THE CRACK TIP OPENING DISPLACEMENT OF SEMI-ELLIPTICAL SURFACE CRACKS IN TENSILE PLATES

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ABSTRACT

The notch opening displacement at seven positions was measured in notched and surface precracked tensile plates, using a specially developed miniature COD-meter. Fracture mechanics are discussed from the viewpoints of materials testing and application, i.e. how to transfer the results to a real structure.

KEYWORDS

Crack opening displacement; surface crack problem; elasto-plastic fracture mechanics; specimen to structure correlation.

INTRODUCTION

The most common flaws in structures are part-through surface or internal cracks of elliptical shape. Due to the three dimensional nature their analysis for elasto-plastic fracture parameters is more complicated than that of plane problems, e.g. through-thickness cracks. For elliptical cracks there are many solutions for the stress intensity factor K_I. From truly elasto-plastic considerations, which provide the crack opening displacement or the J-contour Integral, there are relatively few solutions. This paper presents the results of an experimental investigation of the crack tip opening displacement on semi-elliptical surface cracks in tensile plates.

THEORETICAL BACKGROUND

One of the more successful elasto-plastic concepts of fracture mechanics is that, using the crack tip opening displacement as a parameter. This governs the onset of stable crack growth and possibly also the attainment of crack instability. This parameter is measured with standard bend or compact tension specimens. Assuming at least approximate independence of size and crack as well as loading configuration, it is then applied to large scale structures. In order to do this, a relationship is required between the crack opening displacement δ and the global parameters of the structural problem, namely the dimensions, the crack size, shape and the load.

Such relationships must be based on time consuming and expensive elasto-plastic analyses. Therefore, the practising engineer normally uses the well-known formulae of linear elastic fracture mechanics to convert measured critical values of δ into critical values of the stress intensity factor.

$$\delta = \frac{K_I^2}{E' \sigma_Y} \qquad (1)$$

$$E' = \begin{cases} E \text{ .... plane stress} \\ \dfrac{E}{1-\nu^2} \text{ .... plane strain} \end{cases}$$

and applied to critical conditions, for instance crack initiation,

$$K_c = \sqrt{\delta_c E' \sigma_Y} \qquad (2)$$

K_c is used in connection with the appropriate K_I-solution for the structure often including a plasticity correction. This procedure is justified in the case of first stable crack growth which is usually observed in very ductile materials after limited plasticity. If large plastic zones are involved in the specimen and in the structure, it looses its justification. In the very special case of a plate with a through-crack, the Dugdale crack model may be applied to demonstrate the progressively growing discrepancy between a 'pseudo'-elasto-plastic and a small scale yield solution (Prantl, 1976).

$$\delta = \frac{8}{\pi} \cdot \frac{\sigma_Y}{E} \cdot a \ln \left[\sec \frac{\pi}{2} \frac{\sigma_\infty}{\sigma_Y} \right] \qquad (3)$$

$$\tilde{\delta} = \frac{\pi \sigma_\infty^2 a}{E \sigma_Y} \qquad (4)$$

$$\approx\!\!\delta = \frac{\pi \sigma_\infty^2 a}{E \sigma_Y} \left[1 + \frac{\pi^2}{24} \left(\frac{\sigma_\infty}{\sigma_Y} \right)^2 \right] \qquad (5)$$

A contribution to the existing incomplete knowledge in this field is intended by our experimental investigation. The main purpose is to derive a relationship between δ at the crack leading edge and the load for a specimen representing a simple structure (Prodan and others, 1978). Additionally δ_c for onset of stable crack growth was measured. It will be compared to δ_c, evaluated from CT-specimens of the same material using identical measurement techniques.

EXPERIMENTAL INVESTIGATIONS

To establish δ-values for a specimen to structure correlation we considered a tensile plate with a semi-elliptical surface crack as a simple representation of a real structure. Figure 1 shows a side view of an instrumented plate test. For the characteristic dimensions of the plates, see Table 1.

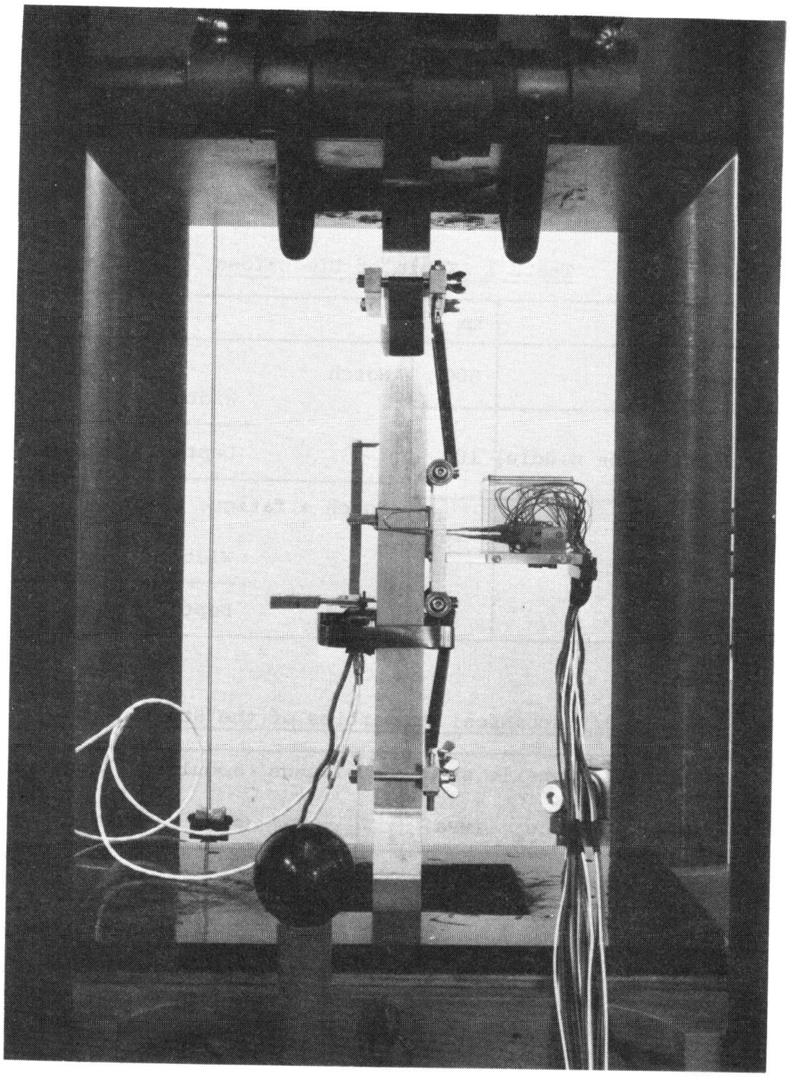

Fig. 1 Test with a tensile plate

The testing material used was the structural steel Ck 15. For the mechanical properties of the steel, see Table 2.

Circular segment notches were machined into one face of the plate specimens. Starting from these notches the plates were precracked under controlled fatigue conditions. The fatigue precracks had approximately semi-elliptical shapes. In the 5 plate specimens we achieved a good reproducibility of the precracks with characteristic dimensions ranging from 14.4 to 15.7 mm depth and 61.5 to 65.4 mm width. In the experiment the plates were loaded to fracture in simple tension. Besides the usually recorded testing parameters, the following quantities were measured:

- The notch opening displacement in seven positions, using a specially developed miniature COD-meter.
- The elongation of the specimens along a gauge length which included the region with the crack.
- The onset of first stable crack growth using acoustic emission techniques, the heat tinting method and fatigue marking technique.

TABLE 1 Table of Dimensions

	mm			mm
Length	800	Notch	Width	60
Width (in the middle)	100		Depth	10
Thickness	28	Notch + fatigue crack	Width	∿ 63
			Depth	∿ 15

TABLE 2 Mechanical Properties of the Steel Ck 15

Yield strength σ_Y (MPa)	Tensile strength σ_B (MPa)	Youngs' modulus E (MPa)	Elongation to fracture (L=5d) (%)
290	450	2.10^5	35

Some details of the above mentioned measurements follow here. Three of the clip gauges of the COD-meter were positioned at the front face of the machined notch. Four were attached to the surface of the plate. In this way it was attempted to register the spatial opening of the whole notch. The clip gauge readings were recorded at different loads for the whole loading interval from zero to maximum or to ∿90 - 95 % of the maximum load, when heat tinting was made. The opening of the crack front was determined by extrapolating the notch opening displacements to the actual crack front. Upon attainment of a certain load, the fatigue crack front moved inside the plate only, whereas very close to the maximum load crack growth became noticeable on the surface. Because of this fact, the onset of stable crack growth was impossible to observe visually. Therefore we used acoustic emission techniques, the heat tinting method and a fatigue marking technique to detect the initiation event. For the assessment of first stable crack growth with acoustic emission techniques, we used the first significant acoustic emission activity, which may be interpreted as excessive crack blunting and possibly onset of stable crack growth.

A total of five tests with tensile plate specimens were performed in air at room temperature. Afterwards CT specimens were taken from the tested plates, two samples from each plate specimen.

RESULTS

Results are given in the following Figs. 2 to 6. Figure 2 presents the clip gauge readings as a function of the load for one of the plates.

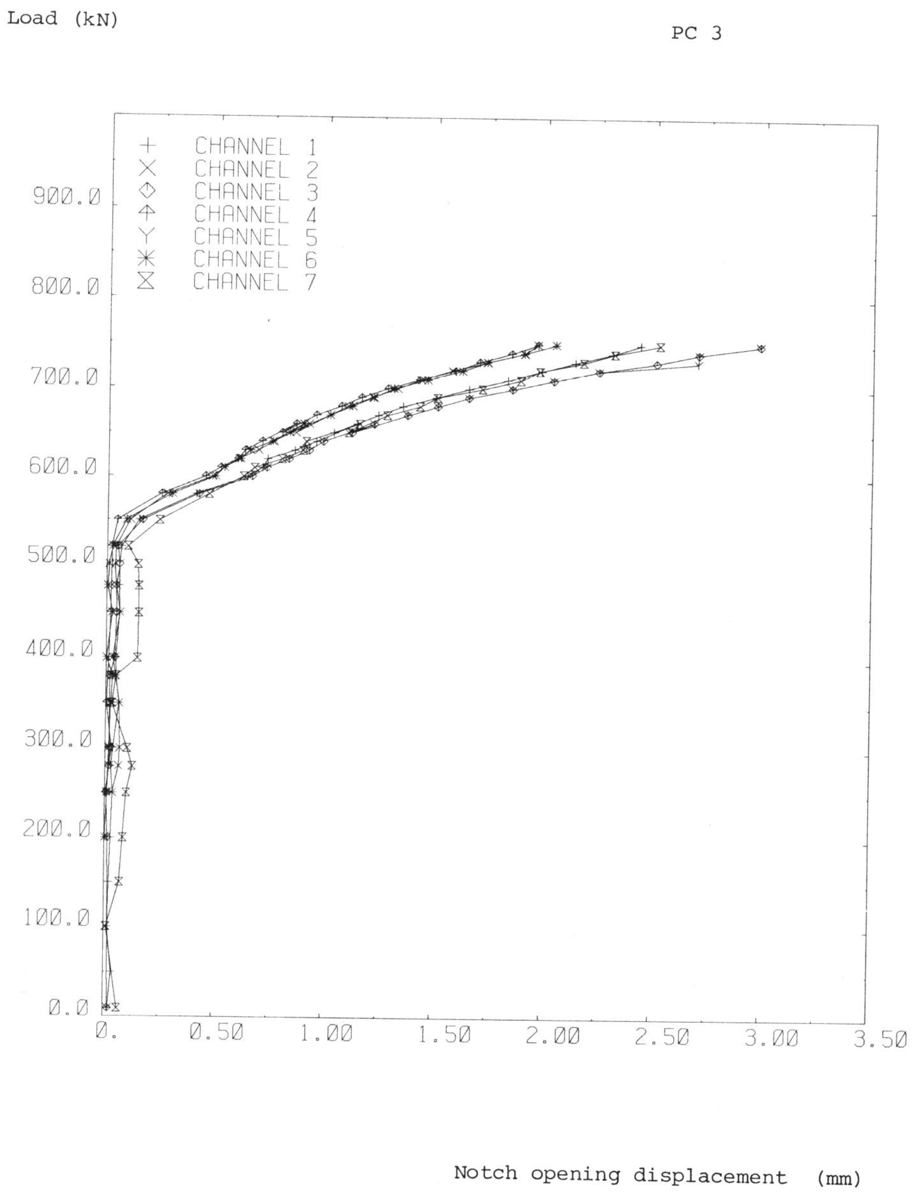

Fig. 2 Clip gauge readings (Channel 1...7) of the measured notch opening versus load

From these readings, δ at the crack leading edge was evaluated by extrapolation (Fig. 3).

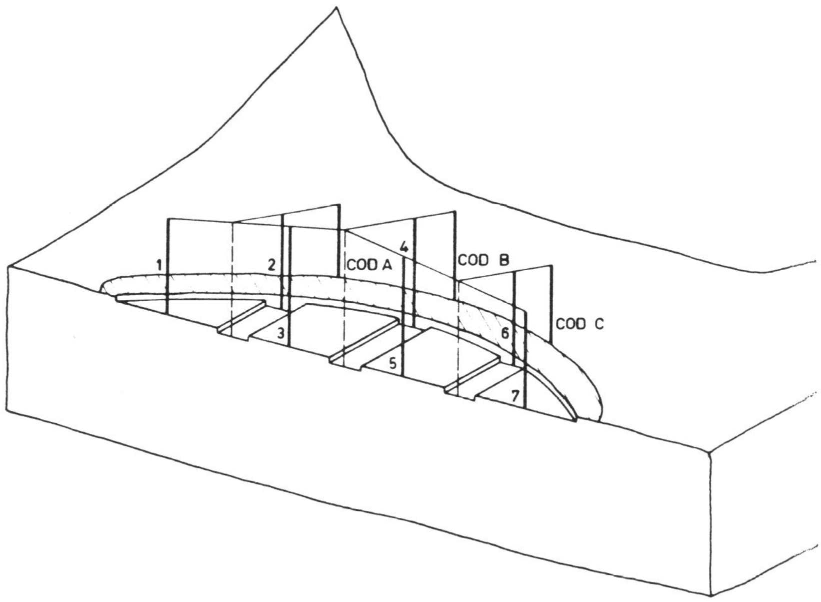

Fig. 3 Illustration of COD-extrapolations

The δ-values against the load and net as well as gross stress are plotted in Fig. 4.

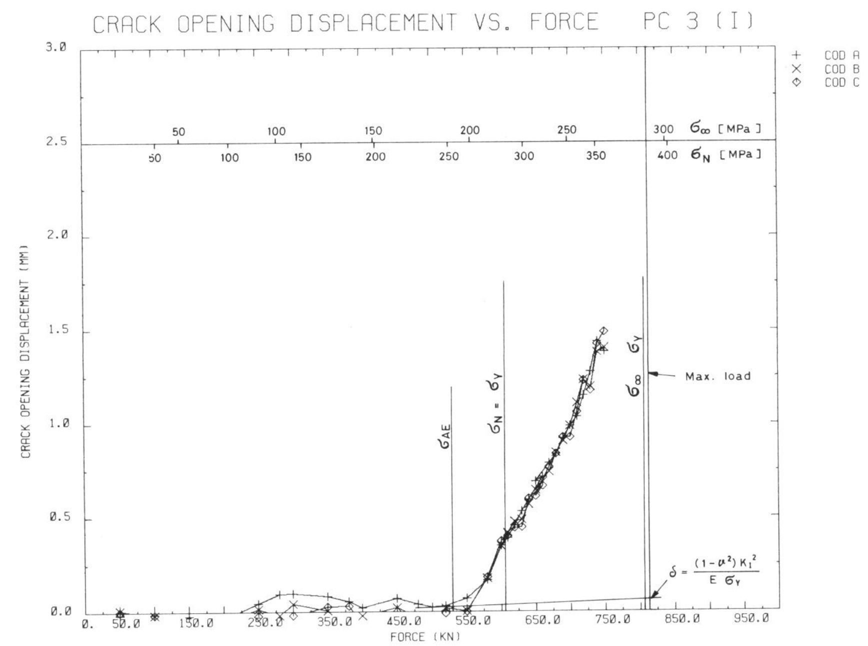

Fig. 4 The extrapolated COD(δ)-values from the clip gauge readings of Fig. 2

Figure 5 shows a summary of the results of four tested plates.

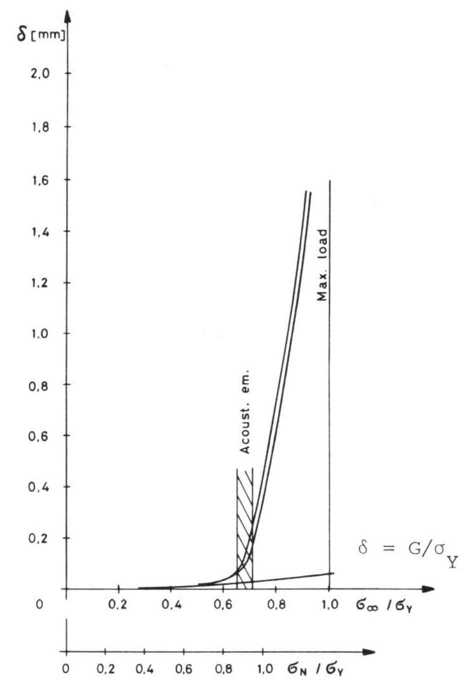

Fig. 5 Summary of the results of 4 tested plates

Clip gauge readings beyond ∿ 90 % of the maximum load showed irregularities mainly caused by excessive deformation of the specimens, which hindered their functioning. One plate did not give satisfactory results, and is therefore not included in Fig. 5. Even this plate showed the same general behaviour than the others, but with a much higher scatter. The load deformation behaviour, the original fatigue crack as well as the final fracture could be reproduced to a high degree (Fig. 6).

The critical δ-values as determined by acoustic emission (AE)-measurement are displayed in Table 3.

TABLE 3 Critical δ_c-Values as Determined by Acoustic Emission Measurement

Plate	1	2	3	4	5
AE-load (MN)	580	540	530	550	530
AE-δ_c (mm)	0,25	0,2	<0,1	0,1	0,15

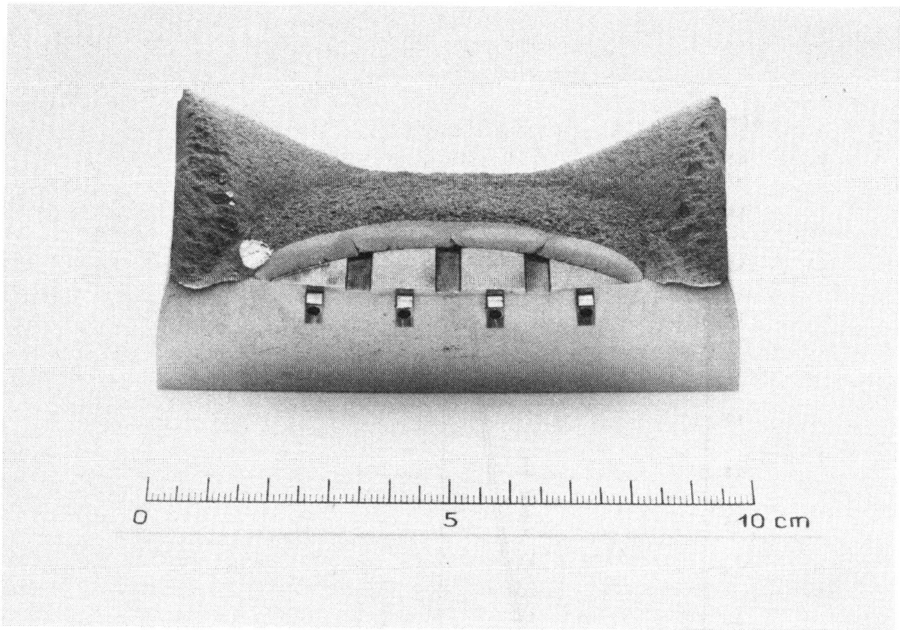

Fig. 6 One of the fracture surfaces

DISCUSSION OF THE RESULTS

The extrapolated δ-values at the crack leading edge (Fig. 4) closely follow the linear elastic crack opening displacement $\delta = G/\sigma_Y$, but the accuracy of the measured δ-values is not better than about 0,1 mm. When the remote stress σ_∞ reaches 70 % of the uniaxial yield stress, (the nominal net section stress is then about 96 % of the yield stress), δ starts to rise rapidly with further loading. At fracture σ_∞ approximately equalled the yield stress. This is incidental, because the stress strain curve of the material shows hardening and the stress state in the plates was, due to bending effects, quite different from uniaxial equally distributed tension. Experiments using wider plates (W/2c at least equal to 5) would be necessary to avoid this effect up to high deformations. Because of this care must be taken when applying the present results to structures of different sizes. It is intended next to analyse the loading condition (remote stress distribution) of the tested plates.

FUTURE PLANS

Investigations similar to the one described here should be repeated for other relevant materials and different crack sizes together with larger plate dimensions.

In the case of part-through cracks no extrapolation formula exists (although one could derive a formula which would be valid in the central region of a surface crack and account for the plastic part of the crack tip opening displacement). Therefore the developed and successfully applied experimental technique currently provides the only possibility to measure δ.

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