ON THE J_{Ic} CONCEPT FOR THE PREDICTION OF CRACK GROWTH INITIATION IN COMPLEX STRUCTURES

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INTRODUCTION

As a consequence of its crack tip characterizing nature, the J-integral introduced by Rice [1] has been proposed as a fracture parameter in the elastic-plastic regime [2]. Its use for fracture safety assessment is predicated on the assumption that a crack will start to extend under increasing load when some critical material value for J is reached. Experimental procedures for determination of this critical value, termed J_{Ic}, have been included in national standards by ASTM (USA) [3] and JSME (Japan) [4].

The key assumption underlying J-based fracture safety assessments is the conformity of J controlled crack initiation and growth behaviour for specimens and for actual structures, i.e. two-dimensionally curved cracks in three-dimensional stress fields. In contrast to the vast amount of literature dealing with the behaviour of test specimens, information about that of actual structures is scarce.
The present paper addresses two issues:

- the difference between specimen J_{Ic} values resulting from the different definitions prescribed by the ASTM and JSME procedures;
- comparison of the crack initiation and growth behaviour in small specimens with that in a (model) structure.

EXPERIMENTS

All specimens and model plates used in this study were cut from the same 55 mm thick plate of a mild steel, designation St 52-3 (DIN 17100/80), with yield strength 348 MPa and ultimate tensile strength 493 MPa. This material is equivalent to BS 4360 gr. D according to British Standards.

Specimen Tests

Multiple specimen J-Resistance tests according to the ASTM procedure [3] were performed on four series single edge notched bend (SENB)

specimens with dimensions (thickness B x width W) 25 x 50 and 40 x 80 mm, both with and without side grooves. The results are shown in Fig. 1. The scatter of the results is relatively small for small crack growth but increases with crack growth, as does the influence of side grooving. J_{Ic} values were determined as the intersection of the blunting line with slope $2\sigma_f$ (flow stress $\sigma_f = \frac{1}{2}(\sigma_Y + \sigma_u)$) and a linear R-curve resulting from a least squares regression through the data points between the 0.15 and 1.5 mm offset lines indicated in Fig. 1. The results of the 40 x 80 specimens are completely valid according to the requirements of [3], but the 25 x 50 specimens violate the size requirements for the points $J > 700$ kJ/m (non-side grooved) and $J > 590$ kJ/m (side grooved). Inspite of this, hardly no size effect can be observed in the resulting J_{Ic} values. The influence of side grooving on J_{Ic} is also minor, though it does affect the crack growth resistance (slope of the R-curve). Several data points in Fig. 1 fall below the ASTM J_{Ic}-values. All these specimens do, however, show some amount of fibrous crack growth. This indicates that the real initiation point is lower than the J_{Ic} points found, which is confirmed by potential drop measurements, i.e. the potential drop records show a change in slope within the range of J-values indicated in Fig. 1.

The results of a J_{Ic} determination according to the JSME critical stretched zone method [4] on a series of 25 x 50 mm non-sidegrooved specimens are summarized in Fig. 2.
The actual slope of the blunting line as determined from a linear regression though the three data points within the range $\frac{1}{2} J_{Ic} < J < J_{Ic}$ appears to be 3.16 σ_f, and hence is appreciably higher than the assumed $2\sigma_f$ in the ASTM procedure. The critical stretched zone width (SZW_c) is taken as the average value measured for five specimens loaded beyond initiation. The resulting J_{Ic}-value, i.e. J on the (experimental) blunting line at $\Delta a = SZW_c$, appears to be 148 kJ/m^2, which is considerably (up to a factor 2.5) lower than the values determined according to the ASTM procedure (cf. Fig. 1). This value is, however, in good agreement with the potential drop initiation predictions, also indicated in Fig. 2. The above findings fit the results reported by Yin et al. [5] on a material with identical specifications but of a smaller thickness of 30 mm.

Model Tests

Fatigue cracks in a structure are most likely to occur at or near welds and at high stress/strain concentrations. The idea of studying cracks in welds was rejected because of the large scatter in material properties, which can obscure the observations considerably. It was therefore decided to investigate a crack in base material at a highly stressed region, viz. a flat plate with a quarter elliptical crack emanating from a central hole (cf. Fig. 3).

The crack was generated from a machined notch by fatigue loading. Subsequently the model was loaded once - by displacement control - up to a load for which crack growth could be expected. After unloading the cracked region was cut from the model and put into an oven for some time to colour the ductile crack growth by heat tinting. Finally, it was cooled in liquid nitrogen and broken to enable observations of the crack surfaces. Stable crack growth was found to have occurred along almost the entire crack front. The actual crack growth measurements are shown in Fig. 5c, where the data points represent the mean value of three closely spaced measuring points.

COMPUTATIONS

A complete three-dimensional elastic-plastic finite element analysis of the model test described in the previous section was performed with the MARC system. For symmetry reasons only one half of the test plate was analyzed as shown in Fig. 4. Details of the analysis are identical to those of a similar analysis of an SENB specimen reported earlier [6]. The applied boundary conditions were derived from the end displacements measured during the test (cf. Fig. 3). The entire analysis up to the final experimental load required 14 inelastic (tangent stiffness) load increments.

Though originally J was only defined as a line integral in two-dimensional bodies [1], it can also be formulated as a surface integral for crack fronts in three-dimensional bodies. An earlier study showed that the most efficient way to calculate this integral is the virtual crack extension method, in combination with an assumed linear J-distribution per element edge along the crack front [7]. The J-distribution calculated by that procedure is shown in Fig. 5a for the final experimental load.

DISCUSSION

Direct comparison between the initiation behaviour of test specimens and the model structure is impossible, because the moment of crack growth initiation in the model could not be detected by the potential drop method. However, by combining the computed J-distribution along the crack front of the model (Fig. 5a) and the experimental crack growth data of the specimens (Fig. 5b) one can obtain a prediction of the crack growth distribution along the crack front. This prediction, taking into account the experimental scatter of the specimen data, is shown in Fig. 5c, together with the experimental values determined at the end of the model test. Almost all experimental points fall within the scatter of the predictions, except for some points near the model surface. This is not surprising as the stress state near the free surface will tend to a plane stress condition, while the specimens were tested in a condition tending to plane strain. By increasing the number of elements along the crack front, in particular near the free surfaces, one could obtain a better finite element approximation of the free surface effects. However, the maximum J-values occur at the interior part of the crack front, and hence the lower surface values are of no interest for the fracture safety assessment. As the remaining J-distribution ($0.25 < s/L < 0.66$, cf. Fig. 5a) is almost constant, no further refinement of the element division for the interior part of the crack front seems to be necessary. All experimental points in this region fall within the scatter of the predictions, implying that the predictions and experiments agree to within experimental scatter. However, because of the relatively large scatter of the specimen results at low crack growth values, also the scatter of the predictions is large (± 20%), and hence no definite conclusions can be drawn on the basis of these results only. This requires the observation of the results from another view point. Fig. 6 gives the computed J-values at the interior part of the crack front as a function of the applied displacement q (average of the displacement transducer readings in Fig. 3). At the final displacement q = 1.55 mm, J is almost a linear function of q, with a slope dJ/dq = 480 kJ/m^2/mm. With the scatter of the specimen data in terms of J equal to 54 kJ/m^2 (cf. Fig 5b), this implies that the range of the applied displacement for which the experimental points at the interior part of the crack front in Fig. 5c fall within the scatter of the prediction amounts $\Delta q = 54/480 = 0.113$ mm, i.e. only 7.3% of the final displacement q = 1.55 mm.

Together with the results of Fig. 5c this seems to justify the conclusion that the predicted crack growth of the model based on finite element computations and experimental specimen data agrees well with the measured crack growth at the end of the model test, and hence that there is indeed conformity of J controlled crack initiation and growth behaviour for cracks in small specimens and in complex stress fields. It should be emphesized that this refers to small amounts of crack growth, i.e. close to initiation, only. For larger amounts of crack growth there appears to be a structural dependence of J-controlled crack growth, in particular between structures loaded in bending and tension [8].

Predictions of the initiation load of a structure will, of course, strongly depend upon the definition of the J_{Ic}-value. As stated before, the potential drop data point towards the lower J_{Ic}-value predicted by the JSME procedure. Even if this tendency would be confirmed by further tests including other materials, this would not preclude the use of ASTM-based J_{Ic}-values for design purpose, as the slope of the R-curve at small crack growth is generally large, i.e. instability is unlikely to occur. However, the credibility of J_{Ic}-test procedures which allow for small amounts of crack growth at the J_{Ic}-point, like the ASTM procedure obviously does, would be served if this amount is fixed. Obviously, a more realistic approximation of the slope of the blunting line would be the first requisite.

CONCLUSIONS

- The critical J-value at the onset of crack growth is considerably overestimated by the ASTM-J_{Ic} procedure. More realistic predictions are obtained from results of the JSME-J_{Ic} procedure which is in good agreement with the potential drop method.
- The initiation and crack growth behaviour of a two-dimensional curved crack in a three-dimensional body in terms of local J-values is in good agreement with that of SENB test specimens.

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REFERENCES

[1] Rice, J.R., "A Path Independent Integral and the Approximate Analysis of Strain Concentrations by Notches and Cracks", Journal of Applied Mechanics 35 (1968), pp. 379/386.

[2] Begley, J.A., Landes, J.D., "The J-Integral as a Fracture Criterion", in: Fracture Toughness, ASTM-STP-514 (1972), pp. 1/20.

[3] ASTM, "Standard Test for J_{Ic}, A Measure of Fracture Toughness", Annual Book of ASTM Standards, E 813-81.

[4] JSME, "Standard Method of Test for Elastic-Plastic Fracture Toughness J_{Ic}", JSME S 001-1981.

[5] Yin, S.W., et al. "An Investigation of the Blunting Line", Engineering Fracture Mechanics (to appear).

[6] Bakker, A., "Elastic-Plastic Fracture Mechanics Analysis of an SENB Specimen", Int. Journal of Pressure Vessels and Piping, 10 (1982), pp. 431/449.

[7] Bakker, A., "On the Numerical Evaluation of J in Three Dimensions", Presented at the AFMMS Conference, Freiburg (FRG), June 1983.

[8] Begley, J.A., Landes, J.D., "Serendipity and the J-integral", Int. Journal of Fracture 12 (1976), pp. 764/766.

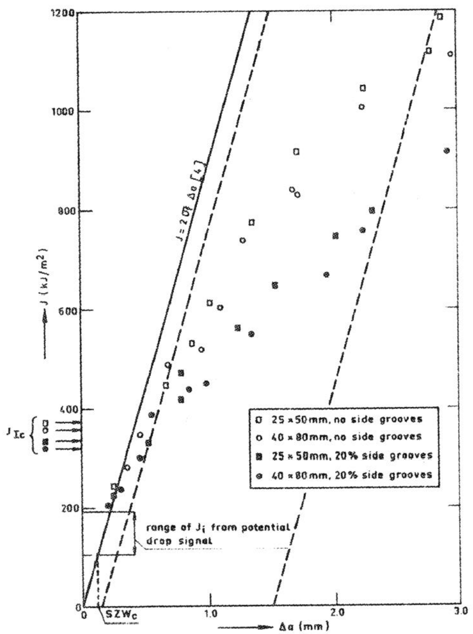

Fig. 1. J-Resistance data for ASTM J_{Ic}-procedure [3]

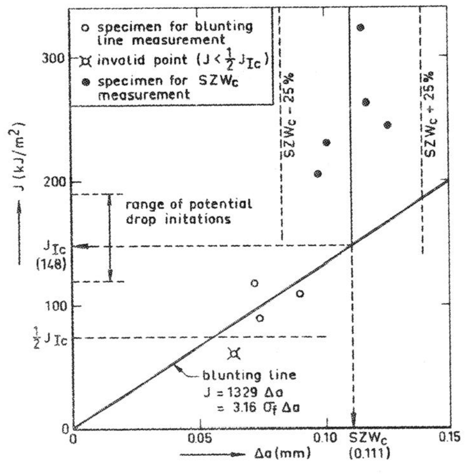

Fig. 2. JSME Critical Stretched Zone procedure [4]

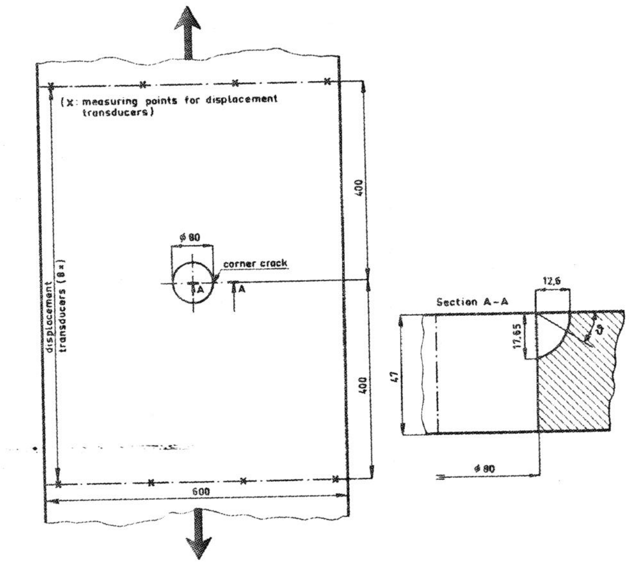

Fig. 3. Model Geometry

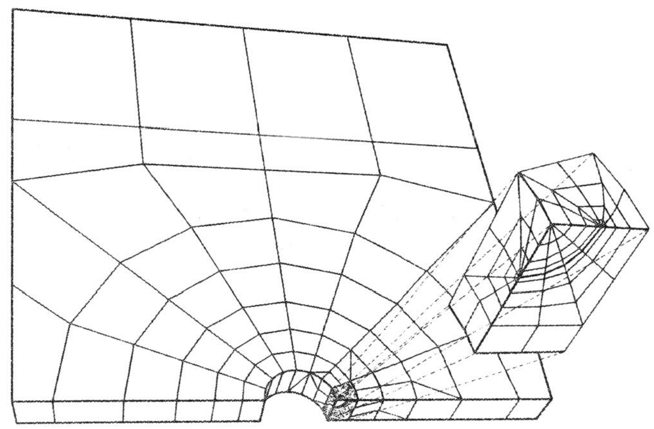

Fig. 4. Finite element mesh

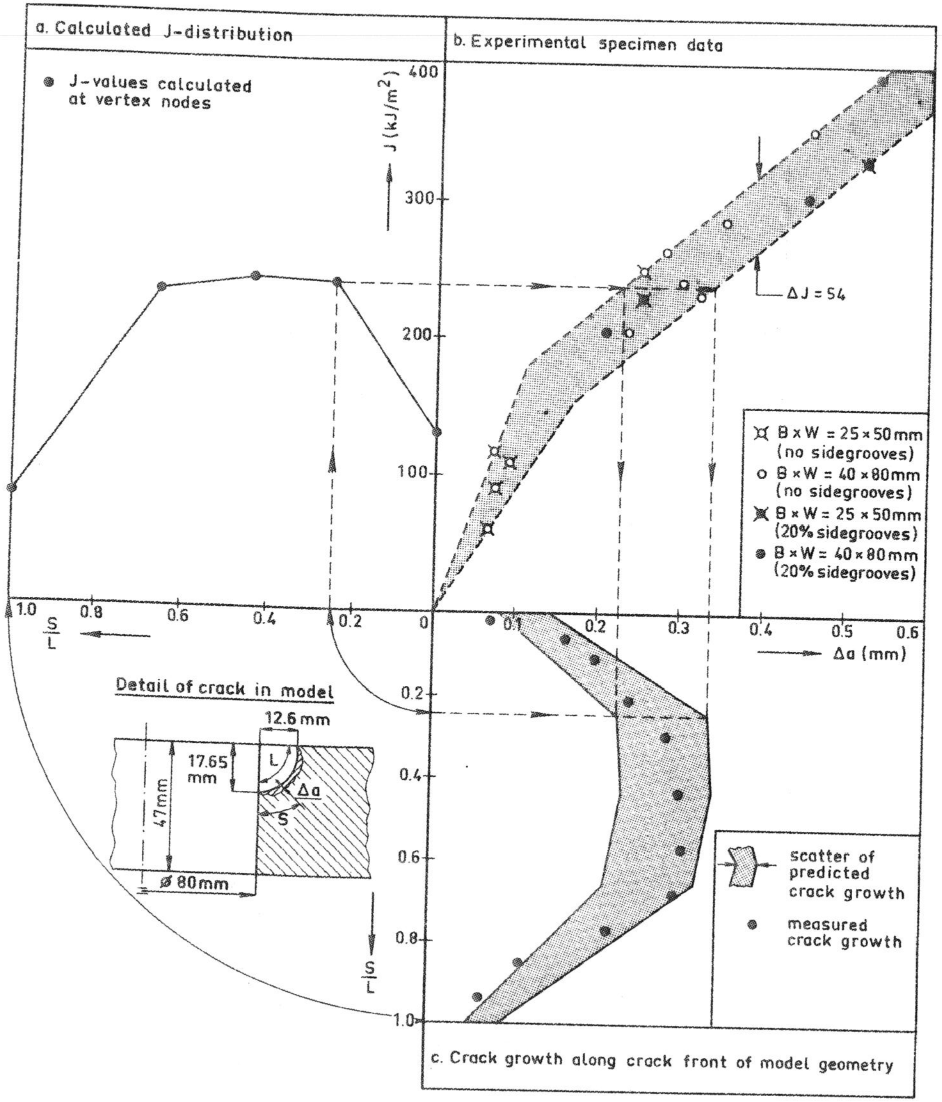

Fig. 5. Prediction procedure

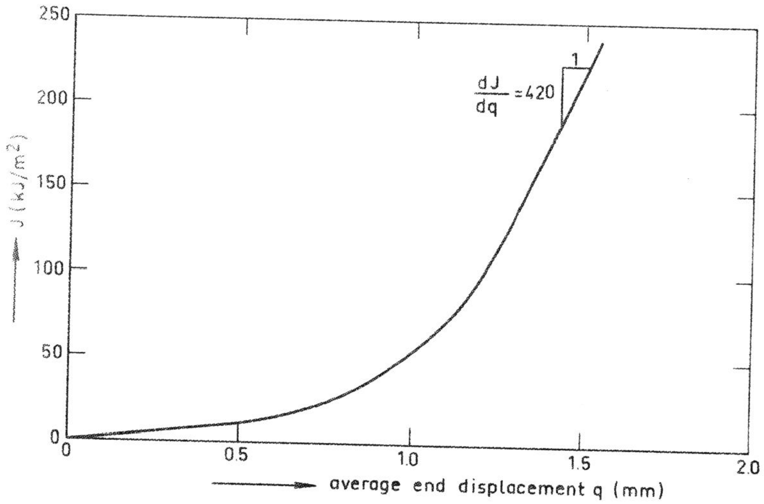

Fig. 6. Calculated J-value along central part of the model crack front as function of applied displacement