISO 178 address the same subject matter, but differ in technical content.

1.7 *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]

D618 Practice for Conditioning Plastics for Testing
D638 Test Method for Tensile Properties of Plastics
D883 Terminology Relating to Plastics
D4000 Classification System for Specifying Plastic Materials
D4101 Specification for Polypropylene Injection and Extrusion Materials
D5947 Test Methods for Physical Dimensions of Solid Plastics Specimens
D6272 Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending
E4 Practices for Force Verification of Testing Machines
E83 Practice for Verification and Classification of Extensometer Systems

[1] These test methods are under the jurisdiction of ASTM Committee D20 on Plastics and are the direct responsibility of Subcommittee D20.10 on 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.

*A Summary of Changes section appears at the end of this standard

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E2309 Practices for Verification of Displacement Measuring Systems and Devices Used in Material Testing Machines

2.2 *ISO Standard:*[3]

ISO 178 Plastics—Determination of Flexural Properties

## 3. Terminology

3.1 *Definitions*—Definitions of terms applying to these test methods appear in Terminology D883 and Annex A2 of Test Method D638.

## 4. Summary of Test Method

4.1 A test specimen of rectangular cross section rests on two supports in a flat-wise position and is loaded by means of a loading nose located midway between the supports. Unless testing certain laminated materials (see 7 for guidance), a support span-to-depth (of specimen) ratio 16:1 shall be used. The specimen is deflected until rupture occurs in the outer surface of the test specimen or until a maximum strain (see 5.1.6) of 5.0 % is reached, whichever occurs first.

4.2 *Procedure A* is designed principally for materials that break at comparatively small deflections and it shall be used for measurement of flexural properties, particularly flexural modulus, unless the material specification states otherwise. Procedure A employs a strain rate of 0.01 mm/mm/min (0.01 in./in./min) and is the preferred procedure for this test method.

4.3 *Procedure B* is designed principally for those materials that do not break or yield in the outer surface of the test specimen within the 5.0 % strain limit when Procedure A conditions are used. Procedure B employs a strain rate of 0.10 mm/mm/min (0.10 in./in./min).

4.4 Type I tests utilize crosshead position for deflection measurement.

4.5 Type II tests utilize an instrument (deflectometer) for deflection measurement.

4.6 The procedure used and test type shall be reported

NOTE 4—Comparative tests may be run in accordance with either procedure, provided that the procedure is found satisfactory for the material being tested. Tangent modulus data obtained by Procedure A tends to exhibit lower standard deviations than comparable results obtained by means of Procedure B.

## 5. Significance and Use

5.1 Flexural properties as determined by this test method are especially useful for quality control and specification purposes. They include:

5.1.1 *Flexural Stress ($\sigma_f$)*—When a homogeneous elastic material is tested in flexure as a simple beam supported at two points and loaded at the midpoint, the maximum stress in the outer surface of the test specimen occurs at the midpoint. Flexural stress is calculated for any point on the load-deflection curve using equation (Eq 3) in Section 12 (see Notes 5 and 6).

NOTE 5—Eq 3 applies strictly to materials for which stress is linearly proportional to strain up to the point of rupture and for which the strains are small. Since this is not always the case, a slight error will be introduced if Eq 3 is used to calculate stress for materials that are not true Hookean materials. The equation is valid for obtaining comparison data and for specification purposes, but only up to a maximum fiber strain of 5 % in the outer surface of the test specimen for specimens tested by the procedures described herein.

NOTE 6—When testing highly orthotropic laminates, the maximum stress may not always occur in the outer surface of the test specimen.[4] Laminated beam theory must be applied to determine the maximum tensile stress at failure. If Eq 3 is used to calculate stress, it will yield an apparent strength based on homogeneous beam theory. This apparent strength is highly dependent on the ply-stacking sequence of highly orthotropic laminates.

5.1.2 *Flexural Stress for Beams Tested at Large Support Spans ($\sigma_f$)*—If support span-to-depth ratios greater than 16 to 1 are used such that deflections in excess of 10 % of the support span occur, the stress in the outer surface of the specimen for a simple beam is reasonably approximated using equation (Eq 4) in 12.3 (see Note 7).

NOTE 7—When large support span-to-depth ratios are used, significant end forces are developed at the support noses which will affect the moment in a simple supported beam. Eq 4 includes additional terms that are an approximate correction factor for the influence of these end forces in large support span-to-depth ratio beams where relatively large deflections exist.

5.1.3 *Flexural Strength ($\sigma_{fM}$)*—Maximum flexural stress sustained by the test specimen (see Note 6) during a bending test. It is calculated according to Eq 3 or Eq 4. Some materials that do not break at strains of up to 5 % give a load deflection curve that shows a point at which the load does not increase with an increase in strain, that is, a yield point (Fig. 1, Curve b), *Y*. The flexural strength is calculated for these materials by letting *P* (in Eq 3 or Eq 4) equal this point, *Y*.

5.1.4 *Flexural Offset Yield Strength*—Offset yield strength is the stress at which the stress-strain curve deviates by a given strain (offset) from the tangent to the initial straight line portion of the stress-strain curve. The value of the offset must be given whenever this property is calculated.

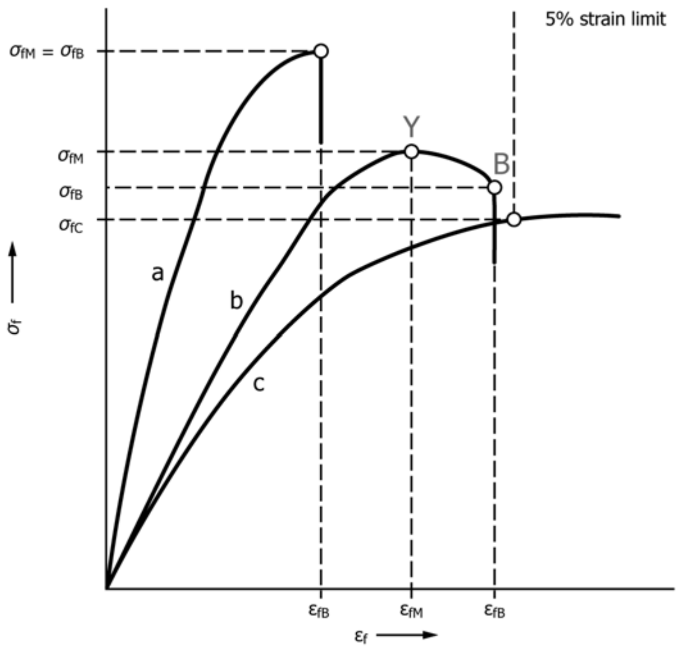
NOTE 8—Flexural Offset Yield Strength may differ from flexural strength defined in 5.1.3. Both methods of calculation are described in the annex to Test Method D638.

5.1.5 *Flexural Stress at Break ($\sigma_{fB}$)*—Flexural stress at break of the test specimen during a bending test. It is calculated according to Eq 3 or Eq 4. Some materials give a load deflection curve that shows a break point, *B*, without a yield point (Fig. 1, Curve a) in which case $\sigma_{fB} = \sigma_{fM}$. Other materials give a yield deflection curve with both a yield and a break point, *B* (Fig. 1, Curve b). The flexural stress at break is calculated for these materials by letting *P* (in Eq 3 or Eq 4) equal this point, *B*.

5.1.6 *Stress at a Given Strain*—The stress in the outer surface of a test specimen at a given strain is calculated in accordance with Eq 3 or Eq 4 by letting *P* equal the load read

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[4] For a discussion of these effects, see Zweben, C., Smith, W. S., and Wardle, M. W., "Test Methods for Fiber Tensile Strength, Composite Flexural Modulus and Properties of Fabric-Reinforced Laminates," *Composite Materials: Testing and Design (Fifth Conference), ASTM STP 674*, 1979, pp. 228–262.




NOTE 1—Curve a: Specimen that breaks before yielding.

Curve b: Specimen that yields and then breaks before the 5 % strain limit.

Curve c: Specimen that neither yields nor breaks before the 5 % strain limit.

**FIG. 1 Typical Curves of Flexural Stress ($\sigma_f$) Versus Flexural Strain ($\varepsilon_f$)**

from the load-deflection curve at the deflection corresponding to the desired strain (for highly orthotropic laminates, see Note 6).

5.1.7 *Flexural Strain, $\varepsilon_f$*—Nominal fractional change in the length of an element of the outer surface of the test specimen at midspan, where the maximum strain occurs. Flexural strain is calculated for any deflection using Eq 5 in 12.4.

5.1.8 *Modulus of Elasticity:*

5.1.8.1 *Tangent Modulus of Elasticity*—The tangent modulus of elasticity, often called the "modulus of elasticity," is the ratio, within the elastic limit, of stress to corresponding strain. It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using Eq 6 in 12.5.1 (for highly anisotropic composites, see Note 9).

NOTE 9—Shear deflections can seriously reduce the apparent modulus of highly anisotropic composites when they are tested at low span-to-depth ratios.[4] For this reason, a span-to-depth ratio of 60 to 1 is recommended for flexural modulus determinations on these composites. Flexural strength should be determined on a separate set of replicate specimens at a lower span-to-depth ratio that induces tensile failure in the outer fibers of the beam along its lower face. Since the flexural modulus of highly anisotropic laminates is a critical function of ply-stacking sequence, it will not necessarily correlate with tensile modulus, which is not stacking-sequence dependent.

5.1.8.2 *Secant Modulus*—The secant modulus is the ratio of stress to corresponding strain at any selected point on the stress-strain curve, that is, the slope of the straight line that joins the origin and a selected point on the actual stress-strain curve. It shall be expressed in megapascals (pounds per square inch). The selected point is chosen at a pre-specified stress or strain in accordance with the appropriate material specification or by customer contract. It is calculated in accordance with Eq 6 by letting m equal the slope of the secant to the load-deflection curve. The chosen stress or strain point used for the determination of the secant shall be reported.

5.1.8.3 *Chord Modulus ($E_f$)*—The chord modulus is calculated from two discrete points on the load deflection curve. The selected points are to be chosen at two pre-specified stress or strain points in accordance with the appropriate material specification or by customer contract. The chosen stress or strain points used for the determination of the chord modulus shall be reported. Calculate the chord modulus, $E_f$ using Eq 7 in 12.5.2.

5.2 Experience has shown that flexural properties vary with specimen depth, temperature, atmospheric conditions, and strain rate as specified in Procedures A and B.

5.3 Before proceeding with these test methods, refer to the ASTM specification of the material being tested. Any test specimen preparation, conditioning, dimensions, or testing parameters, or combination thereof, covered in the ASTM material specification shall take precedence over those mentioned in these test methods. Table 1 in Classification System D4000 lists the ASTM material specifications that currently exist for plastics.

## 6. Apparatus

6.1 *Testing Machine*—A testing machine capable of being operated at constant rates of crosshead motion over the range indicated and comprised of the following:

6.1.1 *Load Frame*—The stiffness of the testing machine shall be such that the total elastic deformation of the system does not exceed 1 % of the total deflection of the test specimen during testing, or appropriate corrections shall be made.

6.1.1.1 *Fixed Member*—A fixed or essentially stationary member holding the specimen supports;

6.1.1.2 *Movable Member*—A movable member carrying the loading nose.

6.1.2 *Loading Noses and Supports*—The loading nose and supports shall have cylindrical surfaces.

6.1.2.1 The radii of the loading nose and supports shall be 5.0 ± 0.1 mm (0.197 ± 0.004 in.) unless otherwise specified in an ASTM material specification or as agreed upon between interested parties.

6.1.2.2 *Other Radii for Loading Noses and Supports*—Alternative loading noses and supports are permitted to be used in order to avoid excessive indentation or failure due to stress concentration directly under the loading nose or if required by an ASTM material specification. If alternative loading nose and support radii are used, the dimensions of the loading nose and supports shall be clearly identified in the test report and reference shall be made to any applicable specifications.

*(1)* Alternative supports shall have a minimum radius of 3.2 mm (⅛ in.) When testing specimens 3.2 mm or greater in depth, the radius of the loading nose and supports are permitted to be up to 1.6 times the specimen depth.

*(2)* The arc of the loading nose in contact with the specimen shall be sufficiently large to prevent contact of the specimen with the sides of the nose. Alternative loading noses shall be sufficiently large to prevent contact of the specimen

with the sides of the nose. The maximum radius of the loading nose shall be no more than four times the specimen depth.

6.1.3 *Drive Mechanism*—A drive mechanism for imparting to the movable member a uniform, controlled velocity with respect to the stationary member, with this velocity to be regulated as specified in Procedure A or B.

6.1.4 *Load Indicator*—A suitable load-indicating mechanism capable of showing the total load applied to specimen when in position on the flex fixture. This mechanism shall be essentially free of inertia lag at the specified rate of testing and shall indicate the load with an accuracy of ±1 % of the indicated value, or better. The accuracy of the testing machine shall be verified in accordance with Practices E4.

6.1.5 *Deflection Measuring Device*—The deflection measuring device used shall be selected from the following two choices:

6.1.5.1 *Type I—Crosshead Position Indicating System*—A suitable deflection indicating mechanism capable of showing the amount of change in crosshead movement. This mechanism shall be essentially free of inertial lag at the specified rate of testing and shall indicate the crosshead movement. The crosshead position indicating system shall be verified in accordance with Practice E2309 and minimally meet the requirements of a Class B system for use in determining strain.

NOTE 10—Machine compliance correction may be applied to correct for lost motion and deflection in the load frame, drive mechanism, load sensor and other elements in order to give a more precise measurement of the deflection of the test specimen. Many manufacturer's machines and/or software packages perform this machine compliance correction. Appendix X1 also provides a means of determining the compliance correction.

6.1.5.2 *Type II—Deflection Indicator (Deflectometer)*—A suitable instrument for more accurately determining the deflection of the specimen at its midpoint (beneath the loading nose). This instrument shall be essentially free of inertia at the specified speed of testing. The deflection indicator system shall be verified in accordance with Practice E83 and minimally meet the requirements of a Class B-2 instrument for modulus and a Class C instrument for other strain measurements.

NOTE 11—It is desirable, but not essential, that this instrument automatically record this distance, or any change in it, as a function of the load on the test specimen or of the elapsed time from the start of the test, or both. If only the latter is obtained, it has been found useful to also record load-time data.

NOTE 12—Practice E83 is intended for extensometers. As such it references gauge length which is not applicable to deflectometers. To satisfy the "fixed value" and "fixed error" requirements in Table 1 of Practice E83, an effective gauge length of 50 mm can be assumed.

6.2 *Micrometers*—Apparatus for measuring the width and thickness of the test specimen shall comply with the requirements of Test Method D5947.

## 7. Test Specimens

7.1 Test specimens that are cut from sheets, plates, or molded or extruded shapes, or molded to the desired finished dimensions are acceptable. The actual dimensions used shall be measured in accordance with Test Methods D5947. The depth of the specimen shall be defined as the thickness of the material. The depth shall not exceed the width (see Note 13). The crosssection of the specimens shall be rectangular with opposite sides flat and parallel (±0.2 mm) and adjacent sides perpendicular along the full length of the specimen.

7.2 Whenever possible, the original surface of the sheet shall be unaltered. However, where testing machine limitations make it impossible to follow the above criterion on the unaltered sheet, one or both surfaces shall be machined to provide the desired dimensions, and the location of the specimens with reference to the total depth shall be noted. Consequently, any specifications for flexural properties on thicker sheets must state whether the original surfaces are to be retained or not. When only one surface was machined, it must be stated whether the machined surface was on the tension or compression side of the beam. Any necessary polishing of specimens shall be done only in the lengthwise direction of the specimen.

NOTE 13—The value obtained on specimens with machined surfaces may differ from those obtained on specimens with original surfaces.

7.3 *Sheet Materials (Except Laminated Thermosetting Materials and Certain Materials Used for Electrical Insulation, Including Vulcanized Fiber and Glass Bonded Mica):*

7.3.1 *Materials 1.6 mm (1⁄16 in.) or Greater in Thickness*—Specimen width shall not exceed one fourth of the support span for specimens greater than 3.2 mm (1⁄8 in.) in depth. Specimens 3.2 mm or less in depth shall be 12.7 mm (1⁄2 in.) in width. The specimen shall be long enough to allow for overhanging on each end of at least 10 % of the support span, but in no case less than 6.4 mm (1⁄4 in.) on each end. Overhang shall be sufficient to prevent the specimen from slipping through the supports. A support span of 16 ± 1 times the depth of the specimen is used for these specimens.

7.3.2 *Materials Less than 1.6 mm (1⁄16 in.) in Thickness*—The specimen shall be 50.8 mm (2 in.) long by 12.7 mm (1⁄2 in.) wide, tested flatwise on a 25.4-mm (1-in.) support span.

NOTE 14—Use of the formulas for simple beams cited in these test methods for calculating results presumes that beam width is small in comparison with the support span. Therefore, the formulas do not apply rigorously to these dimensions.

NOTE 15—Where machine sensitivity is such that specimens of these dimensions cannot be measured, wider specimens or shorter support spans, or both, may be used, provided the support span-to-depth ratio is at least 14 to 1. All dimensions must be stated in the report (see also Note 14).

7.4 *Laminated Thermosetting Materials and Sheet and Plate Materials Used for Electrical Insulation, Including Vulcanized Fiber and Glass-Bonded Mica*—For paper-base and fabric-base grades over 25.4 mm (1 in.) in nominal thickness, the specimens shall be machined on both surfaces to a depth of 25.4 mm. For glass-base and nylon-base grades, specimens over 12.7 mm (0.5 in.) in nominal depth shall be machined on both surfaces to a depth of 12.7 mm. The support span-to-depth ratio shall be chosen such that failures occur in the outer fibers of the specimens, due only to the bending moment. As a general rule, support span-to-specimen depth ratios of 16:1 are satisfactory when the ratio of the tensile strength to shear strength is less than 8 to 1, but the support span-to-depth ratio must be increased for composite laminates having relatively low shear strength in the plane of the laminate and relatively high tensile strength parallel to the support span (32:1 or 40:1

are recommended). When laminated materials exhibit low compressive strength perpendicular to the laminations, they shall be loaded with a large radius loading nose (up to four times the specimen depth to prevent premature damage to the outer fibers.

7.5 *Molding Materials (Thermoplastics and Thermosets)*—The preferred specimen dimensions for molding materials is 12.7 mm (0.5 in.) wide, 3.2 mm (0.125 in.) thick, and 127 mm (5.0 in.) long. They are tested flatwise on the support span, resulting in a support span-to-depth ratio of 16:1 (tolerance ±1). Thicker specimens are to be avoided if they exhibit significant sink marks or bubbles when molded.

7.6 *High-Strength Reinforced Composites, Including Highly Orthotropic Laminates*—The span-to-depth ratio shall be chosen such that failure occurs in the outer fibers of the specimens and is due only to the bending moment. As a general rule, support span-to-depth ratios of 16:1 are satisfactory when the ratio of the tensile strength to shear strength is less than 8 to 1, but the support span-to-depth ratio must be increased for composite laminates having relatively low shear strength in the plane of the laminate and relatively high tensile strength parallel to the support span (32:1 or 40:1 are recommended). For some highly anisotropic composites, shear deformation can significantly influence modulus measurements, even at span-to-depth ratios as high as 40:1. Hence, for these materials, an increase in the span-to-depth ratio to 60:1 is recommended to eliminate shear effects when modulus data are required, it should also be noted that the flexural modulus of highly anisotropic laminates is a strong function of ply-stacking sequence and will not necessarily correlate with tensile modulus, which is not stacking-sequence dependent.

## 8. Number of Test Specimens

8.1 Test at least five specimens for each sample in the case of isotropic materials or molded specimens.

8.2 For each sample of anisotropic material in sheet form, test at least five specimens cut in the desired direction. For the purposes of this test, "lengthwise" designates the principal axis of anisotropy and shall be interpreted to mean the direction of the sheet known to be stronger in flexure. "Crosswise" indicates the sheet direction known to be the weaker in flexure and shall be at 90° to the lengthwise direction. The direction of test, whether it be lengthwise, crosswise, or some angle relative to these shall be noted in the report.

## 9. Conditioning

9.1 *Conditioning*—Condition the test specimens in accordance with Procedure A of Practice D618 unless otherwise specified by contract or the relevant ASTM material specification. Conditioning time is specified as a minimum. Temperature and humidity tolerances shall be in accordance with Section 7 of Practice D618 unless specified differently by contract or material specification.

9.2 *Test Conditions*—Conduct the tests at the same temperature and humidity used for conditioning with tolerances in accordance with Section 7 of Practice D618 unless otherwise specified by contract or the relevant ASTM material specification.

## 10. Procedure

10.1 *Procedure A:*

10.1.1 Use an untested specimen for each measurement. Measure the width and depth of the specimen to the nearest 0.03 mm (0.001 in.) at the center of the support span. For specimens less than 2.54 mm (0.100 in.) in depth, measure the depth to the nearest 0.003 mm (0.0005 in.). These measurements shall be made in accordance with Test Methods D5947.

10.1.2 Determine the support span to be used as described in Section 7 and set the support span to within 1 % of the determined value.

10.1.3 For flexural fixtures that have continuously adjustable spans, measure the span accurately to the nearest 0.1 mm (0.004 in.) for spans less than 63 mm (2.5 in.) and to the nearest 0.3 mm (0.012 in.) for spans greater than or equal to 63 mm (2.5 in.). Use the actual measured span for all calculations. For flexural fixtures that have fixed machined span positions, verify the span distance the same as for adjustable spans at each machined position. This distance becomes the span for that position and is used for calculations applicable to all subsequent tests conducted at that position. See Annex A2 for information on the determination of and setting of the span.

10.1.4 Calculate the rate of crosshead motion as follows and set the machine for the rate of crosshead motion as calculated by Eq 1:

$$R = ZL^2/6d \tag{1}$$

where:

$R$ = rate of crosshead motion, mm (in.)/min,
$L$ = support span, mm (in.),
$d$ = depth of beam, mm (in.), and
$Z$ = rate of straining of the outer fiber, mm/mm/min (in./in./min). $Z$ shall be equal to 0.01.

In no case shall the actual crosshead rate differ from that calculated using Eq 1, by more than ±10 %.

10.1.5 Align the loading nose and supports so that the axes of the cylindrical surfaces are parallel and the loading nose is midway between the supports. Center the specimen on the supports, with the long axis of the specimen perpendicular to the loading nose and supports. The loading nose should be close to, but not in contact with the specimen (see Note 16).

NOTE 16—The parallelism of the apparatus may be checked by means of a plate with parallel grooves into which the loading nose and supports will fit when properly aligned (see A2.3).

10.1.6 Apply the load to the specimen at the specified crosshead rate, and record simultaneous load-deflection data.

10.1.7 Measure deflection either by measurement of the motion of the loading nose relative to the supports (crosshead position) (Type I) or by a deflection indicator (deflectometer) under the specimen in contact with it at the center of the support span, the gauge being mounted stationary relative to the specimen supports (Type II). Load-deflection curves are used to determine the flexural strength, chord or secant modulus or the tangent modulus of elasticity, and the total work as measured by the area under the load-deflection curve. Perform the necessary toe compensation (see Annex A1) to correct for seating and indentation of the specimen and deflections in the machine.

10.1.8 Terminate the test when the maximum strain in the outer surface of the test specimen has reached 0.05 mm/mm (in./in.) or at break if break occurs prior to reaching the maximum strain (Notes 17 and 18). The deflection at which this strain will occur is calculated by letting $r$ equal 0.05 mm/mm (in./in.) in Eq 2:

$$D = rL^2/6d \tag{2}$$

where:

$D$ = midspan deflection, mm (in.),
$r$ = strain, mm/mm (in./in.),
$L$ = support span, mm (in.), and
$d$ = depth of beam, mm (in.).

NOTE 17—For some materials that do not yield or break within the 5 % strain limit when tested by Procedure A, the increased strain rate allowed by Procedure B (see 10.2) may induce the specimen to yield or break, or both, within the required 5 % strain limit.

NOTE 18—Beyond 5 % strain, this test method is not applicable. Some other mechanical property might be more relevant to characterize materials that neither yield nor break by either Procedure A or Procedure B within the 5 % strain limit (for example, Test Method D638 may be considered).

10.2 *Procedure B:*

10.2.1 Use an untested specimen for each measurement.

10.2.2 Test conditions shall be identical to those described in 10.1, except that the rate of straining of the outer surface of the test specimen shall be 0.10 mm/mm (in./in.)/min.

10.2.3 If no break has occurred in the specimen by the time the maximum strain in the outer surface of the test specimen has reached 0.05 mm/mm (in./in.), discontinue the test (see Note 18).

## 11. Retests

11.1 Values for properties at rupture shall not be calculated for any specimen that breaks at some obvious, fortuitous flaw, unless such flaws constitute a variable being studied. Retests shall be made for any specimen on which values are not calculated.

## 12. Calculation

12.1 Toe compensation shall be made in accordance with Annex A1 unless it can be shown that the toe region of the curve is not due to the take-up of slack, seating of the specimen, or other artifact, but rather is an authentic material response.

12.2 *Flexural Stress ($\sigma_f$):*

$$\sigma_f = 3PL/2bd^2 \tag{3}$$

where:

$\sigma$ = stress in the outer fibers at midpoint, MPa (psi),
$P$ = load at a given point on the load-deflection curve, N (lbf),
$L$ = support span, mm (in.),
$b$ = width of beam tested, mm (in.), and
$d$ = depth of beam tested, mm (in.).

NOTE 19—Eq 3 is not valid if the specimen slips excessively between the supports.

12.3 *Flexural Stress for Beams Tested at Large Support Spans ($\sigma_f$):*

$$\sigma_f = (3PL/2bd^2)[1 + 6(D/L)^2 - 4(d/L)(D/L)] \tag{4}$$

where:

$\sigma_f$, $P$, $L$, $b$, and $d$ = the same as for Eq 3, and
$D$ = deflection of the centerline of the specimen at the middle of the support span, mm (in.).

NOTE 20—When large support span-to-depth ratios are used, significant end forces are developed at the support noses, which will affect the moment in a simple supported beam. Eq 4 includes additional terms that are an approximate correction factor for the influence of these end forces in large support span-to-depth ratio beams where relatively large deflections exist.

12.4 *Flexural Strain, $\varepsilon_f$*—Nominal fractional change in the length of an element of the outer surface of the test specimen at midspan, where the maximum strain occurs. It may be calculated for any deflection using Eq 5:

$$\varepsilon_f = 6Dd/L^2 \tag{5}$$

where:

$\varepsilon_f$ = strain in the outer surface, mm/mm (in./in.),
$D$ = maximum deflection of the center of the beam, mm (in.),
$L$ = support span, mm (in.), and
$d$ = depth, mm (in.) of beam tested.

12.5 *Modulus of Elasticity:*

12.5.1 *Tangent Modulus of Elasticity:*

$$E_B = L^3 m/4bd^3 \tag{6}$$

where:

$E_B$ = modulus of elasticity in bending, MPa (psi),
$L$ = support span, mm (in.),
$b$ = width of beam tested, mm (in.),
$d$ = depth of beam tested, mm (in.), and
$m$ = slope of the tangent to the initial straight-line portion of the load-deflection curve, N/mm (lbf/in.) of deflection.

12.5.2 *Chord Modulus ($E_f$)*—

$$E_f = (\sigma_{f2} - \sigma_{f1})/(\varepsilon_{f2} - \varepsilon_{f1}) \tag{7}$$

where:

$\sigma_{f2}$ and $\sigma_{f1}$ = the flexural stresses, calculated from Eq 3 or Eq 4 and measured at the predefined points on the load deflection curve, and $\varepsilon_{f2}$ and
$\varepsilon_{f1}$ = the flexural strain values, calculated from Eq 5 and measured at the predetermined points on the load deflection curve.

12.6 *Arithmetic Mean*—For each series of tests, the arithmetic mean of all values obtained shall be calculated to three significant figures and reported as the "average value" for the particular property in question.

12.7 *Standard Deviation*—The standard deviation (estimated) shall be calculated as follows and be reported to two significant figures:

$$s = \sqrt{\left(\sum X^2 - n\bar{X}^2\right)/(n-1)} \tag{8}$$

where:

$s$ = estimated standard deviation,
$X$ = value of single observation,
$n$ = number of observations, and

$\bar{X}$ = arithmetic mean of the set of observations.

## 13. Report

13.1 Report the following information:

13.1.1 Complete identification of the material tested, including type, source, manufacturer's code number, form, principal dimensions, and previous history (for laminated materials, ply-stacking sequence shall be reported),

13.1.2 Method of specimen preparation,

13.1.3 Direction of cutting and loading specimens, when appropriate,

13.1.4 Conditioning procedure,

13.1.5 Depth and width of specimen,

13.1.6 Reference to this international standard, the Procedure used (A or B), and type test performed (I or II), for example D790–AI. If Type I test, specify if machine compliance is used.

13.1.7 Support span length,

13.1.8 Support span-to-depth ratio if different than 16:1,

13.1.9 Radius of supports and loading noses, if different than 5 mm. When support and/or loading nose radii other than 5 mm are used, the results shall be identified as being generated by a modified version of this test method and the referring specification referenced as to the geometry used.

13.1.10 Rate of crosshead motion,

13.1.11 Flexural strain at any given stress, average value and standard deviation,

13.1.12 If a specimen is rejected, reason(s) for rejection,

13.1.13 Tangent, secant, or chord modulus in bending, average value, standard deviation, and the strain level(s) used if secant or chord modulus,

13.1.14 Flexural strength (if desired), average value, and standard deviation,

13.1.15 Stress at any given strain up to and including 5 % (if desired), with strain used, average value, and standard deviation,

13.1.16 Flexural stress at break (if desired), average value, and standard deviation,

13.1.17 Type of behavior, whether yielding or rupture, or both, or other observations, occurring within the 5 % strain limit, and

13.1.18 Date of specific version of test used.

## 14. Precision and Bias

14.1 Tables 1 and 2 are based on a round-robin test conducted in 1984, in accordance with Practice E691, involving six materials tested by six laboratories using Procedure A. For each material, all the specimens were prepared at one source. Each "test result" was the average of five individual determinations. Each laboratory obtained two test results for each material.

NOTE 21—**Caution:** The following explanations of $r$ and $R$ (14.2 – 14.2.3) are intended only to present a meaningful way of considering the approximate precision of these test methods. The data given in Tables 1 and 2 should not be applied rigorously to the acceptance or rejection of materials, as those data are specific to the round robin and may not be representative of other lots, conditions, materials, or laboratories. Users of these test methods should apply the principles outlined in Practice E691 to generate data specific to their laboratory and materials, or between specific laboratories. The principles of 14.2 – 14.2.3 would then be valid for such data.

**TABLE 1 Flexural Strength**

| Material | Mean, $10^3$ psi | Values Expressed in Units of % of $10^3$ psi | | | |
|---|---|---|---|---|---|
| | | $V_r^A$ | $V_R^B$ | $r^C$ | $R^D$ |
| ABS | 9.99 | 1.59 | 6.05 | 4.44 | 17.2 |
| DAP thermoset | 14.3 | 6.58 | 6.58 | 18.6 | 18.6 |
| Cast acrylic | 16.3 | 1.67 | 11.3 | 4.73 | 32.0 |
| GR polyester | 19.5 | 1.43 | 2.14 | 4.05 | 6.08 |
| GR polycarbonate | 21.0 | 5.16 | 6.05 | 14.6 | 17.1 |
| SMC | 26.0 | 4.76 | 7.19 | 13.5 | 20.4 |

[A] $V_r$ = within-laboratory coefficient of variation for the indicated material. It is obtained by first pooling the within-laboratory standard deviations of the test results from all of the participating laboratories: $Sr = [[(s_1)^2 + (s_2)^2 \ldots + (s_n)^2]/n]^{1/2}$ then $V_r = (S_r$ divided by the overall average for the material) × 100.
[B] $V_r$ = between-laboratory reproducibility, expressed as the coefficient of variation: $S_R = \{S_r^2 + S_L^2\}^{1/2}$ where $S_L$ is the standard deviation of laboratory means. Then: $V_R = (S_R$ divided by the overall average for the material) × 100.
[C] $r$ = within-laboratory critical interval between two test results = 2.8 × $V_r$.
[D] $R$ = between-laboratory critical interval between two test results = 2.8 × $V_R$.

**TABLE 2 Flexural Modulus**

| Material | Mean, $10^3$ psi | Values Expressed in units of % of $10^3$ psi | | | |
|---|---|---|---|---|---|
| | | $V_r^A$ | $V_R^B$ | $r^C$ | $R^D$ |
| ABS | 338 | 4.79 | 7.69 | 13.6 | 21.8 |
| DAP thermoset | 485 | 2.89 | 7.18 | 8.15 | 20.4 |
| Cast acrylic | 810 | 13.7 | 16.1 | 38.8 | 45.4 |
| GR polyester | 816 | 3.49 | 4.20 | 9.91 | 11.9 |
| GR polycarbonate | 1790 | 5.52 | 5.52 | 15.6 | 15.6 |
| SMC | 1950 | 10.9 | 13.8 | 30.8 | 39.1 |

[A] $V_r$ = within-laboratory coefficient of variation for the indicated material. It is obtained by first pooling the within-laboratory standard deviations of the test results from all of the participating laboratories: $Sr = [[(s_1)^2 + (s_2)^2 \ldots + (s_n)^2]/n]^{1/2}$ then $V_r = (S_r$ divided by the overall average for the material) × 100.
[B] $V_r$ = between-laboratory reproducibility, expressed as the coefficient of variation: $S_R = \{S_r^2 + S_L^2\}^{1/2}$ where $S_L$ is the standard deviation of laboratory means. Then: $V_R = (S_R$ divided by the overall average for the material) × 100.
[C] $r$ = within-laboratory critical interval between two test results = 2.8 × $V_r$.
[D] $R$ = between-laboratory critical interval between two test results = 2.8 × $V_R$.

14.2 *Concept of "r" and "R" in* Tables 1 and 2—If $S_r$ and $S_R$ have been calculated from a large enough body of data, and for test results that were averages from testing five specimens for each test result, then:

14.2.1 *Repeatability*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the $r$ value for that material. $r$ is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.

14.2.2 *Reproducibility*—Two test results obtained by different laboratories shall be judged not equivalent if they differ by more than the $R$ value for that material. $R$ is the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.

14.2.3 The judgments in 14.2.1 and 14.2.2 will have an approximately 95 % (0.95) probability of being correct.

14.3 *Bias*—Make no statement about the bias of these test methods, as there is no standard reference material or reference test method that is applicable.

## 15. Keywords

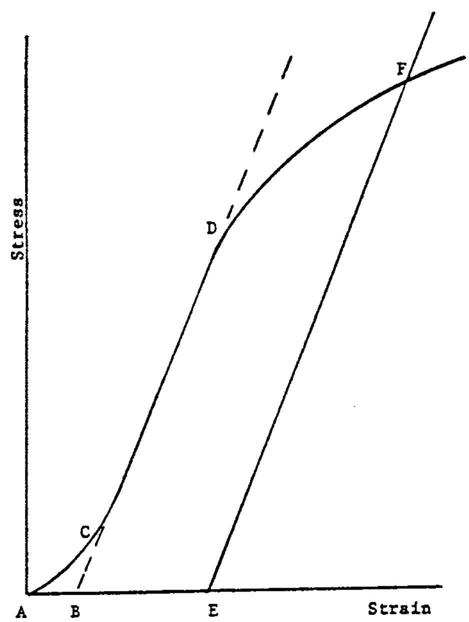
15.1 flexural properties; plastics; stiffness; strength

## ANNEXES

**(Mandatory Information)**

### A1. TOE COMPENSATION

A1.1 In a typical stress-strain curve (see Fig. A1.1) there is a toe region, *AC,* that does not represent a property of the material. It is an artifact caused by a takeup of slack and alignment or seating of the specimen. In order to obtain correct values of such parameters as modulus, strain, and offset yield point, this artifact must be compensated for to give the corrected zero point on the strain or extension axis.

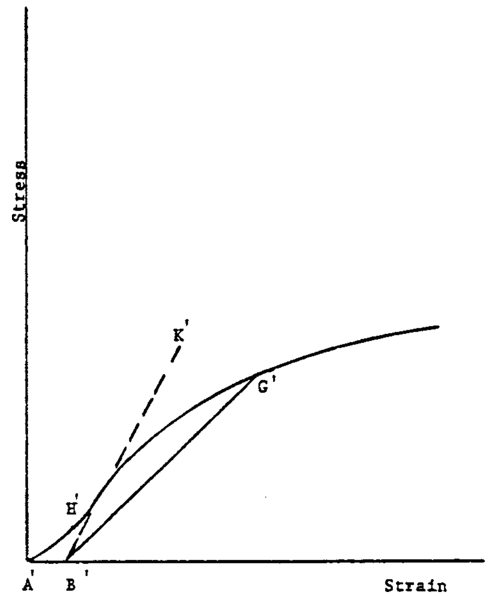



NOTE 1—Some chart recorders plot the mirror image of this graph.

**FIG. A1.1 Material with Hookean Region**

A1.2 In the case of a material exhibiting a region of Hookean (linear) behavior (see Fig. A1.1), a continuation of the linear *(CD)* region of the curve is constructed through the zero-stress axis. This intersection *(B)* is the corrected zero-strain point from which all extensions or strains must be measured, including the yield offset *(BE),* if applicable. The elastic modulus can be determined by dividing the stress at any point along the Line *CD* (or its extension) by the strain at the same point (measured from Point *B,* defined as zero-strain).

A1.3 In the case of a material that does not exhibit any linear region (see Fig. A1.2), the same kind of toe correction of the zero-strain point can be made by constructing a tangent to the maximum slope at the inflection Point *H'.* This is extended to intersect the strain axis at Point *B',* the corrected zero-strain point. Using Point *B'* as zero strain, the stress at any point *(G')* on the curve can be divided by the strain at that point to obtain a secant modulus (slope of Line *B' G').* For those materials with no linear region, any attempt to use the tangent through the inflection point as a basis for determination of an offset yield point may result in unacceptable error.




NOTE 1—Some chart recorders plot the mirror image of this graph.

**FIG. A1.2 Material with No Hookean Region**

## A2. MEASURING AND SETTING SPAN

A2.1 For flexural fixtures that have adjustable spans, it is important that the span between the supports is maintained constant or the actual measured span is used in the calculation of stress, modulus, and strain, and the loading nose or noses are positioned and aligned properly with respect to the supports. Some simple steps as follows can improve the repeatability of your results when using these adjustable span fixtures.

A2.2 Measurement of Span:

A2.2.1 This technique is needed to ensure that the correct span, not an estimated span, is used in the calculation of results.

A2.2.2 Scribe a permanent line or mark at the exact center of the support where the specimen makes complete contact. The type of mark depends on whether the supports are fixed or rotatable (see Figs. A2.1 and A2.2).

A2.2.3 Using a vernier caliper with pointed tips that is readable to at least 0.1 mm (0.004 in.), measure the distance between the supports, and use this measurement of span in the calculations.

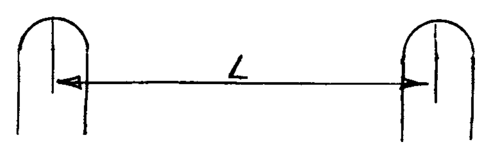



**FIG. A2.1 Markings on Fixed Specimen Supports**

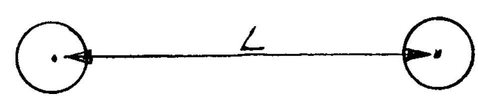



**FIG. A2.2 Markings on Rotatable Specimen Supports**

A2.3 *Setting the Span and Alignment of Loading Nose(s)*—To ensure a consistent day-to-day setup of the span and ensure the alignment and proper positioning of the loading nose, simple jigs should be manufactured for each of the standard setups used. An example of a jig found to be useful is shown in Fig. A2.3.

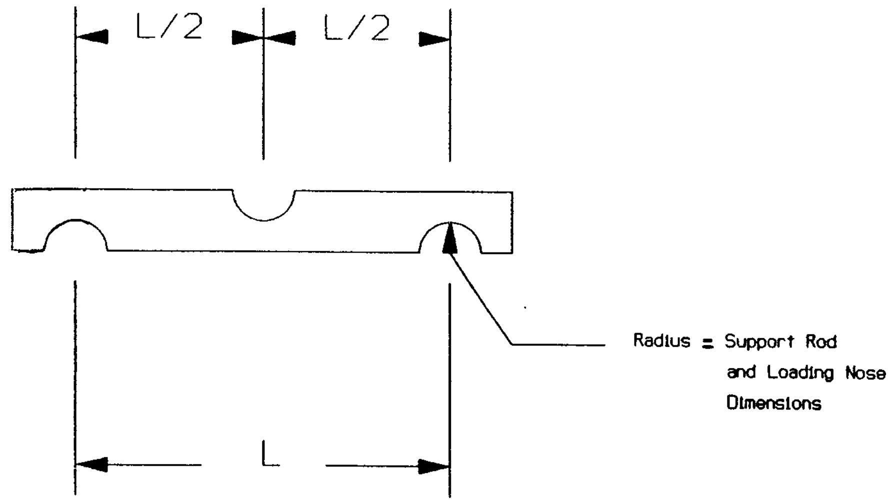



FIG. A2.3 Fixture Used to Set Loading Nose and Support Spacing and Alignment

# APPENDIX

(Nonmandatory Information)

## X1. DEVELOPMENT OF A FLEXURAL MACHINE COMPLIANCE CORRECTION

### X1.1 Introduction

X1.1.1 Universal Testing instrument drive systems always exhibit a certain level of compliance that is characterized by a variance between the reported crosshead displacement and the displacement actually imparted to the specimen. This variance is a function of load frame stiffness, drive system wind-up, load cell compliance and fixture compliance. To accurately measure the flexural modulus of a material, this compliance should be measured and empirically subtracted from test data. Flexural modulus results without the corrections are lower than if the correction is applied. The greater the stiffness of the material the more influence the system compliance has on results.

X1.1.2 It is not necessary to make the machine compliance correction when a deflectometer/extensometer is used to measure the actual deflection occurring in the specimen as it is deflected.

### X1.2 Terminology

X1.2.1 *Compliance*—The displacement difference between test machine drive system displacement values and actual specimen displacement

X1.2.2 *Compliance Correction*—An analytical method of modifying test instrument displacement values to eliminate the amount of that measurement attributed to test instrument compliance.

### X1.3 Apparatus

X1.3.1 Universal Testing machine

X1.3.2 Load cell

X1.3.3 Flexure fixture including loading nose and specimen supports

X1.3.4 Computer Software to make corrections to the displacements

X1.3.5 Steel bar, with smoothed surfaces and a calculated flexural stiffness of more than 100 times greater than the test material. The length should be at least 13 mm greater than the support span. The width shall match the width of the test specimen and the thickness shall be that required to achieve or exceed the target stiffness.

### X1.4 Safety Precautions

X1.4.1 The universal testing machine should stop the machine crosshead movement when the load reaches 90 % of load cell capacity, to prevent damage to the load cell.

X1.4.2 The compliance curve determination should be made at a speed no higher than 2 mm/min. Because the load builds up rapidly since the steel bar does not deflect, it is quite easy to exceed the load cell capacity.

### X1.5 Procedure

NOTE X1.1—A new compliance correction curve should be established each time there is a change made to the setup of the test machine, such as, load cell changed or reinstallation of the flexure fixture on the machine. If the test machine is dedicated to flexural testing, and there are no changes to the setup, it is not necessary to re-calculate the compliance curve.

NOTE X1.2—On those machines with computer software that automatically make this compliance correction; refer to the software manual to determine how this correction should be made.

X1.5.1 The procedure to determine compliance follows:

X1.5.1.1 Configure the test system to match the actual test configuration.

X1.5.1.2 Place the steel bar in the test fixture, duplicating the position of a specimen during actual testing.

X1.5.1.3 Set the crosshead speed to 2 mm/min. or less and start the crosshead moving in the test direction recording crosshead displacement and the corresponding load values.

X1.5.1.4 Increase load to a point exceeding the highest load expected during specimen testing. Stop the crosshead and return to the pre-test location.

X1.5.1.5 The recorded load-deflection curve, starting when the loading nose contacts the steel bar to the time that the highest load expected is defined as test system compliance.

X1.5.2 Procedure to apply compliance correction is as follows:

X1.5.2.1 Run the flexural test method on the material at the crosshead required for the measurement.

X1.5.2.2 It is preferable that computer software be used to make the displacement corrections, but if it is not available compliance corrections can be made manually in the following manner. Determine the range of displacement (D) on the load versus displacement curve for the material, over which the modulus is to be calculated. For Young's Modulus that would steepest region of the curve below the proportional limit. For Secant and Chord Modulii that would be at specified level of strain or specified levels of strain, respectively. Draw two vertical lines up from the displacement axis for the two chosen displacements (D1, D2) to the load versus displacement curve for the material. In some cases one of these points maybe at zero displacement after the toe compensation correction is made. Draw two horizontal lines from these points on the load displacement curve to the Load (P) axis. Determine the loads (L1, L2).

X1.5.2.3 Using the Compliance Correction load displacement curve for the steel bar, mark off L1 and L2 on the Load (P) axis. From these two points draw horizontal lines across till they contact the load versus displacement curve for the steel bar. From these two points on the load deflection curve draw two vertical lines downwards to the displacement axis. These two points on the displacement axis determine the corrections (c1, c2) that need to be made to the displacements measurements for the test material.

X1.5.2.4 Subtract the corrections (c1, c2) from the measured displacements (D1, D2), so that a true measures of test specimen deflection (D1-c1, D2-c2) are obtained.

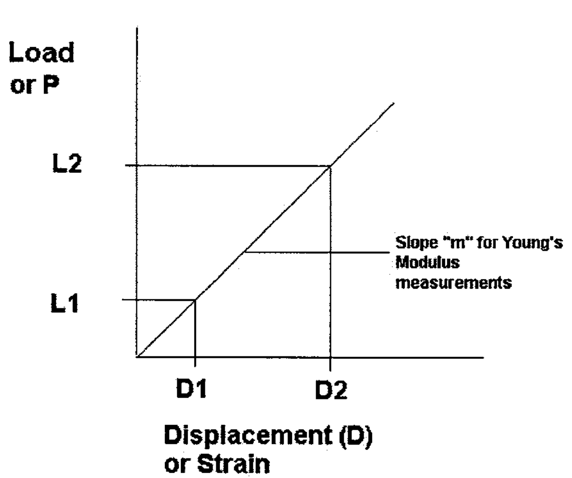



FIG. X1.1 Example of Modulus Curve for a Material

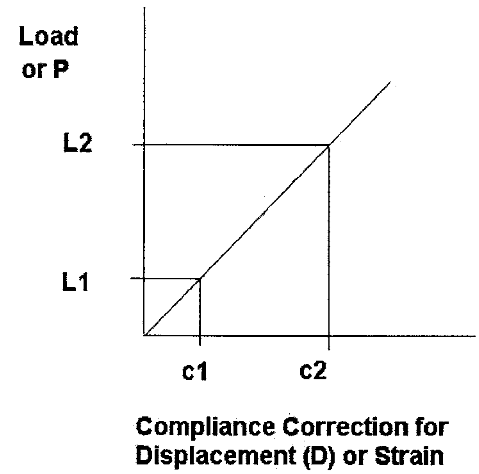



FIG. X1.2 Compliance Curve for Steel Bar

## X1.6 Calculations

X1.6.1 Calculation of Chord Modulus

X1.6.1.1 Calculate the stresses (σf1, σf2) for load points L1 and L2 from Fig. X1.1 using the equation in 12.2, Eq 3.

X1.6.1.2 Calculate the strains (εf1, εf2) for displacements D1-c1 and D2-c2 from Fig. X1.3 using the equation in 12.4, Eq 5.

X1.6.1.3 Calculate the flexural chord modulus in accordance with 12.5.2, Eq 7.

X1.6.2 Calculation of Secant Modulus

X1.6.2.1 Calculation of the Secant Modulus at any strain along the curve would be the same as conducting a chord modulus measurement, except that σf1 = 0, L1= 0, and D1-c1 = 0.

X1.6.3 Calculation of Young's Modulus

X1.6.3.1 Determine the steepest slope "m" along the curve, below the proportional limit, using the selected loads L1 and L2 from Fig. X1.1 and the displacements D1-c1 and D2-c2 from Fig. X1.3.

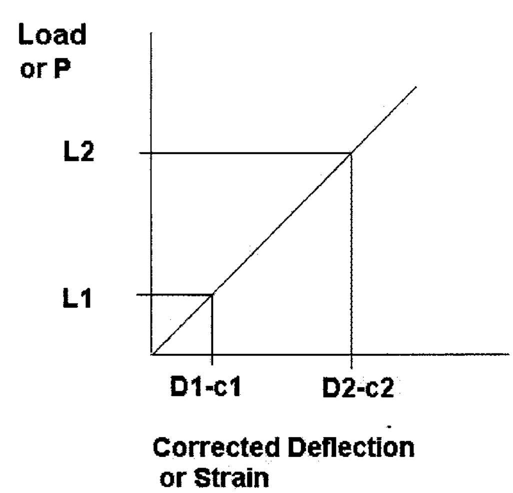



FIG. X1.3 Example of the Material Curve Corrected for the Compliance Corrected Displacement or Strain

X1.6.3.2 Calculate the Young's modulus in accordance with 12.5.1, Eq 6.

## SUMMARY OF CHANGES

Committee D20 has identified the location of selected changes to this standard since the last issue (D790 - 15$^{\varepsilon 2}$) that may impact the use of this standard. (July 1, 2017)

*(1)* Revised 6.1.5.1, 6.1.5.2, 13.1.6
*(2)* Added Note 10 and Note 12.
*(3)* Added Practice E83 to 2.1.