ECCC

ECCC RECOMMENDATIONS - VOLUME 2 Part V [Issue 1]

TERMS AND TERMINOLOGY USED FOR THE GENERATION AND ASSESSMENT OF MULTI-AXIAL FEATURE SPECIMEN AND COMPONENT TEST DATA

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APPROVED **DATE** *31/8/05*

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ABSTRACT

ECCC Recommendations Volume 2 Part V gives the terms and terminology to be used for the generation, collation and assessment of multi-axial feature specimen and component test data within ECCC.

ECCC Recommendations Volume 2 Part V user feedback is encouraged and should be sent to:

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1. FOREWORD

ECCC Volume 2 Part V covers the terms and terminology relating to the generation, and assessment of multi-axial feature and component test data. The document specifically supports the testing guidance Volume 3 Part V [1], Volume 8 providing guidance for the assessment of multi-axial specimen data [2] and Volume 9 which covers high temperature component analysis [3]. For generic terms and terminology, reference should be made to Part 1 of Volume 2.

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

Multi-axial feature specimen tests and component tests are conducted for a variety of reasons. For example they may be performed to directly evaluate the likely performance of engineering structures in service under closely controlled laboratory conditions or to provide the evidence to test the effectiveness of assessment procedures. In addition, multi-axial tests are performed to assess the applicability and effectiveness of:

- representative stress models to characterise material multi-axial rupture behaviour, and/or
- multi-axial rupture ductility models to characterise material multi-axial rupture behaviour.

Some general terms are defined in the following listing,

NAME	*UNIT(S)*	*SYMBOL*
Time	h	t
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 V, 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 multi-axial feature specimen and component test data are listed in the following section.

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	$R_{p0.2}$
Tensile strength	MPa	R_m
Tensile fracture reduction of area	%	Z
Poissons ratio		ν

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, ε_f
Instantaneous plastic strain	%	ε_i
Plastic strain ($\varepsilon_i + \varepsilon_f$)	%	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

In multi-axial feature specimen or component tests, a constant force (F), moment (M), internal pressure (p) and/or torque (τ) is applied to the structure at a constant temperature, T. The loading is applied as quickly as practical. However, where a component test is attempting to simulate service conditions, the rate of loading will be dictated by service loading rates.

With a small number of exceptions (e.g. [4-6]), multi-axial feature specimen and component tests are not covered by published standard procedures. Testing practices are therefore dependent on specific data requirements and the expertise of the individual test laboratory.

The recorded response variable(s) will depend on the nature of the test and the requirement of the test initiator and range from failure time to a comprehensive package including local and global strain measurement and crack development monitoring (involving both on-line and off-line techniques).

4.2 Multi-axial Testpieces

4.2.1 Types

The most commonly used specimen geometries used for multi-axial testing are the circumferentially notched round tensile testpiece, with either a v-notch or a semi-circular (Bridgeman) notch [4], or the thin walled tube testpiece subject to various combinations of axial, torsional, and/or internal pressure loading [5,6]. However, other geometries may be employed, and examples of these are listed in the following table.

NAME	*UNIT(S)*	*SYMBOL*
Circumferentially notched round tensile testpiece, v-notched, semi-circular notched		CNRT
Biaxial plate		
Compact tension testpiece, (with side grooves)		CT, (Cs)
Cruciform		
Tube, pressurised, without and with end-loading (axial loading)		T(p), T(p,F)
Tube, end loaded (axial loaded)		T(F)
Tube, torsion loaded, without and with end-loading (axial loading)		T(τ), T(τ,F)
Tube, torsion loaded with internal pressure, without and with end-loading (axial loading)		T(τ,p_i), T(τ,p_i,F)
Tube, moment		T(M)

4.2.2 Dimensions: CNRT testpieces

The most commonly used multi-axial testpiece is the circumferentially notched round tensile testpiece. This testpiece configuration with a v-notch geometry is widely used for material characterisation, e.g. to characterise notch sensitivity [4,7]. With a semi-circular (Bridgeman) notch geometry, the CNRT configuration may be used to investigate the creep properties of materials over a much wider range of triaxial tensile stress states and to give an indication of how creep strain accumulates under these circumstances [4].

NAME	*UNIT(S)*	*SYMBOL*
Circumferentially notched round tensile testpiece		CNRT
Notch root diameter	mm	d_{no}
Outer diameter	mm	D
Notch root radius	mm	r_{no}
Notch flank angle	°	α

4.2.3 Dimensions: Tube testpieces

Tube testpieces, without or with external circumferential notches in the gauge length, provide the means of generating a wider spectrum of multi-axial stress states than the CNRT geometry. The results from multi-axial tests involving this geometry are therefore necessary to identify the most effective representative stress and ductility models for characterizing the multi-axial creep deformation and rupture behaviour of a given material.

NAME	*UNIT(S)*	*SYMBOL*
Tube testpiece (see options in 4.2.1)		T( )
Inner diameter of gauge length	mm	d_i
Outer diameter of gauge length	mm	d_o
Notch root diameter	mm	d_{no}
Mean diameter of gauge length	mm	d_m
Diameter of end plug	mm	d_{plug}
Diameter ratio, $R = d_o / d_i$		R
Wall thickness of gauge length	mm	t_1
Wall thickness of test piece end	mm	t_2
Parallel length of test section	mm	l
Length of end cap	mm	L
Transition radius	mm	r
Notch root radius	mm	r_{no}
Notch flank angle	°	α

4.2.4 Dimensions: CT(Cs) testpieces

Compact tension testpieces are more commonly regarded as a fracture mechanics testpiece (e.g. [8]). However, the geometry is the preferred multi-axial testpiece geometry for the LICON methodology [9].

NAME	*UNIT(S)*	*SYMBOL*
Compact tension testpiece (with side grooves)		CT (Cs)
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

4.2.5 Dimensions: Other testpieces

Other testpieces such as bi-axial plate and cruciform specimens are used to characterise the multi-axial creep deformation and rupture behaviour of engineering materials (e.g. [10]). Such tests are performed by specialists and the associated terminology varies with user.

4.3 Components

4.3.1 Types

Component test specimens are by their very nature varied as they are derived from the need of each particular industry to test or validate component parts of engineering structures. It is therefore difficult to stipulate specific geometries. However, recent reviews have identified three generic component types: tube/pipe, bend and nozzle/branch geometries [1,11].

Weld(s) may or may not be included as an integral part of the component under test. Only three generic geometries are listed here.

NAME	*UNIT(S)*	*SYMBOL*
Tube		See 4.2.1
Tube with weld under test		T_w
Pipe		P
Pipe with weld under test		P_w
Nozzle/Branch, pressurized		N(p)
Nozzle/Branch, moment in plane/out of plane		N(M_i), N(M_o)
Nozzle/Branch, pressurized with moment		N(p,M)

4.3.2 Dimensions: Tube/Pipe test pieces

One of the most commonly tested components is the tube or pipe geometry with a butt weld. The weld should be centrally placed in the test section. The terminology for the tube/pipe test pieces is already given in section 4.2.3.

4.3.3 Dimensions: Bend test pieces

NAME	*UNIT(S)*	*SYMBOL*
Inner diameter of gauge length	mm	d_i
Outer diameter of gauge length	mm	d_o
Diameter of end plug	mm	d_{plug}
Wall thickness of gauge length	mm	t
Mean radius of bend	mm	R_m
Angle of gauge length	mm	φ

4.3.4 Dimensions: Nozzle/Branch pieces

This is a common component in the power industry and can be in the form of isolated or multiple nozzles/branches.

NAME	*UNIT(S)*	*SYMBOL*
Inner diameter of main vessel	mm	D_i
Outer diameter of main vessel	mm	D_o
Mean diameter of main vessel	mm	D_m
Wall thickness of main vessel	mm	T_v
Inner diameter of nozzle/branch	mm	d_i
Outer diameter of nozzle/branch	mm	d_o
Mean diameter of nozzle/branch	mm	d_m
Wall thickness of nozzle/branch	mm	t
Ratio of vessel/nozzle mean diameters		R
Ratio of vessel diameter/vessel thickness		R_T
Length of vessel	mm	L
Length of nozzle/branch	mm	l
Pitch between multiple nozzle/branch centers	mm	P

4.4 Test Parameters

NAME	*UNIT(S)*	*SYMBOL*
Force, axial force	N	F, F_A
Pressure, internal pressure	MPa	p, p_i
Time	h	t
Temperature	°C	T
Torque	Nm	τ
Moment, in plane, out of plane	Nm	M_i, M_o

5. TEST RESULTS

5.1 Multi-axial Tests

NAME	*UNIT(S)*	*SYMBOL*
Alternating current potential drop crack monitoring		ACPD
Direct current potential drop crack monitoring		DCPD
Crack initiation criterion (e.g. Δa = 0.5mm)	mm	x
Time to creep crack initiation	h	$t_{i,x}$
time to rupture, time to rupture of notched testpiece	h	t_u, t_{nu}
Reduction of area at rupture, in notch root	%	Z_u, Z_{nu}
Axial strain, at crack initiation, at rupture	%	ε_a, ε_{ai}, ε_{au}
Hoop strain, at crack initiation, at rupture	%	ε_h, ε_{hi}, ε_{hu}
Strains in x, y and z directions	%	ε_x, ε_y, ε_z
Axial displacement	mm	δ_a
Change in diameter at notch throat	mm	δ_d

5.2 Component Tests

The terminology defined in the table below is generic to any component specimen geometry. Additional terms for specific geometries may be defined in relation to those given below, e.g. strain results obtained from strain gauges or creep pip measurements.

NAME	*UNIT(S)*	*SYMBOL*
Alternating current potential drop crack monitoring		ACPD
Direct current potential drop crack monitoring		DCPD
Crack dimensions at initiation, depth, length	mm	a_i, c_i
Crack dimensions at rupture, depth, length	mm	a_u, c_u
Crack initiation criterion (e.g. Δa = 0.5mm)	mm	x
Time to creep crack initiation	h	$t_{i,x}$
Time to rupture	h	t_u
Strain at crack initiation	%	ε_i
Strain at rupture	%	ε_u
Displacement	mm	δ
CTOD at creep crack initiation	µm	$\delta_{i,x}$
Specimen dimensions at rupture, as sect. 4.3 with 'u' suffix	mm	*e.g.* D_{ou}

6. ASSESSED RESULTS

6.1 General

Assessed results are those determined from a knowledge of the loading conditions or the directly observed observations. Typically these require reference to established solutions for more commonly adopted testpiece geometries or specific finite element analysis.

6.2 Parameters

NAME	*UNIT(S)*	*SYMBOL*
Elastic stress concentration factor (ratio of maximum axial stress calculated for elastic conditions to the net stress at the same load) – determined from existing solutions (e.g. [12]) or by finite element analysis		k_t
Principal strains, ε_1 is maximum principal strain	%	ε_1, ε_2, ε_3
von Mises strain	%	ε_{VM}
Principal stresses, σ_1 is maximum principal stress	MPa	σ_1, σ_2, σ_3
Principal stresses at skeletal point	MPa	σ_1*, σ_2*, σ_3*
Mean (hydrostatic) stress	MPa	σ_m
Mean (hydrostatic) stress at skeletal point	MPa	σ_m*
Net section stress	MPa	σ_{net}
Reference stress	MPa	σ_{ref}
Representative stress	MPa	σ_{rep}
von Mises stress	MPa	σ_{VM}
von Mises stress at skeletal point	MPa	σ_{VM}*

7. CHARACTERISING FUNCTIONS

7.1 General

The following section reviews and defines various functions used to characterise multi-axial rupture strength and ductility.

7.2 Classical

$$\sigma_{VM} = \frac{1}{\sqrt{2}} \cdot \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{0.5}$$

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

$$\varepsilon_{VM} = \frac{\sqrt{2}}{3} \cdot \left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]^{0.5}$$

7.2.1 Representative Rupture Stresses

$$t_{nu} = C(T)\sigma_{rep}^{-\nu}$$

7.2.1.1 Sdobyrev []

$$\sigma_{rep} = \alpha.\sigma_1 + (1-\alpha).\sigma_{VM} \qquad (0 \le \alpha \le 1)$$

7.2.1.2

$$\sigma_{\text{rep}} = 3.\beta.\sigma_{\text{m}} + (1-\beta).\sigma_{\text{VM}} \qquad (0 \le \beta < 1)$$

7.2.1.3 Cane [13]

$$\sigma_{\text{rep}} = (\sigma_1 / \sigma_{\text{VM}})^{\gamma/\nu}\,\sigma_{\text{VM}} \qquad (0 \le \gamma \le \nu)$$

7.2.1.4

$$\sigma_{\text{rep}} = (3.\sigma_{\text{m}} / \sigma_{\text{VM}})^{\gamma/\nu}\,\sigma_{\text{VM}} \qquad (0 \le \gamma < \nu)$$

7.2.1.5 Hayhurst [14]

$$\sigma_{\text{rep}} = \alpha.\sigma_1 + 3.\beta.\sigma_{\text{m}} + (1-\alpha-\beta).\sigma_{\text{VM}} \qquad (0 \le \alpha+\beta \le 1)$$

and where α, β and γ are material parameters

7.2.1.6 Huddleston [15]

$$\sigma_{\text{rep}} = \frac{3}{2} S_1 \left(\frac{2\sigma_{\text{VM}}}{3S_1}\right)^a \exp\left[b\left(\frac{J_1}{S_{\text{S}}} - 1\right)\right]$$

where S_1 is maximum deviatoric stress and J_1, the first invariant of the stress tensor

7.2.2 Multi-axial Rupture Ductility Models

7.2.2.1 Manjoine [16]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = 2^{(1-3\sigma_{\text{m}}/\sigma_{\text{VM}})}$$

7.2.2.2 Rice & Tracey [17]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = \exp\left(\frac{1}{2} - \frac{3\sigma_{\text{m}}}{2\sigma_{\text{VM}}}\right)$$

matrix hole growth

7.2.2.3 Cocks & Ashby [18]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = \sinh\left[\frac{2(n-1/2)}{3(n+1/2)}\right] \Big/ \sinh\left[\frac{2(n-1/2)\sigma_{\text{m}}}{(n+1/2)\sigma_{\text{VM}}}\right]$$

grain boundary cavity growth

7.2.2.4 Marlof [19]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = \frac{1}{3}\cdot\frac{\sigma_{\text{VM}}}{\sigma_{\text{m}}} = \left(\frac{3}{2}\cdot\frac{\sigma_1-\sigma_{\text{m}}}{\sigma_{\text{VM}}}\right) \Big/ \left(3\cdot\frac{\sigma_{\text{m}}}{\sigma_{\text{VM}}}\right) = \frac{1}{2}\cdot\frac{(\sigma_1-\sigma_{\text{m}})}{\sigma_{\text{m}}}$$

7.2.2.5 Ewald [20]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = \frac{3}{2}\cdot\frac{(\sigma_1-\sigma_{\text{m}})}{\sigma_1}$$

7.2.2.6 Sheng [21]

$$\frac{\bar{\varepsilon}_{\text{f}}}{\varepsilon_{\text{fu}}} = \frac{3}{2}\cdot\frac{(\sigma_1-\sigma_{\text{m}})}{\sigma_{\text{VM}}}\cdot\left(\frac{\sigma_{\text{VM}}}{\sigma_1}\right)^m$$

7.2.2.7 Hales [22]

Diffusion controlled cavity growth

$$\frac{\bar{\varepsilon}_{\mathrm{f}}}{\varepsilon_{\mathrm{fu}}} = \left(\frac{\sigma_{\mathrm{VM}}}{\sigma_1}\right)^{m+1}$$

7.2.2.8 Hales [22]

Constrained cavity growth

$$\frac{\bar{\varepsilon}_{\mathrm{f}}}{\varepsilon_{\mathrm{fu}}} = \frac{2\sigma_1}{3S_1}\left(\frac{\sigma_{\mathrm{VM}}}{\sigma_1}\right)^{m+1}$$

7.2.2.9 Spindler [23]

$$\frac{\bar{\varepsilon}_{\mathrm{f}}}{\varepsilon_{\mathrm{fu}}} = \exp\left[p\left(1-\frac{\sigma_1}{\sigma_{\mathrm{VM}}}\right)+q\left(\frac{1}{2}-\frac{3\sigma_{\mathrm{m}}}{2\sigma_{\mathrm{VM}}}\right)\right]$$

Where p and q are parameters affecting multi-axial stress influence on material ductility

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