Failure Assessment Diagrams for High Temperature Defect Assessment under Variable Loading Conditions.

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ABSTRACT

A two parameter Time Dependent Failure Assessment Diagram (TDFAD) procedure for defect assessment under creep loading builds on the reference stress approach of the R6, Option 2, procedure for defect assessment, with potential failures defined by creep crack initiation and creep rupture. The conventional fracture toughness is replaced by a time-dependent 'creep toughness', and tensile properties are determined from isochronous data at the corresponding assessment time and temperature. The TDFAD approach has recently been formalised and incorporated into R5 as an appendix to Volume 4. In this paper, the TDFAD procedure of R5 is first summarised. Methods are then described, for extending the application of the procedure to non-steady loading conditions of variable stress and/or temperature, using a concept of an equivalent reference stress. A worked example of the procedure is also presented.

INTRODUCTION

In recent years, failure assessment diagram (FAD) methods, such as those of R6 [1], have been extended to the creep regime [2-6]. The FAD becomes time dependent (TDFAD) and together with a time-dependent 'yield stress' is determined using isochronous stress-strain data corresponding to the assessment time and temperature. The conventional fracture toughness used in low temperature assessments is replaced by a time dependent 'creep toughness'. In the absence of creep the approach reduces to an assessment in terms of R6 [1] and, therefore, covers the full range of conditions from zero creep to widespread creep. Hence, the procedure is especially useful for assessments at low creep temperatures where creep strain rates are low and the transition period between the initial loading and the steady state creep condition is large. In these situations more traditional methods based on C(t) and C^* may lead to unduly conservative assessments.

Recently, the TDFAD has been developed into a formal procedure and incorporated into the R5 high temperature assessment procedure [7]. At present this procedure considers only steady loading conditions of constant stress and temperature, although allowance may be made for limited amounts of fatigue crack growth.

Under variable primary loading conditions, the assessment route, described here, is based on dividing the assessment period into discrete time intervals of essentially constant stress and temperature. An equivalent reference stress is then defined as the reference stress, which under steady load and temperature conditions up to the assessment time, produces the same time dependent J value as that produced under the summation of the discrete time intervals. The time dependent J, J(t), is defined in terms of the total strain arising from elastic, plastic and creep strains. The assessment then follows the R5 [7] procedure, for primary loading, with the reference stress replaced by the equivalent reference stress. Application of the method to combined primary/secondary loading conditions is based on defining an equivalent primary reference stress, at selected times during each discrete steady state loading period, which gives the same J(t) value as that for combined primary and secondary loads. This latter approach is similar to that [8] used for time-independent loading in the determination of the plasticity correction factor for secondary stress, ρ, used in R6 [1]. The assessment route then proceeds in the same manner as for primary loading only.

In this paper, the TDFAD procedure of R5 [7] is first summarised. Then, following a detailed description of the assessment route for non-steady loading conditions, a worked example of the procedure is presented.

TIME DEPENDENT FAILURE ASSESSMENT DIAGRAMS

Appendix A8 of Volume 4 of R5 [7].

Equation (A8.1) of Appendix A8 of Volume 4 of R5 [7] defines the time-dependent failure assessment diagram for primary loading by the equation

$$K_r = \left[\frac{E\varepsilon_{ref}}{L_r \sigma^c_{0.2}} + \frac{L_r^3 \sigma^c_{0.2}}{2E\varepsilon_{ref}} \right]^{-\frac{1}{2}} \qquad (1)$$

where ε_{ref} is the total strain at the reference stress given by

$$\varepsilon_{ref} = \varepsilon^{el+pl}(\sigma_{ref}) + \varepsilon^{cr}(\sigma_{ref}, t) \qquad (2)$$

with σ_{ref} defined by, $$\sigma_{ref} = P\sigma_y / P_L(\sigma_y, a) = L_r \sigma^c_{0.2} \tag{3}$$

where P_L is the value of the applied load P corresponding to plastic collapse assuming a yield stress σ_y, a is crack size, and $\sigma^c_{0.2}$ is the 0.2% proof stress from the isochronous stress strain curve at time t.

The assessment point (L_r, K_r) is given by Eqs. (A8.9) and (A8.11) of Appendix 8 of Volume 4 of R5 [7]:

$$L_r = \frac{\sigma^m_{ref}}{\sigma^c_{0.2}} \tag{4}$$

where σ^m_{ref} is the reference stress due to mechanical loading, and for combined mechanical and thermal/residual stresses, with corresponding stress intensity factors K_m and K_T, K_r is given by

$$K_r = \frac{\left\{(K_m)^2\left[E\varepsilon_{ref}/\sigma_{ref}\right] + (K_T)^2 + 2K_m K_T\right\}^{\frac{1}{2}}}{\left[E\varepsilon_{ref}/\sigma_{ref}\right]^{\frac{1}{2}} K^c_{mat}} \tag{5}$$

where K^c_{mat} is a lower bound value of creep toughness, and the quantity $\left[E\varepsilon_{ref}/\sigma_{ref}\right]$ may be determined from the TDFAD, Eq. (1), at the appropriate value of L_r.

It is noteworthy that in comparison to R6 no ρ factor is included in Eq. (5), as it is shown [2] in the derivation of Eq. (5), that without any ρ factor the equation gives a conservative estimate of K_r.

Assessments under Variable Creep Conditions

Primary loading only

For creep assessments involving variable primary loading at a constant temperature, T, as indicated in Figure (1a), an equivalent reference stress, $\overline{\sigma}^{eq}_{ref}$ is defined [3] such that the accumulated creep strain at this stress for the total time, t, is equal to the accumulated creep strain at the reference stress history, Figure (1b);

$$\varepsilon^{cr}_{ref}\left(\overline{\sigma}^{eq}_{ref}, t_{total}\right) = \sum \varepsilon^{cr}_{ref}\left(\sigma_{ref,i}, t_i, T_i\right) \tag{6}$$

The assessment point is then given by, $L_r = \dfrac{\overline{\sigma}^{eq}_{ref}}{\sigma^c_{0.2}}$, $K_r = \dfrac{\overline{\sigma}^{eq}_{ref} K_m}{\sigma^m_{ref} K^c_{mat}}$.

Where K_m is the stress intensity factor for a value of load which corresponds to the reference stress σ^m_{ref} and the TDFAD is based on the total time. Assessments involving varying temperature may be performed in a similar manner. However, this approach is based on widespread creep considerations and to cover the range of creep from zero to widespread conditions $\overline{\sigma}^{eq}_{ref}$ is better defined based on a time dependent J value, J(t), given by

$$J(t) = J_{el} + J_{pl} + J_{cr} \tag{7}$$

This approach is similar that used [8] to define an equivalent reference stress for combined primary and secondary stresses. It is first noted that the TDFAD, Eq. (1), also relates the time dependent stress-strain response of the material, $f\left(\sigma/\sigma^c_{0.2}\right)$, by the equation:

$$K_r = \sqrt{\frac{J_{el}}{J}} = f\left(\frac{\sigma}{\sigma^c_{0.2}}\right) = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \left(\frac{\sigma_{ref}}{\sigma^c_{0.2}}\right)^2 \frac{\sigma_{ref}}{2E\varepsilon_{ref}}\right]^{-\frac{1}{2}} \tag{8}$$

where $J_{el} = K^2/E'$, J is time dependent (=J(t)) and apart from the minor correction term, the second term in the square bracket of Eq. (8) gives,

$$f\left(\sigma/\sigma^c_{0.2}\right) = \left[E\varepsilon_{ref}/\sigma_{ref}\right]^{-1/2} \tag{9}$$

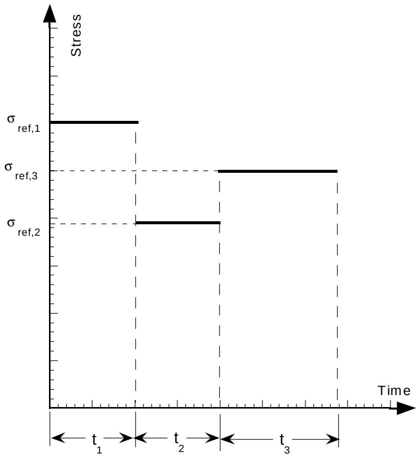

FIG. 1(a)- Schematic loading history

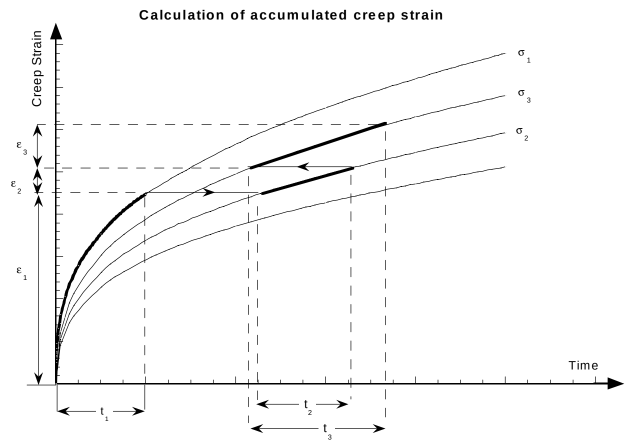

FIG. 1(b)- Calculation of creep strain under primary stress

where ε_{ref} is the strain from the isochronous stress-strain curve, at the appropriate time and temperature, corresponding to the stress σ_{ref}. Thus for constant primary loading, from Eqs. (8) and (9)

$$J(t) = \sigma_{ref}\varepsilon_{ref}R' \tag{10}$$

where ε_{ref} is the total strain arising from elastic, plastic and creep displacements, $\varepsilon_{ref} = \varepsilon^{el} + \varepsilon^{pl} + \varepsilon^{cr}$, and $R' (= K^2/\sigma^2_{ref})$ is a characteristic distance, which is a constant for a given geometry, since both K and σ_{ref} are both directly proportional to applied load.

Hence, from Eqs. (7) and (10), the total time dependent J value , J(t), for variable loading is given by

$$J(t) = \sigma^m_{ref,max}\varepsilon^{el}(\sigma^m_{ref,max})R' + \sigma^m_{ref,max}\varepsilon^{pl}(\sigma^m_{ref,max})R' + \left\{\sum_i \sigma^m_{ref,i}.\Delta\varepsilon^{cr}_i(\sigma^m_{ref,i},\varepsilon^{cr})\right\}R' \tag{11}$$

Here the elastic and plastic contributions to J are for the maximum loading condition up to the assessment time. It should also be noted that the summation term here, {Σ}, is not a summation of J's from different loading conditions but the time dependent contribution to J, in Eq. (7), resulting from the summation of the area under the load displacement curve during creep hold periods.

From Eq. (10), expressing the time-dependent J in terms of the equivalent reference stress, $\overline{\sigma}^{eq}_{ref}$, gives

$$J(t) = \overline{\sigma}^{eq}_{ref}\left(\varepsilon^{el}(\overline{\sigma}^{eq}_{ref}) + \varepsilon^{pl}(\overline{\sigma}^{eq}_{ref}) + \varepsilon^{cr}(\overline{\sigma}^{eq}_{ref})\right)R' \tag{12}$$

and equating J(t) values from Eqs. (11) and (12), the equivalent reference stress, $\overline{\sigma}^{eq}_{ref}$, is obtained from the solution to the equation,

$$\overline{\sigma}^{eq}_{ref}\left(\overline{\sigma}^{eq}_{ref}/E + \varepsilon^{pl}(\overline{\sigma}^{eq}_{ref}) + \varepsilon^{cr}(\overline{\sigma}^{eq}_{ref}, t_{total})\right) = \left(\sigma^m_{ref,max}\right)^2/E + \sigma^m_{ref,max}\varepsilon^{pl}(\sigma^m_{ref,max}) + \sum_i \sigma^m_{ref,i}.\Delta\varepsilon^{cr}_i(\sigma^m_{ref,i},\varepsilon^{cr}) \tag{13}$$

which in the absence of creep reduces to $\overline{\sigma}^{eq}_{ref} = \sigma^m_{ref,max}$, and the assessment simply becomes an R6 assessment [1].

Combined primary and secondary loading.

To apply Eq. (13) for combined primary and secondary loading it is first necessary to define, for each loading period, an equivalent primary reference stress σ^{eq}_{ref} as that stress which produces the same time-dependent J value as that for combined primary and secondary loading. Thus, Eq. (13) becomes

$$\overline{\sigma}_{ref}^{eq}\left(\overline{\sigma}_{ref}^{eq}/E+\varepsilon^{pl}(\overline{\sigma}_{ref}^{eq})+\varepsilon^{cr}(\overline{\sigma}_{ref}^{eq},t_{total})\right)=\left(\sigma_{ref,max}^{eq}\right)^2/E+\sigma_{ref,max}^{eq}\varepsilon^{pl}(\sigma_{ref,max}^{eq})+\sum_i \sigma_{ref,i}^{eq}.\Delta\varepsilon_i^{cr}(\sigma_{ref,i}^{eq},\varepsilon^{cr}) \quad (14)$$

where $\sigma_{ref,max}^{eq}$ is the maximum value of σ_{ref}^{eq} incurred prior to the assessment time. The equivalent primary/secondary reference stress σ_{ref}^{eq} now varies during the hold. Hence, the summation term Σ is summed incrementally not only over load steps but also incrementally during load steps, assuming strain hardening behaviour. The value of σ_{ref}^{eq} at any time, is derived as follows:-

Following an R6 approach [8], the TDFAD, Eq. (8), is defined in terms of the mechanical load alone. Then for combined loading the value of J(t) at failure, as defined by the initiation of crack growth, lies on the curve described by the equation:

$$J(t)=\frac{K^2}{E'}\left[f\left(\frac{\sigma_{ref}^m}{\sigma_{0.2}^c}\right)\right]^{-2} \quad (15)$$

where K is the total $K=K_m+K_T$ for combined loading, and $E'=E$ for plane stress and $E'=E/(1-\nu^2)$ for plane strain. Now for primary loading only, as described by σ_{ref}^{eq}, the elastic stress intensity factor for mechanical loading may be written in terms of a geometrical factor $\bar{a}$, $(\pi\bar{a}=R')$, as

$$K_m=\sigma_{ref}^m(\pi\bar{a})^{1/2} \quad (16)$$

and the value of J(t) at failure lies on the curve,

$$J(t)=\left[\frac{\sigma_{ref}^{eq}}{f(\sigma_{ref}^{eq}/\sigma_{0.2}^c)}\right]^2\frac{\pi\bar{a}}{E'} \quad (17)$$

Hence, for equivalence of J(t) values, from Eqs. (15) and (17)

$$\sigma_{ref}^{eq}\frac{f(\sigma_{ref}^m/\sigma_{0.2}^c)}{f(\sigma_{ref}^{eq}/\sigma_{0.2}^c)}=\frac{K}{(\pi\bar{a})^{1/2}} \quad (18)$$

where K, the total stress intensity factor, is given by Eq. (5) as,

$$K=\frac{\left\{(K_m)^2\left[E\varepsilon_{ref}/\sigma_{ref}\right]+(K_T)^2+2K_mK_T\right\}^{\frac{1}{2}}}{\left[E\varepsilon_{ref}/\sigma_{ref}\right]^{\frac{1}{2}}} \quad (19)$$

Hence, from Eqs. (16), (18) and (19), σ_{ref}^{eq} is defined by the equation,

$$\sigma_{ref}^{eq}=f\left(\frac{\sigma_{ref}^{eq}}{\sigma_{0.2}^c}\right)\left\{\left[\frac{\sigma_{ref}^m}{f(\sigma_{ref}^m/\sigma_{0.2}^c)}\right]^2+\left[\frac{\sigma_{ref}^T}{f(\sigma_{ref}^T/\sigma_{0.2}^c)}\right]^2+\frac{2\sigma_{ref}^m\sigma_{ref}^T}{f(\sigma_{ref}^T/\sigma_{0.2}^c)}\right\}^{1/2} \quad (20)$$

where K_T in Eq. (19) has been defined, in the manner of [8], by:

$$\frac{\sigma_{ref}^T/\sigma_{0.2}^c}{f(\sigma_{ref}^T/\sigma_{0.2}^c)}=\frac{K_T}{(\pi\bar{a})^{1/2}\sigma_{0.2}^c} \quad (21)$$

such that in the absence of primary stress, Eq. (20) gives $\sigma_{ref}^{eq}=\sigma_{ref}^T$.

Eq. (21) may also be written in the form,

$$\sigma_{ref}^T=\frac{K_T}{K_m}\sigma_{ref}^m f\left(\frac{\sigma_{ref}^T}{\sigma_{0.2}^c}\right) \quad (21a)$$

where the function $f(\sigma^T_{ref}/\sigma^c_{0.2})$ is defined by the shape of the TDFAD Eq. (8), which gives

$$f\left(\frac{\sigma}{\sigma^c_{0.2}}\right)=\left[\frac{E\varepsilon_{ref}}{\sigma^T_{ref}}+\left(\frac{\sigma^T_{ref}}{\sigma^c_{0.2}}\right)^2\frac{\sigma^T_{ref}}{2E\varepsilon_{ref}}\right]^{-\frac{1}{2}} \tag{21b}$$

where ε_{ref} is the total strain from the isochronous stress-strain curve, at time t, corresponding to the stress σ^T_{ref}.

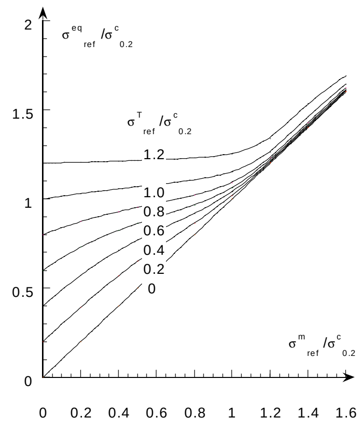

FIG. 2-Definition of time-dependent equivalent reference stress under combined loading.

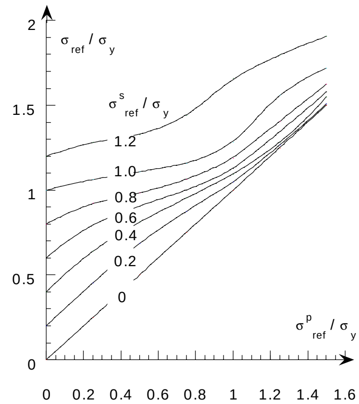

FIG. 3-Definition of time-independent equivalent reference stress under combined loading

Values of Eq. (20) calculated using this function are shown in Figure (2), which may be compared with the equivalent stress, for time-independent combined loading Figure (3), taken from [8], which was used to determine the ρ factor of R6 Appendix 4. For comparison purposes, the TDFAD has been taken as the R6 Option 1 FAD. Hence, the function $f(\sigma/\sigma^c_{0.2})$ is equal to $f(\sigma/\sigma_y)$, and is described by the equation:

$$f(\sigma/\sigma_y)=\left(1-0.14(\sigma/\sigma_y)^2\right)\left(0.3+0.7\exp\left(-0.65(\sigma/\sigma_y)^6\right)\right) \tag{22}$$

(Note: for this case, $\sigma^p_{ref}\equiv\overline{\sigma}_{ref}$, $\sigma^s_{ref}\equiv\sigma^T_{ref}$, $\sigma_{ref}\equiv\sigma^{eq}_{ref}$, $\sigma_y\equiv\sigma^c_{0.2}$.)

The main characteristics of σ^{eq}_{ref}, as shown in Figure (2), are:-

- when the primary load is zero $\sigma^{eq}_{ref}=\sigma^T_{ref}$
- when both σ^m_{ref} and σ^T_{ref} are small compared to $\sigma^c_{0.2}$, $\sigma^{eq}_{ref}=\sigma^m_{ref}+\sigma^T_{ref}$
- as σ^m_{ref} increases σ^{eq}_{ref} approaches σ^m_{ref}
- as time increases $\sigma^c_{0.2}$ decreases and $\sigma^m_{ref}/\sigma^c_{0.2}$ increases, hence, σ^{eq}_{ref} approaches σ^m_{ref}

Hence, at zero time, Figures (2 and 3) show the same trends.

The assessment point for variable creep under combined loading is defined by:

$$L_r=\frac{\overline{\sigma}^{eq}_{ref}}{\sigma^c_{0.2}} \tag{23}$$

$$K_r = \frac{\overline{\sigma}^{eq}_{ref}(R')^{1/2}}{K^c_{mat}} \quad (24)$$

It should be noted that in the absence of primary stress equating σ^{eq}_{ref} to σ^{T}_{ref}, as given by Eqs. (20) and (21), will give a conservative result, if no allowance is made for the creep relaxation of secondary stresses. For this case K_T in Eq. (21) may be replaced by a relaxed time dependent value, K^R_T, in a similar manner to the use of an inelastic secondary stress intensity factor, K^s_J [9] used in Appendix 4 of R6 [1]. For combined primary and secondary stresses, stress relaxation, with elastic follow-up, may be evaluated using the methods of Appendix A6 to Volume 4 of R5. However, the determination of K^R_T is not so straightforward, as K_m is now based on an effective time dependent primary reference stress, due to the accumulation of forward creep strains during creep relaxation. Therefore, in these cases, the neglect of the relaxation of secondary stresses is not as conservative as for secondary stresses acting alone. It is also noteworthy, referring to Figure 2, that with increasing time, $\sigma^c_{0.2}$ reduces and hence L_r increases and σ^{eq}_{ref} tends towards σ^m_{ref} even the absence of a relaxation calculation.

Procedure for Assessments under Variable Creep Conditions

For combined loading conditions the steps of the procedure are as follows:

- Divide the time history into periods of steady loading

- For the first period of steady loading,
  - Evaluate the linear elastic stress intensity factors K_m and K_T and the reference stress σ^m_{ref}.
  - Divide the period into n discrete time increments (i=1 to i=n) and determine the 0.2% proof stress, $(\sigma^c_{0.2})_i$, at times t_i corresponding to the time at the start of each time increment.
  - Evaluate $(\sigma^T_{ref})_i$, at times t_i, from Eqn. (21).
  - Evaluate $(\sigma^{eq}_{ref})_i$, at times t_i, from Eqn. (20).
  - For the first time increment, i=1, determine the creep strain $(\varepsilon^{cr})_1$ at the end of the increment, the creep strain increment $(\Delta\varepsilon^{cr})_1=(\varepsilon^{cr})_1$ and the term $(\sigma^{eq}_{ref}.\Delta\varepsilon^{cr})_1$.
    - For subsequent increments, i=2 to i=n:
      - From the values of creep strain at the end of the (i-1)'th time increment, $(\varepsilon^{cr})_{i-1}$, and reference stress $(\sigma^{eq}_{ref})_i$ determine the creep time t^{cr}_i at the start of the i'th time increment, assuming strain hardening behaviour, as illustrated in Figure (1b).
      - Determine the creep strain $(\varepsilon^{cr})_i$ at the end of the i'th time increment corresponding to the reference stress $(\sigma^{eq}_{ref})_i$, and the time $(t^{cr}_i + (t_{i+1} - t_i))$.
      - Calculate the creep strain increment for the i'th time increment, $(\Delta\varepsilon^{cr})_i = (\varepsilon^{cr})_i - (\varepsilon^{cr})_{i-1}$; the product $(\sigma^{eq}_{ref}.\Delta\varepsilon^{cr})_i$ and hence the summation up to the end of the i'th increment of $\sum \sigma^{eq}_{ref}\Delta\varepsilon^{cr}$.
      - Evaluate $(\overline{\sigma}^{eq}_{ref})_i$, corresponding to the time t_i, from Eqn. (14).
      - Evaluate the assessment point at time t_i, L_r (Eqn. 23) and K_r (Eqn. 24), and compare K_r with K_r for the TDFAD corresponding to the time t_i as calculated from Eqn. (8), with σ_{ref} set equal to $\overline{\sigma}^{eq}_{ref}$. If the K_r (assessment point) is less than the K_r (TDFAD) then failure, as defined by the initiation of creep crack growth, is avoided up to time t_i.
- Repeat for the second period of steady loading. The creep time at the start of the first increment of the second period is determined from the creep strain $(\varepsilon^{cr})_n$ at the end of the first step and the stress σ^{eq}_{ref} at the start of the first increment of the second period.
- Repeat for further periods of steady creep loading.

Worked Example

The worked example is a pressurised thin walled cylinder with a part-through axial defect. The example is chosen as it has previously been analysed using more traditional defect assessment methods of R5 as described in [10].

Specification of problem.

The problem is specified as a Type 316 stainless steel vessel of internal radius 525 mm and 35 mm thickness. A semi-elliptical defect, of depth 7 mm and length 21 mm, is located at the outer surface of the vessel, oriented in an axial-radial direction normal to the surface. The cylinder is subjected to an internal pressure and a linear through-wall thermal bending stress. The example is adapted to a variable creep assessment by dividing the pressure into three hold periods each of 1600 hours, with constant applied pressure values of 5 MPa, 3 MPa and 4 MPa. The temperature and thermal bending stress are

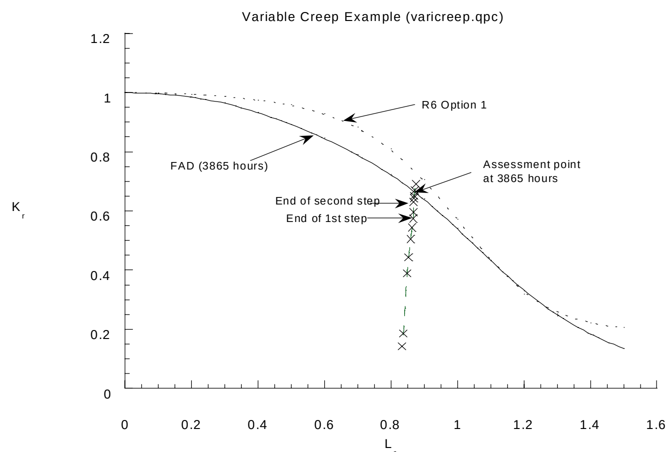

FIGURE 4- Failure Assessment Diagram for Worked Example

TABLE 1 – Results of Worked Example

Step 1: Pressure = 5 MPa, σ^{m}_{ref} = 90.42 MPa, K_m = 11.30 MPa√m, K_T = 6.82 MPa√m

Inc . i	Time (hrs)	$\sigma^{c}_{0.2}$ MPa	$\sigma^{T}_{ref} / \sigma^{c}_{0.2}$ Eq. 21	$\sigma^{eq}_{ref} / \sigma^{c}_{0.2}$ Eq. 20	Creep Time (hrs) at start of inc.	ε^{cr} $\times 10^2$	$\sum \sigma^{eq}_{ref} \Delta\varepsilon^{cr}$	$\bar{\sigma}^{eq}_{ref}$ Eq. 14	L_r Eq. 23	K_{mat}	K_r Eq. 24	K_r TDFAD Eq. 8
	0	140.65	0.3796	0.8336				117.25	0.8336	102.50	0.1430	0.7810
1					0							
	4	139.96	0.3814	0.8359		0.0048	0.0056	117.25	0.8773	78.87	0.1858	0.7686
2					4.107							
	200	137.99	0.3866	0.8423		0.0184	0.0216	117.21	0.8494	37.65	0.3816	0.7359
3					214.93							
	400	137.21	0.3887	0.8450		0.0235	0.0275	117.14	0.8538	33.02	0.4438	0.7243
4					426.59							
	800	136.13	0.3916	0.8485		0.0304	0.0355	117.04	0.8598	28.97	0.5050	0.7091
5					857.13							
	1200	135.30	0.3939	0.8513		0.0356	0.0415	116.96	0.8644	26.83	0.5449	0.6982
6					1291.46							
	1600	134.59	0.3958	0.8537		0.0400	0.0466	116.88	0.8684	25.41	0.5749	0.6893

Step 2: Pressure = 3 MPa, σ^{m}_{ref} = 54.25 MPa, K_m = 6.78 MPa√m, K_T = 6.82 MPa√m

1600			0.7126	7509							
2000	133.96	0.3976	0.7149	7752	0.0412	0.0477	116.33	0.8684	24.36	0.5989	0.6849
2400	133.37	0.3993	0.7170	7994	0.0424	0.0488	115.85	0.8686	23.54	0.6153	0.6808
2800	132.83	0.4008	0.7189	8480	0.0435	0.0499	115.42	0.8689	22.86	0.6311	0.6770
3200	132.32	0.4023	0.7208	8965	0.0446	0.0509	115.03	0.8694	22.29	0.6451	0.6735

Step 3: Pressure = 4 MPa, σ^{m}_{ref} = 72.33 MPa, K_m = 9.04 MPa√m, K_T = 6.82 MPa√m

3200			0.7956	4564							
3600	131.82	0.4037	0.7973	4794	0.0465	0.0530	114.82	0.8710	21.90	0.6584	0.6691
4000	131.35	0.4051	0.7990	5025	0.0484	0.0550	114.62	0.8726	21.37	0.6704	0.6650
4400	130.89	0.4064	0.8005	5490	0.0503	0.0569	114.43	0.8743	20.99	0.6815	0.6611
4800	130.45	0.4077	0.8021	5957	0.0521	0.0588	114.26	0.8759	20.64	0.6918	0.6573

Time for crack incubation: 3865 hours.

the same for all three hold periods, viz. 550°C and 60 MPa respectively. Fracture parameters and material tensile and creep properties have been taken from [10]. Creep toughness has been assumed to be described by equations of the form given in Reference 3. Results of the assessment are shown in Figure 4 and Table 1, which give an incubation time of 3,865 hours.

CONCLUSIONS

The time-dependent failure assessment diagram procedure of R5, used for the prediction of failure as defined by the initiation of creep crack growth and creep rupture, has been described. Details have been presented of how these methods, using the concept of equivalent reference stress, may be applied to the assessment of creep crack initiation under conditions of variable load and displacement controlled stresses. A worked example of the assessment procedure has also been presented.

NOMENCLATURE

Definitions of Reference Stress σ_{ref}.

σ^{m}_{ref} Reference stress due to mechanical load only

$\sigma^{m}_{ref,max}$ Maximum value of σ^{m}_{ref} incurred prior to the assessment time

σ^{T}_{ref} Reference stress due to thermal load only

σ^{eq}_{ref} Reference stress due to mechanical load which produces the same time-dependent J value, J(t), as that for combined σ^{m}_{ref} and σ^{T}_{ref}.

$\sigma^{eq}_{ref,max}$ Maximum value of σ^{eq}_{ref} incurred prior to the assessment time

$\bar{\sigma}^{eq}_{ref}$ Reference stress due to mechanical load which produces the same time-dependent J value, J(t), as that accumulated up to the assessment time from varying values of σ^{eq}_{ref}

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