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Application of Single-Specimen Methods on Instrumented Charpy Tests: Results of DVM Round-Robin Exercises

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Abstract: Based on a previous round-robin exercise of the German DVM task group on “Instrumented Impact Testing” with about 400 instrumented Charpy-specimens being tested, another exercise was performed to explore the possibilities of extended evaluations such as single-specimen methods. The previously determined multi-specimen cleavage J_R -curve serves as a reference. Different methods - e.g., the key-curve method - were applied. Overall, the results are encouraging and the agreement of the calculated J_R -curve with reference data is quite good especially for large amounts of crack extension. There was some uncertainty left in the first part of the J_R -curve, where notch blunting and initiation of crack growth take place, and where the calculated curves tend to overestimate the crack resistance. Results of a new “blind” round-robin indicate improved results in this initial part of the J_R -curve.

Keywords: Charpy test, impact, instrumented impact testing, fracture toughness, crack resistance curve, single-specimen method, key-curve method, dynamic material behavior

Introduction

For existing structures in operation there often is not enough material available to quantify the actual quality of materials. Then testing procedures with small specimens and preferable single-specimen procedures are recommended. The accuracy of single-specimen methods has been investigated by the DVM task group on “Instrumented Impact Testing.” These investigations are based on results of a previous round-robin exercise

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with about 400 instrumented Charpy tests, where three different types of notches – standard V-notch, fatigue-crack and spark-eroded slot – were considered. The effect of the notch geometry and the accuracy of instrumented Charpy tests were the major points of interest of this exercise. The results are reported in [1].

As a side-product, a multi-specimen J_R -curve could be determined by the evaluation of experiments in the transition region as described below. This led to the idea to extend the round-robin to explore the possibilities of single-specimen methods to evaluate J_R -curves when applied to instrumented Charpy tests. Six of the original seventeen participants took part in this task. The participants were free to use an evaluation method of their choice. Two used a key-curve method, one an analytical method based on a two-parameter fracture model to evaluate the measured force-displacement curves, and two applied semi-empirical correlation functions to estimate the J_R -curve just from the Charpy energy. In addition, low-blow tests using specimens with deeper fatigue cracks were performed. The results were encouraging, however, a reduced accuracy at small crack extensions was observed (see [2, 3]).

Actually, the applied single-specimen methods were developed and mainly used for the evaluation of standard precracked test specimens, not for Charpy specimens. Though rather successfully applied to the Charpy specimens as mentioned above, this round-robin exercise was not able to qualify or disqualify the different methods. In order to further explore the potential of single-specimen methods, another “blind” round-robin was initiated within the DVM group in 1998. Some preliminary results are given in this report. They indicate that the accuracy at small crack extensions can be improved.

Multi-Specimen J_R -Data as Reference Data

During the DVM round-robin [1], the accuracy of instrumented Charpy tests and the influence of the notch shape was investigated. Three different notch shapes were considered: V-notches, crack-like spark eroded slots (notch root radius: 0.02 mm), and fatigued cracks, all of a depth of 2 mm.

From all the experiments in the brittle-to-ductile transition regime a so-called “cleavage R-curve” was evaluated. Therefore, the partial energy W_{iu} was determined by integrating the force-displacement curve up to the sudden drop of the force signal, which indicates the end of ductile crack extension by initiation of cleavage fracture. Then a corresponding J-integral value was calculated by applying the equation:

$$J_u \approx \zeta \frac{W_{iu}}{B(W - a_o)} \quad (1)$$

with B being the thickness, W the width and a_o the notch- or crack-depth, respectively, thus for the Charpy specimens $B = W = 10$ mm and $a_o = 2$ mm. The factor ζ was chosen to be 1.46 for $a_o/W = 0.2$ according to [4].

In addition, the ductile crack extension up to the onset of cleavage fracture, $\tilde{A}a$, has to be measured on the fracture surface. These data as obtained from a series of experiments in the transition range are forming a dynamic multi-specimen crack-resistance curve, $J_R = J_u(\tilde{A}a)$, as described in more detail in [1, 2]. Because of the evaluation of experiments in

the transition temperature range, this method can be called a ductile-brittle-transition(DBT)-method with a resulting “cleavage R-curve.”

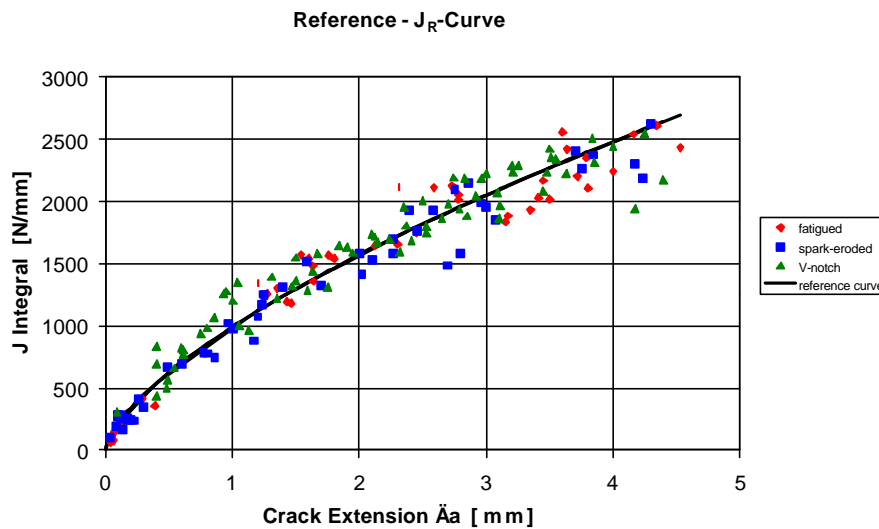


Figure 1 – “Cleavage R-Curve” data of the previous DVM round-robin [1] and exponential fit as reference curve

For all tests in the brittle-to-ductile transition regime, the evaluated J_u -data at the onset of cleavage fracture follow a unique crack resistance curve $J_R = J_u(\Delta a)$ as documented by Fig. 1. Within the observed bandwidth of scatter, the obtained multi-specimen J_R -curve is practically independent of the different notch shapes. Despite usual size requirements not being satisfied, this cleavage J_R -curve can be used for an improved comparative characterization of ferritic steels as discussed in [1]. An exponential curve $J = C \Delta a^p$ fitted through the cleavage data points (see Fig. 1) serves as a reference for comparison with results of single-specimen methods.

Single-Specimen Methods

Key-Curve Method

A well-known single-specimen method is the so-called key-curve method according to Ernst et al. [5, 6]. It is based on the fact, that the shape of the force-displacement curve is directly related to the crack length, i.e., to the ductile crack extension. Therefore, the evaluation of force-displacement curves, $F(s)$, allows calculations of the crack extension and finally the crack resistance in terms of a J_R -curve

$$J(\Delta a(s)) = \frac{h(a_0)}{B \cdot b} \cdot \int_0^s F(s) \cdot ds, \quad (2)$$

where Δa is obtained by integrating the following equation:

$$\frac{da}{ds_{pl}} = \frac{b}{2} \cdot \left(\frac{1}{N \cdot s_{pl}} - \frac{dF/F}{ds_{pl}} \right) \quad (3)$$

with b : ligament width
 N : hardening exponent of the Ramberg-Osgood-material law
 s_{pl} : plastic component of displacement s
 $\frac{dF/F}{ds_{pl}}$: normalized slope of the load-displacement curve

Dahl et al. [7, 8] further developed this procedure and applied it to instrumented Charpy tests. They used spline functions to smooth the force-displacement curves. Finally the resulting J_R -data were fitted by exponential functions.

Ott and Böhme [9] proposed to fit the force-displacement signals at first by polynomial functions of the fourth or fifth order, which consequently enables the derivation of analytical solutions.

Three-Parameter Analysis

Schindler [10] derived a single-specimen evaluation method based on a three-parameter characterization of the J_R -curve (C , p , crack tip opening angle) that just requires the totally absorbed energy W_t and the plastic energy at the maximum of the force displacement curve as experimental input data. In the upper shelf the latter can be approximated by the energy at maximum load, W_m . Precise definitions of W_t and W_m can be found in the draft standard ISO/DIS 14553. Therewith the J_R -curve estimation is given by:

$$J(\Delta a) = \left(\frac{2}{p} \right)^p \cdot \frac{h(a_0)}{B (W - a_0)^{1+p}} \cdot W_t^p \cdot W_m^{1-p} \cdot \Delta a^p \quad \text{for } \Delta a \leq \Delta a_m \quad (4a)$$

$$J(\Delta a) = J(\Delta a_m) + \frac{2 \cdot h \cdot (W_t - W_m)}{B \cdot (b_0 - \Delta a_m)^2} \cdot \left[(\Delta a - \Delta a_m) - \frac{(\Delta a - \Delta a_m)^2}{2b_0} \right] \quad \text{for } \Delta a > \Delta a_m \quad (4b)$$

$$\text{with} \quad \Delta a_m = \frac{W_m \cdot p \cdot b_0}{2W_t} ; \quad p = \frac{3}{4} \cdot \left(1 + \frac{W_m}{W_t} \right)^{-1} ; \quad b_0 = W - a_0 \quad (4c)$$

These three approaches have been applied by the corresponding participants and the

results are given in Fig. 2 in comparison with the reference curve. In addition, the results of the low-blow tests performed by Blumenauer et al. [11] are given. Considering the scatter of the data, the agreement of the different approaches with the experimental results is reasonable. This accuracy is often sufficient for engineering purposes. However, for small crack extensions these methods so far may not be accurate enough for the determination of initiation values.

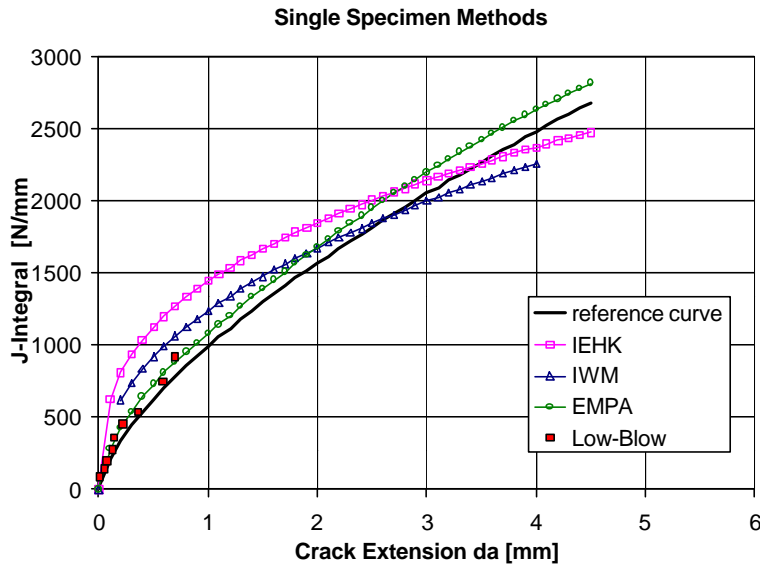


Figure 2 - Results of single-specimen key-curve evaluations and low-blow tests in comparison to the reference curve

Estimation of the J_R -curve from the Charpy Upper Shelf Energy, USE

Several empirical and semi-empirical correlations are available to estimate the fracture toughness from the Charpy upper shelf energy, USE, but only few of them enable the complete J_R -curve to be estimated. Two of these approaches were applied during this exercise.

At the BAM/Berlin [12] a semi-empirical formula was developed to estimate the J_R -curve from the upper shelf energy, USE, of a series of standardized Charpy tests. This procedure was applied by Wobst and his colleagues to one of their round-robin experiments:

$$J(\Delta a) = [J_{ISO-V}]_{\Delta a=0} + \frac{1.03 \cdot (0.4 \cdot USE - C_1^*)}{B \sqrt{a_0(W - a_0)}} \cdot \ln \frac{\sqrt{(W - a_0) + \sqrt{a_0}}}{\sqrt{(W - a_0) - \sqrt{a_0}}} \quad (5)$$

with: $C_1^* = 5 \text{ Joule}$; $[J_{ISO-V}]_{\Delta a=0} = 91 \text{ N/mm}$.

Another estimation formula for the same purpose was obtained by Schindler [13, 14] from the analytical approach described previously (see eqs. (4)) by using the condition that at maximum force $dF/da = 0$. This lead to the relation $W_m = n \cdot W_t$, with n being the hard-

ening exponent in the material law $\sigma = A\epsilon^p$. The exponent can be approximated by the uniform fracture strain determined on a uniaxial tensile test, A_g . Based on experimental results, the exponent p according to (4c) is simplified to be $p = 2/3$, independent of the relation W_m/W_t . With these modifications and assumptions the equations (4a) to (4c) result in:

$$J(\Delta a) = \frac{3}{B(W - a_0)^{5/3}} \cdot USE \cdot A_g^{1/3} \cdot \Delta a^{2/3} \quad \text{for } \Delta a \leq \Delta a_m \quad (6a)$$

$$J(\Delta a) = J(\Delta a_m) + \frac{2.92 \cdot (1 - A_g) \cdot USE}{B \cdot b_0^2} \cdot \left[(\Delta a - \Delta a_m) - \frac{(\Delta a - \Delta a_m)^2}{2b_0} \right] \quad \text{for } \Delta a > \Delta a_m \quad (6b)$$

with $\Delta a_m = \frac{A_g \cdot b_0}{3}$; $b_0 = W - a_0 = 8 \text{ mm}$

The results are presented in Fig. 3 in comparison to the reference curve. Again the overall agreement of the results of both approaches to the experimental multi-specimen data is reasonably good, and might be sufficient for engineering purposes.

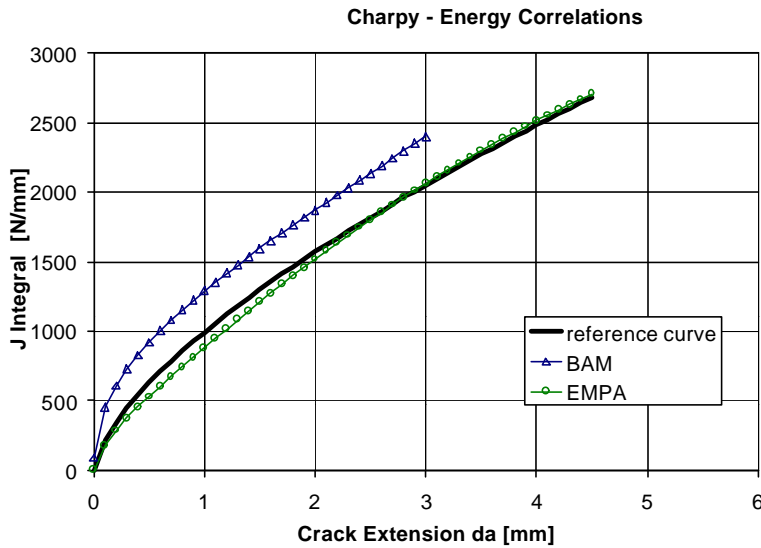


Figure 3 - Results of semi-empirical calculations based on the USE in comparison to the reference curve

Preliminary Results of a Current “Blind” Round-Robin

Though the results are encouraging, the previous comparisons are not appropriate to qualify the corresponding methods, since most of them were developed to evaluate fracture toughness tests rather than Charpy tests, where the size requirements were in general heav-

ily violated and the initial notch sharpness is not sufficient. In order to further evaluate the capability of the applied single-specimen methods, an additional round-robin exercise was performed within the DVM group. The aim was to predict the J_R -curve from just one pre-cracked specimen. It was one essential idea of this exercise that no participant should know the material under investigation and especially the J_R -curves should be unknown. Two materials – a pressure vessel steel of the type A 533 B and a structural steel Fe 510 – were elected as test materials. Pre-cracked Charpy specimens were prepared – the A 533 B ones with side-grooves – and distributed by EMPA to six participants, one specimen for one material each. In addition, ten specimens of each material were sent to Otto v. Guericke University, Magdeburg, where the dynamic J_R -data were determined independently by the low-blow technique by Blumenauer and coworkers [15]. The materials were not specified at that time and EMPA provided just the technical data for yield strength, UTS-point and uniform fracture strain as given in Table 1.

Table 1 - Tensile properties of the test materials

Steel	R_p [N/mm ²]	R_m [N/mm ²]	A_g [%]
A 533 B	470	640	10.6
Fe 510 C	325	540	15.9

Since the evaluation of this round-robin is not yet finished we only show here the results of the authors in comparison with the low-blow data as provided by Blumenauer (Figs. 4 and 5). The curve “IWM” was obtained by the corresponding key-curve procedure as outlined previously (see [9]), the curve “EMPA” was calculated by eqs. (4a) and (4b). Additionally, the blunting line according to the draft standard ISO/DIS 12135 is shown. It is in good agreement with the first few low-blow points and with the initial part of the IWM curve. These results indicate that the corresponding evaluation methods are capable of giving good J_R -approximations even if there is literally just one specimen available. The full evaluation report of this single-specimen round-robin exercise will be published later.

Discussion

Several single-specimen evaluation procedures are described and have been applied during different round-robin exercises of the German DVM task group on “Instrumented Impact Testing.” At first, Charpy-V tests with a relative notch/crack-depth of $a_o/W = 0.2$ were analyzed. The results of the different evaluation procedures were in surprisingly good agreement with a cleavage R-Curve and data of low-blow tests with pre-cracked

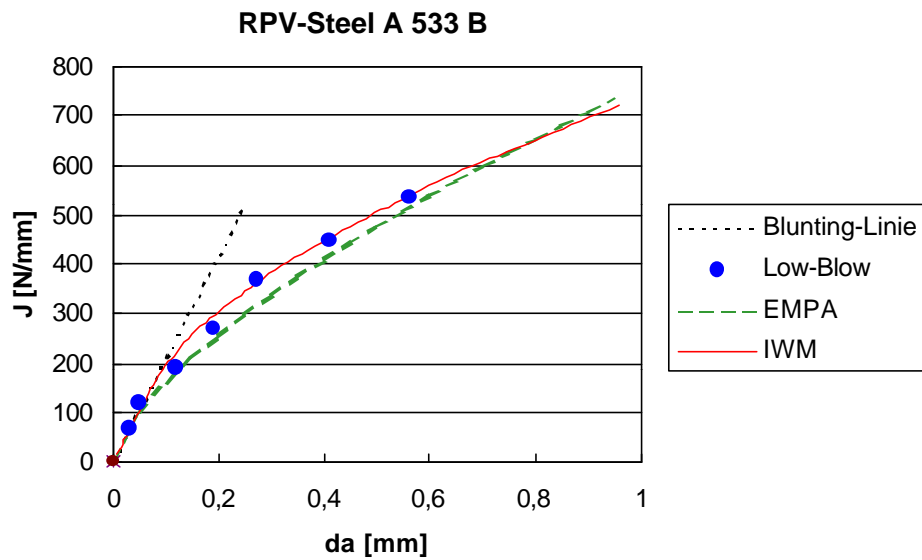


Figure 4 - Results of low-blow tests and key-curve evaluations of impacted precracked and sidegrooved Charpy specimens

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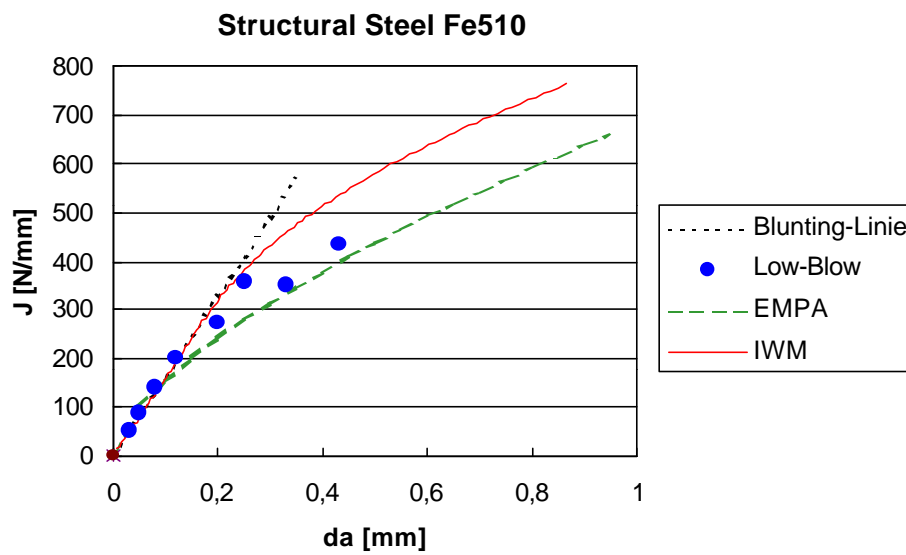


Figure 5 - Results of low-blow tests and key-curve evaluations of impacted precracked Charpy specimens

Charpy specimens ($a_0/W = 0.5$). However, the observed behavior is probably very special for materials with a similar high ductility and toughness, where minimum size requirements of common standards can not be satisfied by Charpy-sized specimens. Furthermore, some input parameters like the strain hardening exponent were chosen by individual best estimate. Thus, the comparisons reported in the first part of the present paper are not well suited to qualify or disqualify any of the applied methods. Finally, at small crack extensions the accuracy of the results was not sufficient to determine reliable crack initiation values.

Therefore, another round-robin concentrated on precracked Charpy specimens with a relative crack length $a_0/W = 0.5$ and preliminary results of IWM and EMPA are reported. For the non-sidegrooved FE 510 specimens there are still some differences, which might be due to a loss of constraint and 3D-effects as documented e.g. by crack front curvature. However, for sidegrooved A 533 B specimens both evaluations agree very well and are confirmed by the results of the low-blow tests (Fig. 4). These results demonstrate the applicability of single-specimen methods and an improved accuracy at small crack extensions.

Conclusion

The single-specimen methods under investigation appeared to be useful tools to estimate the dynamic crack resistance curve from a single instrumented Charpy test. The transferability of the results to real structures has to be handled with care because of the limited size of the specimen. However, single-specimen evaluation methods enable an improved comparison and selection of materials and can be used even if only a limited amount of material is available.

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