Scaling of Charpy Fracture Energy with Specimen Size

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ABSTRACT: The fracture energy of edge-cracked beams under bending is strongly dependent on the specimen size. Therefore the Charpy fracture energy can only be measured on standardized specimen. In this paper a relation between the fracture energy and specimen size is derived analytically, which can be used to scale-up the fracture energy of sub-sized tests. Unlike the common empirical relations, the presented scaling law is applicable to any elastic-plastic material. The results are compared with experimental data obtained from different specimen sizes.

INTRODUCTION

Mainly because of its simplicity, the standard Charpy test is still very popular to characterize toughness, despite of its well known theoretical weaknesses. The measured quantity, the fracture energy KV, is known to be strongly dependent on specimen geometry, size, notch sharpness and loading rate, so the fracture energy of the standard specimen has neither a direct relation to the fracture energy of a structural part nor to fracture toughness in terms of K_{Ic} or J_{Ic}. If there is not enough testing material available for standard specimens to be manufactured, sub-sized specimens have to be used instead of standard ones. A typical miniature specimen is the KLST-specimen according to the German standard DIN 50 115, which has the size 4x3x22 mm, or the „half-Charpy specimen", which is essentially a standard specimen geometrically scaled by a factor of 2. In order to interpret and classify the obtained experimental data, there is a need to compare the measured fracture energy with the standard Charpy fracture energy. The relation of the fracture energy of sub-sized specimens to the one of standard specimens is rather complex, including a significant material-dependent temperature shift due to the reduced constraints, and a strongly non-linear size-dependence of the fracture energy energy, particularly in the upper shelf region. There are several empirical or semi-empirical correlation formulas for this purpose [1–3]. However, the relation appears to be not unique, but size- and also material-dependent.

In the present paper an analytical relation between the fracture energy of different in a predominantly ductile tearing mode and specimen sizes is derived, which can serve as a scaling law of upper-shelf Charpy-type fracture energy. It is experimentally confirmed for various materials.

ESTIMATION OF J-R CURVE FROM A BENDING TEST

As shown by one of the authors in [4-6] the J-R-curve can be estimated from the continuous force-displacement-diagram of a single, uninterrupted, static or dynamic bending test (Fig. 1 and 2) by

$$J(\Delta a) = C \cdot \Delta a^p \qquad \text{for } \Delta a < (W-a_0)/10 \qquad (1)$$

where

$$C = \left(\frac{2}{p}\right)^p \cdot \frac{\eta(a_0)}{B\,(W-a_0)^{1+p}} \cdot W_t^{\ p} \cdot W_{mp}^{\ 1-p} \qquad (2)$$

$$p = \left(1 + \frac{W_{mp}}{2W_t}\right)^{-1} \qquad (3)$$

W_{mp} and W_t are the dissipated energy at maximum force and the total fracture energy, respectively, that can be obtained from the load-displacement diagram (Fig. 2). The factor η is the well known η-parameter for the edge-cracked 3-point bending specimen, which is according to [8]

$$\eta = 13.81 \cdot \frac{a}{W} - 25.12 \cdot \left(\frac{a}{W}\right)^2 \qquad \textit{für } 0<a/W<0.275 \qquad (4a)$$

$$\eta = 1.859 + 0.03/(1-a/W) \qquad \textit{für } a>0.275W \qquad (4b)$$

The crack extension at maximum force F_m was obtained to be

$$\Delta a_m = \frac{W_{mp} \cdot p \cdot b_0}{2W_t} \qquad (5a)$$

According to eqs. (1-3) the J-R curve and $J_{0.2Bl}$ (Fig. 2b) is determined by only two experimental parameters, W_{mp} and W_t, which are well defined in the force-displacement diagram even if it is disturbed by of by dynamic oscillations, as long as the behaviour is essentially quasistatic. Therefore this evaluation procedure is well-suited to be applied to testing at increased loading rates like Charpy tests in the upper shelf.

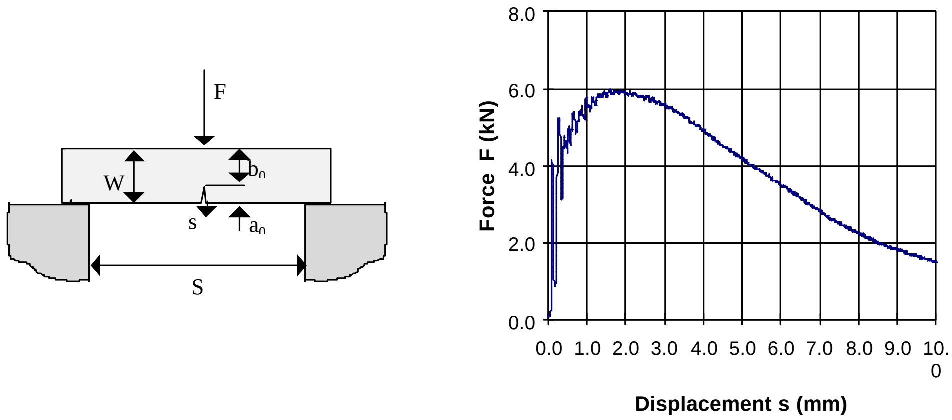
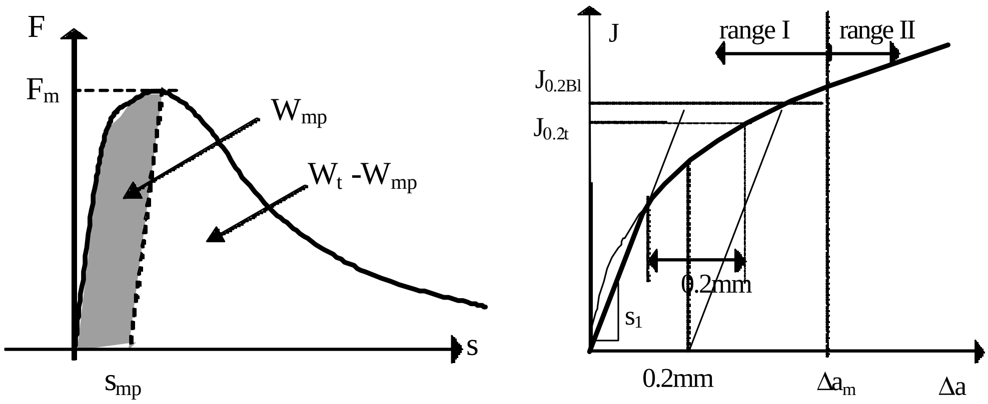


Figure 1 - *Mechanical system (left) and the corresponding force-displacement diagram (right) of a bending test with an edge-cracked specimen in the upper-shelf range.*



(a) (b)

Figure. 2 –*Quasistatic force-deflection diagram (a) and calculated J-R-curve (b) of an instrumented Charpy test (schematic)*

J-R-CURVE FROM NON-INSTRUMENTED TEST

In the case of a non-instrumented impact test like the classical Charpy test, the only available experimental value is the total fracture energy W_t. As shown in [7, 9, 10], by using an additional mathematical condition concerning the crack extension at maximum force, Δa_m was found to be

$$\Delta a_m = \frac{A_g \cdot p \cdot b_0}{2} \tag{5b}$$

where A_g denotes the uniform fracture strain. By comparison with (5a), W_{mp} can be eliminated from (2) and (3), resulting in the following expressions

$$C = \left(\frac{2}{p}\right)^p \cdot \frac{\eta(a_0)}{B \cdot (W - a_0)^{1+p}} \cdot W_t \cdot A_g^{\,1-p} \tag{6}$$

$$p = \left(1 + \frac{A_g}{2}\right)^{-1} \tag{7}$$

Eq. (1), (6) and (7) enable the J-R curve to be determined just from the total fracture energy and the uniform fracture strain. By inserting the corresponding parameters of the standard Charpy tests, i.e. W_t = KV, B = W = 10 mm, a_0 = 2 mm and, according to eq. 4, η = 1.76, the J-R-curve is obtained from a single Charpy test in the upper shelf or upper transition range. The effect of the finite notch root radius is discussed in [9], and the corresponding correction is used in section later on.

SCALING LAW FOR FRACTURE ENERGY

Although the J(Δa)-curve determined by eqs. (1), (6) and (7) is just an extrapolation of the ductile tearing phase into the blunting regime, and not necessarily equivalent to the actual near-initiation J-R-curve of the material (see discussion in next section), it is expected to be size-independent in the range of J-controlled crack-tip-loading, i.e. $\Delta a < W/10$. Hence, from two specimens with different sets of geometrical parameters (W, B, a_0 corresponding to one of the specimen, W', B', a_0' to the other), the same value of the factor C as given in eq. (6) should result. From this condition, one obtains from (6) the following relation:

$$\frac{\eta(a_0/W)}{B\cdot(W-a_0)^{1+p}}\cdot W_t=\frac{\eta(a_0'/W')}{B'\cdot(W'-a_0')^{1+p}}\cdot W_t' \tag{8}$$

Thus, from the fracture energy W_t measured on a specimen with the geometrical parameters W, B, and a_0, the fracture energy W_t' of a specimen of a different size and shape (W', B', a_0') can be calculated as

$$W_t'=\frac{\eta(a_0/W)\cdot B'\cdot(W'-a_0')^{1+p}}{\eta(a_0'/W')\cdot B\cdot(W-a_0)^{1+p}}\cdot W_t \tag{9}$$

The parameter p is given in (7). With some adequate simplification (9) applied to a standard Charpy specimen results in

$$KV'=\frac{5.68}{B}\cdot\eta(a_0/W)\cdot\left[\frac{8}{(W-a_0)}\right]^{2-A_g/2}\cdot W_t \tag{10}$$

In this equation, KV' denotes the upper shelf or upper transition Charpy energy estimated from a Charpy-type test using a sub-sized (or over-sized, respectively) specimen with the dimensions B, W and a_0, which have to be inserted in millimeters. Some experimental validation of (10) is given in section 6. In a similar way, using the corresponding relation given in the previous section, scaling laws for further parameters of instrumented bending tests like W_m or W_t were obtained [6].

EXPERIMENTAL VALIDATION

To verify the formulas derived above the fracture energy measured on sub-sized specimens is scaled-up to standard sized specimens by means of (10) and compared with directly measured standard Charpy fracture energy for materials of different toughness. The materials and specimen sizes used for these comparisons are shown in Table 1 and 2.

The measured fracture energy W_t (mean values of 3 – 5 specimen each) are given in Table 3. Table 4 shows the W_t values given in Table 1 scaled up to the size of standard Charpy specimens obtained by using eq. (10). Compared with the directly measured Charpy fracture energy given in Table

3, the deviations given in percentages in Table 4 are obtained. Regarding the facts that these formulas are purely theoretically derived, without any adjustable factor, and that the (natural) scatter of the Charpy energy is usually as much as up to ±5%, the agreement between measured and scaled fracture energy is very satisfying.

TABLE 1: Geometry of the used specimens (see Fig. 1).

	B [mm]	W [mm]	b_0 [mm]	S [mm]	ç
standard Charpy	10	10	8	40	1.76
KLST	3	4	3	22	1.88
Half-size Charpy	5	5	4	22	1.76

TABLE 2: Material properties of the tested materials

	R_m [N/mm^2]	R_p [N/mm^2]	A_g [-]	Z [-]	E [N/mm2]
Steel A533 B	640	470	0.12	0.55	210000
Bronce GZ-CuSn12Ni	299	178	0.2[1)]	-	120000

1) Estimated from hardening exponent

TABLE 3: Experimental W_t-values measured on standard and sub-sized specimens

	standard Charpy	KLST	Half-size
Steel A355	215 J	8.42 J	29.4 J
Bronce GZ-CuSn12Ni	5.9 J	0.264 J	-

DISCUSSION AND CONCLUSIONS

A scaling law for the total fracture energy has been derived analytically based on simple mechanical models. Roughly, the resulting formula corresponds to the inuitive assumption made in [11] that the fracture energy is proportional to the „ligament volume” (W-a)B. However, according to (9) and (10), there are additional corrections for the notch-depth and the hardening behaviour of the material, which seem to be reasonable from a physical point of view.

The underlying mechanical model is based on the assumption that the involved fracture processes are predominately ductile tearing. Thus, the scaling law (9) or (10) hold only in the upper shelf regime. As discussed in [6, 9], it can be used as an approximation in the upper ductile-to-brittle transition range. However, one has to be aware, that there often is a significant temperature shift due to specimen size, which has to be accounted for. Some empirical data on this subject are given in [1, 2]. Furthermore, the J-R-curve and fracture toughness is in general rate dependent, so the loading rate in terms of dJ/dt or dK_I/dt should be also provided in the test report.

The obtained Charpy energy can be used to estimate the fracture toughness by using the semi-analytical relation given in [9, 10]. Estimation of the fracture toughness $J_{0.2Bl}$ or $J_{0.2t}$ directly from a test of a sub-sized specimen is not recommended, because the empirical modification of p used in [9, 10] depends on the constraints in the eraly tearing phase and corresponds to the standard Charpy specimen. It is expected to be somewhat different for other specimen sizes.

Of course, analytical relations represent approximations, because they are based on simplifying analytical models. Nevertheless, in combination with experimental data, they can be used to establish semi-empirical relations that are much more general and reliable than purely empirical relations.

TABLE 4: Fracture energy KV' estimated from W_t of sub-sized specimens by eq. (10)

	KLST		Half-size	
	W_t'	deviation	W_t'	deviation
Steel	203 J	-3.62%	223 J	+3.8%
Bronce	6.05 J	+2.6%	-	-

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