SMiRT-12 / K. Kussmaul (Editor)

FG15/1

DEFECT ASSESSMENT PROCEDURE: A FRENCH APPROACH FOR FAST BREEDER REACTORS

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1. INTRODUCTION

The Commissariat à l'Energie Atomique (CEA), the Electricité de France (EDF) and the division NOVATOME from FRAMATOME have been conducting collaborative studies in order to produce new procedures or to improve present rules of the RCC-MR code **[1]**. Among these studies, moderate and high temperature flaw assessment procedure for reactor components. As a result of this collaboration, an interim defect assessment procedure, noted Appendix A16 of the RCC-MR, is now available in the first draft version.

This procedure addresses defects detected during in-service inspection for reactor components operating at moderate or high temperature conditions. Three stages have been considered and will be presented here :

- crack initiation,
- subcritical crack growth / propagation under cyclic loading with or without holdtime,
- ligament and crack instabilities by ductile and creep rupture.

Specification of defect size, handbook solutions to calculate the stress intensity factors and the limit loads, simplified methods to estimate J and relevant material properties are also given in the appendix A16.

2. DEFECT SIZE

In order to perform the calculations proposed in the appendix A16, it is necessary to characterize the irregular shape of the existing defect by a geometrically simpler circumscribing curve. As in other codes **[2,3]**, a surface defect is characterised as a semi-ellipse and a buried defect as an ellipse. For multiple cracks, usual crack interaction rules are applied.

3. PROCEDURES WHEN CREEP IS INSIGNIFICANT

3.2. Crack initiation (insignificant creep)

Where the creep is not significant, it is possible for pre-existing defects (not for fatigue defects) to analyse the crack initiation phase by using the σ_d approach ; σ_d is the stress at a distance d from the crack tip, equal to 0.05 mm for 316L stainless steel [4]. The step by step procedure is the following :

step 1 : calculate the range of the elastic stress $\Delta\sigma_{ed}$ at the distance d. When stress intensity factors are available, $\Delta\sigma_{ed}$ can be calculated by Creager [5] simplified equation : $\Delta\sigma_{ed} = \Delta K_I/(2\pi d)^{1/2}$,

step 2 : determine the elastic-plastic strain range $\Delta\epsilon_d$ according to Neuber's rule [6] using the cyclic stress-strain curve (**Fig.1**).

step 3 : determine the number of cycles for initiation N_i by entering the design fatigue curve at $\Delta\epsilon_d/T$ value (**Fig.2**) where T=1.5 for 316L stainless steel.

step 4 : calculate the initiation usage factor $V = n/N_i$, where n is the specified number of cycles.

step 5 : linearly sum the initiation usage factor V due to the specified types of cycles according to the Miner rule to determine the total initiation usage factor V_{tot}. If V_{tot} is less than 1, crack propagation does not start and the stability analysis can be performed on the initial defect size. If V_{tot} is greater than 1, the crack propagation shall be estimated in order to determine the final defect size to be used for the stability analysis.

3.2. Crack propagation (insignificant creep)

The crack growth per cycle under cyclic loading during the residual life shall be estimated from ΔJ evaluation in order to account for plasticity effects. A simplified estimate of crack closure which significantly influences the crack growth is defined in terms of stress ratio R. The step by step procedure is the following :

step 1 : determine the range of J over the cycle : ΔJ.
Handbook solutions, finite element methods may be employed. Simplified method J_s is proposed using reference stress [7,8,9] in order to derive ΔJ from the elastic contribution ΔJ_e : $\Delta J = \Delta J_e.K_{\Delta J}$ with $K_{\Delta J} = [\psi + \Delta\epsilon_{ref}/(\Delta\sigma_{ref}/E)]$ and $\psi = 0.5(\Delta\sigma_{ref})^2/[(\Delta\sigma_{ref})^2 + (S_y)^2]$
When a mechanical load is combined with thermal loading, the reference stress σ_{ref} depends not only on the limit load or on the primary stress range ΔP_{def} in the structure with the defect, but depends also on the secondary stress range ΔQ_{def} (**Fig.3**).

step 2 : determine an effective stress intensity factor range $\Delta K_{eff} = q.[E^*.\Delta J]^{1/2}$ where Young's modulus $E^*=E$ in plane stress and $E^*=E/(1-\nu^2)$ in plane strain, and ν is the Poisson ratio. The crack closure factor q is calculated in terms of stress ratio $R = K_{min}/K_{max}$: $q = [1-0.5R]/[1-R]$ for $R<0$ and $q=1/[1-0.5R]$ for $R>0$.

step 3 : calculate the crack growth for each cycle using the Paris law $(da/dN)_f = C(\Delta K_{eff})^p$, where C and p are material constants, in order to determine the amount of crack extension from the initial crack size a_o in the specified number of cycles.

3.3. Stability analysis (insignificant creep)

When subjected to the specified loadings, the structure with the final defect size does not undergo ductile tearing and crack instability.

3.31 Ductile tearing (insignificant creep)

In order to avoid ductile tearing, the primary stresses in the cracked geometry should not exceed the limits specified for the non defective structure.
For example, if the limit analysis is used, the characteristic stress $S_o = (C/C_L)/R_L$ should not exceed the following values :

- level A : $S_o \leq S_m$
- level C : $S_o \leq Min\{1.35S_m, S_y\}$
- level D : $S_o \leq Min\{2.4S_m, 0.7S_u\}$

where C is the specified load, C_L the limit load for the cracked geometry obtained for an elastic perfectly plastic material with a yield strength R_L.
S_m, S_y, S_u : allowable stress, yield strength and ultimate strength of the material.

3.32 Crack instability (insignificant creep)

The specified loading (C) shall not exceed the loading that induces the crack instability (C_{inst}). That instability loading is deduced from the conditions which signify **(Fig.4)** tangency between the J curve of the defective structure and the J_R material curve (usually, the crack growth is limited to 3mm on this curve) : $J = J_R$ and $dJ/da = dJ_R/da$

4. PROCEDURES WHEN CREEP IS SIGNIFICANT

Where creep is significant, it is necessary to modify the different rules for crack initiation, crack growth, ligament and crack stability.

4.1 Crack initiation (significant creep)

Where creep is significant, crack initiation procedure **[10, 11]** is similar to the RCC-MR creep-fatigue analysis taking into account the value of the stress σ_d at a distance d from the crack tip. The step by step procedure is the following :

step 1 : calculate the range of the elastic stress $\Delta\sigma_{ed}$ at the distance d. When stress intensity factors are available, $\Delta\sigma_{ed}$ can be calculated by Creager simplified equation : $\Delta\sigma_{ed} = \Delta K_I/(2\pi d)^{1/2}$,

step 2 : determine the elastic-plastic strain range $(\Delta\epsilon_d)_{el+pl}$ according to Neuber's rule using the cyclic stress-strain curve ; the corresponding stress range is noted $\Delta\sigma^*$ **(Fig.1)**.

step 3 : determine the amplification of the strain range $(\Delta\epsilon_d)_c$ which results from the effects of time (creep). This amplification is obtained by using the creep law to calculate the creep strain due to an effective stress σ_{kd} at the distance d of the crack tip $\sigma_{kd} = P_{mean} + 0.5.\Delta\sigma^*$, maintained during the holdtime. This formula assumes a total symmetrisation due to the plasticity of the cyclic stress at the crack tip and takes into account the mean value during the cycle of the primary stress P.

step 4 : determine the number of cycles for initiation N_i by entering the design fatigue curve at $[(\Delta\epsilon_d)_{el+pl}+(\Delta\epsilon_d)_c]/T$ value where T=1.5 for 316L stainless steel.

step 5 : calculate the initiation usage factor $V = n/N_i$, where n is the specified number of cycles.

step 6 : linearly sum the initiation usage factor V due to the specified types of cycles according to the Miner rule to determine the total initiation usage factor V_{tot}.

step 7 : determine the time to initiation T_i by entering the S_r design creep rupture curve at σ_{kd} value **(Fig.5)**.

step 8 : calculate the initiation usage factor $W = t/T_i$, where t is the specified holdtime.

step 9 : linearly sum the initiation usage factor W due to the specified types of cycles to determine the total initiation usage factor W_{tot}.

The check on the non-initiation of the crack resulting from the accumulation of the effects of creep and fatigue consists in demonstrating that the representative point $[V_{tot}, W_{tot}]$ is located within the allowable area on the creep-fatigue interaction diagram **(Fig.6)**. If the total damage is acceptable, the crack propagation study is not necessary and the stability study can be done on the initial defect size.

4.2 Creep-fatigue crack propagation

The procedure to determine the crack propagation due to cyclic load changes with holdtime at high temperature is still under discussion. The step by step procedure is the following :

step 1 : calculate the cyclic crack growth per cycle during the transient : $(\delta a)_f = C.(\Delta K_{eff})^p$ as described in section 3.2. At the end of the transient, the crack length is $a = a_o + (\delta a)_f$

step 2 : calculate the creep crack growth per cycle during the holdtime : $(\delta a)_c = \int A.(C^*)^q.dt$ where A and q are material constants. At the end of the holdtime, the crack length is $a = a_o + (\delta a)_f + (\delta a)_c$.
Different methods for estimating the creep parameter C* are proposed in the litterature [12] ; the reference stress method may be used : $C^* = (K_I/\sigma_{ref})^2 \cdot \sigma_{ref} \cdot \dot{\epsilon}_{ref}$.

step 3 : repeate steps 1 and 2 for all the specified cycles to determine the final defect size a_f.

4.3 Stability analysis (significant creep)

Before accepting the defect without reparation, it is necessary to make a check on the resistance of the defective structure to :

- plastic instability of the ligament and short term ductile tearing,
- creep rupture and ductile tearing during the holdtime,

With regard to plastic instability and short term ductile tearing, the same rules as for the case when creep is insignificant have to be satisfied.

With regard to creep rupture during the hold time, the primary stresses in the cracked geometry should not exceed the limits specified for the non defective structure. For example, if the limit analysis is used, the characteristic stress $S_o = (C/C_L)/R_L$ should not exceed the following values :

- level A : $S_o \leq S_t$
- levels C and D : $S_o \leq S_r$

where C is the specified load, C_L the limit load for the cracked geometry obtained for an elastic perfectly plastic material with a yield strength R_L.
S_t, S_r : allowable stress in creep, stress to creep rupture of the material.

With regard to ductile tearing during the hold time, it is necessary to compute J (section 3.32) on the basis of ϵ_{el+pl} enhanced with the creep deformation ϵ_c during the hold time.

5. CONCLUSIONS

As a result of a collaborative effort between CEA, EDF and NOVATOME to produce and improve rules for fast breeder reactors (RCC-MR), an interim defect assessment procedure is now available in the first draft version (appendix A16). This procedure addresses defects detected during in-service inspection for reactor components operating at moderate or high temperature conditions. Three stages have been considered : initiation, propagation under cyclic loading with or without holdtime, ligament and crack instabilities by ductile and creep rupture. For each of these topics, procedures and rules based on fracture mechanics are proposed. Specification of defect size, handbook solutions to calculate the stress intensity factors and the limit loads, simplified methods to estimate J and relevant material properties are also given in the appendix A16.

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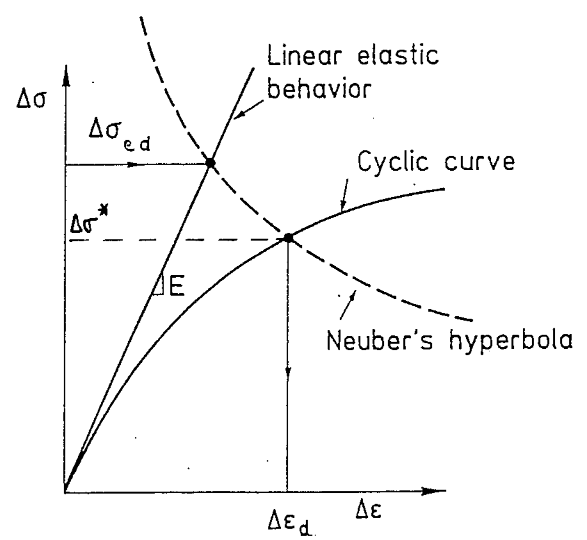

Fig.1 : Determination of $\Delta\epsilon_d$ and $\Delta\sigma^*$

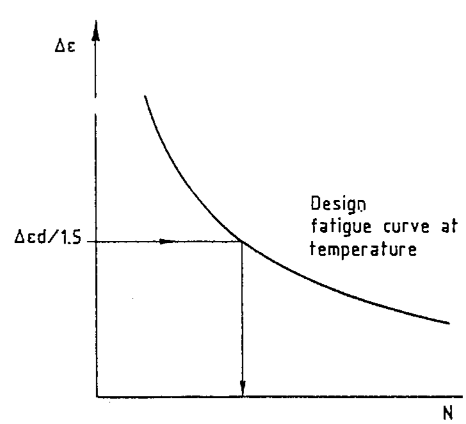

Fig.2 : Number of cycles for initiation N_i

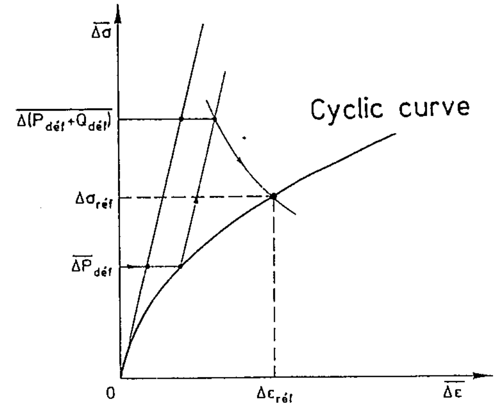

Fig.3 : Determination of $\Delta\sigma_{ref}$

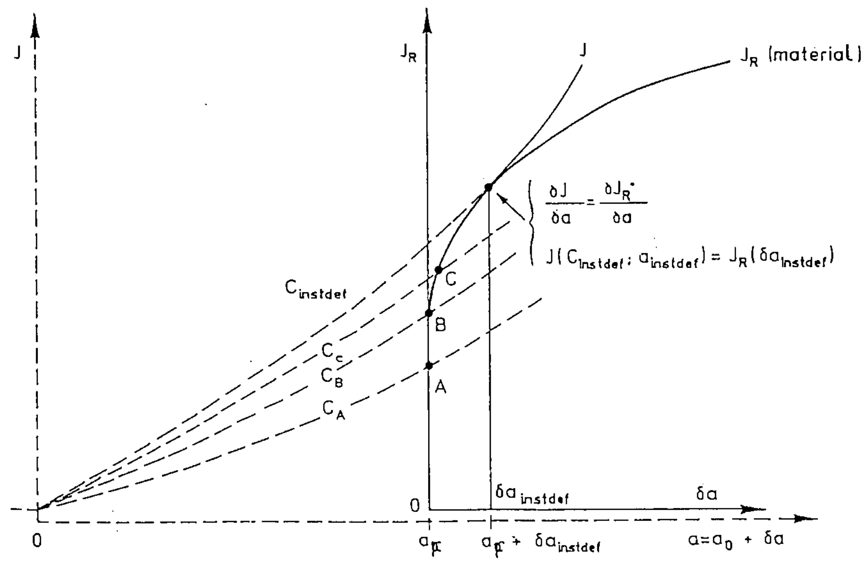

Fig.4 : Determination of the crack instability load $C_{instdef}$

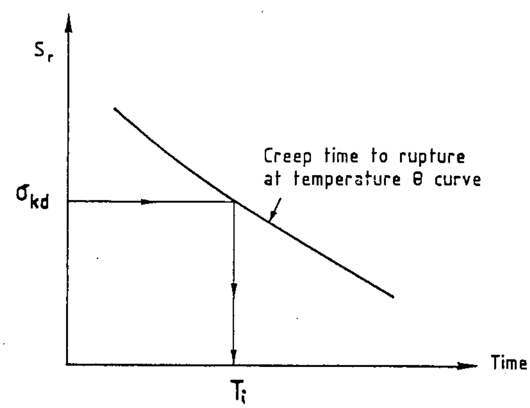

Fig.5 : Determination of time for initiation T_i

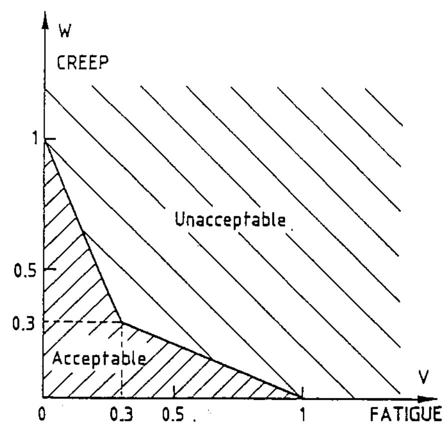

Fig.6 : Creep-fatigue interaction diagram