Designation: E3039 − 20

Standard Test Method for Determination of Crack-Tip-Opening Angle of Ferritic Steels Using DWTT-Type Specimens[1]

This standard is issued under the fixed designation E3039; 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 fracture propagation toughness in terms of the steady-state crack-tip-opening angle (*CTOA*) using the drop-weight tear test (DWTT)-type specimen. The method is applicable to ferritic steels that exhibit predominantly ductile fracture with at least 85 % shear area measured according to Test Method E436 - Standard Test Method for Drop-Weight Tear Tests of Ferritic Steels. This test method applies to ferritic steels with thicknesses between 6 mm and 20 mm. Annex A1 describes the method to test ferritic steels with thicknesses between 20 mm to 32 mm.

1.2 In terms of apparatus, specimen design, and test methodology, this test method draws from Test Method E436 and API 5L3 - Recommended Practice for Conducting Drop-Weight Tear Tests on Line Pipe.

1.3 The development of this test method has been driven by the need to design for fast ductile fracture arrest of axial running cracks in steel high-pressure gas pipelines (**1**). [2]The purpose has been to develop a test to characterize fracture propagation resistance in a form suitable for use as a pipe mill test (**2**). The traditional Charpy test has been shown to be inadequate for modern high toughness pipe steels (**1**). This test method measures fracture propagation resistance in terms of crack-tip opening angle, and is used to characterize ferritic steels.

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

1.5 *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.*

1.6 *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:*[3]

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E436 Test Method for Drop-Weight Tear Tests of Ferritic Steels

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

E1823 Terminology Relating to Fatigue and Fracture Testing

E1942 Guide for Evaluating Data Acquisition Systems Used in Cyclic Fatigue and Fracture Mechanics Testing

E2298 Test Method for Instrumented Impact Testing of Metallic Materials

E2472 Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions

2.2 *ISO Standards:*[4]

ISO 22889 Metallic materials — Method of Test for the Determination of Resistance to Stable Crack Extension Using Specimens of Low Constraint

ISO 14456 Steel — Charpy V-notch Pendulum Impact Test — Instrumented Test Method

2.3 *API Recommended Practice:*[5]

API Recommended Practice 5L3 Drop-Weight Tear Tests on Line Pipe

[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.07 on Fracture Mechanics.

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

[3] 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.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

[5] Available from American Petroleum Institute (API), 1220 L. St., NW, Washington, DC 20005-4070, http://www.api.org.

3. Terminology

3.1 *Symbols:*

a	=	crack size, mm
a_n	=	initial notch depth, mm
b	=	specimen ligament size ($b=W-a$), mm
b_0	=	initial ligament size ($b_0=W-a_n$), mm
C_v	=	full-size Charpy V-notch absorbed energy, J
B	=	specimen thickness, mm
L	=	specimen length, mm
M	=	total mass of the moving striker (hammer), kg
P	=	force, kN
P_m	=	maximum force applied by the hammer during the test, kN
r_p	=	plastic rotation factor
S	=	specimen span between anvil contact points (S = 254 mm for standard DWTT-type tests), mm
t_0	=	time at the beginning of specimen deformation, s
v_0	=	initial striker impact velocity, m/s
W	=	specimen width, mm
σ_y	=	yield strength, MPa
Δ	=	load-line displacement (LLD), mm
Δ_m	=	load-line displacement (LLD) at maximum force, mm
ξ	=	absolute value of slope of the $\ln(P/P_m)$ versus $(\Delta-\Delta_m)/S$ curve as specified in Section 8.

3.2 *Acronyms:*

CTOA	=	crack-tip opening angle, degree
$CTOA_{B/2}$	=	critical crack-tip opening angle in the steady-state stage as determined by this test method, degree
DWTT	=	drop-weight tear test
SE(B)	=	single-edge bend specimen
S-SSM	=	simplified single-specimen CTOA test method

3.3 *Definitions:*

3.3.1 *crack-tip opening angle (CTOA), [deg], n*—angle formed between the fractured surfaces measured at the crack tip.

3.3.2 *critical crack-tip-opening angle* ($CTOA_{B/2}$), *[deg], n*—steady-state value of *CTOA* as measured by this test method, intended to approximate the *CTOA* on the mid-thickness plane as the angle between the crack flanks. The crack flanks extend from the crack tip to one-half of the DWTT-type specimen thickness (*B/2*) behind the crack tip (see Fig. 1) during steady-state propagation.

3.3.2.1 *Discussion*—The shape of the tearing crack is initially dominated by a flat tunneling region that often transitions from flat to slant fracture, and tends to approach a constant tunneling shape after a crack extension of approximately one specimen thickness. The *CTOA* tends to approach a constant, steady-state value ($CTOA_{B/2}$) during propagation through the mid-portion of the original ligament. It must be recognized that the *CTOA* often depends on where it is measured, that is, at what distance behind the crack tip, and the measurement is complicated by tunneling. In this test method, $CTOA_{B/2}$ is defined as the angle between the crack flanks extending from the crack tip to a distance *B/2* along the crack surface. This parameter may be compared with optical measurements made, for example, using pictures of the specimen surface taken with a high-speed camera. Discussion of the optical method is included in Test Method E2472.

3.3.2.2 *Discussion*—This procedure uses $CTOA_{B/2}$ for the critical crack-tip-opening angle to distinguish it from the $CTOA_c$ in Test Method E2472 and ISO 22889, in which *CTOA* is measured or calculated at 1 mm behind the current crack tip.

4. Summary and Significance

4.1 The objective of this test method is to use measurements of force (*P*) versus load-line displacement (Δ) to derive the critical steady-state crack-tip opening angle ($CTOA_{B/2}$) based on the simplified single-specimen method (S-SSM) (**2**). The S-SSM is a further development of the previous two-specimen *CTOA* method (**3**) and simplification of a single-specimen *CTOA* method (**4**). In addition, the calculation of *CTOA* requires a value for the plastic rotation factor (r_p). For typical ferritic steels, values of r_p have been estimated experimentally (**5**), and will be discussed in Section 8.

4.2 The $CTOA_{B/2}$ value derived according to this test method is close to the value in the high-constraint mid-thickness region of the DWTT-type specimens, and is significantly lower than the surface *CTOA* values measured optically (**5, 6**). This reflects the effects of through-thickness constraint and the resulting crack-tip tunneling.

4.3 Steady-state ductile crack propagation velocities range between 12-20 m/s in DWTT-type specimens impacted with a hammer velocity of 5 m/s. The crack velocity decreases as toughness increases (**6**). DWTT-type specimens of steels tested at room temperature usually exhibit shear fracture under

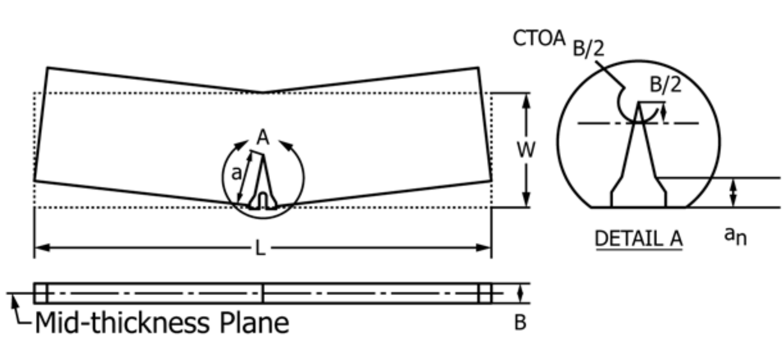

FIG. 1 Measurement point for $CTOA_{B/2}$ and location of mid-thickness plane

impact loading; that is, the flat (tunnelling) morphology at crack initiation usually transitions to a near-45° slant fracture that is considered to be a shear morphology. For pipe steels, this mimics the fracture mode observed in full-scale pipe burst tests.

4.4 The apparatus, specimen dimensions and testing procedure in this test method are the same as those described in Test Method E436 or API RP 5L3 and Test Method E2298, see Section 2. The intent is to adopt the standardized DWTT test procedures, machines (for example, hammer and anvil supports), and instrumentation requirements to the maximum extent possible. The following sections provide specific requirements, procedures and calculations for determining *CTOA*.

5. Apparatus

5.1 The test shall be conducted using a test machine that has sufficient energy to completely break the specimen in one impact. The key dimensions, shown in Fig. 2, are: distance between supports (span) S = 254 mm (10 in.), radius of impact hammer striking edge = 25.4 mm (1 in.), and radius of fixed support anvils = 19 mm (0.75 in.). Drawings of the test fixture and specimen can also be found in Test Method E436 or API RP 5L3.

5.2 The initial velocity v_0 of the hammer at impact shall be 5 m/s ≤ v_0 ≤ 10 m/s and shall be known within ± 5%, as discussed below.

5.3 For force measurement and displacement determination, the provisions of Test Method E2298 shall apply. Instrumentation shall be used to determine force-time or force-displacement curves.

5.4 *Force Measurement:*

5.4.1 Force shall be measured by means of an electronic sensor (piezoelectric load cell, strain gauge load cell or a force measurement derived from an accelerometer).

5.4.2 The force measuring system (including strain gauges, wiring, and amplifier) shall have a bandwidth of at least 100 kHz as discussed in Guide E1942.

5.4.3 The signal shall be recorded without filtering. Post-test filtering, however, is allowed as detailed in Test Method E2298, 7.2 but efforts should be taken to avoid introducing errors through filtering, as discussed in Guide E1942.

5.4.4 Calibration of the recorder and measurement system may be performed statically in accordance with the accuracy requirements given in 5.4.4.1. For pendulum machines, it is recommended that the force calibration be performed with the striker attached to the pendulum assembly. The strain gauge signal conditioning equipment, cables, and recording device shall be used in the calibration. In most cases, a computer is used for data acquisition and the calibration shall be performed with the voltage read from the computer. The intent is to calibrate with the electronics and cables which are used during actual testing.

5.4.4.1 The static linearity and hysteresis error including all parts of the force measurement system up to the recording apparatus shall be within ± 2 % of the recorded force, between 50 % and 100 % of the nominal force range, and within ± 1 % of the full scale force value between 10 % and 50 % of the nominal force range as detailed in Test Method E2298, 7.2.4.1.

NOTE 1—For testing in accordance with this test method, it is recommended to calibrate the instrumented striker up to 500 kN.

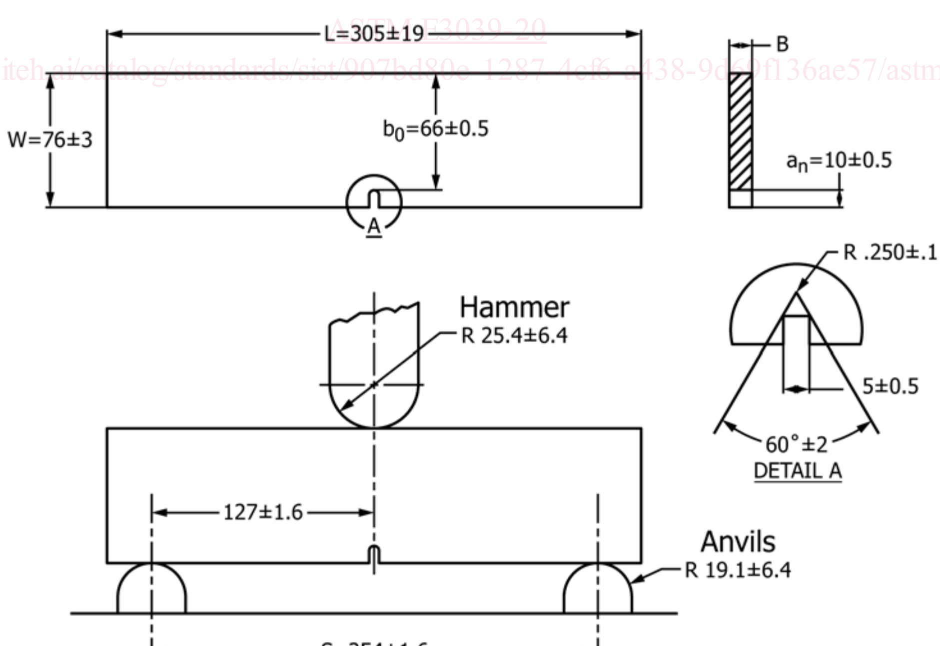

FIG. 2 Dimensions (in mm) of the machine-notched specimen (top) and supporting anvils (bottom). The anvils are fixed in position.

5.4.5 Recalibration shall be performed if the instrumented striker has undergone dismantling or repair, unless it can be shown that removal of the striker from the test machine and subsequent re-attachment to the machine does not affect the calibration.

5.5 *Displacement Determination:*

5.5.1 Displacement shall be measured using a non-contacting transducer according to 5.5.4 or calculated using force-time measurements with Newton's equations of motion as outlined in 5.5.2.

5.5.2 Assuming a rigid striker of mass *m* with an initial velocity v_0 the velocity $v(t)$ at the contact point as a function of elapsed time is calculated as:

$$v(t) = v_0 - \frac{1}{m}\int_{t_0}^{t} P(t)dt \quad (1)$$

If the specimen is assumed not to lift off at the anvils the bending displacement $\Delta(t)$ is evaluated from:

$$\Delta(t) = \int_{t_0}^{t} v(t)dt \quad (2)$$

5.5.3 For drop weight and pendulum machines, the initial impact velocity needed to perform the above integrations is calculated from:

$$v_0 = \sqrt{2gh_0} \quad (3)$$

where:

g = local acceleration due to gravity, and
h_0 = height of striker from point of release to point of initial impact.

5.5.3.1 Alternatively, for drop weight and pendulum machines, it is acceptable to use for v_0 the optically measured velocity registered when the pendulum passes through its lowest position and strikes the specimen.

5.5.4 Displacement can also be determined by non-contacting measurement of the displacement of the striker relative to the anvil using optical, inductive, or capacitive methods. The signal transfer characteristics of the displacement measurement system shall correspond to that of the force measuring system in order to minimize phase difference and data skew errors, as discussed in Guide E1942. The displacement measuring system shall be designed for maximum nominal values of 40 mm. Linearity errors in the measuring system shall yield measured values to within ± 2 % over a range of 1 mm to 40 mm. Measurements up to 1 mm may not be sufficiently accurate to determine the displacement within ± 2 %. In this case, the displacement of the specimen shall be determined from the time measurement and the striker impact velocity as indicated in Eq 1 and Eq 2.

5.6 The recording apparatus (that is, high-speed data acquisition system and instrumented striker) shall comply with Test Method E2298 Section 7. Data acquisition systems that are commercially available for instrumented Charpy tests are acceptable if they meet the accuracy requirements defined here for this test. Force-time data acquisition at a rate of 10^6/s (1 MHz) or greater is required (**5**,**6**).

6. Specimen

6.1 The specimen width and length shall be W = 76 mm and L = 305 mm (Fig. 2). Any orientations and locations may be used provided they are agreed upon between the testing facility and the client and reported with the test results. For pipe steels, the specimen preparation shall be according to 6.2, 6.3 and 6.4.

6.2 For seamless pipes, the specimen can be removed at any location, but for welded pipes the specimen shall be taken from a location approximately 90° from the weld (**7**). The specimens shall be oriented in C-L orientation according to Terminology E1823-13. Other orientations and locations may be used provided they are agreed upon between the testing facility and the client and reported with the test results. The specimen width and length shall be W = 76 mm and L = 305 mm (Fig. 2).

6.3 Specimens shall have full pipe thickness to avoid any effect that a reduction in thickness might have on *CTOA*.

6.4 The specimens shall be flattened to remove the pipe curvature from the test specimen according to Test Method E436 or API RP 5L3.

6.5 Acceptable notches are a pressed notch with depth 5 mm ± 0.5 mm as per Test Method E436 or API RP 5L3, or a straight machined notch with depth 10 mm ± 0.5 mm as shown in Fig. 2. It has been shown that pressed notches and straight notches produce equivalent $CTOA_{B/2}$ values, that is, the type of notch does not strongly influence fracture propagation toughness or the slope of the force versus deflection curve beyond the maximum force (**8**, **9**). Because only the post-maximum-force data is analyzed, other notch types with sharper notch tip radii (for example, fatigue precrack or chevron notch) are also acceptable.

6.6 The dimensional tolerances of the specimen and the supports shall be as prescribed in Test Method E436 or API RP 5L3.

6.7 Tests are considered invalid if the specimen buckles during impact. For specimens less than 10 mm thick, anti-buckling guides may be needed to prevent buckling and lateral sliding of the specimen on the supports. Simple guides placed at the ends of the DWTT-type specimens mounted on the anvils have proven to be effective (**6**). Fig. 3 shows an example of an anti-bucking fixture; the arrows indicate the components of the fixture. When using anti-buckling guides, a thin film of lubricant at the contact areas shall be used to minimize the friction between the guides and the specimen at the areas of contact.

7. Procedure

7.1 The test requires recording force versus displacement data from a time prior to impact until after the specimen is completely fractured, to ensure that all relevant data is recorded. Force and displacement shall be measured and recorded according to 5.5 and 5.6.

7.2 In the temperature range from -73 °C to 100 °C employ the procedure described in 7.2.1 and 7.2.2.

7.2.1 Completely immerse the specimens in a bath of suitable liquid at a temperature within ± 3 °C of the desired

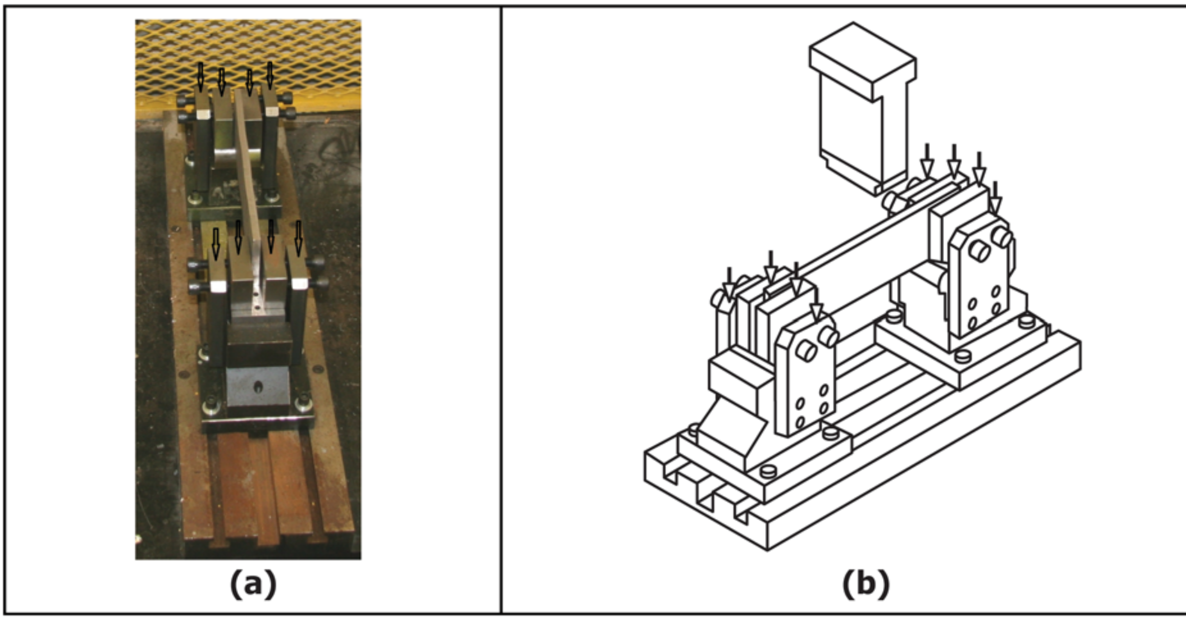

FIG. 3 An example of optional anti-buckling guides for ferritic steel specimens with wall thickness less than 10 mm

test temperature for a minimum of 15 min prior to testing. If multiple specimens are conditioned at once, separate the specimens by a distance at least equal to the thickness of the specimen. Make provision for circulation of the bath to ensure uniform bath temperature.

NOTE 2—For testing at room temperature (19-25 °C), there is usually no need to employ a liquid bath.

NOTE 3—Alternatively, other methods of heating and cooling may be used provided it can be shown that the uniformity meets or exceeds the method in 7.2.1.

7.2.2 Remove the specimens from the bath and break as described herein within 10 s of removal from the bath. If the specimens are held out of the bath longer than 10 s return them unbroken to the bath for a minimum of 10 min. Do not handle the specimen in the vicinity of the notch by devices whose temperature is appreciably different from the test temperature.

7.3 For temperatures outside the range specified in 7.2, maintain the specimen temperature at the time of impact within ±4 °C of the desired test temperature.

7.4 Insert the specimen in the testing machine so that the notch in the specimen lines up with the centerline of the striker within 1.59 mm (1⁄16 in.). Also, center the notch in the specimen between the supports on the anvil.

8. Calculations

8.1 Striker force and the corresponding displacement data are required for CTOA calculation. Typical force-time, displacement-time, and force-displacement records are shown in Fig. 4.

8.2 The procedure for calculating *CTOA* is given below.

8.2.1 Find the maximum force value (P_m) and the corresponding load-line displacement value (Δ_m) (Fig. 4).

8.2.2 Calculate and plot $\ln(P/P_m)$ versus $(\Delta - \Delta_m)/S$ for all data points beyond maximum force point (P_m, Δ_m) (that is, the data corresponding to fracture propagation, see Fig. 5).

8.2.3 Find (ξ), the absolute value of the slope of the $\ln(P/P_m)$ versus $(\Delta - \Delta_m)/S$ curve, all data corresponding to $\ln(P/P_m)$ values between -0.5 and -1.2, that is, between the dashed lines in Fig. 5 for the 10 mm deep notched specimen, and to $\ln(P/P_m)$ values between -0.7 and -1.4 for the 5 mm deep notched specimen (see Note 4).

NOTE 4—This force range spans the steady-state region of crack propagation through the central part of the ligament. This region has been found to extend from a = 25 mm to a = 40 mm (**2**), that is, b = 51 mm to b = 36 mm, for the standard-size 10 mm deep notched specimen. Since the force $P = 4A^*\sigma_f Bb^2/S$, where A^* is a constant approximately equal to 0.35 and σ_f is the flow stress (average of yield and tensile strengths), it follows that $P/P_m = (b/b_0)^2$. Assuming that the crack initiates at maximum force and that this corresponds to the initial ligament length b_0 = 66 mm, it follows that the steady-state region occurs between P/P_m = 0.60 and P/P_m = 0.30, that is, between $\ln(P/P_m)$ = -0.5 and $\ln(P/P_m)$ = -1.2. For the 5 mm deep notched specimen, assuming that the crack initiates at maximum force and that this corresponds to the initial ligament length b_0 = 71 mm, it follows that the steady-state region occurs between P/P_m = 0.52 and P/P_m = 0.26. that is, between $\ln(P/P_m)$ = -0.7 and $\ln(P/P_m)$ = -1.4.

8.2.4 Calculate $CTOA_{B/2}$ according to the following equation:

$$CTOA_{B/2} = \frac{8r_p}{\xi}\frac{180}{\pi} \quad (4)$$

where:

r_p = the rotation factor,
ξ = the absolute value of the slope, and
CTOA = in units of degrees.

The value of r_p for ferritic steels shall be

$$r_p = 0.58\frac{C_v}{\sigma_y \cdot B} + 0.55 \quad (5)$$

where the units of C_v, σ_y and B are given in 3.1.

NOTE 5—The plastic rotation factor (r_p) stems from the "plastic hinge model" (**10, 11**) that assumes that the two arms of a SE(B) specimen rotate symmetrically about an axis of rotation in the uncracked ligament. The ratio of the distance between the crack tip and the hinge point to the length of the remaining ligament is defined as the plastic rotation factor (r_p); its