Designation: E 561 – 98

Standard Practice for *R*-Curve Determination[1]

This standard is issued under the fixed designation E 561; 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 practice covers the determination of resistance to fracturing of metallic materials by *R*-curves using either the center-cracked tension panel M(T), the compact specimen C(T), or the crack-line-wedge-loaded specimen C(W), to deliver applied stress intensity factor, *K*, to the material. An *R*-curve is a continuous record of toughness development in terms of K_R plotted against crack extension in the material as a crack is driven under a continuously increased stress intensity factor, *K*.

1.2 Materials that can be tested for *R*-curve development are not limited by strength, thickness, or toughness, so long as specimens are of sufficient size to remain predominantly elastic throughout the duration of the test.

1.3 Specimens of standard proportions are required, but size is variable, to be adjusted for yield strength and toughness of the materials.

1.4 Only three of the many possible specimen types that could be used to develop *R*-curves are covered in this practice.

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

2. Referenced Documents

2.1 *ASTM Standards:*

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[2]

E 616 Terminology Relating to Fracture Testing[2]

E 647 Test Method for Measurement of Fatigue Crack Growth Rates[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *crack size, a* (L)—a lineal measure of a principal planar dimension of a crack. This measure is commonly used in the calculation of quantities descriptive of the stress and displacement fields, and is often also termed crack length.

3.1.1.1 *Discussion*—In practice, the value of a is obtained from procedures for measurement of physical crack size, a_p, original crack size, a_o, and effective crack size, a_e, as appropriate to the situation being considered.

3.1.2 *physical crack size,* a_p (L)—the distance from a reference position to the observed crack front. This distance may represent an average from several measurements along the crack front. The reference position depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate.

3.1.3 *original crack size,* a_o (L)—the physical crack size at the start of testing.

3.1.4 *effective crack size,* a_e (L)—the physical crack size augmented for the effects of crack-tip plastic deformation.

3.1.4.1 *Discussion*—Sometimes the effective crack size, a_e, is calculated from a measured value of a physical crack size, a_p, plus a calculated value of a plastic-zone adjustment, r_Y. A preferred method for calculation of a_e compares compliance from the secant of a load-deflection trace with the elastic compliance from a calibration of the specimen.

3.1.5 *plastic-zone adjustment,* r_Y (L)—an addition to the physical crack size to account for plastic, crack-tip deformation effects on the linear-elastic stress field.

3.1.5.1 *Discussion*—Commonly the plastic-zone adjustment is given by:

$$r_Y = \frac{1}{2\pi}\frac{K^2}{\sigma_Y{}^2}\text{, for plane-stress mode 1, and}$$

$$r_Y = \frac{\alpha}{2\pi}\frac{K^2}{\sigma_Y{}^2}\text{, for plane-strain mode I,}$$

where $\alpha \simeq$ ⅓ to ¼ and σ_Y is the effective yield strength.

In this practice, plane-stress mode 1 is assumed.

3.1.6 *crack extension,* Δa (L)—an increase in crack size.

3.1.6.1 *Discussion*—For example, Δa_p or Δa_e is the difference between the crack size, either a_p (physical crack size) or a_e (effective crack size), and a_o (original crack size).

[1] This practice is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.07 on Linear–Elastic Fracture.

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[2] *Annual Book of ASTM Standards*, Vol 03.01.

3.1.7 *stress–intensity factor, K,* K_1, K_2, K_3 ($FL^{-3/2}$)—the magnitude of the ideal-crack-tip stress field (a stress-field singularity) for a particular mode in a homogeneous, linear-elastic body.

3.1.7.1 *Discussion*—Values of *K* for modes 1, 2, and 3 are given by:

$$K_1 = \lim_{r \to o} [\sigma_y (2 \pi r)^{1/2}],$$

$$K_2 = \lim_{r \to o} [\tau_{xy} (2 \pi r)^{1/2}], \text{ and}$$

$$K_3 = \lim_{r \to o} [\tau_{yz} (2 \pi r)^{1/2}].$$

where r = a distance directly forward from the crack tip to a location where the significant stress is calculated.

3.1.7.2 *Discussion*—In this practice, plane-stress mode 1 is assumed.

3.1.8 *crack-extension resistance,* K_R ($FL^{-3/2}$), and G_R or J_R(FL^{-1})—a measure of the resistance to crack extension expressed in the same units as the stress-intensity factor, *K*, the crack-extension force, *G*, or values of *J* derived using the J-integral concept.

3.1.8.1 *Discussion*—See definition of *R-curve.*

3.1.9 *R-curve*—a plot of crack-extension resistance as a function of slow-stable crack extension, Δa_p or Δa_e.

3.1.9.1 *Discussion*—For specimens discussed in Practice E 561, influence of in-plane geometry appears to be negligible, but *R*-curves normally depend upon specimen thickness and, for some materials, upon temperature and strain rate.

3.1.10 *crack displacement (*L)—the separation vector between two points (on the surfaces of a deformed crack) that were coincident on the surfaces of an ideal crack in the undeformed condition.

3.1.10.1 *Discussion*—In this practice, *displacement, v,* is total displacement as measured by clip gages or other devices spanning the crack. Measurement points on C(W) and C(T) specimens are identified as locations V_0, $V1$, and $V2$.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *plane-stress fracture toughness,* K_c—in Practice E 561, the value of K_R at the instability condition determined from the tangency between the *R*-curve and the applied *K* curve of the specimen.

3.2.1.1 *Discussion*—See the discussion of plane-strain fracture toughness in Terminology E 616.

3.2.2 *fixed-load or fixed-displacement applied K curves*—curves obtained from a fracture mechanics analysis for the test specimen configuration. Assume a fixed applied load or displacement, then generate a curve of *K* versus the crack size as the independent variable.

4. Summary of Practice

4.1 During slow-stable fracturing, the developing crack growth resistance, K_R, is equal to applied *K*. The crack is driven forward by increments of increased load or displacement. Measurements are made at each increment for calculation of *K* values which are individual data points lying on the *R*-curve for the material.

4.2 The crack starter is a low-stress-level fatigue crack.

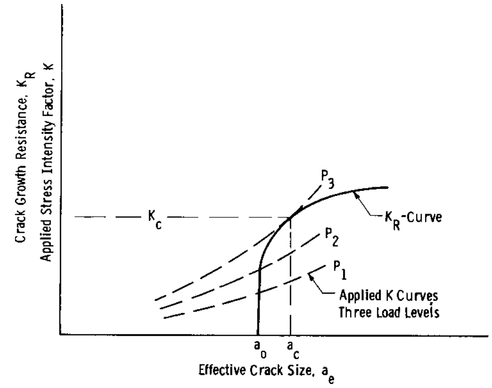

FIG. 1 Schematic Representation of R-Curve and Applied *K* Curves to Predict Instability; K_c, P_3, a_c, Corresponding to an Initial Crack Size, a_o

4.3 Methods of measuring crack growth and of making plastic-zone corrections to the physical crack length are prescribed. Expressions for the calculation of crack-extension force are shown.

5. Significance and Use

5.1 *R*-curves characterize the resistance to fracture of materials during incremental slow-stable crack extension and result from growth of the plastic zone as the crack extends from a sharp notch. They provide a record of the toughness development as a crack is driven stably under increasing applied *K*. They are dependent upon specimen thickness, temperature, and strain rate.

5.2 For an untested geometry, the *R*-curve can be matched with the applied *K* curves to estimate the load necessary to cause unstable crack propagation at K_c (**1**)[3]. (See Fig. 1.) In making this estimate, *R*-curves are regarded as though they are independent of starting crack length, a_0, and the specimen configuration in which they are developed. For a given material, material thickness, and test temperature, they appear to be a function of crack extension, Δa, only (**2**). To predict crack instability in a component, the *R*-curve may be positioned as in Fig. 1 so that the origin coincides with the assumed initial crack length, a_0. Applied *K* curves for a given configuration can be generated by assuming applied loads or stresses and calculating applied *K* as a function of crack length using the appropriate expression for *K* of the configuration. The unique curve that develops tangency with the *R*-curve defines the critical load or stress that will cause onset of unstable fracturing.

5.3 If the *K*-gradient (slope of the applied *K* curve) of the specimen chosen to develop an *R*-curve has negative characteristics (Note 1), as in the crack-line-wedge-loaded specimen of this method, it may be possible to drive the crack until a maximum or plateau toughness level is reached **(3, 4, 5)**. When a specimen with positive *K*-gradient characteristics (Note 2) is used, the extent of the *R*-curve which can be developed is terminated when the crack becomes unstable.

[3] The boldface numbers in parentheses refer to the list of references appended to this practice.

NOTE 1—Fixed displacement in crack-line-loaded specimens result in a decrease of K with crack extension.

NOTE 2—With load control, K usually increases with crack extension and instability will occur at maximum load.

6. Apparatus

6.1 *Grips and Fixtures for Middle Cracked Tension Specimens,* M(T)—In the center-cracked tension tests, the grip fixtures are designed to develop uniform load distribution on the specimen. To ensure uniform stress entering the crack plane, when single pin grips are used, the length between the loading pins shall be at least three specimen widths, 3W. For panels wider than 12 in. (305 mm), multiple pin grips are mandatory, and because such fixtures deliver uniform stress, the length requirement (between the innermost row of pins) is relaxed to 1.5W. A typical grip arrangement shown in Fig. 2 has proven useful. Pin or gimbal connections are located between the grips and loading machine to aid the symmetry of loading. If extra-heavy-gage ultra-high-strength materials are to be tested, the suitability of the grip arrangement may be checked using the *AISC Steel Construction Manual*.

6.2 *Grips and Fixtures for Compact Specimens,* C(T)—The grips and fixtures described in Test Method E 399 are recommended for R-curve testing where C(T)-type specimens are loaded in tension.

6.3 *Fixtures for Crack-Line-Wedge-Loading*, C(W):

6.3.1 Where wedge loading is used, a low-taper-angle wedge with a polished finish and split-pin arrangement shown in Fig. 3 is used. Sketches of a segmented split-pin system which has proved effective for maintaining the load line independent of rotation of the specimen arms are provided in Fig. 4. It has been found convenient to use a wedge whose included angle is 3°. With proper lubrication and system alignment a mechanical advantage of five can be expected. Thus, a loading machine producing ⅕ the maximum expected test load will be adequate. The wedge must be long enough to develop the maximum expected crack-opening displacement. The maximum required stroke can be calculated from the maximum expected displacement v, using the EBv/P values found in Table 1, the maximum expected K level in the test, and the wedge angle.

6.3.2 The wedge-load blocks which drive the load sectors are constrained on top (not shown) and bottom to restrict motion to a plane parallel to the plane of the specimen. This allows the load to be applied or released conveniently without driving the load blocks and sectors out of the hole in the specimen. The wedge-load blocks are designed so that line contact exists between the wedge-load block and the load sector at a point that falls on the load line of the specimen. This enables the load sectors to rotate as the wedge is driven and the original load line is maintained. Any air- or oilhardening tool

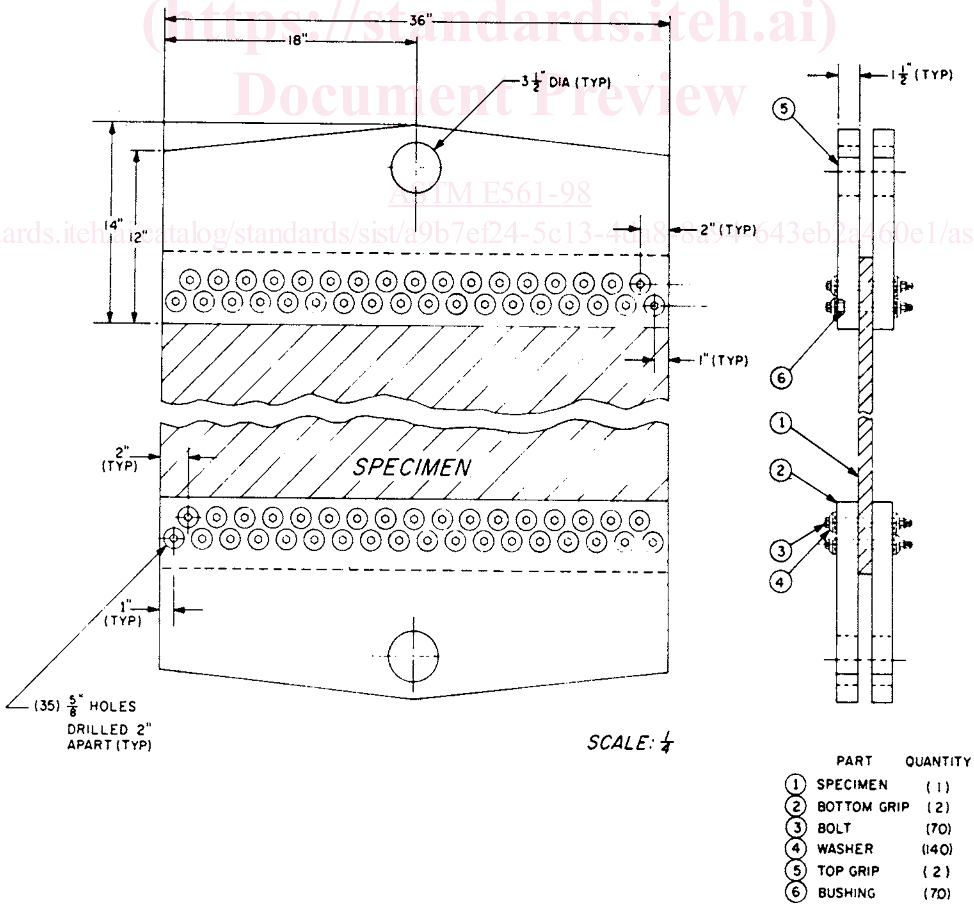

FIG. 2 Middle-Cracked Tension Panel Test Setup

TABLE 1 Dimensionless Stress Intensity Factors and Compliance in Plane Stress for the Recommended C(T) and C(W) Specimens

NOTE 1—$H/W = 0.6$.
V_1 at $0.1576W$ from loading pin centerline; see Fig. 8(a).
V_0 at $0.25W$ from loading pin centerline; see Fig. 8(a).

a/W^A	C(T) or C(W) $KBW^{1/2}/P^B$	C(T) EBv/P^C at V_0	C(T) EBv/P^C at V_1	C(W) EBv/P^C at V_1	a/W^A	C(T) or C(W) $KBW^{1/2}/P^B$	C(T) EBv/P^C at V_0	C(T) EBv/P^C at V_1	C(W) EBv/P^C at V_1
.350	6.392	29.89	25.82	22.83	.480	9.093	50.15	44.31	41.52
.355	6.475	30.44	26.33	23.35	.485	9.230	51.24	45.30	42.52
.360	6.558	31.01	26.85	23.88	.490	9.369	52.36	46.33	43.55
.365	6.644	31.59	27.38	24.43	.495	9.512	53.51	47.38	44.61
.370	6.730	32.20	27.94	24.99	.500	9.659	54.71	48.48	45.70
.375	6.818	32.82	28.50	25.57	.505	9.810	55.93	49.60	46.83
.380	6.906	33.45	29.08	26.16	.510	9.964	57.20	50.76	47.99
.385	6.988	34.10	29.68	26.76	.515	10.123	58.51	51.95	49.18
.390	7.090	34.77	30.29	27.38	.520	10.286	59.86	53.19	50.42
.395	7.183	35.46	30.91	28.02	.525	10.453	61.25	54.47	51.70
.400	7.279	36.16	31.55	28.67	.530	10.625	62.70	55.78	53.02
.405	7.376	36.88	32.21	29.33	.535	10.802	64.18	57.15	54.38
.410	7.475	37.62	32.88	30.01	.540	10.984	65.72	58.56	55.79
.415	7.576	38.37	33.57	30.71	.545	11.172	67.32	60.01	57.24
.420	7.678	39.15	34.27	31.42	.550	11.364	68.96	61.52	58.75
.425	7.783	39.94	34.99	32.15	.555	11.583	70.67	63.08	60.31
.430	7.890	40.75	35.73	32.90	.560	11.767	72.43	64.70	61.92
.435	7.999	41.59	36.49	33.67	.565	11.978	74.25	66.37	63.60
.440	8.110	42.44	37.27	34.45	.570	12.195	76.14	68.10	65.32
.445	8.223	43.31	38.07	35.25	.575	12.420	78.10	69.89	67.12
.450	8.340	44.21	38.89	36.08	.580	12.651	80.12	71.74	68.97
.455	8.458	45.14	39.73	36.93	.585	12.890	82.22	73.66	70.89
.460	8.580	46.08	40.60	37.80	.590	13.136	84.40	75.65	72.88
.465	8.704	47.06	41.49	38.69	.595	13.391	86.64	77.72	74.94
.470	8.830	48.06	42.40	39.61	.600	13.654	88.98	79.85	77.07
.475	8.960	49.09	43.34	40.55					

[A] Inverted form from Ref. **(13)**:

$$a/W = C_0 + C_1(U) + C_2(U)^2 + C_3(U)^3 + C_4(U)^4 + C_5(U)^5$$
$$U = 1/[(EBv/P)^{1/2} + 1]$$

	C_0	C_1	C_2	C_3	C_4	C_5
C(T) at V_1	+1.0008	−4.4473	+15.400	−180.55	+870.92	−1411.3
C(T) at V_0	+1.0010	−4.6695	+18.460	−236.82	+1214.9	−2143.6

Accuracy is a; ±0.0005W

[B] From Refs. **(14, 15)**:

$$KWB^{1/2}/P = \frac{(2 + a/W)[0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]}{(1 - a/W)^{3/2}}$$

[C] From Ref. **(12)**:

$$EBv/P = A_0 + A_1(a/W) + A_2(a/W)^2 + A_3(a/W)^3 + A_4(a/W)^4$$

	A_0	A_1	A_2	A_3	A_4
C(T) at V_0	+120.7	−1065.3	+4098.0	−6688.0	+4450.5
C(T) at V_1	+103.8	−930.4	+3610.0	−5930.5	+3979.0
C(W) at V_1	+101.9	−948.9	+3691.5	−6064.0	+4054.0

Accuracy ±0.4 %%   0.35< a/W < 0.60

steel will be suitable for making the wedge and wedge-load blocks. A maraging 300-grade steel should be used for the load sectors. The diameter of the sectors shall be slightly smaller (nominally 1⁄32 in. (0.79 mm)) than the diameter of the drilled hole in the specimen.

6.4 *Face Plates to Prevent Sheet Buckling*—Buckling may develop in unsupported specimens depending upon the sheet thickness, material toughness, crack length, and specimen size. Buckling seriously affects the validity of a *K* analysis and is particularly troublesome when using compliance techniques to determine crack length. It is therefore required that rigid face plates be affixed to the M(T), C(T), and C(W) specimens in critical regions. A procedure for the detection of buckling using autographic records is described in 8.6.

6.4.1 For the M(T) specimen, the buckling restraints shall be attached to the central portion of the specimen. The plates shall be so designed to prevent sheet kinking about the crack plane and sheet wrinkling along the specimen width.

6.4.2 For C(T) and C(W) specimens, the portion of the specimen arms and back edge which are in compression should be restrained from buckling. For sheet specimens it is convenient to use a base plate and cover plate with ports cut in the cover plate at appropriate locations for attaching clip gages and for crack length observations. Friction between buckling restraints and specimen faces is detrimental and should be minimized as much as possible.

6.4.3 Lubrication shall be provided between the face plates and specimen. Care shall be taken to keep lubricants out of the crack to avoid possible crack acceleration due to aggressive attack. Sheet TFE-fluorocarbon or heavy oils or both can be used. The initial clamping forces between opposing plates need not be excessive, but of the order of a few pounds.

TABLE 2 Double Compliance Elastic Calibration Curve—CT and C(W) Specimens (12)

NOTE 1—Applicable only to the *V*1 and *V*2 locations shown in Fig. 8*a* and Fig. 8*b*.

a/w	*v*1/*v*2[A]		*a/w*	*v*1/*v*2[A]		*a/w*	*v*1/*v*2[A]		*a/w*	*v*1/*v*2[A]	
	C(W)	CT		C(W)	CT		C(W)	CT		C(W)	CT
0.350	4.74	5.56	0.415	3.27	3.67	0.480	2.72	2.96	0.545	2.42	2.56
0.355	4.54	5.25	0.420	3.22	3.59	0.485	2.70	2.92	0.550	2.40	2.53
0.360	4.36	5.00	0.425	3.16	3.53	0.490	2.67	2.88	0.555	2.38	2.50
0.365	4.24	4.78	0.430	3.11	3.46	0.495	2.64	2.85	0.560	2.36	2.48
0.370	4.09	4.62	0.435	3.06	3.39	0.500	2.62	2.81	0.565	2.34	2.46
0.375	3.97	4.47	0.440	3.02	3.33	0.505	2.59	2.78	0.570	2.32	2.44
0.380	3.85	4.33	0.445	2.97	3.27	0.510	2.57	2.74	0.575	2.31	2.42
0.385	3.74	4.22	0.450	2.93	3.22	0.515	2.54	2.71	0.580	2.29	2.40
0.390	3.64	4.11	0.455	2.89	3.17	0.520	2.52	2.68	0.585	2.27	2.38
0.395	3.55	4.01	0.460	2.85	3.13	0.525	2.50	2.66	0.590	2.25	2.36
0.400	3.47	3.91	0.465	2.82	3.08	0.530	2.48	2.63	0.595	2.24	2.35
0.405	3.39	3.82	0.470	2.79	3.04	0.535	2.46	2.60	0.600	2.23	2.33
0.410	3.33	3.75	0.475	2.76	3.00	0.540	2.44	2.58			

[A] *v*1/*v*2 is moderately affected by clip gage span with less than ½ % error introduced by using 0.8-in. (20.3-mm) span instead of measurements on the crack line.

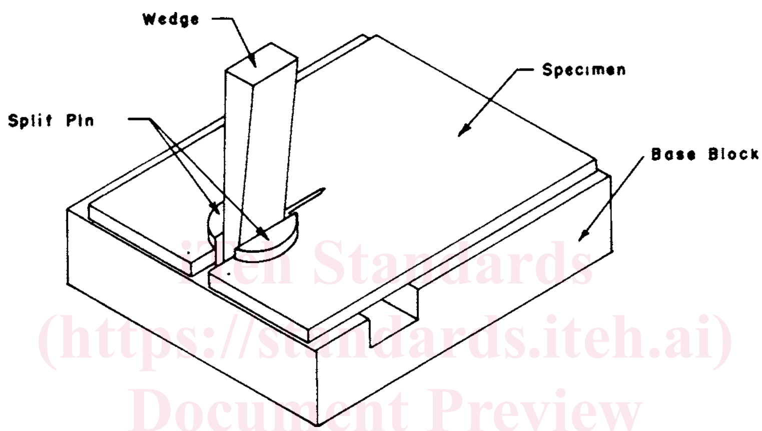

FIG. 3 Crack-Line-Loaded Specimen with Displacement-Controlled Wedge Loading

6.5 *Displacement Gages*—Displacement gages are used to measure accurately the crack-opening displacement across the crack at a preselected location and span. In testing small C(W) and C(T) specimens, the gage recommended in Test Method E 399 may have a sufficient linear working range to be used. However, in testing larger specimens where *W* is larger than 5 in. (127 mm), displacements may be of such a magnitude that gages with greater working ranges of the type shown in Fig. 5 are needed. The use of point contacts eliminates error in the readings from the hinge-type rotation of C(T) and C(W) specimens. The precision of all types of gages shall be checked in accordance with the calibration procedure outlined in 6.3.2 of Test Method E 399. In addition, absolute accuracy within 2 % over the working range of the gage is required for use with compliance measurements. The gages shall be recalibrated periodically.

6.5.1 A recommended gage for use in M(T) panels, that is inserted into a drilled hole with a machined-in circular knife edge, is shown in Fig. 6 **(6)**. The diameter, d_i, is the gage length 2Y and it should be within 3 % of the dimension 2Y used in the calibration. Detail drawings on the gage are given in Fig. 7. Radius of the attachment tip should be less than the radius of the circular knife edge in the specimen. Proper construction techniques and required electronic procedures are specified in Test Method E 399.

6.5.2 The gage recommended in 6.5.1 is preferred from the standpoint of excellent linearity characteristics and ease of attachment. However, other types of gages used over different span lengths are equally acceptable provided the precision and accuracy requirements are retained. For example, the conventional clip gage of Test Method E 399 may be used with screw attached knife edges spanning the crack at a chosen span 2Y. In M(T) tests it is necessary to be cautious in choosing the proper compliance calibration curve to go with such arrangement, because compliance is a function of *Y/W*.

6.6 *Optical Equipment*—If the material being tested is sufficiently thin so that the crack-tip contour does not vary significantly from surface to midthickness, crack growth can be followed by surface observations using optical equipment. If load is sustained at given increments so that the crack stabilizes, crack length can be determined within 0.01 in. (0.2 mm) using a 30 to 50-power traveling-stage microscope. A movie camera recording system may be useful. A common technique is to record simultaneously load and crack growth using two synchronized cameras.

6.7 *Other Equipment*—Other methods of measuring crack length are available, such as eddy-current probes, which are most useful with nonferrous material, or electrical-resistance measurements, where the extension of the crack is determined from electrical potential differences.

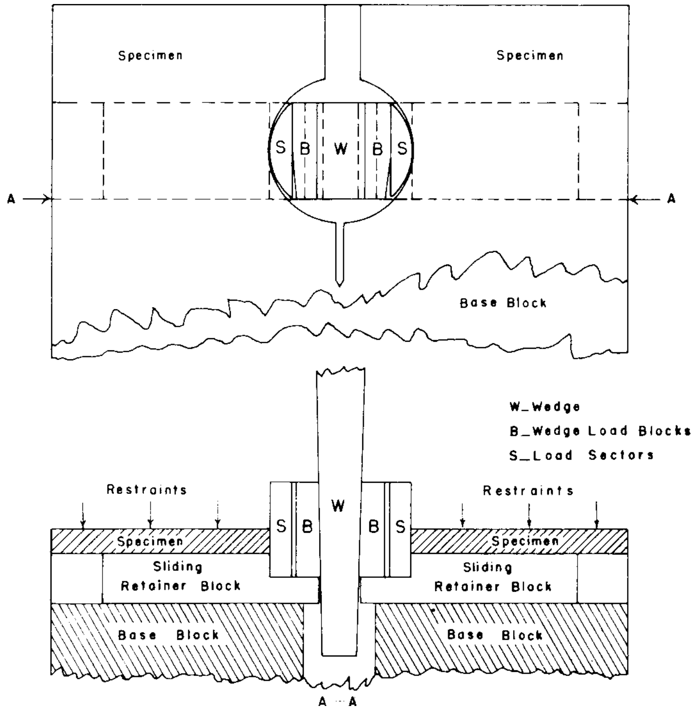

FIG. 4 Detail of Special Wedge and Split-Pin Setup Designed to Prevent Load-Line Shift

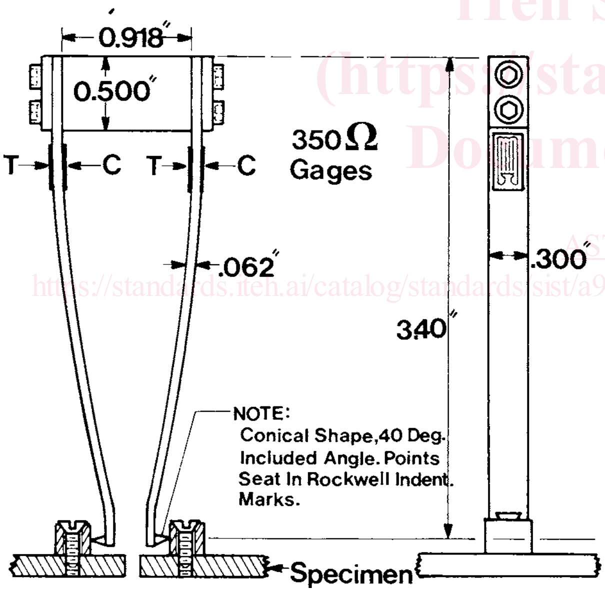

FIG. 5 Enlarged Clip Gage for Double Compliance Work

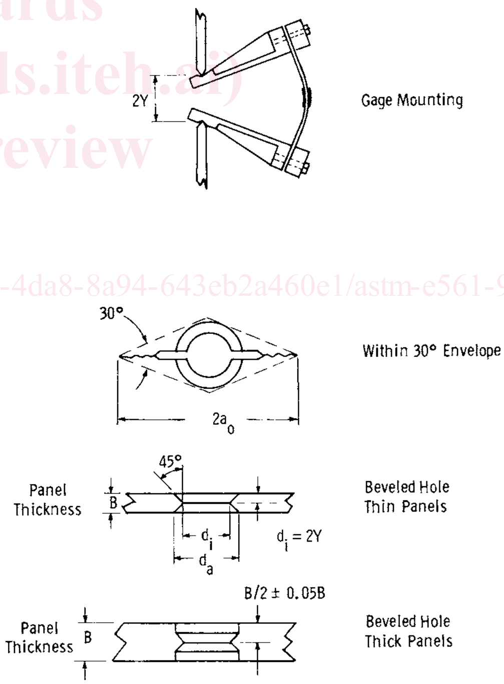

FIG. 6 Recommended Gage for Use in Drilled Hole M(T) Panels

7. Specimen Configuration, Dimensions, and Preparation

7.1 *Specimen Size*—In order for the *K* analysis to be valid, the specimen ligaments in the plane of the crack must be predominantly elastic at all values of applied load.

7.2 For the M(T) panel, the net section stress based on the physical crack size must be less than the yield strength of the material. The M(T) panel width, *W*, is optional provided the requirement of 7.1 is observed. The needed width to be below material yield may be estimated from the maximum expected plastic-zone size, r_Y (see 9.1.4), which is directly proportional to the square of the material toughness-to-yield strength ratio. As a guide, a specimen $27r_Y$ wide and ⅓ notched is expected to fail at a net section stress equal to the yield strength **(7)**. It therefore is desirable to have an estimate of the maximum *K* expected in the test before designing the specimen. As an aid,