Time-dependent mechanical behaviour of wood and implication for painted panels

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Content:
- Introduction / Explaining the present condition
- Compression set and cupping of painted panels
- Modelling of compression set
- Conclusions / research needs
Introduction
Aims and approach

• Aim = find the optimal conservation conditions for wooden artworks
• Approach = produce mechanical models able to simulate the consequences of any action
• Models can
  (1) explain the present condition of an artwork
  (2) describe its present behaviour
  (3) predict the consequence of future conditions and/or actions
• A model doing both (1) and (2) is more convincing for (3)
• In panel paintings:
  (1) = permanent curvatures, cracks, patterns of craquelures
  (2) = reaction to frame, to microclimate
  (3) = change of frame or HT control, risk assessment (climatic accident, transportation…)
• Use of models can be
  - specific to a given artwork
  - general: assess conservation procedures, microclimate requirements...
Introduction / Explaining the present condition

The bent shape

- max deflection 11 mm
- Double curvature typical of a panel restrained on 4 edges, partially avoided by the crack

Shadow moiré observation of the surface topography
Introduction / Explaining the present condition

Double curvature & crack

- In case of Mona Lisa panel
  - cupping was restrained on upper and lower edges
    - double curvature
  - radial crack started from upper edge
Craquelure patterns in the paint layer (E. Ravaud 2006)

- quadrangular
- vertical
- inclined
- horizontal
Explaining the present shape
The typical deformation of painted panel

- Why do all unrestrained painted panels bent the same way, whatever the ring structure?
Compression set and cupping of painted panels

hygroelastic viewpoint

- panel = multi-layer
- in each layer:
  - elastic spring $\varepsilon^e = J_e \sigma$
  - expansion $\varepsilon^h = \alpha \cdot \Delta h$
- gradients along thickness
  - of moisture $h$
  - of properties $\alpha, J_e$
Compression set and cupping of painted panels

**hygroelastic viewpoint**

- response to a step of RH change
  - short term: independent on ring structure (moisture gradient)
  - long term: ring orientation dominates (expansion ratio gradient)
- fully reversible

![Diagram showing pith orientation and RH changes](image)
Compression set and cupping of painted panels
Mechano-sorptive effect

干
湿
干
湿

\( h = h_{\text{min}} \leftrightarrow h_{\text{max}} \)

观察到
“计算得到”

CORRECTED CREEP

\( \varepsilon - \varepsilon^h \)

LOGARITHM OF TIME

\( h = h_{\text{max}} \)

\( h = h_{\text{min}} \)
Compression set and cupping of painted panels

hygroviscoelastic viewpoint

- 2 types of Kelvin links:
  - viscelastic
  - mechanorptive
Cupping of painted panels

**hygroviscoelastic viewpoint**

- Flying wood: Evidence of tension/compression set
  - Permanent curvature observed after a humidity cycle
  - Essentially unrelated to ring structure
  - Irreversibility originates from mechanosorptive deformation, either tensile or compressive
- But why should contraction dominate over extension?

![Diagram showing RH and curvature relationships](image)
Compression set and cupping of painted panels

Origin of a panel curvature: the compression set

- Evidence of compression set in T direction (Hoadley 1995)
  - (A) free swelling/shrinkage: reversible
  - (B) free shrinkage, no swelling: evidence of compression set
  - (C) fully clamped: higher crack risk

- Explanation of compression set by Hoadley (1995)
  - During humidification at 2.5% compression, elastic limit has been exceeded. Wood « plastifies » 2% at unloading
  - During drying, wood subject to 2% tension that exceeds the elastic rupture
Compression set and cupping of painted panels

Origin of a panel curvature

- Slower moisture uptake from the painted face
- Restrained swelling of the back face
- Compressive stress
- Compression set
- Gradient of compression set results in permanent cupping

In panel paintings:
- Asymmetry of moisture movements causes cupping
- Compression set on the back face causes *permanent* cupping
- Partial restraint by the frame & crossbars may cause wood cracking
Compression set and cupping of painted panels

‘quasi’ reversibility of compression set

- Cupido’s arrow by l'oue (1982)
  - two different pieces of wood, no gluing:
    only wood rheology involved
  - how did the arrow penetrate the heart?
Compression set and cupping of painted panels

‘quasi’ reversibility of compression set

- Radial compression at increasing levels:
  - In dry condition, large permanent strain after each unloading
  - In wet condition, ‘almost’ full recovery + damage are observed

→ changing mc ~ wet?

compression with lateral restraint after Liu et al. (1993b)
Compression set and cupping of painted panels

**Why may wood not break in tension**

- Yes, wood exceeds linear limit, but ‘plastifies’ (with some damage?) being softened by humidification

![Graph showing stress-strain relationship](image)

Hoadley (1995)

- Yes, during drying a deformation is temporarily blocked (~2%) but recovers a part of it through mechanosorption
  - (A) free swelling/shrinkage
  - (B) free shrinkage, no swelling:
    - (C) fully clamped: higher crack risk

→ Evidence of compression set by no crack occurrence

DRY → WET → DRY
Modelling of compression set

Experimental data

![Graph showing compression set data]

**Experimental data**

- **STRAIN (%)**
  - epsA%
  - epsB%
  - epsB_calc

- **STRESS (MPa)**
  - sigB Mpa
  - sigB_calc

- **STRESS (MPa)**
  - sigC Mpa
  - sigC_calc
Modelling of compression set
Experimental data

- Experimental data

- Stress MPa vs. Imposed Strain % (-\(\varepsilon_A\))

Data for sigB and sigC, with calculated values sigB_calc and sigC_calc plotted on graphs.
Equations of the rheological model

\[ \varepsilon = \varepsilon^e + \varepsilon^h + \sum \varepsilon^v_i + \sum \varepsilon^ms_j + \varepsilon^p \]

- total strain:
  \[ \varepsilon^e = J^e \sigma \]
- elastic strain:
  \[ \frac{d\varepsilon^v_i}{dt} = \frac{(J^v_i \sigma - \varepsilon^v_i)}{\tau_i} \]
- viscoelastic strains:
  \[ \frac{d\varepsilon^ms_j}{dh} = \frac{(J^ms_j \sigma - \varepsilon^ms_j)}{\mu_j} \]
- mechanosorptive strains:

Compliances dependency on mc:

\[ \log J = A(h) + B(h) \log \tau + C(h) \log^2 \tau \]

\( (J = J_e, J^v_i, J^ms_j) \)
Equations of the rheological model

- combined plasticity & damage
  - relative plastic stress: \( s = \frac{\sigma_p}{\sigma_y} \) \( sp = \min[\sigma_y; \sigma(t)] < 0 \)
  - plastic strain: \( \varepsilon^p = (1-\lambda) f(s) J^0.\sigma \)
  - compliance change: \( J = Z J^0 \) \((J = Je, J^i, J^{ms})\)
  - damage factor: \( Z = 1 + \lambda .f(s)/s \)
  - anelastic function \( f(s) = m(s -1)^{1+n} \)
Conclusion

• Accounting for post linear time-dependent phenomena is required to explain the permanent cupping of panel painting
  - hygromechanical couplings between moisture changes and stress (mechanosorptive effect)
  - permanent microbuckling (compression set)
  - as damage is probably involved, the analysis of the shape generation is required to predict correctly the present and future hygromechanical behaviour of the object

• Application to modelling of panels painting in progress (cf talk of J. Colmars tomorrow)
  - model validation through case studies
  - application to simulate ranges of situations
Research needs

• Need for better knowledge of material properties of aged/ancient wood
  - heat and mass transfer
  - expansion ratios
  - Viscoelastic, mechanosorptive behaviour
  - damage evidence?

• Need for improved & validated models for predictive simulation:
  - to be used for case studies, with adjustment of parameters
  - to support assessment & improvement of current practices

• Integrated approach of the wooden support and the paint layer?
Thank you