FRACTURE ASSESSMENT IN DUCTILE TEARING SITUATIONS

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ABSTRACT

Current requirements have led to the extension of existing design approaches in order to make defect assessments in materials which fail by a tearing mechanism. This paper discusses the critical events applicable to a tearing mechanism of crack growth, and explains how the maximum load point experienced with stable crack extension represents instability under load controlled conditions, i.e. deadweight loading. The conditions necessary to ensure that conservative measurements of this maximum load toughness are made in the laboratory relative to structural situations are outlined. The use of maximum load toughness values in the well established crack opening displacement (COD) design curve defect assessment procedure is also discussed. The recently proposed J-integral design curve is presented in a slightly simplified form and the compatibility with the COD curve is demonstrated. The use of the design curve assessment procedures is thus extended to provide estimates of allowable defect sizes for materials behaving in a fully ductile manner.

KEYWORDS

Through thickness cracks; surface cracks; fracture toughness; ductile fracture; tearing; maximum load toughness; ductile instability; test specimens; COD design curve; J design curve.

INTRODUCTION

The onset of crack growth by a cleavage mechanism in a test sample is generally an unstable event accompanied by a rapid decrease in load bearing capacity and as a result is independent of the loading system energy. In contrast, initiation of a ductile tear usually occurs under stable conditions with the applied load often increasing as the crack extends. The ductile instability itself is dependent on the loading system energy and may occur after extensive stable crack extension. Therefore different parameters govern the conditions for instability depending on whether the mode of failure is by a microvoid coalescence (tearing) or a cleavage mechanism.

Because of the uncertainties concerning the prediction of ductile instability conditions under extensive plasticity, many workers have tended to restrict interest to linear elastic conditions, or make use of the usually very conservative initiation of tearing toughness measurements. Since ductile tearing is generally accompanied by extensive plasticity and ductile instability can occur at toughness levels an order of magnitude greater than initiation values, these restrictions can result in excessive conservatism when related to actual structural behaviour.

In ductile tearing situations Towers and Garwood [1980 (a) and (b)] have suggested that the maximum load toughness values obtained in bend geometries would be conservative when related to instability in tensile loaded geometries, subject to various conditions on specimen size and loading configuration. In this paper the significance of maximum load toughness relative to the toughness at the instability event is briefly discussed, and the incorporation of these maximum load toughness values into the existing defect assessment procedures of the COD and J-integral (or J) design curves is then proposed. The necessary limitations on testing geometries and loading configurations for the conservative application of these proposals are outlined.

RELEVANCE OF MAXIMUM LOAD TO INSTABILITY

An instability analysis in ductile tearing situations would ideally consist of a comparison between the material's resistance to crack growth (termed an R-curve) and the variation of the driving force curves of the loading system with crack growth. The condition of instability is defined as tangency between the R-curve and the relevant driving force curve. This is shown schematically in Fig. 1a with the corresponding load versus load point displacement trace depicted in Fig. 1b. It can be seen from these figures that point 4 corresponds to instability for sustained loading, or load control, and also corresponds to maximum load. For displacement controlled load application, however, instability cannot occur at point 4 as tangency between the driving force curves and the R-curve cannot be achieved. Loading can be continued to point 5, and beyond, under displacement control without instability occurring and with a corresponding reduction in load level. The concept that the toughness at maximum load corresponds to the load controlled instability point, which has been discussed elsewhere by Towers and Garwood [1980(a)], is an obvious consequence of the fact that instability must occur when the maximum load a member can withstand is sustained despite increasing load point displacement.

From the above discussion it is apparent that, under displacement control, the maximum load point will occur at a lower displacement than ductile instability irrespective of the system energy. The fracture toughness corresponding to maximum load is thus a conservative measure of the toughness at instability caused by any displacement controlled loading. This argument depends on constancy of material sampled, specimen geometry, loading configuration, crack growth mechanism (i.e. tearing) and lack of time dependent effects, aspects which have been discussed in detail by Towers and Garwood [1980b].

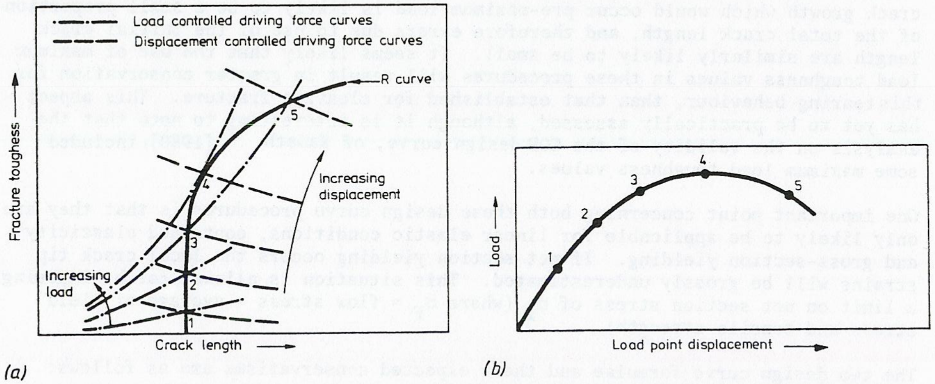

Fig.1. a) Schematic representation of driving force curve/R-curve instability assessment; b) load v. load displacement trace corresponding to instability analysis shown in Fig.1a.

LABORATORY DETERMINATION OF MAXIMUM LOAD TOUGHNESS

Specimen Geometry and Loading Configuration

The variation of maximum load toughness with specimen geometry and loading configuration has been discussed elsewhere, i.e. Towers and Garwood [1980(a) and (b)]. It was suggested that the higher constraint due to loading configuration and/or specimen design would cause a reduction in maximum load toughness values. A similar effect would be experienced by reducing the ligament length of the test specimen.

In order to make conservative assessments of the two common structural situations, i.e. a through thickness crack and a surface crack subjected to predominantly tensile loading, Towers and Garwood [1980(a) and (b)] made the following recommendations:

Through thickness cracks. To assess the through thickness crack situation (as typically depicted in Fig. 2), maximum load toughness values should be measured using the full plate thickness 'preferred testpiece' bend specimen of BS5762:1979 'Methods for crack opening displacement (COD) testing', (this test specimen is shown in Fig. 3). These values would, in general, be conservative relative to a through crack in a structure behaving in a ductile manner, as outlined by Towers and Garwood [1980a].

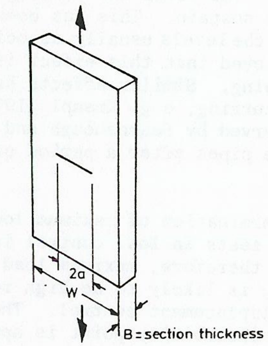

Fig.2. Typical through thickness crack configuration.

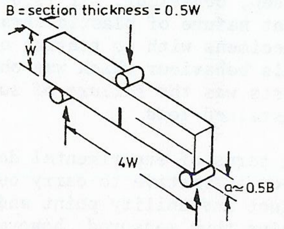

Fig.3. Preferred test piece of BS 5762: 1979.

Surface cracks. To provide conservative assessments of the toughness of surface cracks, as typically depicted in Figs 4a and 4b, maximum load toughness values should be measured using the 'subsidiary testpiece', of BS5762: 1979 (Fig. 5) with restrictions concerning the specimen thickness, B. The equality of B and W for the 'subsidiary testpiece' shown in Fig. 5 is purely arbitrary and it is feasible that the possible plane-strain constraint of the structural situation, Figs 4a and 4b, would not be satisfactorily modelled by a testpiece with B = W. This point is discussed by Towers and Garwood [1980a], the recommended methods for ensuring sufficient through specimen thickness constraint being the imposition of a minimum size on specimen thickness or the use of sidegrooving. Also, the crack length in the 'subsidiary testpiece', 'a' in Fig. 5, should be made equal to or greater than the crack length in the structural situation. Therefore the crack length which is chosen for assessing tearing behaviour may conflict with that which would be chosen for assessing resistance to cleavage fracture, [Towers and Garwood (1980b)], and thus it may need to be decided which fracture mode is of greater concern, or interest, before specifying the test specimen crack length.

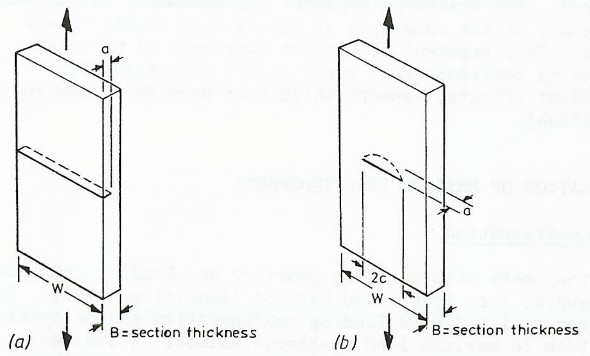

Fig.4. Typical surface crack configurations.

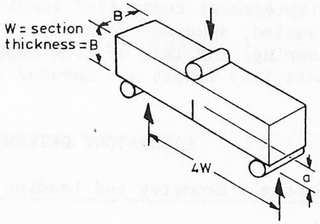

Fig.5. Subsidiary test piece of BS 5762: 1979.

Method of Laboratory Load Application

One aspect which has been neglected in the comparison of loading configuration and specimen geometry effects is the dependence of tearing on the rate of loading or displacement of the specimen. The lower the loading rate, the lower the maximum load the tearing specimen can sustain. This has been observed to occur in various steels at temperatures below the levels usually associated with rate dependent, or creep, behaviour. It is believed that this effect is merely due to the rate dependent nature of plastic straining. Similar effects have been observed in tensile specimens with no tearing occurring, e.g. Krempl [1979]. One practical example of this behaviour which was observed by Fearnehough and Jones [1978] in pipeline proof tests was the failure of some pipes after a period of stable tearing occurring under sustained load.

In terms of experimental determination of maximum load toughness, it would at first seem attractive to carry out tests in load control in an attempt to obtain a distinct instability point and, therefore, maximum load toughness value. The toughness value thus measured, however, is likely to be high relative to maximum load toughness values obtained under displacement control. There are two reasons for this. Firstly, as the maximum load instability point is approached the rate of displacement will rapidly rise which may cause an elevation in the load carrying capacity of the specimen and, therefore, the fracture toughness. Secondly, in displacement controlled tests on materials with a high work hardening capacity it is common to obtain load versus displacement traces with a long plateau at maximum load. In these cases it is usual to define the maximum load toughness as the value corresponding to the first attainment of the maximum load plateau, thus underestimating the toughness at the load controlled instability point.

In conclusion, maximum load toughness values obtained in displacement control using 'slow' loading rates, i.e. with the testing time to maximum load taking several minutes, should be sufficiently low to allow for any rate dependent plastic flow, provided the maximum load point is defined as the first attainment of maximum load plateau, consistent with BS5762:1979 stipulations. This conclusion has yet to receive experimental justification, however, and should thus be treated with caution.

Crack Length to be used for Calculation Purposes

As the precise maximum load point is difficult to define (particularly for long maximum load plateaux), it is not possible to establish the precise crack length at maximum load. Similarly, if the test is carried out in load control, the crack length at instability will not usually be apparent on the fracture face. It is therefore recommended that the initial fatigue crack length be used in analysis of maximum load toughness values. This procedure is consistent both with the definition of J in the J_{Ic} testing procedure of Clarke and co-workers [1979] and with the definition of an original crack tip COD. Use of the initial fatigue crack length in the estimation of maximum load toughness will result in differing values from those calculated using the current crack tip measurement at maximum load. The differences produced are generally expected to be small, however, and the consistent definition and ease of measurement make use of the initial crack length in the calculations worthwhile.

INCORPORATION OF MAXIMUM LOAD TOUGHNESS VALUES INTO EXISTING DEFECT ASSESSMENT PROCEDURES

There is a multiplicity of defect assessment procedures which have mainly been developed to avoid cleavage fracture occurring in ferritic steels, or other 'brittle' fracture modes where linear elastic conditions are applicable, i.e. in low toughness aluminium alloys, high strength steels. Although it is probable that maximum load toughness values could be incorporated into many of these assessment procedures, the present paper concerns itself only with single parameter design curve procedures. The first of these procedures is the COD design curve which, since its original introduction, [Burdekin and Dawes (1971)], has been used successfully in many structural integrity assessments, particularly for weldments. Some examples of the structures for which this procedure has been used are listed by Harrison and co-workers [1979]. The second procedure considered is the J design curve, which has recently been suggested by Turner [1978].

The COD and J design curves provide upper bounds on the COD or J value which would exist for a crack of given length at the given strain which would have existed in the absence of the crack. (The upper bound nature of these curves has been demonstrated both experimentally, for the COD design curve - Dawes [1979], and relative to computer simulations for the J design curve, Turner [1978]). There are no inherent reasons why maximum load toughness values of COD or J should not be incorporated into these procedures, any more than there are for toughness values corresponding to initiation of tearing or to cleavage fracture. A possible uncertainty however, is the crack length of interest, as crack growth may occur prior to maximum load. This uncertainty is not considered practically important as the crack growth which would occur pre-maximum load is likely to be a small proportion of the total crack length, and therefore errors due to use of the initial crack length are similarly likely to be small. It seems likely that the use of maximum load toughness values in these procedures will result in greater conservation for this tearing behaviour, than that established for cleavage fracture. This aspect has yet to be practically assessed, although it is interesting to note that the analysis on the validity of the COD design curve, of Kamath [1980], included some maximum load toughness values.

One important point concerning both these design curve procedures is that they are only likely to be applicable for linear elastic conditions, contained plasticity and gross-section yielding. If net section yielding occurs the local crack tip strains will be grossly underestimated. This situation is allowed for by imposing a limit on net section stress of σ_f (where σ_f = flow stress = average of yield stress and tensile strength).

The two design curve formulae and their expected conservatisms are as follows:

COD Design Curve

The COD design curve is given by the formula [Dawes (1979)]:

$$\Phi = \frac{\delta_c}{2\pi e_Y \bar{a}_{max}} = \left(\frac{e}{e_Y}\right)^2 \quad \text{for} \quad \frac{e}{e_Y} \le 0.5$$

$$= \left(\frac{e}{e_Y} - 0.25\right) \quad \text{for} \quad \frac{e}{e_Y} \ge 0.5$$

Where δ = crack opening displacement (COD)
δ_c = critical value of δ
e = applied strain in the absence of the crack
e_Y = yield strain
$\bar{a}_{max}$ = maximum allowable half length of a through thickness crack

This design curve has an inherent factor of safety of 2 on crack size if linear elastic conditons exist (assuming a plane of stress equivalence between δ and G - Dawes [1979]). An average factor of safety of approximately 3 has also been obtained by Kamath [1980] in an analysis of wide plate data over a large range of applied strain levels.

J Design Curve

A J based design curve has been proposed by Turner [1978] as given by:

$$\frac{J_c}{G_Y} = \left(\frac{e}{e_Y}\right)^2 \quad \text{for} \quad \frac{e}{e_Y} < 0.85$$

$$= 5\left(\frac{e}{e_Y} - 0.7\right) \quad \text{for } 0.85 < \frac{e}{e_Y} \le 1.2$$

$$= 2.5\left(\frac{e}{e_Y} - 0.2\right) \quad \text{for} \quad \frac{e}{e_Y} > 1.2$$

Where: e and e_Y are defined above
J_c = critical value of J
G = strain energy release rate
G_Y = value of G corresponding to applied stress of yield magnitude

This curve is an upper bound to the computed data for many goemetries with large scale yielding occurring. To maintain the conservatism which is implicit for large scale yielding, since an upper bound to the data has been taken, for low strains it is suggested by the authors that a safety factor of two on J (and therefore crack size) should be introduced at the elastic end of the scale. This is compatible with the safety factor for the elastic region of the COD design curve.

While incorporating this small alteration to the design curve it was considered useful to simplify the curve to two interconnecting lines, and the resulting simplified J design curve becomes:

$$\frac{J_c}{G_Y} = 2\left(\frac{e}{e_Y}\right)^2 \quad \text{for} \quad \frac{e}{e_Y} \le 1.0$$

$$= 2.5\left(\frac{e}{e_Y} - 0.2\right) \quad \text{for} \quad \frac{e}{e_Y} \ge 1.0$$

The original curve proposed by Turner [1978] and this simplified version are plotted in Figure 6

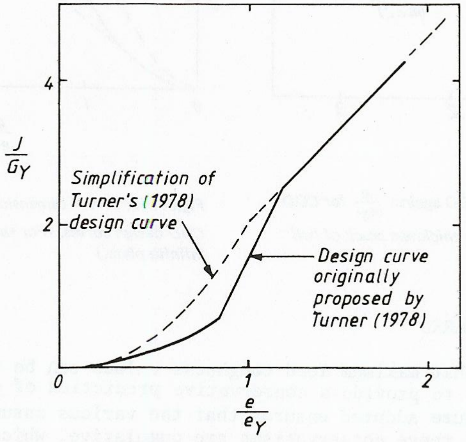

Fig.6. J-design curves showing Turner's (1978) original proposal and the presently proposed simplified version.

COD/J Design Curve Comparison

Comparison of the COD and J design curves can be achieved by converting between J and δ using the formula $J = m\sigma_Y\delta$, where m is a 'constant', and σ_Y = material yield strength. Unfortunately, no single value of m is appropriate (the value can vary approximately between 1 and 2.5) and for the present purposes both m = 1 and m = 2 have been used, which would approximately represent plane stress and plane strain conditions respectively. The comparison has been carried out for a through thickness crack of length 2a in an infinite plate subjected to a remotely applied tensile strain e. The COD design curve and the simplified J design curve are compared in terms of COD in Figure. 7 and in terms of J in Figure 8. It is seen that the two curves show close correspondence in their trends with increasing strain, particularly for near-plane stress conditions.

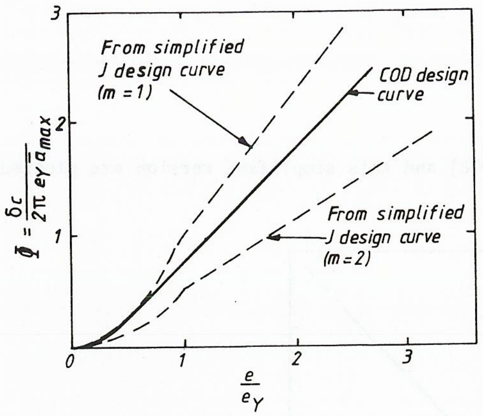

Fig.7. Plot of non-dimensional COD against $\frac{e}{e_Y}$ for COD and J design curves. (For through thickness crack of half length $\bar{a}$ in an infinite plate.)

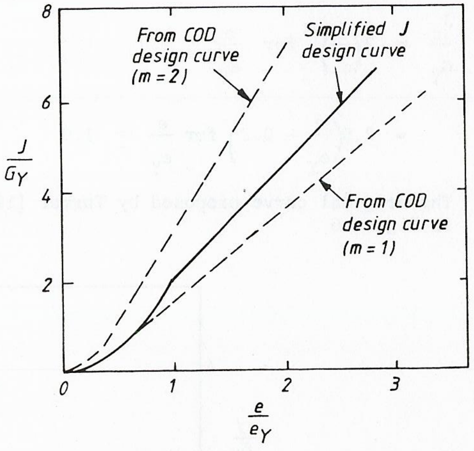

Fig.8. Plot of non-dimensional J against $\frac{e}{e_Y}$ for J and COD design curves. (For through thickness crack in an infinite plate.)

CLOSING REMARKS

It is suggested above that maximum load toughness values can be incorporated into two design curve approaches to provide a conservative prediction of ductile instability conditions. The procedure adopted ensures that the various assumptions made are conservative. Although these conservatisms are cumulative, which will almost certainly result in much larger factors of safety occurring for ductile tearing situations than those pertaining to cleavage fracture, the assumptions are inevitable to account for such variations as loading mode, loading configuration and defect geometry safety in one design procedure. However, the incorporation of maximum load toughness values in the design procedures does remove the unduly conservative restriction imposed by the use of initiation of tearing toughness measurements. The effect of the over conservatisms remaining could be reduced by testing the defect and the loading mode of interest with the relevant applied loading conditions (i.e. tension or bending). If such steps are to be considered which might relax the inherent conservatisms in the approach other factors must be borne in mind. These include the strain rate dependence effects which have been demonstrated for various steels and which require important consideration under load control conditions. The effect of prior plastic deformation on material toughness must also be taken into account. This latter effect is normally allowed for by simulating the restraint conditions, or prior plastic deformation, present in the area of interest. In addition to these considerations, factors such as the presence of secondary stresses and environment must be, of course, taken into account.

DISCUSSION AND CONCLUSIONS

The suggestion that maximum load toughness should be established in test specimens loaded in bending to give a conservative estimate of the instability toughness of a predominantly tensile loaded structural situation is reiterated. The 'preferred testpiece' of BS 5762:1979 'Methods for Crack Opening Displacement (COD) Testing' is recommended for measuring toughness values to assess through thickness defects and the 'subsidiary testpiece' of this standard is recommended for measuring toughness values to assess surface breaking defects, (with some reservations on specimen thickness and crack depth). It is further suggested that these maximum load toughness values can be incorporated into the existing COD design curve procedure, or into a slightly modified J design curve procedure, to provide conservative estimates of ductile instability conditions.

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REFERENCES

Burdekin, F.M. and M.G. Dawes [1971]. Practical use of linear elastic and yielding fracture mechanics with particular reference to pressure vessels. Conference on Practical Application of Fracture Mechanics to Pressure Vessel Technology, I. Mech. E., London, 28-37

Clarke, G.A., W.R. Andrews, J.A. Begley, J.K. Donald, G.T. Embley, J.D. Landes, D.E. McCabe and J.H. Underwood [1979]. A Procedure for the determination of ductile fracture toughness values using J integral techniques. J. of Testing and Evaluation, 7, No. 1, 49-56

Dawes, M.G. [1979]. The COD design curve. 2nd Advanced Seminar on Fracture Mechanics, ISPRA, Italy.

Fearnehough, G.D. and D.G. Jones [1978]. An approach to defect tolerance in pipelines. Conference on Tolerance of Flaws in Pressurised Components, I.Mech.E., London, 205-228.

Harrison, J.D., M.G. Dawes, G.L. Archer and M.S. Kamath [1979]. The COD approach and its application to welded structures. ASTM-STP-668, 606-631.

Kamath, M.S. [1980]. The COD design curve: An Assessment of Validity using Wide Plate Tests. Int.J.Pressure Vessels, Piping. Accepted for Publication.

Krempl. E. [1979]. An experimental study of room-temperature rate-sensitivity, creep and relaxation of AISI Type 304 stainless steel. Int.J.Mech.Phys.Solids, Vol. 27, 363-375.

Towers, O.L. and S.J. Garwood [1980(a)]. Maximum load toughness. Int.J.Fracture, 16, R85-R.90

Towers, O.L. and S.J. Garwood [1980(b)]. The geometry dependence and significance of maximum load toughness values. ECF3, Imperial College, London, Accepted for publication.

Turner, C.E. [1978]. A J design curve based on estimates for some two dimensional shallow notch configurations. CSNI Report 32, Vol. 2, 18.1 - 18.20.