SIMPLIFIED FRACTURE TOUGHNESS MEASUREMENT BY DROP WEIGHT LOADING

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Fracture mechanics has so far failed to identify an attractive alternative to the Charpy for routine approval testing. This paper proposes testing an uninstrumented full thickness fracture mechanics specimen to a set displacement under drop weight loading. The test can be used as a very simple go/no go test for approval at a given J_c or δ_c level. More controversially, it can be interpreted in terms of energy dissipation rate, D. This latter quantity has been proposed many times as a fracture criterion, but is generally rejected because of its geometry dependence. It is argued here that the uncertainties inherent in the use of D are not serious enough to outweigh its advantages as a physically realistic and easily calculated measure of structural fracture safety.

INTRODUCTION

This paper describes a new test and analysis procedure developed by the author to give rapid, yet reliable, measurements of fracture toughness. The new procedure has been given the descriptive acronym SIFT (Simplified Fracture Toughness). The test uses a full product thickness, fracture mechanics, three point bend geometry, dynamically loaded to a prescribed deformation by drop weight loading. No instrumentation is used. The specimen is simply inspected to determine the extent of crack propagation that has occurred at the end of the test. The test can be conducted to obtain fracture toughness information at a single temperature (most appropriately the minimum service temperature), or conducted over a range of temperatures to determine the ductile to brittle transition temperature.

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TEST METHOD

Figure 1 shows the test assembly in schematic form. Tests to date have been performed with a 590 Kg mass dropped from a height of 1.68 metres. This gives a nominal input velocity of 5.74 m/s and an energy available for fracture of 9700 Joules. The falling mass provides a significant excess of energy over that needed to deform the specimen (less than 1000J for structural steels up to 50 mm thick). This ensures a constant rate of specimen displacement. The excess energy is absorbed by a damping system. A hydraulic circuit holds the anvil rigid while the specimen is deforming. When the falling tup hits the displacement stops, the pressure in the hydraulic circuit is released, allowing the anvil to come to rest on the test machine dampers.

Figure 2 shows a series of repeat tests on a normalised CMn steel conducted over a range of temperatures. All the samples have been subjected to the same nominal loading condition, which was achieved by stopping the tup after the specimen has reached a set displacement, which can, in turn, be translated to an imposed crack tip opening displacement, δ, or J integral. If cleavage fracture occurs, the specimen is free to deform ahead of the arrested tup and give an additional displacement. Figure 2 clearly shows the transition with temperature between structurally safe and unsafe behaviour at the imposed J and δ value. Further information on crack advance can be obtained by heat tinting and breaking open the specimens.

The chosen maximum J value can be varied by altering the displacement at which the tup is arrested. In practice, it is expected that only one value would be used for a given test series. The specimens in Figure 2 have been subjected to a nominal displacement of 2.85 mm which translates to a δ of 0.8 mm and a J value of 0.6 MN/m. If cleavage fracture occurs before these values this will be clear from the specimen behaviour and fracture surfaces. At its simplest level the test thus provides a go/ no go result on whether a minimum required J_c or δ_c has been met. If the specimen exhibits ductile tearing various simplified calculations can be performed to deduce the slope of the J or δ tearing resistance curve. An alternative, safety case for avoidance of ductile tearing instability can be based on Griffith theory and the concept of an energy dissipation rate for crack propagation.

CASE FOR THE USE OF ENERGY DISSIPATION RATE

The possibility of using energy dissipation rate, D, as a measure of fracture toughness has been suggested in many published papers. In recent years the major proponents of the method have been Turner and Kolednik (1). D is defined as the rate of increase in total energy dissipation , U_{diss}, with increasing crack , A:

$$D = \frac{dU_{diss}}{dA} \quad (1)$$

It is common to divide dU_{diss} between an area term, R, which accounts for the creation of the new crack surface including shear lips, and a volumetric term, S, which accounts for the spread of plastic work through the whole cracked structure:

$$dU_{diss} = RdA + S(bdA) \tag{2}$$

where ligament length, b, is introduced as a geometric scaling factor which reflects plastic zone size.

The major criticism levelled against the use of D as a toughness parameter is that it is highly geometry dependent. This has led many investigators to look for ways of separating remote and local plasticity in an attempt to recapture a material property. An example of this is the 'essential work of fracture' approach first proposed by Cotterel and Reddel (2). The alternative approach is to try to develop scaling laws which predict how D will vary with geometry. An example of this is the method of Priest and Holmes (3) developed for pipeline analysis.

A full understanding of scaling laws for D is some way off, but for present purposes the simple proposal will be made that the value of D measured in a deeply notched testpiece of full structural thickness is a safe lower bound for structural prediction. This statement is not uncontroversial, as it is often assumed that D will decrease under conditions of small scale yielding.

Consider the range of material behaviours which might be encountered in a deeply notched SIFT test as defined in Figure 3. All materials are proposed to initiate at similar values of J_i which are achieved close to plastic limit load. A material which initiates with $J_i = G_i$ and propagates with $D = J_i = G_i$ would be a Griffith material, and it is straightforward to calculate the relationship between crack extension and imposed displacement. Observation of a crack extension greater than this in the SIFT test implies a material with D less than the J_i. This is usually the case for cleavage fracture due to rate effects on toughness; but even cleavage fracture may have a D in excess of J_i if significant shear lips develop. If cleavage fracture is avoided, metals can show a spectrum of tearing behaviour, which can be broadly categorised by yield stress to Young's modulus ratio. High strength metal alloys ($\sigma_y/E > .0075$) approach Griffith behaviour; while for low strength structural alloys ($\sigma_y/E < .003$) D is commonly well in excess of J_i.

Two plausible explanations for the excess of D over J_i are shear lip development and the lower strain singularity at a propagating crack tip. If a material shows D well in excess of J_i for small scale testing, this effect will continue to be exhibited for a large crack in a predominately elastic structure. The area component R will increase because of the relaxation of the ligament towards plane stress. The volumetric component will increase because the larger structure can accommodate a larger plastic zone. A very large structure of a ductile material may be in LEFM globally because the plastic energy is small compared to the elastic energy, but this doesn't prevent the absolute value of D reaching its potential maximum by virtue of the large absolute size of the plastic zone and development of fully slant fracture on the plane stress ligament. The limiting case is that for a Griffith material where D is invariant with size. In every other case it is postulated that a small square ligament in bending will act to minimise D. Experimental evidence in support of increasing D with increasing ligament size is provided by Watson and Jolles (4).

DERIVATION OF TOUGHNESS PARAMETERS FROM THE SIFT TEST

Estimates of J and D may be made from the imposed final displacement using the formulae below:

$$J_f = G_f + \frac{(P_{Li} + P_{Lf})(q_f - q_{fe})}{B(W - a_i)} \tag{3}$$

$$D = \left[\frac{1}{B(a_f - a_i)}\right]\left[\left(\frac{P_{Li} + P_{Lf}}{2}\right)\right] q_f - \frac{P_{Lf}\, q_{fe}}{2} - \frac{J_i B(W-a)}{2} \tag{4}$$

$$\frac{dJ}{da} = \frac{J_f - J_i}{a_f - a_i} \tag{5}$$

where
- f refers to conditions at the end of the test after crack advance by tearing
- i refers to conditions at crack initiation
- q is total load point displacement
- q_e is the elastic component of load point displacement
- a, W, B specimen dimensions, normal nomenclature
- P_L plastic limit load.

The quantities G_f, P_L, and q_e are calculated from published analytical expressions. The initiation value of J, J_i, has to be guessed. An overestimate of J_i will lead to a conservative estimate of D and dJ/da.

APPLICATION OF THE SIFT TEST

The SIFT test has been applied in the author's laboratory to a range of structural steels, welds, and castings in the strength range 350 to 700 MPa. A major advantage of the test is that it gives a direct indication of fracture safety at minimum service temperature. Modern structural steels and welds invariably exhibit Charpy upper shelf behaviour at minimum service temperature, but this doesn't guarantee safety from cleavage in the presence of a fatigue crack. Charpy test specifications account for this with sub-ambient test temperatures such as -40°C, but notch acuity effects can still mean that the Charpy seriously underestimates the risk of cleavage fracture at minimum service temperature.

The most straightforward use of the SIFT test is as a go/no go test for cleavage at a given applied J at minimum service temperature. The analysis in this paper points out that a broader picture can be established in terms of energy dissipation rate, D. This can be used to highlight the hierarchy of fracture risk from both tearing and cleavage. A major advantage of the SIFT approach is that it circumvents troublesome arguments over the significance of short arrested cleavage cracks (pop-in) mixed with tearing in weld and HAZ fracture mechanics tests.

Consider a realistic crack driving force for a large structure. Take the pessimistic view that a very large (500 mm) through crack might escape detection. At an applied stress of 300 MPa the crack driving force G in a steel structure would be 340 kJ/m^2. This can be compared with the typical figures for energy dissipation rate, D, measured by SIFT testing in a range of structural steels and welds:

Upper shelf	5,000 to 10,000 kJ/m^2
Upper transition (pop-in)	1,000 to 1500 kJ/m^2
Mid transition	250 to 500 kJ/m^2
Lower shelf	<100 kJ/m^2

It can be seen that a very wide margin of safety exists at upper shelf conditions, and that pockets of cleavage mixed with tearing in the upper transition could also be justified. Use of D further down the ductile to brittle transition, and for materials with low tearing resistance, is possible, but requires more careful analysis. In all cases the advantages of D are the absence of restrictive test validity criteria, and the ability to compare all materials, product thicknesses, and failure modes with a common index.

REFERENCES

(1) Turner, C. E. and Kolednik, O. *A simple test method for energy dissipation rate, CTOA and the study of size and transferability effects for large amounts of ductile crack growth,* Fatigue & Fracture of Engineering Materials & Structures, The International Journal, Vol 20, No 11, pp 1507-1528, 1997.

(2) Cotterell, B. and Reddel, J. K. *The essential work of plane stress ductile fracture,* International Journal of Fracture Vol 13, No 3, June 1977.

(3) Priest, A. H. and Holmes, B. *A multi-test piece approach to the fracture characterisation of linepipe steels,* International Journal of Fracture, Vol 17, No 3, June 1981.

(4) Watson, T. J. and Jolles, M. I. *Plastic Energy Dissipation as a Parameter To Characterise Crack Growth,* Fracture Mechanics: Seventeenth Volume, ASTM STP 905, pp 542-555, 1986.

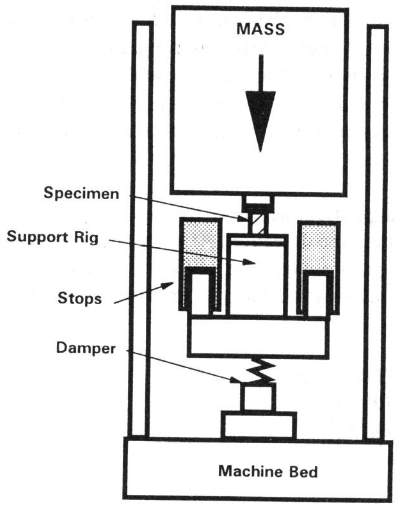

Figure 1 Schematic of test rig

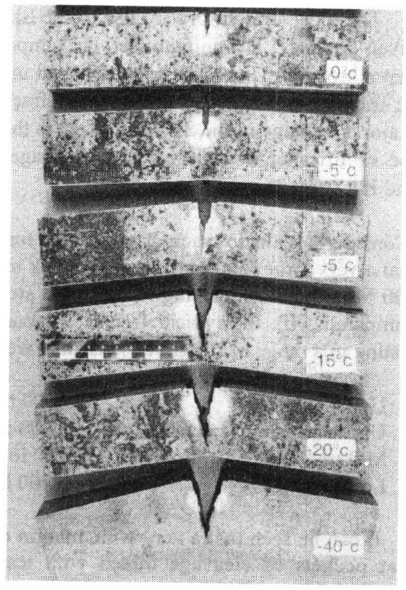

Figure 2 Typical test series, structural steel

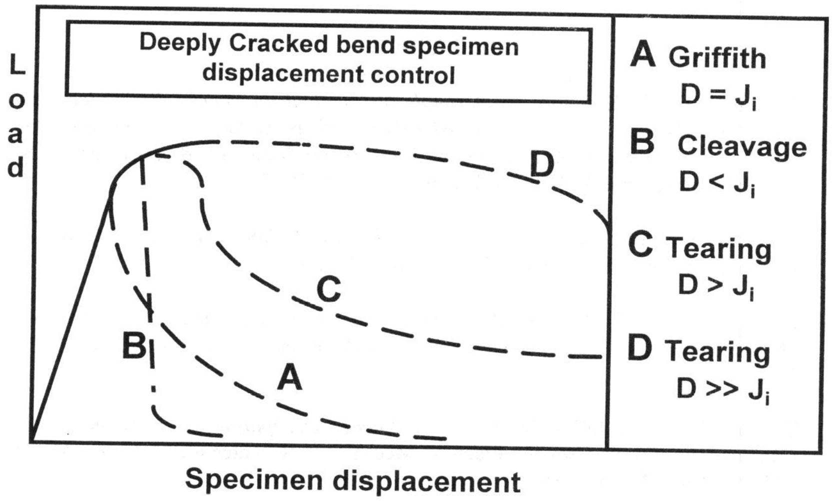

Figure 3 Some possible load/deflection behaviours depending on material characteristics