THE J-BASED FRACTURE ASSESSMENT METHOD, EnJ, AND APPLICATION TO TWO STRUCTURAL DETAILS

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ABSTRACT

A J-based fracture safe design method, called EnJ, broadly comparable to the well-known COD and R-6 methods, is briefly outlined. It offers an estimate of the applied severity in a cracked component in terms of a non-dimensionalised J as a function of the effective strain applied to the component. The effective strain is itself stated in terms of the stress in the uncracked body and simple factors depending on loading and configuration. The method is here applied to an un-stress-relieved weld crack and to cracks buried beneath a region of stress concentration. Comparison is made with previously published data.

KEYWORDS

Fracture mechanics, J-contour integral, design methods, significance of defects.

INTRODUCTION

Several attempts have been made to define a quick, simple, yet realistic route for assessing the significance of defects where lefm seems inadequate because of either the ductility of the material or the presence of stresses near yield level. In the UK, the COD method (BSI, 1980), is used for a variety of steel structures and the so-called R-6 method (Harrison and others, 1976) for many pressure vessels. More recently, a J-based method, now called EnJ, has been presented (Turner, 1981, 1983), and another derived under the auspices of the Electric Power Research Institute (EPRI)[1], has been published in full (Kumar, German and Shih, 1981) and simplified form (Bloom and Malik, 1982), particularised towards nuclear grade pressure vessels. The simplified version, though restricted to certain grades of steel over 102mm thick, is in essence a modified form of R-6, and all the methods are by no means as dissimilar as they may at one time have seemed. R-6, EPRI and EnJ, all use J, in distinction to the BSI method which uses COD. The

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two can be related by stating $J = m\sigma_y\delta$ where usually $1 < m < 3$. The value of m varies with extent of plasticity, hardening and configuration but opinion differs on whether J or δ is the better representation of crack tip behaviour. For lefm, $J \equiv G = m\sigma_y\delta$. Since the EnJ method is not yet widely known, the main features are recounted. The other methods are not restated since they have already been widely published, although remarks on the differences from EnJ are made. In all the methods it is intended that J (or δ) is estimated and then restricted to a critical value, the fracture toughness, J_c (or δ_c), although the practical meaning of that term differs in the various methods, unless behaviour is clearly brittle. Extension of the methods to account for R-curve behaviour is not detailed here.

THE EnJ METHOD

The ordinate of the EnJ diagram, is the normalised value J/G_y, where G_y is the value of G at $\sigma = \sigma_y$, i.e.

$$J/G_y = (J/G)(\sigma/\sigma_y)^2 = JE/Y^2\sigma_y^2 a = JE/\pi\sigma_y^2\bar{a} = \delta E/m\pi\sigma_y^2\bar{a} \qquad \text{Eqns. 1a-d}$$

where σ_y is yield stress, a is crack size, E is modulus. Y is the lefm shape factor defined by

$$K = Y\sigma\sqrt{a} \qquad \text{Eqn. 2}$$

where σ is the nominal elastic stress. When the crack size is unknown, it may be more convenient to use the equivalent crack concept as in the COD method, whence in Eqn.1a $\pi\bar{a} = Y^2 a$. The ordinate of the COD diagram, $\delta E/2\pi\sigma_y a$, can be taken as $J/2mG_y$. The ordinate of the R-6 and EPRI diagrams is $\sqrt{G/J}$ which relates to EnJ by Eqn.1a. The R-6 and EPRI methods both use a normalised load Q/Q_c as abscissa, where Q_c is the "collapse load" of a local region adjacent to the ligament. EPRI makes further allowance for work hardening. Both COD and EnJ notionally use normalised strain, but accept that in the near lefm regime, the uncracked body stress, σ/σ_y, is used since it is often the only known design term. COD also uses σ/σ_y as an estimate of e/e_y for values not exceeding two, but the EnJ treatment differs. The EnJ equations relate J to an effective strain, e_f/e_y,

$$\text{For } e_f/e_y < 1.2: \qquad J/G_y = (e_f/e_y)^2\,(1+0.5(e_f/e_y)^2) \qquad \text{Eqn. 3a}$$

$$\text{For } e_f/e_y \geq 1.2: \qquad J/G_y = 2.5\{(e_f/e_y) - 0.2\} \qquad \text{Eqn. 3b}$$

If (W or B/b)$(\sigma/\sigma_y) > 1$ or $Y/\sqrt{\pi} >$ (W or B)/b, then the ligament should be examined for collapse. Eqn. 3c

W is width (two dimensions), B is thickness (three dimensions), b is ligament.

In the near lefm regime Eqn.3a is used with the effective strain ratio taken as σ/σ_y, where σ is the nominal stress as in Eqn.2. If the ligament yields but collapse cannot occur, then Eqn.3b is used with the "cracked body structural strain, (cbse)/e_y" as described further below. In the intermediate region, if $(W/b)(Y/\sqrt{\pi})(\sigma/\sigma_y) > 1$, then the cbse should usually be used, even though σ/σ_y is itself low. Eqn.3c contains a reminder that plastic collapse must be considered on its own merits. When an assessment is made, the user must decide whether the cracked body is liable to collapse at or soon after net ligament yield, or whether the load applied to the cracked region will be redistributed because of the configuration of the body and its loading system. If collapse is possible, then closer study would have to be made of a safe limiting state but EnJ and COD methods do not include such an assessment within their own methodology.

Some Details of the EnJ Estimation Procedure

Primary stresses. With a suitable combination of moderate work hardening and rather small loss of section (shallow notches) the strain distribution along a component, other than at the notch tip itself, is reasonably uniform even after an appreciable amount of yielding.

The EnJ equations are based on 2D computed cases for such configurations, as detailed by Turner (1979). The cbse concept was introduced (Turner, 1981, 1983) as means of defining for practical purposes the strain at which the EnJ equations were to be entered beyond lefm. Clearly, with yielding in a statically indeterminate structure, the nominal condition is a compromise between a remote strain that would be elastic, and a local ligament strain that, with a deep notch, could greatly exceed the yield strain. The cbse concept applies to the three-dimensional cases where there are elastic load paths in parallel with the crack, or to two-dimensional cases where yielding may occur at such a low value of nominal stress, σ, that direct use of Eqn.3a with $e_f = \sigma$ is inadequate. The latter includes both deep notch cases and certain configurations (such as SENT and CT pieces) where the nominal stress σ is not representative of the collapse mode. These cases are usually indicated by $Y/\sqrt{\pi} > W/b$, leading to the recommendations already made. If there are no elastic load paths in parallel with a crack, then extensive plasticity is either collapse dominated, with deformation restricted by high hardening, or is displacement controlled to a reference strain value some distance from the crack. In either case the plastic component of J that is concentrated into the notched region may be larger than for most other cases and thus may require special attention.

The cbse is an estimate of the applied severity, e_f/e_y, relevant to a structure where the ligament is so close to yield that deformation is controlled by neither lefm nor plastic plastic behaviour because plasticity is too extensive for the former and too restricted by parallel elastic paths for the latter. Suggestions for the cbse are listed, Table 1. The geometric factor, α, is a measure of the augmentation of strain due to ratio of slip line field length to the length to reach the undisturbed or reference state. Note, only the plastic component of strain is focussed into the crack, there being a general elastic strain governed by the maximum load transmitted by the ligament and the region over which that is distributed, leading to the factor β. Thus, the concept is cbse = (nominal e/e_y + localised e_{pl}/e_y). The derivations are from two dimensional analysis with a three-dimensional correction proposed on heuristic grounds.

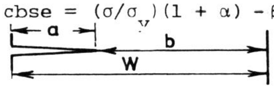
In COD and EnJ collapse is examined separately in its own right, if it is an important issue. In the R-6 method one diagram embraces both fracture and plastic collapse, although where there are elastic paths in parallel, as for a buried or part through flaw, the definition of collapse refers to a local region extending beyond the flaw by a distance of about one thickness. The EPRI simplified diagram also uses interpolation between lefm and plastic collapse, though extended on the abscissa to allow for work hardening and using different interpolations between lefm and collapse according to the crack depth to thickness ratio.

A further feature of both R-6 and COD methods is that with yield of the net ligament adjoining a deep part-through or buried crack, it is recategorised in its through thickness extent, as a size that is specified in each method but embraces an area appreciably larger than the crack itself. It is then argued that if such a recharacterised crack is not acceptable, nor is the real crack, despite the significant change in severity between the two cases. The unknown value of this change in severity may lead to a conservative recharacterisation method. EnJ does not directly use recharacterisation, because the idea of a "cracked body structural strain" (cbse) itself based on the localisation of strain if the ligament yields, obviates the need for separate treatment. However expressed, the user retains the final responsibility for identifying the stress systems and failure modes that are relevant. The procedure, be it COD, R-6, EnJ or other, helps evaluate the behaviour quantitatively.

TABLE 1 Suggested values of the cracked body structural strain (cbse)

Two dimensions: cbse = $(\sigma/\sigma_y)(1 + \alpha) - \beta$

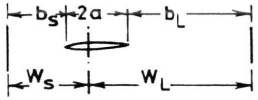
A Edge crack:



1) tension; $\alpha = W/b$, $\beta = 1$; 2) bending; $\alpha = W/b$, $\beta = b/W$

3) combined tension and bending;† $\alpha = W/b$, $\beta = (\sigma_t + \sigma_b\{b/W\})/\sigma$

B Buried crack :



$b = b_s + b_L = W-2a$

$W = W_s + W_L$

1) tension a) if $W\sigma_t < b\sigma_y$ $\alpha = W_s/b_s$; $\beta = 1$

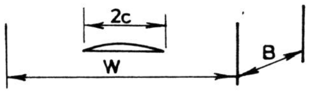
b) if $W_\sigma t \geq b\sigma_y$ $\alpha = W_L/b_s$; $\beta = (b/W)(W_L/b_s)$

2) bending (tensile ligament denoted t) $\alpha = W_t/b_t$, $\beta = b_t/W_t$

3) combined tension and bending;† $\alpha = W_t/b_t$, $\beta = (\sigma_t + (b_t/W_t)\sigma_b)/\sigma$

Three dimensions: cbse = (Two dims. case)$(2 + \{B/W\})/(2 + \{B/2c\})$

C Edge or buried crack :



Other cases:

D Values of the augmentation factor α can be estimated from slip line field size and of the reduction factor β from the ligament to width ratio.

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† σ_t is the tension stress and σ_b the bending stress such that $\sigma=\sigma_t+\sigma_b$

Attention is also drawn in an approximate way in EnJ to the effect of biaxial loading, the main effect being to alter the fully plastic condition at which collapse may occur. It was remarked (Turner, 1979) that, for plane strain, the effect of transverse stress at constant axial load (where transverse compression increases J) is the reverse of the effect of transverse strain at fixed axial displacement (whereby transverse tension increases J) the latter being relevant to some thermal cases.

Secondary stress systems. J is estimated from Eqn.3a, b, separately for mechanical stress, σ_m, and residual or thermal stress, σ_r or σ_{th} to give J_m, J_r, or J_{th}. The terms are combined to give the total J value by adding

$$J^\beta = (J_m^{\ \beta} + J_r^{\ \beta} + J_{th}^{\ \beta}) \text{ where } 0.5 < \beta < 1 \qquad \text{Eqn. 4}$$

according to $\beta = 0.5 + (\sigma_m+\sigma_r+\sigma_{th})/2\sigma_y$ (though not exceeding unity) i.e.

$\beta = 1/2$ for elastic conditions and 1 for plastic. Use of the cbse concept may be necessary if restraint can induce reaction stresses of general yiel level, but it is not necessary for self-equilibriating compatibility stres The value of residual stress is a separate issue and must be chosen, as fo the other methods, in the light of experience. For un-stress-relieved weld $\sigma_r=\sigma_y$, is normally advocated. Eqn.3a permits the choice of σ_r up to $1.2\sigma_y$ and this may be necessary if high constraint exists, and cleavage is a ris For stress concentrations, Eqn.3a is used with the appropriate lefm value Y, whilst cbse < 1. If cbse > 1, an estimate must be made of the uncrack body strain at the point of concentration to give the effective strain, e_f/e_y.

Toughness value. Space permits only the briefest statement. If cleavage a risk, full thickness pieces should be tested, and if impulsive loading i a risk, impact tests should be conducted. If cleavage is not a risk, the standard J test (ASTM, 1981) can be used to determine an initiation toughn J_{Ic}, which can be used with no allowance for crack growth. If a known amou of stable tearing is allowed for, the corresponding post-initiation value toughness J_r can be used for occasional high loads in the absence of time-dependent effects. This usage is akin to the use of G_c in lefm plane stress problems and is justified in other studies not yet fully published.

TWO APPLICATIONS

A first problem is taken from Smith and others (1982) for a crack at the t of a butt weld in a steel plate 40mm thick, after growth by fatigue to a depth of 5.75mm, Fig.1.a. There is an applied tension of 117MN/m^2 and a residual stress taken as yield level, here 340MN/m^2. Smith's treatment is two-dimensional and uses a computed shape factor, Y, appropriate to the configuration, rather than an estimate of the stress concentration at the toe as specified in BSI (1980). Because the member is part of a stiff assembly, deformation with "ends parallel" is assumed. A value Y = 2.44 is[2] estimated here by an approximate weight function method for the edge notch case with uniform residual stress. The term $(W/b)(Y\sqrt{\pi})(\sigma/\sigma_y) \simeq 0.55 < 1$, and collapse is not in question, so for the mechanical stress, $e_f/e_y = \sigma/$ $= 117/340 = 0.344$. Using Eqn.3a $(J/G_y) = 0.126$, whence J = 0.0242MN/m.

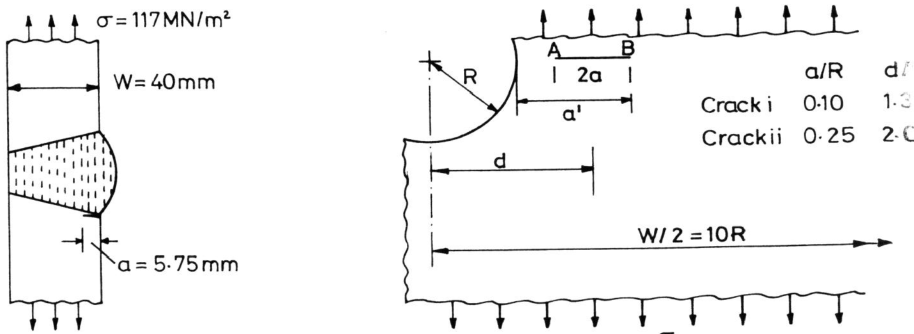

Fig.1 Configurations studied

a) toe crack in butt weld; b) crack buried near a stress concentrati

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2. I am indebted to my colleague, Dr.R.M.Curr, for this estimate.

For residual stress, $e_f/e_y = \sigma_r/\sigma_y = 1$, so that $(J/G_y)_{res} = 1.5$ and using the same value of Y, $J = 0.0288$ MN/m. Since $\sigma_m + \sigma_r > \sigma_y$, the J values are added directly with $\beta = 1$ to give, $J = J_{mech} + J_{res} = 0.0312$ MN/m. For safety, $J_c > J$. Smith found $\delta_c = 0.13$mm. To compare the two, $J = m\sigma_y\delta$ is used with $m = 2$, whereby J_c (implied from Smith) is 0.075 MN/m. It is often argued that the BSI (1980) method contains a deliberate factor of safety because it assesses an acceptable crack, not a critical crack size. Allowing a factor of two on Smith's value of COD for this effect would imply a value of $J = 0.038$ MN/m. A value found using R-6, Rev.1 (see Harrison and others, 1976; Rev.1, 1977) gave $J = 0.042$ MN/m.

The EnJ method is also applied to the local but intense yielding in the small ligament between a buried defect and a hole that itself causes an elastic stress concentration of three, such as an unreinforced service access or hand hold. The configurations of two such cracks are shown, Fig. 1.b. There are no residual stresses. Computed results, expressed in terms of J/G, were given by Sumpter and Turner (1976) and are reproduced, Fig.2. The original analysis was restricted to the 'deep' end of the crack on the grounds that at the near surface end of the crack, the value of J could be arbitrarily high if the ligament were sufficiently small, and failure of the component would depend on the conditions at the 'deep' end. There is, however, some interest in the tip close to the surface if the failure of the small ligament were to allow corrosive media into the crack, or perhaps if the failure were by cleavage that might trigger a more extensive event.

In the near lefm regime the first EnJ equation (Eqn.3a) is used for both configurations. The estimated values are changed from J/G_Y to J/G by dividing by $(\sigma/\sigma_y)^2$ to suit the form of the published data. If absolute values of J are required, the value of the lefm shape factor Y can be taken from the literature, with which the values of Y computed by Sumpter and Turner (1976) were shown to be within a few per cent.

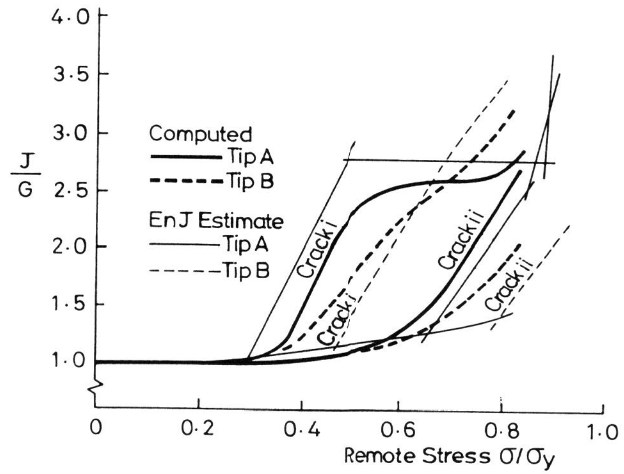

Fig.2. Computed and estimated values of J/G as a function of applied stress for a crack buried near to hole in a plate in tension.

For crack ii), where the crack is buried at an appreciable depth, the effect of the stress concentration might be expected to become insignificant as yielding progresses, so that the cbse term for a buried crack in tension, Table 1, case B1a, with yielding of the small ligament (between crack tip A and the hole) is used beyond lefm. The solution is extended further by use of Table 1, case B1b, for yield to the outer edge of the plate. As seen Fig.2, these three solutions predicted the computed data quite adequately.

For crack i) the behaviour is more complex. Immediately following the lefm regime, which itself is less extensive than for crack ii), there is a regime where the effect of the concentration dominates the crack tip A. Table 1, case B1a, is then modified with α taken as $(k_t - 1)$ and β as b_s/W_s ($k_t = 3$ here, and b_s and W_s are defined in Table 1). This is followed by a regime where the extent of the plastic zone at the hole can embrace slip to the inner end of the crack, so that $\alpha = (b_s + 2a)/b_s = 2$; and $\beta = (b_s/b_s + a)\alpha = 1$, to give a region of virtually constant J/G with the small ligament fully yielded, but overall behaviour dominated by the yield spreading from the inner end of crack (tip B). Finally, yield of the large ligament gives a solution from Table 1, case B1b, similar to crack ii) (though differing in value because of the different cracked ligament size), $\alpha = W_L/b_s = 43.5$; $\beta = (b/W)\alpha = 42.5$. These estimated values are shown Fig.2, where they fit the data fairly well.

DISCUSSION

For the first problem the methods are fundamentally in good agreement, subject to the uncertainty over the value of m relating J to COD, but the difference of intent (acceptable or critical) of the assessments and the characteristics of the present example must be recalled. In this problem many complexities are absent and the assumption of deformation with 'ends parallel' is easily acceptable in all methods. The results are, however, dominated by the residual stress term for which a common assumption (of yield stress magnitude) aids but does not ensure a common answer. The treatment by Smith and others (1982) differs from that of BSI (1980) and use of Rev.1 rather than Rev.2 for the R-6 value quoted are both factors likely in this problem to enhance accord with the EnJ method. Nevertheless, a number of comparative studies have been made (Turner, 1984) that show good general agreement (when based on the same intent) although many factors can lead to poorer agreement.

In the second problem the methods other than EnJ seem inappropriate in that they would be restricted either by collapse load of the small ligament, or, with recategorisation, to assessment of a notional defect of length a' = crack + ligament (Fig.1b). The agreement between the estimates using EnJ with the cbse concept and the computed data is surprisingly good, although it is doubtful whether the estimates could have been made without prior knowledge of the results, at least in a qualitative sense. The values of cbse used, other than those for Table 1, are derived by the same argument, namely, that α is a multiplying factor depending on the ratio of distance to "undisturbed" field divided by length of local slip field, and that β is a reduction due to the ligament limit load being carried by some wider part of the whole component. The only explicit guidance taken from the computed data was the value of remote stress ($\sigma/\sigma_y = 0.57$) at which the uncracked body plastic zone had spread to an axial distance around the hole equal to the inner end of the crack, $b_s + 2a$, thereby giving the onset of the regime of near constant J/G. Without that guidance, the regime of near constant J/G could occur at an unknown value. This link between the previous k_t dominated behaviour and the final regimes dominated by the inner end of the crack is no doubt configuration-dependent (on a ratio such as d/R and $b_s/2a$). Indeed, both it and the k_t dominated regime are absent for the more deeply buried crack ii), as already noted.

CONCLUSIONS

A simple method, called EnJ, for estimating J in order to assess the significance of defects, has been outlined. The first example confirms previous comparisons which show a general agreement between EnJ, COD, R-6, and simplified EPRI methods, although there may be significant differences of detail. Secondly, EnJ has been used to estimate J at defects buried in a region with high local yielding. The EnJ predictions are in fair agreement with finite element results, although some reliance was placed on knowing the computed data, at least for the uncracked body, to give quantitative guidance, when the extent of local plasticity in the uncracked body dominates the behaviour of the crack tip.

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