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Assessment of Defects: The c.o.d. Approach [and Discussion]

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Assessment of defects: the c.o.d. approach

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In welded construction particular problems arise with the application of fracture mechanics for the assessment of the effect of defects on structural performance. In many practical cases the use of plane strain linear elastic fracture mechanics methods is invalidated by the actual material thicknesses of interest, by residual stresses or by local stress concentration effects, and by local yielding.

The crack opening displacement approach was originally devised as a means of extending linear elastic methods to more widespread application to welded structures. This required the development of a means of assessing fracture toughness, and a means of relating this fracture toughness to the applied loading conditions, and to sizes and types of defects which might be present. The success of this method of assessing defects over a period of some 10–12 years will be illustrated, together with a discussion of the inherent limitations of the approach and possible improvements resulting from recent research into slow tearing and design curve relationships.

Introduction

Linear elastic fracture mechanics (l.e.f.m.) treatments have now been well established for many years for the assessment of the significance of defects in structures and materials for which the analyses are valid. Such treatments have been widely used for high-strength materials in which fracture occurs from defects without major deviation from linear elastic conditions. These treatments also apply to very thick components of lower-strength structural and pressure vessel steels in some cases, where the thickness is sufficient to maintain conditions approximating to plane strain at the tip of crack-like defects.

In welded constructions in the structural and pressure vessel fields, however, a number of complications arise that invalidate the linear elastic basis of l.e.f.m. treatments. Among these complications are the following:

(*a*) welding residual stresses of magnitude up to yield stress;

(*b*) stress concentrations due to geometrical discontinuities, or deviations from intended geometry;

(*c*) various material toughnesses and strengths in different parts of welded joints;

(*d*) the thickness of materials of interest is often such that valid plane strain l.e.f.m. fracture toughness measurements cannot be made at the temperature and loading rate of interest in the service application.

The crack opening displacement (c.o.d.) approach to assessment of defects was developed specifically to be able to overcome the above complications.

History and development of the c.o.d. approach

The problem of brittle fracture failure of welded steel structures was one studied at the British Welding Research Association (now the Welding Institute) from the formation of its research laboratories at Abington, near Cambridge. The notched and welded wide plate tension test developed at Abington (Wells 1956) was the first laboratory test demonstration of the service problem of low-stress fractures in welded structural steels. It was always recognized that this large-scale test was very expensive, and impracticable for a whole range of investigations of different steels, welding conditions, temperatures and other variables. Nevertheless, a number of investigations were carried out to determine safe minimum operating temperatures for typical mild steel pressure vessel steels, and these formed the basis for some British Standard requirements for low-temperature containment structures (Woodley *et al.* 1964). The acceptance criteria adopted were that a plate containing small crack-like defects at a butt weld, and in a region of yield residual stresses, should withstand applied loading to produce plastic strains of at least four times yield strain without fracture initiation. It is not practicable with such tests to examine the effects of different welding consumables and procedures, and effects of different defect sizes, and some simpler form of test was required to examine the effects of such variables.

At the same time as work proceeded on wide plate tests, the research team at B.W.R.A. was also working on methods of extending the validity of l.e.f.m. treatments to the lower-strength structural steels and welded applications. The concept of critical crack opening displacement at the crack tip as a measure of fracture toughness was first put forward by Wells (1961) and independently by Cottrell (1961). Wells developed his analysis to give estimates of the energy absorption required in the Charpy V-notch impact test to give a minimum toughness sufficient to ensure a transition away from plane strain conditions (Wells 1961), and later related this toughness requirement to defect size effects (Wells 1965*a*).

Consideration of the relation between applied stress, defect size and crack tip displacement was developed for anti-plane strain by Bilby *et al.* (1963) and independently by Burdekin & Stone (1966) for direct tension loading. It was found that the theoretical model on which these analyses were based did not match experimental results and this led to recommendations at Conferences on the Significance of Weld Defects (Burdekin *et al.* 1967; Harrison *et al.* 1968). The full background to the relation between applied strain, defect size and opening displacement at the crack tip was explained by Burdekin & Dawes (1971), leading to their proposal for a 'design curve' relation which is now the basis of the c.o.d. approach to the assessment of the significance of defects. This design curve approach was originally proposed as an upper-bound relation to the experimental results obtained from a series of large-scale double edge notched tension tests, in which the c.o.d. at the crack tip, the defect size and the applied strain were plotted in non-dimensional relation consistent with the theoretical analyses. The design curve proposals were subsequently modified by Dawes (1974) in the region of strains below yield to give the currently adopted version of the design curve:

$$\frac{\delta}{2\pi e_y a} = \left(\frac{e}{e_y}\right)^2, \quad \frac{e}{e_y} \leqslant 0.5;$$

$$\frac{\delta}{2\pi e_y a} = \frac{e}{e_y} - 0.25, \quad \frac{e}{e_y} \geqslant 0.5.$$

The question of assessment of the significance of weld defects has been considered by committees of the International Institute of Welding (Anon. 1975), and of the British Standards Institute (Anon. 1976), and the c.o.d. assessment method has been adopted as part of their approaches. A summary description of these methods is given in a treatise on tolerances for flaws in pressure components (Burdekin 1979).

In putting forward proposals for the use of critical crack opening displacement to fracture initiation as a measure of fracture toughness, the references cited above recognized that the critical value of c.o.d., δ_c, for fracture, would be dependent on material temperature, loading rate and triaxiality of stress. The effect of triaxiality of stress has often been assumed to be primarily one of thickness in determining whether plane strain conditions predominate, but two of the original contributions on this work pointed out that once plastic zones and slip lines developed, the constraint and triaxiality at the crack tip would depend also on in-plane geometry and loading systems (Wells *et al.* 1964; Wells 1965 *b*). These aspects are discussed further later.

The link between crack opening displacement fracture toughness tests and notched and welded wide plate tests was demonstrated in two pieces of work by Burdekin (1967 *a*, *b*). In this work the effect of local embrittlement at the tip of crack-like defects subject to thermal straining during cooling of a weld was demonstrated in small-scale notched bend tests, and the results compared with wide-plate tension tests containing similar defects. This type of embrittlement is relevant to carbon manganese steels, but other types of embrittlement may occur in other weldments or steels. In severe cases of local embrittlement at welds, however, the ruling fracture toughness will be the dynamic toughness of the material immediately outside the embrittled zone, and this will depend upon the strain rate sensitivity of the particular steel.

In the I.I.W. (Anon. 1975) and B.S.I. (Anon. 1976), the methods of assessment were developed to include treatments of different defect shapes and to include treatments for welding residual stresses and stress concentration effects. Crack-like defects are divided into three categories, namely through-thickness defects, surface defects and embedded defects. From the linear elastic stress intensity factor solutions for model cracks of these three different kinds, curves were derived defining the relative severity of these different defect types in terms of the defect dimensions. For through-thickness defects the controlling dimension is the defect length, whereas for surface and embedded thickness defects the controlling dimension is the defect height. The I.I.W. and B.S.I. methods of assessment use an effective defect parameter $\bar{a}$ which has different interpretations for the different types of defect to give the same equivalent severity. Experimental fracture tests have confirmed that these calculations based on linear elastic solutions remain basically valid in the yielding régime.

The treatment of welding residual stresses put forward in the c.o.d. approach has been that residual stresses should be regarded as an increment of applied strain of yield magnitude, additional to the strains due to external loading. It is recognized that this is a conservative assumption, and alternative less stringent proposals are currently under consideration. These alternatives include taking account of lower estimates of the maximum residual stress value in some circumstances, and also considering the effect of the total energy available in the residual stress field on energy release rates (Turner 1979).

In regions of stress concentration the original proposals for the c.o.d. approach again took a conservative view by treating defects at stress concentrations as being located entirely within a uniform strain field of magnitude equal to the peak strain in the stress concentration region. More accurate assessments of the severity of defects in stress concentration regions can, of course, be obtained by taking account of the strain gradients away from the peak value. For the linear elastic régime, values of stress intensity factors at defects in stress concentration regions can be calculated by numerical analysis methods for particular cases, but solutions for the yielding régime are at present relatively few. It has been suggested that provided yielding is contained, a sufficiently accurate estimate of severity of defects may be obtained by using linear elastic solutions with plastic zone corrections (Sumpter & Turner 1976). The whole question of design curve relationship and critical values of fracture toughness is considered later.

A number of papers have been published by authors from the Welding Institute concerning use of the c.o.d. approach in the assessment of defects, and selected aspects of these are discussed later.

Current position of c.o.d. approach and relation to other methods of assessment of defects

It should be emphasized that the c.o.d. approach is in no way competitive with linear elastic fracture mechanics, but seeks to provide an extension to l.e.f.m. that can be applied to welded steel structures in common use. The detailed application of the method is best summarized in the British Standards Institution documents (Anon. 1976) and the revised version issued as a B.S.I. Published Document in 1980 (Anon. 1980).

The B.S.I. document includes both l.e.f.m. and c.o.d. methods of assessment of defects, and also permits other methods to be used if agreed between the various parties involved. Guidance is given on the use of the c.o.d. method both for assessing the acceptability of known detected defects, and for the setting of acceptance levels for defects in advance of construction for particular applications. For welded structures with stress concentration regions and/or residual stresses, the l.e.f.m. methods are not acceptable if local yielding occurs but guidance is given on using the c.o.d. method for such cases. This document also includes acceptance levels for types of weld defect other than crack-like or planar defects, and also gives guidance on the significance of defects on fatigue behaviour.

An alternative method of assessment of defects has been developed by research teams in the Central Electricity Generating Board (C.E.G.B.), and presentations on this alternative method (known as the C.E.G.B. approach) are made in the paper by Williams & Neate (this symposium). The method is based upon the two-criteria approach (Dowling & Townley 1975), with the extremes of behaviour controlled by linear elastic conditions at one end and by plastic collapse at the other end. The interpolation between these conditions is achieved by a non-dimensionalized curve based on the post-yield fracture mechanics treatment due to Heald *et al.* (1972). This interpolation curve is closely related to the c.o.d. design curve concept in that it is derived from the strip yield model. The C.E.G.B. approach considers applied loading conditions, however, and does not consider the relation between applied strains and crack tip conditions. Furthermore, the deviation from linear elastic conditions and the achievement of collapse load conditions are assumed to occur at fixed points on a non-dimensional diagram of the ratio load/critical l.e.f.m. fracture load against load/plastic collapse load. These assumptions cannot enable a single design assessment curve to be used for assessing the effect of known defects.

The C.E.G.B. approach appears straightforward in its presentation. In practice it is not incompatible with the c.o.d. approach but in general it gives comparable results except where different assumptions and detailed treatments are adopted, for example at stress concentration regions. One difficulty, however, is the assessment of fracture toughness in the C.E.G.B. approach to enable the l.e.f.m. ratio to be calculated. For ordinary structural steels it is not generally possible to make valid measurements of plane strain fracture toughness under l.e.f.m. conditions at normal temperatures and slow loading rates. The deviation from plane strain conditions will be controlled by the absolute defect size, plate thickness and yield stress, but not necessarily by the collapse load condition. There is, therefore, inherent uncertainty about the linear elastic limit of validity in this approach, although in practice with relatively small defect sizes this does not seem to be serious. Work on the treatment of residual stresses by this approach is also now being done.

Much attention has been given in recent years to the J-contour integral analysis for elastic plastic fracture mechanics, and again there is a separate contribution to this Discussion Meeting in this area, by Turner. The J-contour integral method has close analytical relationships with the c.o.d. approach, although it is claimed to have a more rigorous theoretical basis. For the assessment of fracture toughness it has been suggested that a critical value of the J-contour integral at fracture calculated from the total work done on the toughness test specimen up to fracture is a measure of fracture toughness, which can be related to l.e.f.m. plane strain fracture toughness (Begley & Landes 1972). It has also been suggested that this critical value of J is closely related to critical c.o.d. by the formula

$$J = m\sigma_y \delta,$$

where m depends upon constraint.

As discussed later, the question of the effect of constraint on critical c.o.d. values is of importance, but the effect of constraint on critical values of J, interpreted as an absorbed work rate term, has still to be resolved.

For the application of elastic plastic fracture mechanics with J-contour integral methods, two practical approaches have been suggested. The first of these is that in situations of contained yielding it is adequate to use l.e.f.m. solutions with a plastic zone correction, and the second is the proposal of J-design curves discussed by Turner (this symposium). In practice the c.o.d. design curve and J-design curves are closely similar for simple geometries in which the defect is a small proportion of the total cross sectional area. As mentioned previously, analyses of the effect of residual stresses from the point of view of the J-contour integral approach are also now being put forward that suggest a less severe effect than the addition of a strain increment of yield magnitude. These proposals must be examined in the light of experimental results and service failures on structures where residual stresses were known to be a factor and where the c.o.d. approach has successfully accounted for the failures.

Much attention has been focused recently on research into stability of tearing fracture by using J-contour integral or c.o.d. resistance curves. It has been suggested that the important parameter controlling the stability of tearing is the tearing modulus (Paris *et al.* 1977):

$$T_{mat} = (E/\sigma_y^2)\,(\mathrm{d}J/\mathrm{d}a)$$

compared to applied loading conditions. This tearing modulus is effectively controlled by the slope of the resistance curve, and the important aspects of applied loading conditions include the stiffness and energy available in the structure. It should be noted, however, that research has shown that although the c.o.d. resistance curve for displacement at the original crack tip shows the same features as the J-resistance curve, the instantaneous opening displacement at the moving crack tip appears to remain constant (Turner 1978). The implications of this on critical values of fracture toughness are discussed later.

Applications of the c.o.d. approach

The c.o.d. approach to assessment of defects has been widely used in the investigation of failures and in the selection of material toughness requirements and specification of allowable defect sizes in construction.

In the assessment of failures it has been found that the c.o.d. method gives a conservative estimate of allowable defect sizes compared with the actual defect size that precipitated failure. This is inherent to the method, because of the upper bound nature of the design curve. Comparison of predictions of allowable defect sizes with actual defects in wide plate tests at the stress or strain level that caused initiation of fracture, with allowable defect sizes calculated from bend test toughness results and the c.o.d. design curve, has shown an average safety factor of about 2.5, and suggested the design curve to have 95% confidence (Kamath 1978). These results include toughness scatter. The degree of conservatism has been one feature subject to criticism by some industrial users, and this is discussed further later.

Although the c.o.d. approach has been used in the offshore industry, there has been an unfortunate tendency for some specifying authorities to compound safety factors and insist on excessively stringent requirements as mandatory. Used intelligently as the basis for guidance, the approach allows selection of appropriate welding consumables, welding procedures and non-destructive testing limits. The features that cause particular difficulty are the definition of the critical value of c.o.d. when slow stable tearing initiation occurs, and the wide scatter in toughness test results. Both of these problems are also inherent in the C.E.G.B. and J-contour integral approaches, but the problems tend not to be given the same attention in these cases.

There are many cases in welded structures where defects that are inherently small may occur, and it is relatively easy to show with the c.o.d. approach that such defects are within allowable tolerances for non-fatigue situations, provided very low toughness conditions are avoided. For example, surface defects of height 3 mm, and buried defects of height 6 mm, would normally require a minimum critical c.o.d. at the minimum service temperature of only 0.04 mm, allowing for design stresses of two-thirds yield and full yield residual stresses. Such a low toughness value is not difficult to avoid in many normal structural applications for operation at U.K. atmospheric temperatures with minimum precautions. Defect sizes of this order are typical of those associated with a single run of manual welding, and are also about at the limits of non-destructive testing for measurement in simple butt weld joints. It should be noted that the inherent dimensions of slag inclusions and porosity are also of this order, and although such defects would be expected to be less severe than planar defects, even moderate toughness is sufficient to avoid fracture problems from them.

The c.o.d. approach has also been used on many occasions independently by the author and others to assess the acceptability of known detected defects in particular cases, and has been found suitable for general guidance purposes.

Limitations of the c.o.d. approach and current research areas

Toughness measurement

Two features of toughness measurement outside the plain strain l.e.f.m. régime cause problems to all methods of assessment of defects including the c.o.d. approach. First, the onset of crack extension by stable tearing presents the difficulty of whether this same mode of cracking will occur in the service situation, and secondly whether it will also be stable in that situation.

In research on the *J*-contour integral methods it has been suggested that plane strain l.e.f.m. fracture toughness measurements can be derived from small-scale laboratory tests provided the specimen thickness satisfies the requirement

$$B > 25\, J_{Ic}/\sigma_y.$$

In the c.o.d. approach it has been recommended that tests should be carried out on the actual thickness of interest, unless valid plane strain l.e.f.m. results are obtained at a lower thickness. It must be recognized and accepted much more widely than at present, however, that a single parameter measure of fracture toughness cannot be expected to be adequate for all situations. In particular, the degree of constraint and triaxiality of stress at the crack tip will have a major influence on the onset and type of fracture in structural steels. Once yielding occurs in the laboratory specimens, the constraint will be markedly affected by the type of specimen. For example, in order of increasing constraint, common types of laboratory test specimen would be expected to rank as follows: centre notched tension (low constraint), single edge notched tension, compact tension, notched bend, double edge notched tension. Further variations in constraint would be expected due to defect size/ligament size ratios, and due to crack front curvature. Since the notched bend and compact tension tests are of medium to high constraint, it is more likely that lower toughness results would be obtained in such tests where general yield occurs than would be obtained in a service situation. It is not surprising, then, that c.o.d. bend test results generally give very conservative predictions of allowable defect sizes in centre notched plate test situations, because the constraint factors are different. It is also important to recognize that in practical service situations the through crack and embedded crack are likely to be low constraint situations, and the surface crack of only moderate constraint unless high bending stresses are present. Experimental and theoretical work on the effects that control constraint, fracture mode and initiation toughness is currently in progress in several programmes in the U.K., including the author's.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Mention has already been made of the assessment of stability of tearing fracture by the tearing modulus, T_{mat}. Experimental work has shown that the slope of the resistance curve varies with type of fracture test specimen but that the worst case is recorded for notched bend specimens. Since, apart from any highly constrained situations at stress concentration regions, the notched bend test probably gives a conservative estimate of constraint compared with most service situations, and the notched bend test gives a conservative resistance curve, it would seem entirely reasonable to accept that if slow stable crack growth occurs in a notched bend specimen of full thickness, the same stable crack growth will occur in practice in service before instability. This suggests that it is not necessary to limit the critical fracture toughness event to the first extension of fracture, but that in notched bend tests the critical value may be taken to be close to the maximum load condition. It has previously been suggested that the appropriate value is the value of c.o.d. at 95% of the maximum load in cases where slow tearing behaviour occurs, and present research results appear to support this.

A further problem in the assessment of toughness measurements is the statistical scatter that occurs. Current research at U.M.I.S.T. is looking at methods of relating characteristic values of toughness results to overall probability of failure, and methods of assessing the characteristic value from a small number of test results. This will be the subject of other publications.

Design curve aspects

In seeking relations between applied loading, crack size, and local crack tip conditions when yielding occurs, Burdekin & Stone (1966) analysed the strip yield model for overall strain on a gauge length $2y$, as well as the opening displacement at the real crack tip, at the same values of the ratio applied stress/yield stress. It was found that the resulting curves of non-dimensional c.o.d. against strain were dependent on the ratio crack length/gauge length. The model assumed plane stress conditions, with yield at the crack tip occurring at the uniaxial yield stresss and the overall strain was that relevant to the cracked structure. Experimental results on aluminium sheet confirmed the analysis in the low-strain region. In the high-strain region the theoretical curves became linear, of slope such that displacements at the crack tip were equal to overall displacements at gauge length points.

Further extensive series of tests on double edge notched steel plate tension tests showed, however, that the theoretical dependence on the crack length/gauge length ratio did not occur in practice (Burdekin & Stone 1966). At the time this discrepancy was attributed to triaxiality and work hardening effects. It was accepted that the experimental behaviour in the double edge notched steel tension tests was representative of the way in which cracks in real structures would behave, and these results were therefore used as the basis of the c.o.d. design curve, drawn as an upper bound to the experimental results. Some criticism has been expressed in the past that the strain in the design curve axes was that of the cracked structure in the experimental tests, whereas for application purposes the strain used is that in the structure in the region of a crack as if the crack were not present.

The reasons for the different behaviour of the double edge notched plates and the strip yield model can be understood from consideration of the work of Soete & Denys (1979) and the J-contour integral design curve analyses of Turner (this symposium). Soete & Denys have carried out several series of centre notched steel tension plates on different combinations of strengths of materials and welded joints. They found that at crack lengths below a certain value (termed by them critical crack length), the crack did not influence the yielding pattern of the plate significantly, and general yield occurred over the whole plate length. At crack lengths above this value, yielding occurred by slip line mechanisms from the crack tips on the net section only. This critical crack length was dependent on the strain-hardening characteristics of the material, and to some extent on plate width. In the analyses of Turner (this symposium), the overall behaviour of a cracked structure is divided into four different régimes, namely linear elastic, contained plasticity, net section yield and gross general yield. The strip yield model analyses of Burdekin & Stone (1966) effectively consider the first three of these régimes, but the spread of yielding is confined to the cracked section, so that dependence of strains on gauge length is inevitable. The variations in the crack length/gauge length ratio for the double edge notched steel plate tension tests were achieved in practice by variations in notch depth (a) from 12 to 225 mm on a fixed gauge length ($2y$) of 1 m, the plate width also being 1 m.

The shallow depth edge notches were not sufficient to restrict yielding to the cracked section, so that in these cases general yield occurred over the whole plate length, and the displacements at the crack tip were lower than those at the gauge length positions. The theoretical relation, from the strip yield model for the higher values of crack length/gauge length ratio were consistent with the experimental results for the deep double edge notch tension tests, and in these cases yielding would have been confined to the net section only. This explains why in practice all of the experimental results fell into one general area of the curve of non-dimensional c.o.d. against strain.

An important implication from the above arguments is that where the crack is smaller than the size to cause yielding on the net cross section, it is immaterial whether the strain is determined in the presence of the crack or in its absence. Clearly, cracks of a size to cause yielding on the remaining general cross section would be in the category of causing general plastic collapse, and would be eliminated by consideration of that mode of failure.

It is also important to consider the implications of type and extent of yielding on the behaviour of part-thickness surface or embedded defects, rather than the through-thickness type of crack implicitly assumed in the arguments above. For part-thickness defects of limited length, if the length is less than the critical length of through-thickness defect to cause net cross sectional yielding, then the part-thickness defect will also behave as if in a uniform strain field as far as overall behaviour outside its length is concerned. The ligament of material in the thickness direction will be the most severely loaded, however, and precautions must be taken to avoid snap through failure of the ligament and the development of a through-thickness running crack of length equal to the length of the original part-thickness defect. For these reasons, the ruling dimension for characterizing a part-thickness defect, when the net section stress on the remaining ligament in the thickness reaches yield stress, is taken as defect length plus defect height, This allows for the additional displacement that would occur at mid-length position within a through-thickness crack compared with that at the ends of the crack, to ensure that the displacement along the remaining ligaments of part-thickness defects is not underestimated. As noted previously, the constraint and triaxiality in the remaining ligaments are likely to be low, unless bending stress are present, or two surface cracks grow towards each other in the same plane.

In addition to consideration of the above areas, current research is looking at methods of predicting relations between applied strains, defect size and crack tip conditions in strain gradient and stress concentration regions, which are less conservative than assuming a uniform strain of peak magnitude, and do not demand a finite element elastic plastic analysis for each individual case.

Application to weldments

Two aspects of the assessment of the significance of defects in weldments already referred to merit further consideration. The first of these is the effect of variations in strength and toughness between adjacent regions in a weldment. Attempts to measure toughness by current standard J_{Ic} testing methods on bend or compact tension specimens with the crack in a butt welded joint, and arms of different strength material, will certainly give incorrect results. Indeed, interpretation of the significance of the J-contour integral in a complex situation of varying material stress–strain relationships is a wholly new field for further research. The c.o.d. approach attempts to focus on behaviour at the crack tip and hence is less prone to such problems than the methods with remote measures. Nevertheless, slip line fields may be affected by such material variations, and care must be exercised in relying on calibrations between crack tip and crack mouth displacements. The effect of overmatching strength in transverse butt welds in protecting against fracture has of course been known for many years.

The second aspect is the effect of residual stresses on defects in service. There is currently much discussion on their severity compared with service loading from a fracture mechanics point of view. One must distinguish between the reaction type of residual stress, where a whole panel or component is left in residual tension reacted by the surrounding structure, and the self-balancing type of residual stress, where the stresses at the weld are reacted within the same panel or component in the parent material adjacent to the weld. The former type act over a much more extensive zone than the latter, and may well be equivalent to a uniform stress under fixed grip conditions. There are nevertheless many examples of short arrested brittle fractures occurring under the self-balancing type of system without external load. For defects that are small compared with the extent of the residual stress zone in an as-welded structure, it remains the case that the residual stresses must be regarded as equivalent to an increment of strain equal to yield. If cracks form after welding of a size comparable to the residual stress zone, there will be relaxations in the residual stresses and the energy balance conditions will alter. It is in these areas that current debate is occurring.

Basic design philosophy

The present trend in Europe and the U.K. in the structural field is for design methods to be based on limit-state design principles, in which the structure is designed to have an equal probability of failure by all possible modes. No design codes include a satisfactory treatment for fracture on these lines, but part of the work of the research group is aimed at this problem. This requires the use of statistical methods of assessment of scatter of fracture toughness, and of distributions of occurrence of defects, and their interaction. Attention is currently being paid to statistical methods looking at the interactions of tails of distributions, and to the appropriate types of distribution for defects and toughness.

Conclusions

The crack opening displacement approach to assessment of the significance of defects has been successfully applied to defects in welded structures for over 10 years, as a relatively simple but conservative extension to linear elastic fracture mechanics methods. Rigid application without consideration of additional factors will sometimes lead to excessively conservative and stringent requirements. Among the reasons for this are the following.

Critical c.o.d. measurements of fracture toughness are dependent on material, temperature, strain rate and triaxiality of stress. Triaxiality is itself affected by geometric effects of thickness, and of type and geometry of fracture test specimen. Bend and compact tension specimens will often have a higher triaxiality condition than many service situations outside the limits of l.e.f.m. methods, and hence give a lower and more conservative estimate of toughness relevant to the service situation. Recent research appears to confirm that the critical value of toughness in a bend or compact tension test where stable tearing occurs may be taken as the value just before maximum load for a test-piece of standard geometry.

The c.o.d. design curve is not greatly dissimilar from design curves put forward for the *J*-contour integral and C.E.G.B. approaches. The reasons for differences between experimental behaviour and theoretical strip yield model analysis have been explained as depending upon whether net section or gross yield occurs. In practice, defects causing net section yield will be excluded by consideration of yield and collapse behaviour, so that the c.o.d. design curve does represent behaviour in the region beyond l.e.f.m. before collapse. The C.E.G.B. approach is expressed in terms of load rather than strain, and does not therefore consider the possible deviations of strains from the strip yield model analysis.

The c.o.d. approach has advantages when the assessment of toughness of weldments with varying material strength has to be carried out.

Current work is aimed at reducing the uncertainties and conservatism of present approaches for assessment of the significance of defects when valid plane strain l.e.f.m. techniques cannot be used. It is hoped to be able to extend the treatments in a manner compatible with limit-state design methods with the use of statistical methods for assessing characteristic values of toughness and for assessing interactions between toughness and defect distributions to give overall probability of failure.

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Discussion

B. A. Bilby, F.R.S. (*Department of the Theory of Materials, University of Sheffield, U.K.*). When discussing the relative merits of J and δ it should perhaps be remembered that the symbol J is used in several different ways. In particular, use is made both of a definition of J in terms of a line integral and in terms of the variation with crack length of areas under load–extension or moment–angle curves. These definitions are equivalent strictly only for elastic materials, linear or nonlinear. Since most experimental measurements are based on the determination of these curves, it might be helpful if different symbols were used for these two definitions, and indeed also for the various other integrals related to J that coincide with it for elastic materials but differ from it under more general conditions.

It should also be noted that there are two extreme approaches to the fracture problem. The first seeks to avoid as far as possible any discussion of the details of the physical processes occurring at the crack tip and looks for one or more characterizing parameters whose critical values, measured in the testing laboratory, can be used to assess the safety of structures. The second approach puts more emphasis on improving our natural knowledge of fracture, in the belief that this will ultimately lead to a greater control of it. Clearly, despite the pressing demands on the engineer for immediate decisions, both approaches must be pursued, not least because changes in the physical processes of fracture can alter the characterizing parameters dramatically.

However, there are some half-way houses between these two extremes. One is to make a very simple theory and try to back up its predictions with empirical results. An example of this approach began with the use by Cottrell of the D.B.C.S. model and a critical displacement criterion. Related approaches have also been developed, both at the Welding Institute and within the Central Electricity Generating Board. The D.B.C.S. curve can provide an interpolation between low stress failures according to linear elastic fracture mechanics and high-stress failures at a stress comparable with the strength of the material ahead of the crack. In the development discussed at this symposium by Harrison & Milne, the high-stress failures are linked with plastic collapse. The resulting failure locus incorporates linear fracture mechanics at one end and failure by plastic collapse at the other. The method is thus not wholly an empirical one and, backed by much experience of actual failures and the inclusion of appropriate safety factors, seems to be of practical use. It must never be forgotten, however, that the D.B.C.S. model used is extremely simple. No effort must therefore be spared to extend this approach by using models that include more features of the real crack tip field; for example, by using relaxation on slip planes inclined to the crack itself. It seems particularly important that this should be done if problems associated with crack growth are to be discussed because, as Rice has emphasized, the simple D.B.C.S. model has no wake.

F. M. Burdekin. Professor Bilby's perspective view of the J, c.o.d. and C.E.G.B. approaches is valuable for drawing attention to both the limitations and attributes of these methods. Although numerical studies have shown equivalence between the line integral and energy absorption interpretations of J for materials with plasticity characteristics, this does not necessarily imply total equivalence of the different definitions of J for all materials and all geometries. It is therefore particularly important to distinguish the particular version of the definition of J being used in particular circumstances.

It is agreed that both the fundamental and the applied approaches to fracture should be followed jointly, since both have a contribution to make to our understanding of fracture. The strip yield model considered to some degree in both the c.o.d. and C.E.G.B. approaches is a valuable baseline but performance in experiments and in service must be taken into account, together with the theoretical predictions. Nevertheless we must continue to strive to improve the models used for theoretical analysis to reproduce the true behaviour of the material.

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