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ECCC RECOMMENDATIONS - VOLUME 2 Part IV [Issue 2]

TERMS AND TERMINOLOGY USED FOR THE GENERATION AND ASSESSMENT OF CREEP CRACK INITIATION DATA

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TERMS AND TERMINOLOGY USED FOR THE GENERATION AND ASSESSMENT OF CREEP CRACK INITIATION DATA

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On behalf of ECCC

ABSTRACT

ECCC Recommendations Volume 2 Part IV gives the terms and terminology to be used for the generation, collation and assessment of creep crack initiation data within ECCC.

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1. FOREWORD

ECCC Volume 2 Part IV covers the terms and terminology relating to the generation, assessment and application of creep crack initiation (CCI) data. The document specifically supports the CCI testing guidance Volume 3 Part IV [1] and, in future, Volume 7 providing guidance for the assessment of creep crack initiation data.

Following a general introduction, nomenclature is listed in sections relating to material details, testing details, test results and assessed results. Finally, a list of load functions are defined.

2. GENERAL

Creep crack growth (CCG) testing methods are now relatively well established, at least for parent steels, e.g. [2]. For ductile steels in particular (typically A_u >5%), creep cracking does not develop immediately from the start of test [3] (Fig. 1). Ignoring the practical implications of this incubation period can lead to overly conservative predictions of high temperature defect tolerance. Creep crack initiation (CCI) tests are performed specifically to determine the parameters required to characterise the onset of creep cracking from a pre-existing defect. These enable component lifetimes to be based on *i)* a *no-crack-extension* criterion or *ii)* total creep crack development time, i.e. $t_{i,x} + t_g$.

There is currently no Standard for CCI testing, but guidance is given in ECCC Volume 3 Part IV [1]. There are now several approaches by which CCI data can be used to assess defect acceptability in high temperature components (e.g. [4-7]). Of particular interest to ECCC are the two-criteria approaches [4,7] and this is reflected by the focus of the terminology listed in Section 6.

Some general terms are defined in the following listing,

NAME	*UNIT(S)*	*SYMBOL*
Creep crack growth		CCG
Creep crack initiation		CCI
Time, time to creep crack initiation[1], creep crack growth time	h	t, $t_{i,x}$, t_g
Temperature	°C	T
Strain	%	ε
Strain rate	%/h	$\dot{\varepsilon}$
Stress, initial stress	MPa	σ, σ_o

3. MATERIAL DETAILS

For this issue of Part IV, the reader is referred to Volume 2 Part I for more comprehensive guidance on the ECCC recommended terms and terminology for material pedigree data. However, the symbols needed to characterise the uniaxial material properties necessary for the assessment of CCI data are listed in the following section.

[1] See also Sects. 5, 6.2

3.1 Material Properties

3.1.1 Tensile

NAME	*UNIT(S)*	*SYMBOL*
Tensile fracture elongation	%	A
Elastic modulus, elastic modulus at temperature	GPa	E, E_T
E' equals E for plane stress, and $E/(1-\nu^2)$ for plane strain	GPa	E'
0.2% proof strength	MPa	$R_{P,0.2}$
Tensile strength	MPa	R_m
Tensile fracture reduction of area	%	Z
Poissons ratio		ν

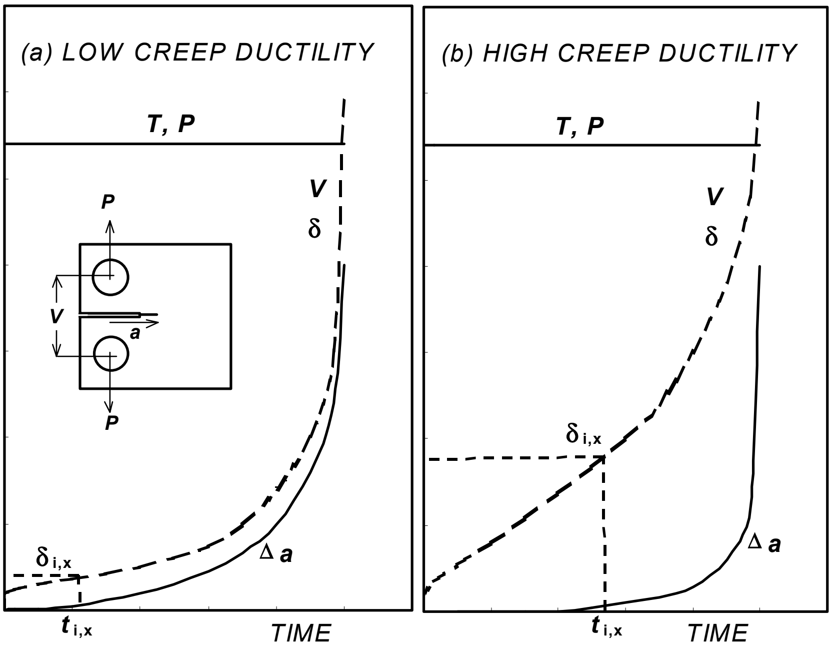

Fig. 1 Variation of load line (crack tip) displacement and creep crack extension with time, at constant load and temperature (diagrams showing the effect of creep ductility) [3]

3.1.2 Creep

NAME	*UNIT(S)*	*SYMBOL*
Constant in Norton or Norton-Bailey creep equations		D
Creep damage fraction		D_c
Stress exponent in Norton or Norton-Bailey creep equations		n
Time exponent in Norton-Bailey creep equation		p
0.2% creep (plastic strain) strength at time, t, and temperature, T	MPa	$R_{p0.2/t/T}$
1% creep (plastic strain) strength at time, t, and temperature, T	MPa	$R_{p1/t/T}$
2% creep (plastic strain) strength at time, t, and temperature, T	MPa	$R_{p2/t/T}$

NAME	*UNIT(S)*	*SYMBOL*
Elastic strain	%	ε_e
Creep strain	%	ε_c
Instantaneous plastic strain	%	ε_i
Plastic strain	%	ε_p
Permanent strain	%	ε_{per}

3.1.3 Rupture

NAME	*UNIT(S)*	*SYMBOL*
Creep rupture elongation for time, *t*, and temperature, *T*	%	$A_{u/t/T}$
Time to rupture	h	t_u
Rupture strength for time, *t*, and temperature, *T*	MPa	$R_{u/t/T}$
Creep rupture reduction of area for time, *t*, and temperature, *T*	%	$Z_{u/t/T}$

4. TESTING DETAILS

4.1 Overview

A creep crack initiation test is performed in a similar way to a creep crack growth test [2]. A constant load, *P*, is applied to a fracture mechanics testpiece soaking at a constant temperature, *T* (Fig. 1). The load is applied as quickly as possible.

Where feasible (e.g. in continuous measurement tests), the load and load line displacement should be recorded during loading to enable total energy to crack initiation to be determined.

During test, *i)* the load line and (ideally) crack tip displacements and *ii)* crack length are monitored to enable the determination of:
- time to crack initiation (for a given crack initiation criterion), and
- appropriate crack tip characterising parameters, e.g. $\delta_{i,x}$, $C^*_{o,x}$.

4.2 Testpiece

4.2.1 Types

The most commonly used specimen geometries used for CCI testing are the compact tension testpiece and double edge notched tension testpiece (Fig. 2). Other high temperature fracture mechanics testpiece geometries are acknowledged in the following table.

NAME	*UNIT(S)*	*SYMBOL*
Centre cracked tension testpiece		CCT, MT
C-ring testpiece		CS(T)
Compact tension testpiece, (with side grooves)		CT, (Cs)
Double edge notched tension testpiece, (with side grooves)		DENT, (Ds)
Round notched bar tensile testpiece		RNB(T)
Single edge notched bend testpiece		SENB
Single edge notched tensile testpiece		SENT

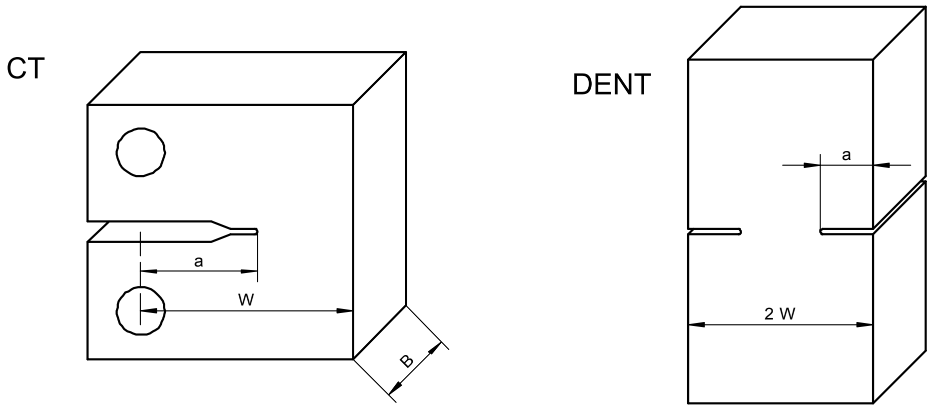

Fig. 2 Compact tension and double edge notched tension testpieces

4.2.2 Dimensions

NAME	*UNIT(S)*	*SYMBOL*
Crack depth	mm	a
Initial crack depth	mm	a_o
Thickness	mm	B
Net section thickness	mm	B_N
Side-groove depths	mm	n_1, n_2
Width	mm	W

4.2.3 Test Types

NAME	*UNIT(S)*	*SYMBOL*
Continuous test method		CTM
Interrupted test method		ITM
Multi-specimen method		MSM
Single specimen method		SSM

4.3 Test Parameters

NAME	*UNIT(S)*	*SYMBOL*
Alternating current potential drop crack monitoring		ACPD
Direct current potential drop crack monitoring		DCPD
Applied load	N	P
Time	h	t
Temperature	°C	T
Load line displacement (total)	mm	V
Crack tip opening displacement	mm	δ

5. TEST RESULTS

Testpiece dimensions may also classed as test results if actual values have to be confirmed by post-test inspection, e.g. B_N (or n_1+n_2), a_o

NAME	*UNIT(S)*	*SYMBOL*
Initial crack depth	mm	a_o
Final crack length	mm	a_f
Crack extension	mm	Δa
Crack initiation criterion (e.g. Δa = 0.5mm)	mm	x
Crack growth rate (per unit time)	mm/h	$\mathrm{d}a/\mathrm{d}t$, $\dot{a}$
Time to creep crack initiation	h	$t_{i,x}$
Load line displacement	mm	V
Total load line displacement	mm	V_{tot}
Elastic load line displacement	mm	V_e
Instantaneous plastic load line displacement	mm	V_p
Load line displacement due to creep	mm	V_c
Load line displacement due to creep at initiation	mm	$V_{c,x}$
Load line displacement rate due to creep	mm/h	$\mathrm{d}V_c/\mathrm{d}t$, $\dot{V}_c$
Crack tip opening displacement	mm	δ

6. ASSESSED RESULTS

6.1 Overview

Initially, and consistent with the description of other sub-critical crack growth mechanisms, creep crack development was characterised in terms of stress intensity factor, K, until it was recognised that this linear elastic parameter was only applicable to those circumstances where creep ductility is very low and/or geometrical constraint is very high. Focus then switched to the use of C^* as a means of characterising the local stress-strain rate fields at any instant around the crack tip but this parameter also proved to have its limitations, only providing geometry independent descriptions of creep crack development under conditions of large-scale steady-state creep deformation. For the small scale creep and/or transient creep regimes, $C(t)$ and C_t are more appropriate parameters [8,9]. Relationships between $C(t)/C^*$, C_t/C^* and the non-dimesional time ratio t/t_T are given for a CT testpiece deforming in plane strain with n = 5 are shown in Fig. 3, where

$$t_T = \frac{K^2}{E'.C^*.(n+1)}$$

6.2 Parameters

NAME	*UNIT(S)*	*SYMBOL*
A line or surface integral based parameter used to characterise the local stress-strain rate fields at any instant around the crack front in a body deforming due to creep. The parameter characterises crack-tip stress-strain rate fields under conditions of steady-state large-scale creep.	MPa.m/h	C^*

NAME	*UNIT(S)*	*SYMBOL*
Short time creep characterising parameter	MPa.m/h	C_t
Primary creep characterising parameter	MPa.m/h	C_h
Values of C^* at crack initiation	MPa.m/h	$C^*_{o,x}$, $C(t)_{o,x}$
Crack tip opening displacement	μm	CTOD, δ
Deformation state (e.g. plσ for plane stress deformation or plε for plane strain deformation)		ds
Elastic-plastic crack tip characterising parameter	N/mm	J
Stress intensity factor	MPa√m	K_I
Critical stress intensity factor	MPa√m	K_{IC}
Stress intensity factor at initial crack length	MPa√m	K_{Ii}
Stress intensity ratio in TDFAD		K_r
Stress ratio in TDFAD		L_r
Limit- load yield ratio		m, $m_{yc,ds}$
Limit length in specimen with dominant ligament damage (ductility) dependent depth of stress redistribution zones behind crack tip	mm	r_{pl}
Stress intensity ratio in two-criteria diagram		R_K
Stress ratio in two-criteria diagram		R_σ
Time to creep crack initiation	h	$t_{i,x}$
Creep redistribution time	h	t_{red}
Transition time - the time when the small-scale-creep stress fields equal the extensive steady-state creep fields characterised by C^*	h	t_T
Tresca yield criterion		T
Time dependent failure assessment diagram		TDFAD
Yield criterion (e.g. T for Tresca or VM for von Mises		yc
Elastic energy on loading	Nmm	U_e
Plastic energy on loading	Nmm	U_p
Energy accumulated due to creep deformation, to crack initiation	Nmm	$U_{c,x}$
Crack initiation criterion (e.g. Δa = 0.5mm)	mm	x
Two criteria diagram		2CD
CTOD at creep crack initiation	μm	$\delta_{i,x}$
Equivalent limit-load reference stress	MPa	σ_{equiv}, $\sigma_{yc,ds}$
Nominal stress, according to ASTM	MPa	σ_n
Nominal stress according to Siebel	MPa	$\sigma_{n,pl}$
Reference stress	MPa	σ_{ref}
von Mises yield criterion		VM
Sigma-d, stress at characteristic distance, x	MPa	$\sigma_{D,x}$

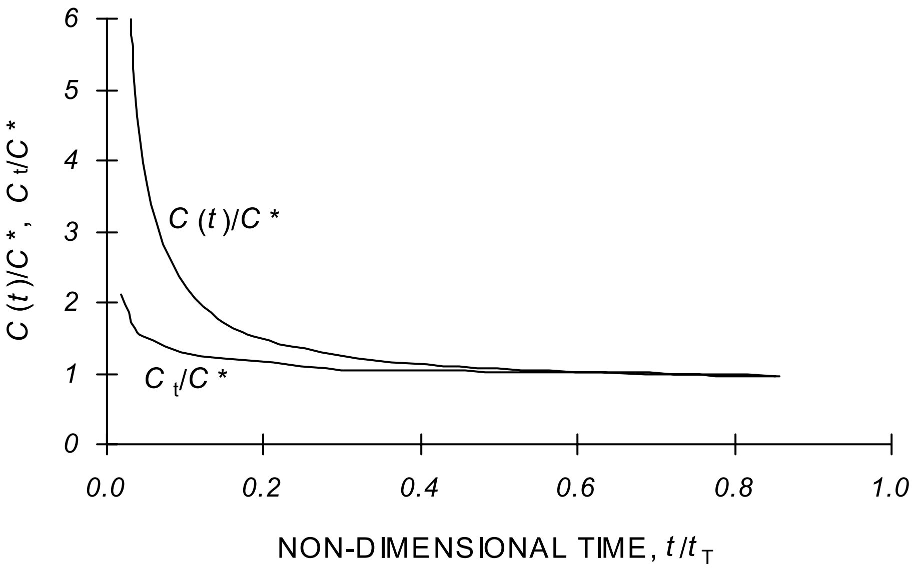

Fig. 3 Variation of $C(t)$ and C_t with time for a CT testpiece deforming in plane strain with $n = 5$

6.3 Material Characterising Parameters

NAME	*UNIT(S)*	*SYMBOL*
Material fracture toughness value in terms of J	Nm	J_c
Material creep toughness at time, t, and temperature, T	MPa√m	$K^{c}_{mat,x/t/T}$
Stress intensity factor at initiation of engineering size crack	MPa√m	$K_{li,x/t/T}$
Exponent in $da/dt(C^*)$ creep crack growth law		q
Constant in $da/dt(C^*)$ creep crack growth law		γ

7. DATA ASSESSMENT

7.1 General

Section 5 defines σ_{ref}, K, J and C^* expressions for compact tension and double edge notched tension testpieces, these being the most commonly adopted CCI specimen geometries [1], and the testpieces for which acceptable size criteria are defined. The expressions for other geometries will be included in later issues as their σ_{ref}, K and C^* capacities become more completely characterised in terms of their geometry dependence.

7.2 Load Functions

7.2.1 Nominal Stresses

7.2.1.1 Compact Tension Testpiece (Fig. 2a)

7.2.1.1.1 ASTM

$$\sigma_n = \frac{P}{(B.B_N)^{0.5}.(W - a_o)}.\left(1 + 3.\frac{W + a_o}{W - a_o}\right)$$

7.2.1.1.2 Siebel

$$\sigma_{\mathrm{n,pl}} = \frac{P}{(B.B_{\mathrm{N}})^{0.5}.(W-a_{\mathrm{o}})}.\left(1+2.\frac{W+a_{\mathrm{o}}}{W-a_{\mathrm{o}}}\right)$$

7.2.1.2 Double Edge Notched Tension Testpiece (Fig. 2b)

$$\sigma_{\mathrm{n}} = \sigma_{\mathrm{n,pl}} = \frac{P}{(B.B_{\mathrm{N}})^{0.5}.(W-a_{\mathrm{o}})}$$

7.2.2 Equivalent Limit-Load Reference Stresses

The listed limit-load yield ratios originate from reference 10. This reference provides a comprehensive source of *m* values for a range of testpiece and component geometries.

7.2.2.1 Compact Tension Testpiece (Fig. 2a)

$$\sigma_{\mathrm{equiv}} = \sigma_{\mathrm{yc,ds}} = \frac{P}{B_{\mathrm{N}}.W}.\frac{1}{m_{\mathrm{yc,ds}}}$$

7.2.2.1.1 Plane Stress Tresca

$$m_{\mathrm{T,pl}\sigma} = \left[2+2.(a_{\mathrm{o}}/W)^2\right]^{0.5} - (1+a_{\mathrm{o}}/W)$$

7.2.2.1.2 Plane Strain Tresca

$$m_{\mathrm{T,pl}\varepsilon} = [2.702+4.599.(a_{\mathrm{o}}/W)^2]^{0.5} - (1+1.702.a_{\mathrm{o}}/W)$$

7.2.2.1.3 Plane Stress Mises

$$m_{\mathrm{VM,pl}\sigma} = [2.155.(1.155.(a_{\mathrm{o}}/W)^2+1)]^{0.5} - (1.155.a_{\mathrm{o}}/\mathrm{W}+1)$$

7.2.2.1.4 Plane Strain Mises

$$m_{\mathrm{VM,pl}\varepsilon} = 1.155.\left\{[2.702+4.599.(a_{\mathrm{o}}/W)^2]^{0.5} - (1+1.702.a_{\mathrm{o}}/W)\right\}$$

7.2.2.2 Double Edge Notched Tension Testpiece (Fig. 2b)

$$\sigma_{\mathrm{equiv}} = \sigma_{\mathrm{yc,ds}} = \frac{P}{2.B_{\mathrm{N}}.(W-a_{\mathrm{o}})}.\frac{1}{m_{\mathrm{yc,ds}}}$$

7.2.2.2.1 Plane Stress Tresca

$$m_{\mathrm{T,pl}\sigma} = 1$$

7.2.2.2.2 Plane Strain Tresca

$$m_{\mathrm{T,pl}\varepsilon} = 1+\ln\left(\frac{1-0.5.a_{\mathrm{o}}/W}{1-a_{\mathrm{o}}/W}\right) \qquad 0 < a_{\mathrm{o}}/W < 0.442$$

$$m_{\mathrm{T,pl}\varepsilon} = 2.57 \qquad 0.442 < a_{\mathrm{o}}/W < 0.5$$

7.2.2.2.3 Plane Stress Mises

$$m_{\mathrm{VM,pl}\sigma} = 1+0.54.a_{\mathrm{o}}/W \qquad 0 < a_{\mathrm{o}}/W < 0.143$$

$$m_{\mathrm{VM,pl}\sigma} = 1.155 \qquad 0.143 < a_{\mathrm{o}}/W < 0.5$$

7.2.2.2.4 Plane Strain Mises

$$m_{\mathrm{VM,pl}\varepsilon} = 1.155.\left\{1 + \ln\left(\frac{1 - a_o/W}{1 - 2.a_o/W}\right)\right\} \qquad 0 < a_o/W < 0.442$$

$$m_{\mathrm{VM,pl}\varepsilon} = 2.968 \qquad 0.442 < a_o/W < 0.5$$

7.2.3 Stress Intensity Factors

$$K_\mathrm{I} = \frac{P}{(B.B_\mathrm{N}.W)^{0.5}}.f(a/W)$$

7.2.3.1 Compact Tension Testpiece (Fig. 2a)

$$f(a/W) = 29.6.(a/\mathrm{W})^{0.5} - 185.5.(a/\mathrm{W})^{1.5} + 655.7.(a/\mathrm{W})^{2.5} - 1017.(a/\mathrm{W})^{3.5} + 638.9.(a/\mathrm{W})^{4.5}$$

7.2.3.2 Double Edge Notched Tension Testpiece (Fig. 2b)

$$f(a/W) = 1.4.(a_o/\mathrm{W})^{0.5} + 0.2556.(a_o/\mathrm{W})^{1.5} - 1.5.(a_o/\mathrm{W})^{2.5} + 2.42.(a_o/\mathrm{W})^{3.5}$$

7.2.4 C* Solutions

7.2.4.1 Compact Tension Testpiece (Fig. 2a)

$$C^* = \frac{P.\dot{V}_c}{B_\mathrm{N}.(W-a)}.\frac{n}{n+1}.\left(2 + 0.522.\frac{(W-a)}{W}\right)$$

7.2.4.2 Double Edge Notched Tension Testpiece (Fig. 2b)

$$C^* = \frac{P.\dot{V}_c}{2.B_\mathrm{N}.(W-a)}.\frac{h_1}{h_3}.\frac{\sqrt{3}}{2} \qquad \text{for plane stress}$$

$$C^* = \frac{P.\dot{V}_c}{2.B_\mathrm{N}.(W-a)}.\frac{h_1}{h_3}.\frac{2.(W-a)}{0.72.W + 1.82.(W-a)} \qquad \text{for plane strain}$$

where h_1 and h_3 are constants given in reference 8

8. REFERENCES

1 ECCC Recommendations Volume 3, 2003, 'Part IV: Testing practices for the generation of creep crack initiation data', eds. Klenk, Müller, F. & Gengenbach, T., publ. ETD.
2 E1457, 2000, 'Standard test method for measurement of creep crack growth rates in metals', ASTM Standards, v03.01.
3 Holdsworth, S.R., 1992, 'Initiation and early growth of creep cracks from pre-existing defects', Materials at High Temperatures, 10, 2, 127-137.
4 R5, 2003, 'Assessment procedure for the high temperature response of structures', Issue 3, British Energy.
5 BS 7910, 2000, 'Guidance on methods for assessing the acceptability of flaws in metallic structures', British Standards Institution.
6 Drubay, B., Chapuliot, S., Lacire, M-H. & Marie, S., 2001, 'A16: Guide for defect assessment and leak before break analysis', CEA, Direction de L'Energie Nucleaires, Report DM2S, SEMT/LISN/RT/01-043/A.
7 Ewald, J., Sheng, S., Klenk, A. & Schellenberg, G., 2001, 'Engineering guide to the assessment of creep crack initiation on components by two-criteria-diagram', Int. J. Pres. Ves. Piping, 78, 937-949.

8 Riedel, H., 1987, Fracture at High Temperatures, MRE - Springer Verlag
9 Webster, G.A. & Ainsworth, R.A., 1994, High Temperature Component Life Assessment, Chapman & Hall.
10 Miller, A.G., 1988, 'Review of limit loads of structures containing defects', Int. J. Pressure Vessels & Piping, 32(1-4), 197-327.