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The Measurement of Fracture Toughness and the Application of Fracture Mechanics Assessment Methods to Weldments

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ABSTRACT Over the last nine years one of the most widely used defect assessment procedures has been the British Standard document BS PD6493 : 1980 'Guidance on some methods for the derivation of acceptance levels for defects in fusion welded joints'. This document has recently been completely revised and will shortly be reissued.

The principal procedures adopted for fracture and fatigue considerations are outlined and the major changes discussed. Particular attention is given to the revised fracture sections which now combine CTOD procedures with approaches developed in the CEGB R6 documents. A three level fracture mechanics approach has now been adopted dependent on the input data and material being considered and the sophistication of the analysis deemed appropriate.

Two separate routes through the procedures are defined, dependent on whether toughness inputs are in terms of CTOD or K (or K derived from J).

Specific aspects of the Assessment Methods also dealt with in the paper are.

(i) The measurement of fracture toughness for welded joints.
(ii) The effect variability of input data on the safety factors in the assessment procedures.
(iii) The treatment of applied and residual stresses.

In addition, the problem of geometric constraint and the influence of complex loading on fracture performance and prediction is discussed by reference to the behaviour of uniaxial and biaxial wide plates and bend tests over the transition range for ferritic steels.

Introduction

On 15 August 1989 the BSI WEE 37 Committee met and agreed the final changes to the revisions to PD6493 : 1980. This revised procedure is due to appear early in 1991 and is entitled *Guidance on Methods for Assessing the Acceptability of Flaws in Welded Structures*, PD6493 : 1991.

The background to revisions to the fracture sections of PD6493 have been discussed in some detail in references (1) and (2). This paper denotes the latest changes to the revisions and also discusses the recent advances in fracture toughness measurements which are relevant as input to fracture assessment procedures. Particular attention is also given to (i) variability of input data, (ii) the treatment of secondary stresses, and (iii) the influence of complex loading on fracture predictions.

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PD 6493 FRACTURE ASSESSMENT

	a) KNOWN DEFECT	b) LIMITING DEFECT SIZE
REQUIRED INPUTS:	Stress (applied + residual) Defect size Toughness (K_{mat} or δ_{mat})	Stress (applied + residual) Toughness (K_{mat} or δ_{mat})

(a)

ASSESSMENT LEVEL	TOUGHNESS INPUT AND ASSESSMENT PROCEDURE	
	K_{mat}	δ_{mat}
1 SCREENING LEVEL	K_{IC}, Cv or K_J LEFM (with safety factor of 2) procedure	δ_c, δ_u or δ_m CTOD design curve procedure
2 NORMAL LEVEL	K_{IC} or K_J R6 revision 2 procedure	δ_c, δ_u or δ_m modified strip yield model
3 ADVANCED LEVEL	K_J or K-R curve R6 revision 3 procedure	δ_c, δ_u, δ_m or δ-R curve R6 revision 3 based reference stress procedure

(b)

Fig 1 The revised PD 6493 fracture assessment procedure.
(a) Required inputs to the fracture assessment
(b) The three levels of fracture assessment

Summary of revisions to the fracture sections of PD6493

In concept, the revised PD6493 fracture assessment methods should provide all the advantages of the CTOD based approaches combined with those of the CEGB R6 approach, in particular the use of a fracture assessment diagram (FAD). It was also the aim when making the revisions, to take advantage of the latest developments in assessment methods in particular those described in the CEGB R6 Rev 3 **(3)** procedure and in research papers from The Welding Institute (TWI) **(4)(5)**.

A three level approach has been adopted (see Fig. 1) for the revised fracture assessment. Throughout the procedures, alternative treatments are given depending on whether toughness has been measured in terms of K (i.e., K_{Ic} or K_J) or CTOD.

Level 1 is a 'screening level' consistent with the PD6493 : 1980 approach and incorporates linear elastic fracture mechanics treatments (with a safety factor of two on flaw size) and (for steels and aluminium alloys) the CTOD design curve. The major change here is the use of a Failure Assessment Diagram (Fig. 2) in which both fracture and plastic collapse need to be considered (see reference **(2)** for the derivation of the FAD). This treatment replaces the recategorisation procedures in the original document whereby, for

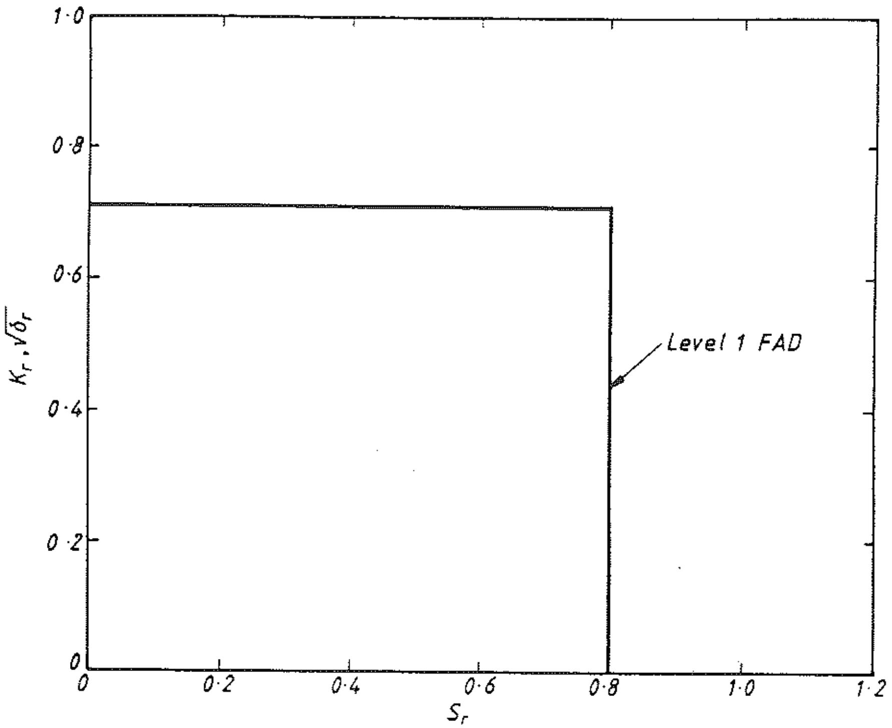

Fig 2 Level 1 failure assessment diagram

example, sub-surface imperfections were recategorised as surface breaking if the remaining ligaments were predicted to fail by collapse. The recategorised defect would then be assessed for fracture. The recategorisation procedure although designed to prevent collapse is an indirect method of assessment and in fact was often overlooked by users of the document.

Level 2 is regarded as the 'normal' assessment route and is based on the strip yield model approach **(5)** which also formed the basis of the CEGB R6 Rev 2 procedure **(6)** (see Fig. 3). There is no inbuilt safety factor in this approach.

Level 3 is regarded as the 'advanced' assessment level where the FAD is interpreted from the relevant stress/strain data for the material under consideration. This level is particularly relevant to high work hardening materials and/or fully ductile materials where the crack growth resistance curve is available and a tearing instability assessment can be performed. For areas such as heat affected zones (HAZs) associated with welds, where a relevant stress/strain curve cannot be measured, the FAD of R6 Rev 3 Option 1 **(3)** has been adopted (see Fig. 4). As with Level 2, this procedure has no fixed safety factor incorporated.

The assessment diagrams of Figs 2, 3, and 4 have axes of K_r or $\sqrt{\delta_r}$ depending on the toughness input and S_r (L_r for Level 3) where K_r and $\sqrt{\delta_r}$ are the ratio of *elastic* driving force (K_I, δ_I) to fracture toughness (K_{mat}, δ_{mat}). S_r is the ratio of applied stress to the collapse strength of the cracked component and L_r is the ratio of applied stress to the yield strength of the cracked component. The effect of plasticity in increasing the driving force is taken into account by the shape of the assessment diagram.

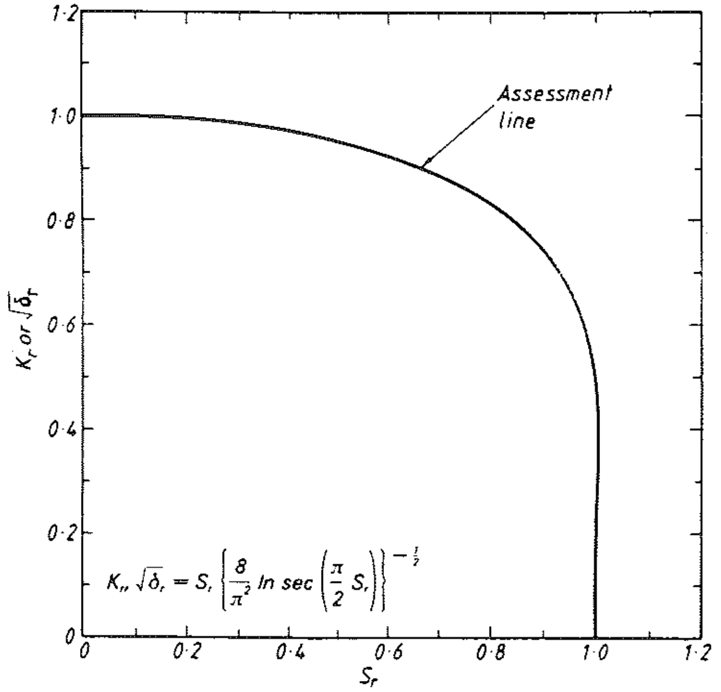

Fig 3 The failure assessment diagram for Level 2

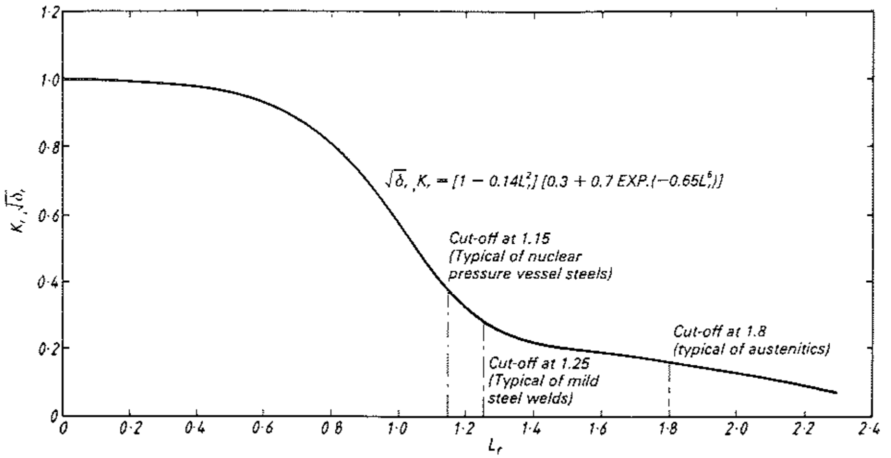

Fig 4 Universal failure assessment diagram for use with Level 3 when relevant stress–strain data is not available

Fracture toughness measurements

Measurement of CTOD

As noted above, the form of toughness data (i.e., whether in terms of CTOD or K) influences the route through the revised PD6493. The sophistication and accuracy of the data also influences the level of assessment adopted. For Level 1, K estimates may be based on Charpy energy levels to derive K_{mat} and an appendix in the revised PD 6493 will cover recommended procedures. For CTOD, δ_{mat} will generally be based on the minimum of three results from three point bend tests where δ_c, δ_u, and δ_m are obtained from full section thickness tests according to BS 5762 or ASTM 1290 (which has recently been released). Initiation of tearing (δ_i) is not normally recommended for Level 1 or 2 assessments, the relevant δ_u or δ_m value being considered appropriate for the assessment procedure. The bend geometry is considered sufficiently constrained to induce cleavage at a lower measured toughness than would be apparent in structurally relevant geometries **(7)**. The philosophy of using maximum load toughness (δ_m) values is fully discussed in **(8)**. However, to ensure conservatism the revised PD6493 suggests that if the ligament in the structural configuration is less than that in the test specimen, the δ_m value obtained from relevant toughness tests should be reduced by the ratio of the uncracked ligaments. This should compensate for the geometry dependence of δ_m with ligament size.

A British Standard entitled 'Determination of the fracture toughness of metallic materials' is currently in preparation which interprets all fracture toughness procedures, e.g., BS 5762, 5447, and will be the first to incorporate procedures for testing weld metal heat affected zones (HAZs). To date, procedures such as references **(9)** and **(10)** define test techniques for weldments. Morland **(11)** has recently reviewed test procedures. One important aspect to note is that the BS and ASTM definition of CTOD differ. In the ASTM procedure CTOD (δ) is defined as

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_Y E} + \frac{r_p(W-a_0)V_p}{r_p(W-a_0)+a_0+Z} \tag{1}$$

where

$r_p = 0.44$ for bend specimens and

$$\left.\begin{array}{l} r_p = 0.47 \text{ for } 0.45 \geqslant a_0/W \leqslant 0.5 \\ \quad = 0.46 \text{ for } 0.50 < a_0/W \leqslant 0.55 \end{array}\right\} \text{ for C(T) specimens}$$

BS 5762 adopts an r_p of 0.4 for the bend geometry. Thus the ASTM formula will result in marginally higher CTOD values than the BS. The BS, incidentally, does not provide for the use of C(T) specimens.

The integrated British Standard procedure will also extend to the consideration of 'pop-in' events, which is currently covered in an appendix to BS PD6493, the same procedure having been adopted for ASTM 1290 based on (unpublished) proposals by Dawes and Reemsnyder as outlined below.

Assessment of pop-in crack extension

Referring to Fig. 5, ASTM 1290 suggests the following course of action.

(a) Draw the tangent QA and a parallel line BC through the maximum load point associated with the particular pop-in under consideration.
(b) Draw the line CD and the line BE parallel to the load axis.
(c) Mark the point F at the intersection of the lines CD and BE.
(d) For loads corresponding to EF/EB < 0.95, calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements V_c or V_u, respectively (i.e., point B in Fig. 5), according to section 8.2 in BS5762 : 1979.
(e) For loads corresponding to EF/EB ⩽ 0.95, the pop-in may be ignored provided that an examination of the fracture surfaces shows:
    (1) no evidence that the maximum pop-in crack extension has exceeded 0.07 a_0 or 0.04 $(W - a_0)$;
    (2) no evidence that the pop-in crack extension has terminated by intergranular cracking, or cleavage in metallic materials other than steels.
(f) For loads corresponding to EF/EB ⩾ 0.95, maximum pop-in extensions > 0.07 a_0 or > 0.04 $(W - a_0)$, or terminal crack extension by intergranular cracking or cleavage cracking in metallic materials other

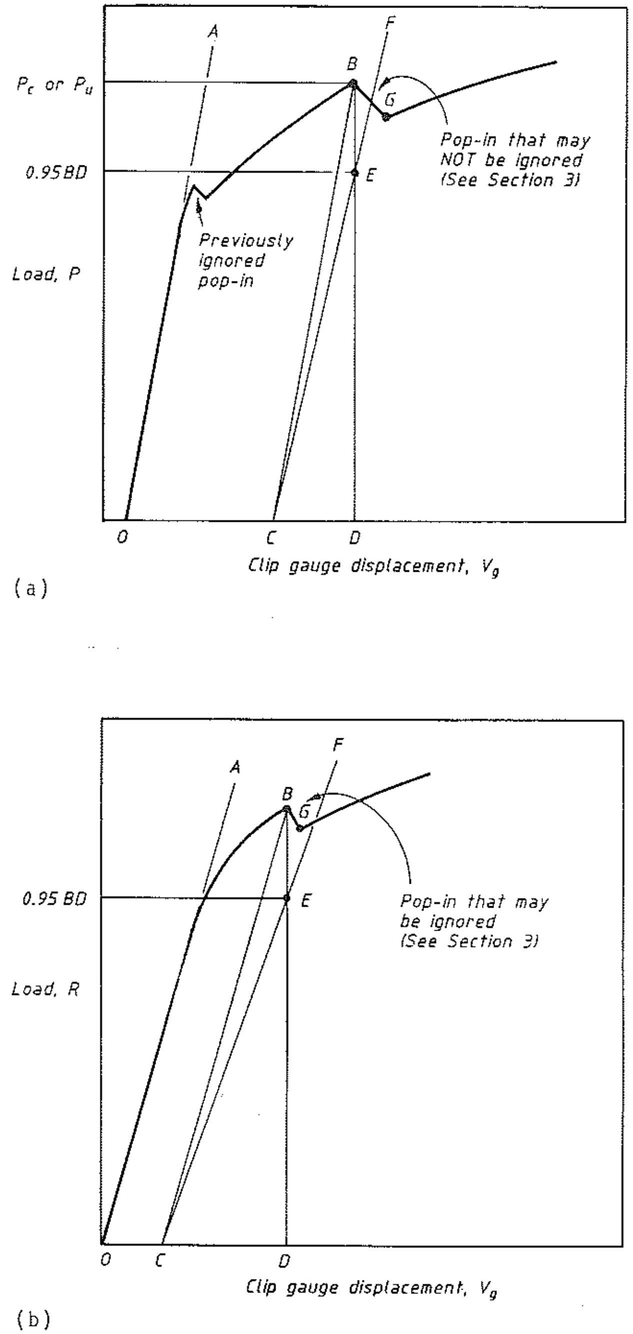

Fig 5 The significance of pop-in as interpreted from ASTM 1290. Note: slope of line CF is exaggerated for clarity

than steels, or calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements V_c or V_u respectively, according to section 8.2 in BS5762 : 1979. Alternatively, when the minimum average pop-in crack velocities and maximum stress wave velocities are measured or known for the particular micromechanisms of crack growth and materials concerned, it may be agreed to ignore the pop-ins provided that specific criteria are satisfied (see reference **(12)**).

Although an individual pop-in may be ignored on the basis of these criteria, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weldment, a small pop-in may be recorded because of fortuitous positioning of the fatigue pre-crack tip. Thus, a slightly different fatigue pre-crack position may give a larger pop-in, which could not be ignored. In such circumstances the specimens should be sectioned after testing, and examined to ensure that the crack tips have sampled the maximum amount of brittle microstructure in the weld or parent metal region of interest.

Variability of toughness data

For Level 2 assessments a lowest bound treatment (i.e., a conservative stress estimate is used together with the minimum of three relevant toughness measurements) can still be adopted to give conservative results. It is recommended by the revision to PD6493 that more tests are carried out and more sophisticated data handling treatments are adopted for Level 2 assessments compared to Level 1. Table 1 gives the equivalent input to the assessment procedure when a larger data is available to give the equivalent confidence to the use of the minimum of three toughness tests **(13)**. The minimum of three has been treated as a characteristic value corresponding to the 20th percentile with 50 percent confidence or 33rd percentile with 70 percent confidence and used as a mean minus one standard deviation.

Limits are also advised on scatter of the data to ensure that individual data points are not unrepresentative. If the minimum δ_{mat} is less than 50 percent of the average of three tests or the maximum is twice the average then a further three tests are recommended.

The revised PD6493 also considers the use of partial safety factors based on the average of the input distributions (see reference **(14)**). This treatment is discussed in an appendix for Level 2 analyses and requires knowledge of the statistical distributions for toughness, stress and defect incidence.

Table 1 Equivalent fracture toughness value to the minimum of three results

Number of tests	*Equivalent value*
3–5	Lowest
6–10	Second lowest
11–15	Third lowest

Ductile tearing assessments

Tearing instability assessments using a Level 3 approach to the revised PD6493 will require the measurement of a relevant resistance curve using procedures such as the EGF document **(15)** (which is based on reference **(16)(17)** and the results of a round-robin exercise **(18)** sponsored by the European Community Bureau of Reference (BCR) and ASTM 1152 can be employed. These test procedures are also reviewed in reference **(11)**.

Stress treatments

The definitions of stresses to be considered for the revised fracture assessments are very similar to those adopted for PD 6493 : 1980. There is a significant change from the 1980 version however, in that more sophisticated stress analyses are allowed for (and indeed recommended) for the higher levels of assessment.

Primary stresses (P) are those stresses conventionally regarded as due to applied loads, such as dead weight, wave, and wind loading, pressurisation etc. In a structure free from imperfections and made from a ductile material, such loads, if steadily increased, would cause failure by plastic collapse.

Secondary stresses (Q) are stresses which are self equilibrating across the net section under consideration and are relaxed by deformation without contributing to collapse. These are normally due to residual welding stresses or thermal stresses. However, in some cases, particularly when analysing specific components, thermal stresses and 'built in' stresses due to fabrication may have to be treated as primary stresses if they are not self equilibrating across the net section due to long range reaction or restraint effects.

Peak stress (F) is defined as that quantity which, when added to the primary and secondary stress components, allows for the presence of geometric discontinuities such as a hole, a welded attachment etc. Thus, defining the stress concentration factor of the discontinuity as K_t, which acts on the primary stresses only, F is $(K_t - 1)P$. In many cases stress concentration effects may be allowed for in the calculation of the stress intensity factor, K_I (e.g., when M_k factors are available for weld toe effects) and in such cases $F = 0$ provided no other major geometrical discontinuities (such as a hole) are present.

Level 1

The treatment of stresses proposed for the Level 1 assessment of the revision to PD 6493 is consistent with the CTOD route in the 1980 version, i.e., the sum of the stresses $P + Q + F$ is taken to act as a uniform stress σ_1 across the entire section containing the defect to be considered. The stresses can either be resolved onto the plane at right angles to the defect, or the defect dimensions can be resolved onto a plane at right angles to the maximum principal stress direction. The linearisation treatment proposed for stresses below yield in the 1980 document for K analysis is now not included at Level 1, but is considered as a Level 2 or Level 3 procedure. It is required for fatigue assessments however.

In structures in the as-welded condition, the tensile residual stress (part or whole of Q) should be assumed to be equal to the room temperature yield strength of the material in which the flaw is located for flaws lying in a plane transverse to the welding direction (i.e., stresses parallel to the weld) and to the lesser of the yield strength of the weld or parent metal for flaws lying in a plane parallel to the welding direction (i.e., stresses perpendicular to the weld).

In structures subject to post weld heat treatment (PWHT), the residual stresses will not in general be reduced to zero. The level of residual stresses remaining after PWHT in welds may be estimated on the basis of stress relaxation tests for weld or weld parent material specimens as appropriate. Where these data are not available it may be assumed for carbon manganese low alloy steels that the stresses after PWHT in an enclosed furnace according to BS 5500 procedures are 30 percent of the room temperature weld metal yield strength for stresses parallel to the weld and 15 percent of the room temperature weld metal yield strength for stresses transverse to the weld. Local heat treatment may leave significantly higher residual stresses and specific assessments should be made for each case.

Level 2 and 3

The stress treatment adopted for Level 1 is very simple and conservative and consistent with the assessment route, toughness inputs, and safety factor assumed for this level. However, where more detailed stress information is available, advantage may be taken of this to achieve more accurate predictions by moving to a Level 2 or 3 assessment. The actual distribution of stresses $(Y\sigma)$ in the vicinity of the flaw is required for input to the assessment. These may be used directly to determine the stress intensity at the tip of the defect using existing solutions or appropriate finite element methods. Alternatively they may be split into membrane and bending components of the primary stress P_m and P_b and the membrane and bending components Q_m and Q_b of the secondary stresses can be obtained by 'linearisation' over the defect length as illustrated in Fig. 6. Thus the primary stress $(Y\sigma)_p$ and the secondary $(Y\sigma)_s$ are made up of the following factors

$$(Y\sigma)_p = \frac{1}{\phi}\left(M_{km} M_m P_m + M_{kb} M_b P_b\right)$$

$$(Y\sigma)_s = \frac{1}{\phi}\left(M_m Q_m + M_b Q_b\right) \tag{2}$$

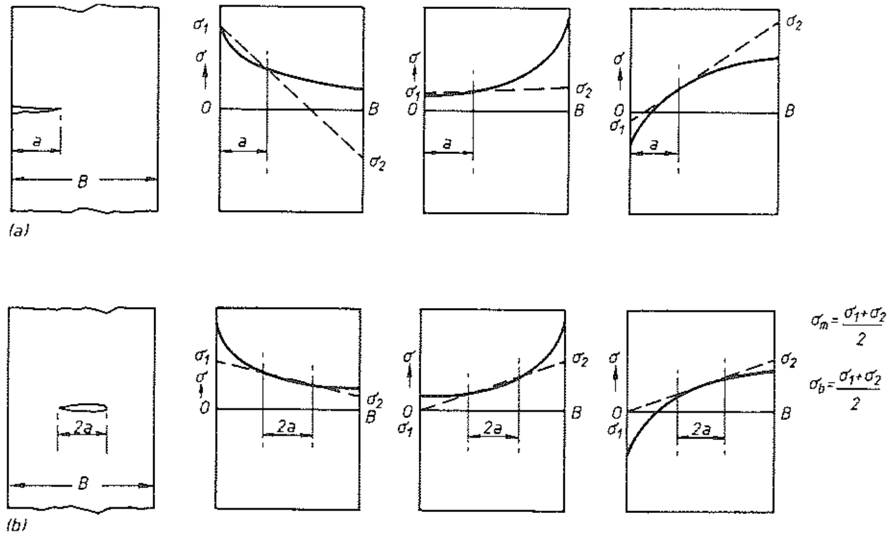

Fig 6 **Linearisation of stress distribution for known defects:**
(a) surface flaws,
(b) embedded flaws.
Note. Any linearised distribution of stress is acceptable provided that it is greater than or equal to the magnitude of the real distribution over the flaw surface

Where Φ is the flaw shape parameter, subscripts m and b donate membrane and bending components of the distributions, and the M factors can be obtained from relevant stress intensity handbook solutions, but are also in diagrams and equations in an appendix to the document.

The peak stress F is not required at Levels 2 and 3 because weld toe effects are included in the magnification factor M_k and additional SCF effects must be allowed for directly on the primary stress $(Y\sigma)_p$ (e.g., where a major geometrical discontinuity such as a hole is present).

When the secondary stress distribution is known, the effects of the interaction between primary and secondary stresses must be allowed for. This is done via the ρ parameter as defined by the CEGB R6 Rev 3 procedure (**3**).

Guidance on the general form of residual stress distributions for use at Levels 2 and 3 is included in the document, (see reference (**2**)). Unfortunately it is relatively rare for the true residual stress distribution to be known with sufficient confidence to permit significant reductions to the conservative assumptions given above. Where the distribution of residual stresses in an as-welded structure is unknown then the residual stress component (σ_R) should be assumed to be uniform and equal to the appropriate material yield strength as for Level 1 (i.e., $\sigma_R = \sigma_m = \sigma_Y$). To accommodate the relaxation of residual stresses with applied loading, a reduction in the residual stress assumed in the analysis is proposed in the revised document, however. The philosophy behind this relaxation is that for high primary stress levels the sum of the net section

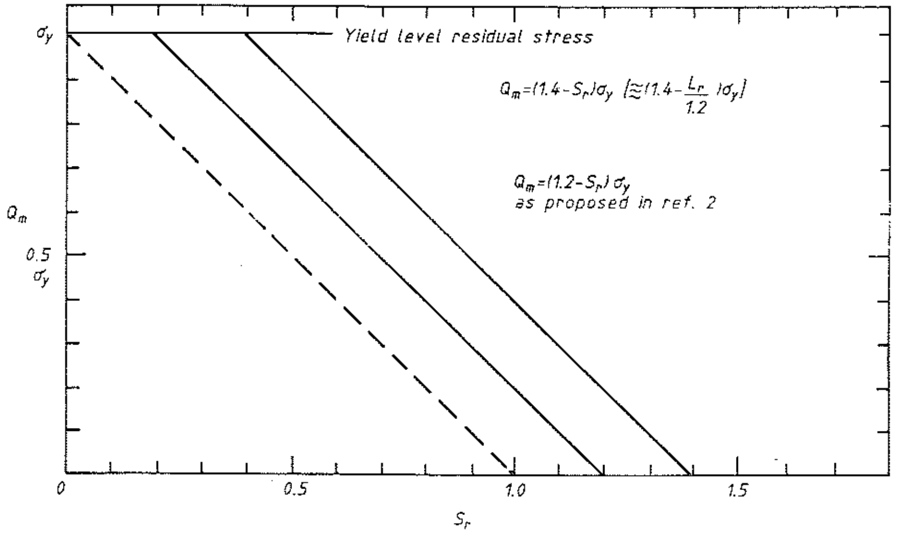

Fig 7 **Comparison of residual stress relaxation treatments**

stress, σ_n, and the secondary membrane stress component, Q_m, will be limited by the flow strength, σ_f, of the material **(19)**.

For a material with no strain hardening, the flow strength equals the yield strength and thus, as S_r increases from zero to 1, so Q_m reduces linearly from σ_y to zero (see Fig. 7). Thus, comparisons of the effect of the flow strength assumption have been made **(2)** on the basis that this linear behaviour is offset for higher flow strength assumptions, as shown in the figure. As an initial assumption, the flow strength was set at $1.2\sigma_y$ **(2)**. Although the assumption of $\sigma_f = 1.2\sigma_y$ gives similar predictions to the Level 1 approach with yield level residual stresses assumed throughout (see reference **(2)** for details), further validation **(20)** has indicated that a level of $1.4\sigma_y$ is necessary to ensure conservatism in specialised circumstances.

This gives the following criteria for the assumed level of residual membrane stress for Level 2 assessments as shown in Fig. 7

$$Q_m = \sigma_y \text{ or } \left(1.4 - \frac{\sigma_n}{\sigma_f}\right)\sigma_y, \quad \text{whichever is the lesser} \tag{3}$$

and for Level 3

$$Q_m = \sigma_y \text{ or } \left(1.4 - \frac{\sigma_n}{1.2\sigma_Y}\right)\sigma_y \quad \text{whichever is the lesser} \tag{4}$$

The influence of proof testing

To demonstrate structural integrity, many fabrication codes, paricularly those relating to pressure vessels, call for a proof test. The significance of proof testing has recently been reviewed **(21)**. An extensive experimental programme (using fracture toughness tests and uniaxial and biaxial wide plates) is currently in progress at The Welding Institute designed to assess the significance of proof loading on subsequent performance **(22)**.

Results to data on parent materials ASTM A533B and BS 1501-224-490B, indicate that the maximum benefit occurs on the lower shelf where apparent increases in K_c (linear elastic stress intensity factor at fracture) of >40 percent are achieved (see Fig. 8). In the transition régime, only marginal increases are evident. In terms of CTOD and J a reduction in toughness in the transition régime was measured, but the load bearing capacity of the specimen was not reduced. In fact, the load to cause structural failure after the proof load actually increases at lower temperatures, provided the level of the proof load is above the load which would have caused failure at the lower temperature.

Tests on as-welded panels, without cracks, indicate that longitudinal residual stresses can be reduced from 400 N/mm^2 to 100 N/mm^2 by the application of a preload in a direction perpendicular to the welding axis (Fig. 9). In general, the amount of reduction is of the same order of magnitude as the level of the preload stress **(19)(22)** and is similar to that achieved by PWHT procedures. The distribution of stresses is different for mechanically stress relieved and PWHT welds, however.

In recognition of the reduction of residual stresses by a proof test, for fracture assessments at lower temperatures, the revisions to PD6493 allow a reduction of the assumed secondary membrane stress Q_m from the application of equations (3) or (4) using the proof test conditions, i.e., for calculations of Q_m using equations (3) and (4), σ_y and σ_f relate to the yield and flow properties at the temperature of the proof test and σ_n is the net section stress induced by the proof test.

The influence of constraint

The adoption of two separate routes through the fracture assessment procedures of the revised PD6493 (see Fig. 1), dependent on whether toughness data is in terms of K or δ, is necessitated by the traditional problem of what constraint or m factor to apply for the structure.
Where m is given by

$$\frac{K_{\mathrm{mat}}^2}{E} = m\sigma_y\,\delta_{\mathrm{mat}} \tag{5}$$

If both J and δ_{mat} are determined from a single test and the J value is subsequently used to derive K_{mat}, then m is of course known for that material with that test geometry. Use of the respective K_{mat} and δ_{mat} values from this test will undoubtedly result in a larger crack size prediction for the K route than for the δ route using the revised PD6493, since an m of 1 (plane stress) is used in deriving the driving force δ_I from $K_I^2/\sigma_y E$.

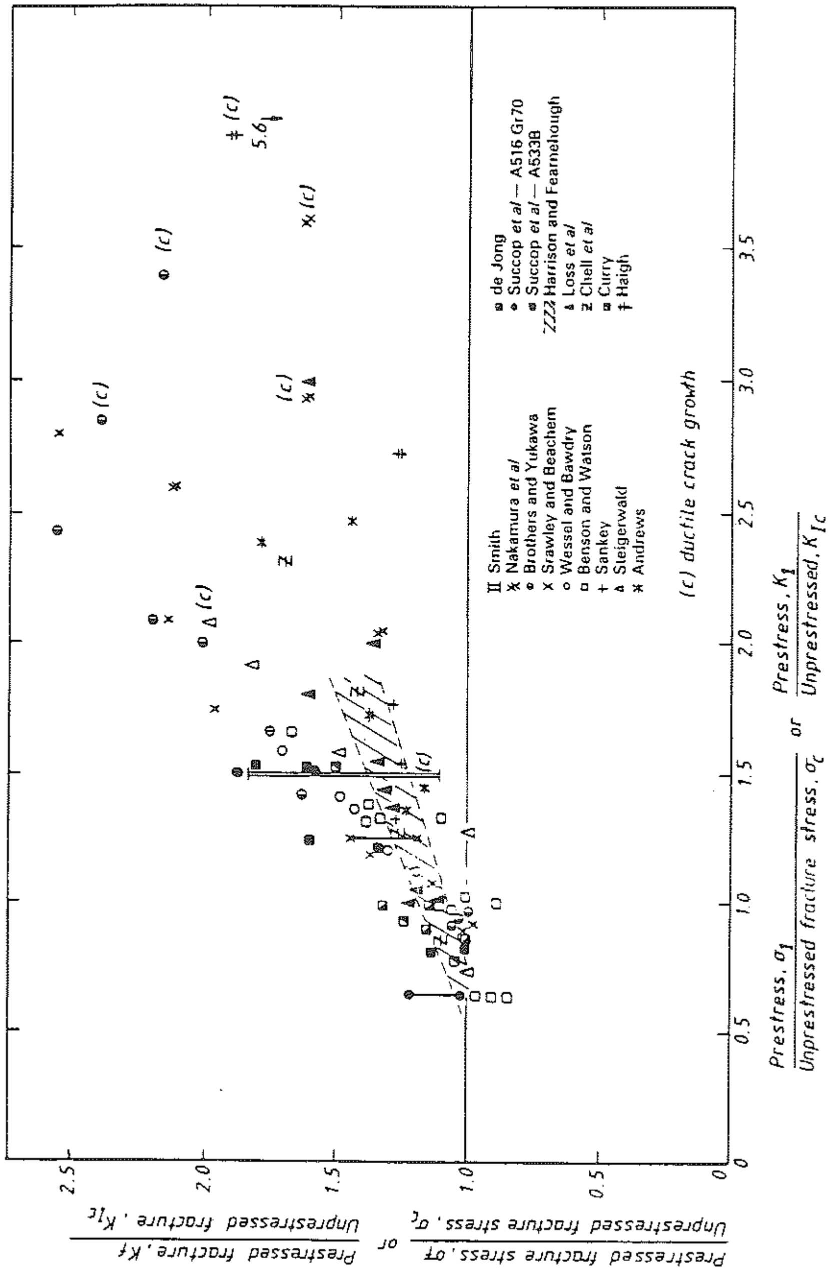

Fig 8 Experimental data on the effects of warm prestress for the 'load, unload, cool, fracture' loading cycle (see reference (21) for sources of the data)

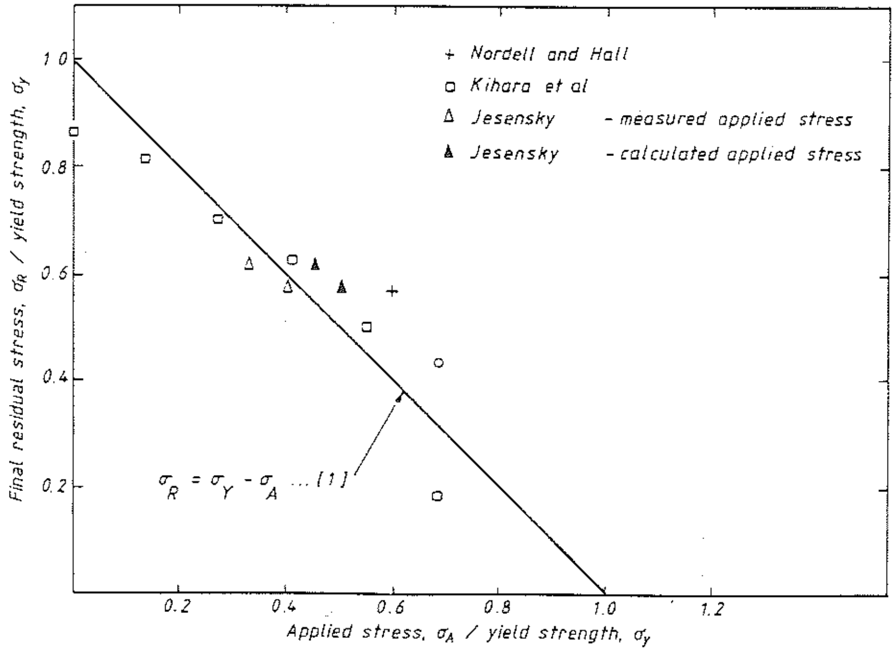

Fig 9 Variation of measured residual stress after overload with applied stress (see reference (19) for sources of the data)

Thus the use of J from tests may be regarded (by the indiscriminate user of the procedure) as having an advantage over CTOD. In reality of course, what this option is doing is reducing the inherent safety factor below that determined by Kamath **(23)** based on CTOD for Level 1 procedures at ~2.5. For the higher level assessment levels, where a partial safety factor approach is adopted, a higher safety factor would be required for J based procedures than for CTOD since the values quoted in the procedure are based on CTOD and hence already include an allowance for the m factor effect.

Where m is known for the structure (e.g., determined from an appropriate finite element analysis), appropriate allowances can (and should) be made for 'critical' assessments.

The influence of constraint and the characterisation of fracture through the transition region are very complex subjects.

A recent programme of tests at TWI has examined the influence of biaxiality on the behaviour of 50 mm thick A533B on the upper shelf, lower shelf, and in the transition regime **(24)–(26)**. These tests were conducted using a purpose built rig in which a cruciform specimen (see Fig. 10) is located so that a central region (~500 × 500 mm) experienced uniform (equibiaxial) stressing ($k = 1$) or, to simulate pressure vessel and pipeline applications, a two to one stress field ($k = 1/2$). These tests have been compared to the behaviour of uniaxial

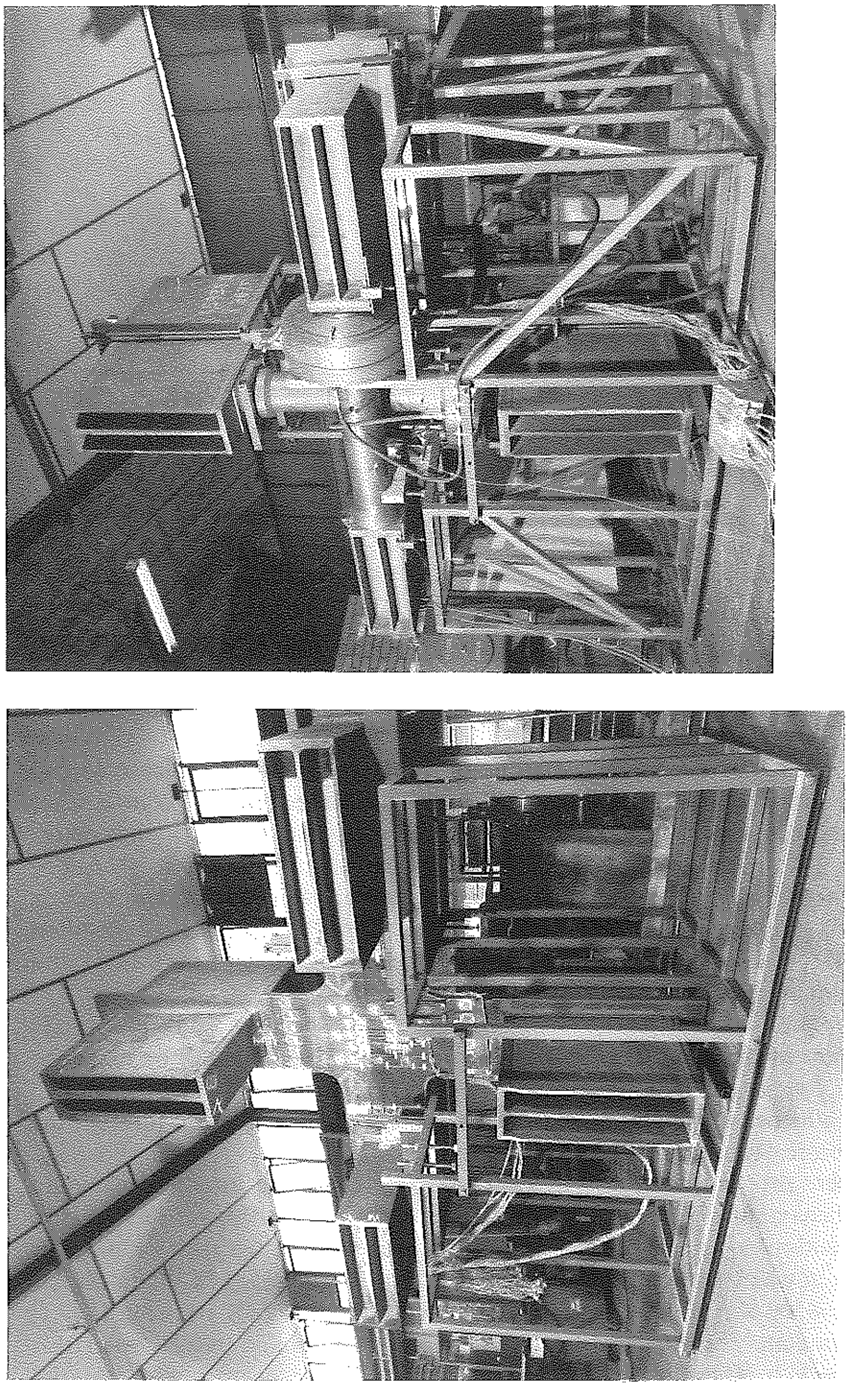

Fig 10 Biaxial specimen with:
(a) transverse loading beams in place;
(b) vertical and horizontal load capsules in place (A corresponding pair is mounted behind the specimen.)

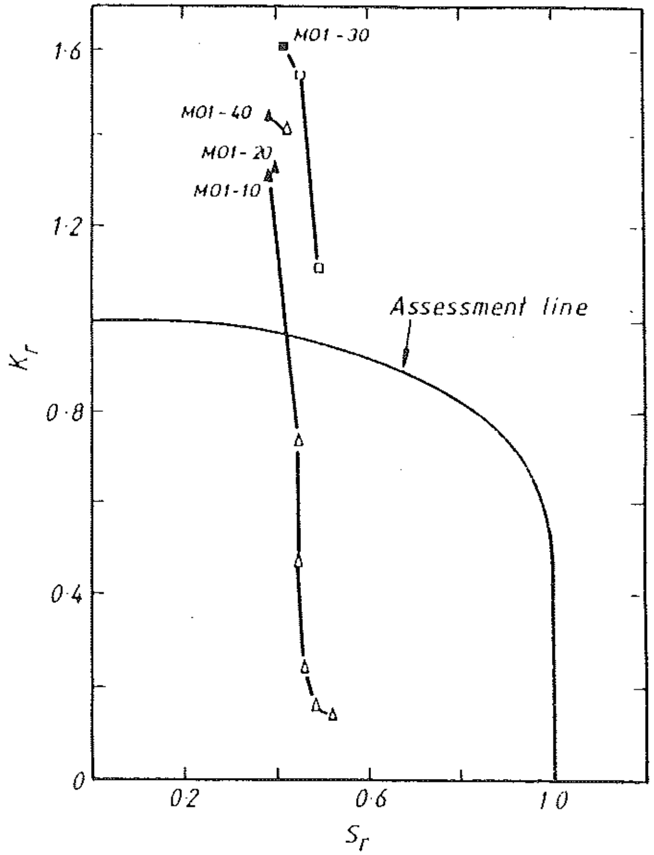

Fig 11 Comparison of wide plate results with the failure assessment diagram

($k = 0$) wide plates, and small scale three point bend tests performed to appropriate test standards. (k is defined as the stress parallel to the crack/stresses transverse to the crack).

On the lower shelf, where linear elastic conditions predominate, using a 50 mm thick surface notched geometry, failure conditions for equibiaxial and uniaxial tension loadings were conservatively predicted from full thickness bend test results using a Level 2 type fracture analysis (see Fig. 11 and reference **(25)**). The stress intensity factor (K_c) at failure appeared marginally lower under biaxial conditions and much greater plasticity (as measured by CTOD) was apparent under uniaxial loading at failure (see Fig. 12). The lower shelf experiments **(25)** however did confirm that the K (elastic and not that derived from J) was characteristic of the cleavage fracture under both uniaxial and biaxial loading. CTOD (and also J) were not characteristic of the cleavage fracture conditions but did illustrate the varying amounts of plasticity evident under different constraint conditions.

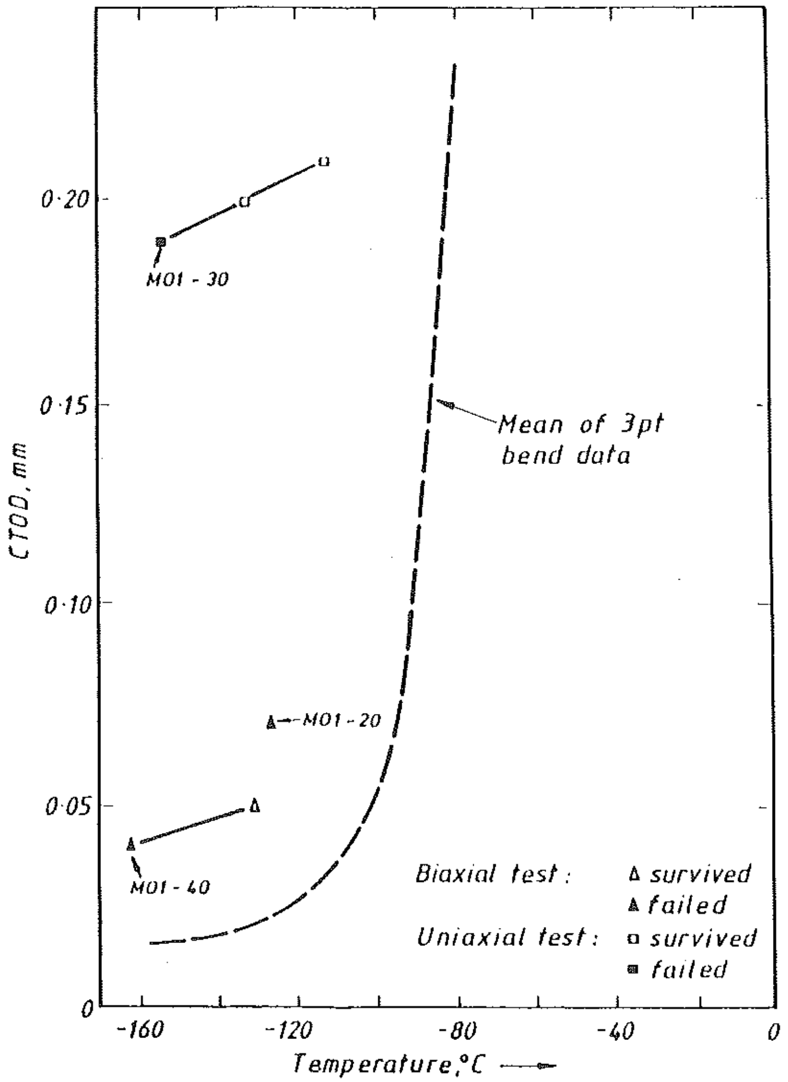

Fig 12 Comparison of CTOD from wide plate and three point bend tests

In contrast, tests on the upper shelf (at +70°C) on 25 mm thick test pieces using a surface notched geometry (24) have demonstrated that CTOD (under plane strain conditions) versus ductile crack extension curves are independent of whether the loading is biaxial or uniaxial conditions (see Fig. 13). However, for through-thickness cracks additional constraint is provided by the biaxiality and a lower CTOD *R* curve is apparent (see Fig. 14). It would also appear that plane sided three point bend specimens are sufficiently constrained to model biaxial tension.

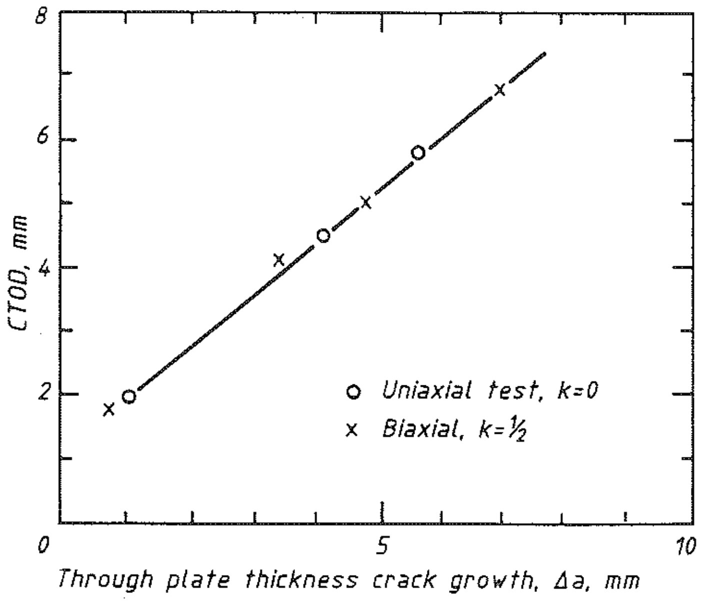

Fig 13 Crack tip opening displacement (CTOD) versus crack extension of the semi-elliptical notch through the plate thickness (CTOD was estimated using a double clip gauge arrangement mounted centrally at the mouth of the notch)

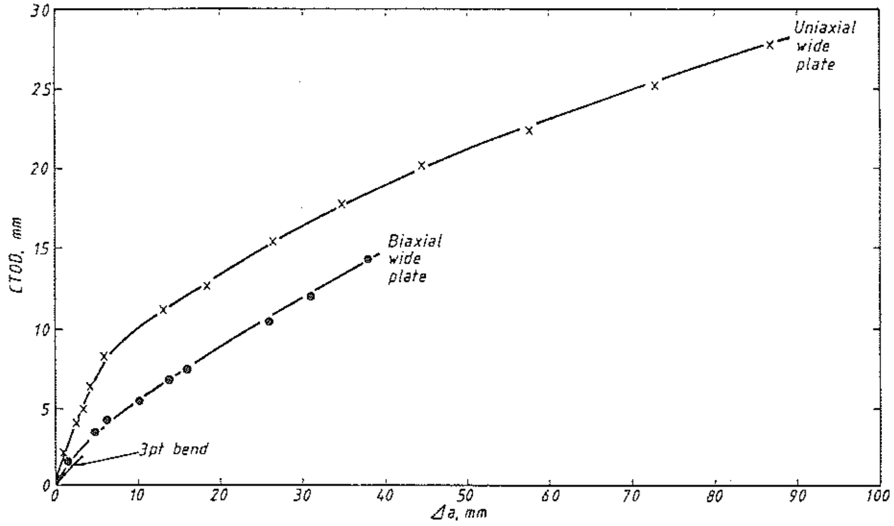

Fig 14 Comparison of CTOD *R* curves, uniaxial and biaxial through-thickness notched wide plates, and SENB specimens

As this test programme has indicated that linear elastic parameters predict cleavage fracture conditions and elastic–plastic parameters describe tearing resistance, the question remains how to characterise material resistance in the transition region?

PD6493 suggests the use of δ_u values from bend specimens to predict a structural cleavage failure conservatively. The philosophy here stems from the empirical validation of the CTOD design curve procedures **(6)(18)** where sufficient constraint is induced in the bend test to predict conservatively that experienced in structural circumstances (i.e., m in the 'full thickness' fracture toughness test is higher than that in the structure and since the applied CTOD is derived conservatively assuming $m = 1$ the parameter $\sqrt{\delta_r}$ is overestimated).

In reality, the onset of cleavage is more likely to be described by the stress level induced at the crack tip which in turn relates to the 'elastic' K. Figure 15 shows the transition curve measured on the 50 mm thick A533B from reference **(23)** in terms of 'elastic' K whilst Fig. 16 shows the transition in terms of K (J) and CTOD. As can be seen, the 'elastic' K contribution is dependent on specimen size and thus the relevance of K (J) and CTOD depend entirely on the use of adequately constrained and sized specimens. It is for these reasons that no J test is currently defined for cleavage fracture prediction and that the measurement of fully ductile conditions in a small 'subsized' bend test gives no guarantee that cleavage will not be experienced in a predominately elastically loaded structure.

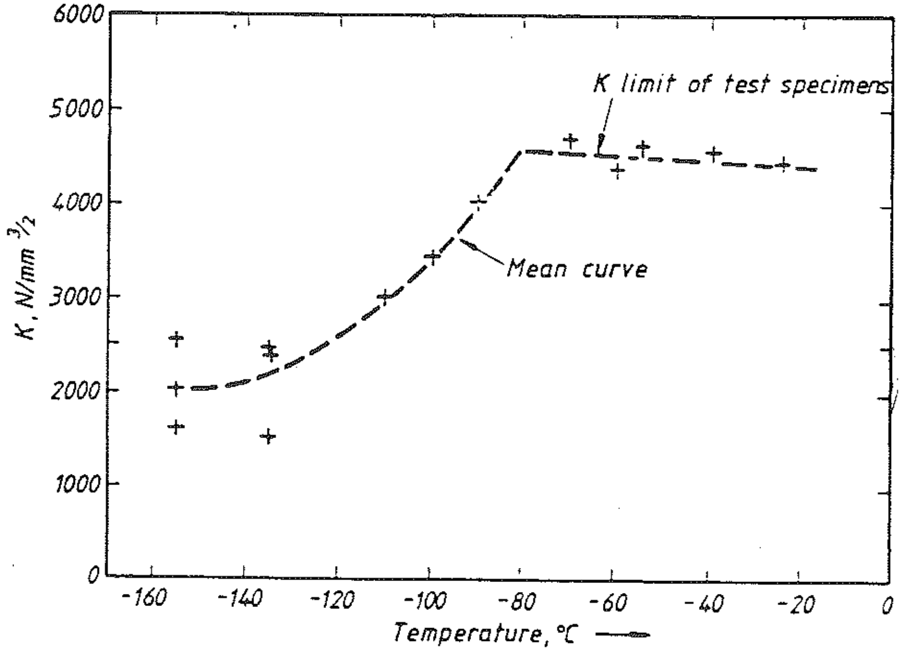

Fig 15 ***K* transition curve of three point bend data**

To examine the accuracy of the above philosophy and whether a split criterion approach (i.e., 'elastic' K for cleavage and CTOD or K (J) for ductile fracture) is viable, tests are currently underway examining uniaxial and biaxial performance in the transition region using nominally identical wide plates (the results of these tests will be reported in reference **(27)**).

Summary and conclusions

(1) The approaches adopted for the fracture sections of the revisions to the defect assessment procedure in BS PD6493 are described.
(2) Fracture toughness measurements to be used as input to the assessment procedure are also discussed.
(3) Detailed treatments of applied and residual stresses recommended for the procedure are described. In particular, reduced levels of residual stresses to be assumed for high applied load levels are proposed.
(4) The influence of proof testing on subsequent low temperature fracture performance is described. Benefits in load bearing capacity of the structure at low temperature are apparent provided the proof test load exceeds that which would have caused failure at the lower temperature.
(5) Welding residual stresses are shown to be reduced by the proof test and proposals for allowing for this reduction in the revised PD6493 are outlined.
(6) The influence of constraint, in particular under biaxial loading conditions, is discussed. It is suggested that linear elastic fracture mechanics characterises cleavage fracture whilst elastic–plastic parameters describe tearing resistance. It is suggested that the elastic–plastic parameters are applicable as input to fracture assessment procedures provided that the structural constraint is modelled adequately. A 'split' criterion approach is proposed, where the risk of cleavage can be assessed by the 'elastic' K capability of the test specimen.

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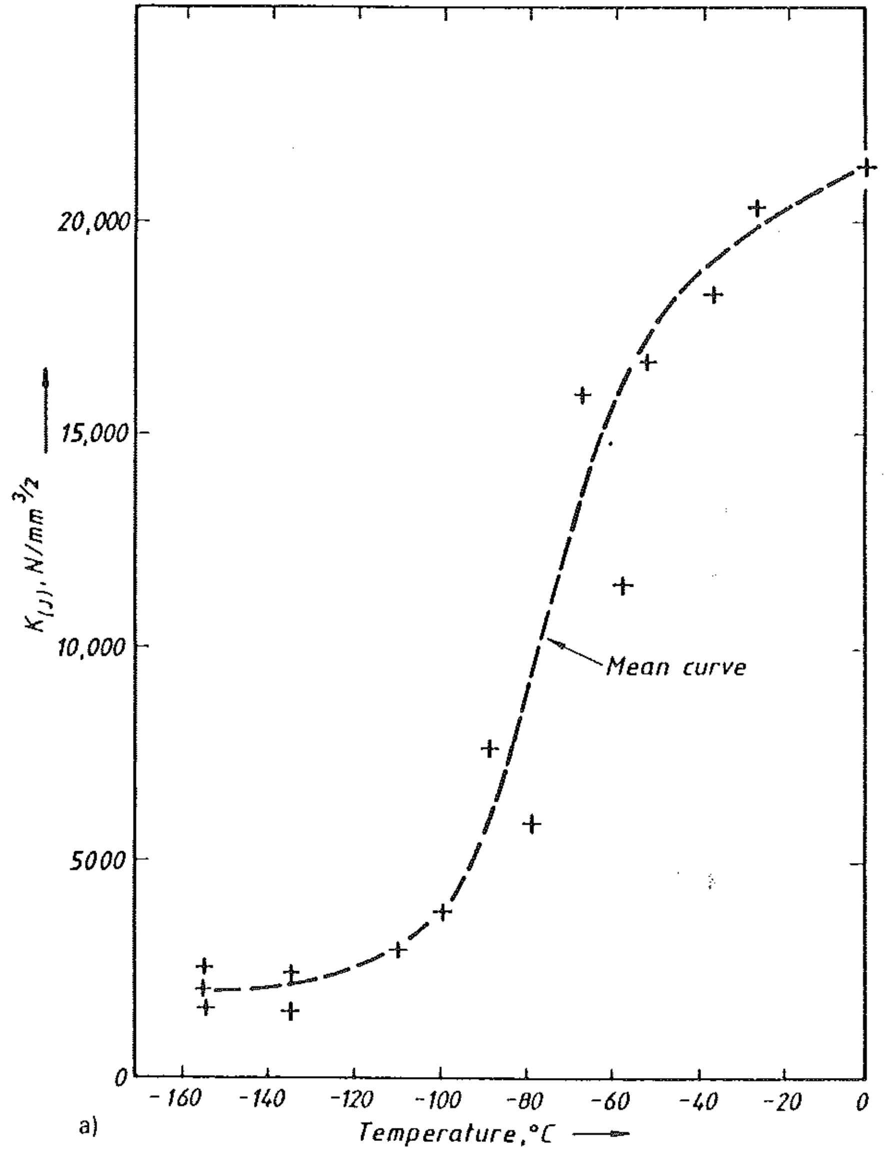

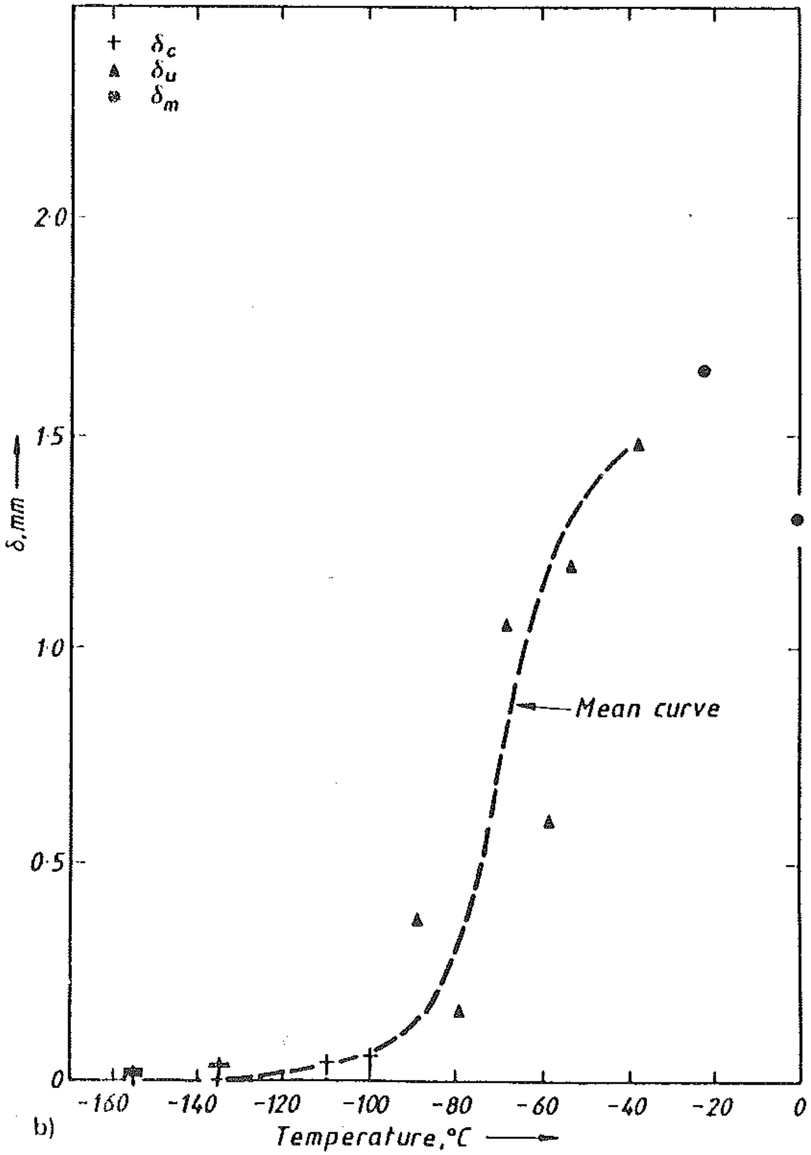

Fig 16 (a) Transition curve of K_J determined using J integral measurements from the three point bend data;
(b) CTOD transition curve determined from three point bend specimens

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