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# ADVANCES IN THE R5 AND R6 DEFECT ASSESSMENT PROCEDURES

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## ABSTRACT

The R5 and R6 defect assessment procedures address crack growth at high and low temperatures, respectively. These procedures continue to be developed. In R5, the methods for treating stress relaxation have been extended to combined primary and secondary stresses allowing for both creep deformation and crack growth. The transient crack tip field parameter C(t) has also been evaluated for combined primary and secondary loading allowing for plastic as well as creep deformation. In both cases, the results have been derived in terms of a reference stress and these are presented in the paper. Although the basic R6 procedures remain unchanged, revisions have been made to a number of the advanced approaches, including the treatment of constraint and the use of global limit loads. These revisions are described. Finally, the paper discusses how the advances in R5 and R6 are being incorporated in other procedures, including the British Standard Guide BS7910 and the FITNET procedure being produced by a European network.

**Keywords:** R5, R6, Defect assessment.

## 1. INTRODUCTION

R5 [1] contains procedures for assessing the integrity of components operating at high temperatures and addresses both uncracked and cracked components. The R5 approach for high temperature assessment of defect-free components was summarized in [2] while [3] described the approach for defective components. The procedures for assessing cracks in components operating in the creep range were first produced over 15 years ago [4]. These became Volume 4 of R5 with methods for treating creep-fatigue crack growth later added as Volume 5. Developments in methods for assessing both creep and creep-fatigue crack growth [5-7] led to updates to both Volumes 4 and 5 and to parts of the R5 approach being included in the British Standards document BS7910 [8], as described in [9]. The creep and creep-fatigue crack growth procedures in R5 were combined to form a new Volume 4/5 for R5 Issue 3 in 2003 [3]. This paper presents the basic aspects of this procedure in Section 2 and then recent developments are described in Section 3.

Approaches for the assessment of the integrity of components operating below the creep range containing flaws have undergone extensive development worldwide. In the UK, two recent developments have been the production of BS7910 [8] and the development of Revision 4 of R6 [10]. As these procedures are well established, the basic methods are not described here and instead Section 4 describes recent developments in R6.

The advances in R5 and R6 are being incorporated in other procedures, including the British Standard Guide BS7910 and a European FITNET procedure. These wider developments are discussed in Section 5 with particular attention paid to the FITNET procedure.

 

## 2. CURRENT R5 METHODS

For steady state creep, the crack tip stress and strain rate fields (and hence creep crack growth rates) may be characterized by the $C^*$ parameter [6]. In R5, $C^*$ is estimated in terms of a reference stress

$$\sigma_{ref}^{p} = P\sigma_y / P_L(\sigma_y, a) \tag{1}$$

$P_L$ is the value of the load P corresponding to plastic collapse assuming a yield stress $\sigma_y$. The effect of the flaw size, a, is included in evaluating the plastic collapse load. Once the reference stress is calculated, $C^*$ is obtained from

$$C^* = \sigma_{ref}^{p} \dot{\varepsilon}_c [\sigma_{ref}^{p}(a), \varepsilon_c] R' \tag{2}$$

Here, $\dot{\varepsilon}_c$ is the creep strain rate at the current reference stress and creep strain, $\varepsilon_c$, accumulated under the reference stress history up to time t; that is, a strain hardening rule is used to define creep strain rates under increasing stress. The use of reference stress techniques enables realistic creep laws to be used rather than simple secondary creep rates. The characteristic length, $R'$ is defined by

$$R' = (K^p / \sigma_{ref}^{p})^2 \tag{3}$$

where $K^p$ is the stress intensity factor due to primary load only. As both $K^p$ and $\sigma_{ref}^{p}$ are directly proportional to P, the value of $R'$ is independent of the magnitude of P. However, $R'$ does vary with crack size and, when creep crack growth is being considered, both K and $\sigma_{ref}^{p}$ are calculated for the defect size equal to the size of the original crack plus the amount of creep crack growth. The value of $R'$ is also different at the surface and deepest points of a semi-elliptical surface defect due to differences in the values of $K^p$. Equation (2) applies for primary loading in the steady state. For other loadings, estimates of $C^*$ are described in Section 3. Once $C^*$ has been calculated, the crack extension is obtained from creep crack growth data generally presented in the form:

$$\dot{a} = A(C^*)^q \tag{4}$$

where A and q are material constants.

Prior to steady state creep, the increased amplitude of the crack tip fields at short times may be defined by the transient parameter C(t) [6]. It is assumed that at these short times, eqn (4) may be generalized to

$$\dot{a} = A[C(t)]^q \tag{5}$$

R5 gives an interpolation formula for C(t) during the transition between initial elastic loading and steady state secondary creep as

$$\frac{C(t)}{C^*} = \frac{(1 + \varepsilon_c / \varepsilon_e)^{1/(1-q)}}{(1 + \varepsilon_c / \varepsilon_e)^{1/(1-q)} - 1} \tag{6}$$

where $\varepsilon_c$ is the accumulated creep strain at time t and $\varepsilon_e$ is the elastic strain. The exponent in the creep crack growth law of eqn (4) is $q \simeq n/(n+1)$ where n is the exponent in the power law creep expression

$$\dot{\varepsilon}_c / \dot{\varepsilon}_o = (\sigma / \sigma_o)^n \tag{7}$$

Equation (6) is extended to more general loadings and to plasticity on initial loading in Section 3 below.

## 3. RECENT DEVELOPMENTS IN R5

 

Two recent developments are described here. First, the generalization of eqns (1-3) to combined primary and secondary loading is presented in Section 3.1. This includes relaxation of the reference stress, and the corresponding value of $C^*$, as the secondary stresses relax. Section 3.2 then describes the extension of eqn (6) to cover both combined loading and plasticity on initial loading that is often associated with high secondary stresses.

## 3.1 Reference stress for combined primary and secondary loading

If the initial response on loading is elastic an initial estimate of the total reference stress due to combined primary and secondary loading, $\sigma_{ref}$ , is

$$\sigma_{ref} = \sigma_{ref}^{p} (K^{p} + K^{s}) / K^{p} \tag{8}$$

where $K^{p}, K^{s}$ are the stress intensity factors for the primary loading and the secondary loading, respectively. The primary load P is assumed fixed so that eqn (1) can be written

$$\sigma_{ref}^{p} = Pf(a/w) \tag{9}$$

and

$$K^{p} = Pg(a/w) \tag{10}$$

where f(a/w) and g(a/w) are limit load and stress intensity factor functions that depend on the crack size, a, and section width, w. The secondary stresses may relax and it is assumed here that the corresponding stress intensity factor can be written in a similar form to equation (10) as

$$K^{s} = Q(t, a/w)h(a/w) \tag{11}$$

where Q is a stress or load type term that can relax with both time, t, and crack extension, in general, and h(a/w) is a stress intensity factor function.

If the limit load $P_L$ is written as

$$P_L = m(a/w)Bw\sigma_y \tag{12}$$

where m(a/w) is a non-dimensional function, B is a length (e.g. thickness for a test specimen) and $\sigma_y$ is the yield strength used to define the limit load, then eqn (1) gives

$$\sigma_{ref}^{p} = \frac{P}{P_L}\sigma_y = \frac{P}{m(a/w)Bw} \tag{13}$$

Inserting the reference stress definition of eqn (8) into eqn (2) gives the value of $C^*$ for the initial loading conditions. However, the secondary stress contribution to eqn (8) can relax due to creep and can also relax if the crack tip grows out of the region of high secondary stress. In order to evaluate this relaxation, it is assumed that eqn (8) not only defines the initial reference stress but also applies as relaxation of Q occurs. Then it is possible to differentiate eqn (8) to obtain the total relaxation rate. In the absence of crack extension, an elastic follow-up factor Z gives the partial relaxation rate as

$$\frac{\partial\sigma_{ref}}{\partial t} = -E\dot{\varepsilon}_c / Z \tag{14}$$

Combining the total relaxation rate obtained from differentiating eqn (8) with the partial relaxation rate from eqn (14) gives the final relaxation equation

$$\frac{\dot{\sigma}_{ref}}{\sigma_{ref}} + \left(\frac{m'}{m}\right)\left(\frac{\dot{a}}{w}\right) + \frac{E\dot{\varepsilon}_c}{Z\sigma_{ref}} - \frac{K^{s}\sigma_{ref}^{p}}{K^{p}\sigma_{ref}}\left(\frac{\dot{a}}{w}\right)\left[\frac{h'}{h} - \frac{g'}{g} + \frac{Q'}{Q}\right] = 0 \tag{15}$$

where $m' = \dfrac{dm}{d(a/w)}$, $g' = \dfrac{dg}{d(a/w)}$, $h' = \dfrac{dh}{d(a/w)}$, $Q' = \dfrac{\partial Q}{\partial(a/w)}$ and $\dot{\sigma}_{ref} = \dfrac{d\sigma_{ref}}{dt}$. Equation (15) may also be expressed in terms of the stress intensity factors $K^{p}, K^{s}$ rather than the functions h, g and the load quantity Q. The resulting equation, which is given below, may be more convenient for application purposes.

 

$$\frac{\dot{\sigma}_{ref}}{\sigma_{ref}} + \left[ \frac{K^s}{\left(K^p + K^s\right)} \left\{ \frac{\partial K^p / \partial (a/w)}{K^p} - \frac{\partial K^s / \partial (a/w)}{K^s} \right\} - \frac{\partial \sigma^p_{ref} / \partial (a/w)}{\sigma^p_{ref}} \right] \frac{\dot{a}}{w} + \frac{E\dot{\varepsilon}_c}{Z\sigma_{ref}} = 0 \qquad (16)$$

The derivation of these equations follows the approach in [11] and is omitted here for brevity.

The results of applying eqns (15,16) are shown schematically in Fig. 1. Results both with ($\dot{a} > 0$) and without ($\dot{a} = 0$) crack growth are included to illustrate the separate contributions to relaxation arising from creep strain and crack growth.

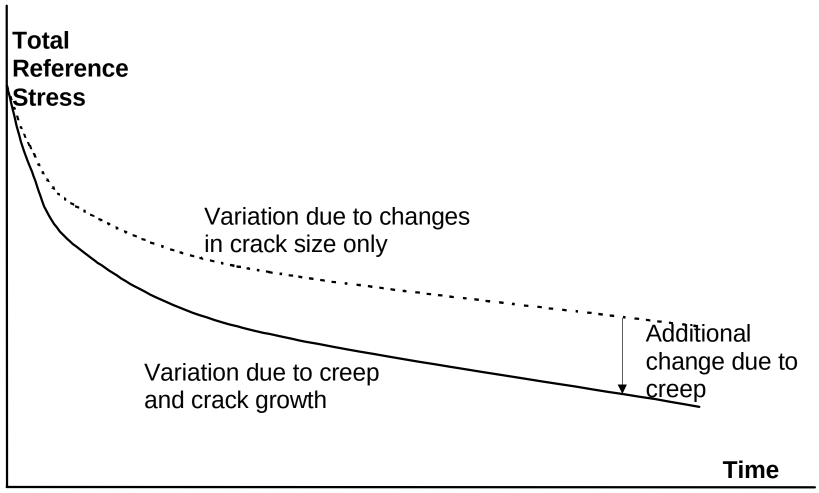


*Figure 1 Schematic variation of reference stress for a defect present at t = 0.*

Sample results from a practical application for a crack postulated to occur in the region of a high welding residual stress are shown in Fig. 2. Without secondary stress, the reference stress is low and rises with crack extension due to the corresponding reduction in collapse load. In this case, the crack is circumferential in a pressure loaded cylindrical type geometry and the increased net axial stress as the crack extends has only a weak effect on the limit load, which is mostly determined by the hoop stress. With secondary stresses, the changes in reference stress are much greater and crack extension leads to significant reductions in reference stress. This has a major impact on $C^*$ and the corresponding amount of crack growth from eqn (4).

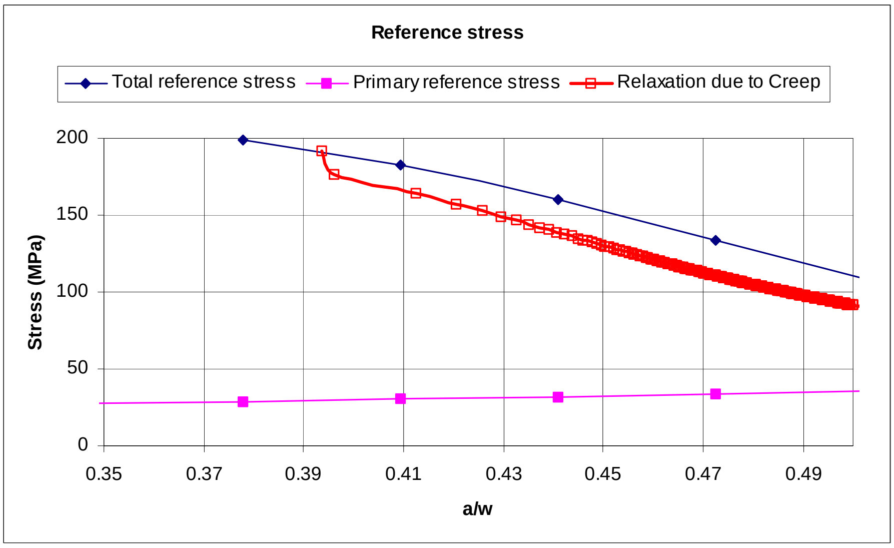


*Figure 2 Sample results for changes in primary and total reference stresses.*

### 3.2 Transient Creep Effects for Combined Loading with Initial Plasticity

R5 presents equations for the transient creep parameter C(t) for both elastic response on initial loading and elastic-plastic response on initial loading, but the results for elastic-plastic response apply only for primary loading. Here, a generalization of the solution is given to combined primary and secondary loading, when initial loading leads to elastic-plastic response. The approach follows that in [11,12] and assumes that plasticity and creep are described by power-law equations of the form $\varepsilon_p = \beta\sigma^\mu$ and $\dot{\varepsilon}_c = D\sigma^n$, with $\mu = n$. Although the derivation is complex, the main result can be written in a form that appears as a straightforward extension of the existing solutions in R5. Therefore only this main result is presented here, with algebraic details omitted for brevity. For combined loading, a conservative estimate of C(t) is given by

$$\frac{C(t)}{C^*} = \left(\frac{\sigma_{ref}}{\sigma_{ref}^p}\right)^{n+1} \left[\frac{\left(\varepsilon_{ref} / \varepsilon_{ref}^0\right)^{n+1}}{\left(\varepsilon_{ref} / \varepsilon_{ref}^0\right)^{n+1} - \left(\sigma_{ref}^0 / E\varepsilon_{ref}^0\right)}\right] \tag{17}$$

where $\sigma_{ref}$ is the total reference stress as in Section 3.1 and $\varepsilon_{ref}$ is the total strain at $\sigma_{ref}$. In eqn (17), $C^*$ refers to the value evaluated for the primary loading only. The initial value of the total reference stress is $\sigma_{ref}^0$, defined by eqn (8) for elastic response on initial loading. In order to use eqn (17), it is necessary to estimate $\varepsilon_{ref}^0$, which is the total elastic-plastic strain corresponding to $\sigma_{ref}^0$. For elastic behaviour on initial loading, this is simply $\sigma_{ref}^0 / E$. Equation (17) may also be expressed as

$$\frac{C(t)}{C^*} = \left(\frac{\sigma_{ref}\,\dot{\varepsilon}_{c,ref}}{\sigma_{ref}^p\,\dot{\varepsilon}_{c,ref}^p}\right) \left[\frac{\left(\varepsilon_{ref} / \varepsilon_{ref}^0\right)^{n+1}}{\left(\varepsilon_{ref} / \varepsilon_{ref}^0\right)^{n+1} - \left(\sigma_{ref}^0 / E\varepsilon_{ref}^0\right)}\right] \tag{18}$$

where $\dot{\varepsilon}_{c,ref}$ and $\dot{\varepsilon}_{c,ref}^p$ are the creep strain rates at $\sigma_{ref}$ and $\sigma_{ref}^p$ respectively, which generalizes eqn (6) to combined loading.

For pure primary loading, eqn (18) can be written

$$\frac{C(t)}{C^*} = \frac{\left(\varepsilon_{ref}^{e+p+c} / \varepsilon_{ref}^{e+p}\right)^{n+1}}{\left(\varepsilon_{ref}^{e+p+c} / \varepsilon_{ref}^{e+p}\right)^{n+1} - \left(\varepsilon_{ref}^{e} / \varepsilon_{ref}^{e+p}\right)} \tag{19}$$

where superscripts e, e+p and e+p+c denote elastic, elastic-plastic and elastic-plastic plus creep, respectively. This generalizes eqn (6) to the case when plasticity occurs on initial loading.

For pure primary loading, it is straightforward to evaluate the strain terms in eqn (19) as the reference stress is well defined from the limit load expression of eqn (1). For more general loading, the initial strain term may be obtained from an estimate of the initial value of J, $J_0$. By analogy with eqn (2) this is given by

$$J_0 = \sigma_{ref}^0 \varepsilon_{ref}^0 R' \tag{20}$$

The R6 procedure [10] may be used to estimate $J_0$ and gives

$$\frac{K^p + VK^s}{\sqrt{EJ_0}} = f(L_r) \tag{21}$$

where V is the parameter in R6 for treating interactions between primary and secondary stress and $f(L_r)$ is defined by the failure assessment diagram (Option 1, 2…). Then,

$$J_0 = \frac{\left(K^p + VK^s\right)^2}{Ef^2(L_r)} \tag{22}$$

From eqn (20),

$$\sigma_{ref}^0 \varepsilon_{ref}^0 \left(K^p / \sigma_{ref}^p\right)^2 = \frac{\left(K^p + VK^s\right)^2}{Ef^2(L_r)} \tag{23}$$

 

or

$$\sigma^0_{ref}\,\varepsilon^0_{ref} = \frac{\left(\sigma^p_{ref}\right)^2}{E}\,\frac{\left(1+VK^s/K^p\right)^2}{f^2\left(L_r\right)} \tag{24}$$

This may be used to define $\varepsilon^0_{ref}$ if the shape of the stress-strain curve is known.

## 4. RECENT DEVELOPMENTS IN R6

The defect assessment procedures of R6 are well established, having first been issued nearly 30 years ago. Since then there have been major developments in fracture mechanics understanding and the production of Revision 4 of R6 in 2001 [10] represented a significant advance in the assessment approach. Some subsequent developments and modifications to R6 were described in [13]. More recently, further changes to R6 Revision 4 have been made and these were issued in late 2004. These included:

- A revised section on Evaluation of Fatigue and Environmentally Assisted Crack Growth.
- A revised section on Load History Effects.
- A revised procedure for Leak-before-Break Assessment.
- A revised compendium of Homogeneous Limit Load Solutions.
- A new compendium of normalized Constraint Parameters.
- Updated Validation and Worked Examples.

All of these developments are not described here but instead attention is focussed on two areas: limit loads and constraint parameters. Information on some of the other developments may be found in [13].

### 4.1 Limit Load Solutions

The limit load is one of the key input parameters for both R6 and R5 assessment, as shown by eqn (1). It is used directly in R6 to define the load, $L_r$, parameter and measure closeness to plastic collapse. The limit load also enables an estimate to be made of the crack driving force, J, via the reference stress J-estimation of eqn (20). The choice of an appropriate limit load is then crucial to the results of an assessment. Advice on deriving the limit load is given in R6 with compendia of limit loads for specimens and components.

One important consideration in choosing a limit load is the distinction between 'local' and 'global' limit loads for surface defects. The former relates to yielding of the ligament ahead of the flaw, the latter to collapse of the entire structure. Hence the local limit load is always less than or equal to the global limit load and may lead to a more conservative assessment. For through-wall flaws, there is no distinction. Over the last few years, there has been ongoing work within R6 that has led to a revised compendium of Limit Load Solutions for Homogeneous Components. Firstly, a few of the less used solutions have been removed and the content made consistent with the stress intensity factor compendium in R6. Secondly, the solutions for plates and cylinders, in particular, have been extended to include both local and global solutions. This is based on an extensive series of finite element calculations by Lei [14-16], for semi-elliptical defects in plates under tension, bending, and combined tension and bending, which have demonstrated that an appropriate global limit load characterises the maximum J along the crack front, as shown in Figure 3. Results in the literature have led to similar conclusions for both plates and cylinders with axial or circumferential flaws.

### 4.2 Constraint Solutions

When performing an assessment using the basic procedures of R6, there is an element of conservatism so that, in general, reserve factors tend to be underestimated. For example, the fracture toughness is normally derived from deeply cracked bend specimens using testing standards designed to provide a material property which is independent of specimen size and geometry. However, there is considerable evidence that resistance to fracture is increased when specimens with shallow cracks, or specimens in tension, are tested. This is referred to as ‘low constraint’. In order to reduce over-conservative predictions of failure by taking account of constraint effects, both the level of structural constraint and the sensitivity of the material’s fracture resistance to constraint need to be quantified.

 

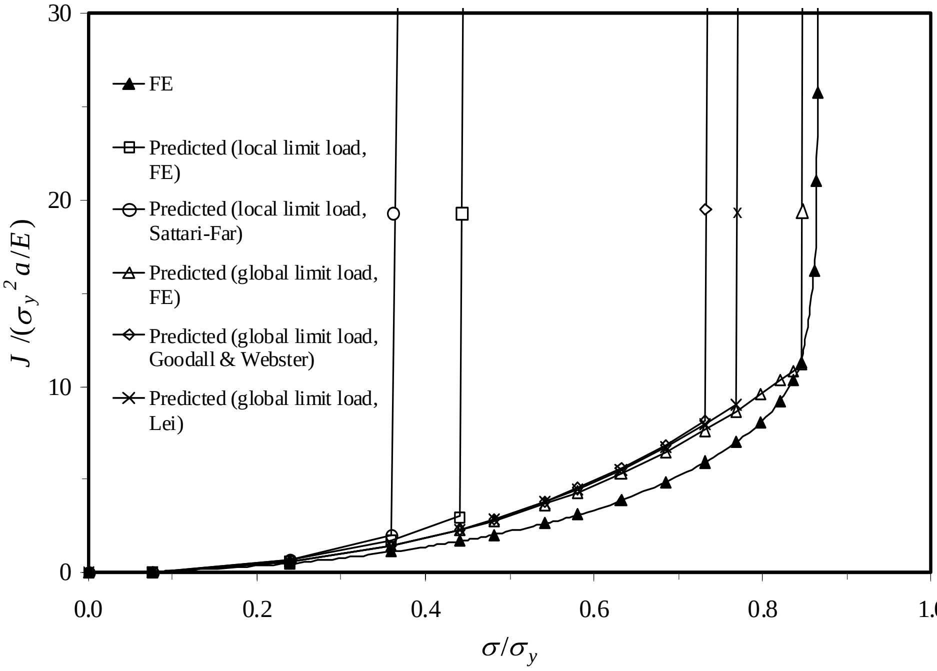


*Figure 3. Crack driving force J at deepest point of crack against applied stress $\sigma$ - plate under tension with surface semi-elliptical crack [14]. The FE results and predictions based on various local or global limit load solutions are shown.*

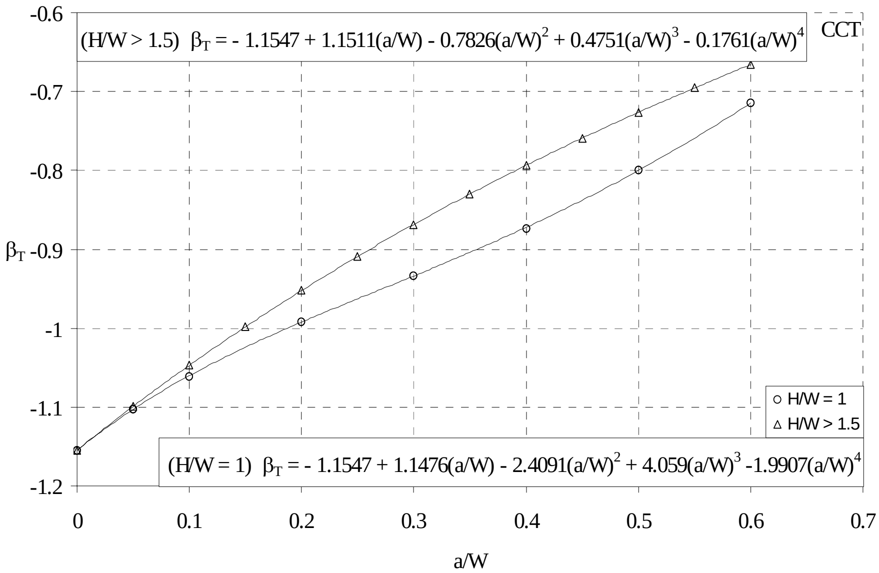


*Figure 4. Normalized constraint solution for a centre-cracked plate under uniaxial tension (CCT) with crack size 2a in a plate of width 2W and height 2H.*

The level of constraint is taken into account in R6 by a parameter, $\beta$, defined in terms of the elastic T-stress or the normalised elastic-plastic hydrostatic stress, Q, such that $\beta_T = T/\sigma_{ref}$ or $\beta_Q = Q/L_r$. Low constraint corresponds to $\beta < 0$. The compendium of $\beta$ solutions in R6 initially covers elastic, $\beta_T$, solutions. The values of T-stress used to calculate $\beta_T$ were derived from finite element analyses for a range of normalised crack depths, and the limiting value at short crack depths fitted to an analytical solution. Results are given for seven plane or axisymmetric geometries (centre-cracked plate in uniaxial tension; centre-cracked plate in equibiaxial tension; double edge-cracked plate in uniaxial tension; single edge-cracked plate in uniaxial tension; single edge-cracked plate in pure bending; single edge-cracked plate in 3 point bend; and circumferentially cracked cylinder in tension), with an example of the solutions shown in Figure 4:

## 5. BRITISH STANDARDS AND EUROPEAN DEVELOPMENTS

BS7910 [8] was published in 1999 and covered fracture, fatigue and creep. An amended version of BS7910 was produced in 2000 correcting a number of typographical errors and technical inconsistencies in the 1999 version. The developments in BS7910 have been described in [9]. A second amendment to BS7910 will be issued shortly, covering typographical corrections collected more recently. More extensive revisions to BS7910 are currently being progressed by a BSi Committee. These will make BS7910 more in line with the R6 and FITNET (see below) documents.

The European Community are currently funding a project FITNET to review existing fitness-for-service procedures and develop an updated procedure to cover structural integrity analysis to avoid failure due to fracture, fatigue, creep and corrosion. FITNET is a four-year project that started in 2002. The developments in R5 and R6 are being actively incorporated in the FITNET procedure. The FITNET network currently consists of 50 organisations from 16 European and three non-European countries representing various industrial sectors and academia. Further information can be found in [17]. Standardization at the European level for industrial structures and products is covered by CEN. FITNET has prepared a draft fitness-for-service procedure that has been submitted to CEN under the CEN Workshop Agreement (CEN WA22) route towards standardization. The completion of the FITNET fitness-for-service procedure will take account of public comments received through the CEN process.

## 6. CONCLUSIONS

This paper has described some recent developments in the R5 and R6 procedures. These developments reduce conservatisms in defect assessment by allowing for relaxation of secondary stresses and by taking account of reduced constraint. In parallel with the R5 and R6 developments, activities within British Standards and Europe are also developing defect assessment procedures and these activities have been briefly described.

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