Fracture Control in Welded Structures

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INTRODUCTION

The importance of the design function is paramount in the assessment of structural integrity. All welded structures will contain flaws of some form or other and it is the function of the designer to determine the acceptable levels of flaws for any particular service environment. For fracture-safe structures the three relevant parameters, fracture toughness, flaw size and acting stress or strain level, must be manipulated to determine the most satisfactory design procedure. Most structures will be designed by traditional procedures, that is the structure will be sized on strength alone and the materials for the project will be chosen. At this stage a consideration of the risks of brittle fracture will usually be made by reference to material properties such as K_{1c} or COD. The question the designer asks at this stage is whether or not a fracture problem exists and this may be answered in many cases by reference to service experience or existing fracture toughness data. If the initial assessment of the problem indicates a likelihood of fracture it is essential to employ the techniques of linear elastic fracture mechanics (K_{1c}) and general yielding fracture mechanics (COD) to quantify this risk. This involves the assessment of candidate materials and welding processes using the techniques of linear elastic fracture mechanics and general yielding fracture mechanics. Engineering decisions with regard to the significance of weld defects in terms of the duty cycle of the plant under consideration may then be made. It is the purpose of this paper to describe such methods of assessing the significance of flaws.

DEFECT TOLERANCE EQUATIONS

The defect tolerance parameters are those which are proportional to the flaw size to cause failure and result from a consideration of the equations relating plane strain stress intensity factor and critical crack opening displacement to the applied conditions of load and geometry. For the simplest case of a through crack in an infinite plate, and the acting stress expressed as a function of yield stress (σ_Y):

$$a_f = C_1 \left(\frac{K_{1c}}{\sigma_Y}\right)^2$$

and $a_f = C_2 \left(\frac{\delta_c}{e_Y}\right)$

where a_f is the flaw size to cause failure and C_1 and C_2 are constants. These constants depend in the simplest case on the ratio of the acting stress to the yield stress. For more realistic cases, the constants may also include the effect of finite plate width and flaw shape. It should be noted that, for the linear elastic defect tolerance equation, the value of σ_Y relates to the σ_Y which is used as a design basis; in other words in most cases the value of σ_Y will be the value of the room temperature yield stress which has been used to determine the design stress. Whereas the e_Y term in the general yielding expression, relates to the value of $\frac{\sigma_Y}{E}$ controlling the extent of the plastic zone ahead of the crack tip.

One of the main tasks in fracture mechanics at the moment is the definition of the values of C_1 and C_2 for specific detail geometries. There are several methods of defining these constants and the techniques of elastic finite element analyses will yield the relationship between K and load for a wide range of geometries so that the value of C_1 may be determined. It is necessary, however, to resort to elastic-plastic finite element analyses to define the constant C_2. It is also possible to determine C_2 from experimental measurements of crack opening displacement and applied stress or strain and this paper describes tests carried out to determine the relationship between developed COD and applied strain in large notched plates of different geometry.

EXPERIMENTAL DETAILS

To determine the relationship between COD and applied overall strain the following test series on plates nominally 0. 9 m, square have been done.

Series A – 57 mm thick mild steel double edge notched tension tests

Series B – 25 mm thick carbon manganese steel (BS 4360 Grade 43C) centre notched tension tests, welded, double chevron notch in plate preparation.

Series C – 25 mm thick carbon manganese steel (BS 1501-224) surface notched tension tests.

Series A tests were instrumented with the rotating paddle type COD meter to determine crack opening displacement at the tip of a sawn notch as loading progressed. Tests were carried out over a range of temperatures -60°C to 0°C, as summarised in Fig. 1. Displacement measurements for all tests were obtained from strain gauged proving rings spanning the overall plate width and end beams of the loading rig. Overall strain measurements determined in this way were also checked against strain measurements obtained from local gauge lengths over the surface of the plate using an extensometer. Plots of applied load against proving ring output were also obtained for each test. To enable the results to be normalised in terms of yield strain, tensile tests were also done on No. 12 Hounsfield specimens (see Fig. 1). From the load/COD/overall deflection records it was possible to obtain a relationship between crack opening displacement and applied strain. The strain data were determined from the nominal end displacement divided by the plate width. To reduce the temperature dependence of the results the crack opening displacement data were normalised as $\Phi = \dfrac{\delta}{2\pi e_Y a}$. The results of these tests as Φ against $\dfrac{e}{e_Y}$ are shown in Fig. 1. These data range up to a strain level up to about 2. 4 e_Y and a Φ value of about 1. 7.

The results at the two tests of series B as Φ against $\dfrac{e}{e_Y}$ are shown in Fig.2. These values were obtained from the rotating paddle COD meter near the surface of the plate and may be regarded, if anything, as an overestimate of the developed COD which would occur at the mid thickness position. The test at 0°C remained unbroken after two loadings, that is the first load is applied and the limit of extension of the loading rig is reached and the testpiece unloaded.

The sharp increase in Φ values at $\dfrac{e}{e_Y}$ corresponding to a value of about 2 for the test at +10°C is attributed to the added contribution to the measured crack opening displacement by the stable ductile movement of the crack.

Series C plates contained a single surface notch at the centre. The notches were cut with a slitting wheel in the surface of the plate to a depth of about 13 mm. The first plate was tested with a notch finished to a width of 0. 15 mm and the notch in the second plate was fatigue cracked at a low stress intensity factor range.

For the mechanically notched plate a rotating paddle type COD meter was inserted at the centre of the crack to measure at the bottom of the sawn notch. Both tests were done at room temperature to avoid problems of condensation at low temperatures. The results of the sawn notch plate are shown in Fig. 3 as Φ against $\dfrac{e}{e_Y}$ using the measured values of COD. The Dugdale solution for a through crack in tension for $\dfrac{\sigma}{\sigma_Y} < 1$ is also shown in this figure. It can be seen that the surface notch configuration permits much larger developed COD for the unit applied strain than either the double edge notched tests or the centre notched tests.

For the fatigue notched testplate, measurements of opening displacement were made at the open end of the notch (V_g) using a double beam cantilever clip gauge. Measurements of V_g so determined have been reduced to the equivalent crack tip crack opening displacement and the relationship between Φ and $\dfrac{e}{e_Y}$ determined as shown in Fig. 3. A similar pattern is shown to the results of a sawn notch test – that is, high initial Φ per unit $\dfrac{e}{e_Y}$ for the first loading and the reduced levels for subsequent loading.

IMPLICATION OF THE RESULTS

For comparison purposes the results of all these tests are drawn together and shown in a single plot in Fig. 4. To manipulate the defect tolerance equations, two of the parameters (i. e. flaw size, acting stress or strain and fracture toughness as K_{1c} or COD) must be known. By assuming that the plasticity is contained by surrounding elastic material it is reasonable to relate stresses linearly to strains. A membrane stress or $\frac{2}{3}\sigma_Y$, therefore, would give rise to a stress level of about 2 x e_Y at a geometric stress concentration factor of 3. On this basis it is possible to enter the data of Fig. 4 to determine the developed COD level for a particular geometry. In other words, the constant C_2 may be evaluated. For example, for the Series C tests at $\dfrac{e}{e_Y} = \frac{2}{3}$, $\Phi = 3.0$, i.e. $\dfrac{\delta}{2\pi e_Y a} = 3.0$ and $a = \dfrac{1}{3.02\pi}\dfrac{\delta}{e_Y}$ and for the critical value of COD, $a_f = 0.05\,\dfrac{\delta_c}{e_Y}$.

CONCLUSIONS

It is possible to propose realistic methods of assessing the significance of weld defects provided analytical or experimental compliance calibrations are available to determine the constants which relate the flaw size to cause failure to the defect tolerance parameters. This report details such methods for three plate geometries and wider application of these methods will come when more similar data are available for a wider range of detail geometries.

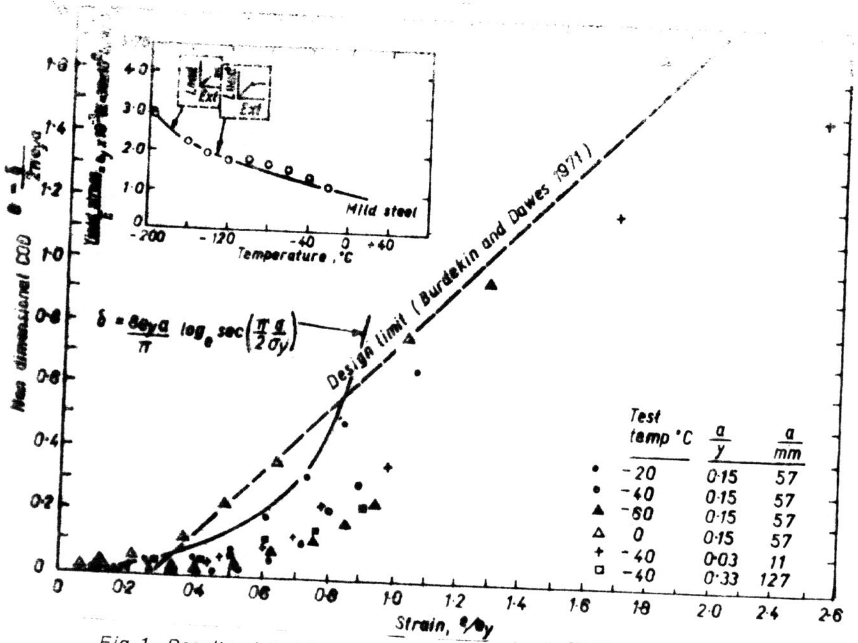

Fig. 1. Results of double edge notched tension tests (DENTT) – Φ against $\frac{e}{e_Y}$.

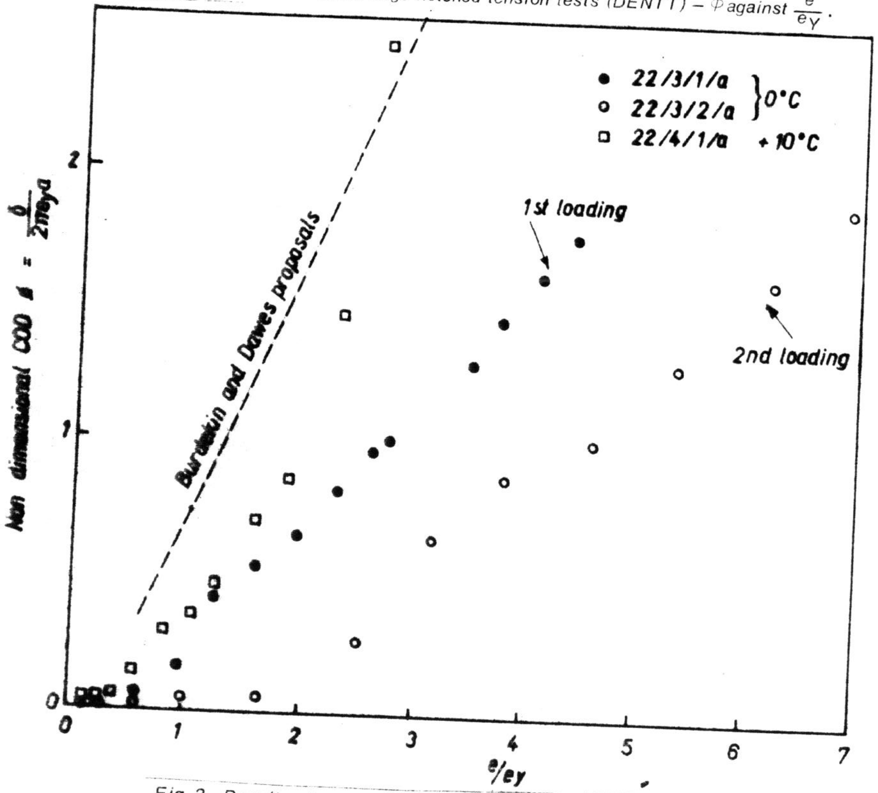

Fig. 2. Results of centre notched tension (welded) tests – Φ against $\frac{e}{e_Y}$.

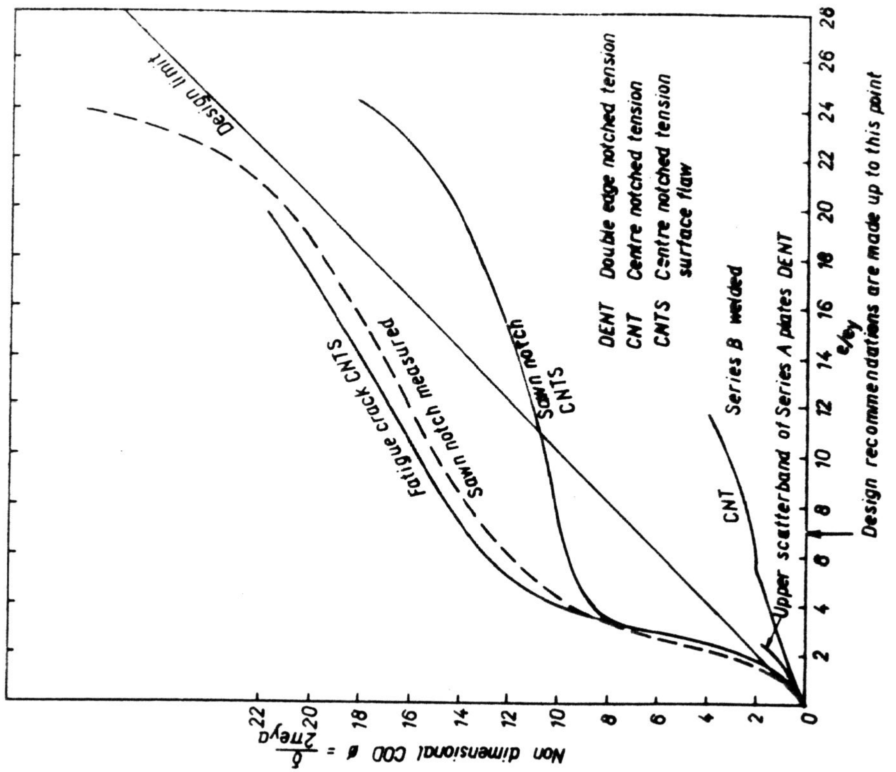

Fig. 4. Summary of Series A, B and C tests.