EFFECT OF CRACK DEPTH ON FRACTURE MECHANICS PROPERTIES ESTIMATED FROM INSTRUMENTED PRECRACKED CHARPY-TYPE TESTS

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In dynamic testing of small specimens, using initial crack lengths of less than the common 0.5W offers several experimental advantages. The effect of the crack length on the fracture behaviour of pre-cracked Charpy specimens was investigated theoretically and experimantally: Two possible constraint parameters, T and m, the slope of the linear relation between J and CTOD, are studied theoretically, and the dynamic J-R-curves and δ-R-curves are determined experimentally by the low-blow-technique for different crack-lengths in the range of $0.3<a_0/W<0.55$, with and without side-grooves. The results show no clear trend towards lower J with increasing a_0. The behaviour of the specimens with shorter pre-cracks and side-grooves is about the same as with longer cracks without side-grooves. The effect rather is within the scatter band of the tests. These results indicate that m is at least as important as T as a constraint parameter. It seems that a_0/W can be reduced to 0.3 without much loss of conservativity.

INTRODUCTION

J-R-curves are known to depend on the degree of constraints in the vicinity of the crack tip. If the latter are not sufficient then the J-R-curve is rising too steep after crack initiation, leading to non-conservative fracture toughness values such as $J_{0.2/Bl}$ that are derived therefrom. It is well known that the initial crack length ratio a_0/W (Fig. 1) is one of the main parameters that affects the constraints. For this reason, the current standards for J-R-curve or J_{Ic} determination (e.g. [1]) require initial crack lengths of minimum 0.45 W in the case of CT or bend specimens. At present time, lacking standards for dynamic fracture toughness testing, the ones of quasistatic testing are usually adapted, including the requirements concerning a_0/W. However, when using small or miniature specimens such as pre-cracked Charpy specimens these relatively deep pre-cracks might not be the optimum choice, since there are special experimental and physical aspects to be taken into account. These kinds of tests are not expected to give standard fracture toughness values. Instead, features like repeatability, unambiguity, simplicity and optimum use of the often limited test material are often more important. As discussed in the next section, these aspects make shorter initial cracks appear to be preferable. Therefore, in the guidelines for performing

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instrumented Charpy-type tests within the Swiss irradiation surveillance program [2, 3], using $a_0/W=0.3$ is recommended. In the present paper the effect of such relatively small a_0/W-ratios on the fracture behaviour of precracked Charpy specimen in dynamic bending is investigated. For this purpose the dynamic J-R-curve and δ-R-curve for specimens with different crack lengths are compared with each other. Furthermore, the question of constraints is considered from a theoretical point of view.

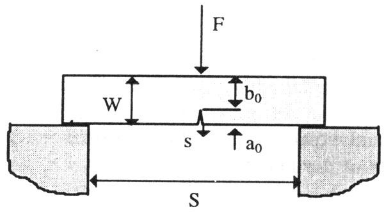


Fig. 1: Mechanical system of Charpy-type tests on pre-cracked specimens

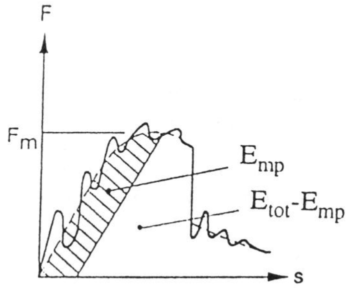


Fig. 2: Schematic force-displacement diagram

ADVANTAGES OF USING SHORTER PRE-CRACKS

Dynamic testing of small specimens exhibits some special difficulties concerning the evaluation of fracture toughness. Usually the only measurement is the force displacement diagram (Fig. 2), whereas crack extension can not be measured. The latter has to be calculated from the F(s)- diagram to determine the J-R-curve or fracture toughness in terms of $J_{0.2/BI}$ [4-6], so it is important that this curve, which is disturbed by dynamic oscillations as schematically shown in Fig. 2, can be evaluated with reasonable accuracy. Furthermore, due to the small specimen size, the range of validity of the J-R-curve is rather small, which makes the evaluation of transferable J values questionable. Reducing the initial crack length from the "standard" $a_0/W=0.5$ to about 0.3 as recommended in [1, 3] reveals the following beneficial effects:

- The force is signal is higher (proportional to b_0^2), thus less affected by the oscillations.
- Energy quantities like total fracture energy E_{tot} and the energy at maximum load, E_{mp}, which play a key role in the evaluation according to [5, 6], are higher (proportional to b_0^2.) thus obtainable with a higher accuracy.
- The range of "validity" of the J-R-curve, which according to the current fracture mechanics standards is limited to $J<(\sigma_f b_0)/25$ and $\Delta a<b_0/10$ is extended [6].
- The elastic component of J is higher (proportional to b_0), and the plastic rotation angle of the ligament bending is smaller (proportional to b_0^{-1}), which is beneficial in various respects.
- The shape of the ligament, which in the case of bending is known to affect the constraints significantly, is closer to the square of standard CT-specimens.

For these reasons, from a practical point of view, using initial cracks as short as possible would be desirable in dynamic testing of small specimens.

THEORETICAL CONSIDERATIONS

To characterise the triaxiality of the stress in the vicinity of the crack tip the elastic T-stress [7] is a suitable parameter, since it can be calculated by a linear-elastic FE-model. Nevertheless it is known to be meaningful even in cases of full plastic yielding of the ligament. The constraints are considered to be sufficient if $T>0$, whereas for negative values of T they decrease with decreasing constraints [7, 8]. In the case of an edge crack in a beam under three-point bending T changes from negative to positive at about $a/W=0.4$ and reaches its saturation value of

$$T = \frac{0.85 \cdot M}{B \cdot (W - a_0)^2} = 0.21 \cdot c \cdot \sigma_f \qquad (1)$$

at $a_0/W \cong 0.5$ [9]. In (1) M denotes the bending moment, σ_f the flow stress, B the specimen thickness and c the factor that appears in the equilibrium equation

$$M = \frac{F \cdot S}{4} = \frac{c \cdot \sigma_f \cdot B \cdot b_o^2}{4} \qquad (2).$$

which ranges between 1 (for plane stress) and about 1.4 (for plane stress; see below). Thus, regarding T, the common requirement $a_0/W>0.45$ is justified. However, in the case of fully plastic yielding like in a ductile fracture of a small specimen, the constraints are not likely to be entirely determined by T. There are further parameters that are related to constraints, one of them being the factor m in the relation

$$J = m \cdot \sigma_f \cdot \delta \qquad (3)$$

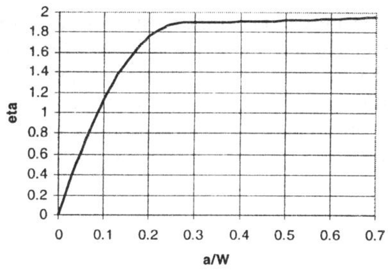
where δ is the crack tip opening displacement. m depends on the local yield conditions, thus reflects the constraints [10]. By combining some basic equations of fracture mechanics of an edge-cracked beam in bending one finds m to be

$$m \cong 0.568 \cdot c \cdot \eta \qquad (4)$$

where η is the well-known factor that relates J to the absorbed plastic energy, E_p, by

$$J = \frac{\eta \cdot E_p}{B \cdot b_0} \qquad (5)$$

η as a function of crack length is shown in Fig. 3, and $c \cong 1$ for shallow cracks or deep cracks in plane stress, and $c \cong 1.4$ for deep cracks in plane strain. In the context of plastic bending, plane strain requires $b_0/B<1$, $J<(\sigma_f\ b_0)/25$, and a crack can be considered to be "deep" if η does not significantly deviate from its "deep-crack value" $\eta=2$ [11] According to Fig. 3 this is the case for $a_0/W>0.25$. Evidently this criterion for "saturation" of m is much less restrictive than the one concerning T. Which one is physically more relevant is investigated experimentally in the next section by comparing dynamic J-R-curves of different a_0/W ratios.



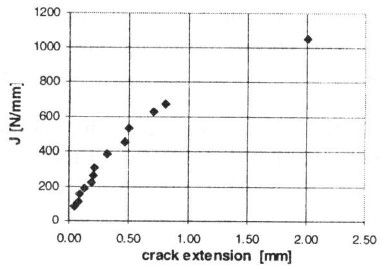


Fig. 3: *η as a function of crack depth (from [8])*

Fig. 4: *Example of a dynamic J-R-curve obtained by low-blow technique ($a_0/W=0.4$)*

EXPERIMENTAL RESULTS

To obtain a J-R-curve for dynamic loading the low blow technique is suitable. This tests can be performed on a standard Charpy pendulum hammer, if it allows to vary the initial potential energy E_0. Its idea is to provide the specimen with only a small amount of impact energy E_0, such that the crack extends only a short distance Δa. The corresponding J-value is readily obtained by using $E_p=E_0$ in (5). Choosing different values of E_0 results in different Δa, so from a number of equal specimens a curve $J(\Delta a)$ can be drawn which represents the dynamic J-R-curve.

In the present investigation a structural steel Fe520 (R_p=340MPa, R_m=540MPa, σ_f=440 MPa) was chosen as a representative test material. Five series of about 12 standard Charpy specimens each (W=B=10mm) were provided with fatigue cracks of different initial crack lengths a_0 (2.8, 3.2, 4.0 and 5.5 mm), two of them additionally with 20%-side-grooves. Fig. 4 shows an example of the J-R-curve obtained for $a_0/W=0.4$. Besides, the crack tip opening displacement δ was measured by linear extrapolation of the relative displacement of the crack faces to the initial crack tip, which results in an independent determination of the δ-R-curve (Fig. 5). By combining the J-R-curve and the δ-R-curve, the relation $J(\delta)$ as theoretically given by (3) is obtained (Fig. 6). From this example one can see that $J(\delta)$ in fact is rather linear, the slope of the curve representing the value $m\cdot\sigma_f$ as defined in (3). The results of all tests are shown in Fig. 7. To make the picture clearer, the data points beyond crack initiation (assumed to be those of Δa>0.25mm) were fitted to curves of the form

$$J = C \cdot \Delta a^{p} \tag{6}$$

a_0/W	side-grooves	$m\cdot\sigma_f$ [N/mm^2]	C	p	s_1 [N/mm^2]
0.28	yes	1245	697	0.44	1553
0.32	no	1067	787	0.59	1229
0.40	no	987	845	0.58	1356
0.40	yes	1099	771	0.62	1354
0.55	no	1038	667	0.60	1133

Table 1: *Experimental results (see eqs. (3), (6), (7) for definition of the given parameters)*

(Fig. 8, Table 1). From the slope of the regression line of the J-Δa-data in the range J<250N/mm the values of $m\cdot\sigma_f$ are determined (Table 1) Furthermore, the slope of the blunting line, which is commonly represented in the form

$$J=s_l\ \Delta a = d\cdot\sigma_f\cdot\Delta a, \qquad (7)$$

was evaluated as the regression line of the J-Δa-data points in the range J<250 N/mm. The obtained slopes s_l are shown in Table 1.

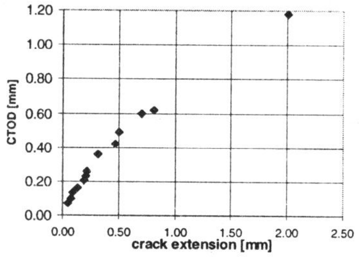


Fig. 5: Example of a measured δ-R-curve (a_0/W=0.4)

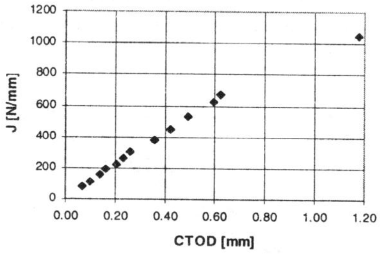


Fig. 6: Example of the experimentally determined relation J(δ) (for a_0/W=0.4)

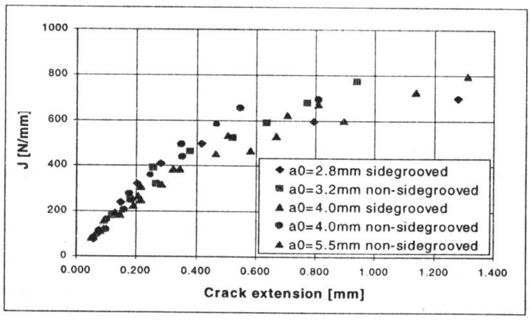


Fig. 7: Low-Blow data obtained from tests with different initial crack lengths.

DISCUSSION AND CONCLUSIONS

According to the results summarised in Table 1 there is no evidence for a dependence of m from a_0/W (but a minor increase due to side-grooves), indicating that m is at its saturation level for the considered a_0/W-ratios as predicted theoretically. In the J-R-curves (given by C and p) there seems to be some minor effect of a_0/W, but a clear trend can hardly be identified, since the effect of side-grooves and scatter seems to be of about the same magnitude as the one of the crack length in the considered range of a_0/W. At least the dependence of the J-R-curves is not as significant as expected from the variation of the T-in this range of crack lengths, indicating that additional parameters like m or the shape of the ligament are as important as the T-stress to characterise constraints. Thus, it seems that the range of allowed a_0/W can be extended down to about a_0/W=0.3, provided b_0/B is less than 1 (as fulfilled for Charpy specimens anyway). Thus, in dynamic testing of small specimens the advantages of using relatively short pre-cracks are likely to exceed the disadvantages. For compensation the use of side-grooves is recommended.

The factor most affected by crack length is s_1 or d, which is decreasing with increasing a_0. Based on the static flow stress, which is about σ_f=440MPa, the factor d ranges from 3.52 for a_0/W=0.28 to 2.58 for a_0/W=0.55. It has been noticed in [12] that on small specimens determination of near-initiation J-values by the experimental 0.2mm offset blunting line like $J_{0.2/Bl}$ tends to result in too high J-values. Oviously this problem is more pronounced in the case of deeper cracks. More conservative near-initiation toughness like J_0, $J_{0.2}$ or $J_{0.2t}$ as defined in [12] are preferable.

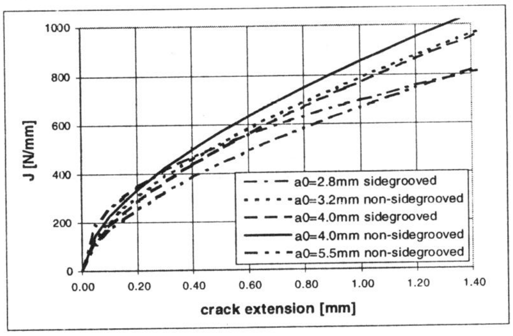


Fig. 8: J-R-curves obtained by fitting the data of Fig. 7 for Δa>0.25mm to a power-law $J=C\cdot\Delta a^p$ (see table 1 for the corresponding parameters)

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