12. Round Robin Test as a Comparison of Crack Opening Displacements

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Abstract

The value of the crack opening displacement has been determined on two CT-specimens each in nine testing institutions. The crack opening displacement δ was established in accordance with the procedures by DD 19 (Elliot, Wells), Hollstein/Blauel, Schmidtmann/Ruf, Seidl, optically at the specimen surface, extrapolating several displacement measurements to the crack tip and by means of the infiltration technique.

It has been shown that in case of a specific stress intensity the variations of δ among the participants are relatively small within the scope of one evaluation process; whereas the various evaluation procedures result in different crack opening displacements.

Comparative investigations in literature applying Finite Element Calculations and silicone rubber "castings" at the crack front on the one hand and optical procedures on the other showed that optical procedures adequately reflect the crack opening displacement in the specimen surface area. The values in the internal part being higher by about 15 % correspond to the values gained from extrapolation.

The Ad-hoc-Group "Crack Opening Displacement" of the DVM-Fracture Group has the objective to compare the available test methods for determining crack opening displacements.

At the time being there are considerable differences concerning the relevant procedures for the determination of crack opening displacement in the individual testing sites of the institutions and companies. Thus, the Round Robin Test was intended to illustrate to which extend the various methods differ from one another. The testing institutions listed in the table 1 have been concerned with the Round Robin Test. The COD-methods used by them in general have been marked x in table 2. In addition the crack opening displacement was analysed on the same specimens using the procedures identified by (x), enabling in such a way a direct comparison between the results.

Kraftwerk Union

participant	tester no
RWTH EHK Aachen	1
MPI Düsseldorf	2/3
IFKM Freiburg	4
AEG Frankfurt	5
Sulzer AG Winterthur	6
KWU-R 413 Erlangen	7
KWU-TWE Mülheim	8
IfaM Bremen	9

Participants of Round Robin Test M78 570

Table 1

Kraftwerk Union

COD test methods	tester no 1	2	3	4	5	6	7	8	9
Elliot				(x)					
Wells	x 1)	x 2)	(x) 2)	(x) 2)			(x) 2)	(x) 2)	(x) 2)
Hollstein / Blauel				(x)					
Schmidtmann / Ruf	(x)	(x)	(x)						
Seidl					x				
optical on the specimen surface	(x)			x			x		
infiltration technique			x						
extrapolation						x		x	

( ) additional evaluation
1) with clip gauge displacement on specimen surface
2) with clip gauge displacement in load-line

Evaluation methods for COD-determination of each participant M78 571

Table 2

The values of the crack opening displacement (COD) were determined applying the following methods:

1. COD by DD 19 of British Standard Institution [1]

   These methods proceed from the assumption that the displacement will be established at any position within the notch of the fracture mechanics specimen using a relevant gauge and that the load-displacement curve will be recorded during the test.

The crack opening displacement δ can be determined by extrapolating the value of the clip gauge displacement v to the tip of the crack.

- Procedure according to Elliot [2]

This model starts from the assumption that the notch and crack contour will be essentially rigid when the specimen is loaded. The crack faces separate around a rotation centre being at a distance $r \cdot (w - a)$ from the crack tip. The crack opening displacement can be calculated from

$$\delta = \frac{r\ (w - a)}{r\ (w - a) + a + z} \cdot v \qquad (1)$$

Experiments at various structural steels performed by Ingham [3] showed that the constant rotation factor r = 0,33 aproximately describesthe interrelation between clip gauge displacement v and crack opening displacement δ.

- Procedure according to Wells [4]

This procedure is based on the assumption made by Elliot [2]. The position of the rotation centre is, however, treated in dependance on the load or crack opening. The crack opening displacement δ is determined by the following equations:

$$\delta = \frac{0,45\ (w - a)}{0,45\ w + 0,55 \cdot a + z} \cdot (v - v') \quad \text{for } v>2v' \qquad (2)$$

$$\delta = \frac{0,45\ (w - a)}{0,45\ w + 0,55 \cdot a + z} \cdot \frac{v^2}{4 \cdot v'} \quad \text{for } v<2v' \qquad (3)$$

$$v' = \gamma \cdot R_e \cdot w \ \frac{(1 - v^2)}{E}$$

γ - here for CT specimens

2. Procedure according to Hollstein/Blauel [5]

It is also based on equation (1), considering, however, a rotation centre being dependent on displacement. The rotation factor r is:

$$r = 11.6\ \frac{v_1}{w} + 0.1 \qquad (4)$$

This equation was developed from optical measurements on different thick CT specimens out of the steel 22 NiMoCr 37. The crack length a included in equation (1) won't be established by ASTM E 399, but constitutes:

$$a = a_s$$

measured at the specimen surface.

3. Procedure according to Seidl [6]

The crack opening displacement δ will be determined in a distance to the crack tip, which corresponds to the plastic zone r_y, by extrapolating the displacement v measured at the load line.

The rotation centre for the extrapolation process is situated at the tip of the effective crack length a_{eff}, consisting of the crack length a_0, determined by ASTM E 399 and the effective crack prolongation Δa_{eff}:

$$a_{eff} = a_0 + \Delta a_{eff} \qquad (5)$$

The crack opening displacement is

$$\delta = v_{load\ line} \cdot \frac{(r_y + \Delta a_{eff})}{a_{eff}} \qquad (6)$$

with

$$r_y = \frac{1}{6\pi} \frac{(K_{max})}{(R_{p0,2})} \quad \text{and} \qquad (7)$$

$$K_{max} = \frac{F_{max}}{B \cdot w} \sqrt{a_0} \cdot Y \frac{(a_0)}{(w)} . \qquad (8)$$

The effective crack length a_{eff} shall be determined from the test record $F = f\ (v_1)$ and the compliance calibration curve $\frac{E \cdot B \cdot v}{F} = f(a)$. Thus, at a specific load or displacement the ratio v/F and the relevant crack length a_{eff} out of the compliance curve may be established.

4. Procedure according to Schmidtmann/Ruf [8]

When extrapolating the displacement to the crack tip, the bending of the crack contour by exponent H is taken into consideration in conformity with visually observed crack opening displacements. The crack opening displacement is given by

$$\delta = \frac{r_y^H}{(a + z + r_y)^H} \cdot v \qquad (9)$$

where r_y = the radius of the plastic zone.

The exponent H is determined with respect to two displacement measurements by equation:

$$H = \frac{\ln\ (v_2 / v_1)}{\ln\ (\ (a - x_2 + r_y)\ /\ (a - x_1 r_y)\ )} \qquad (10)$$

resulting in H_{MPI} = 0,75 and H_{EHK} = 0,8. x_1, x_2 are the distances to the load line, where the clip gauge displacement v_1 and v_2 are measured.

5. COD from optical measurements at the specimen surface

Grids are applied to the lateral faces of the specimen in a photo-chemical or mechanical way. During the test the propagating crack tip is being filmed together with the load-displacement curve. The values of the crack opening displacement are determined by evaluating the negatives or positives and shall be appointed to the relevant load or displacement.

6. Determination of the crack profile by means of the infiltration technique [11]

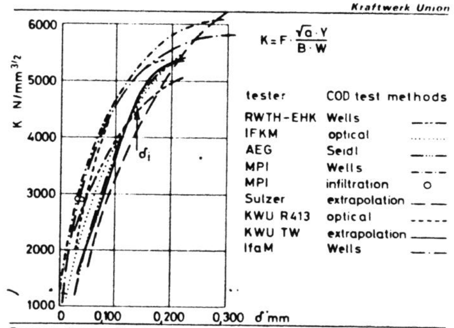
Crack opening displacements may be analyzed by establishing the crack profiles at the specimen surface in an optical way. Within the specimen crack profiles may be investigated using curable silicone-rubber. The liquid rubber is pressed into the loaded crack by means of a vacuum pump. After curing the crack will be extended or the specimen completely broken and the silicone "casting" may be investigated in a scanning electron microscope.

7. COD by extrapolation of several displacement measurements [9]

At measuring points being differently distant to the crack tip in the notch centre, the clip gauge displacements v is established during loading and extrapolated to the crack tip. Thereby, an integral mean value of the crack opening displacement is measured across the crack front.

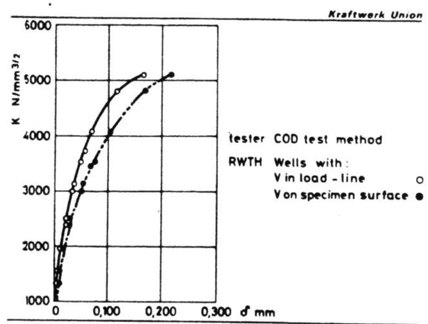
Elastic-plastic one- and two-dimensional Finite Element Calculations at CT-specimens of various materials -, i.e. differing hardening behaviour and strength -, have shown that this linear extrapolation is suitable within a region being beyond the pin holes up to the crack tip.

The test material was a 12 % CrMoV-steel with a yield strength of $R_{po,2}$ = 660 N/mm^2 and a Young's modulus of E = 214.000 N/mm^2. Two CT2-specimens (thickness 50 mm) were loaded until fracture at a test temperature of 50°C by each investigator. Fig. 1 illustrates the stress intensities K, by ASTM E 399, as a function of the experimentally determined crack opening displacement δ for one specimen per each tester.



Stress intensity factors as a function of crack opening displacements M78 572

figure 1



Stress intensity factors as a function of crack opening displacements M78 573

figure 2

There was stable crack growth before the final rupture in case of all the specimens. Using various specimens the critical J-integral of about 110 N/mm was determined by a v-Δa-curve. The critical crack opening displacement being optically measured at the specimen surface is δ_i = 0.14 ± 0.03 mm. The rupture occurred at fracture toughness in the range of 5.000-6.000 $N/mm^{2/3}$.

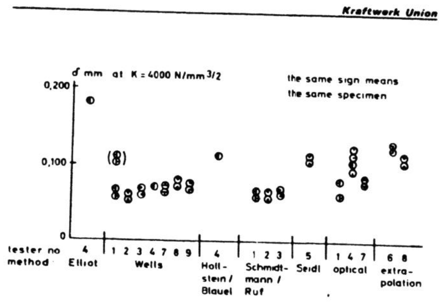
The material was not as homogenous as assumed due to the different yield and fracture behaviour on the one hand. This fact complicated the determination of the critical crack opening displacement and thus the basis of comparison of the measuring results and on the other hand caused deviations of the fracture toughness.

The deviations of the measured crack opening displacement values parallel to increasing stress intensity, however, may be attributed to this fact only partially.

In order to exclude the influence of the material inhomogeneity as far as possible, the stress intensity crack opening displacement curves shall be furtheron compared only with respect to slight plastic deformations in case of which the load as a function of displacement will be predominantly linear. The influence of the crack length will be eliminated by conversion to stress intensity. Thus, the deviations of the displacements up to a stress intensity of about 4.300 $N/mm^{3/2}$ will primarily be caused by the different evaluation methods. For crack opening displacements at the same stress intensities the analysis according to the Wells-procedure results in the lower limit whilst that according to the extrapolation method results in the upper limit of the scatter band regarding the measuring results. In this connection a certain inconsistency of the Wells-method was detected (fig. 2). The calculation of crack opening displacement δ from the clip gauge displacement within the load line leads to smaller crack opening displacements than the calculations with clip gauge displacements at the specimen's front face. The K-δ-curve established in such a way may be easily incorporated in the measuring results scatter band (fig. 1). The same applies to the displacements being optically determined at the specimen surface and those according to the procedure of Seidl.

In case of stress intensities of K = 2.930 $N/mm^{3/2}$ crack opening displacements of δ = 0,040 and 0,035 mm were determined along the crack front by means of the infiltration technique as shown in fig. 1. This does not prove definitely the correctness of the displacements calculated according to Wells, as these tests were performed at higher temperatures for the first time at MPI.

Fig. 3 shows the crack opening displacements determined with respect to the various evaluation methods and at a stress intensity of K = 4.000 $N/mm^{3/2}$.



Comparison of COD test results calculated with different methods at K = 4000 $N/mm^{3/2}$ M78 574

figure 3

Scatter of δ-values within a certain procedure - exclusive of optical ones - is relatively small. The different evaluation methods, however, lead to different crack opening displacement values as it is especially obvious in case of those measured values marked ◐, for instance, which were established on the same specimen. The procedure according to Elliot results in an extremely high δ-value whereas the method according to Wells achieves a small value.

The Finite Element Calculations performed by Friedel [10] gain an adequate agreement of the displacements calculated for the specimen surface of 3CT-specimens with optically determined values. Furthermore, these calculations as well as experiments applying the infiltration technique by Robinson and Tetelmann [11] show crack opening displacements being 15 % higher in the specimen centre than at the specimen surface. Thus, it may be deducted from the investigation results at hand that for the one thing the optical procedures may reproduce the crack opening displacement in an adequate way at the specimen surface. On the other hand the crack opening displacement values being 10-20 % higher when determined by means of the extrapolation method do suitably represent the conditions within the specimen. Further investigations are planned and shall help to clarify the here shown differences.

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