ESTIMATION OF THE DYNAMIC J-R-CURVE FROM A SINGLE IMPACT BENDING TEST

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A method is presented that enables a dynamic J-R-curve to be determined from the load vs. displacement diagram of a single specimen, e.g. from an instrumented Charpy-type test. The method is based on a theoretical analysis of the fracture process in bending by means of a two-parameter (CTOD and CTOA) model of crack initiation and growth, which results in a simple algebraic evaluation formula. The only required experimental input data are the energy consumed up to maximum load and the total fracture energy, both being well defined and easy to obtain. This makes the evaluation reproducible and unambiguous. The resulting J-R-curves are in good agreement with the ones obtained by multi-specimen techniques. Once knowing the J-R-curve, fracture toughness parameters can be readily obtained.

INTRODUCTION

Determining fracture toughness or the J-R-curve of elastic-plastic materials like structural steels under a high loading rate ("dynamic J-R-curve") is a rather difficult task. The main problem is to measure and record the crack extension during the rapid fracture process. In general, the only possibility is to use multi-specimen techniques like low-blow tests (test with limited initial impact energy) or tests interrupted by means of a stop block. However, for practical puposes, multi-specimen techniques are often not appropriate, e.g. because of shortage of testing material, limited time or a too small testing budget. In these cases, an evaluation method is required which is able to deliver approximate but reproducible toughness values even from a single test specimen. In the following, a method is presented that serves for this purpose. Based on a simple analytical model, it enables the crack extension and, therewith, the dynamic J-R-curve to be calculated from a continuous load-displacement-diagram, which is obtained from instrumented testing of precracked Charpy specimens or similar impact bending tests.

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DERIVATION OF THE EVALUATION FORMULA

The J-R-curve of an elastic-plastic three-point bend specimen is given by the equation (see [1]):

$$J(\Delta a) = \frac{K_I^2(F, a_0 + \Delta a)}{E}(1-\nu^2) + \frac{\eta \cdot E_p(\Delta a)}{B \cdot (b_0 - \Delta a)} \tag{1}$$

where denotes the eta-factor (η=2 for relatively deeply cracked bend specimens), E_p the dissipated (non-recoverable) part of the absorbed energy (which is a function of the crack extension Δa), B and b_0 the thickness and width of the ligament, respectively (Fig 1). For the sake of simplicity, we neglect in the following the first part of (1), which represents the elastic component of J, because - when dealing with J-R-curves of elastic plastic material - it is usually small compared to the plastic component of J. The general form of the J-R-curve is shown in Fig. 2: Within the so-called J-controlled region (region I), which is limited by about $0<\Delta a< b_0/10$, it is common to approximate it by the potential function

$$J(\Delta a) = C \cdot \Delta a^p \qquad \text{for } \Delta a < b_0/10 \tag{2}$$

with C and p introduced as material-dependent constants [2]. Furthermore, in this region, J is uniquely connected to the crack tip opening displacement δ by

$$J = \sigma_{fd} \cdot m \cdot \delta(\Delta a) \tag{3}$$

where σ_{fd} is the local dynamic flow stress and m a factor of about 1. The boundary between region I and II at $\Delta a = \Delta a_B$ is arbitrary, as long as Δa_B is of the order of magnitude of $b_0/10$. A suitable choice is $\Delta a_B = \Delta a_m$, the latter being the crack extension at maximum load F_m (Fig. 3). As shown below (see eq. (18)), Δa_m fulfils in general the requirement $\Delta a_m < b_0/10$. Therewith, the J-R-curve in the region II becomes (see (1)):

$$J(\Delta a) = \frac{\eta \cdot E_{mp}}{B \cdot b_0} + \frac{\eta \cdot E_{tmp}(\Delta a)}{B \cdot (b_0 - \Delta a)} \qquad \text{for } \Delta a > \Delta a_m \tag{4}$$

where E_{mp} and E_{tmp} denote the energy consumed up to the point of maximum force and in the subsequent tearing phase, respectively. According to basic principles of mechanics, the latter is determined by

$$E_{tmp}(\Delta a) = \int_{\theta(\Delta a_m)}^{\theta(\Delta a)} M(\Delta a) \cdot d\theta = \int_{b_0 - \Delta a_m}^{b_0 - \Delta a} M(b) \cdot d\theta(b) \;, \tag{5}$$

$b = b_0 - \Delta a$ denoting the actual ligament width. In the tearing phase after maximum load (range II according to Fig. 2), a plastic hinge is formed in the ligament, thus

$$M(b) = \frac{c}{4}\sigma_{fd} \cdot B \cdot b^2 \;, \tag{6}$$

where c represents a non-dimensional factor that takes the value 1 for plane stress and about 1.45 for plane strain. Stable tearing crack growth is governed by the crack tip opening angle CTOA, which is defined as

$$CTOA = \frac{d\delta}{da} \tag{7}$$

and which is assumed to be approximately constant for tearing crack growth with $\Delta a > \Delta a_m$ [3, 4]. For crack extension in bending (Fig. 4) this leads for kinematical reasons to

$$d\theta(b) = -\frac{CTOA}{z \cdot b} db \tag{8}$$

where $z \cdot b$ denotes the location of the center of rotation. Inserting (8) and (6) into (5) gives

$$E_{tmp} = \frac{B \cdot c}{8z} CTOA \cdot \sigma_{fd} \cdot [\, 2b_0 \cdot (\Delta a - \Delta a_m) - (\Delta a - \Delta a_m)^2 \,] \tag{9}$$

By inserting (9) in (4), then taking the derivative with respect to Δa and comparing the resulting expression at $\Delta a = \Delta a_m$, with the derivative of (3), which is

$$\frac{dJ}{da} = \frac{dJ}{d\Delta a} = \frac{\eta \cdot c}{4z} CTOA \cdot \sigma_{fd} = \frac{d\delta}{da} \cdot m \cdot \sigma_{fd} \quad , \tag{10}$$

one obtains, by using (7),

$$z = \frac{\eta \cdot c}{4m} \tag{11}$$

The same expression was found in [5] for stationary cracks, which indicates that z is likely to remain about constant for the subsequent crack growth process.

Inserting (11) and (9) in (5) leads to

$$E_{tmp} = \frac{m}{4} CTOA \cdot \sigma_{fd} \cdot [\, b_0 \cdot (\Delta a - \Delta a_m) - (\Delta a - \Delta a_m)^2 \,] \tag{12}$$

The unknown CTOA is determined from the total energy E_{tot} consumed during the fracture (Fig. 3). The corresponding equation

$$E_p(\Delta a = b_0) = E_{mp} + E_{tmp}(\Delta a = b_0) = E_{tot} \tag{13}$$

delivers

$$CTOA = \frac{2\eta \cdot (E_{tot} - E_{mp})}{B \cdot m \cdot \sigma_{fd} \cdot (b_0 - \Delta a_m)^2} \tag{14}$$

According to (2), (4), (12) and (14), the J-R-curve can be described by

$$J(\Delta a) = C \cdot \Delta a^{p} \qquad \text{for } \Delta a \leq \Delta a_m \qquad (15a)$$

$$J(\Delta a) = J_{mp} + s_2 \left[(\Delta a - \Delta a_m) - \frac{(\Delta a - \Delta a_m)^2}{2b_0} \right] \qquad \text{for } \Delta a > \Delta a_m \qquad (15b)$$

where

$$J_{mp} = \frac{\eta \cdot E_{mp}}{B \cdot b_0} \qquad s_2 = \frac{2 \cdot \eta \cdot (E_{tot} - E_{mp})}{B \cdot (b_0 - \Delta a_m)^2}$$

The three unknowns in eq. (15), Δa_m, C and p, are determined by the following matching conditions of eqs. (15a) and (15b) at $\Delta a = \Delta a_m$:

$$J^{I}(\Delta a_m) = J^{I}(\Delta a_m) = J_{mp} \qquad (16a)$$

$$\frac{dJ^{I}}{d\Delta a}(\Delta a_m) = \frac{dJ^{II}}{d\Delta a}(\Delta a_m) = s_2 \qquad (16b)$$

$$\frac{d^2 J^{I}}{d\Delta a^2}(\Delta a_m) = \frac{d^2 J^{II}}{d\Delta a^2}(\Delta a_m) = -\frac{s_2}{b_0} \qquad (16c)$$

Herein, the superscripts I and II indicate correspondence to range I (i.e. eq. (15a)) and II (15b), respectively (see Fig. 2). One obtains therefrom

$$C = \left(\frac{2}{p}\right)^{p} \cdot \frac{\eta(a_0)}{B_N (W - a_0)^{1+p}} \cdot E_{tot}^{\ p} \cdot E_{mp}^{\ 1-p} \qquad (17)$$

$$\Delta a_m = \frac{E_{mp} \cdot p \cdot b_0}{2E_{tot}} \qquad (18)$$

$$p = \left(1 + \frac{E_{mp}}{2 \cdot E_{tot}}\right)^{-1} \qquad (19)$$

Eq. (15) with (17 - 19) determine the desired J-R-curve. Note that only E_{mp} and E_{tot} are needed as experimental input data, which both can be obtained from the load-displacement diagram very easily and unambiguously. Concerning the exponent p, it is recommended to use the semi-empirical modification (20) instead of (19), as discussed in the next chapter.

DISCUSSION

Modification of the exponent p. The above formulas to determine the J-R-curve contain no free parameter. If adjustments to empirical J-R-curves should be made, they should be made on p rather than on any other of the calculated parameters, because the former (eq. (19)) follows just from (16c), which is physically a weaker condition than (16a) and (16b). Actually, p as given in (19) is usually somewhat too large, leading to too low J-R-curves (see examples in Fig. 5 and 6, dashed lines). In order to find an improved value for p, it is suggested to perform, as a second test, a low blow test with an impact energy of E_{mp}, which is known from the first (full blow) test. From the optically measured crack extension in comparison with the theoretical value given by (18) the empirical value of p can be determined. However, in most cases the following semi-empirical modification of (19),

$$p = \frac{3}{4} \cdot \left(1 + \frac{E_{mp}}{E_{tot}} \right)^{-1} \quad , \qquad (20)$$

which is based on a number of experiments, is sufficiently accurate and recommended to be used instead of (19). The effect of this modification in comparison with experimental multi specimen data is shown by two examples in Fig. 5 and 6, where the dashed line corresponds to (19) and the full lines to (20).

Determination of fracture toughness. A near-initiation J-Integral, $J_{d0.2/Bl}$, can be determined analogously to the static $J_{0.2/Bl}$ as defined in [2] by the intersection of the J-R-curve as given above with the 0.2 mm offset blunting line. For dynamic testing, the blunting line can be conservatively approximated by the straight line

$$J = s_1 \cdot \Delta a \cong 3.0 \cdot \sigma_{fd} \cdot \Delta a \cong 3 \cdot \frac{F_m \cdot S}{b_0^2 \cdot B} \cdot \Delta a \qquad (21)$$

[4]. To account for the elastic component of $J_{d0.2/Bl}$, which is neglected in the above formulas, either the K_I - term as given in (1) and calculated for the maximum load $F=F_m$ should be added, or, as a simpler and conservative possibility, E_{mp} can be replaced by E_m in (17) and (18), the latter denoting the full strain energy of the specimen at maximum load (plastic plus elastic strain energy).

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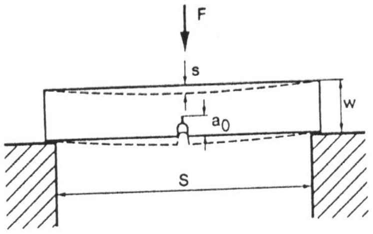

Fig. 1: Mechanical system of the impact bending test

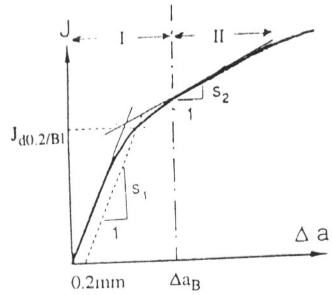

Fig. 2: Schematic representation of a J-R-curve

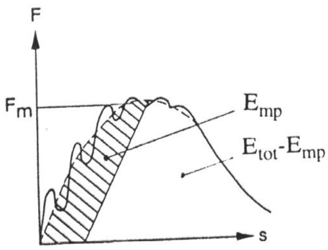

Fig. 3: Force vs. displacement diagram

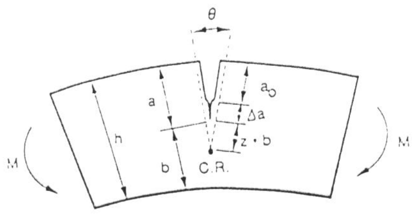

Fig. 4: Definition of local parameters at the Fracturing section

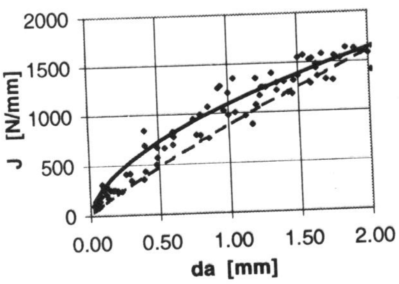

Fig. 5: Calculated J-R-curve of a pressure vessel steel, compared with the experimental cleavage data from [6].

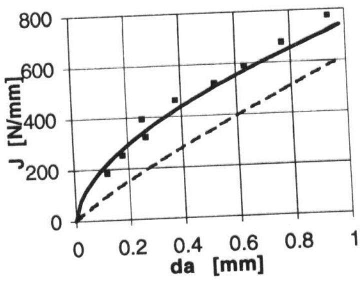

Fig. 6: Calculated J-R-curve of a structural steel Fe520, compared with low-blow data (a_0=3.2 mm)