THE ROLE OF THE STATISTICAL DISTRIBUTION OF THE MICROSTRUCTURAL PARAMETERS ON THE DAMAGE OF MATERIALS

D. François

Laboratoire de Mécanique, Sols, Structures et Matériaux. Ecole Centrale Paris, Grand Voie des Vignes, F-92295 Châtenay-Malabry, FRANCIA.

ABSTRACT OF THE INVITED LECTURE

In composite materials the inclusions display statistical distributions of sizes, orientations, shapes and local volume fractions. Calculations, as well as experiments, show that their influence on the elastic properties are relatively weak. However they play a major role when considering the damage. In this contribution we wish to emphasize this point by three examples.

The first one concerns a syntactic foam, a material which is made of tiny hollow glass spheres embedded in an epoxy resin. The diameters of these microspheres vary between 20 and 200 micrometers whereas their wall thickness remains about constant and equal to 1 to 2 micrometers. The model of Hashin and Shtrikman, or a three phases model, allow to compute the elastic modulus and to check that the results match the experiments. Observations show that the first glass spheres to break are the larger ones. The computation indeed confirms that they sustain the larger stress. As the load on the composite is increased smaller and smaller microspheres are broken until the fracture can propagate in the epoxy resin. The decrease of the elastic moduli associated with the fracture of the microspheres enhances the stress concentrations, thus producing more fractures and this interaction leads to an instability. The size distribution of the microsphere appears as a major controlling factor and a good adjustment of this parameter could provide a material with improved damage tolerance.

The second example is an unidirectional glass fibers epoxy resin composite. When this material is loaded microcracks start in a few fibers and soon propagate in mode I. Observations and computations show that the critical points are the ones where the local volume fraction is higher. Misorientations play also a very important role as they induce a much higher loading in some fibers. They are unavoidable but a certain control could be beneficial. When the mode I cracks reach a certain size they stop and the fracture continues as a shear fracture along the glass fibers interfaces. Once again the local volume fraction controls this phenomenon. It can be shown that, at the tip of the mode I crack, the shear stress along the fibers interfaces increases faster than the normal stress on the crack plane as the crack propagates.

Lastly we consider an aluminium matrix graphite fibers composite. Once again the fluctuations of the local volume fraction of fibers do not have much influence on the elastic moduli. However cracks start at the interface between the fibers and the matrix and they propagate by shear instabilities where the local volume fraction is the higher. This can be explained by computations which at first give the critical macroscopic stresses to cancel the residual thermal stresses around the fibers, and then the intensity of the local plastic strain. The damage probability can be estimated as a function of the distribution of the local volume fraction of fibers. Some arrangements of the fibers yield a larger strain concentration at their tip than others. This kind of study can help in the design of a better material.

THE USE OF FRACTURE MECHANICS TO ASSESS THE SIGNIFICANCE OF DEFECTS IN STRUCTURES

S.J. Garwood

The Welding Institute. Abington. Cambridge CB1 6AL (U.K.)

Abstract.- The application of fitness for purpose concepts to assess the significance of defects has been common practice in the U.K. since BSI PD 6493 was introduced over ten years ago.

With the advance of fracture mechanics methods, the procedures used have been revised and extended. A revision of BSI PD 6493 is about to be issued which updates the approaches adopted and also incorporates the R6 concepts developed by the CEGB.

This lecture will highlight the need for fitness for purpose concepts and describe the three level fracture assessment procedure which has been incorporated into PD 6493. Finally some practical examples will be described.

1. INTRODUCTION

Various flaws which can arise from the manufacturing processes can be classed as follows:

PLANAR: Cracks, Lack of penetration, etc.

NON-PLANAR: Slag inclusions, Porosity.

GEOMETRIC: Misalignment, Angular distortion.

For every application there will be a limiting flaw size which, if present, will cause the material to fail under the service loading. Assessments of the significance of flaws are aimed at establishing what this limiting size is under a particular set of circumstances. They are usually based on fracture mechanics concepts, which relate the effect of the flaw to the stress level and material properties. An important property is the resistance to fracture, or toughness. The inter-relationship between toughness, stress and flaw size can be represented by a triangle, as in Fig.1. Knowledge of any two values enables the limiting value of the third to be calculated. In simple terms, if the critical value of flaw size is exceeded the material will fail. Failure may occur by one of several mechanisms. All modes of failure which could be influenced by a flaw need to be considered. BSI PD6493:1980 (Ref.1) identifies the following:

Fracture
Fatigue
Plastic collapse
Leakage
Corrosion/erosion
Buckling
Creep

Components containing significant fabrication defects which go undetected and enter service may experience premature in-service crack and/or suffer catastrophic failure. Fabrication defects may grow by mechanisms such as creep, fatigue, corrosion, stress corrosion, leading to eventual failure by a brittle or ductile fracture, plastic collapse, buckling or leakage.

One of the most common in-service cracking mechanisms in oil rigs, cranes, earth moving vehicles, etc which are subjected to cyclic stressing is fatigue. This failure mechanism is characterised by a smooth fracture face often with 'beach' marks caused by the amplitude of the cyclic loading change.

In unflawed material, there is a definite initiation period before any crack growth occurs, but in welded joints where inclusions and small imperfections are associated with the toes of welds, the initiation period is dominated by propagation of the crack and the fatigue life of welded components is therefore a function of the geometry of the joint (see Fig.2). If defects are present, these can reduce the life of the welded component drastically. One of the most recent catastrophic failures due to fatigue was the offshore platform, the Alexander Keilland.

Fatigue crack propagation rates are a function of the stress intensity factor K as illustrated in Fig.3. In corrosive environments the rate of fatigue cracking can be accelerated dramatically.

Another major cause of catastrophic failure is brittle fracture. Although fatigue cracking is more common, the progressive nature of crack extension does at least allow for the possibility of detection by NDT during periodic inspections. In contrast, brittle fractures are sudden and the consequences can be totally disastrous. The increased use of welding and hence the likelihood of defects, for the fabrication of structures in the 1950s brought with it a number of spectacular failures such as broken ships and pressure vessels. Although improvements to materials and fabrication methods have now decreased the incidence of brittle failures, they do still occur. In brittle fracture, the material, typically ferritic steels, has relatively low resistance to cleavage fracture at the operating temperature (see Fig.4). The mechanism is characterised by chevron marks on the fracture faces pointing back to the origin of the failure.

In high temperature service, another common cracking mechanism is creep. This is a progressive intergranular cracking mechanism associated with a high service temperature. Steels, depending on their composition, have different temperatures above which creep cracking becomes a risk. In common with fatigue and stress corrosion however, fabrications entering service with defects can have a reduced life. The presence of such defects can provide the site for creep crack growth which may eventually lead to catastrophic failure by another mechanism.

Other sub-cricital crack growth mechanisms include corrosion and various forms of hydrogen cracking. In many instances, the geometry of the fabrication and the presence of subsceptible microstructures and/or welding residual stresses are sufficient to cause problems. However, if frabrication defects are present, then the incidence of cracking mechanisms can be increased dramatically during the service life of the vessel.

When extensive sub-critical crack growth occurs, the final failure may be ductile in nature. Although the micromechanism is ductile, the energy absorbed by the fracture process can still be low (particularly in the presence of hydrogen or when in-service embrittlement has occurred e.g. temper embrittlement or neutron irradiation). In these circumstances the material behaves in an essentially brittle manner. In other cases, the defect is, or becomes, large enough to induce yielding on the remaining cross section and gross deformation or plastic collapse occurs. When multiple defects are present the localised linking of defects can occur with time. Although nominally more stable than brittle fracture, the consequences of a ductile failure can be equally catastrophic.

In this lecture the fracture assessment methods of PD6493 will be discussed in detail particular consideration being given to the variability of input data and its effect on the risk of failure.

2. THE CTOD DESIGN CURVE

Internationally BSI PD6493:1980 (1) is perhaps the most widely used defect assessment procedure. The fracture section of this document uses linear elastic fracture mechanics and the CTOD design curve approaches with inputs of a stress and fracture toughness to allow the assessment of the acceptability of a known defect or the prediction of acceptable defect sizes. Linear elastic treatments have a nominal safety factor of two on defect size. The CTOD design curve (2) is employed for elastic-plastic assessments in PD6493. Kamath (3) examined the factors of safety derived from a comparison of the minimum of three results from CTOD tests with the performance of a wide plate with a known flaw. It is important to note that the levels of safety quoted are representative only of the data handling treatment employed (i.e. the use of the minumum of three data points) and the relationships between bending and tension, the relatively uniform stress field in a wide plate test and the assumption of yield magnitude residual stresses for the as-welded tests. The factors of safety do not give guidance on the overall reliability of the assessment procedure.

3. REVISIONS TO PD6493

It is proposed that an update be made to the Fracture sections of PD6493 as discussed in Refs 4 and 5. This will take the form of a three level approach (see Fig.5) similar to that proposed by Anderson, Leggatt and Garwood (6) drawing on the recent advances in fracture analyses represented by the CEGB R6 Rev.3 document (7) and by recent publications by The Welding Institute

(4,8).

The CTOD design approach represents Level 1 in the proposed procedure and this level is seen as a basic screening approach. The general approach i.e. Level 2, is based on a collapse modified strip yield model (8), analogous to the CEGB R6 Rev.2 procedure (9). Level 3 of the approach will adopt a reference stress procedure (10) which is seen as a specialised approach for tearing analyses and for use with high work hardening materials.

Level 1 has an implied, but variable, safety factor. Level 2 is a nominally critical analysis but, assumes 'worst case' inputs to give an adequate level of safety. When considering a detected flaw, the parameters K_r or $\sqrt{\delta_r}$ and S_r can be determined and the point plotted on a failure assessment diagram (FAD) (see Fig.6), K_r is the ratio of the applied stress intensity to the material toughness in terms of K, δ_r is the ratio of the applied CTOD to the material toughness in terms of CTOD, and S_r is the ratio of the applied stress to the collapse strength.

If the assessment point lies inside the envelope of the FAD, it is safe, if outside it is unsafe and should be repaired.

If the component is subjected to fatigue, its fatigue life must also be considered. In the fracture assessment, all flaws are considered to be planar (i.e. cracks) for conservatism. In the proposed revision to the fatigue assessment of PD6493 (11) planar and non-planar flaws are considered separately. Fracture mechanics is used to asses the life of planar flaws where crack growth rates are based on the Paris law (see Fig.3). i.e. $da/dN=A(\Delta K)^m$.

Knowledge of the flaw size to cause final failure allows the prediction of the initial flaw sizes by numerical integration.

This procedure can be very time consuming however and PD6493 also contains a simplified procedure based on the comparison of S-N curves which represent the actual and required fatigue strengths of the flawed weld. A grid of S-N curves is used, each curve representing a quality category derived using fracture mechanics. The weld and flaw geometry being considered defines the quality category and using the full applied stress range an assessment can be made to assess whether the detected defects will have an adequate fatigue life.

4. SAFETY FACTOR TREATMENTS

In any assessment of the significance of weld imperfections or defects, it is important to recognise that there will be uncertainties in some of the data inputs, and there will be scatter in material properties. The traditional method of dealing with these uncertainties is to use upper bound estimates of those parameters affecting applied loading severity, and lower bound estimates of those parameters concerned with material resistance, with an additional global safety factor determined on the basis of judgement and experience. In the case of assessment of the significance of defects, this would imply that upper bound estimates are required for those data contributing to the calculation of applied stress intensity factor or applied crack tip opening displacements, and lower bound estimates for material fracture toughness.

For the Level 1 assessment procedure, this is indeed the case, and an additional overall safety factor is incorporated by the form of the assessment diagram as a box, with limits on K_r of 0.71 and S_r of 0.8. At Level 1 there will normally be additional in-built conservatism, from the treatment of stress gradient regions and residual stresses as uniform tension values equal to the peak magnitude. The inherent safety factor in the CTOD design procedure has been taken into account and made compatible with the alternative LEFM procedure by the assessment diagram box at Level 1. The Level 2 procedure is intended to give a reasonably close estimate of actual failure conditions and may be regarded as having no in-built safety factor in the fracture mechanics relationships. Thus at Level 2, if the assessment curve did in fact predict failure accurately, the input data parameters were known precisely, the assessment would result in predictions of critical flaw sizes. In this case it is up to the user to decide on the level of safety required, and it is most important that sensitivity studies are carried out to ensure that small changes in input data do not produce substantial changes in the safety assessment. It is therefore required for Level 2 assessments either that the user does determine upper bound estimates of applied load/stressing conditions and flaw sizes and lower bound estimates of fracture toughness, or that the user adopts the recommendtions for partial coefficient treatments covered in an appendix to the procedure. The same situation applies to Level 3 treatments, where the form of the assessment diagram, and the fracture mechanics relationships underpinning this are intended to give the most accurate prediction possible of failure conditions for specific materials. Thus again at Level 3, either upper bound estimates of applied severity conditions and lower bound estimates of toughness should be used, or the partical coefficient approach from the appendix should be used, in both cases with appropiate sensitivity studies.

A comparison of the ratio of predicted CTOD against actual CTOD calculated using the three levels of assessment for a surface notched wide plate is shown in Fig.7. This figure indicates that the safety factors for the Level 1 procedure reduce as the applied stress level increases. This trend is not very apparent in Kamath's validation data, however, since conservative plastic collapse analyses prevent the application of the Level 1 procedure at very high (>0.8) ratios of primary stress to flow stress. Figure 7 also indicates that the strip yield model (which forms Level 2 of proposed revision) has a much lower safety factor than Level 1 below a primary stress to flow stress ratio of 0.8. However, the Level 2 is not a critical analysis as illustrated in Fig.8, conservative results being predicted owing to other assumptions in the data treatment of the wide plate tests analysed.

At all three levels, the toughness estimate to be used must take account of the scatter inherent to this property. For Levels 1 and 2, the minimum of three test results can be used provided excessive scatter is not present in these three results. Guidance is given on this aspect. Where excessive scatter is shown, and/or more test results are available, guidance is given in the appendix on which value to be taken as representing toughness from a set of results. For example, for up to five tests the lowest value should be taken, from six to ten tests the second lowest should be taken, and from eleven to fifteen the third lowest results should be taken. These recommendations are based upon equivalent probability of occurrence from binomial theorem analysis (12). Where more that 15 results are available from the same sample source, it is recommended that they be analysed statistically assuming either a log normal or Weibull distribution, and the mean minus one standard deviation characteristic value should be used together with the appropriate partial coefficient.

The appendix on safety factors and number of tests gives details of an optional treatment for partial safety factors on stress, flaw size and toughness. Recommendations are given for partial coefficients for alternative failure consequences, described as moderate or severe. Moderate is interpreted as local failure which would not cause complete structural collapse, and severe is interpreted as a risk of complete structural collapse or severe hazard. Reliability analyses were carried out using the fracture mechanics equations of the Level 2 assessment method, taking into account different variables and distributions of the input data, to obtain a target notional probability of failure linked to the failure consequences (13). The statistical distributions assumed for uncertainties in stress and flaw size estimates were normal distributions, and the statistically distribution assumed for toughness was log normal or Weibull. The type of reliability analysis carried out used the first order second moment method to estimate the reliability index, and hence the probability of failure. The adoption of a single overall safety factor on flaw size is inefficient, and the most consistent results are obtained by use of partial coefficients applied to each of the input data variables. The resulting recommendations are shown in the table.

5. IN CONCLUSION

The revised PD6493 brings together the latest research and experience from around the world, and from a range of different industries. In particular the document now brings together the principles adopted in the 1980 edition of PD6493, and those of the CEGB R6 method.

The revised fracture clauses will offer compatibility with existing PD6493:1980 treatments at the simple screening level, but will offer the opportunity of more accurate assessments removing some of the conservatism inherent to the PD6493:1980 treatment at the normal and advanced treatment levels. The assessment diagram approach forces the user to consider both fracture and plastic collapse, but retains the simplicity of using elastic methods for calculating crack driving force parameters, the effects of plasticity being taken into account in the assessment diagram itself.

6. REFERENCES

[1] BSI PD6493:1980 'Guidance of some methods for the derivation of acceptance levels for defects in fusion welded joints'.

[2] Harrison J.D., Dawes M.G., Archer G.L. and Kamath M.S.: 'The CTOD approach and its application to welded structures', ASTM STP668, 1979, pp.606-631.

[3] Kamath M.S.: 'The CTOD design curve; An assessment of the validity using wide

plate tests', Int. J. of Pressure Vessels and Piping, Vol.9, 1981, pp. 79-105.

[4] Garwood S.J., Willoughby A.A., Leggatt R.H. and Jutla T.: 'Crack tip opening displacement (CTOD) methods for fracture mechanics assessments: Proposals for revisions to PD6493', in ASFM-6 -The Assessment of Cracked Components by Fracture Mechanics EGF publication 5, Mechanical Engineering Publications Ltd.

[5] Burdekin F.M., Garwood S.J. and Milne I.: 'The basis for the technical revisions to the fracture clauses of PD6493', Paper 37 International Conference on Weld Failures (WELDTECH 88), London, 21-24 November 1988.

[6] Anderson T.L., Leggatt R.H. and Garwood S.J.: 'The use of CTOD methods in fitness for purpose analysis' in 'The crack tip opening displacement in elastic plastic fracture mechanics' ed. K.H. Schwalbe, Publisher Springer-Verlag, Heidelberg 1986, pp. 281-313.

[7] Milne I., Ainsworth R.A., Dowling A.R. and Stewart A.T.: 'Assessment of the integrity of structures containing defects', CEGB Report R/H/R6 - Rev.3, May 1986.

[8] Garwood S.J.: 'A crack tip opening displacement (CTOD) method for the analysis of ductile materials', ASTM STP 945, to be published.

[9] Harrison R.P., Loosemore K., Milne I. and Dowling A.R.: 'Assessment of the integrity of structures containing defects', CEGB Report R/H/R6 - Rev.2, April 1980.

[10] Ainsworth R.A.: 'The assessment of defects in structures of strain hardening material', Eng. Fract. Mech., Vol.19, p.633, 1984.

[11] Maddox S.J.: 'Revisions of the fatigue clauses in BS PD6493', Paper 47, International Conference on Weld Failures (WELDTECH 88), London, 21-24 November 1988.

[12] Jutla T. and Garwood S.J.: 'Interpretation of fracture toughness data', Met. Con. 1987, Vol.19, No.5, 276R-281R.

[13] Plane C.A., Cowling M.J., Nwegbu V. and Burdekin F.M.: 'The determination of safety factors for defect assessment using reliability analysis methods'. Third IOS Symposium, Glasgow, September 1987.

TABLE 1. Partial safety factors for stress, flaw size (on mean/best estimate values) and toughness (on characteristic value) for fracture assessment (from Refs 5 and 13).

	Partial factors for failure consequences	
Data variable	**Moderate**	**Severe**
Stress (measured), (C.O.V. 5%) γ_s	1.1	1.4
Stress (measured), (C.O.V. 30%) γ_s	1.2	1.6
Flaw size (S.D. 1-5 mm) γ_a	1.0	1.2
Flaw size (S.D. 10 mm) γ_a	1.1	1.4
Toughness K_{mat} (min 3) γ_t	1.0	1.2
Toughness δ_{mat} (min 3) γ_t	1.0	1.4

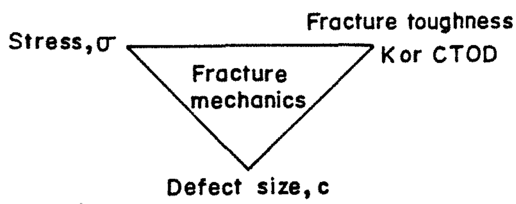

Fig.1. Relationship between the principal parameters for fracture mechanics analysis.

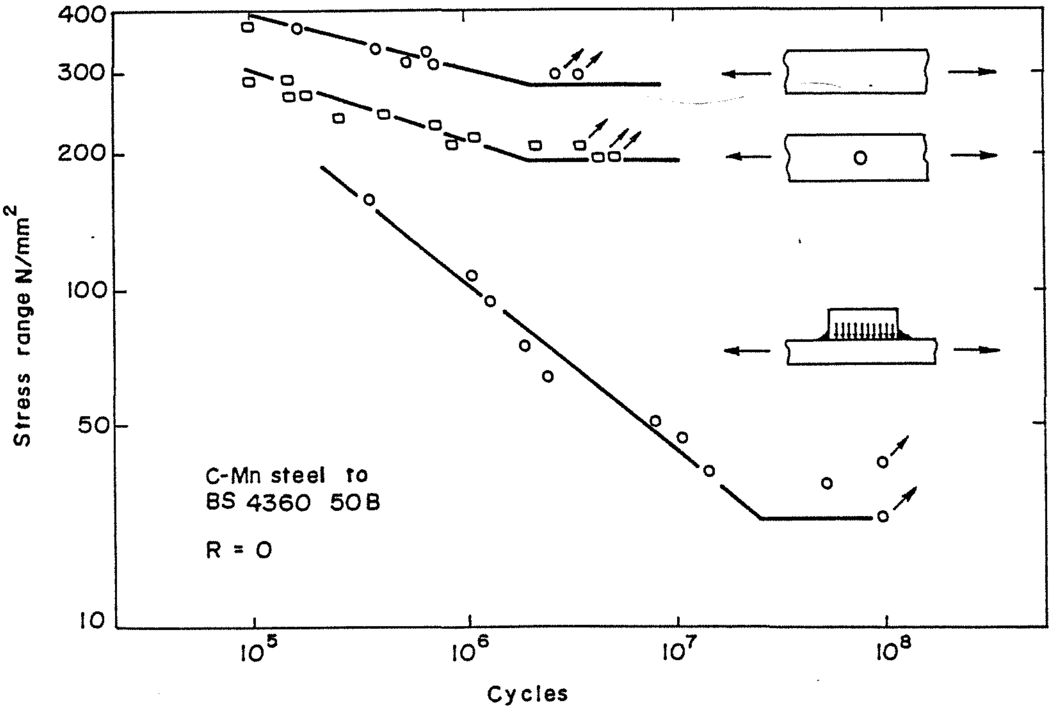

Fig.2. Comparison between the fatigue strengths of plain steel, notched plate and welded attachments.

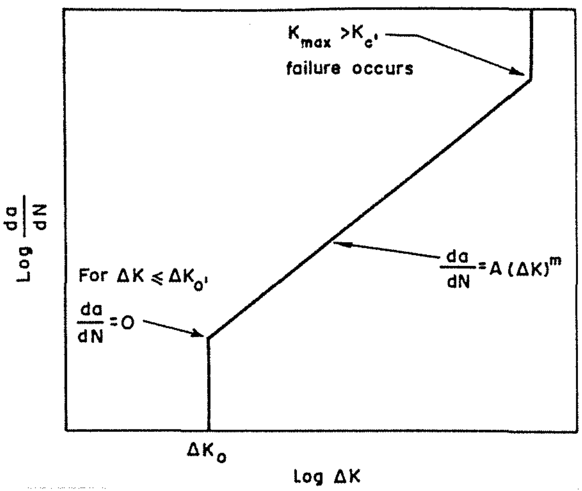

Fig.3. Assumed fatigue crack propagation relationship.

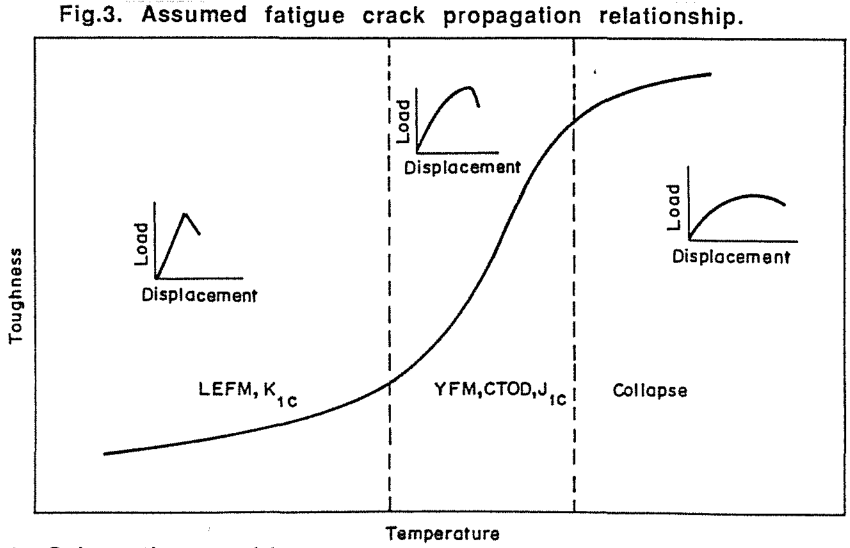

Fig.4. Schematic transition curve showing regions for application of LEFM, YFM and collapse.

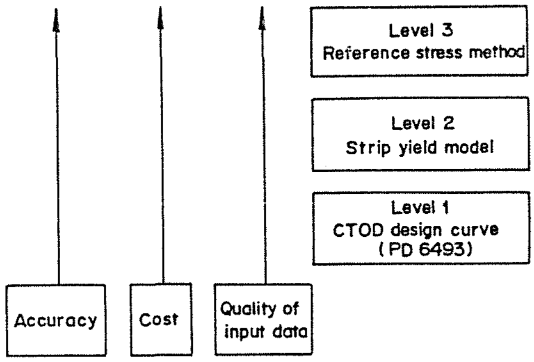

Fig.5. CTOD methods in fitness-for-purpose analyses.

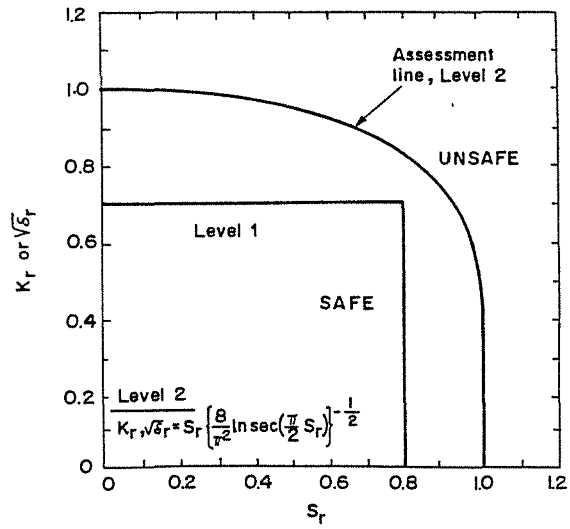

Fig.6. The failure assessment diagrams for Level 1 and Level 2.

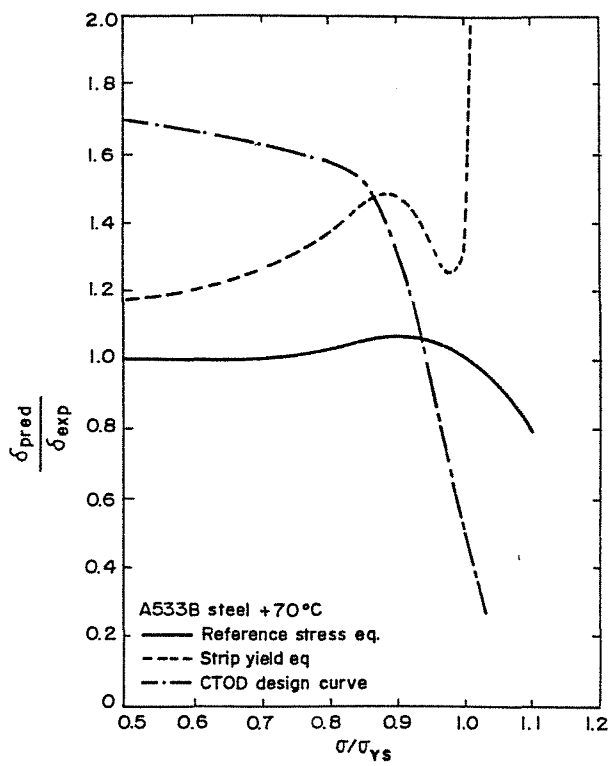

Fig.7. Safety factor on applied CTOD for the three assessment equations.

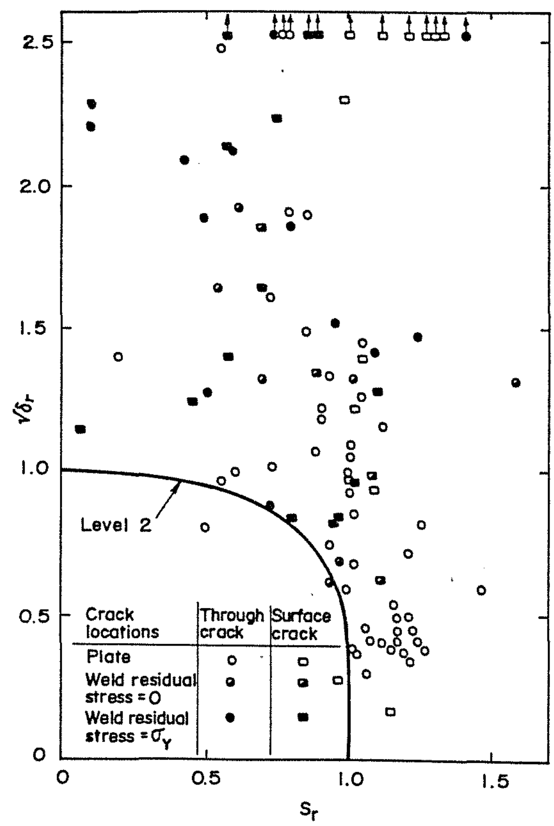

Fig.8. Comparison of wide plate tests with the Level 2 assessment line.