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ASTM E08.07.09 Analytical Round-Robin on the Use of DC Electrical Potential Difference for the Measurement of Crack Size in Ductile Fracture Testing

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Abstract

The Direct Current Electrical Potential Difference (DCEPD) technique has been used for many years in fatigue and fracture testing for monitoring crack propagation in metallic materials. The principle of DCEPD methods is that when a constant current flows through a cracked specimen, the voltage change measured across the crack plane can be analytically related, empirically related, or both, to the change in crack size. In fatigue testing, performed within the limits of Linear Elastic Fracture Mechanics, crack propagation is the sole source of potential change. In ductile fracture testing, additional contributions from specimen dimension changes and crack-tip plastic deformation (blunting) have to be accounted for and distinguished from the DCEPD increase caused by crack growth. The ASTM E08.07.09 Task Group, formed in 2013 and chaired by the author, has been developing an annex for ASTM E1820, Standard Test Method for Measurement of Fracture Toughness, which focuses on the use of DCEPD measurements for the prediction of crack size and crack extension in ductile fracture toughness tests. This article presents the analysis of an analytical round-robin, in which 8 participants analyzed 24 existing fracture toughness data sets using two different approaches, based on the analysis of the displacement versus DCEPD and force versus DCEPD, respectively. The comparison between these two approaches and the implications for the ASTM E1820 annex being developed are the focus of this article.

Keywords

Direct Current Electrical Potential Difference; potential difference; fracture toughness; J-R curve; crack size; ductile crack extension

The ASTM E08.07.09 Task Group and Its Analytical Round-Robin

Since 2013, the ASTM E08.07.09 Task Group has been developing a new Annex for ASTM E1820, with the title *Guidelines for the Use of Direct Current Electric Potential Difference Methods for the Determination of Crack Size*. This draft Annex includes several published relationships between crack size and potential difference for Compact Tension [C(T)] and Single-Edge Bend [SE(B)] specimens.

For the application of Direct Current Electrical Potential Difference (DCEPD) methods to ductile fracture toughness testing, the establishment of the potential, V_0 , corresponding to crack initiation is of paramount importance. Two approaches are available for this, one based on the analysis of the DCEPD versus displacement (crack mouth opening displacement [CMOD] or load-line displacement [LLD]) data, and the other based on the analysis of the force versus DCEPD data. These two methods are indicated here as Displacement-Based Approach (DBA) and Force-Based Approach (FBA), respectively.

DBA

The point corresponding to V_0 , where ductile tearing initiates from the plastically deformed (blunted) crack tip, corresponds to the change in slope in the DCEPD versus displacement test diagram (Fig. 1). On the force versus displacement test record, this point must fall between the end of the initial linear portion of the curve and the maximum recorded force.

FBA

The linear portion of the force (F) versus DCEPD curve, which is linearly fitted in order to obtain a force-dependent V_0 expressed as $V_0 = CF + D$ (Fig. 2), corresponds to the slight increase of crack size caused by crack-tip blunting whilst the global specimen behavior remains elastic. The regression line is generally called the V_0 -line.

In 2016, Task Group members decided to provisionally remove the FBA from the draft ASTM E1820 Annex, thereby only allowing the determination of V_0 from the analysis of the DCEPD versus displacement diagram (Fig. 1). However, the Task Group also decided to initiate an analytical round-robin with the primary aim of quantifying the scatter in V_0 using the displacement-based approach, and the consequent uncertainty in the predictions of crack size, a , and crack extension, Δa . A secondary objective of this round-robin was to compare the reliability of the force-based approach to that of the displacement-based approach before confirming the decision of excluding this approach from the draft ASTM E1820 Annex.

The ASTM E08.07.09 Round-Robin

Eight participants analyzed 24 existing ductile fracture toughness data sets (18 from C(T) and 6 from full-size precracked Charpy, PCVN, specimens). C(T) specimen thicknesses ranged from 10 mm to 25 mm (0.4 T to 1 T), and initiation toughness levels (J_Q) were between approximately 90 kN/m and 900 kN/m.

All participants used the displacement-based approach (“basic” participation level), and six also employed the force-based approach to establish the V_0 -line (“extended” participation level). A mixture of analytical methods and more empirical (“eyeball”) approaches were used by the participants.

RESULTS: DISPLACEMENT-BASED APPROACH

No specific guidelines were provided for the determination of the point of slope change on the DCEPD versus LLD/CMOD diagram corresponding to V_0 , i.e., the initiation of stable crack extension following crack-tip blunting. As a result, half of the participants (1, 2, 4, and

6) used some type of analytical approach, while in the case of the remaining four (3, 5, 7, and 8) a more subjective “eyeball” approach was employed in at least part of the analysis. Table 1 presents the average, minimum, and maximum values of V_0 reported by participants, as well as the standard deviation (absolute and relative) among the round-robin participants.

RESULTS: FORCE-BASED APPROACH

Similar to the displacement-based approach, participants were allowed to use their own methodology to select and linearly fit the early portion of the DCEPD versus force diagram. Of the six participants that provided results for this method, three (3, 5, and 8) visually identified the linear portion of the curve, while the remaining three (1, 2, and 4) used a numerical approach. Two participants (6 and 7) did not provide results for the force-based approach. Table 2 presents the slope of the V_0 -line (fitting line), C , in the same format as Table 1, i.e., average, minimum, maximum, absolute standard deviation, and relative standard deviation among the responding round-robin participants. The values of the intercept D are not presented here. In Table 2, it's interesting to note that relative standard deviations from reported slope values are generally much higher than relative standard deviations of V_0 values in Table 1.

Calculations of Crack Size from Round-Robin Results

The current draft of the ASTM E1820 Annex (A18) includes several relationships between DCEPD and crack size, which have been published and successfully used for both C(T) and SE(B) specimens [1–3]. Each relationship is strictly valid for a specific measurement configuration (location of current inputs and voltage probes) and is not applicable if inputs or probe locations are different. For data sets CT-12 to CT-18, the exact relationship used by the lab to calculate crack size from DCEPD measurements was available, whereas for the remaining 17 data sets such relationship was not disclosed. For CT-12 to CT-17, the measurement configuration (Fig. 3) exactly matched the one for which Hackett, Kirk, and Hays [3] developed the following empirical correlation:

$$\frac{a}{W} = \left[0.2864 \left(\frac{V}{\bar{V}} - 0.5 \right) \right]^{0.3506} \quad (1)$$

where $\bar{V}$ corresponds to $\bar{a} \approx 0.5W$ and is calculated from V_0 using the following relationship:

$$\bar{V} = \frac{V_0}{3.4916 \left(\frac{a_0}{W} \right)^{2.8523} + 0.5} \quad (2)$$

In the case of CT-18, a relationship developed in-house was employed for the calculation of crack size.

All analyses presented in the remainder of this article were performed only on these seven data sets, for which an “exact” relationship between crack size and DCEPD was available.

For these seven data sets, final ductile crack extensions were calculated and compared to the values measured on the fracture surfaces (a_p). Table 3 provides calculated values of ductile crack extension corresponding to the minimum ($a_{V0,min}$) and maximum ($a_{V0,max}$) values of V_0 for the displacement-based approach, and to the lowest (a_{Cmin}) and highest (a_{Cmax}) slope of the V_0 -lines, based on the round-robin results. Table 3 also reports the differences between minimum and maximum values of predicted crack extension in millimeters and as a percentage of the average round-robin mix/max predictions. Note that, for the displacement-based approach, any value of V_0 corresponding to a data point below the elastic limit or above maximum force was excluded from the analysis.

Although relative standard deviations in Table 2 are much larger than in Table 1, the spread of predicted values from FBA is consistently smaller than for DBA, and in most cases much smaller. For the seven data sets considered, the mean difference between maximum and minimum predicted a is 0.20 mm (9.2 %) for the displacement-based approach and 0.04 mm (2 %) for the force-based approach. This information is also depicted in Fig. 4. It must be noted, however, that DBA results were provided by all participants (eight labs), while only six labs furnished FBA results.

Comparison between Predicted and Measured a Values and Validity of the Predictions

According to ASTM E1820-15a (Section 9.1.5.2), any crack extension prediction must agree with the measured value within ± 15 % of a_p if $a_p < 15$ % of b_0 (initial uncracked ligament size), and within ± 3 % of b_0 thereafter. The minimum and maximum predicted crack extensions from the round-robin results (see Table 3) were evaluated against these validity requirements, and the results are shown in Table 4 for the two methods.

Even though only a fraction of the data sets were evaluated through exact matches to the model and even some of the “exact” data files failed the validity requirements shown in Table 4, it is observed that the force-based approach is more consistently valid. In particular, all force-based round-robin results are valid for four of the seven “exact” data sets.

The mean predicted crack extensions, $(a_{V0,min} + a_{V0,max})/2$ and $(a_{Cmin} + a_{Cmax})/2$, are compared to each other in Fig. 5 and to measured values in Fig. 6. It can be observed that FBA yields predictions that are systematically higher than DBA and therefore closer to the physical measurements (Fig. 5). A generalized trend of under-prediction can be observed for both methods (Fig. 6).

Calculations of J -Integral at Crack Initiation

The last step in the analysis of the round-robin results (data sets CT-12 to CT-18) included the use of some of the V_0 values and V_0 -lines provided by participants (namely, minimum and maximum V_0 ; shallowest and steepest V_0 -lines) to establish J - R curves and J_Q values (crack resistance curves and provisional values of J -integral at crack initiation) in accordance with Annexes A8 and A9, respectively, of ASTM E1820-15a. The value of J -integral for

each data point was calculated according to the procedure for the Resistance Curve Method in Annex A2 for C(T) specimens. J_Q values are given in Table 5 for both DBA and FBA.

The calculations performed indicate that the spread in J_Q for the force-based approach is lower in every case (Fig. 7 and Table 5). The average spread J_Q (with respect to the average between $J_{Q_{\min}}$ and $J_{Q_{\max}}$) is 26.2 % for DBA and 13.1 % for FBA.

In the bar chart of Fig. 8, we compare the mean values of J_Q $\bar{J}_Q = \frac{J_{Q_{\min}} + J_{Q_{\max}}}{2}$, from the two approaches. $\bar{J}_Q$ from FBA is systematically lower than that obtained from DBA for all data sets. On average, FBA average values are 20 % lower than DBA average values. However, because both DBA and FBA calculated crack extensions were found to systematically underestimate measured values (Table 4), it can be contended that even the lower critical values calculated from FBA are probably overpredicting the actual J_Q values.

Conclusions

The most significant conclusions emerging from the analysis of the ASTM E08.07.09 round-robin results are the following.

- In the absence of specific guidelines provided in the current E1820 draft Annex, participants used different approaches for the determination of V_0 (displacement-based approach) or the establishment of the V_0 -line (force-based approach). Methods ranged from fully or partially numerical to more subjective (“eyeball” approach).
- In terms of ductile crack extension predicted from DCEPD measurements, the FBA yielded less scatter than the DBA based on the values provided by the participants. This was observed in spite of the fact that FBA slope values from participants exhibited much more scatter than DBA V_0 values.
- Irrespective of the calculation method used (DBA or FBA), predictions of crack extensions based on DCEPD measurements predictions tend to be systematically lower than optical measurements.
- FBA predictions of crack extension are consistently higher than DBA predictions. Consequently, FBA values are closer to the measured values and are more likely to satisfy the validity requirements of the current ASTM E1820-15a.
- The trends observed for a predictions are fully confirmed in terms of engineering initiation of ductile tearing (J_Q): the force-based approach shows less scatter than the displacement-based approach, and critical J values from FBA are lower than from DBA (as a consequence of providing higher values of a , and therefore less steep J - R curves).

The outcome of this round-robin does not support the exclusion of the force-based approach from the draft E1820 Annex that is being developed by the E08.07.09 Task Group. However, the prevailing opinion inside the ASTM Task Group (based on testing experience) is

currently to prescribe DBA as the reference method and include FBA as an alternative approach.

For future investigations, it will be useful to compare the outcome of DCEPD methods (both DBA and FBA) in terms of critical J -integral value, with other ductile fracture toughness procedures, such as multiple-specimen or single-specimen methodologies (elastic compliance and normalization data reduction).

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FIG. 1.
Determination of V_0 from the DCEPD versus CMOD/LLD record.

FIG. 2.
Determination of the V_0 -line from the force versus DCEPD record.

FIG. 3.
Measurement configuration used for data sets CT-12 to CT-17.

FIG. 4. Comparison between minimum and maximum a_{pred} values based on the round-robin results.

FIG. 5.
Comparison between average predictions from DBA and FBA.

FIG. 6. Comparison between average predicted and measured crack extensions. Straight lines are linear fits to experimental data (same color as the corresponding symbols) and show that FBA predictions are systematically closer to measured crack extensions.

FIG. 7. Differences between minimum and maximum J_Q values calculated from the round-robin results by means of DBA and FBA.

FIG. 8.
Comparison between average J_Q values calculated from the round-robin results using DBA and FBA.

TABLE 1

Round-robin results for the displacement-based approach.

Data set	Average (μV)	$V_{0,\text{min}}$ (μV)	$V_{0,\text{max}}$ (μV)	σ (μV)	σ (%)
CT-1	2,092.4	2,057.7	2,100.0	15.47	0.7 %
CT-2	1,609.5	1,579.5	1,655.6	27.66	1.7 %
CT-3	2,237.4	2,196.0	2,287.8	30.93	1.4 %
CT-4	592.6	586.0	600.8	6.85	1.2 %
CT-5	581.8	577.2	588.1	3.72	0.6 %
CT-6	592.5	587.5	599.6	4.73	0.8 %
CT-7	348.4	338.2	352.2	4.58	1.3 %
CT-8	350.7	340.2	355.7	4.64	1.3 %
CT-9	320.8	300.0	329.7	8.85	2.8 %
CT-10	538.4	534.6	546.5	3.77	0.7 %
CT-11	486.8	483.3	490.3	2.94	0.6 %
CT-12	94.0	92.9	95.2	0.67	0.7 %
CT-13	102.1	101.1	103.2	0.64	0.6 %
CT-14	88.1	87.2	89.2	0.54	0.6 %
CT-15	93.4	93.0	93.8	0.27	0.3 %
CT-16	86.6	85.9	87.4	0.70	0.8 %
CT-17	85.8	85.5	86.6	0.36	0.4 %
CT-18	727.4	713.0	737.0	6.82	0.9 %
PCVN-1	2,994.5	2,965.5	3,024.0	21.17	0.7 %
PCVN-2	3,536.1	3,494.3	3,581.6	32.83	0.9 %
PCVN-3	3,905.4	3,860.0	4,258.4	33.65	0.9 %
PCVN-4	835.4	800.9	846.0	19.44	2.3 %
PCVN-5	823.3	788.3	840.5	16.84	2.0 %
PCVN-6	792.1	758.4	805.3	14.68	1.9 %

TABLE 2

Round-robin results for the force-based approach (slopes of the V_0 -line).

Data set	Average ($\mu\text{V/kN}$)	$C_{\min}$ ($\mu\text{V/kN}$)	$C_{\max}$ ($\mu\text{V/kN}$)	σ ($\mu\text{V/kN}$)	σ (%)
CT-1	21.043	4.927	66.320	22.930	109.0 %
CT-2	23.234	8.446	38.300	14.286	61.5 %
CT-3	32.056	6.618	72.520	21.837	68.1 %
CT-4	0.415	0.218	0.659	0.164	39.6 %
CT-5	0.234	0.151	0.324	0.066	28.2 %
CT-6	0.302	0.223	0.337	0.043	14.2 %
CT-7	0.186	0.089	0.433	0.133	71.6 %
CT-8	0.185	0.059	0.288	0.101	54.5 %
CT-9	0.179	-2.897	3.901	2.629	1,470.3 %
CT-10	0.053	0.034	0.067	0.012	21.7 %
CT-11	0.025	-0.002	0.070	0.027	107.7 %
CT-12	0.075	0.063	0.094	0.010	14.0 %
CT-13	0.073	0.054	0.085	0.012	16.3 %
CT-14	0.053	0.044	0.060	0.006	11.4 %
CT-15	0.046	0.039	0.057	0.006	12.2 %
CT-16	0.068	0.042	0.093	0.024	36.0 %
CT-17	0.055	0.048	0.064	0.005	9.7 %
CT-18	0.064	0.050	0.078	0.012	18.9 %
PCVN-1	6.24	3.193	16.339	5.032	80.6 %
PCVN-2	20.25	12.981	27.577	5.612	27.7 %
PCVN-3	13.51	3.303	27.620	8.791	65.1 %
PCVN-4	4.13	2.656	6.657	1.344	32.5 %
PCVN-5	5.47	3.607	7.099	1.328	24.3 %
PCVN-6	4.79	3.703	5.938	0.798	16.7 %

TABLE 3
Round-robin results in terms of minimum and maximum predicted crack extensions.

Data set	Displacement-Based Method			Force-Based Method		
	a _{VB,min} (mm)	a _{VB,max} (mm)	Difference	a _{C,max} (mm)	a _{C,min} (mm)	Difference
			(mm) (%)			(mm) (%)
CT-12	2.51	2.25	0.26 9.2 %	2.52	2.46	0.05 1.9 %
CT-13	2.44	2.22	0.22 7.9 %	2.41	2.36	0.05 1.7 %
CT-14	5.26	5.04	0.22 3.8 %	5.26	5.25	0.01 0.2 %
CT-15	3.34	3.25	0.09 2.1 %	3.32	3.30	0.02 0.4 %
CT-16	3.44	3.24	0.20 4.3 %	3.57	3.46	0.11 2.3 %
CT-17	0.62	0.47	0.16 22.7 %	0.67	0.63	0.04 5.5 %
CT-18	1.55	1.29	0.26 14.4 %	1.43	1.40	0.04 2.3 %

Note: The smallest and the largest percent differences are highlighted in green and pink, respectively.

TABLE 4
Validity of predicted crack extensions from DBA and FBA, and comparison with measured crack extensions (a_p).

Data set	Displacement-Based Method				Force-Based Method				a_p (mm)
	$a_{v0,min}$		$a_{v0,max}$		a_{Cmin}		a_{Cmax}		
	(mm)	VALID	(mm)	VALID	(mm)	VALID	(mm)	VALID	
CT-12	2.51	YES	2.25	NO	2.49	YES	2.55	YES	2.79
CT-13	2.44	NO	2.22	NO	2.39	YES	2.44	YES	2.75
CT-14	5.26	YES	5.04	NO	5.27	YES	5.27	YES	5.90
CT-15	3.34	NO	3.25	NO	3.33	NO	3.34	NO	4.40
CT-16	3.44	NO	3.24	NO	3.47	NO	3.58	NO	4.77
CT-17	0.62	YES	0.47	NO	0.64	YES	0.68	YES	0.69
CT-18	1.55	NO	1.29	YES	1.61	NO	1.65	NO	1.80

Note: Validity is marked in green (YES) and pink (NO).

TABLE 5

Calculated values of J_Q corresponding to V_{0min} and V_{0max} for the displacement-based approach, and to C_{min} and C_{max} for the force-based approach.

Data set	Displacement-based approach			Force-based approach		
	$J_{Q,V0min}$ (kN/m)	$J_{Q,V0max}$ (kN/m)	J_Q	$J_{Q,Cmin}$ (kN/m)	$J_{Q,Cmax}$ (kN/m)	J_Q
CT-12	146.97	213.99	37.1 %	155.47	135.04	14.1 %
CT-13	126.72	180.81	35.2 %	133.44	126.38	5.4 %
CT-14	145.34	212.39	37.5 %	157.77	149.36	5.5 %
CT-15	122.71	133.04	8.1 %	124.86	119.08	4.7 %
CT-16	129.01	153.21	17.1 %	136.80	94.45	36.6 %
CT-17	131.67	154.74	16.1 %	127.12	118.56	7.0 %
CT-18	382.26	528.41	32.1 %	314.69	261.15	18.6 %

Note: Smallest and largest spreads (J_Q) are highlighted in green and pink, respectively.