BSSM seminar Celebrating 50 years of BSSM: Showcase on leading edge experimental techniques

A special event to celebrate the BSSM fiftieth anniversary

3rd and 4th November 2014 Venue: National Physical Laboratory, UK.

 $I_arepsilon(arphi)$

TEDDINGTON





GDR CNRS 2519 MESURES DE CHAMPS ET IDENTIFICATION EN MECANIQUE DES SOLIDES

LABORATOIRE DE MÉCANIQUE ET GÉNIE CIVIL - UM2/CNRS

Full-field measurements & Identification in solid mechanics

Thermomechanical analysis of material behaviour J. Barton & A. Chrysochoos

Part 2: Dissipation to characterise irreversible deformation mechanisms

A. Chrysochoos – LMGC – Montpellier University - France GDR CNRS 2519





Goals

Observing kinematic and energetic effects accompanying the material transformations

Constructing energy balances – consistency of behavioral models

Quantitative imaging techniques – full-field measurements

IRT : since 1983 - DIC : since 1991 - DIC & IRT : since 2000

DIC - Mechanics

- displacement fields
- strain and strain rate
- stress
- deformation energy rate

IRT - Thermodynamics

- absolute temperature
- heat source (via the heat equation)
- intrinsic dissipation
- coupling sources

Outline

Theoretical background

- dissipation, energy storage
- thermomechanical (thm) coupling effects

Experimental tools

- temperature fields
- displacement fields

Focusing on cyclic loading

Case study #1 : HCF of steel

- material vs. structure effects
- properties of intrinsic dissipation fields

Case study #2 : LCF of rubber

- intrinsic dissipation vs. strong coupling + thermal dissipation

Concluding comments

Theoretical background

Thm constitutive equations

Generalised standard material formalism

[Halphen & Nguyen, 75]

state variables	$\{T, \varepsilon, \alpha\}$
internal/free energy potential state equations	$e(s, \varepsilon, \alpha) \qquad \psi(T, \varepsilon, \alpha) \\ -s = \psi_{,T} \qquad \sigma^{r} = \rho \psi_{,\varepsilon} \qquad \mathbf{A}_{\alpha} = \rho \psi_{,\alpha}$
dissipation potential evolution equations	$\varphi(q, \dot{\varepsilon}, \dot{\alpha}; T,)$ $-\frac{\nabla T}{T} = \varphi_{,q} \qquad \sigma^{\text{ir}} = \varphi_{,\dot{\varepsilon}} \qquad X_{\dot{\alpha}} = \varphi_{,\dot{\alpha}}$

Material degradation

Irreversibility

Heat diffusion

 $d_1 = \sigma^{\text{ir}} : \dot{\varepsilon} + X_{\alpha} . \dot{\alpha}$ $d_2 = \phi_{,q} . q = -\frac{\nabla T}{T} . q$ 4

Energy balance (I)



Energy balance (II)

• rate of internal energy

 $\rho \dot{e} = \rho C \dot{T} + (\sigma^{r} : \dot{\epsilon} + A \dot{\alpha}) - (T \sigma^{r}_{T} : \dot{\epsilon} + T A_{T} \dot{\alpha})$ $= \rho C \dot{T} + w_e^{\bullet} + w_s^{\bullet} - w_{thc}^{\bullet}$ « thc » = thermomechanical couplings heat equation $\rho C \dot{T} + \operatorname{div} \mathbf{q} = \boldsymbol{\sigma}^{\operatorname{ir}} : \dot{\boldsymbol{\varepsilon}} - \mathbf{A} \cdot \dot{\boldsymbol{\alpha}} + T \boldsymbol{\sigma}_{T}^{\operatorname{r}} : \dot{\boldsymbol{\varepsilon}} + T \mathbf{A}_{T} \cdot \dot{\boldsymbol{\alpha}} + r_{e}$ d_1 kinematics required comments C.3: $\dot{T} = \frac{\partial T}{\partial t} + \frac{\mathbf{v}}{\mathbf{v}} \nabla T$ C.1: C specific heat C.2: q = -k.qradT

Experimental tools

Quantitative imaging – full field measurement system

CCD camera

- max frame rate 20 Hz
- 1280×1024 pixels
- 13×13 µm²
- 14 bits
- δx ≈ 0.1 mm (min 15 μm)

Refs

[Wattrisse et al., Exp. Mech, 2001] [Chryso et al., IJES, 2000]



- Hydraulic testing machine
- load cell : ± 25 kN
- frame : ± 100 kN
- max($f_{\rm L}$)= 50 Hz en $R_{\rm s}$ = -1

- IRFPA camera
- [3,5] mM
- max frame rate 250 Hz
- 640×320 pixels
- 18×23 µm²
- 14 bits
- δx ≈ 0.1 mm
 - (min 25 µm)
- *δT* ≈ 0.02 °C

Combining DIC & IRT



Stress derivation



e: thickness, w: width, L: length

① stress triaxiality neglected

plane stress

$$\begin{cases} \frac{\partial \sigma_{xx}(x, y, t)}{\partial x} + \frac{\partial \sigma_{xy}(x, y, t)}{\partial y} = 0\\ \frac{\partial \sigma_{xy}(x, y, t)}{\partial x} + \frac{\partial \sigma_{yy}(x, y, t)}{\partial y} = 0 \end{cases}$$

2 no volume variation

③ uniform distribution of tensile stress over a cross-section

④ no overall shear loading

⑤ no lateral stress

Heat rate

Heat equation averaged over the sample thickness

$$\rho C \left(\frac{\partial \bar{\theta}}{\partial t} + v_x \frac{\partial \bar{\theta}}{\partial x} + v_y \frac{\partial \bar{\theta}}{\partial y} + \frac{\bar{\theta}}{\tau_{th}} \right) - k \left(\frac{\partial^2 \bar{\theta}}{\partial x^2} + \frac{\partial^2 \bar{\theta}}{\partial y^2} \right) = \bar{w}_h^{\cdot}$$

Direct estimate of heat sources using noisy and discrete thermal data

Thermal noise

- uniform power spectrum
- Gaussian probability distribution

Refs: IJES : 2000 EXP-MECH : 2007 JoMMS : 2010 EXP-MECH : 2014

Estimate of the partial derivative operators

- thermal data projection onto spectral solutions (1995)
- periodic expansion and convolutive filtering by DFT (2000)
- local approximation of θ using I.sq. fitting (2004)
- POD: pre-filtering of thermal fields (2013)



Focusing on cyclic tests

Monochromatic uniaxial loading

Focus on a load-unload cycle



(*i*) $W_{def} = \int_{t_{\mathcal{A}}}^{t_{\mathcal{B}}} \sigma :\dot{\varepsilon} dt = \int_{t_{\mathcal{A}}}^{t_{\mathcal{B}}} d_1 dt + \int_{t_{\mathcal{A}}}^{t_{\mathcal{B}}} (\rho \dot{e} - \rho C \dot{T} + w_{thc}^{\bullet}) dt$ (*ii*) Hysteresis loop : $W_{def} = A_h$ (for uniaxial loading) (*iii*) Load-unload cycle = thermodynamic cycle $W_{def} = \int_{t_{\mathcal{A}}}^{t_{\mathcal{B}}} d_1 dt + \int_{t_{\mathcal{A}}}^{t_{\mathcal{B}}} w_{thc}^{\bullet} dt$ 12

IR image processing



13

Fatigue loading



figure m_i : series of "mini" cycle blocks (3000 cycles) at different stress ranges: energy balance at "constant fatigue state"

*p*_i: large blocks (100 000 cycles) at constant stress range: energy balance evolution induced by fatigue mechanisms

highest stress range ≈ fatigue limit

Thermal and calorific effects

HCF test on DP 600 steel



15

Dissipation properties (I)

 f_L = 30Hz and R_σ = -1



Dissipation properties (II)



energy safeguard: kinetics of fatigue progress

Case study #2 : back to thm couplings

The most simplistic non-adiabatic thermoelastic (the) model...



Thm couplings vs. viscosity



Visco-analysis of polymers - Dynamic Mechanical Analysis (DMA) 19

Entropic elasticity of natural rubber



Gough (1805) – Joule (1857) – Treloar (1960)

 $e(s,\varepsilon) = e_{nr}(T)$ perfect gas analogy $\psi_{nr}(T,\varepsilon) = TK_1(\varepsilon) + K_2(T)$ $W_{def}^{\bullet} = W_h^{\bullet}$ [Saurel, PhD 99] [Honorat, PhD 06] [Caborgan, PhD 11]

Concluding comments

- Full-field measurements Material vs. Structure effects
- Temperature, the 1st state variable ... thermal effects vs. calorimetric effects not totally intrinsic (heat diffusion)
- Heat sources of different nature Thm coupling sources : thermo-sensitivity dissipation sources : irreversibility of material deformation
- Energy balance and constitutive equations stored energy / state laws dissipated energy / evolution law
- Rate-dependent behaviour d₁ (viscosity) vs. [thm coupling + d₂ (heat diffusion)]