PAPER 3 (SESSION I)

# Direct surface measurement of the crack opening displacement of mild steel Charpy specimens

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**Summary**
Direct photographic measurements have been made of the C.O.D. of mild steel Charpy specimens at the onset of fracture in three point slow-bending and impact. By using side notches a plane crack front was formed and the C.O.D. values consistent with this were found to be independent of notch acuity, in a comparison of V notched and fatigue cracked specimens. Observations of the shape of the crack front during fracture in plain and in side notched specimens indicate that the respective crack shapes were independent of strain rate and notch acuity.

## Introduction

Recently attention has been focused on a fracture mechanics approach to low-strength structural steels. Wells [1] has developed an approach for the initiation of cleavage fracture at stresses above the yield consistent with the initiation of fracture when the opening at the tip of the crack reaches a critical value, the crack opening displacement (C.O.D.). The specific value of C.O.D. obtained at the crack tip at the instant of fracture is considered to be a measure of the toughness or notch ductility of the particular material.

Crack opening displacements have been measured in a variety of ways. Burdekin and Stone [2] and Wells [1, 3] used a torsional paddle gauge located at the bottom of the machined slit that acted as a blunt crack in wide plate and massive slow-bend specimens. Ford *et al.* [4] inferred C.O.D. values for Charpy specimens from the load-time curves of a fully instrumented impact test, and from the load-displacement curves of a slow bend test. Values of C.O.D. were obtained for Charpy specimens tested in slow bending by Elliott and May [5] using a clip gauge attached to the specimen surface.

Current interest in C.O.D. measurements of Charpy specimens has exposed the uncertainty involved in comparing slow bend and impact values obtained by different methods of measurement. The present work was undertaken to establish directly measured values of C.O.D. for Charpy specimens by a method that could be used in any test situation.

## Experimental method

10 × 10 × 55 mm Charpy V-notched specimens were tested in impact and three-point slow bend. Plain and side-notched specimens, with and

without fatigue cracks at the root of the machined notch, were compared to establish the effect of shear lip formation and notch acuity on the C.O.D. for fracture initiation measured at the specimen surface. Details of the side-notch and of the fatigue-cracked specimen are given in Figs. 1 (a) and 1 (b).

Crack opening at the notch was measured from photographs of the specimen surface during loading. The impact specimens, tested on a fully-instrumented machine, were photographed using the time delay technique adapted by Wraith [6], so that specimen displacement could be related to the load displayed on the load-time curve. Incremental changes in delay time in successive identical tests yielded a series of photographs from which a continuous record of surface behaviour throughout deformation and fracture could be implied. The opening of the notch in the slow bend test ($7 \times 10^{-4}$ in/sec crosshead velocity) was also recorded photographically; the photographs were referred to a load-displacement curve for the test.

Plain specimens were inscribed with marks defining a gauge length of 0·2 in across the notch; the boundaries of the side notch defined the gauge length in the side notched specimens. Opening displacements were measured from the points where the gauge marks met the edge of the V-notched face. Tests were done at 100 °, 20 °, –70 °, –40 ° and –100 °C.

Examination of the shape of the ductile crack front was carried out for the four types of specimen used. The shape of the crack was established by cracking specimens in slow-bend and in impact at 20 °C until varying amounts of ductile crack propagation had occurred, then breaking the specimens in impact at –80 °C. The boundary between the ductile and cleavage fracture regions produced in the specimen showed the form of the ductile crack front (Fig. 2) and the relative positions of the crack at the centre and at the surface of the specimen could be measured.

The steel composition (weight per cent) was C 0·12-0·16, Mn 0·42, Si 0·06, S 0·03, P 0·01, and the ductile-to-brittle transition temperature (40 ft lb Charpy) was +20 °C.

## Results and discussion

Values of crack opening displacement for fracture initiation for all specimens are summarised in Table 1, where results are quoted for each test temperature. Figs. 3 and 4 indicate the types of curves for C.O.D. versus load (reported as ratio of load to general yield load) obtained from the tests in impact and slow bend for plain and side notched specimens.

At –40 °C and –70 °C the C.O.D. values are the same for plain and side-notched specimens tested in impact, whilst the values at 20 °C and 100 °C differ for the two types, reflecting the effectiveness of side notches in suppressing surface shear lips.





The difference that arises from the use of side notches is presented quantitatively in Fig. 5, where the position of the crack in the centre of the specimen is compared directly with its position at the specimen surface during cracking of the two types of specimen. It is clear that the shape of the crack front is the same during fracture in slow bending and impact, and that the side notches are completley effective in producing a straight crack front.

In the slow bend tests, the transition from ductile fracture initiation to cleavage initiation occurred between –70 °C and –100 °C and was accompanied by an expected decrease in the C.O.D. The appearance of a surface crack coincided with maximum load at all temperatures in tests of side notched specimens and at –70 °C and –100 °C in tests of plain specimens. Surface cracking did not appear until well after maximum load in tests of plain specimens at higher temperatures.

Similar behaviour is seen in the impact tests. The delay of 600-700 $\mu$ secs in the appearance of surface cracking after maximum load in ductile, plain specimens is the time required for the convex (thumb-nail) crack front to develop.

The introduction of a fatigue crack in the plain Charpy specimens caused a decrease in the C.O.D. for fracture in both the impact and slow bend tests, where the crack was initiated by shear. It had no significant effect on the C.O.D. for cleavage fracture.

In the case of the side notched specimens, the introduction of a fatigue crack (Fig. 1 (b)) caused no significant variation in the C.O.D. value for either ductile or cleavage cracks in slow bend or impact tests (Table 1). It would appear that notch acuity, within the range of notch root radii investigated (≤ 0·01 in), has little or no effect on the value of C.O.D. obtained, provided the effect of shear lips can be eliminated.

By comparing photographs of the same specimen before impact (in place on the anvils of the Charpy machine) and at an instant during deformation, the deflection of the specimen can be measured at that time. On the basis of a suggestion by Wells [7] that a critical C.O.D. value may be related to specimen deflection, Ford *et al.* [4] calculated crack opening from deflection estimates using the formula:

$$\Delta = 0{\cdot}4 d\delta / L$$

where $\Delta$ = C.O.D., $\delta$ = specimen deflection at the onset of fracture, $d$ = ligament length and $L$ = half span of the specimen supports. A comparison of the calculated C.O.D. and the corresponding direct measurements, taken from specimens during testing (Fig. 6), indicates that the formula is valid for C.O.D. ≤ 0·020 in. This corresponds with the maximum value of C.O.D. observed for side notched specimens.

Ford *et al.* [4] found that the C.O.D. values from static tests were consistently higher than those from impact tests. The present results are in general agreement with these findings, with the exception of the values for cleavage initiated fracture which is independent of testing method (strain rate).

**Conclusions**

(1) Crack opening displacement values consistent with the initiation of a flat crack can be obtained in Charpy specimens by the use of side notches.
(2) Comparison of side notched fatigue-cracked and side notched Charpy V-notched specimens indicated that the C.O.D. value is independent of notch acuity (for $\rho = 0{\cdot}010$ in).
(3) The shape of the crack front that developed in the plain and in the side notched specimens was independent of strain rate and notch acuity.
(4) The assumption of the Wells formula relating C.O.D. to specimen deflection is valid up to C.O.D. values of about 0·020 in for the Charpy impact test.

**Acknowledgments**

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**References**

1. WELLS, A. A. *Brit. Welding J.*, vol. 10, p. 563, 1963.
2. BURDEKIN, F. M. and STONE, D. E. W. *J. Strain Anal.*, vol. 2, p. 145, 1966.
3. WELLS, A. A. *Brit. Welding J.*, vol. 12, p. 2, 1965.
4. FORD, G., RADON, J. C. and TURNER, C. E. *J. Iron and Steel Inst.*, vol. 205, p. 854, 1967.
5. ELLIOTT, and MAY, M. J., B.I.S.R.A., Report MG/C/51/58.
6. WRAITH, A. E. *J. Sci. Instrum.*, vol 44, p. 873, 1967.
7. WELLS, A. A. Symp. on Crack Propagation, Paper No. B4, Cranfield, 1961.

*Table 1*
*Values of critical C.O.D. for mild steel*

| *Test Temperature* ℃ | *Test method* | *Crack opening displacement (inches ×10³)* | | | |
|---|---|---|---|---|---|
| | | *Plain* | | *Side-notched* | |
| | | *V-notch* | *Fatigue-cracked* | *V-notch* | *Fatigue-cracked* |
| + 100 | Impact | 67·9 | 54·9 | 20-23 | 21·4 |
| + 20 | | 53·8-61·3 | | 15·0 | |
| − 40 | | 5·0 | 4·5-5·3 | 5·3 | 4·6-5·1 |
| − 70 | | 5·1 | | 5·1 | |
| + 20 | Slow bend | 73-81 | 45-52 | 36-43 | 36·6 |
| − 40 | | 54-60 | | 38-44 | |
| − 70 | | 45 | | 27 | |
| − 100 | | 4·0 | 4·5 | 4·5 | 4·7 |





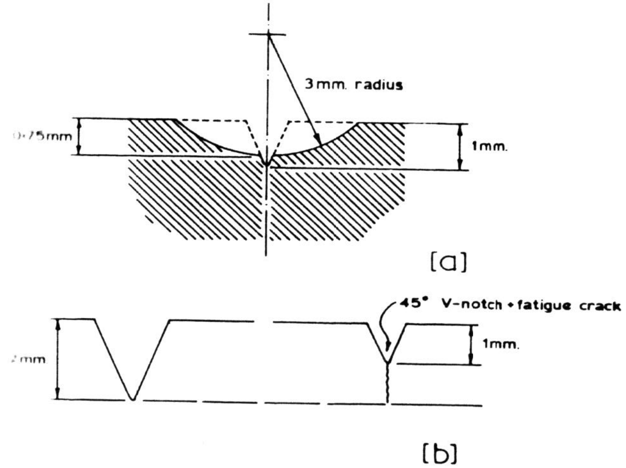


Fig. 1. (a) Side notch profile (b) Charpy V-notch and fatigue crack details.

(a) (b) (c) (d)

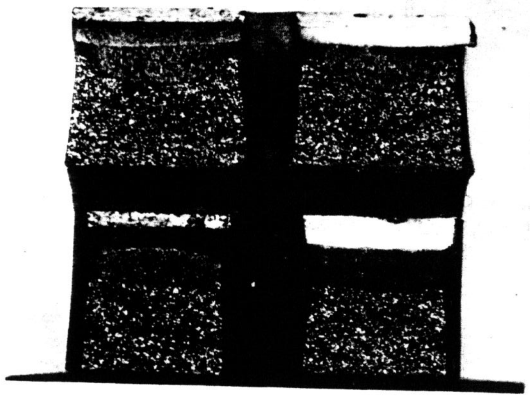

Fig. 2. Crack front shapes in plain Charpy specimens with (a) fatigue crack and (b) Charpy V-notch; and side notched specimens with (c) fatigue crack and (d) Charpy V-notch.

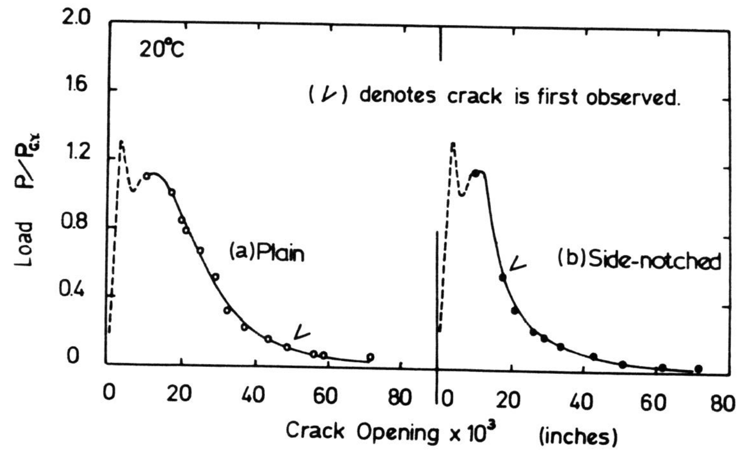


Fig. 3. Crack opening displacement versus ratio of load to general yield load, measured in impact on (a) plain (b) side notched specimens at + 20°C.

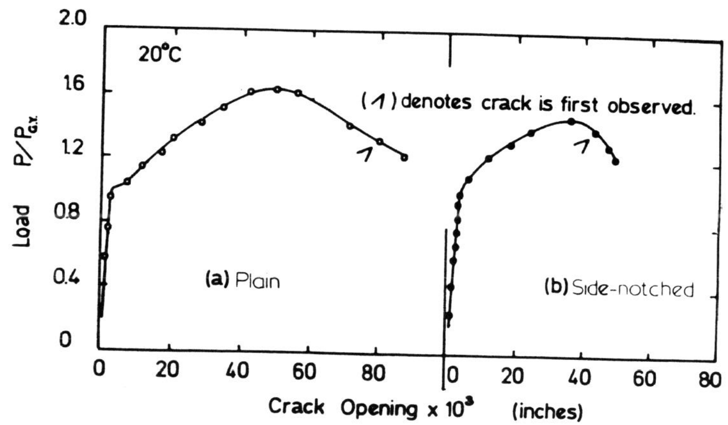


Fig. 4. Crack opening displacement versus ratio of load to general yield load, measured in slow bend on (a) plain (b) side notched specimens at + 20 C.





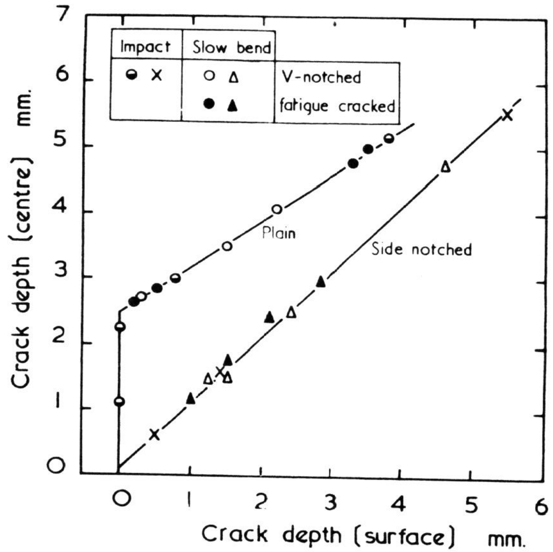


Fig. 5. Relative positions of crack at centre and at surface in plain and side notched, Charpy V-notch and fatigue cracked specimens in impact and slow bend.

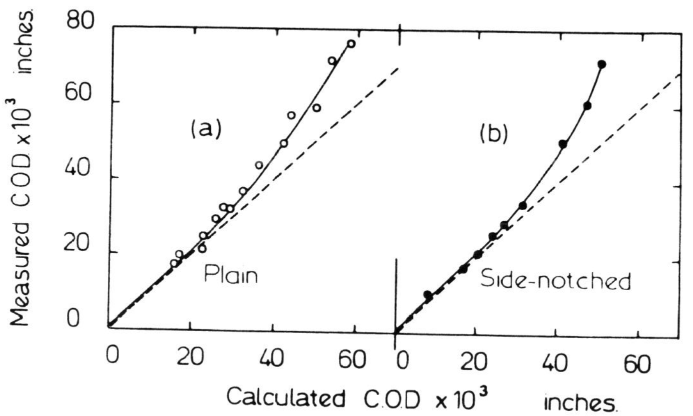


Fig. 6. A comparison of measured and calculated C.O.D. values in (a) plain and (b) side notched specimens in impact at + 20 C.